Naval Facilities Engineering Systems Command

Naval Facilities Engineering and Expeditionary Warfare Center
and Naval Facilities Engineering Systems Command Atlantic

Final

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

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Executive Summary

This report entitled "Reanalysis of the Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings" is an update to the 2015 report entitled "A Quantitative Decision Framework for Assessing Navy Vapor Intrusion Sites," prepared by the Naval Facilities Engineering Systems Command (NAVFAC) Engineering and Expeditionary Warfare Center, NAVFAC Atlantic, and CH2M HILL, Inc. (now part of Jacobs Engineering Group Inc.) under the Department of the Navy's (Navy's) Environmental Sustainability Development to Integration (NESDI) program. The analyses documented in the 2015 NESDI report have been updated to include vapor intrusion (VI) data obtained from additional buildings at Department of Defense (DoD) installations, and this report documents those updates.

The primary objective of the 2015 NESDI project was to develop a vapor intrusion (VI) quantitative decision framework (QDF), including a flowchart, VI potential scorecard, and decision matrix, that can be used to systematically evaluate multiple lines of evidence obtained as part of VI assessments. The QDF provides a tool that can be used to assess VI potential based on existing site information, prioritize initial VI investigations, evaluate data to determine whether or not the VI pathway is likely complete, and guide long-term stewardship decisions. The QDF can be incorporated into Navy VI guidance documents, training, and other evaluation tools.

In support of the QDF, the project involved developing and analyzing a database of empirical VI data collected at DoD installations where investigations have been conducted to characterize VI potential of subsurface vapors resulting from historical releases of volatile organic compounds (VOCs). The database and associated analyses focus on chlorinated VOC VI data from nonresidential buildings (i.e., commercial or industrial buildings) and is referred to as the "DoD VI Industrial Database." The initial 2015 DoD VI Industrial Database contained data from 49 buildings at 12 DoD installations located in the United States. The database was updated in 2017 to include a total of 79 buildings at 22 DoD installations. The data include building information and indoor air, subslab soil gas, and groundwater data collected between 2008 and 2017 from 299 individual sample zones within the 79 buildings. The installations are located in a variety of regions and climates of the United States, and the buildings represent typical nonresidential structures. The buildings were constructed between 1905 and 2011, and their footprints range from 1,600 to 800,000 square feet.

As part of the updated database analyses presented in this report, single variable and multivariate analyses of geological and building parameters were performed to identify key factors influencing VI potential and the relationships between these factors. The project also included an analysis of subslab soil gas and groundwater attenuation factors (AFs) using methods consistent with those of the United States Environmental Protection Agency (USEPA) in the evaluation of their VI database (which primarily includes residential buildings). The AFs, which represent the reduction in vapor concentrations between the subsurface vapor source and indoor air, are used to calculate risk-based VI screening levels. The generic default AFs recommended in USEPA's 2015 VI guidance are based solely on residential building data, so the default AFs are not appropriate for large commercial and industrial buildings because their use results in an overestimation of potential VI-related risks and leads to additional, unnecessary VI investigations.

Many factors can influence VI; therefore, professional judgment was applied that considered consistency across different VOCs and representativeness based on sample size. Statistical test results were also reviewed for consistency with known physical mechanisms that support the observations.

Results of the analyses indicate that a subslab soil gas AF of 0.001 (10^{-3}) and groundwater AF of 0.0001 (10^{-4}) are defensible defaults (based on the 95th percentiles) for large nonresidential buildings. The results are summarized as follows:

- Using screening methods consistent with those used by USEPA to evaluate residential data in their VI database, we performed data analyses on the DoD VI Industrial Database. Results support the use of default subslab soil gas and groundwater AFs of 0.001 (10^{-3}) and 0.0001 (10^{-4}), respectively, for conducting VI assessments and for developing VI screening levels at large commercial and industrial buildings. These generic

AFs result in screening levels that are 30 times and 10 times greater than the USEPA generic residential building-based subslab soil gas and groundwater AFs of 0.03 and 0.001 (10^{-3}), respectively.

- Strong evidence suggests that indoor air concentrations do not rise linearly with subslab soil gas or groundwater concentrations, and that greater VOC concentrations in the subsurface result in relatively more attenuation (lower AFs) to the indoor air. Indoor air concentrations only increase 2 times when subslab soil gas concentrations increase about 4 times or when groundwater concentrations increase about 40 times.
- Single variable analyses using either subslab soil gas or indoor air concentrations (as the outcome variable) and distance to primary VOC release point (as the predictor variable) support that greater subslab soil gas and indoor air concentrations are generally associated with shorter distances to primary release.
- Single variable analyses using either subslab soil gas or indoor air concentrations (as the outcome variable) and soil type (as the predictor variable) show that greater subslab soil gas and indoor air concentrations are generally associated with fine soil than with coarse soil. These observations reflect the likely presence of vadose zone sources near the buildings and the fact that residual sources tend to be more prevalent in fine soil.
- Single variable analyses using subslab soil gas concentrations (as the outcome variable) and depth to groundwater (as the predictor variable) show that greater subslab soil gas concentrations are generally associated with shallower depths to groundwater. Multivariate analyses show a discernable trend of greater indoor air concentrations for shallower groundwater depths when considering only data associated with coarse soil.
- Neither the single variable nor the multivariate analyses show a statistically significant correlation between indoor air concentrations (as the outcome variable) and sample zone area, building area, or building volume (as the predictor variable). Greater areas or volumes would be expected to exhibit smaller indoor air concentrations given the increased potential for dilution of vapors entering the sample zone or building; however, other uncontrolled variables may play an important role, including air exchange rate and VOC source size.
- Single variable analyses using either subslab soil gas or indoor air concentrations (as the outcome variable) and the presence of an exterior (perimeter) wall in the sample zone (as the predictor variable) do not identify a statistically significant trend. The 2015 analyses identified greater subslab soil gas and indoor air concentrations when an exterior wall was present in the sample zone; however, the updated analyses (presented herein) could not replicate those initial findings, which were based on a smaller dataset. This lack of correlation may be attributable to increased air exchange via leakage through the building envelope.
- Single variable analyses using indoor air concentrations (as the outcome variable) and the presence and type of a heating, ventilation, and air conditioning (HVAC) system (as the predictor variable) indicate that an engineered HVAC system in the sample zone of interest has a protective effect, with generally lower indoor air concentrations attributable to VI in sample zones where an engineered HVAC system is present. This trend is conceptually supported by the fact that HVAC systems tend to increase air exchange and maintain positive pressurization within the sample zone.
- Single variable analyses using subslab soil gas concentrations, indoor air concentrations, or AFs (as the outcome variable) and period of construction (as the predictor variable) show that buildings constructed during World War II (WWII) or during the early years of the Cold War (through the late 1950s) tend to be associated with greater VOC concentrations in subslab soil gas. The indoor air concentrations and AFs, however, suggest more variability, likely because of poor weatherization and high air exchange rates in buildings from that era. Overall, the data suggest that WWII-era buildings often have strong subslab sources and could have elevated indoor air concentrations if they were renovated in a way that increased weatherization or reduced ventilation but did not decrease infiltration exposure.

- Single variable and multivariate analyses using indoor air concentrations (as the outcome variable) and sample zone or building use (as the predictor variable) suggest greater indoor air concentrations in sample zones (or buildings) with office use than with warehouse use. Several underlying mechanisms may explain this trend (e.g., overall zone or building size, air exchange, presence of roll-up doors). Regardless of trend, it may be appropriate to prioritize sampling in offices rather than in warehouses when other factors are similar given that offices are generally more densely occupied than warehouses, and office workers often remain at one location for longer periods of time during their shifts.
- Analyses of preferential pathways in the dataset indicate an inconsistent relationship between the presence of atypical preferential pathways and subslab soil gas concentrations. There is no indication in the dataset that atypical preferential pathways generally increase indoor air concentrations in sample zones where they are present compared to sample zones where they are absent. This does not eliminate the possibility that atypical preferential pathways could contribute to increased indoor air concentrations in some instances, as supported by other studies.

The VI potential scorecard and associated score weights were updated to reflect the above analyses (Figure 8-2), with the range of weights tailored to emphasize the importance of certain predictor variables consistent with the analytical results. This scorecard can be applied at the sample zone or building level. The greater the score, the greater the VI potential assigned to the sample zone or building of interest. The scores and relative weights are assigned as follows:

- The scorecard continues to consider two cases: whether both subslab soil gas and groundwater data are available or whether only groundwater data are available.
- The most weight is given to the magnitude of groundwater concentrations and subslab soil gas concentrations (if available) with scores increasing commensurate with the trends obtained from the DoD VI Industrial Database analyses. The greatest scores are assigned to the most elevated subslab soil gas or groundwater concentrations relative to the applicable VI screening levels. Both groundwater and subslab soil gas data are considered if available; however, subslab soil gas data are weighted more heavily than groundwater data in the overall score.
- Substantial weight is also given to the potential that a vadose zone source is near the building or sample zone of interest, with the higher scores assigned to the shortest distances to the primary release point or high-concentration source zone, and with greater weight assigned to fine soil than to coarse soil.
- If subslab soil gas data are unavailable, the depth to groundwater is considered, with higher scores assigned to shallow water tables.
- The presence of an engineering HVAC system is taken into consideration, with a greater score assigned to a sample zone or building without an HVAC system (reflecting an increased potential for a complete VI pathway).
- The building construction era is also taken into consideration, with a greater score assigned to buildings constructed during WWII or the early Cold War (reflecting an increased potential for a complete VI pathway).

The VI potential scorecard can be used to support building evaluation and VI investigations across an installation or site (Figure 8-4). Combined with indoor air data in a matrix format (Figure 8-5), the VI potential score can help decision makers evaluate whether observed indoor air concentrations are reasonably attributable to VI through a multiple line-of-evidence analysis. The VI potential score can also be used to support long-term stewardship decisions (Figure 8-6).

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Acronyms and Abbreviations

$\mu g/m^3$	micrograms per cubic meter
3D	3 dimensional
AF	attenuation factor
ANOVA	analysis of variance
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BASE	Building Assessment and Survey Evaluation
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CCN	category code number
CFM/ft2	cubic foot per minute per square foot
CH2M	CH2M HILL, Inc.
CRREL	Cold Regions Research and Engineering Laboratory
CSM	conceptual site model
DCA	dichloroethane
DCE	dichloroethene
DoD	Department of Defense
GC/MS	gas chromatography/mass spectrometry
HVAC	heating, ventilation, and air conditioning
iNFADS	internet Navy Facilities Asset Data Store
IQR	interquartile range
LOESS	locally estimated scatterplot smoothing
NA	not available
NAVFAC	Naval Facilities Engineering Systems Command
Navy	Department of the Navy
NEDD	NIRIS Electronic Data Deliverable
NESDI	Navy's Environmental Sustainability Development to Integration Program
NIRIS	Navy Installation Restoration Information Solution
PCE	tetrachloroethene
QDF	quantitative decision framework
r2	coefficient of determination ("R squared")
RCRA	Resource Conservation and Recovery Act
SAP	Sampling and Analysis Plan
TCA	trichloroethane
TCE	trichloroethene
UFP-QAPP	Uniform Federal Policy – Quality Assurance Project Plan
USEPA	United States Environmental Protection Agency
VC	vinyl chloride
VI	vapor intrusion
VOC	volatile organic compound
WWII	World War II

SECTION 1

Introduction

1.1 Background

In 2015, the Naval Facilities Engineering Systems Command (NAVFAC) Expeditionary Warfare Center, NAVFAC Atlantic, and CH2M HILL, Inc. (CH2M) (now part of Jacobs Engineering Group Inc.) completed a research project entitled *A Quantitative Decision Framework for Assessing Navy Vapor Intrusion Sites* (Venable et al., 2015), funded through the Department of the Navy's (Navy's) Environmental Sustainability Development to Integration (NESDI) program. The primary project objective was to develop a quantitative decision framework (QDF) that can be incorporated into Navy vapor intrusion (VI) guidance documents, training, and other evaluation tools. The project involved developing and analyzing a database of empirical data collected at Department of Defense (DoD) installations, including Navy installations, where the VI potential has been investigated. In this context, VI potential is defined as the potential for subsurface vapors related to historical releases of chlorinated volatile organic compounds (VOCs) to migrate into overlying DoD buildings, with building use limited to nonresidential settings (i.e., commercial and industrial). In the rest of this report, this database is referred to as the "DoD VI Industrial Database."

As documented in Venable et al. (2015), single variable and multivariate analyses of geological and building parameters were performed to identify the key factors influencing VI potential and the relationships between these factors in support of the QDF. The QDF provides a prediction of VI potential based on analysis of data collected at a variety of DoD commercial and industrial buildings, and can be used to prioritize initial VI investigations, evaluate multiple lines of evidence to determine whether detected indoor air concentrations are VI-related, and guide long-term stewardship decisions.

The project also conducted analyses of normalized indoor air concentrations—commonly called attenuation factors (AFs; USEPA, 2015)—for commercial and industrial buildings using methods consistent with those used by the United States Environmental Protection Agency (USEPA) in the evaluation of their VI database (USEPA, 2012a). The AFs, which represent the reduction in vapor concentrations between the subsurface source and indoor air, underlie the risk-based groundwater and soil gas VI screening levels frequently used during the initial phase of VI investigations. The USEPA (2012a) VI dataset is composed primarily of data from residential structures.[1] The AF distributions presented in USEPA (2012a) and USEPA's recommended generic AFs (USEPA, 2012a, 2015) are derived based solely on chlorinated VOC data in residential buildings. These generic AFs have been shown to be overly conservative when applied to commercial or industrial buildings at DoD installations (Venable et al., 2015).

The initial 2015 DoD VI Industrial Database contained VI-related data from 49 commercial and industrial buildings from 12 DoD installations located in the United States. This database was updated in 2017 to include a total of 79 buildings from 22 DoD installations. The analyses in Venable et al. (2015) have also been updated to include the data from the expanded database and this report documents these updates. A list of specific tasks is presented in the next section.

[1] The building types represented in USEPA (2012a) database include residential (85 percent), institutional or commercial (10 percent), and multi-use (residential and nonresidential) buildings (5 percent); however, USEPA analyses are focused on chlorinated VOCs in residential settings (USEPA, 2012a, Sections 2.3 and 4.1).

1.2 Overview of Updated Analyses

The updated analyses were completed using data from the 79 buildings[2] in the DoD VI Industrial Database and included the following tasks:

- Paired subslab soil gas-indoor air and groundwater-indoor air data were analyzed using different source strength screens—similar to USEPA's methodology (USEPA, 2012a)—to observe subslab soil gas-to-indoor air and groundwater-to-indoor air AF distribution changes and stabilization with increasing screen strength, including the median (50th percentile), as well as the 90th and 95th percentiles of the AF distributions. This serves as the basis for establishing the generic AFs. Source strength screens include several multipliers of background concentrations (consistent with USEPA's [2012] approach), as well as common source strength screens across all VOCs (i.e., fixed subslab soil gas concentrations or fixed groundwater vapor concentrations across all VOCs). The objective of these analyses was to identify source strength screens and generic AFs that are not significantly influenced by background sources.
- The subslab soil gas-to-indoor air and groundwater-to-indoor air AF distributions were calculated at the building level using the selected source strength screens obtained from the previously mentioned analyses.
- The subslab soil gas-to-indoor air and groundwater-to-indoor air AF distributions were calculated at the sample zone level (instead of at a building level) using the selected source strength screens.
- The previously mentioned analyses were implemented using average subslab soil gas and average indoor air concentrations. For comparison and to evaluate the significance of source strength, the subslab soil gas-to-indoor air AF distribution was also calculated using the maximum subslab soil gas and indoor air concentrations.
- Specific datasets (e.g., Cold Regions Research and Engineering Laboratory [CRREL] data) were evaluated for potential biases and potential impacts on the AF distributions (e.g., review of installation and building information for potential background contributions that may impact the measured indoor air concentrations).
- Multivariate analyses were performed to evaluate the relationships between subslab soil gas-indoor air concentrations and other variables, including groundwater depth, soil type, groundwater concentrations, and building characteristics (e.g., dimension; volume; use; and heating, ventilation, and air conditioning [HVAC] type).
- Data associated with atypical preferential pathways were analyzed to assess possible relationships with distance to primary release.

The previously mentioned analyses were used to prepare revisions to the QDF as follows:

- The scorecard was revised to adjust weight ranges and include (or exclude) specific parameters (without complete restructuring of the scorecard).
- An interactive spreadsheet was prepared for conducting site scoring, with Excel workbook set up to score individual buildings or sample zones.

[2] Three of the buildings were excluded from most analyses due to the presence of atypical VI preferential pathways; however, these buildings remain part of the atypical preferential pathway analyses.

SECTION 2

Methods

This section provides an overview of the methods used to process and analyze data.

2.1 Department of Defense Vapor Intrusion Industrial Database Overview

In 2015, the DoD created a first-of-its-kind VOC VI database for DoD commercial and industrial buildings under the NESDI program (Venable et al., 2015), and this database was updated to include a total of 79 buildings[3] from 22 DoD installations (Figure 2-1). It is comparable in the number of results and size to the USEPA VI database (USEPA, 2012a).

A detailed description of the DoD VI Industrial Database structure is provided in Section 5.2 of the final report for NESDI #476 (Venable et al., 2015) and in the associated DoD NESDI VI Database User's Guide (CH2M et al., 2017).

The final distribution of building size for the 79 buildings in the DoD VI Industrial Database is as follows:

- 11 buildings have footprint areas greater than 100,000 square feet
- 26 buildings have areas ranging from 20,001 to 100,000 square feet
- 29 buildings have areas ranging from 5,001 to 20,000 square feet
- 13 buildings have areas of 5,000 square feet or less

The DoD VI Industrial Database includes both commercial and industrial buildings, with most uses commonly found at DoD installations (e.g., maintenance, offices, storage). Buildings included in the USEPA VI database are primarily single-family residences.

The 79 buildings correspond to 299 sample zones, [4] with each building having one or more sample zones (up to 17 in one building).[5]

2.2 Department of Defense Vapor Intrusion Industrial Database Refinements

Following its expansion, the DoD VI Industrial Database was further refined in 2019 to incorporate the latest information for locations where new knowledge had been gained about atypical preferential pathways or background (indoor or outdoor) sources, which could influence the classification of datasets already input. The database was also modified to allow data filtering using different source strength screens (see Section 2.3).

[3] The database includes three buildings where atypical VI preferential pathways were identified. These three buildings are not part of the analyses presented in this report, except for the analyses related to atypical preferential pathways (Section 7).

[4] VI in large commercial or industrial buildings must often be evaluated by specific sample zones depending on a number of factors, including HVAC configuration, air exchange, and air flow. A building (or sample) zone can be defined as an enclosed, occupied location within a building where at least one indoor air sample has been collected. This zone should have limited air mixing with other building zones and be defined so that air is expected to be reasonably well and rapidly mixed throughout the zone.

[5] Of these 299 sample zones, 25 zones were excluded from most analyses: 20 zones are within the 3 above-referenced buildings with atypical VI preferential pathways; and 5 zones from 2 buildings were excluded based on upper floor locations.

Review of the expanded database indicated the presence of outliers, primarily associated with the CRREL installation.[6] Further discussions were held with facility personnel to obtain updated information regarding investigation status and determination of atypical preferential pathways and background sources (Appendix A). Based on the additional investigation, the CRREL main building was found to have a significant background indoor source from former cold box insulation. During removal, the cold box insulation was found to be soaked with fluids, including trichloroethene (TCE). Additionally, a persistent source affecting the second floor was found to be related to roofing material on one end of the building. Based on this information, sample zones located in the main laboratory building were excluded from the analyses due to the presence of a background indoor source. Sample zones in the sub-basement of the laboratory building addition were also excluded because this building is connected to the main laboratory building through doorways on all floors. In several other cases, data collected on second floors were found and excluded from the analysis for consistency.

2.3 Department of Defense Vapor Intrusion Industrial Database Modification

The analyses presented in this report were used to examine the effect of source strength screen on the overall VI dataset, particularly on the changes in subslab soil gas-to-indoor air and groundwater-to-indoor air AF distributions (see Sections 4.1 and 4.2). These analyses were intended to examine the effects of background source contributions on the data, consistent with the approach used by USEPA (2012a). To implement the source strength screening procedures (further discussed in Section 2.4), the DoD VI Industrial Database (developed in Access) was modified so that each sample zone and data pairing had the ability to be filtered based on different source strength screens. Specifically, the new source strength screen fields made it possible to filter out sample zone data for a relatively strong source strength screen while keeping these same data with a weaker screen. To that end, the Access database queries that were used to generate the flat file[7] were modified so the flags would be generated based on the selected source strength screen. Additional information about the database modifications is included in Appendix B.

2.4 Data Analysis Methods

The procedures for analyzing the DoD VI Industrial Database were modeled closely on those used with the USEPA VI database analysis (USEPA, 2012a). This section provides an overview of these methods, along with specifics relative to the updated DoD VI Industrial Database. Additional information can be found in the original data analysis report (Venable et al., 2015).

Consistent with NESDI #476 (Venable et al., 2015), a subset of VOCs was selected for detailed analysis. The following VOCs were selected based on the size of the dataset and because of their common presence at DoD facilities:

- 1,1,1-Trichloroethane (1,1,1-TCA)
- cis-1,2-dichloroethene (cis-1,2-DCE)
- trans-1,2-dichloroethene (trans-1,2-DCE)
- Tetrachloroethene (PCE)
- TCE
- Vinyl chloride (VC)

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[6] The CRREL is part of the United States Army Corps of Engineers (USACE) Engineering Research and Development Center (ERDC).

[7] The flat file is a file that contains the individual indoor air, subslab soil gas, and groundwater vapor concentration records extracted from the DoD VI Industrial Database. These records are processed in “R” for graphical display or statistical analysis.

- 1,1-Dichloroethane (1,1-DCA)
- 1,1-Dichloroethene (1,1-DCE)
- 1,2-DCA

2.4.1 Background Value Selection

The USEPA VI database relies on source strength screens for filtering out subslab soil gas-indoor air or groundwater-indoor air data pairs that likely introduce bias into the analyses and AF distributions (USEPA, 2012a). This bias potential is related to background VOC source contributions to indoor air, which may occur even in the absence of VI. In the USEPA (2012a) VI database analysis, a source strength screen filters out subslab soil gas-indoor air data pairs for a given VOC whenever the subslab soil gas concentration of the data pair is less than 50 times (50X) the background indoor air value for this VOC. Similarly, a source strength screen filters out groundwater-indoor air data pairs for a given VOC whenever the groundwater[8] concentration of the data pair is less than 1,000 times (1,000X) the background indoor air value for this VOC. The background indoor air value used by USEPA for each VOC was taken as the median of the 90th percentile background concentrations in North American residences obtained from the USEPA study compilation (USEPA, 2011, Table ES-1; USEPA, 2012a, Table 5). Select VOCs, such as cis-1,2-DCE and 1,1-DCA, did not have background indoor air values and, therefore, none of their data pairs were screened out in the USEPA (2012a) VI database.

Consistent with USEPA's approach, the 2015 DoD VI Industrial Database analysis used 90th percentile background VOC concentrations (Venable et al., 2015, Section 5.3.5, Table 5-3). Given the commercial and industrial nature of the DoD VI Industrial Database, the background values were derived from USEPA's Building Assessment and Survey Evaluation (BASE) study indoor air distribution, which is focused on nonresidential buildings (NYSDOH, 2006, Appendix C, Section C.2, Table C2; USEPA, 2017, 2020).

For the analyses presented in this report, the background VOC values were adjusted relative to those used in the Venable et al. (2015) analysis. The rationale for adjusting the background values is discussed in the survey of background VOC studies (Appendix C) and is summarized as follows:

- The data from the BASE studies were collected during the period 1994-1998, which is 10 to 20 years older than the sampling data in the DoD VI Industrial Database (2008-2017). There is evidence to suggest that typical background VOC concentrations have decreased both in indoor and outdoor (ambient) air during that period (USEPA, 2011, Figures 1 and 2; USEPA, 2019, Exhibit 9).
- Reporting limits from the BASE study are greater than those that can be achieved in more recent studies, such that select VOCs that were historically below reporting limits now exhibit some detectable background levels in indoor air.
- Select VOCs, including 1,2-DCA, that were not present in indoor air during the 1990s have been more prevalent in later decades (Doucette et al., 2010; USEPA, 2011, Figure 1).

Table 2-1 presents the background VOC values selected for this project along with the associated source strength screens. The background value selections can be summarized as follows:

- TCE, PCE, and 1,1,1-TCA – Values equal to half of the BASE study 90th percentile concentrations were selected to account for the decrease in background concentrations for these three VOCs during the period since the BASE study was conducted. The resulting values were found to be consistent with data obtained in more recent studies (Appendix C).
- 1,1-DCE, VC, cis-1,2-DCE, and 1,1-DCA – The BASE study 90th percentiles for these four VOCs were below detectable levels. As a substitute, the medians of the 90th percentile concentrations obtained from the USEPA residential study compilation were used consistent with the USEPA VI database approach (USEPA, 2011, Table

[8] Specifically, the VOC concentration in vapor that is in equilibrium with groundwater.

ES-1; USEPA, 2012a, Table 5). Accordingly, background values remain below reporting limit for cis-1,2-DCE and 1,1-DCA but yield detectable levels for 1,1-DCE and VC.

- 1,2-DCA – The BASE study 90th percentile for this VOC was below its reporting limit. More recent studies observed detectable background levels in indoor air for this compound (Appendix C). A background value was selected based on a recent nonresidential study (Rago, 2015).
- trans-1,2-DCE – Neither residential nor nonresidential studies reported background levels above reporting limits for this VOC; however, there is some evidence to suggest trans-1,2-DCE can be found in indoor air at background concentrations due to its usage as a solvent and specialty cleaner. Although no background value was set for the purpose of this project, fixed source strength screens were able to filter out potential background contributions related to this VOC.

2.4.2 Data Pairing

2.4.2.1 Subslab Soil Gas-Indoor Air Data Pairing

Because several indoor air or subslab soil gas samples were collected from select sample zones as part of one-time or multiple sampling events, rules were defined to average and pair subslab soil gas and indoor air data. These rules are discussed in more detail in Section 4.1 with a variety of examples. The rules can be summarized as follows:

- Subslab soil gas-to-indoor AF calculations were based on VOC data pairs located within a given building sample zone, with both samples collected as part of the same sampling event (defined as a period of within 14 days or less).
- Where more than one subslab soil gas or indoor air sample were collected within a sample zone during a given sampling event, a single AF value was calculated for the sample zone by using the ratio of the arithmetic averages of the indoor and subslab soil gas concentrations obtained within the sample zone. The source strength screen was applied to the average subslab soil gas concentration for the sample zone.
- The source strength screen was applied on a sampling event basis, such that a given sample zone could have sampling events that passed the source strength screen and other sampling events that failed the screen (any such event would have had an average subslab soil gas concentration below the screen). This approach differs from Venable et al. (2015) where all sampling events of a sample zone passed the source strength screen as long as at least one sampling event passed.

2.4.2.2 Groundwater-Indoor Air Data Pairing

Where groundwater data were available, each sample zone was associated with a set of four groundwater concentrations, as follows:

- The minimum and maximum concentrations measured in monitoring wells within 100 feet of the sample zone perimeter in any direction.
- The minimum and maximum (interpolated) concentrations beneath the sample zone determined using an iso-concentration map.

Only groundwater concentrations measured within a year of an indoor sampling event were paired with the indoor air data. An exception could be made if the VOC plume beneath the sample zone was stable over a multi-year period or if several indoor air sampling events were conducted over a period exceeding one year.

For certain buildings, different sample zones could be associated with different sets of groundwater concentrations. This is because each sample zone could have a different group of monitoring wells within 100 feet of its perimeter, particularly for buildings with large footprints and/or multiple monitoring wells nearby. Once a set of monitoring wells was assigned to a sample zone, a single set of groundwater concentrations was associated with that sample zone, such that the groundwater concentrations could be associated with several indoor air sampling events within that zone. In other words, the groundwater concentrations associated with a given sample zone remained unchanged for different sampling events.[9]

Multiple indoor air concentrations obtained within the same sample zone were averaged similar to the approach described for the subslab soil gas-indoor air data pairs (Section 2.4.2.1). The pairing rules are discussed in more detail in Section 4.2 with a variety of examples.

2.4.3 Accounting for Background

Screening procedures for accounting for background sources in the DoD VI Industrial Database were modeled closely on those used in USEPA VI database (USEPA, 2012a). The objective of these procedures was to limit the influence of background VOC contributions on the AF statistical analyses (Sections 4.1 and 4.2). Section 2.4.3.1 summarizes the approaches for subslab soil gas-indoor air data pairs. Section 2.4.3.2 summarizes the approaches for groundwater-indoor air data pairs.

2.4.3.1 Subslab Soil Gas-Indoor Air Data Pair Screening

The following screening/filtering steps were applied to the subslab soil gas-indoor air dataset:

- Step 1 – Data pairs with subslab soil gas concentrations below detection limits were generally excluded. This step, which is termed by USEPA (2012a) as the “subsurface concentration screen,” is intended to reduce the influence of potential background VOC indoor or outdoor sources that are unrelated to VI. For data pairs where several subslab soil gas samples were collected from the same sample zone during a given sampling event, the average subslab soil gas concentration was used and concentrations below detection limit, if present, were assumed to be equal to the detection limit for computing the average. Subslab soil gas-indoor air pairs with only non-detects in subslab soil gas were excluded.
- Step 2 – Information about indoor or outdoor background VOC sources provided in site investigation reports was reviewed. These reports often contained background source survey information, with a few explicitly identifying specific background VOC sources pertinent to the investigations. Cases where a specific indoor source was identified were excluded from the analysis.
- Step 3 – Indoor-to-subslab soil gas concentration ratios were calculated for different analytes. Analytes with ratios that were different from the other analytes by one order of magnitude or more were assumed to indicate the potential influence of a background source. This step along with Step 2 are equivalent to USEPA’s (2012a) “data consistency screen.”
- Step 4 – Data were compared with site-specific outdoor (ambient) air concentrations where available to assess the potential for outdoor background sources to influence measured indoor air concentrations. Data pairs where the indoor air concentrations were less than two times the measured outdoor air concentration(s) were excluded from the AF calculations given the likelihood that outdoor air is an important source contribution to the measured indoor air concentrations. Steps 1 through 4 define what USEPA calls the “baseline screen.”
- Step 5 – Cases where significant atypical preferential pathways were confirmed during the VI investigation were excluded from the AF calculations. An atypical preferential pathway (also referred to as a “strict” preferential pathway in this report) is one by which vapor may move into a sample zone in a less inhibited manner than the traditional pathway due to a high-permeability conduit that can serve as a high-capacity transport pathway from a VOC vapor source to the building. Examples of atypical preferential pathway include sewer lines and utility tunnels or vaults (TSERAWG, 2020). Floor and foundation cracks and expansion joints are not considered atypical preferential pathways.

[9] This approach differed from that used for the subslab soil gas-to-indoor air AF analyses, where indoor air data were paired with subslab soil gas concentrations collected during the same sampling event, defined as a period of within 14 days or less (Section 2.4.2.1).

- Step 6 – Subslab source strength screening was conducted using the selected background values discussed in Section 2.4.1. Different source strength screens were tested to examine their effects on the dataset and AF distributions, including multiples of the background values ranging from 10 to 1,000 times (10X to 1,000X) the selected background value for a given VOC, as well as fixed source strength screens ranging from 100 to 1,000 micrograms per cubic meter ($\mu g/m^3$) (Table 2-1). The effects of these source strength screens are further discussed in Section 4.1.2.

Table 2-2 shows the number of indoor air data points remaining after each step for the nine VOCs of interest referenced in Section 2.4. The source strength screen applied for preparing this table is 1,000 times (1,000X) background for VOCs with background values (TCE, PCE, 1,1,1-TCA, 1,1-DCE, 1,2-DCA, and VC) and 1,000 $\mu g/m^3$ for VOCs without background values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE). As further explained in Section 4.1.2.1, these source strength screens were commonly selected for analyzing subslab soil gas-indoor air data pairs presented in this report.

2.4.3.2 Groundwater-Indoor Air Data Pair Screening

The following screening/filtering steps were applied to the groundwater-indoor air dataset:

- Step 1 – Only groundwater-indoor air data pairs with detectable groundwater concentrations for a given VOC were considered. This step corresponds to USEPA's "subsurface concentration screen" (USEPA, 2012a). This step is intended to remove data pairs from the analysis in which indoor air detections are unlikely to be related to VI from groundwater.
- Step 2 – Groundwater-indoor air data pairs were excluded in instances where there were no detections of a given VOC in subslab soil gas; however, this screening was conducted at the building level. In other words, a groundwater-indoor air data pair associated with a sample zone could be screened in without detection in subslab soil gas if there was another zone in the building with a detection in subslab soil gas. A groundwater-indoor air data pair with no detection in subslab soil gas beneath the sample zone or beneath other zones of the same building was screened out. This step is intended to remove data pairs from the analysis for which the groundwater concentration is not sufficiently high to result in detectable VOC concentrations in subslab soil gas.
- Step 3 – Information was reviewed about indoor and outdoor background source(s) provided in site reports. The "background" table in the DoD VI Industrial Database was used to document whether indoor detections were related to outdoor air detections or a confirmed indoor source. Cases where an outdoor source or a confirmed indoor source was identified were excluded from the analyses.
- Step 4 – Indoor-to-subslab soil gas concentration ratios were calculated for different VOCs. VOCs with ratios that were different from the other analytes by one order of magnitude or more were assumed to indicate the potential influence of a background source. Steps 3 and 4 are equivalent to USEPA's "data consistency screen" (USEPA, 2012a).
- Step 5 – Indoor air data were compared with site-specific outdoor (ambient) air concentrations, where available, to assess the potential for outdoor background sources to influence measured indoor air concentrations. Data pairs where the indoor air concentrations were less than two times the measured outdoor air concentration(s) were excluded from the AF calculations, given the likelihood that outdoor air is the primary source of the measured indoor air concentrations. Steps 1 to 5 are equivalent to what USEPA calls the "baseline screen" process (USEPA, 2012a).
- Step 6 – Cases where significant atypical preferential pathways (as defined in Section 2.4.3.1) were confirmed during the VI investigation were excluded from the AF calculations.
- Step 7 – Groundwater source strength screening was conducted using the values discussed in Section 2.4.1. Prior to screening, groundwater concentrations were converted to vapor concentrations using Henry's law at 20 degrees Celsius (referred to as the groundwater vapor concentration; USEPA, 2012a). Different source strength screens were tested to examine their effects on the dataset and AF distributions, including multiples

of the background values ranging from 100 to 5,000 times (100X to 5,000X) the selected background value for a given VOC, as well as fixed source strength screens ranging from 1,000 to 100,000 µg/m^3 (Table 2-1). The source strength screen was applied to both the maximum measured groundwater vapor concentration and the maximum interpolated groundwater concentration (Section 2.4.2.2). This means that an indoor air groundwater vapor data pair passing the source strength screen (i.e., retained for inclusion in the AF calculations) met the following conditions:

– The sample zone had a well within 100 feet where the groundwater vapor concentration was above the source strength screening concentration (i.e., the maximum measured groundwater vapor concentration exceeded the source strength screen).

– Part of the sample zone was above an area of a groundwater plume with a vapor concentration above the source strength screening concentration (i.e., the maximum interpolated groundwater vapor concentration exceeded the source strength screen).

The effects of these source strength screens are further discussed in Section 4.2.

Table 2-3 shows the number of indoor air data points remaining after each step for the nine VOCs of interest referenced in Section 2.4. The source strength screen applied for preparing this table is 5,000 times (5,000X) background for VOCs with background values (TCE, PCE, 1,1,1-TCA, 1,1-DCE, 1,2-DCA, and VC) and 10,000 µg/m^3 for VOCs without background values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE). As further explained in Section 4.2.2.1, these source strength screens were commonly selected for analyzing groundwater-indoor air data pairs presented in this report.

2.4.4 Single Variate Analysis Methods

The methodology of the single variate data analysis was identical to that reported in Venable et al. (2015), except as described in this report.

Data were plotted and analyzed using the R software package (R Core Team, 2018; Venables et al., 2018). The primary graphical tool for the analysis was the ggplot2 library of the R-statistical software. To compare the statistical distributions between samples, the function “geom_boxplot” was used (Wilcox et al., 2014). In the geom_boxplot function, the upper and lower “hinges” correspond to the first and third quartiles (25th and 75th percentiles, respectively); the middle “hinge” correspond to the 50th percentile (median of the sample). Regarding the whiskers, the lower and upper whiskers represent the maximum and minimum values from the distribution and the intermediate whiskers correspond to the fences that define the outliers. The outliers follow a standard definition of “outlier”, where the upper fence (whisker) extends from the hinge to the highest value that is within 1.5 * IQR of the hinge, where IQR is the interquartile range (IQR), or distance between the first and third quartiles. The intermediate whisker between the minimum and the first quartile extends from the hinge to the lowest value within 1.5 * IQR of the hinge. Data beyond the end of the intermediate whiskers up until the maximum or minimum whiskers are outliers, and plotted as points (McGill et al., 1978).

Statistical analyses for categorical variables, such as soil type and presence of exterior wall, used the unpaired two-samples Wilcoxon test (also known as Wilcoxon rank sum test or Mann-Whitney test), which is a non-parametric alternative to the unpaired two-samples t-test, which can be used to compare two independent groups of samples. This analysis used a standard definition of statistical significance (p-value of less than 0.05), unless otherwise indicated. The p-value is the probability of obtaining results that are at least as extreme as the observed results assuming that the null hypothesis is correct.

The statistical significance of various quantiles for soil type and presence of exterior wall was calculated using the qcomhd function of the WRS2 package of the R-statistical software (Wilcox et al., 2014). The function compares user-defined quantiles of both distributions using a Harrell–Davis estimator in conjunction with a percentile bootstrap and the sequentially rejective technique derived by Hochberg (Hochberg, 1988). With the Hochberg method, the function controls the probability of Type 1 errors[10] as the function tests each quantile. Given that small-sized samples are used, the p-value calculated for each quantile must be lower than a quantile-specific critical value to demonstrate significance. Additional discussion and examples of p-value comparison for each quantile are provided in Section 3.3.

Note that it is possible to have a trend that reaches statistical significance as measured by the p-value, but for which the predictor variable has little influence on the outcome variable as indicated by a low coefficient of determination or "R squared" (r^2). This is especially true for a process like VI where the outcome variables (e.g., indoor air or subslab soil gas concentration) are known to be a function of many interacting predictor variables (USEPA, 2012a, 2012b, 2015). A p-value indicating statistical significance combined with a low r^2 would suggest that the predictor variable being studied is not the most important predictor. In this report, the r^2 and p-values are presented as part of the analytical results, but a critical evaluation is also conducted in light of the following:

- Consistency (or lack thereof) in results across multiple VOCs and across multiple methods of statistical analysis (e.g., single variable and multivariate)
- Consistency of results with reasonable chemical, physical, historical, or building science mechanisms

The reader should also note that the assumption in the statistical calculations that the measurements are independent of each other and randomly drawn from the underlying population is not completely satisfied. For instance, the dataset often contains several sampling events from the same sample zone. The dataset also includes several sample zones within a given building or several buildings within a given installation. In some cases, the data are aggregated across sampling events or across sample zones to limit and evaluate potential bias effects; however, the lack of independence in the dataset may still affect the r^2 and p-values.

Finally, the reader should recognize that there is an inherent bias in the dataset in that the buildings and installations included were thoroughly studied examples of potential VI available at the time the data were compiled. Thus, the dataset predominantly includes buildings that—given the site-specific information and the VI state of knowledge at that time of sampling—were believed to have sufficient VI-related risk to merit sampling. This inherent bias would tend to be in the direction of higher indoor air and subslab soil gas concentrations.

The results of the single variable analyses (Sections 3 and 4) were used to target specific multivariate analyses of interest (Section 5; see also Section 2.4.5).

2.4.5 Multivariate Analysis Methods

Multivariate analyses were performed to evaluate potential relationships between outcome variables (i.e., subslab soil gas and indoor air concentrations) and variables that are known to be related through theoretical considerations, such as groundwater depth, soil type, and groundwater concentrations. This analysis was initially done exploratorily by using the Scatterplot3d functionality in R including exploring log-transformed depth as a variable (R Core Team, 2018; R Studio Team, 2019). The significance of the observed predictor variables from the exploratory analysis was then tested quantitatively using multiple regression or analysis of variance (ANOVA) techniques.[11]

To implement multivariate analysis, a data subset was created using the flat file to filter down records using the baseline and atypical preferential pathway screens discussed in Section 2.4.3, along with a VOC-specific source strength screen for each data record as follows (see also Section 2.4.3):

- For subslab soil gas-indoor air data:
  - Use 1,000 times (1,000X) background as a subslab soil gas screen for VOCs with an established background level (TCE, PCE, 1,1,1-TCA, VC, 1,1-DCE, 1,2-DCA)

[10] A type 1 error is the rejection of a true null hypothesis, also referred to as a "false positive".

[11] The ANOVA routines were implemented in the statistical program R as described at https://www.datanovia.com/en/lessons/anova-in-r/#report.

  - Use a constant value screen of 1,000 µg/m^3 for subslab soil gas for VOCs without measurable background level (cis-1,2-DCE, trans-1,2-DCE, 1,1-DCA).

- For groundwater-indoor air data:
  - Use 5,000 times (5,000X) background as a groundwater screen for VOCs with an established background level (TCE, PCE, 1,1,1-TCA, VC, 1,1-DCE, 1,2-DCA)
  - Use a constant value screen of 10,000 µg/m^3 for groundwater vapor for VOCs without measurable background level (cis-1,2-DCE, trans-1,2-DCE, 1,1-DCA).

Additional transformed variables were identified for this analysis based on professional judgment or experience from prior analyses (Venable et al., 2015) as follows:

- Log of groundwater depth
- Season, with "winter season" represented by sampling during the 4-month period from November to February
- Ratio of maximum groundwater vapor concentration to groundwater depth
- Square root of ratio of maximum groundwater vapor concentration to groundwater depth
- Presence or absence of an exterior wall in the sample zone
- Soil type, divided into the following subcategories: fine and coarse.

The following plots were produced with Scatterplot3d using the screened data:

1. Indoor air concentration (z-axis) as a function of groundwater depth (x-axis) and groundwater concentration (y-axis), with data grouped using different symbol colors to represent fine, coarse, and unknown soil types.
2. The same approach described in number 1 was applied after filtering out data based on a distance to primary release of less than 30 feet. This is intended to focus data analysis on sample zones where VI originates primarily from groundwater.12
3. Subslab soil gas concentration (z-axis) as a function of groundwater depth (x-axis) and groundwater concentration (y-axis) data were filtered as described in number 2 (i.e., filtering out data with a distance to primary release of less than 30 feet) and grouped by the soil types as described in number 1.
4. Indoor air concentration (z-axis) as a function of subslab soil gas concentration (x-axis) and sample zone area (y-axis), with data grouped using different symbol colors to represent whether large open doors were suspected. The presence or absence of large open doors were assigned based on:
   - The primary use category code number (CCN) from the internet Navy Facilities Asset Data Store (iNFADS).
   - A categorization based on whether closed or open doors were expected in a particular zone CCN. For example, the primary use CCNs for "painting and finishing hangar" and "warehouse" were considered as likely to have large open doors. The primary use CCNs for "Bathroom" and "classroom" were considered unlikely to have open doors.
5. Indoor air concentration (z-axis) as a function of subslab soil gas concentration (x-axis) and sample zone area (y-axis), with data grouped using different symbol colors to represent different zone uses.
6. Same as number 5, but only including data collected in the winter.

[12] This analysis is a simplified version of a prior analysis (see Venable et al., 2015, Section 5.3.7). This also assumes that the point of release is small and well identified.

7. Indoor air concentration (z-axis) as a function of subslab soil gas concentration (x-axis) and building area (y-axis), with data grouped using different symbol colors to represent different building uses (i.e., same as number 5, except sample zone area is replaced by building area).
8. Indoor air concentration (z-axis) as a function of subslab soil gas concentration (x-axis) and building volume (y-axis), with data grouped using different symbol colors to represent different building uses (i.e., same as number 7, except building area is replaced by building volume).

Single Variable Analysis – Factors Affecting Subslab Soil Gas Concentrations

For the analysis included in this section, the outcome variable is the subslab soil gas concentration. While subslab soil gas concentrations can be influenced by background sources, the concentration attributable to background sources in subslab soil gas would be expected to rarely exceed the 90th percentile background indoor air concentration. Therefore, for this analysis, it was determined that it was not necessary to apply the selected source strength screens to subslab soil gas data (see source strength screening in Section 2.4.3.1).

Cases where there is little attenuation from groundwater vapor to subslab have been identified for coarse soils from database analyses and three-dimensional modeling (USEPA, 2012a, 2012b). Therefore, where needed in this section, the least restrictive groundwater source strength screen (100 times the background value or 1,000 $\mu g/m^3$ constant value when a background value was not available) was used to generate the updated plots.

3.1 Groundwater Concentration

Conceptually, greater subslab soil gas concentrations under a building would be expected to be associated with greater groundwater concentrations near that building. For a groundwater source, greater groundwater concentrations would theoretically be expected to result in greater soil gas concentrations adjacent to the water table, which in turn would lead to greater subslab soil concentrations assuming an identical depth to groundwater (USEPA, 2012b). For a vadose zone source, greater subsurface soil gas concentrations would be expected to result from greater near-source soil gas concentrations, which on the basis of the mass partitioning equation (EQM, 1997) would reflect a greater amount of contaminant mass in the subsurface and, therefore, a greater amount of mass available for leaching to groundwater.

The previous analysis (Venable, et al., 2015) concluded:

> "As expected and where there were sufficient data to provide an adequate sample size for analysis, subslab PCE and TCE soil gas concentrations increased with increasing groundwater concentrations ….This observation does not, however, provide information on whether the vadose zone soils or groundwater are currently serving as the primary source of contaminant mass, nor does it provide information on whether leaching from soil to groundwater or volatilization from groundwater to soil gas, dominate the mass transfer at the time of sampling. The observation does show that the two lines of evidence, groundwater and subslab soil gas, will generally be correlated."

For the expanded analysis, Figures 3-1 through 3-3 show plots of subslab soil gas concentration as a function of groundwater vapor concentration[13] associated with PCE, TCE, and cis-1,2-DCE, respectively. TCE and cis-1,2-DCE (Figures 3-2 and 3-3) show some correlation between groundwater and soil gas concentrations. The percent of the variance in subslab soil gas concentration explained by the groundwater data (from the r^2 of a linear fit in the log-log plots) is 8 percent (0.08) for TCE and 42 percent (0.42) for cis-1,2-DCE (which is predominantly formed under anaerobic conditions, most often in groundwater). The weakest r^2 was observed for PCE where there was essentially no correlation (1 percent [0.01]; Figure 3-1). A high groundwater concentration does not definitively

[13] Specifically, the groundwater vapor concentrations that are plotted correspond to the maximum measured groundwater concentrations (Section 2.4.2.2). The "stacked" pattern of groundwater vapor concentrations that is visible on Figures 3-1 through 3-3 is due to the fact that all subslab soil gas data from sampling events within a given sample zone are associated with the same maximum measured groundwater concentration (see Sections 2.4.2.2 and 4.2.1.1). In addition, several sample zones within a given building can have the same maximum measured groundwater concentration.

predict a high subslab soil gas concentration for any of the VOCs, but for most compounds high subslab soil gas concentrations are somewhat more likely to be found when higher groundwater concentrations are present. The lack of a strong correlation between these variables could be because the correlation between groundwater and subslab soil gas concentrations varies based on the thickness and grain size of the intervening vadose zone (USEPA, 2012b). An alternative interpretation is that at many of these sites, vadose zone mass storage is the dominant source continuing to supply VOCs to the subslab. In the multivariate analysis section (Section 5), an attempt is made to address that question by examining this relationship as a function of distance to point of primary release.

3.2 Building Area

USEPA (2012b, 2013) has hypothesized that larger buildings will have a capping effect increasing subslab soil gas concentrations. It has also been hypothesized by others that larger buildings would provide more dilution for VOCs once they intrude into indoor air and thus result in lower indoor air concentrations relative to smaller buildings (USEPA, 2015, Section A.4).

The previous analysis (Venable, et al., 2015) concluded:

> "Several studies [...] indicate that concentrations in soil gas and groundwater beneath a building slab or other lower permeability surface are increased by a capping effect that limits volatilization from groundwater to ambient air, especially below the center of a large building and suggesting higher subslab soil gas concentrations beneath large buildings, given a constant groundwater plume strength. No consistent pattern was observed in the dataset relating subslab soil gas concentration to building area across most compounds…However, a trend was apparent that the intermediate biodegradation products cis-1,2-DCE and 1,1-DCA were unlikely to be present in high concentrations under small buildings, and more likely to be observed under large buildings."

In the expanded analysis (Figures 3-4 through 3-9),[14] TCE concentrations in subslab soil gas increase slowly with increasing building size (Figure 3-5). The $r^2 = 0.1$ indicates that this effect may explain 10 percent of the variance in subslab soil gas concentration and the p-value indicates it is unlikely to be due to chance. The results for trans-1,2-DCE and 1,1-DCA are also statistically significant and show increasing concentration with increasing building size, although the sample size is small. The $r^2 = 0.79$ for trans-1,2-DCE (Figure 3-7) and 0.49 for 1,1-DCA (Figure 3-8) suggest that building size may have a greater role in the formation/retention of these compounds. There is, however, no apparent (or statistically significant) trend for PCE (Figure 3-4) or cis-1,2-DCE (Figure 3-6).

Building area will be discussed further with the multivariate analysis in Section 5 and the sample zone area factor in Section 4.3.

3.3 Soil Type

Conceptually, fine soil types (i.e., silt or clay) have lower permeability and hold a greater amount of moisture than coarse material (i.e., sand or gravel), such that that fine-grained material is expected to act as a barrier to vapor transport (USEPA, 2012b) and limit potential VI concerns if the source lies below the fine soil. VOCs released directly to fine soils would be less subject to natural attenuation resulting from volatilization and thus may remain present in higher concentrations than if the release occurred to coarse soils. Overall, the effect of soil type on the magnitude of subslab soil gas concentrations may depend on multiple factors, including the location of the vapor source relative to the building (e.g., vadose zone source of vapors versus groundwater source of vapors, depth to groundwater, lateral distance), the presence of subsurface heterogeneities, and the moisture distribution.

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[14] The stacked data point pattern visible in Figures 3-4 through 3-9 is due to the fact that multiple subslab soil gas data points (from various sampling events and sample zones) can be associated with the same building. In addition, a few buildings have identical or near identical areas (i.e., footprints).

The previous analysis (Venable et al., 2015) concluded:

> "Higher subslab soil gas concentrations were associated with fine (i.e., silt or clay) soil types for PCE; TCE; trans-1,2-DCE; cis-1,2-DCE; 1,1,1-TCA; and 1,1-DCE. The median concentration in fine soils exceeded the median concentration in coarse soils by 20 times for PCE and TCE. Higher normalized subslab soil gas concentrations were also associated with fine soils for PCE and TCE. These results suggesting a higher soil gas concentration in fine soils was unexpected but may have a physical explanation. Fine soils can result in a more even soil moisture distribution from the water table to the surface, which some modeling studies suggest would result in significantly higher subslab soil gas concentrations with fine soils. Although fine soils are generally expected in the vapor intrusion literature to be protective by reducing the rate of contaminant migration through advection and diffusion from groundwater, there are indications in the literature that an opposite effect may in fact occur. In the modeling study, Shen et al. (2013) predicted that in clay soil types that moist soils are present much closer to the foundation than would be true for a sand soil. Thus, they predict that at equilibrium, the VOC concentrations from a groundwater source will be closer to the building with fine soils. The NESDI study, unlike previous VI studies, included a significant number of buildings in which the primary release of contaminants occurred. In buildings where the release occurred, the association of fine soils with higher subslab concentrations with fine soils is expected since fine soils reduce mass transport through volatilization and leaching."

In the expanded analysis, the results were more complex and the differences between coarse and fine soils were more subtle (Table 3-1; Figures 3-10 through 3-15). In the Wilcoxon-Mann-Whitney tests of the medians of the detectable data, there were only two VOCs for which the subslab soil gas concentration associated with fine soil was significantly higher (1,1-DCA and VC)[15] and two cases where the opposite was true (PCE and 1,1,1-TCA) (see Table 3-1).[16] With PCE, however, the maximum subslab soil gas concentrations were higher in the fine soil cases. Thus, statistics for each percentile of the distribution were computed and the data reviewed to determine if a particular soil type was associated with a significantly different probability of having a very high subslab soil gas concentration. For PCE, the 60th through 90th percentiles were higher for fine soil but with the adjusted critical values[17] only the 80th percentile was significantly different (Table 3-2). For TCE, coarse was higher for all percentiles, but none were significantly different (Table 3-3). The differences in the upper percentiles were not significant for cis-1,2-DCE, 1,1,1-TCA, and 1,1-DCA (not provided in tables for brevity). Significant differences in the upper percentiles with the subslab soil gas concentrations associated with fine soil being higher were observed for 1,1-DCE and VC (Tables 3-4 and 3-5) although the number of detectable samples was low in those instances. Thus, the higher subslab soil gas concentrations in fine soil are only observed in this expanded analysis for the lower chlorinated compounds, which are often degradation products.

[15] Note that fine is also higher for 1,1-DCE but it barely missed significance p = 0.0504 (Table 3-1).

[16] For TCE, the coarse median was higher, but barely missed significance p = 0.0559 (Table 3-1).

[17] In short, the p-value required to determine significance is made more stringent because multiple comparisons are being made. The statistical significance of various quantiles for soil type and presence of exterior wall was calculated using the qcomhd function of the WRS2 package of the R-statistical software (Wilcox et al., 2014). The function compares user-defined quantiles of both distributions using a Harrell–Davis estimator in conjunction with a percentile bootstrap and the sequentially rejective technique derived by Hochberg (Hochberg, 1988). With the Hochberg method, the function controls the probability of Type 1 errors as the function tests each quantile. Given that small-sized samples are used, the p-value calculated for each quantile must be lower than a quantile-specific critical value to demonstrate significance.

3.4 Distance to Primary Release

Conceptually, the potential for VI would be expected to diminish as the distance to primary release increases. For a building for which the release is nearby and results in a vadose zone source of vapors, soil gas concentrations resulting from diffusive migration of vapors through the vadose zone would theoretically be expected to decrease with distance away from the source. Therefore, buildings further away from the release would be associated with lower subslab soil gas concentrations (USEPA, 2012b). For a groundwater source of vapor, VOCs would migrate in groundwater from the release location to the building via diffusive and advective transport in groundwater. Again, buildings further away from the release point would be less likely to exhibit elevated subslab soil gas concentrations as a result of this release.

The previous analysis (Venable et al., 2015) concluded:

> "For most compounds and as expected, subslab soil gas concentrations were highest when distance from the sample zone to the primary release was low. This trend was observed for PCE (… r^2=0.20 p<0.001), TCE (… r^2=0.37 p<0.001), 1,1-DCA (…. r^2=0.74 p<0.001). The proportion of variability explained by this variable (r^2) was one of the highest for any variable evaluated in this project."

For the expanded analysis, Figures 3-16 through 3-23 show plots of subslab soil gas concentration as a function of distance to primary release for various VOCs of interest. [18] In the expanded analysis, the relationship between concentration and distance continues to be highly statistically significant for PCE (Figures 3-16 and 3-17) and TCE (Figures 3-18 and 3-19) with decreasing concentration with distance. With much smaller datasets, 1,1-DCA still shows a significant decreasing trend (Figures 3-20 and 3-21), but trans-1,2-TCE shows an increasing trend (Figures 3-22 and 3-23), an indication that trends derived from too few data points and distances to primary release may not be as reliable as larger datasets such as those associated with PCE or TCE.[19] Results for cis-1,2-DCE and VC were insignificant. This analysis supports the retention of distance to primary release as a line of evidence in the QDF. Current industry practice generally manages VI using a single value such as 100 feet for the inclusion distance and thus effectively does not consider VI any more likely at 10 feet from the release point than at 90 feet. Thus, the QDF provides a graduated, categorical scale that can predict decreased probability of VI as distance increases.

3.5 Depth to Groundwater

USEPA presents its database analysis of residential VI using groundwater depth bins, the shallowest of which is less than 1.5 meters (4.9 feet; USEPA, 2012a). USEPA observed a modest decrease in normalized indoor air concentration (or AF) with increasing depth. The strongest break point in the USEPA (2012a) data analysis is generally assumed to occur where groundwater is less than 1.5 meters (4.9 feet or approximately 5 feet) below the structure, and thus screening using default groundwater-to-indoor air AFs is often only conducted with groundwater deeper than 5 feet.

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[18] The stacked data point pattern visible on Figures 3-16 through 3-23 is due to the fact that multiple subslab soil gas data points (from various sampling events) can be associated with the same sample zone and thus the same distance to primary release.

[19] Review of the underlying trans-1,2-DCE dataset associated with Figures 3-22 and 3-23 shows that the data associated with a distance to primary release near 0 feet correspond to several sample zones in one building at one installation. The review also shows that the data on the figures associated with distances to primary release near 50, 75, and 100 feet correspond to several sample zones within a single building at another installation. For this latter building, the subslab soil gas data also suggest substantial biodegradation from PCE and TCE to cis- and trans-1,2-DCE. While this biodegradation process most often results in much less trans-1,2-DCE than cis-1,2-DCE (Bradley, 2003), the cis- and trans-1,2-DCE concentrations in subslab soil gas beneath this building are within the same order of magnitude and, as a result, the trans-1,2-DCE concentrations are substantially more elevated than typically observed at other buildings or installations where trans-1,2-DCE is present in subslab soil gas. Therefore, the overall increasing trend shown on these figures, which is based on only two buildings, should not be viewed as a representative trend.

In the previous DoD VI Industrial Database report (Venable et al., 2015), there was not a significant relationship between depth to groundwater and indoor air concentration. However, variables based on groundwater concentration divided by depth were found to be significant in the multivariate analysis.

The expanded analysis is presented in Figures 3-24 through 3-31.[20] In this analysis, PCE shows a much wider range of subslab soil gas concentrations with shallow groundwater than with deep groundwater (Figure 3-24). However, the effect is not statistically significant in a linear regression. There is a common pattern in the TCE, cis-1,2-DCE, VC, 1,1-DCE, and 1,2-DCA plots (Figures 3-25 through 3.28 and Figure 3-31); i.e., generally decreasing subslab soil gas concentration with increasing depth to groundwater. The exception is the data with a depth to groundwater of 40 feet, which all come from one site. For this site, the strongest source is likely in shallow soil rather than groundwater. In the case of cis-1,2-DCE, despite the high concentration data at 40 feet, the overall trend of decreasing concentration with increasing depth still achieves statistical significance (Figure 3-26).

There is little visually apparent trend for 1,1,1-TCA and 1,1-DCA, which may be because there is a relatively narrow range of depths represented in the dataset (Figures 3-29 and 3-30). However, for those two VOCs, there is a statistically significant increase in subslab soil gas concentration with increasing depth to water. This outcome is likely due to the above-referenced high concentrations data at 40 feet, which influence the overall dataset. Since these results come from a single installation, this is probably an anomaly that indicates that other factors, such as concentration at the water table or soil type, are more important than depth to groundwater. This question will be explored in more depth in the multivariate analysis (Sections 5.1 and 5.2).

Although the bulk of the data for the chlorinated ethenes supports decreasing subslab soil gas concentration with increasing depth to groundwater, the results are not always consistent or statistically significant.

Depth to groundwater was not considered as a line of evidence in the initial QDF (Venable et al., 2015) but was included in the 2018 revision (CH2M, 2018). The current analysis suggests that inclusion of depth to groundwater as a line of evidence in the QDF could be appropriate when the groundwater is known to be the primary VOC source for a particular building. This variable was evaluated more extensively in Section 4.6 and then again in the multivariate analysis section (Section 5).

3.6 Exterior Wall Presence

Conceptually, the presence of an exterior building wall in a given sample zone could play an important role in determining VI potential. For instance, the sample zone could be more susceptible to vapor entry through a building perimeter crack. Conversely, the presence of an exterior wall may limit the mass flux of VOC vapors into the overlying structure because vapors can also migrate exterior to the building beyond the capping effect of the slab (USEPA, 2012b).

The previous analysis (Venable et al., 2015) concluded:

> "Median subslab soil gas concentrations for PCE and 1,1,1-TCA were significantly higher in sample zones with exterior walls. 1,1-DCE and 1,1-DCA were also significantly more likely to be detected in subslab soil gas beneath sample zones with an exterior wall… This is a novel finding that requires replication in future studies…"

For the expanded analysis, box-and-whisker plots of subslab soil gas concentrations beneath sample zones with or without an exterior wall are presented in Figures 3-32 through 3-38.

The only statistically significant differences in the medians show the opposite pattern, i.e., that concentrations are higher in zones without exterior walls for cis-1,2-DCE, 1,1-DCA, and trans-1,2-DCE (Table 3-6). Note that cis-1,2-DCE and 1,1-DCA are frequently found in soils as anaerobic degradation products of TCE and 1,1,1-TCA,

[20] The stacked data point pattern visible in Figures 3-24 through 3-31 is due to the fact that multiple subslab soil gas data points (from various sampling events and sample zones) can be associated with the same maximum measured groundwater concentration (as noted in Section 3.1) and thus the same depth to groundwater.

respectively (Lawrence, 2006). Thus, the increased concentration of these VOCs beneath the building is mechanistically reasonable because there would be less opportunity for oxygen replenishment in those zones.

For several VOCs (PCE, TCE, 1,1,1-TCA, and 1,1-DCA), there are more high concentration outlier points (i.e., points plotted above the box) in sample zones with exterior walls. The quantile distributions were reviewed to further understand this (Tables 3-7 through 3-10). For PCE, the subslab soil gas concentrations with exterior wall are higher from the 60th to 90th percentiles but only the 90th percentile is statistically significant (Table 3-7). For TCE, the no exterior wall condition is higher at all percentiles, with the 90th percentile being statistically significant (Table 3-8). For 1,1,1-TCA, the no exterior wall condition is higher at all percentiles with the 10th to 80th percentiles being statistically significant (Table 3-9). For 1,1-DCA, the no exterior wall condition is higher at all percentiles with the 70th and 80th percentiles being statistically significant (Table 3-10).

This analysis does not support retaining exterior wall as a line of evidence in its current form in the QDF.

SECTION 4

Single Variable Analysis – Factors Affecting Indoor Air Concentrations

4.1 Effect of Subslab Soil Gas Concentration on Indoor Air Concentration

This section presents the results of the subslab soil gas-to-indoor air AF distribution analyses conducted using subslab soil gas-indoor air data pairs from the DoD VI Industrial Database.

The previous analysis (Venable et al., 2015) concluded:

> "If expressed as AFs, the PCE and TCE plots suggest that use of an AF of 0.001 for military nonresidential buildings is appropriate in the absence of atypical preferential pathways. That value would be 100x less conservative than the value of 0.1 currently in use in the USEPA (2014) VISL calculator for both the residential and commercial scenarios."[21]

This section expands on the previous analysis, examines the relationships between subslab soil gas and indoor air, and reviews results of AF statistics associated with the expanded DoD VI Industrial Database to determine whether the addition of buildings substantially change conclusions drawn in Venable et al. (2015). As will be discussed in this section, the updated analyses demonstrate that a subslab soil gas-to-indoor air AF of 10^{-3} (0.001) continues to be defensible and conservative for predicting indoor air concentrations on the basis of subslab soil gas data for commercial and industrial buildings.

4.1.1 Preliminary Considerations

This section provides an overview of the various plots that will be discussed in the rest of Section 4.1, as well as the assumptions and rules used to support their preparation.

The analyses presented in Section 4.1 use several averaging and screening methods. The averaging methods were used to obtain a single subslab soil gas-indoor air data pair to represent a sample zone when several sampling locations were available for that zone. Details regarding each set of averaging and screening methods are provided in the following subsections as a set of rules, with supporting explanations as appropriate and illustrative examples. The examples provided focus on TCE, but additional VOCs are discussed in later sections.

4.1.1.1 Subslab Soil Gas-Indoor Air Concentration Plots for Each Data Pair

This section introduces the concept of subslab soil gas-indoor air data pairs and data pair combinations generated for individual sample zones and sampling events. Once generated, the data pairs are averaged as further described in Section 4.1.1.2, the relationships between subslab soil gas and indoor air graphically examined, and the associated AF statistics computed as further described in Section 4.1.2.

Figures 4-1a and 4-1b show individual subslab soil gas-indoor air concentration plots for TCE showing all individual data pairs passing the 10X and 1,000X background source strength screens, respectively (see Section 2.4.3.1 for subsoil soil gas-indoor air data pair and source strength screening).[22] A total of 983 pairs passed the 10X

[21] In 2015, USEPA's default subslab soil gas-to-indoor air AF value was changed from 0.1 to 0.03 (USEPA, 2015, 2021) based on the findings of the USEPA VI database study (USEPA, 2012a).

[22] The locally estimated scatterplot smoothing (LOESS) fits shown on the figures are discussed in Section 4.1.2.

background source strength screen, whereas a smaller number of pairs (565 pairs) passed the stronger 1,000X background source strength screen.

The data pairs are plotted using the following set of rules:

- There are as many data pairs as there can be subslab soil gas-indoor air pair combinations for a sampling event in a sample zone. For example, for a sample zone where three subslab soil gas and two indoor air samples were collected during a given sampling event, six points are shown corresponding to each possible subslab soil gas-indoor air data pair combination.
- For a given source strength screen, data pairs are only plotted if the average subslab soil gas concentration passes the screen. For the previous example, the six points are plotted if the average subslab soil gas concentration for the sample zone during the sampling event passes the source strength screen (i.e., the arithmetic average of the three subslab soil gas concentrations is greater than 10X background [21 $\mu g/m^3$ for TCE], Figure 4-1a, or 1,000X background [2,100 $\mu g/m^3$ for TCE], Figure 4-1b).
- Under these averaging rules, there can be pair combinations where the individual subslab soil gas concentration is less than the source strength screen, but the average subslab soil gas concentration for the sample zone and sampling event is greater than the source strength screen.
- None of the individual pairs are shown if the average subslab soil gas concentration fails the source strength screen, even if one individual subslab soil gas concentration passes the screen.
- Sampling events for a given sample zone are screened independently. The earlier example with six individual pairs may pass the source strength screen for a given event but may fail an earlier or subsequent sampling event, in which case the individual pair combinations associated with the sampling event that failed the source strength screen will not be included.[23]
- Pairs with non-detects in indoor air are shown with the indoor air concentration plotted equal to the detection limit.

4.1.1.2 Subslab Soil Gas-Indoor Air Concentration Plots for Each Sample Zone and Sampling Event

This section describes the averaging technique used to generate a single subslab soil gas-indoor air data pair for a given sample zone and sampling event. Once generated, the set of averaged data pairs is used to examine the relationships between subslab soil gas and indoor air, and also to compute the AF statistics on a sample zone and sampling event basis as further described in Section 4.1.2.

Figures 4-2a and 4-2b show subslab soil gas-indoor air concentration plots for TCE, with each data pair corresponding to a sample zone average for a given sampling event passing the 10X and 1,000X background source strength screens, respectively. A total of 145 sample zone average pairs passed the 10X background source strength screen, whereas a smaller number of pairs (58 pairs) passed the stronger 1,000X background source strength screen.

The data pairs are plotted using the following set of rules:

- Each subslab soil gas-indoor air data point represents the arithmetic average of the subslab soil gas concentrations plotted against the arithmetic average of the indoor air concentrations for a given sample zone and a given sampling event. Therefore, in the example presented in Section 4.1.1.1 with three subslab soil gas and two indoor air concentrations and six resulting subslab soil gas-indoor air combinations, there would be only one data point.

[23] Source strength screening at the individual sampling event level is intended to screen out sampling events in a given sample zone where background source-related contributions may become too important relative to VI-related contributions. This approach is different from Venable et al. (2015) where all sampling events of a sample zone were screened in if at least one sampling event was screened in. Generally, this would be a reasonable expectation because subslab soil gas concentrations in a given sample zone do not change substantially between sampling events. However, certain sample zones in the DoD VI Industrial Database have exhibited large reductions in subslab soil gas concentrations between sampling events and, accordingly, it was decided to screen data out at the individual sampling event level.

- For the data pair to be plotted, the average subslab soil gas concentrations must have passed the corresponding source strength screen. Because only averages are plotted (and not the individual pairs as was the case for Figures 4-1a and 4-1b), there cannot be average subslab soil gas concentrations that are less than the source strength screen of interest. For example, for the 10X background source strength screen plot (Figure 4-1a), there are no pairs with an average subslab soil gas concentration below 21 $\mu g/m^3$ (10X background). Likewise, there are no pairs with a concentration below 2,100 $\mu g/m^3$ (1,000X background) for TCE (Figure 4-1b).
- For a given sample zone, each sampling event is treated separately, meaning that each sampling event that passed the screen is represented by one data point, while the sampling events that failed the screen are not plotted. Therefore, a given sample zone can have more data points on a subslab soil gas-indoor air data plot associated with a lower source strength screen than a stronger source strength screen.[24]
- On Figures 4-2a and 4-2b, only detectable indoor air data are included. For a sampling event for a given sample zone for which there were no detections in indoor air, a data point will not be shown. If there is more than one indoor air concentration for that sample zone and sampling event, the average subslab soil gas-indoor air data pair will only be shown if at least one of the indoor air data points has a detectable concentration. The average indoor air concentration will only reflect the average of the detected concentrations.

4.1.1.3 Subslab Soil Gas-Indoor Air Concentration Plots for Each Sample Zone and Sampling Event – Plots with Detectable Indoor Air Only Versus Indoor Air Non-Detects Plotted at Detection Limit

This section examines subslab soil gas-indoor air data pairs—where each pair is associated with a given sample zone and sampling event similar to Section 4.1.1.2—and illustrates the effects of accounting for indoor air data that are below detection limit. Datasets generated with and without indoor air non-detects are further analyzed and the respective AF statistics compared in Section 4.1.5.

Figures 4-3a and 4-3b represent subslab soil gas-indoor air concentration plots for TCE, with each data pair corresponding to a sample zone average for a given sampling event passing the 10X background source strength screen. Figure 4-3a is identical to Figure 4-2a and includes only detectable concentrations in indoor air (i.e., indoor air non-detects excluded). The dataset includes 145 pairs shown. Figure 4-3b includes non-detects in indoor air plotted at the detection limit. The dataset for Figure 4-3b includes 192 pairs, which is greater than the 145-pair set for Figure 4-3a because indoor air non-detects are included.

The data pairs are plotted using the following set of rules:

- For Figure 4-3a, only detectable indoor air data are included; this means that a sampling event for a given sample zone for which there were no detections in indoor air will not have a data point shown. By contrast, this data point will be represented on Figure 4-3b, using the indoor air detection limit as the indoor air concentration or the average of the detection limits if there are several indoor air non-detects in the sample zone during the sampling event. Two examples of non-detect pairs are shown on Figure 4-3b (see pairs inside the blue circle; these two pairs correspond to two different building sample zones and sampling events at one installation). These two pairs are not shown on Figure 4-3a because the corresponding indoor air concentration for each pair was below detection limit.
- If there is more than one indoor air concentration for a given sample zone and sampling event, the average subslab soil gas-indoor air data pair will only be shown on Figure 4-3a if at least one of the indoor air data points has a detectable concentration. The average indoor air concentration will only reflect the average of the detected concentrations (i.e., non-detects excluded from the average). For Figure 4-3b, the average indoor air concentration will include the indoor air non-detects at detection limit. This means that the average indoor air concentrations may somewhat change between Figures 4-3a and 4-3b. An example of such

[24] Refer to explanations in the preceding footnote.

occurrence is shown on both figures (green circles). In this example, the average indoor air concentration when accounting for indoor air non-detects (Figure 4-3b) is slightly greater[25] than the average that includes only the detectable concentrations (Figure 4-3a). The average subslab soil gas concentration is the same since the change in calculation approach applies to indoor air.[26]

4.1.1.4 Subslab Soil Gas-Indoor Air Concentration Plots for Each Sample Zone and Sampling Event – Plots Using Average Concentrations Versus Plots Using Maximum Concentrations

This section examines subslab soil gas-indoor air data pairs—where each pair is associated with a given sample zone and sampling event similar to Section 4.1.1.2—and illustrates the effects of using maximum subslab soil gas and indoor air concentrations instead of average concentrations. Datasets generated with maximum and average concentrations are further analyzed and the respective AF statistics compared in Section 4.1.6.

Figures 4-4a and 4-4b show subslab soil gas-indoor air concentration plots for TCE, with each data pair corresponding to a sample zone average for a given sampling event passing the 10X background source strength screen. Figure 4-4a is identical to Figure 4-2a and uses the average subslab soil gas and indoor air concentrations for each sample zone and sampling event. Figure 4-4b uses the maximum subslab soil gas and indoor air concentrations. The dataset includes 145 pairs in both cases.

The data pairs are plotted using the following set of rules:

- For Figure 4-4b, the source strength screen is applied identical to the dataset used to prepare Figure 4-4a. That is, the screen is applied to the average subslab soil gas concentration. Note that there are cases where it can fail even if the maximum subslab soil gas concentration passes the screen because of averaging (Section 4.1.1.1). The difference between Figures 4-4a and 4-4b is the position of each data pair on the plots, which moves from the average subslab soil gas and indoor air concentrations (Figure 4-4a) to the maximum subslab soil gas and indoor air concentrations (Figure 4-4b). An example of such shift is shown on both figures (green circle). There is no shift for a sampling event and sample zone for which there is only one subslab soil gas-indoor air data pair since the average and maximum values are identical.
- On Figures 4-4a and 4-4b, only detectable indoor air data are included. Similar plots can be generated showing indoor air non-detects taken at detection limit. The indoor air concentration shown will be either the maximum indoor air concentration measured during the event or the greatest detection limit.

4.1.1.5 Subslab Soil Gas-Indoor Air Concentration Plots Representing Each Sample Zone Averages for All Sampling Events

This section describes the averaging technique used to generate a single subslab soil gas-indoor air data pair for a given sample zone. Once generated, the set of averaged data pairs is analyzed and used to compute the AF statistics on a sample zone basis as further described in Section 4.1.3. These AF statistics are also compared to those obtained on a sample zone and sampling event basis (Section 4.1.2).

Figures 4-5a and 4-5b show subslab soil gas-indoor air concentration plots for TCE, with each data pair corresponding to sample zone averages for all sampling events passing the 10X and 1,000X background source strength screens, respectively. A total of 80 sample zone average pairs passed the 10X background source strength screen, whereas a smaller number of pairs (37 pairs) passed the stronger 1,000X background source strength screen.

The data pairs are plotted using the following set of rules:

[25] The average of four detectable indoor air concentrations of TCE plotted on Figure 4-3a is 4.75 µg/m^3. Figure 4-3b also includes a non-detect with a detection limit of 13 µg/m^3, such that the average for the five indoor air data points becomes 6.4 µg/m^3.

[26] Note that in certain instances where there is a sample zone with both subslab soil gas detects and non-detects during the same sampling event, such that the average subslab soil gas concentration is greater than (and thus passes) the source strength screen, the non-detect subslab soil gas data will not be represented or averaged in the plot that shows indoor air detects only. These cases are uncommon.

- Each subslab soil gas-indoor air data point represents the average of the subslab soil gas concentrations plotted against the average of the indoor air concentrations for a given sample zone and all sampling events that passed the source strength screen. For instance, if there were three sampling events in a sample zone represented on Figure 4-2a—i.e., three events that passed the 10X background source strength screen—then one point representing the average[27] is plotted on Figure 4-5a.
- If a sample zone included events that passed a given source strength screen and other events that failed the screen, then the average for all events only includes the events that passed the screen.
- On Figures 4-5a and 4-5b, only detectable indoor air data are included. Similar plots can be generated showing sample zone averages for all sampling events where indoor air non-detects are taken at detection limit, with some of the averaging considerations presented in the previous bullets and in Section 4.1.1.3.

4.1.1.6 Subslab Soil Gas-Indoor Air Concentration Plots Showing Building Level Averages for All Sampling Events

This section describes the averaging technique used to generate a single subslab soil gas-indoor air data pair for each building. Once generated, the set of averaged data pairs is analyzed and used to compute the AF statistics on a building basis as further described in Section 4.1.4. These AF statistics are also compared to those obtained on a sample zone and sampling event basis (Section 4.1.2) and on a sample zone basis (Section 4.1.3).

Figures 4-6a and 4-6b represent subslab soil gas-indoor air concentration plots for TCE, with each data pair corresponding to the building average for all building zones and sampling events passing the 10X and 1,000X background source strength screens, respectively. A total of 39 sample zone average pairs passed the 10X background source strength screen, whereas a smaller number of pairs (20 pairs) passed the stronger 1,000X background source strength screen.

The data pairs are plotted using the following set of rules:

- Each subslab soil gas-indoor air data point represents the average of the subslab soil gas concentrations plotted against the average of the indoor air concentrations for a given building. The average includes all sampling events of all sample zones that passed the source strength screen. For example, consider a series of sampling events that passed the 1,000X background source strength screen at a given building. If there were three sampling events in a sample zone and two sampling events in another sample zone of the same building (represented by five data points on Figure 4-2b and two data points on Figure 4-5b), and if these five events represented all the sampling events that had passed the 1,000X background source strength screen in the building, then the building level average plotted on Figure 4-6b would be represented by one point representing the average[28] of these five events.
- Building-level averages for a given source strength screen only include sample zones and sampling events that passed the screen.
- On Figures 4-6a and 4-6b, only detectable indoor air data are included. Similar plots can be generated showing building level averages where indoor air non-detects are taken at detection limit, with some of the averaging considerations presented in the previous bullets and in Sections 4.1.1.3 and 4.1.1.5.

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[27] Note that in the average for all sampling events, each sampling event is weighted by the number of pair combinations associated with this event. For instance, a sampling event for a sample zone with three subslab soil gas samples and two indoor air samples, which correspond to six pair combinations, will count six times in the average. If the subsequent sampling event for the sample zone has only one subslab soil gas sample and two indoor air samples, which correspond to two pair combinations, then this event will count twice in the average. The average of both events will be the average of eight combinations for both events (six plus two), and thus the first event will have three times the weight of the second event. To examine the effect of this averaging method, an evaluation was conducted by looking at the AF distribution when assuming sampling event averages counting equally toward the average for all events. The AF statistics (i.e., median and 90th and 95th percentiles) were found to be generally consistent with the AF statistics associated with the weighted average approach.

[28] Note that for the calculation of the average, each sampling event is weighted by the number of pair combinations associated with this event. Therefore, sample zones with more subslab soil gas and indoor air data obtained during an individual sampling event, as well as sample zones where more sampling events were conducted, will weigh more in the calculation of the average.

4.1.2 Attenuation Factors Derived Using Sample Zone Averages for Individual Sampling Events

This section focuses on subslab soil gas-to-indoor air AFs obtained from individual sampling events conducted in separate sample zones. Averaging rules and examples of data plots (for TCE) corresponding to a sample zone average for a given sampling event were provided in Section 4.1.1.2. This section builds upon these averaging rules, evaluates the effects of increasing the source strength screen, and considers other VOCs in addition to TCE.

4.1.2.1 Effect of Increasing Source Strength Screen on Attenuation Factors

The objective of the source strength screen is to limit the effect of background source contributions to the AFs consistent with the USEPA (2012a) methodology (see Section 2.4). As the source strength screen increases, background influence is progressively eliminated and the median and percentiles of the AF distribution are expected to stabilize. An idealized subslab soil gas-indoor air concentration plot with a series of data points takes the shape of a hockey stick, with the blade portion of the stick (lower subslab soil gas concentrations) representing the data influenced by background sources and the shaft portion of the stick (larger subslab soil gas concentrations) representing the data where this influence is less important (USEPA, 2012a, Figure 7a). Evaluating the source strength screen is analogous to determining the subslab soil gas concentration above which the blade portion of the hockey stick transitions to the shaft.

Figures 4-7 to 4-10 show paired subslab soil gas-indoor air concentration plots for TCE, PCE, cis-1,2-DCE, and 1,1-DCA, respectively, with progressively increasing source strength.[29] Only detectable indoor air concentrations are shown using the averaging rules discussed in Section 4.1.1. Also shown on the figures is a blue line and shaded area corresponding to the LOESS fits. This LOESS fit can be understood as the hockey-stick fit of the data. As can be seen on the 10X background source strength screen concentration plots for TCE and PCE (upper plots of Figures 4-7 and 4-8), there is still a noticeable hockey stick blade for the lower subslab soil gas concentrations, but the transition to the shaft (i.e., the inflection point) occurs near a concentration of approximately 1,000X the background value (2,100 $\mu g/m^3$ for TCE and 8,000 $\mu g/m^3$ for PCE). Greater source strength screens (100X and 1,000X background) do not have the hockey-stick shape, an indication that the influence of background contributions is less prevalent for these datasets. The relationship between LOESS-fit shape and source strength screen is less evident for cis-1,2-DCE and 1,1-DCA (Figures 4-9 and 4-10); however, the datasets are smaller than those for TCE and PCE.

Figures 4-11 and 4-12 show the subslab soil gas-to-indoor air AF distributions for varying source strength screens for TCE and PCE, respectively. The AFs are obtained by using the ratio of the average indoor air concentration to the average subslab soil gas concentration using all the data pairs plotted on Figures 4-7 and 4-8, respectively. The changes in AF distribution visible on Figures 4-11 and 4-12 reflect the influence of background sources. As shown on these figures, the lower source strength screen (10X background) is associated with a bimodal distribution. This distribution shifts to a log-normal-like distribution as the source strength screen increases to 1,000X background, with most AFs in the range of 10^{-5} to 10^{-3}. Thus, the source strength screen progressively eliminates the relatively elevated AFs that likely reflect background sources.

Summaries of descriptive statistics for the AF distributions associated with TCE, PCE, cis-1,2-DCE, and 1,1-DCA as a function of source strength screen are provided in Tables 4-1 to 4-4, respectively, and the associated box-and-whisker plots are shown in Figures 4-13 to 4-16. As can be seen on the figures, the AF distribution statistics, including the median (50th percentile), 90th percentile, and 95th percentile, tend to stabilize as the source strength screen increases. Similarly, Figures 4-17a and 4-17b show plots of the 90th and 95th percentile AFs associated with TCE and PCE as a function of source strength screen. The figures show that the plots flatten out with increasing source strength, an indication that background source effects are limited once the source strength screen exceeds 1,000X background. An additional increase in source strength screen would not be expected to

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[29] Note that for TCE (Figure 4-7), the plots associated with the 10X and 1,000X background source strength screens are identical to those shown on Figures 4-2a and 4-2b.

substantially change the trend in AFs. On the basis of these figures, a source strength screen of 1,000X background (for VOCs with background values) or 1,000 µg/m^3 (for VOCs without background values) appears to be adequate to filter out potential background contributions when assessing AF distribution statistics.

4.1.2.2 Recommended Generic Subslab Soil Gas-to-Indoor Air Attenuation Factor for DoD Industrial Buildings

Figure 4-18 shows paired subslab soil gas-indoor air concentration plots for VOCs that were part of this analysis. Consistent with the source strength screen recommendations made in the previous section, the pairs on the plots passed either the 1,000X background source strength screen for VOCs with background values (TCE, PCE, 1,1,1-TCA, 1,1-DCE, and VC) or the 1,000 µg/m^3 source strength screen for VOCs without background values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE).[30] Pairs with an indoor air concentration below detection limits are not shown. Table 4-5 provides a summary of descriptive statistics for the AF distribution associated with the VOC data pairs shown on Figure 4-18; the associated box-and-whisker plot is shown on Figure 4-19. As shown on Figure 4-18, none of the pairs are associated with a subslab soil gas-to-indoor air AF that exceeds USEPA's generic AF of 0.03 (USEPA, 2015) and only one pair exceeds an AF of 10^{-2}. This is noteworthy because the AF of 0.03 derived by USEPA corresponds to the 95th percentile AF obtained from statistical analysis of USEPA's residential data; an AF of 10^{-2} would correspond approximately to USEPA's 87th percentile residential AF (USEPA, 2012a).

As shown on Table 4-5, the 90th percentile AFs range from 2.1×10^{-5} to 1.5×10^{-3} depending on the VOC. Based on the analyses shown on Figure 4-19, a subslab-to-indoor air AF of 10^{-3} (0.001) is found to be appropriate to conservatively predict indoor air concentrations on the basis of subslab soil gas data for commercial and industrial buildings in the DoD VI Industrial Database. The value of 10^{-3} corresponds to the 93rd percentile AF of all the VOC data pairs shown on Figure 4-18.

As will be discussed in Section 4.1.5, accounting for indoor air non-detects in the analyses has only a limited effect on this result.

4.1.3 Attenuation Factors Derived Using Sample Zone Averages – Averaging for All Sampling Events Versus Averaging for Individual Sampling Events

This section focuses on subslab soil gas-to-indoor air AFs obtained from sample zone averages for all sampling events passing a given source strength screen. Examples of data plots using this type of averaging were shown in Section 4.1.1.5. The objective of this section is to review the AF distribution and statistics associated with this approach and compare them to the distribution and statistics obtained for the individual sampling event approach that was discussed in Section 4.1.2.

Figures 4-20 to 4-23 show paired subslab soil gas-indoor air concentration plots for TCE, PCE, cis-1,2-DCE, and 1,1-DCA, respectively, using the selected 1,000X background source strength screen (for TCE and PCE) or 1,000 µg/m^3 constant value source strength screen (for cis-1,2-DCE and 1,1-DCA) consistent with the recommendations in Section 4.1.2.1. Only detectable indoor air concentrations are shown using the averaging rules discussed in Section 4.1.1. Each (a) part of the figures shows the plot with the corresponding source strength screen obtained using the individual sampling event approach (i.e., see Section 4.1.2 and Figures 4-7 to 4-10), whereas the (b) part of the figures shows the approach using sample zone averages for all sampling events.[31] As can be seen, there is generally little difference in LOESS fit.

Figures 4-24 to 4-27 show the subslab soil gas-to-indoor air AF distributions for TCE, PCE, cis-1,2-DCE, and 1,1-DCA, respectively, using the selected source strength screens (same as for Figures 4-20 to 4-23). Each (a) part of

[30] There were no pairs meeting the various filtering criteria for 1,2-DCA.

[31] Note that Figure 4-20b for TCE is identical to Figure 4-5b.

the figures shows the AF distributions using the individual sampling event approach (see Section 4.1.2),[32] whereas the (b) part of the figures shows the approach using sample zone averages for all sampling events. As can be seen, there is generally limited difference in AF distribution for a given VOC between both approaches.

Tables 4-6 to 4-9 summarize descriptive statistics for the AF distributions associated with TCE, PCE, cis-1,2-DCE, and 1,1-DCA as a function of source strength screen with AF data obtained from the indoor air to subslab soil gas concentration ratios corresponding to sample zone averages for all sampling events. Figure 4-28 shows a box-and-whisker plot comparing the AF distribution statistics using this approach versus the individual event approach discussed in Section 4.1.2.[33] As can be seen from these box-and-whisker plots, there is generally little difference in 50th (median), 90th, and 95th percentiles between approaches. Similarly, Figures 4-29a and 4-29b, which show plots of the 90th and 95th percentile AFs associated with TCE and PCE as a function of source strength screen, are similar to the corresponding plots developed for AF data derived from individual sampling events (Figures 4-17a and 4-17b).

Collectively, the data show that using AF data derived from sample zone averages for all sampling events yields AF distributions and statistics that are comparable to those derived from sample zone averages for individual sampling events (Section 4.1.2). Therefore, the results and the 10^{-3} subslab soil gas-to-indoor air generic AF recommendations obtained using the latter approach (individual sampling events) are unchanged.

4.1.4 Attenuation Factors Derived Using Buildings Averages for All Sampling Events Versus Attenuation Factors Derived Using Prior Approaches

The AF distribution analyses conducted in Sections 4.1.2 and 4.1.3 were repeated using the building level averages, which correspond to the averages of all building zones and sampling events passing a given source strength screen, as discussed previously in Section 4.1.1.6. Table 4-10 compares the subslab soil gas-to-indoor air AF statistics obtained for TCE, PCE, cis-1,2-DCE, and 1,1-DCA using the building average approach, as well as the approaches discussed in the previous sections, i.e., the AF distributions based on building sampling averages per sampling event (Section 4.1.2) and for all sampling events (Section 4.1.3). The source strength screen is either 1,000X background (for TCE and PCE) or 1,000 $\mu g/m^3$ (for cis-1,2-DCE and 1,1-DCA) consistent with the Section 4.1.2.1 recommendations. Figures 4-30 and 4-31 provide box-and-whisker comparisons of the AF distributions for these VOCs using each approach. As shown on the table and figures, there is limited differences in 50th (median), 90th, and 95th percentiles between the building average approach and the prior two approaches.

Given that there are only limited differences between the three averaging approaches discussed previously (i.e., per sampling event, per sample zone, and per building), the remainder of Section 4.1 focuses on a single approach and uses the sample zone average per sampling event as the default approach for analyzing AF distribution data.

4.1.5 Attenuation Factors Derived Using Detectable Indoor Air Data Only Versus Indoor Air Non-Detect Data Plotted at Detection Limit

The AF distribution approach based on building sampling averages per sampling event (Section 4.1.2) used detectable indoor air data only. In this section, this distribution is compared to that obtained using non-detect data plotted at detection limit using the averaging rules detailed in Section 4.1.1.3.

Figures 4-32 to 4-35 show paired subslab soil gas-indoor air concentration plots for TCE, PCE, cis-1,2-DCE, and 1,1-DCA, respectively, using the selected 1,000X background source strength screen (for TCE and PCE) or 1,000 $\mu g/m^3$ constant value source strength screen (for cis-1,2-DCE and 1,1-DCA) consistent with the recommendations in Section 4.1.2.1. Each (a) part of the figures shows the plot with the corresponding source

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[32] Figure 4-24a for TCE and Figure 4-25a for PCE correspond to the 1,000X background source strength screen plots shown on Figures 4-11 and 4-12, respectively.

[33] The individual event ("per event") box-and-whisker plots for TCE, PCE, cis-1,2-DCE, and 1,1-DCA on Figure 4-28 correspond to the 1,000X background or 1,000 $\mu g/m^3$ source strength screen shown in Figures 4-13 to 4-16, respectively. See also Figure 4-19.

strength screen obtained using detectable indoor air data only, whereas the (b) part of the figures shows the approach using indoor air non-detects plotted at the detection limit.[34]

Table 4-11 compares the subslab soil gas-to-indoor air AF statistics obtained for TCE, PCE, cis-1,2-DCE, and 1,1-DCA using detectable indoor air only and using non-detects plotted at detection limits. Again, the source strength screen is either 1,000X background (for TCE and PCE) or 1,000 µg/m^3 (for cis-1,2-DCE and 1,1-DCA). Figure 4-36 provides a box-and-whisker comparison of the AF distributions for these VOCs using both approaches. As shown on the table and figure, there is generally limited differences in 50th (median), 90th, and 95th percentiles between both approaches, with only a slight decrease in 90th and 95th percentile AFs when pairs with non-detects in indoor air are included to the analysis, but no change in overall trend.[35] Similarly, Figure 4-37, which presents plots of the 90th and 95th percentile AFs associated with TCE and PCE as a function of source strength screen, shows limited changes only. The slight decrease in 90th and 95th percentiles when including non-detects (taken at detection limit) is due to the fact that additional subslab soil gas-indoor air data pairs are being added to the dataset that have relatively small indoor air concentrations (since these concentrations are taken equal to the detection limit) and thus relatively small AFs. This means that the proportion of relatively high AFs within the dataset decreases and accordingly the upper percentile AFs decrease.

This analysis confirms that a subslab soil gas-to-indoor air AF of 10^{-3} (0.001) derived in Section 4.1.2.2 using detectable indoor air data remains appropriate when also considering indoor air non-detects. This 10^{-3} AF can conservatively predict indoor air concentrations on the basis of subslab soil gas data for DoD commercial and industrial buildings. The analysis confirms the results of Venable et al. (2015).

4.1.6 Attenuation Factors Derived Using Maximum Subslab Soil Gas and Indoor Air Concentrations Versus Average Concentrations

The AF distribution approach based on building sampling averages per sampling event (Section 4.1.2) used average subslab soil gas and indoor air concentrations. In this section, this distribution is compared to that obtained using maximum subslab soil gas and indoor air concentrations using the averaging rules detailed in Section 4.1.1.4.

Table 4-12 compares the subslab soil gas-to-indoor air AF statistics obtained for TCE, PCE, cis-1,2-DCE, and 1,1-DCA using the average and maximum subslab soil gas and indoor air concentrations. Consistent with previous sections, the source strength screen is either 1,000X background (for TCE and PCE) or 1,000 µg/m^3 (for cis-1,2-DCE and 1,1-DCA). Only detectable indoor air concentrations are shown using the averaging rules discussed in Section 4.1.1.

Figure 4-38 provides a box-and-whisker comparison of the AF distributions for these VOCs using both approaches. As shown on the table and figure, there is generally limited differences in 50th (median), 90th, and 95th percentiles between both approaches. Similarly, Figure 4-39, which presents plots of the 90th and 95th percentile AFs associated with TCE and PCE as a function of source strength screen, shows limited changes only.

This analysis shows that using maximum subslab soil gas and indoor air concentrations instead of average concentrations to compute AFs and their associated statistics does not modify prior conclusions.

4.2 Effect of Groundwater Concentration on Indoor Air Concentration

This section presents the results of the groundwater-to-indoor air AF distribution analyses conducted using groundwater-indoor air data pairs from the DoD VI Industrial Database.

34 Note that Figures 4-32a, 4-33a, 4-34a, and 4-35a are identical to Figures 4-20a, 4-21a, 4-22a, and 4-23a, respectively.

35 Note that multivariate statistical analyses include non-detects in indoor air.

The previous analysis (Venable et al., 2015) concluded:

> "For the screened datasets, calculated on a sample zone basis, only one result suggests a groundwater AFvi of >0.0005 across all three compounds: PCE, TCE, and cis-1,2-DCE. Most of the data suggest a groundwater AFvi< 0.0001. This suggests that a groundwater AFvi of 0.0001 could be used for most DoD commercial/industrial buildings."

This section expands on the previous analysis, examines the relationships between groundwater and indoor air, and reviews results of AF statistics associated with the expanded DoD VI Industrial Database to determine whether the addition of buildings substantially change conclusions drawn in Venable et al. (2015). As will be shown in this section, the updated analyses demonstrate that a groundwater-to-indoor air AF of 10^{-4} continues to be defensible and conservative for predicting indoor air concentrations on the basis of groundwater data for commercial and industrial buildings.

4.2.1 Preliminary Considerations

This section provides an overview of the various plots that will be discussed in the rest of Section 4.2, as well as the assumptions and rules used to support their preparation.

The analyses presented in Section 4.2 use several averaging and screening methods. The averaging methods were used to obtain a single groundwater-indoor air data pair to represent a sample zone when sampling locations were available for that zone. Details regarding each set of averaging and screening methods are provided in the following subsections as a set of rules, with supporting explanations as appropriate and illustrative examples. The examples provided focus on TCE, but additional VOCs are discussed in later sections.

4.2.1.1 Groundwater-Indoor Air Concentration Plots Representing Each Data Pair

This section introduces the concept of groundwater-indoor air data pairs and data pair combinations generated for individual sample zones and sampling events. Once generated, the data pairs are averaged as further described in Section 4.2.1.2, the relationships between groundwater and indoor air graphically examined, and the associated AF statistics computed as further described in Section 4.2.2.

Figures 4-40a and 4-40b represent individual groundwater-indoor air concentration plots for TCE showing all individual data pairs passing the 100X and 5,000X background source strength screens, respectively (see Section 2.4.3.2 for groundwater-indoor air data pair and source strength screening).[36] A total of 432 pairs passed the 100X background source strength screen, whereas a smaller number of pairs (241 pairs) passed the stronger 5,000X background source strength screen.

The data pairs are plotted using the following set of rules:

- A sample zone is associated with a unique set of groundwater vapor concentrations, including the maximum measured and maximum interpolated groundwater concentrations (Section 2.4.2.2). These concentrations remain the same regardless of the indoor air sampling event (Section 2.4.2.2).
- By convention, the groundwater vapor concentrations that are plotted on Figures 4-40a and 4-40b, as well as subsequent figures associated with Section 4.2, are the maximum measured groundwater concentrations (and not the maximum interpolated concentrations). In this report, and unless otherwise noted, the term "groundwater vapor concentration" refers to the maximum measured groundwater vapor concentration. As noted in Section 2.4.3.2., this concentration is obtained by converting the groundwater concentration to an equivalent vapor concentration using Henry's Law (USEPA, 2012a).

[36] Note that for groundwater-indoor air concentration data, source strength screens ranging from 100X and 5,000X background are used (see Section 2.4.3.2 and Table 2-1), whereas for subslab soil gas-indoor air concentration data, source strength screens ranged from 10X to 1,000X background (see Section 2.4.3.1 and Table 2-1, as well as Section 4.1). This is because groundwater vapor concentrations exhibit more attenuation than subslab soil gas concentrations.

- There are as many data pairs as there can be groundwater vapor-indoor air pair combinations for a sampling event in a sample zone. For a sample zone where, for instance, three indoor air samples were collected during a given sampling event, three points are shown corresponding to each possible groundwater vapor-indoor air data pair combination. Because the groundwater vapor concentration (i.e., based on the above convention, the maximum measured concentration) is the same, the three points are aligned vertically on the plot.
- For a given source strength screen, data pairs are only plotted if both the maximum measured and maximum interpolated groundwater vapor concentrations pass the screen (Section 2.4.3.2). For the previous example, the three points are plotted if the two maximum groundwater vapor concentrations associated with the sample zone and sampling events pass the source strength screen, i.e., each of the two concentrations is greater than 100X background (210 μg/m^3 for TCE for Figure 4-40a) or 5,000X background (10,500 μg/m^3 for TCE for Figure 4-40b).
- None of the individual pairs are represented if one of the two maximum groundwater vapor concentrations fails the source strength screen. For instance, Figure 4-40b shows no pairs where the TCE groundwater vapor concentrations are less than 10,500 μg/m^3.
- For subslab soil gas-indoor air data pairs (Section 4.1), sampling events for a given sample zone were screened independently. In the case of groundwater-indoor air data pairs, the same groundwater vapor concentrations are used for different sampling events of a given sample zone. Therefore, for a given source strength screen, there cannot be sampling events that pass while other sampling events fail; the sampling events of a sample zone will either pass or fail entirely.
- Different sample zones (or even different buildings of the same installation) may be assigned the same nearby groundwater monitoring well and, therefore, the same maximum measured groundwater vapor concentration.[37] Consequently, two or more sample zones with the same groundwater vapor concentration are generally expected to simultaneously pass or fail a given source strength screen.[38]
- Pairs with non-detects in indoor air are shown with the indoor air concentration plotted equal to the detection limit.

4.2.1.2 Groundwater-Indoor Air Concentration Plots for Each Sample Zone and Sampling Event

This section describes the averaging technique used to generate a single groundwater-indoor air data pair for a given sample zone and sampling event. Once generated, the set of averaged data pairs is used to examine the relationships between groundwater and indoor air, and also to compute the AF statistics on a sample zone and sampling event basis as further described in Section 4.2.2.

Figures 4-41a and 4-41b represent groundwater-indoor air concentration plots for TCE, with each data pair corresponding to a sample zone average for a given sampling event passing the 100X and 5,000X background source strength screens, respectively. A total of 181 sample zone average pairs passed the 100X background source strength screen, whereas a smaller number of pairs (130 pairs) passed the stronger 5,000X background source strength screen.

The data pairs are plotted using the following set of rules:

- Each groundwater-indoor air data point represents the maximum measured groundwater vapor concentration plotted against the arithmetic average of the indoor air concentrations for a given sample zone and a given sampling event. Therefore, in the example presented in Section 4.2.1.1 with three indoor air

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[37] Note that the maximum interpolated groundwater vapor concentrations may vary based on the locations of the sample zones or buildings relative to the groundwater plume.

[38] Note that it is possible for two sample zones with the same maximum measured groundwater vapor concentration to not simultaneously pass the source strength screen. This could happen in instances where one sample zone has a maximum interpolated groundwater vapor concentration that passes the source strength screen whereas the other sample zone does not (see Section 2.4.3.2).

concentrations and three resulting groundwater-indoor air combinations, there would be only one data point corresponding to the average indoor air concentration.

- For the data pair to be plotted, the groundwater vapor concentration must have passed the corresponding source strength screen. As noted in Section 4.2.1.1, a single groundwater vapor value is used for all sampling events of a given sample zone, such that either none or all of the sampling events of a given sample zone will pass a given source strength screen. In other words, each of the sampling events of a given sample zone that passed a given source strength screen will be represented by one data point on the plot (assuming there are detections in indoor air; see last bullet) and all the points will be vertically aligned since they share a single groundwater vapor concentration.
- Different sample zones (or even different buildings of the same installation) may share the same groundwater vapor concentration. Assuming that this concentration passes a given source strength screen, all of the data points on the corresponding groundwater-indoor air plot will be vertically aligned, with each point corresponding to the average indoor air concentration of an individual sampling event of a particular sample zone.
- On Figures 4-41a and 4-41b, only detectable indoor air data are included. This means that a sampling event for a given sample zone for which there were no detections in indoor air will not have a data point shown. If there is more than one indoor air concentration for that sample zone and sampling event, the average indoor air data point will only be shown if at least one of the indoor air data points has a detectable concentration. The average indoor air concentration will only reflect the average of the detected concentrations.

4.2.1.3 Groundwater-Indoor Air Concentration Plots Representing Each Sample Zone and Sampling Event – Plots with Detectable Indoor Air Only Versus Indoor Air Non-Detects Plotted at Detection Limit

This section examines groundwater-indoor air data pairs—where each pair is associated with a given sample zone and sampling event similar to Section 4.2.1.2—and illustrates the effects of accounting for indoor air data that are below detection limit. Datasets generated with and without indoor air non-detects are further analyzed and the respective AF statistics compared in Section 4.2.4.

Figures 4-42a and 4-42b represent groundwater-indoor air concentration plots for TCE, with each data pair corresponding to a sample zone average for a given sampling event passing the 100X background source strength screen. Figure 4-42a is identical to Figure 4-41a and includes only detectable concentrations in indoor air (i.e., indoor air non-detects excluded). The dataset includes 181 pairs shown. Figure 4-42b includes non-detects in indoor air plotted at the detection limit. The dataset for Figure 4-42b includes 284 pairs, which is greater than the 181-pair set for Figure 4-42a since indoor air non-detects are included.

The data pairs are plotted using the following set of rules:

- For Figure 4-42a, only detectable indoor air data are included; this means that a sampling event for a given sample zone for which there were no detections in indoor air will not have a data point shown. By contrast, this data point will be represented on Figure 4-42b, using the indoor air detection limit as the indoor air concentration or the average of the detection limits if there are several indoor air non-detects in the sample zone during the sampling event. An example of a non-detect pair is shown on Figure 4-42b (see pair inside the blue circle corresponding to a sampling event in a building sample zone). This pair is not shown on Figure 4-42a because the corresponding indoor air concentration was below detection limit.
- If there is more than one indoor air concentration for a given sample zone and sampling event, the average indoor air data point will only be shown on Figure 4-42a if at least one of the indoor air data points has a detectable concentration. The average indoor air concentration will only reflect the average of the detected concentrations (i.e., non-detects excluded from the average). For Figure 4-42b, the average indoor air concentration will include the indoor air non-detects taken at detection limit. This means that the average indoor air concentrations may somewhat change between Figures 4-42a and 4-42b. An example of such

occurrence is shown on both figures (green circles). In this example, the average indoor air concentration when accounting for indoor air non-detects (Figure 4-42b) is slightly lower[39] than the average that includes only the detectable concentrations (Figure 4-42a).

4.2.1.4 Groundwater-Indoor Air Concentration Plots Representing Each Sample Zone Averages for All Sampling Events

This section describes the averaging technique used to generate a single groundwater-indoor air data pair for a given sample zone. Once generated, the set of averaged data pairs is analyzed and used to compute the AF statistics on a sample zone as further described in Section 4.2.3. These AF statistics are also compared to those obtained on a sample zone and sampling event basis (Section 4.2.2).

Figures 4-43a and 4-43b represent groundwater-indoor air concentration plots for TCE, with each data pair corresponding to a sample zone average for all sampling events passing the 100X and 5,000X background source strength screens, respectively. A total of 83 sample zone average pairs passed the 100X background source strength screen, whereas a smaller number of pairs (46 pairs) passed the stronger 5,000X background source strength screen.

The data pairs are plotted using the following set of rules:

- Each groundwater-indoor air data point represents the maximum measured groundwater vapor concentration of a given sample zone that passed the source strength screen plotted against the average of the indoor air concentrations of all sampling events for that sample zone. For instance, if there were three sampling events in a sample zone represented on Figure 4-41a—i.e., three events that passed the 100X background source strength screen—then one point representing the average[40] is plotted on Figure 4-43a.
- Indoor air data for all sampling events associated with a sample zone that passed a source strength screen will be included in the calculation of the average since, as noted previously (Section 4.2.1.2), there cannot simultaneously be passing and failing events for a given source strength screen.
- On Figures 4-43a and 4-43b, only detectable indoor air data are included. Similar plots can be generated showing sample zone averages for all sampling events where indoor air non-detects are taken at detection limit, with some of the averaging considerations presented in the previous bullets and in Section 4.1.1.3.

4.2.2 Attenuation Factors Derived Using Sample Zone Averages for Individual Sampling Events

This section focuses on groundwater-to-indoor air AFs obtained from individual sampling events conducted in separate sample zones. Averaging rules and examples of data plots (for TCE) corresponding to a sample zone average for a given sampling event were provided in Section 4.2.1.2. This section builds upon these averaging rules, evaluates the effects of increasing the source strength screen, and considers other VOCs in addition to TCE.

4.2.2.1 Effect of Increasing Source Strength Screen on Attenuation Factors

As discussed in Section 2.4, the objective of the source strength screen is to limit the effect of background source contributions to the AFs consistent with the USEPA methodology (USEPA, 2012a). As the source strength screen increases, background influence is progressively eliminated and the median and percentiles of the AF distribution are expected to stabilize. This approach was previously used for subslab soil gas-indoor air data (Section 4.1.2.1) and is also used for groundwater-indoor air data.

[39] There is only one detectable indoor air concentration of TCE plotted as 0.55 µg/m^3 on Figure 4-42a. Figure 4-42b also includes seven non-detects collected in the same sample zone during the same sampling event, with detection limits ranging from 0.20 to 0.26 µg/m^3 (average of about 0.22 µg/m^3), such that the average for the eight indoor air data points becomes 0.26 µg/m^3.

[40] Note that in the average for all sampling events, each sampling event is weighted by the number of pair combinations associated with this event. This averaging approach is similar to that discussed for subslab soil gas-indoor air data pairs (see Section 4.1.1.5).

Figures 4-44 to 4-46 show paired groundwater-indoor air concentration plots for TCE, PCE, and cis-1,2-DCE, respectively, with progressively increasing source strength.[41] Only detectable indoor air concentrations are shown using the averaging rules discussed in Section 4.2.1. Also shown on the figures is a blue line and shaded area corresponding to the LOESS fits. As noted in Section 4.2.1.1, the groundwater vapor concentrations that are plotted correspond to the maximum measured concentrations for each sample zone.

Figures 4-47 to 4-49 show the groundwater-to-indoor air AF distributions for varying source strength screens for TCE, PCE, and cis-1,2-DCE, respectively. The AFs are obtained by using the ratio of the average indoor air concentration to the groundwater vapor concentration (i.e., the maximum measured concentration) using all the data pairs plotted on Figures 4-44 to 4-46, respectively. The changes in AF distribution visible on Figures 4-47 to 4-49 reflect the influence of background sources. As shown on these figures, increasing source strength screens progressively eliminates the relatively elevated AFs that more likely reflect background sources and thus do not reflect attenuation of vapors into the building.

Summaries of descriptive statistics for the AF distributions associated with TCE, PCE, and cis-1,2-DCE as a function of source strength screen are provided in Tables 4-13 to 4-15 and the associated box-and-whisker plots are shown on Figures 4-50 to 4-52. As can be seen on the figures, the AF distribution statistics, including the median (50th percentile), 90th percentile, and 95th percentile, tend to stabilize as the source strength screen increases to approximately 5,000X background (approximately 10,000 $\mu g/m^3$); however, further changes are noticeable once the source strength screen increases to 100,000 $\mu g/m^3$. This may be the result of both the reduced sample size (i.e., the low number of data pairs or AFs for deriving the distribution statistics), as well as the elimination of data pairs with groundwater vapor concentrations in the range 10,000 to 100,000 $\mu g/m^3$, for which background contributions are likely less important than VI contributions. Similar trends can be observed on Figures 4-53a and 4-53b, which show plots of the 90th and 95th percentile AFs associated with TCE and PCE as a function of source strength screen. On the basis of these figures, a source strength screen of 5,000X background (for VOCs with background values) or 10,000 $\mu g/m^3$ (for VOCs without background values) are adequate to filter out potential background contributions when assessing AF distribution statistics.

4.2.2.2 Recommended Generic Groundwater-to-Indoor Air Attenuation Factor for DoD Industrial Buildings

Figure 4-54 show paired groundwater-indoor air concentration plots for all VOCs that were part of the analysis. Consistent with the source strength screen recommendations made in the previous section, the pairs on the plots passed either the 5,000X background source strength screen for VOCs with background values (TCE, PCE, 1,2-DCA, and VC) or the 10,000 $\mu g/m^3$ source strength screen for VOCs without background values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE).[42] Pairs with an indoor air concentration below detection limit are not shown. Table 4-16 provides a summary of descriptive statistics for the AF distribution associated with the VOC data pairs shown on Figure 4-54; the associated box-and-whisker plot is shown on Figure 4-55. As shown on Figure 4-54, none of the pairs are associated with a groundwater-to-indoor air AF that exceeds USEPA's generic AF of 10^{-3} (USEPA, 2015) and very few pairs exceed an AF of 10^{-4}. This is noteworthy because the AF of 10^{-3} derived by USEPA corresponds to the 95th percentile AF obtained from statistical analysis of USEPA's (2012a) primarily residential data; an AF of 10^{-4} would correspond approximately to USEPA's 57th percentile residential AF.

As shown in Table 4-16, the 90th percentile AFs range from 1.1×10^{-6} to 1.2×10^{-4} depending on the VOC. Based on the analyses shown on Figure 4-55, a groundwater-to-indoor air AF of 10^{-4} is defensible and conservative for predicting indoor air concentrations on the basis of groundwater data for commercial and industrial buildings in the DoD VI Industrial Database. The value of 10^{-4} corresponds to the 97th percentile AF of all the VOC data pairs shown on Figure 4-54.

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41 Note that for TCE (Figure 4-44), the plots associated with the 10X and 5,000X background source strength screens are identical to those shown on Figures 4-41a and 4-41b.

42 There were no pairs meeting the various filtering criteria for 1,1,1-TCA and 1,1-DCE.

As will be shown in Section 4.2.4, accounting for indoor air non-detects in the analyses has only limited effect on this result.

4.2.3 Attenuation Factors Derived Using Sample Zone Averages – Averaging for All Sampling Events Versus Averaging for Individual Sampling Events

This section focuses on groundwater-to-indoor air AFs obtained from sample zone averages for all sampling events passing a given source strength screen. Examples of data plots using this type of averaging were shown in Section 4.2.1.4. The objective of this section is to review the AF distribution and statistics associated with this approach and compare them to the distribution and statistics obtained for the individual sampling event approach that was discussed in Section 4.2.2.

Figures 4-56 to 4-58 show paired groundwater-indoor air concentration plots for TCE, PCE, and cis-1,2-DCE, respectively, using the selected 5,000X background source strength screen (for TCE and PCE) or 10,000 $\mu g/m^3$ fixed source strength screen (for cis-1,2-DCE) consistent with the Section 4.2.2.1 recommendations. Only detectable indoor air concentrations are shown using the averaging rules discussed in Section 4.2.1. Each (a) part of the figures shows the plot with the corresponding source strength screen obtained using the individual sampling event approach (i.e., see Section 4.2.2 and Figures 4-44 to 4-46), whereas the (b) part of the figures shows the approach using sample zone averages for all sampling events.[43] As can be seen, there is generally limited difference in LOESS fit.

Tables 4-17 to 4-19 summarize descriptive statistics for the AF distributions associated with TCE, PCE, and cis-1,2-DCE as a function of source strength screen with AF data obtained from the indoor air to groundwater vapor concentration ratios corresponding to sample zone averages for all sampling events. Figure 4-59 shows a box-and-whisker plot comparing the AF distribution statistics using this approach versus the individual event approach discussed in Section 4.2.2.[44] As can be seen from these box-and-whisker plots, there is generally little difference in 90th and 95th percentiles between approaches. Similarly, Figures 4-60a and 4-60b, which show plots of the 90th and 95th percentile AFs associated with TCE and PCE as a function of source strength screen, are similar to the corresponding plots developed for AF data derived from individual sampling events (Figures 4-53a and 4-53b).

Collectively, the data show that using AF data derived from sample zone averages for all sampling events yields AF distributions and statistics that are comparable to those derived from sample zone averages for individual sampling events (Section 4.2.2). Therefore, the results and 10^{-4} groundwater-to-indoor air generic AF recommendations obtained using the latter approach (individual sampling events) are unchanged.

4.2.4 Attenuation Factors Derived Using Detectable Indoor Air Data Only Versus Indoor Air Non-Detect Data Plotted at Detection Limit

The AF distribution approach based on building sampling averages per sampling event (Section 4.2.2) used detectable indoor air data only. In this section, this distribution is compared to that obtained using non-detect data plotted at detection limit using the averaging rules detailed in Section 4.2.1.3.

Figures 4-61 to 4-63 show paired groundwater-indoor air concentration plots for TCE, PCE, and cis-1,2-DCE, respectively, using the selected 5,000X background source strength screen (for TCE and PCE) or 10,000 $\mu g/m^3$ fixed source strength screen (for cis-1,2-DCE) consistent with the recommendations in Section 4.2.2.1. Each (a) part of the figures shows the plot with the corresponding source strength screen obtained using detectable indoor

[43] Note that Figure 4-56b for TCE is identical to Figure 4-43b.

[44] The individual event ("per event") box-and-whisker plots for TCE, PCE, and cis-1,2-DCE on Figure 4-59 correspond to the 5,000X background or 10,000 $\mu g/m^3$ source strength screen shown on Figures 4-50 to 4-52, respectively. See also Figure 4-55.

air data only, whereas the (b) part of the figures shows the approach using indoor air non-detects plotted at the detection limit.[45]

Table 4-20 compares the groundwater-to-indoor air AF statistics obtained for TCE, PCE, and cis-1,2-DCE using detectable indoor air only and using non-detects plotted at detection limits. The source strength screen is either 5,000X background (for TCE and PCE) or 10,000 µg/m^3 (for cis-1,2-DCE). Figure 4-64 provides a box-and-whisker comparison of the AF distributions for these VOCs using both approaches. As shown on the table and figure, there are some differences in 50th (median), 90th, and 95th percentiles between both approaches; however, the differences do not change the conclusion that a groundwater-to-indoor air AF of 10^{-4} is an upper-bound conservative AF that appropriately characterizes the groundwater-indoor air dataset.[46] Similarly, Figure 4-65, which presents plots of the 90th and 95th percentile AFs associated with TCE and PCE as a function of source strength screen, shows some limited changes.

This analysis confirms that a groundwater-to-indoor air AF of 10^{-4} derived in Section 4.2.2.2 using detectable indoor air data only remains appropriate when also considering indoor air non-detects. This 10^{-4} AF can conservatively predict indoor air concentrations on the basis of groundwater data for commercial and industrial buildings. The analysis confirms the results of Venable et al. (2015).

4.3 Sample Zone Area Effect on Indoor Air Concentration

Conceptually, for a given VOC vapor source of finite size, a large sample zone area would be expected to offer more opportunity for dilution of VOC vapors—and thus result in lower indoor air concentrations—relative to a sample zone of smaller area; however, there may be other factors to take into consideration, such as interior height or air exchange rate (USEPA, 2015).

The previous analysis (Venable et al., 2015) concluded:

> "Increasing sample zone area was significantly associated with decreasing indoor concentration on a log-log plot. This fits a mechanistic hypothesis that the indoor concentration should be highly diluted in large, well-mixed sample zones if the source is:
>
> - Due to a discrete activity
> - A preferential pathway
> - If vapors are intruding through only a portion of the floor in a large space."

In the previous analysis, the trend was statistically significant for TCE and cis-1,2-DCE but not for PCE.

The results of the expanded analysis are shown on Figures 4-66 to 4-73 for PCE, TCE, cis-1,2-DCE, and trans-1,2-DCE, respectively, with two plots per VOC showing the data with indoor air non-detects plotted at detection limit and with indoor air detects only. Specifically, the figures show normalized indoor air concentrations (i.e., subslab soil gas-to-indoor air AFs) plotted as a function of sample zone area. In these plots, the baseline, atypical preferential pathway, and selected source strength screens have been applied (i.e., 1,000X background or 1,000 µg/m^3 constant value depending on the VOC; Section 2.4.3.1), with each data point representing one sampling event in a sample zone.

Overall, the data shown on the various figures do not show a statistically significant downward trend with sample zone area. The plots for PCE indicates no clear trend (Figures 4-66 and 4-67). In the largest dataset (TCE), the plots suggest a V-shaped behavior, but there is no obvious physical mechanism that would explain this trend (Figures 4-68 and 4-69). The cis-1,2-DCE dataset shows an increasing (but not significant) trend of concentration with

[45] Note that Figures 4-61a, 4-62a, and 4-63a are identical to Figures 4-56a, 4-57a, and 4-58a, respectively.

[46] The most notable difference is the shift in the AF distribution for cis-1,2-DCE, which can be explained by the large change in size of the dataset; the number of data pairs increased from 25 to 78 when including the indoor air non-detects (Figure 4-64).

increasing sample zone area (Figures 4-70 and 4-71). The trans-1,2-DCE dataset shows a significant increasing trend with increasing sample zone area (Figures 4-72 and 4-73); this trend is consistent whether the data is analyzed with or without non-detects, but the size of the trans-1,2-DCE dataset is relatively small compared to the other VOCs.

For the two degradation VOCs (cis- and trans-1,2-DCE), the trend is in the opposite direction from what was expected based on the mechanistic hypothesis discussed at the beginning of this section. It is easy to hypothesize mechanisms by which degradation VOCs might have increased concentrations in subslab soil gas. However, it is more difficult to posit mechanisms to explain the behavior observed here—an increase in normalized indoor air concentration (or AF).

The other VOCs, not shown for brevity, do not show statistically significant trends and/or have insufficient data to reasonably evaluate trends. This suggests that sample zone area should be dropped from the QDF at this time. There is insufficient evidence to support a hypothesis that larger sample zones lower indoor air concentrations. However, the following should be noted:

- Assigning the boundaries of sample zones is one of the least certain elements of the data entry process that underlies this dataset. Tracer data or detailed HVAC maps would facilitate an analysis of above-grade zones. The spatial segmentation of the building below grade is often different from that above grade, which further complicates this analysis.
- Some of the support for the inclusion of sample zone area in the original QDF came from the multivariate analysis. The multivariate analysis for sample zone area-related variables is discussed in Section 5.

4.4 Exterior Wall Effect on Indoor Air Concentration

As previously noted in Section 3.6, the presence of an exterior building wall in a given sample zone could play an important role in determining VI potential (e.g., building perimeter crack for soil gas entry, and wall penetrations for air exchange); however, the nature and relative importance of factors that are conducive to more (or less) VI for a sample zone where an exterior wall is present are not straightforward.

The previous analysis (Venable et al., 2015) concluded:

> "A statistically significant higher median indoor air concentration of TCE was observed in sample zones with exterior walls. The odds of detection in indoor air were higher in sample zones with exterior walls for 1,1-DCA; PCE; and TCE. Median subslab soil gas concentrations for PCE and 1,1,1-TCA were significantly higher in sample zones with exterior walls. 1,1-DCE and 1,1-DCA were also significantly more likely to be detected in subslab soil gas beneath sample zones with an exterior wall. When the indoor air data were normalized, there was not a consistent exterior wall effect on the normalized indoor air concentration. Thus, the physical reasons for this observation of a higher median indoor concentration or a higher likelihood of detection in indoor air (for some compounds) are likely a complex combination of vadose zone and building envelope factors. This is a novel finding that requires replication in future studies."

The results of the expanded data analysis are presented on Figures 4-74 through 4-79 for several VOCs of interest. These figures show comparative box-and-whisker plots of indoor air concentrations for sample zones with and without exterior wall. The concentrations were obtained after applying the baseline, atypical preferential pathway, and selected source strength screen (i.e., 1,000X background or 1,000 µg/m^3 constant value depending on the VOC; Section 2.4.3.1) at the individual sampling event level. The overall visual appearance of the box-and-whisker plots is that the presence of an exterior wall increases the range of the observed indoor air concentrations, including the maximum and the IQR; however, this appearance could also result from the fact that there are more data points for sample zones with an exterior wall than without one and, therefore, review of the results of statistical tests comparing the quartiles is also needed (Tables 4-21 through Table 4-26).

Focusing only on the detected concentrations, results can be summarized as follows:

- For PCE (Table 4-21, Figure 4-74), the 90th percentile value of indoor air concentration is significantly higher and the 10th percentile value is significantly lower when an exterior wall is present.
- For TCE (Table 4-22, Figure 4-75), the 10th through 70th percentile values of indoor air concentration are lower when an exterior wall is present, but only the 30th percentile is statistically significantly lower.
- For cis-1,2-DCE (Table 4-23, Figure 4-76), the 50th percentile of indoor air concentration is significantly lower when an exterior wall is present.
- For trans-1,2-DCE (Table 4-24, Figure 4-77), there are no statistically significant quartiles.
- For 1,1,1-TCA (Table 4-25, Figure 4-78), the 90th percentile value of indoor air concentration is significantly higher and the 10th percentile value is significantly lower when an exterior wall is present.
- For 1,1-DCA (Table 4-26, Figure 4-79), the 50th through 90th percentile values of indoor air concentration are significantly higher when an exterior wall is present, although the number of detectable samples with no exterior wall is low (n = 4).
- For 1,1-DCE, there were only four detectable samples and the detection limits for the non-detects were frequently higher in concentration than the detects, so no meaningful comparison could be made.
- For 1,2-DCA and VC, there were no data associated with sample zone with no exterior wall, so no meaningful comparison could be made.

Thus, the evidence for an exterior wall effect on indoor air concentrations is limited and/or inconsistent. Exterior walls appear to be associated with a higher variability in indoor air concentrations and, conversely, a sample zone located in the middle of a building with no exterior walls does not have as much variability. Higher variability could be mechanistically expected in a zone with exterior walls because wind loads can lead to high differential pressures at the foundation edge and move subslab soil gas concentrations temporarily nearer to the wall/slab crack on one side of the building (USEPA, 2012b). These observations, however, should be interpreted with caution because they are somewhat inconsistent across VOCs and come from relatively small sample sets which were not randomly selected.

4.5 Distance to Primary Release Effects on Indoor Air

As previously noted in Section 3.4, the potential for VI would be expected to diminish as the distance to the point or area of primary release increases. Accordingly, indoor air concentrations would be expected to be lower in sample zones that are located further away from the primary release.

The previous analysis (Venable et al., 2015) concluded:

> “After data screening to remove indoor sources, a relationship is observable for both PCE …and TCE ….although for TCE there is a higher degree of scatter. The relationship for PCE is especially clear with both the distance and PCE concentration log transformed yielding an $r^2 = 0.33$ with a highly significant p=0.0031 (N=24).”

The results of the expanded analysis for TCE, PCE, and trans-1,2-DCE are presented on Figures 4-80 through 4-86, with each plot showing indoor air concentrations as a function of distance to primary release using one of several types of scale (i.e., log-log, semi-log, or linear scale). The data are screened as shown in the figures (i.e., baseline, atypical preferential pathway, and source strength, consistent with the approaches described in Sections 2.4.3.1 and 2.4.3.2 for subslab soil gas-indoor air and groundwater-indoor air data pairs, respectively).[47]

[47] The stacked data point pattern visible on Figures 4-80 through 4-86 is due to the fact that multiple indoor air data points (from various sampling events) can be associated with the same sample zone and thus the same distance to primary release.

The PCE log-log plot retains a similar general shape of concentrations decreasing with distance but is not always statistically significant (Figure 4-80). The r^2 is strong (0.20 and 0.32) and the significance tends to be greatest (p =0.02 and 0.05) when the data are plotted on a log-log plot relative to the semi-log or linear scale plots (Figures 4-81 and 4-82). The effect of the data being screened to remove background source influence based on subslab soil gas data versus groundwater data is also shown on these figures as the (a) and (b) parts, respectively. Because of data availability considerations,[48] these plots can reflect different groups of sites. For example, the PCE indoor air concentration versus distance plot, shown using the semi-log scale and screened using groundwater, has a very strong correlation (r^2 = 0.54) and is statistically significant (p = 0.001; Figure 4-81b). The subslab screened version of the same plot (Figure 4-81a) is not significant (p = 0.18), presumably because the data points at 500 feet from primary release were included in the subslab soil gas-screened plot but not the groundwater-screened plot.

The general appearance of the TCE plot remains similar to those presented in Venable et al. (2015), although there are several more data points corresponding to indoor air concentrations greater than 20 $\mu g/m^3$ at distances of 100 feet or more (Figures 4-83 through 4-85). When visualized on a log-log plot, which tends to emphasize data with a distance to primary release between 1 and 10 feet, there is no predictive power (Figure 4-83). However, the semi-log and especially the linear scale plots of TCE show visually that the proportion of high indoor air concentration results decreases with increasing distance from the point of primary release (Figures 4-84 and 4-85, respectively). This pattern is not significant in a linear least squares fit, although the fit is not statistically well-suited for detecting a nonlinear pattern of this type.

Although the dataset is small, the results from trans-1,2-DCE do show a statistically significant decrease from the point of primary release (Figure 4-86). Thus, short distances to primary release are associated with the potential for, but not the certainty of, elevated indoor air concentrations.

The effects of distance to primary release on indoor air concentration are further examined in the multivariate discussion in Section 5.

Given the predictive power of distance to primary release for subslab soil gas concentration (Section 3.4), it is appropriate to retain distance to primary release as a line of evidence in the QDF.

4.6 Groundwater Depth Effects on Indoor Air Concentration

Previous VI studies have focused on the protective effect of groundwater depth in separating a conventional groundwater VI source from buildings (USEPA, 2012a, 2012b, 2015). Such effects are relatively weak and reach an asymptote with increasing depths (Figures 4-87 and 4-88). Figure 4-88 shows that the effect of a difference between a water table at 3 meters and a water table at 8 meters on indoor air concentration is modest and that the flow of soil gas into the building may be slightly higher in the 8-meter case.

There was not a significant relationship between depth to groundwater and indoor air concentration in the previous analysis (Venable et al., 2015, Section 6.2.2.7). However, variables based on groundwater concentration divided by depth were found to be significant in the multivariate analysis.

The results of the expanded analysis are presented on Figures 4-89 through 4-94 for several VOCs of interest, with each plot showing indoor air concentrations as a function of depth to groundwater using a semi-log or log-log scale as the (a) and (b) parts of each figure, respectively. The data are screened as shown in the figures (i.e., baseline, atypical preferential pathway, and source strength, consistent with the approach described in Section 2.4.3.2 for groundwater-indoor air data pairs).[49]

[48] For instance, indoor air data tend to be collected along and paired with subslab soil gas data; however, groundwater data may not readily be available to form indoor air-groundwater data pairs.

[49] The stacked data point pattern visible in Figures 4-89 through 4-94 is due to the fact that multiple indoor air data points (from various sampling events and sample zones) can be associated with the same maximum measured groundwater concentration (Sections 2.4.2.2 and 4.2.1.1) and thus the same depth to groundwater.

Most of the results plotted on Figures 4-89 through 4-94 show significant trends (i.e., $p < 0.05$) of indoor air concentration increasing with increasing depth to groundwater as follows:

- PCE semi-log plot (r^2 =0.15)
- TCE semi-log plot (r^2 =0.35)
- TCE log-log plot (r^2 = 0.40)
- cis-1,2-DCE semi-log plot (r^2 = 0.28)
- cis-1,2-DCE log-log plot (r^2 = 0.23)
- trans-1,2-DCE semi-log plot (r^2 =0.39)
- trans-1,2-DCE log-log plot (r^2 =0.34)
- 1,1-DCE semi-log plot (r^2 = 0.76)
- 1,1-DCE log-log plot (r^2 = 0.62)
- VC semi-log plot (r^2 =0.44)
- VC log-log plot (r^2 = 0.50)

These results are relatively strong predictors despite contradicting theoretical expectations of depth providing a protection against VI. However, only in the cases of TCE and VC are the trends visually persuasive (Figures 4-90 and 4-94). In many cases, the fits may be driven by the high concentration data at 40 feet, which all comes from one site. In this case, the strongest source is likely in shallow soil rather than groundwater.

One possible explanation for this unexpected result is that in many cases in the DoD VI Industrial Database, the groundwater is not the primary source of VOCs, even in cases where the groundwater concentration is sufficient to pass a stringent groundwater-based source strength screen. In cases where the mass was primarily stored in the vadose zone, the higher flow of soil gas into the building that would be expected in the drier cases (i.e., cases where the water table was deep beneath a building) might produce the observed results by carrying into the structure a larger volume of impacted soil gas.

Taken together, the evidence from subslab soil gas (Section 3.5) and indoor air concentrations suggest that higher concentrations at or within the building are favored by shallow groundwater depth. Depth to groundwater was not considered as a line of evidence in the original QDF (Venable et al., 2015), although it was incorporated as a factor in the recent revised QDF (CH2M, 2018). The current analysis indicates that inclusion of depth to groundwater as a line of evidence in the QDF is defensible when the groundwater is known to be the primary VOC source.

4.7 Soil Type Effects on Indoor Air Concentration

As previously noted in Section 3.3, fine soil types (i.e., silt or clay) have lower permeability and hold a greater amount of moisture than coarse material (i.e., sand or gravel), such that that fine-grained material are expected to act as a barrier to vapor transport and limit potential VI concerns. VOCs released into fine soils are also less likely to be naturally attenuated through volatilization or other physical mechanisms.

The previous analysis (Venable et al., 2015) concluded:

> "Soil type appears to have an effect on subslab soil gas concentrations and subslab soil gas concentrations in turn appear to affect indoor concentrations. Thus, by the transitive property of logic, soil type would be expected to affect indoor concentrations. ….Note however, that the effect of soil type appears to be less dramatic on indoor air concentration (3 to 5 times for PCE and TCE) than on subslab soil gas concentration (20 times for PCE and TCE). This phenomenon is

> expected, because fine soils directly beneath the building are expected to limit the transport of chlorinated solvents, but also the flow rate of soil gas into the structure."

The results of the expanded data analysis are presented on Figures 4-95 through 4-100 for several VOCs of interest, with a summary provided in Table 4-27 (for indoor air detects only). The figures show comparative box-and-whisker plots of indoor air concentrations for coarse and fine soil types. The concentrations were obtained after applying the baseline, atypical preferential pathway, and selected source strength screens (i.e., 1,000X background or 1,000 $\mu g/m^3$ constant value depending on the VOC; Section 2.4.3.1) at the individual sampling event level.

When considering indoor air detects only (Table 4-27; see also Figures 4-95 and 4-96), fine soils are associated with higher median indoor air concentrations for both PCE and TCE (in each case with a p-value of less than 0.05). The magnitude of these effects is often large; for example, the median PCE concentration in indoor air within sample zones overlying fine soil is 13.6 $\mu g/m^3$ compared to 0.0995 $\mu g/m^3$ for sample zones overlying coarse soil. Median indoor air concentrations in sample zone overlying fine soils are also higher than for coarse soils in the case of cis-1,2-DCE (Figure 4-97) and 1,1-DCA (Figure 4-100), but the differences are not statistically significant ($p = 0.306$ and $p = 0.239$, respectively; Table 4-27). For 1,1,1-TCA, coarse soils result in greater indoor air concentrations than for fine soils (Table 4-27; see also Figure 4-98), but this result is not statistically significant either ($p = 0.68$; Table 4-27).

For VC, 1,1-DCE, 1,2-DCA, and trans-1,2-DCE, there are not sufficient detectable data that pass the screening for comparisons.

It is expected from the literature and first principles that fine soils directly underlying a building will have at least the following five types of effects:

- Limiting transport of VOCs upward from impacted groundwater to buildings that overlie contaminated groundwater plumes (USEPA, 2012b).
- Limiting the rate at which soil gas can be drawn into the structure (USEPA, 2012b).
- Limiting the vertical transport of VOCs downward through the vadose zone at sites where solvents were discharged (USEPA, 1994).
- Limiting the rate of volatilization (natural attenuation) of solvents from the vadose zone (Brusseau, 1995).
- Controlling the rate of oxygen transfer and thus the presence of anoxic and anaerobic zones in the immediate subslab area (USEPA, 2013), thereby influencing the biological production of incomplete dechlorination products (Lawrence 2006; Stroo et al., 2010).

The complex pattern of the data reported for fine soil effects on subslab soil gas concentration and indoor air concentration in Sections 3.3 and 4.7, as well as Section 5 (multivariate analysis) likely reflects the combined effect of these multiple processes. Overall, the results are consistent with the understanding embodied in the 2015 and 2018 versions of the QDF (Venable et al., 2015; Lund et al., 2018), which use fine soil type as an influencing factor for high indoor air concentrations in proximity to a point of release.

SECTION 5

Multivariate Analysis

In presenting the results of the multivariate analysis of the DoD VI Industrial Database, multiple rotated views of the same 3-dimensional (3D) graph are provided to aid in visual comprehension. Each data point shown on the graphs corresponds to the average indoor air concentration and/or average subslab soil gas concentration obtained for a given sampling event in a given sample zone, with each data point having passed the various screens presented in Sections 2.4.3, 4.1.2, and 4.2.2, including the baseline, atypical preferential pathway, and selected source strength screens applied to the full dataset. Non-detects in indoor air are taken at the detection limit.

The VOCs with the largest available datasets and the VOCs with the highest degree of chlorination (PCE, TCE, and 1,1,1-TCA) are interpreted first in each section. In general, these VOCs are more likely to have been the original product released. 1,1-DCA, 1,2-DCA, and trans-1,2-DCE[50] may be present either as an original release from use as a solvent or as degradation products of higher chlorinated compounds. VC and two of the three DCE compounds (1,1-DCE and cis-1,2-DCE) are most likely to be present as degradation products of more highly chlorinated compounds (Lawrence, 2006). VOCs with three or fewer data points after the various screens were applied are not presented.

In some cases, the results of a general linear model are presented. General linear models are a broadening of multiple linear regression, which allow a combination of continuous and categorical predictor variables to be used to model a single continuous outcome variable. Figure 5-1 provides a guide on how to read the output report for the general linear model.

5.1 Transport from Groundwater to Indoor Air by Soil Type and Groundwater Depth

To examine the effect of variables pertaining to vadose zone transport processes on VI, data were plotted in 3D as follows: X = groundwater depth, Y = groundwater concentration, Z= indoor air concentration. The data were grouped using symbol colors into fine, coarse, and unknown ("NA" for not available) soil types. Conceptually, more elevated indoor air concentrations would generally be expected to be associated with more elevated groundwater vapor concentrations and shallower groundwater (USEPA, 2012b).

The PCE results across all soil types are somewhat noisy—and the amount of data points limited—but are visually suggestive of a weak trend of increasing indoor air concentration with increasing groundwater concentrations (Figure 5-1), as would be expected. The coarse soil data plotted by themselves visually indicate higher indoor air concentrations with the highest groundwater vapor concentrations. The indoor air concentrations in the fine soil cases are generally higher than would be expected with a similar groundwater vapor concentration in coarse soil. Taken as a whole, there is no clear trend with depth to groundwater. The coarse soil data plotted by themselves visually show a higher indoor air concentration with shallow groundwater; however, the data points associated with shallow groundwater also have elevated groundwater vapor concentrations. The fine soil data correspond almost entirely to a groundwater depth of 10 feet and thus are not a diverse enough dataset to interpret with regard to depth. None of the terms in the statistical general linear model are statistically significant.

The TCE results with all soil types together are also difficult to interpret (Figure 5-2). The highest indoor air concentrations are associated with concentrations in groundwater vapor greater than 2,000,000 µg/m^3. The highest indoor air concentrations are visually associated with either deep groundwater and fine soils or, in one

[50] Over the past couple of decades, trans-1,2-DCE has been used as a solvent and specialty cleaner (Appendix C).

case, unknown soil type and very shallow groundwater (2 feet). With coarse soil, there is only a slow (and noisy) rise of indoor air concentration with increasing groundwater vapor strength, but indoor air concentrations visually appear higher for groundwater depths of 6 feet or less. With fine soils, the highest indoor air concentrations are visually associated with deep groundwater (approximately 40 feet) and groundwater vapor around 2,000,000 $\mu g/m^3$. A further increase in groundwater vapor concentration with fine soils does not cause a continued increase in indoor air concentration. This supports the hypothesis that vadose zone mass storage is likely the primary source of indoor air impacts in many fine soil cases. The computed general linear model finds the depth to groundwater term to be highly significant but with a positive coefficient (such that indoor air concentration is predicted to increase with increasing groundwater depth). Soil type is also significant, and the coefficient suggests that fine soil may be associated with increased indoor air concentration (Figure 5-2).

The cis-1,2-DCE results associated with all soil types included are difficult to interpret (Figure 5-3). There is no visually apparent trend in indoor air concentration as a function of groundwater vapor concentration. The cis-1,2-DCE concentrations in indoor air are quite low overall. The highest concentrations were observed with shallow water table and high groundwater vapor concentrations, as would be expected, but the second highest indoor air concentration was observed for a low groundwater vapor concentration and deep groundwater. This might occur if the true source of the cis-1,2-DCE was shallow soil and not deep groundwater; however, the way the dataset was processed does not allow the VOC source to be systematically distinguished. The coarse dataset alone has a similar interpretation to the combined soil type dataset, and there are relatively few fine soil cases. There are no significant terms in the general linear model.

There is a relatively narrow range of depths (5 to 9 feet) and measured groundwater vapor concentrations available for 1,1-DCA (Figure 5-4); however, the available data visually suggest that, as expected, higher indoor air concentrations are associated with shallower groundwater depths and higher groundwater vapor concentrations.

The highest vinyl chloride concentrations in indoor air remain relatively low (less than 0.6 $\mu g/m^3$) (Figure 5-5). These concentrations are visually associated with fine soil with depths to groundwater of 5 to 7 feet and groundwater vapor concentrations around 100,000 $\mu g/m^3$. The results are consistent with the mechanistic understanding of VC fate in the subsurface. Coarse soils are more likely to be aerobic. VC is generated as a product of incomplete anaerobic biodegradation and has a short half-life in aerobic soils. The general linear model indicates that fine soil increases indoor air concentration. The other terms are not significant.

When the data for all VOCs are analyzed together (Figure 5-6), the general linear model shows two significant terms, as follows:

- Higher indoor air concentrations are associated with fine soil types.
- Significantly higher indoor air concentrations for a given set of groundwater concentration and depth are observed for PCE relative to other VOCs. This finding may reflect the fact that PCE does not readily degrade in the vadose zone.

5.2 Transport from Groundwater to Indoor Air by Soil Type and Groundwater Depth – Locations Distant from Primary Release

For this analysis, the dataset was restricted to locations distant from the source—those with distances to primary release of more than 30 feet—to focus the analysis on cases that were most likely to be controlled by groundwater transport as opposed to vadose zone sources. To examine the effect of variables pertaining to vadose zone transport processes on VI, data were plotted in 3D similar to Section 5.1, with X = groundwater depth, Y = groundwater concentration, Z = indoor air concentration. The data were grouped using symbol colors into fine, coarse, and unknown ("NA" for not available) soil types.

When analyzed with this focus on groundwater transport, PCE shows a visual trend in which indoor air concentration slowly rises with increasing groundwater vapor concentration (Figure 5-7). Peak PCE concentrations are also visually associated with shallow groundwater depths or fine soils. The general linear model finds a significant relationship between increasing indoor air concentrations and groundwater vapor concentrations and fine soil significantly contributing to increased indoor air concentration. It must be recognized, however, that the dataset is limited in size.

Using this same type of analysis, the highest TCE concentrations in indoor air are visually associated with the combination of fine soil and relatively high groundwater vapor concentration (1,800,000 µg/m^3; see two fine soil, deep groundwater data points with indoor air concentrations greater than 100 µg/m^3 on Figure 5-8). Among the coarse soil data, however, higher indoor air concentrations visually occurred more frequently with shallow groundwater depths. The general linear model finds soil type to be the most significant term (i.e., fine soil increasing indoor air concentration). Surprisingly, the model also finds depth to groundwater to be significant with a positive coefficient (i.e., the deeper the groundwater, the greater the indoor air concentration). These results are likely driven by the two indoor air data points with concentrations greater than 100 µg/m^3.

There is insufficient data for 1,1,1-TCA, cis-1,2-DCE, trans-1,2-DCE, or VC to conduct analyses with this approach.

When the data for all VOCs are analyzed with this approach, the two fine soil, deep groundwater TCE data points still stand out visually on the plot as having unusually high indoor air concentrations (Figure 5-9). When these data points are excluded, the overall trend is one of slowly increasing indoor air concentration with groundwater vapor concentration. Higher indoor air concentrations appear to be associated with groundwater depths around 5 feet; the shallower data points show relatively lower concentrations. However, this finding could be an artifact of a small sample size because the nine sample zones in the DoD VI Industrial Database with a depth to groundwater of less than 5 feet had low groundwater concentrations compared to sample zones with depth to water of 5 feet or greater. Similar to the above analyses for PCE and TCE, the general linear model finds a significant association between fine soil type and higher indoor air concentration. The model also associates higher indoor air concentrations with greater depths to groundwater (probably driven by those two deep data points) and higher groundwater vapor concentrations.

5.3 Transport from Groundwater to Subslab Soil Gas by Soil Type and Groundwater Depth – Locations Distant from Primary Release

To obtain more information about vadose zone transport and attenuation, the dataset was restricted to locations distant from the source—those with distances to primary release greater than 30 feet (similar to the approach used in Section 5.2). This focuses the analysis on cases that were most likely to be controlled by groundwater transport as opposed to vadose zone sources. To examine the effect of variables pertaining to vadose zone transport processes on VI, data were plotted in 3D as follows: X = groundwater depth, Y = groundwater concentration, Z = subslab soil gas concentration. Similar to Sections 5.1 and 5.2, the data were grouped using symbol colors into fine, coarse, and unknown (“NA”) soil types. There were insufficient data to compute a general linear model for any of the analytes individually. Conceptually, more elevated subslab soil gas concentrations would generally be expected to be associated with more elevated groundwater vapor concentrations and shallower groundwater, with the subslab soil gas concentrations expected to decrease as the depth to water increases. However, the relationship between subslab soil gas concentration and depth is not expected to be linear (USEPA, 2012b).

The results of this analysis indicate a general visual trend for PCE of increasing subslab soil gas concentration with increasing groundwater vapor concentration and decreasing groundwater depth (Figure 5-10). Given roughly equivalent conditions, the fine data points appear to have concentrations at or above what would have been inferred from the coarse data alone. This suggests that the fine data points may reflect direct vadose zone impacts of the releases, even though the distance to primary release was believed to be greater than 30 feet. Such a situation could be due to multiple points of release or lateral movement of released solvents in the vadose zone. Investigators frequently first obtain groundwater data and stratigraphy information before obtaining soil gas information. Although continuous fine soil layers are expected to be protective against VI from groundwater, mass at the water table can be a signal of historical vadose zone releases. Another possible explanation is a time lag between subslab soil gas and groundwater conditions. Carr et al. (2010) have shown examples where groundwater may have been cleaned up (either through remediation or natural attenuation) but where finer vadose zone material overlying groundwater continues to store VOC mass in equilibrium with past groundwater conditions. As a result of this lag, the soil gas concentrations reflect earlier, more elevated groundwater concentrations.

For TCE, the coarse soil data visually indicates that relatively high subslab soil gas concentrations (greater than 150 $\mu g/m^3$) are most common with depths to groundwater of 6 feet or less (Figure 5-11). The deep groundwater cases have relatively modest groundwater vapor strength (29,000 $\mu g/m^3$ or less). However, there is one exception among the coarse soil data, with a subslab soil gas concentration of 12,600 $\mu g/m^3$, a groundwater vapor concentration of 28,700 $\mu g/m^3$, and a depth to groundwater of 33 feet—a case which suggests minimal vadose zone attenuation. Among the fine soil data, two data points exhibit elevated subslab soil gas concentrations combined with relatively elevated depth to groundwater (up to 195,000 $\mu g/m^3$ in subslab soil gas, with 1.86 million $\mu g/m^3$ in groundwater vapor and a depth to groundwater of 40 feet). Similar to PCE, the existence of such data points suggests direct vadose zone impacts of the releases, even though the distance to primary release was believed to be greater than 30 feet. Alternately, as discussed in this section for PCE, this could reflect vadose zone mass that was transported at a time when the groundwater concentration was higher than it is currently.

For cis-1,2-DCE, trans-1,2-DCE, 1,1-DCA, 1,2-DCA, the available data include only one soil type and a narrow range of depths to groundwater. As a result, the data are not interpreted separately.

For VC, the only data that passed screening was from relatively shallow groundwater depths (7 feet or shallower) (Figure 5-12). There are only two data points with relatively high subslab soil gas concentrations (greater than 1,000 $\mu g/m^3$). One is very shallow (2 feet to groundwater), with an unknown soil type, a groundwater vapor concentration of 895,000 $\mu g/m^3$, and a subslab soil gas concentration of 9,000 $\mu g/m^3$. The second has a depth to groundwater of 7 feet, with a groundwater vapor concentration of 109,000 $\mu g/m^3$ and a subslab soil gas concentration of 40,000 $\mu g/m^3$, suggesting little vadose zone attenuation. Many other cases show a more dramatic degree of attenuation, which is expected because VC is aerobically degraded.

When the data for all VOCs are aggregated (Figure 5-13), there is a general visual trend of increasing subslab soil gas concentration with increasing groundwater vapor concentration and decreasing depth to groundwater, which is consistent with the conceptual model.

In the dataset for all VOCs limited to fine soils only (Figure 5-14), there is a visually clear trend of increasing subslab soil gas concentration with increasing groundwater vapor concentration but no clear trend regarding depth. Some of the highest subslab soil gas concentrations (mentioned previously) are associated with depths to groundwater of 40 feet.

In the dataset for all VOCs limited to coarse soils only (Figure 5-15), the trend of increasing subslab soil gas concentration with decreasing depth to groundwater is visually clear, as is the trend of increasing subslab soil gas concentration with increasing groundwater vapor concentration.

The only statistically significant terms in the general linear model of this dataset (limited to distance to primary release greater than 30 feet) associated higher indoor air concentrations with cis-1,2-DCE and trans-1,2-DCE (given a particular depth to groundwater and groundwater vapor concentration). It is possible that this finding reflects the formation of these somewhat stable degradation products at a distance from the source.

5.4 Transport and Dilution from Subslab To Indoor Air as a Function of Sample Zone Area and Presumed Open Doors

Conceptually, increased sample zone area and open bay doors would result in increased air exchange and increased dilution of indoor air concentrations. To examine this hypothesis, data were plotted in 3D as follows: X =

subslab soil gas concentration, Y = sample zone area, and Z = indoor air concentration. The data were grouped by whether open doors were suspected based on the primary use of the zones (i.e., grouped based on closed, open, or unknown ["NA" for not available]). The categorization as to closed or open doors is shown in Table 5-1. For the statistical test, it was also hypothesized that the indoor air concentration was expected to increase with increasing subslab soil gas concentration.

For PCE (Figure 5-16), the trend of decreasing concentration with increasing sample zone area is visually clear. There also appears to be a trend of increasing indoor air concentration with increasing subslab soil gas concentration. When removing the sample zones for which insufficient information is available to classify the probable door status, the closed-door cases do not show a simple easily interpretable pattern. The general linear model does not have any statistically significant terms.

For TCE (Figure 5-17), there is a visually clear trend of increasing indoor air concentration with increasing subslab soil gas concentration, but there is no clear trend with sample zone area. When removing the sample zones for which insufficient information was available to classify the probable door status, a visual trend of slightly higher concentrations with presumed closed doors is apparent (even though some of the highest indoor air concentrations occur for uses with doors that are presumed closed). For TCE, there is no statistically significant terms in the general linear model.

Seven of the nine 1,1,1-TCA data points are clumped in one area with subslab soil gas concentrations between 190,000 and 1,600,000 µg/m^3 (Figure 5-18), indoor air concentrations between 2 and 7.7 µg/m^3, and sample zone areas below 20,000 square feet. Thus, it is difficult to visually discern a strong trend. The general linear model finds only a significant association between increasing subslab soil gas concentration and increasing indoor air concentration.

In the cis-1,2-DCE dataset (Figure 5-19), indoor air concentrations are consistently greater than 1 µg/m^3 when subslab soil gas concentrations are relatively elevated (i.e., greater than 100,000 µg/m^3); however, a few indoor air concentrations greater than 1 µg/m^3 are observed with substantially lower subslab soil gas concentrations. There is not a visually clear trend with sample zone area overall. When removing the sample zones for which insufficient information is available to classify the probable door status, the highest concentrations are visually associated either with closed doors or very small suspected open-door zones. The general linear model indicates a significant association between subslab soil gas concentration and indoor air concentration. Suspected open doors is also a significant term reducing the predicted indoor air concentration.

For trans-1,2-DCE (Figure 5-20), most of the data visually support a trend of decreasing indoor air concentration with increasing sample zone area, even though this trend is weak. Most of the data is also consistent with increasing indoor air concentration with increasing subslab soil gas concentrations. The sole suspected closed-door data point is the highest concentration data point (10 µg/m^3), with a moderate subslab soil gas concentration (3,800 µg/m^3) and a relatively large sample zone area (43,000 square feet). The general linear model calculations indicate a strong correlation of increasing indoor air concentration with subslab soil gas concentration. There is also a statistically significant reduction of indoor air concentration with suspect open-door status, but since there is only one suspected closed-door case, this result should be interpreted cautiously.

The 1,1-DCE dataset has only five points after screening and does not show any clearly interpretable trends (Figure 5-21).

The observed indoor air concentrations of 1,1-DCA are all quite small with only one data point above 1 µg/m^3. A weak trend of decreasing concentration with increasing sample zone area can be discerned (Figure 5-22).

VC concentrations in indoor air are small, with only one data point exceeding 0.8 µg/m^3. No clear trends are apparent in the 3D plots (Figure 5-23).

When the data for all VOCs are graphed together (Figure 5-24), using the selected screening level for each compound, the overall trend visually shows increasing indoor air concentrations with increasing subslab soil gas concentration, as expected. The trend with regard to sample zone area is not monotonic, apparently suggesting a minimum in indoor air concentration as a function of subslab soil gas concentration in sample zones between roughly 1,500 and 15,000 square feet. There is not an obvious physical explanation for that apparent trend. When the unknown door classification is removed, there is not an obvious, consistent differentiation in the dataset based on suspected door status. The only significant term in the general linear model forecasts increased indoor air concentration with increased subslab soil gas concentration.

In summary, several VOCs show increasing indoor air concentrations with increasing subslab soil gas concentrations, as expected. Several individual VOC datasets support the hypotheses of higher concentrations with closed doors or in smaller sample zones, but not enough replication to support an overall conclusion.

Based on the results of the analysis and professional judgment, the attempt to predict indoor air concentrations using inferences about open doors drawn from zone primary use information failed. This does not necessarily prove that open doors are irrelevant to indoor air concentration. Direct observation and control of large open doors during sampling would undoubtedly be better than inferring door status from zone use. This information is typically obtained as part of building surveys conducted at the time of sampling.

5.5 Transport and Dilution from Subslab To Indoor Air as a Function of Sample Zone Area and Zone Use

Conceptually, increased sample zone area would result in increased dilution of indoor air concentrations, which would be generally protective of VI, if the amount of VOCs mass entering the zone remained constant. To examine this hypothesis, data were plotted in 3D as follows: X = subslab soil gas concentration, Y = sample zone area, and Z = indoor air concentration. The data were grouped with different colors based on the variable “zone use standardized”. This is similar to the analysis in Section 5.4, except that data are sorted by use based on the detailed primary use Category Code Number (CCN), into a small number of categories as follows:

1. Bathroom/locker
2. Industrial/shop
3. Kitchen/break
4. Mixed use
5. Office
6. Other
7. Residential
8. Retail
9. Warehouse
10. Unknown (“NA” when no information is available)

Note that this discussion emphasizes particular categories of sample zone use because the dataset is otherwise similar to that discussed in Section 5.4.

When the mixed use and unknown use zones are omitted for TCE, the visual trend of increasing indoor air concentration with increasing subslab soil gas concentration is evident (Figure 5-25). Based on use, an office or industrial/shop appears to have a somewhat higher indoor air concentration than a warehouse with a similar subslab soil gas concentration. Conceptually, this would be expected, since warehouses are generally much larger sample zones than offices. Yet, each type of usage is associated with a wide range of indoor air concentrations. There are no significant terms in the general linear model but increasing subslab soil gas concentration came close to significance as a predictor of indoor air concentration ($p = 0.067$).

For PCE, the visual trend of increasing indoor air concentration with subslab soil gas concentration is steep for the identified uses other than “warehouse” (Figure 5-26). Although the dataset is limited, the warehouse indoor air concentrations appear to be lower than would have been forecast given the very high subslab soil gas concentrations in those zones (i.e., greater than 1 million µg/m^3). The general linear model shows a counterintuitive result of a significant negative coefficient for subslab soil gas concentration (meaning the model predicts greater indoor air concentrations for smaller subslab soil gas concentrations). The general linear model also associates higher indoor air concentrations with office and warehouse uses and lower concentrations with industrial/shop use. This model may not be completely reliable because there are relatively few data points for each use type.

For cis-1,2-DCE (Figure 5-27), only six data points remain after eliminating the unknown use and mixed use categories. Four of the data points are industrial/shop, which visually show a relatively steep increase in indoor air concentration with increasing subslab soil gas concentration. The sole warehouse data point has a somewhat lower indoor air concentration than would have been expected for its subslab soil gas concentration. The general linear model shows a significant trend of increasing indoor air concentration with increasing subslab soil gas concentration.

No discernable trend can be ascertained for trans-1,2-DCE and 1,1-DCE (Figures 5-28 and 5-29). For VC (Figure 5-30), the kitchen/breakroom and office uses appear to have, on average, higher concentration than the unknown uses, although the sample size is very small.

When the data for all VOCs are analyzed together (Figures 5-31 and 5-32), there is a visual association of higher indoor air concentration with higher subslab soil gas concentration, as expected; however, the indoor air concentration trend with sample zone area is not monotonic, with generally lower indoor air concentrations associated with sample zones with an area in the intermediate range of 1,500 to 15,000 square feet. In the general linear model, the only significant term associates higher indoor air concentrations with warehouse uses (Figure 5-31). The evidence from the single VOC analyses suggested that warehouse uses have somewhat lower indoor air concentrations than would be anticipated in a zone with a different use given a constant subslab soil gas concentration. The result of the general linear model with all VOCs considered together, including the VOCs that only have a few data points, reach the opposite conclusion. We know generally that not all warehouses are alike—some have large doors open all day, and some do not. Therefore, these contradictory results suggest that warehouse use should not be considered as a factor in the QDF.

5.6 Transport and Dilution from Subslab To Indoor Air as a Function of Sample Zone Area and Zone Use – Winter Data

This analysis is similar to that presented in Section 5.5, but uses only winter data. Conceptually, winter (where outdoor temperatures are significantly lower than indoor temperatures) is a period during which advective driving force for VI is expected to be greater than during other seasons. During that time, increased soil gas entry would be expected to result in greater indoor air concentrations, assuming similar or lower air exchange rates than during other seasons. However, it has been shown that the air exchange rate also increases with colder temperatures, so the response of particular buildings to the driving force provided by the stack effect depends on the distribution of the leakage area among the floor, walls, ceiling, and similar (Song et al., 2014).

Only a small amount of winter-only data remains following implementation of the other screens on an individual VOC basis (Figure 5-33). Like the all-season data (Figure 5-31), the all-VOC winter-only data show a non-monotonic response to sample area

Restricting the analysis to winter data reduces the number of data points, but it also increases the significance of many of the predictors in the general linear model. In this analysis, increasing indoor air concentration is significantly associated with increasing subslab soil gas concentration and decreasing sample zone area. Indoor air concentrations were also predicted to be significantly higher for PCE; it is unclear whether any physical meaning could be ascribed to that result as it could be an artifact of a small sample set.

5.7 Transport and Dilution from Subslab To Indoor Air as a Function of Building Area and Building Use

To examine the hypothesis that building area (instead of the sample zone areas in Sections 5.5 and 5.6) would provide substantial dilution in some building types and would be protective against VI, data were plotted in 3D as follows: X = subslab soil gas concentration, Y = building area, and Z = indoor air concentration, grouping the data with colors by standardized building use: industrial/shop, office, or unknown ("NA").

PCE results (Figure 5-34) show a visual trend of decreasing concentration with increasing building area. When data associated with unknown use are not shown, clear groupings are visually apparent: higher indoor air concentrations associated with office uses and relatively small building areas; and lower indoor air concentrations associated with industrial/shop uses and relatively large building areas. The only significant term of the general linear model associates office use with higher indoor air concentrations, which appears to occur because the subslab soil gas concentrations are higher in the office cases studied here.

TCE indoor air concentrations do not show a visually clear trend with building area (Figure 5-35). Within the small number of data points in the industrial/shop and office groups, trends of increasing indoor air concentration with increasing subslab soil gas concentration are visually observed. The office buildings are smaller in size than the industrial/shop buildings, but do not show distinctly different concentrations. The general linear model results show a significant term for increasing indoor air concentration with increasing subslab soil gas concentration. The model results also yield a significant term for decreasing indoor air concentration with increasing building area.

The relatively small dataset for 1,1,1-TCA (Figure 5-36) does not show a visually clear trend for indoor air concentration as a function of building area, potentially because only a narrow range of building areas are represented. The 1,1,1-TCA plots visually show the expected increase of indoor air concentration with increasing subslab soil gas concentration. There is insufficient data to apply the general linear model.

The most elevated cis-1,2-DCE concentrations in indoor air are visually associated with large building areas and high subslab soil gas concentrations (Figure 5-37). The only significant term in the general linear model is a positive association of indoor air concentration with subslab soil gas concentration.

There is not a clear visual trend in indoor trans-1,2-DCE concentrations as a function of building area (Figure 5-38). There are no significant terms in the general linear model.

There is not a clear visual trend in indoor 1,1-DCE concentrations as a function of building area, building use or soil gas concentration because the dataset is sparse (Figure 5-39). There are no significant terms in the general linear model.

With 1,1-DCA, there is an apparent trend of increasing indoor air concentrations with increasing building area (Figure 5-40). However, the number of data points is modest, and the range of building areas studied is narrow (less than one order of magnitude). The general linear model does find a significant relationship for increasing indoor air concentration with increasing building area.

Observed indoor air concentrations of VC are low (Figure 5-41) (all but one are less than 0.6 $\mu g/m^3$). Given the modest size of the dataset and the degree of scatter, there is not a clear visual interpretation regarding building area. There are no significant terms in the general linear model.

Combining the data for all VOCs, the increase in indoor air concentration with increasing subslab soil gas concentration is visually apparent (Figure 5-42). A visual inspection shows a wide range of indoor air concentrations corresponding to the full range of building areas, suggesting that building area is not a major predictor variable. When the dataset is limited to the industrial/shop and office building uses, the interpretation is largely unchanged. However, it is noticeable that many (but not all) of the highest indoor air concentrations are in the office buildings and are associated with high subslab soil gas concentrations. In the general linear model, the only statistically significant term indicates an increased indoor air concentration among the office buildings.

5.8 Transport and Dilution from Subslab To Indoor Air as a Function of Building Volume and Building Use

To examine the hypothesis that building volume would provide substantial dilution—at least in some building types—and would be protective against VI, the data were plotted with X = subslab soil gas concentration, Y = building volume, and Z= indoor air concentration. The data are grouped with colors by standardized building use. This is similar to the approach presented in Section 5.7, except that building volume is used instead of building area.

The PCE data show a clear visual trend of declining concentration with increasing building volume and a general trend of increasing indoor air concentration with increasing subslab soil gas concentration (Figure 5-43). The office cases available for PCE have strong subslab soil gas concentrations and relatively small volumes, while the industrial/shop cases have larger volumes (as might be expected). The only significant term in the general linear model associated higher indoor air concentrations with the office building use type.

The TCE data do not show a clear visual relationship between building volume and indoor air concentration (Figure 5-44). TCE does show a general visual trend of increasing indoor air concentration with increasing subslab soil gas concentration. When the data from only the clearly identified building types (industrial/shop and office) are plotted, there is an absence of a clear trend in concentration with building volume, even within the industrial/shop subgroup. The general linear model has a significant term indicating an increase of indoor air concentration with increasing subslab soil gas concentration. The general linear model also associates a significantly lower indoor air concentration with the mixed use group of buildings.

The available 1,1,1-TCA data span only about one order of magnitude in building volume (Figure 5-45) and it is therefore not surprising that there is not a strong visual trend on that axis. There were not enough data to complete a general linear model.

The cis-1,2-DCE data lack a clear visual trend relating indoor air concentration to building volume either for the dataset as a whole or the only specific use category available—industrial/shop (Figure 5-46). There is a visible general increasing trend of indoor air concentration with subslab soil gas concentration. The general linear models only significant term associated higher indoor air concentrations with higher subslab soil gas concentrations.

Plots 1 to 3 of Figure 5-47 consider all VOCs together and all building uses. As expected, there is a distinct visual trend for increasing indoor air concentration with increasing subslab soil gas concentration. There is not a logical monotonic trend in indoor air concentration as a function of building volume. The data trend in the mixed use cases are not clearly distinct from the office or industrial/shop uses.

Plots 4 to 6 of Figure 5-47 consider all VOCs together, but look only at the office buildings and the industrial/shop buildings (i.e., eliminating the unknown [NA] and mixed use cases). The office buildings are lower in volume and visually exhibit slightly higher indoor air concentrations for a given subslab soil gas concentration. The general linear model confirms that the office buildings are significantly higher in concentration. This is the only term that is significant in the model. This is not a finding that would be expected from the general VI conceptual site model (CSM). Office buildings would typically be expected to have lower subslab sources and be fitted with controlled/forced ventilation from engineered HVAC systems that would result in lower indoor air concentrations. Conversely, the worst-case VI condition for a sample zone or building would be a combination of a strong subslab source, the absence of an HVAC system, and little natural ventilation (e.g., closed doors).

The office and industrial/shop buildings demonstrate a clear visual trend of increasing indoor air concentration with increasing subslab soil gas concentration, whether viewed as individual categories or with both categories of use together. Among the industrial/shop buildings there is not a clear trend with building volume. If just the office buildings are considered (Plots 7 and 8 of Figure 5-47), there is an insufficient range of volumes to observe a possible effect of volume.

5.9 Conclusions from Multivariate Analysis

In this portion of the project, multivariate analyses were performed on the DoD VI Industrial Database to evaluate relationships between an outcome variable (e.g., subslab soil gas or indoor air concentration) and predictor variables that are known to be related to the outcome variable through theoretical considerations (e.g., groundwater depth, soil type, and groundwater concentration). The multivariate analyses were conducted after applying the baseline, atypical preferential pathway, and selected source strength screens (i.e., 1,000X background or 1,000 $\mu g/m^3$ constant value depending on the VOC; see Sections 2.4.3, 4.1.2, and 4.2.2) aggregated at the sampling event and sample zone level, so that each individual sampling event that passed the screens was presented, but the data from multiple soil gas or indoor air monitoring points within a sample zone were averaged. Non-detects in indoor air were taken equal to the detection limit.

A series of multivariate analyses were conducted, focusing on factors influencing transport from groundwater to subslab soil gas (and ultimately to indoor air) as a function of groundwater depth and soil type. The effect of groundwater concentration on subslab soil gas concentration was analyzed after restricting the dataset to locations distant from the source—those with distances to primary release greater than 30 feet (Section 5.3). The objective of the 30 feet restriction was to focus the analysis on cases that were most likely controlled by groundwater transport as opposed to vadose zone sources. A general trend of increasing subslab soil gas concentration with increasing groundwater vapor concentration and decreasing depth to groundwater was observed consistent with expectations. Among the fine soil cases, a correlation between subslab soil gas and groundwater vapor concentrations was noted, but there was no clear trend regarding depth to groundwater. For many of the fine soil cases, the data points have subslab soil gas concentrations at or above what would have been inferred from the coarse soil data at similar groundwater vapor concentrations. This suggests that some of the fine data points may reflect direct vadose zone impacts of the releases, even though the distance to primary release was believed to be greater than 30 feet. Such a situation could be due to multiple points of release or lateral movement of released solvents in the vadose zone, which could occur for example through drainage lines (e.g., an imperfectly sealed storm or sanitary sewer) or drainage layers (e.g., gravel bed). Alternately, this trend could reflect stored VOC mass in the vadose zone that migrated at a time when the groundwater concentration was higher than it was when the data for this analysis were collected.

The influence of groundwater concentration, groundwater depth, and soil type on indoor air concentration was analyzed both without and after limiting distances to primary release of greater than 30 feet (Sections 5.1 and 5.2, respectively). In general, the trend of increasing indoor air concentration with increasing groundwater concentration was found to have a flat slope, even though AF-based approaches presume a 1:1 slope (in the log-log space).

After restricting the dataset to locations greater than 30 feet from the point of primary release to exclude data that were presumed to be associated with vadose zone sources, fine soil types were found to be associated with higher indoor air concentrations than coarse soil types. This suggests that the protective effect of fine soils on transport upward from groundwater is outweighed by the tendency of fine soils to retain VOC mass in the vadose zone, even when the sample zone is more than 30 feet away from the presumed point of release. The multivariate analysis also showed that groundwater depth is correlated to indoor air concentration when the soil type is coarse; i.e., shallower groundwater depths in coarse soil types are generally associated with greater indoor air concentrations, consistent with the expectation that there would be less attenuation of subsurface concentrations over a relatively thin vadose zone.

Default AF analyses and modeling conventions commonly assume that when groundwater is shallower than 5 feet, indoor air concentrations may be markedly higher than expected because diffusion no longer limits mass transport. There is little evidence in data from the DoD VI Industrial Database that as the water tables become shallower than 5 feet, the indoor air concentrations increase precipitously as a function of groundwater vapor concentration.

It has previously been hypothesized that buildings or zones with large square footage, large volume, or open bay doors are expected to have lower indoor air concentrations than smaller sample zones. This hypothesis assumes that the dilution potential of the larger rooms will outweigh any increase in mass flux due to a potentially larger source area beneath the floor. This hypothesis is also based on a judgment that DoD warehouse-style buildings with open roll-up doors display greater air exchange rates. Open doors were associated with higher air exchange rates in one study of commercial buildings (Bennett et al., 2012; USEPA, 2018, Table 19-31). However, data from others (Turk et al., 1987; USEPA, 2018, Table 19-30) suggest that the air exchange rate of naturally ventilated commercial buildings is similar to or less than those of office or educational spaces. The standards of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) call for the following outdoor air rate in cubic feet per minute per square foot (CFM/ft^2) (ASHRAE, 2003):

- Residences including barracks – 0.06
- Offices – 0.06
- Cafeteria – 0.18
- Storage rooms – 0.12
- Shipping/receiving – 0.12
- Warehouses – 0.06
- Wood/metal shop in an educational facility – 0.18

ASHRAE also calls for certain minimum exhaust rates also expressed in CFM/ft^2; those exhaust rates would require equivalent supply rates as follows:

- Auto repair shop – 1.5
- Parking garages – 0.75
- Woodwork shop/classroom – 0.5
- Kitchen, commercial – 0.70
- Janitor, trash, recycle – 1.0

Thus, ASHRAE calls for a ventilation in a warehouse that is equivalent to a residence (0.06 CFM/ft^2), but expects greater ventilation rates in many other types of building and zone uses, including shops.

The DoD VI Industrial Database does not directly record the status of any large doors at the time of sampling. Nor does the database have information on any ventilation standards that these spaces were historically designed to meet. The database generally includes information about the area and volume of buildings and sample zones, as well as in many cases the current uses of those buildings or zones.

In one analysis (Section 5.4), the data were grouped based on whether large doors were expected to be open on the basis of the known primary use and typical building design associated with such use (based on general experience and professional judgment). Indoor air concentrations data were then graphed as a function of subslab soil gas concentration and sample zone area. The analysis determined that there were individual VOC datasets that supported the hypothesis of higher concentrations with closed doors or in smaller sample zones, but not enough replication to support an overall conclusion. This does not necessarily prove that open doors are irrelevant to indoor air concentration. Direct observation and control of large open doors during sampling would undoubtedly be better than inferring door status from zone use.

When the indoor and subslab soil gas data for all VOCs were graphed together with sample zone area (Section 5.5), the overall trend showed increasing indoor air concentrations with increasing subslab soil gas concentrations, as would be expected. However, the trend with regard to sample zone area was not monotonic and suggested generally lower indoor air concentrations in sample zones with an area in the intermediate range of 1,500 to 15,000 square feet. There is not an obvious physical explanation for the non-monotonic trend. A similar non-monotonic relationship with sample zone area was also observed when the data analysis was limited to samples collected in winter (Section 5.6). When building area (rather than sample zone area) was analyzed, a relationship between building area and indoor air concentration could not be established consistently across several VOCs (Section 5.7). Nor could a consistent relationship be established between building volume and indoor air concentration (Section 5.8).

SECTION 6

Analysis of Building Characteristics

This section presents the DoD VI Industrial Database analyses and results related to building characteristics. The various characteristics are discussed under separate subsections. As part of this effort, single variable analyses of field site data were conducted (similar to those in Sections 3 and 4). Because many factors can influence VI, these analyses could be confounded by variables that are not controlled between the cases examined. In interpreting the statistical calculations performed, it should be recognized that the observations in this dataset are not from an ideal random sample, but clustered into a limited number of installations and buildings sampled. Therefore, cautious professional judgment was applied that viewed the results of the statistical tests in light of the following:

- Consistency (or lack thereof) between the results observed for different VOCs with similar chemical structures and similar behavior in the vadose zone
- Plausibility of the statistically indicated conclusions in light of known physical mechanisms
- An assessment of sample size

The reader should be aware that the absence of a statistically significant effect of a predictor variable on the outcome variable is not proof that no relationship exists between the two. Absence of statistical significance could occur, for example, when the effect of the predictor variable is real but not dominant and the sample size is modest.

6.1 Building and Zone Use

This analysis was conducted to see whether data are indicative of a relationship between VOC indoor air concentrations related to VI and building or zone use. To that end, indoor air data associated with subslab soil gas data that passed the various screens, including the baseline, atypical preferential pathway, and source strength screen (see Sections 2.4.2.1 and 4.1.2.1), were used for this analysis. The results for various VOCs are presented on the box-and-whisker plots shown on Figures 6-1 through 6-5, with each (a) and (b) parts of the figures showing the plots for building use and sample zone use, respectively.

When viewed at the building use level, there is not a clear and consistent pattern across VOCs relating indoor air concentration to use. For PCE, the indoor air concentrations for office buildings are statistically significantly higher than those for industrial/shop or “NA” (i.e., unknown) uses (Figure 6-2a). The indoor air samples come from a series of three buildings at one facility that are located near a former dry cleaner and/or an industrial sewer line. Some of these samples were collected from bathrooms within the office buildings. For TCE, the industrial/shop category shows statistically significantly higher concentrations than both the mixed use and “NA” categories (Figure 6-1a).

When viewed at the sample zone use level, there does not appear to be a clear and consistent pattern across VOCs relating indoor air concentration to use, even among the group of data points with sufficient source strength for this analysis. For TCE (Figure 6-1b), the mean for warehouse use is statistically significantly higher than the mean for industrial/shop use; however, the IQRs for these two uses significantly overlap, making the finding less persuasive. For PCE (Figure 6-2b), there are statistically significant comparisons as calculated; for example, warehouse is again higher than industrial/shop. However, given the very small sample sizes and the potential for clustering of samples, great weight should not be placed on these findings. There is a possible physical mechanism that could explain these findings: industrial/shop uses are more likely to have designed exhaust ventilation than warehouses. Exhaust ventilation will increase air exchange rates but can also increase soil gas entry rates by depressurizing buildings.

The lack of a pattern may be the result of several factors. First, the indoor air data may be less a reflection of the zone use than the subslab soil gas concentration beneath the zone. Second, the sample size for each use is very limited, even for TCE (Figure 6-1), with most data reported as NA, meaning that the use is unknown. Building or sample zone uses could also have changed over time. The use information in the DoD VI Industrial Database is from the time that the building was sampled, not necessarily the time that a pollutant release occurred. The sample size is limited because the box-and-whisker plots only represent indoor air data for which the associated subslab soil gas data passed the various screens, including the source strength screen. Thus, there are limitations to this analysis.

Conceptually, it is difficult to determine whether a particular use would be associated with greater concentrations. For instance, warehouses would be expected to be associated with a large sample zone volume and, therefore, generally diluted VOC concentrations in indoor air; however, warehouses are used for storage of a wide variety of materials, some of which may contain chlorinated VOCs. Office use would be expected to be associated with smaller air volumes and thus potentially greater indoor air concentrations, but the presence of an HVAC system in these spaces would also be expected to limit the potential for soil gas entry (see also Sections 6.2 and 6.3 for HVAC discussion). Office uses themselves are unlikely to be associated with significant use or release of chlorinated VOCs.

Additionally, it should be noted that in the multivariate analysis, office uses were at times shown to be statistically significantly higher for indoor air concentration. The most persuasive analysis is discussed in Section 5.7, which examined indoor air concentration as a function of subslab soil gas concentration, building area, and building use; however, the analysis in that section is significantly influenced by the same data points from three office buildings at the same installation. These data points also caused the higher PCE concentrations in office building uses seen on Figure 6-2a. Differences between the results in Section 5.7 and those in Section 6.1 could be due to the fact that the multivariate analyses controlled for the effect of certain confounding variables, such as subslab soil gas concentration and building area.

The reader should also be aware that this dataset does not constitute a representative sample of all DoD office buildings or office sample zones. Because sites were selected for the DoD VI Industrial Database on the basis of data availability in indoor air, subslab soil gas, and/or groundwater, it is biased toward including cases where the VI potential was high. Thus, the office buildings analyzed as part of this project are likely those overlying relatively strong sources, which generally suggest a prior industrial use in the same building or in proximity to the building.

Because the finding of higher concentrations in office building uses is driven only by one compound (PCE) and only a few buildings from one installation, the building or sample zone use criteria is not recommended for inclusion in the QDF.

6.2 Heating, Ventilation, and Air Conditioning System Presence

This analysis focused on examining indoor air data relationship with HVAC system presence and type. The term HVAC was understood in this project to mean systems that provided heating and/or cooling. Types were classified as “engineered”, “zone specific”, “none”, and “NA” with the following meanings:

- Engineered HVAC systems are generally centralized and professionally designed. They often are based on forced hot or cooled air distribution (i.e., from a heat pump or from a centralized chiller). This term would also encompass certain steam- or hot water-based systems that do not use forced air.
- “Zone specific” HVAC systems in DoD industrial buildings commonly supply heat through thermal radiation either from electrical resistance heating, or steam- or hot water-fed radiative heating devices. Zone specific cooling systems frequently include “window unit” air conditioners, which are sometimes installed between enclosed spaces and more open areas within the building, or are installed through exterior walls. Window unit air conditioners frequently provide cooling without introducing outdoor air. Zone specific cooling systems in DoD buildings also include evaporative coolers (i.e., “swamp coolers”).
- The classification “none” was applied when it was clear that no heating or cooling equipment was installed.
- The classification “NA” (unknown) was applied when no information was available about HVAC systems.

Similar to the previous section, only indoor air data associated with subslab soil gas data that passed the various screens, including the source strength screen, were used for this analysis. Conceptually, the presence of a forced air-based HVAC system in a given sample zone would be expected to typically result in lower VOC concentrations in indoor air because the operation of the HVAC system—if it introduces outdoor air—generally results on average in zone pressurization conditions that tend to limit soil gas entry.[51] Zones in commercial buildings with professionally designed forced air HVAC systems would have been designed to supply a certain minimum amount of outdoor air, detemined based on the number of persons expected to occupy the space, its use, and/or its size. Those quantities of outdoor air are specified for specific types of spaces in DoD standards, which often refer to industry standards prepared by ASHRAE (see Section 5.9). The amount of air exchange that occurs in zones with a "zone specific" HVAC system or no HVAC system ("none") is less well controlled, and can be either high or low depending on the weathertightness of the building envelope and the position of windows or doors.

The results of the HVAC system analysis are presented on Figures 6-6 through 6-10 for several VOCs of interest. The figures show box-and-whisker plots of indoor air concentration as a function of HVAC system presence and type. The analysis determined that the difference between the overall mean concentrations between the categories of engineered HVAC systems, no HVAC, and zone specific HVAC is significant for TCE but not for the other VOCs (see ANOVA tests in Figures 6-6 to 6-10).[52]

For TCE (Figure 6-6), the indoor air concentrations associated with the engineered HVAC systems are notably lower than those associated with the other categories (no HVAC present, zone specific HVAC, or unknown). The individual pairwise comparisons are significant between engineered HVAC and "none" (no HVAC) and between "none" and zone specific HVAC.

For PCE (Figure 6-7), the visual appearance of the box-and-whisker plot might suggest again that the zones without HVAC systems ("none") have higher indoor air concentrations than the other two categories (engineering HVAC or unknown) by about an order of magnitude, but this result does not reach statistical significance because there are only a limited number of "none" cases (and no case with zone specific HVAC), and because there are several cases for which the engineered HVAC systems are present and the indoor air concentration is greater than 10 $\mu g/m^3$. Despite these limitations, it is apparent—similar to TCE and consistent with the conceptual understanding of the effect of HVAC operation on VI—that the absence of HVAC is generally expected to result in greater concentrations of PCE in indoor air.

For 1,1,1-TCA (Figure 6-9), there is some visual apparence on the box-and-whisker plot that engineered HVAC operation results in indoor air concentrations that are typically two orders of magnitude lower than the other two categories (none or unknown); however there is only one data point for the "none" category. No significant weight should be ascribed to a difference between engineered HVAC systems and buildings in which the type of HVAC system is unknown. Additionally, there is no visually apparent trend for the cis-1,2-DCE and 1,1-DCA plots (Figures 6-8 and 6-10); however, the proportion of engineered HVAC in the dataset is lower for these two VOCs than for PCE and TCE, and the proportion of "NA" (unknown if an HVAC system is present) is greater.

Similar to Section 6.1, limitations related to this analysis include the overall limited number of indoor air data and the fact that there may be important variations in subslab soil gas concentrations between zones even if all these concentrations passed the source strength screen.

On balance, it is recommended that engineered HVAC be included in the QDF as a modestly weighted protective factor for the following reasons:

- The VOC with the largest sample size (TCE) showed a statistically significant effect.

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[51] Note that there could still be negative pressurization near the return and stronger positive pressurization near the supply

[52] In the reports of the one-way ANOVA, "DFn" is degrees of freedom in the numerator, "DFd" is degrees of freedom in the denominator, "p" is the p-value; p < 0.05 is marked with a * if it is significant, and "ges" is the generalized effect size. In reading the ANOVA tables in this section, it is helpful to familiarize oneself with the category titles on the X axis of the figure immediately above each table. In the numbered rows, "group 1" is being compared to "group 2", with each group being named with only the first four or five characters of its name. The main variable of interest is the adjusted p-value. Attention should also be given to the number of samples in each group as shown in the box-and-whisker plot immediately above each table.

- Although not reaching statistical significance, the data for several other VOCs suggested a protective effect of engineered HVAC.
- There are physically plausible mechanisms previously discussed in this section by which engineered HVAC systems could provide a protective effect. As will be discussed in Section 6.3, the effect for TCE is again significant when the dataset was limited to winter only.

6.3 Heating, Ventilation, and Air Conditioning System Presence – Winter Data

The comparison conducted in Section 6.2 was repeated for winter cases only. Winter corresponds to the season where use of heating equipment is expected to be common in the temperate portion of the United States in which almost all of the studied sites are located (Figure 2-1). Some forced air HVAC systems may be supplying outdoor air when they are operated to provide heating or cooling, but may not be operated during seasons where neither heating nor cooling is needed. Conceptually, engineered HVAC systems operating in the winter could potentially provide a protective effect by supplying outdoor air or providing positive pressurization in some cases. Either engineered or zone specific HVAC systems operating in winter would also provide a driving force for advective VI through stack effects.

Except for TCE, there was an insufficient number of indoor air sampling results obtained during the winter and passing the data screens for evaluating the various types of HVAC systems. For TCE (Figure 6-11), there are significant differences between the HVAC types as indicated by the overall ANOVA test. The HVAC "none" cases show substantially higher indoor air concentrations. Similar to Figure 6-6, the statistically significant pairwise comparisons are between engineered HVAC and none (no HVAC) and between "none" and zone specific HVAC. This result should be taken with caution given the very limited number of indoor air data points. As discussed at the end of Section 6.2, however, the balance of the evidence leads to a recommendation that engineered HVAC systems be included as a modestly weighted protective factor in the QDF.

6.4 Flooring Type

To examine the hypothesis that floor coverings might be protective against VI (for example, by reducing the loss of VOCs from the vadose zone through natural volatilization) or that they might exacerbate VI (for example by disguising slab flaws), the indoor air data were analyzed by looking at their relationship with flooring type. The results of this analysis are presented as box-and-whisker plots of indoor air concentrations, which are provided on Figures 6-12 through 6-21 for several VOCs of interest. Similar to the previous sections, only indoor air data associated with subslab soil gas data that passed the various screens, including the source strength screen, were used for this analysis. As previously noted, this is intended to address potential background contributions to the indoor air, including in this case potential contributions from the floor covering or associated adhesives (USEPA, 2011).

An ANOVA analysis was used to test the difference of the means of the various flooring categories. Similar to the analyses presented in previous sections, box-and-whisker plots with both indoor detects and non-detects (taken at the detection limit) are presented (Figures 6-12, 6-14, 6-16, 6-18, and 6-20). An analysis was also conducted with indoor air detects only (Figures 6-13, 6-15, 6-17, 6-19, and 6-21).

Overall, the results of the analysis and visual trends are not consistent between VOCs. Adding to the uncertainty of the evaluation is the overall limited number of samples and the fact that the range of subslab soil gas concentrations varies by several orders of magnitude between zones, even if all these concentrations passed the source strength screen.

While the visual appearance of the TCE box-and-whisker plots (Figures 6-12 and 6-13) is that bare concrete may be associated with higher indoor air concentrations than other flooring categories, the means of the groups were not statistically different in the ANOVA test ($p = 0.319$ including non-detects and $p = 0.24$ with detectable results only). The sample size for the identified flooring groups other than bare concrete was small (i.e., less than 10 samples when floor type is known). Note that higher indoor air concentrations associated with bare concrete relative to other flooring categories would suggest that floor covering could provide some degree of protection against VI.

For PCE (Figures 6-14 and 6-15), the highest indoor air concentrations are observed for the “vinyl tile or sheet” (vinyl) flooring category, and the ANOVA was statistically significant (both with and without non-detects) for the overall comparison, as well as for the individual comparison between the “bare concrete” and “vinyl” categories. In that case, higher indoor air concentrations associated with vinyl relative to other flooring categories would suggest that this type of floor covering could exacerbate VI. However, because there is no readily apparent physical reason to expect a different trend between TCE and PCE in migration across the building envelope, there is presently no clear indication that floor covering has a significant effect on the occurrence of VI. Effects other than flooring type are likely to be more important in this dataset.

There were no significant differences between flooring categories for cis-1,2-DCE and 1,1,1-TCA (Figures 6-16 to 6-19). However, the probative value of these negative findings is limited by sample size. While they provide no proof that flooring type is irrelevant, they currently suggest that flooring type may not have a significant effect in this dataset.

For 1,1-DCA, the ANOVA output showed a significant difference between means of flooring categories (Figures 6-20 and 6-21); however, the detectable sample size was small (n = 1 for vinyl tile or sheet) and this result is not viewed as a meaningful trend.

The observations presented in this section could, for certain data, illustrate an indirect relationship between floor type and indoor air concentrations because bare concrete floors and, to a lesser extent, vinyl or sheet flooring are associated with industrial and other utilitarian uses. Carpets are most often associated with office or residential uses. Epoxy coatings are frequently applied to floors to improve lighting, cleanliness, chemical resistance, and slip resistance (UFC, 2004). Thus, it is quite possible that the observations of correlation for some VOCs to particular current floor covering types are confounded by other unobserved factors, including sample zone or building use.

It is possible that sealants or coatings might at least temporarily reduce VI, although they are generally viewed as unreliable as a stand-alone strategy without being coupled with subslab depressurization (USEPA, 2008). It is also possible that carpets could serve inadvertently as a sorbent for VOCs (Tichenor et al., 1991; Xie and Suuberg, 2019) or even as a barrier to entry. It is thus recommended that future studies expand the number of cases with flooring materials other than bare concrete to determine if this variable has any importance. Alternately, additional multivariate statistical analyses of the current dataset could be undertaken to include floor covering as a variable.

Based on the results of this analysis, which shows that there is not a consistent relationship between floor type and indoor air concentrations across the VOCs studied, and which raises concerns about potential confounding factors, inclusion of criteria based on floor covering in the QDF is not currently recommended.

6.5 Building Construction Date Effect on Subslab Soil Gas Concentrations

The hypothesis that subslab soil gas concentrations related to VI are correlated with date of construction was tested. The data were grouped based on decades and major historical eras. Specifically, it was hypothesized that there might be differences in structures constructed before World War II (WWII; i.e., prior to 1939), during WWII (1939-1945), 1946-1959, 1960-1979, and 1980-2000. There are several reasons why a pattern might be observed:

- Many DoD buildings constructed during WWII were constructed as temporary buildings, but later reclassified as permanent or semi-permanent and often continue to be uses (R. Christopher Goodwin and Associates, Inc., 1997).

- Sequential additions to buildings have frequently occurred over time, which complicate site delineation and may introduce potential entry pathways at junctions between additions (Cox, 2013; Lund and Lind, 2016).
- TCE and PCE were extensively used during WWII and their national production increased sharply beginning at that time. TCE production decreased significantly after 1970. PCE production declined after 1980 (Doherty, 2010a, 2010b, 2012).
- Disposal practices for chlorinated solvents are also believed to improve over time with the onset of environmental regulations (Doherty, 2010a).
- In recent decades, DoD has substantially reduced the use of TCE (Davis, 2009; DoD, 2010).
- The processes that lead to the formation of chlorinated solvent degradation products frequently occur over decades (Bradley, 2003; Lawrence, 2006; Stroo et al., 2010).

The data were analyzed in the following two ways:

- A one-way ANOVA test of the means of the subslab soil gas concentrations in buildings within each construction era
- A regression of the log of subslab soil gas concentration versus year of construction

The subslab soil gas concentration results are presented on Figures 6.22 through 6.26 for selected VOCs. These figures show box-and-whisker plots of subslab soil gas concentrations associated with various construction eras, including prior to 1939, 1939-1945 (WWII), 1946 to 1959, 1960 to 1979, 1980 to 2000, and “NA” (unknown). The baseline and atypical preferential pathway screens were applied to the data, but not the source strength screen since the effect of background contributions to subslab soil gas concentrations is expected to be limited.

As shown on the figures, there are significant differences in the observed subslab soil gas concentrations for buildings built in different historical eras, with the general trend being that the WWII-constructed (and early Cold War period) buildings have the highest mean subslab soil gas concentrations. Overall, it is apparent that older buildings are typically associated with greater VOC concentrations in subslab soil gas. Conceptually, this result would simply reflect that older buildings have a longer operational history and thus a greater potential for a VOC release to have occurred. Older buildings are also more likely to have been in operation at a time where usage of certain VOCs, such as TCE, were more prevalent. In addition, older buildings, particularly those built during WWII, are more likely to include certain features that would have been consistent with construction standards of the time, but may have offered a pathway for historical chemical release (e.g., floor drains, dry wells, unlined pits, septic systems). There is a potential that buildings that were built with the intention of using them temporarily or built under the intense schedule pressure of wartime would have had lower quality building envelopes.

Specifically, the results can be summarized as follows:

- TCE concentrations in subslab soil gas (Figure 6-22) were highest beneath the buildings built between 1939 and 1945. The ANOVA testing showed a significant difference between the various construction eras, with a generalized effect size (“ges”) suggesting that building age predicted 23 percent of the variability in the subslab soil gas concentrations (“ges” value of 0.233). The significant pairwise comparisons (i.e., $p < 0.05$) included those between the pre-1939 buildings and the 1939-1945 buildings, the pre-1939 buildings and those built from 1980-2000, the 1939-1945 buildings and those built from 1960-1979, and the 1939-1945 buildings and those built from1980-2000. The slope of the linear regression between year of construction and log of subslab soil gas concentration was negative and significant, indicating a general decrease in concentration in more recent buildings; however, the r^2 indicates only 6 percent of the variance is explained by the linear regression, most likely because the concentrations in the pre-1939 buildings are lower than the 1939-1945 buildings.
- PCE concentrations in subslab soil gas (Figure 6-23) were highest for the 1939-1945 and 1946-1959 construction eras. The ANOVA testing showed a significant difference between the various construction eras, with a generalized effect size suggesting that building age predicted 25 percent of the variability in the subslab

soil gas concentrations (“ges” value of 0.247). Similar to TCE, various significantly different pairwise comparisons were also observed between groups (e.g., pre-1939 buildings and those built between 1960 and 1979, 1939-1945 buildings and those built between 1960 and 1979, and 1939-1945 buildings and those built between 1980 and 2000). The slope of the linear regression between year of construction and log of subslab soil gas concentration was negative and significant, indicating a general decrease in concentration in more recent buildings. Similar to TCE, however, the r^2 indicates only 6 percent of the variance is explained by the linear regression, most likely because the concentrations in the pre-1939 buildings are lower than the 1939-1945 and 1946-1959 buildings.

- Similar to TCE and PCE, cis-1,2-DCE concentrations (Figure 6-24) were highest beneath the buildings built between 1939 and 1945 and between 1946 and 1959. The ANOVA testing showed a significant difference between the various construction eras, with a generalized effect size suggesting that building age predicted 32 percent of the variability in the subslab soil gas concentrations (“ges” value of 0.321). Significant pairwise comparisons were also observed between groups as shown in the figure. The slope of the linear regression between year of construction and log of subslab soil gas concentration was negative and significant, indicating a general decrease in concentration in more recent buildings. Similar to TCE and PCE, the r^2 indicates only 3 percent of the variance is explained by the linear regression, likely for the same reasons provided previously.
- 1,1,1-TCA concentrations (Figure 6-25) were highest beneath the buildings built between 1939 and 1945, as well as those built from 1946 to 1959. The ANOVA testing showed a significant difference between the eras with a generalized effect size suggesting that building age predicted 41 percent of the variability in the subslab soil gas concentrations (“ges” value of 0.405). Significant pairwise comparisons were also observed between groups. The slope of the linear regression between year of construction and log of subslab soil gas concentration was negative and significant, indicating a general decrease in concentration in more recent buildings. The r^2 shows that 20 percent of the variance in the subslab soil gas concentration is explained by the linear regression.
- 1,1-DCA concentrations (Figure 6-26) were highest beneath the buildings built between 1939 and 1945 and between 1946 and 1959. The ANOVA testing showed a significant difference between the eras with a generalized effect size suggesting that building age predicted 35 percent of the variability in the subslab soil gas concentrations (“ges” value of 0.354). Similar to the other VOCs, significant pairwise comparisons were also observed between groups. The slope of the linear regression was not significant ($p > 0.05$), likely because the relationship between eras is not linear with time.

6.6 Building Construction Date Effect on Indoor Air Concentration

For the same historical reasons outlined in Section 6.5 regarding the effect of building construction date on subslab soil gas concentration, the differences in indoor air concentration as a function of construction date were also examined. The results of the analysis are presented on box-and-whisker plots of indoor air concentrations provided on Figures 6-27 through 6-31 for several VOCs of interest. For this analysis, the baseline, atypical preferential pathway, and source strength screens were applied to the data.

For some of the constituents (e.g., TCE; Figure 6-27), indoor air concentrations visually appear to be correlated with date of construction. Higher concentrations are especially prevalent in structures constructed before or during WWII (pre-1939 and 1939-1945 construction eras). Conceptually, this result could simply reflect the longer operational history of older buildings and resulting increased VI potential, as discussed in the previous section. In addition, due to their age, these older buildings are more likely to have preferential pathways (e.g., floor cracks, perimeter gap) that facilitate soil gas entry, as well as certain construction features that may offer both a pathway for a historical chemical release and, if still present, a vapor entry point (e.g., floor drains connected to dry wells).

The data were analyzed in the following two ways:

- A one-way ANOVA test of the means of the indoor air concentrations in buildings within each construction era
- A regression of the log of indoor air concentration versus year of construction

The results by VOC indicate that the only significant difference in indoor air means was observed for 1,1,1-TCA (Figure 6-30); note, however, that the sample size is very small (ten indoor air concentration data points). There were no significant differences for the other VOCs (TCE, PCE, cis-1,2-DCE, and 1,1-DCA). No significant slope was observed for any of the VOCs.

The strongest evidence of greater risk for buildings constructed during the WWII and early Cold War years comes from the subslab soil gas concentration data (Section 6.5). As will be shown in Section 6.7, however, the AF data suggest that the AFs for these years are actually lower, possibly because of poor weatherization/higher air exchange rates. The combination of these factors likely explains why the indoor air results reported in this section by building age show fewer significant comparisons.

6.7 Building Construction Date Effect on Normalized Indoor Air Concentration (Attenuation Factor)

For the same reasons outlined in Sections 6.5 and 6.6 regarding building construction date effect on subslab soil gas and indoor air concentrations, the differences in subslab soil gas-to-indoor air AF as a function of date of construction were also examined. The results of the analysis are presented on box-and-whisker plots of AFs provided on Figures 6-32 through 6-36 for selected VOCs. For this analysis, the baseline, atypical preferential pathway, and source strength screens were applied to the data.

The general pattern is that samples from the 1939-1945 buildings show a lower AF (i.e., more attenuation) compared to the other date groupings. There is a statistically significant result in the ANOVA test across groups for TCE, cis-1,2-DCE, 1,1,1-TCA, and 1,1-DCA, but not for PCE.

For TCE, the individual pairwise comparison between pre-1939 buildings and 1939-1945 buildings is significant (Figure 6-32). For cis-1,2-DCE, 1,1,1-TCA, and 1,1-DCA, the individual pairwise comparisons between the 1939-1945 buildings and the 1946-1959 buildings are significant (Figures 6-34 to 6-36).

It is possible, as noted in Section 6.6, that these results could be due to the 1939-1945 buildings generally being well ventilated/poorly weatherized. These AF trends could explain why despite the consistently higher subslab soil gas concentrations beneath the 1939-1945 buildings, the indoor air concentrations do not vary as much with building age as do the subslab soil gas concentrations.

SECTION 7

Atypical Preferential Pathways Analyses

Atypical preferential pathways (also referred to as "strict" preferential pathways in this report) were evaluated based on the dataset within the updated DoD VI Industrial Database. The data that were used for the analysis presented in this section were flagged in the database to indicate that a "strict" preferential pathway was present based on ascertainable evidence of an atypical preferential pathway. The criteria for designating strict preferential pathways used in this project is further discussed in the prior QDF report (Venable et. al., 2015, Section 5.2.4.2).

7.1 Atypical Preferential Pathway Methods

To evaluate the effects of atypical preferential pathways on the distance to primary release analysis, parts of the previous analyses were repeated using the following samples:

- Samples that were screened out from prior analyses on the basis of the preferential pathway screen because an atypical preferential pathway was present (i.e., "strict preferential pathway = true")
- Samples that were eliminated from the main analysis dataset because of the prevalence of multiple background sources or the use of second floor sampling locations

There were 26 sample zones in the dataset where the strict preferential pathway was coded in the DoD VI Industrial Database as "true" (i.e., evidence of an atypical preferential pathway) for one or more VOCs. The 24 sample zones with PCE data were drawn from six buildings at four installations. The 26 sample zones with TCE data were drawn from eight buildings on six installations. There were sufficient data to conduct the distance analysis only for PCE and TCE (i.e., locations with atypical or "strict" preferential pathways, as well as known distances to the location of primary release).

Graphs showing the relationship of subslab soil gas concentration to distance to primary release, as well as graphs of indoor air concentration versus distance to primary release were then reexamined to discern the potential impact of atypical preferential pathways.

Examples of the cases analyzed include the following:

- Sanitary sewers at an installation where their role as preferential pathways has been unambiguously demonstrated with smoke testing, HAPSITE portable gas chromatography/mass spectrometry (GC/MS) testing, or building pressure cycling
- A large "cutout of exposed soil"
- A sampling location directly above a grate for an interior drainage ditch
- An underground utility trench connecting a source area to a building
- A 6-foot by 5-foot tunnel used for storage and utilities connecting two buildings

General linear models were used to evaluate the effect of preferential pathways on indoor air concentrations. These models are able to handle both continuous predictor variables (such as concentrations and distances) and categorical variables (such as strict preferential pathways = "true" or "false", where "true" is based on evidence of an atypical preferential pathway).[53] Using this approach, general linear models were fitted, and the quality of the model fits and the significance of the model terms evaluated for the following:

- Indoor air concentration (unscreened) as a function of groundwater vapor concentration, distance to primary release, and strict preferential pathway (true/false)

[53] In the R software, the conditions "true" and "false" are assigned the codes 1 and 0, respectively.

- Indoor air concentration (after applying the baseline screen and the 5,000X background groundwater vapor source strength screen for PCE and TCE) as a function of groundwater vapor concentration, distance to primary release, and strict preferential pathway (true/false)
- Indoor air concentration (unscreened) as a function of subslab soil gas concentration, distance to primary release, and strict preferential pathway (true/false)
- Indoor air concentration (after applying the baseline screen and the 1,000X background subslab soil gas source strength screen for PCE and TCE) as a function of groundwater vapor concentration, distance to primary release, and strict preferential pathway (true/false)

7.2 Atypical Preferential Pathway Results

The definition of atypical or “strict” preferential pathway given in Venable et al. (2015) can include atypical preferential pathways that connect the building to the subslab and/or those that constitute unusually large openings in the building envelope. Therefore, atypical preferential pathway effects on subslab (Section 7.2.1) and indoor air concentrations (Section 7.2.2) were both evaluated. Two methods were used for the concentration evaluations; these methods are presented sequentially as follows:

- Single variable linear regression fits (Section 7.2.2)
- General linear models (Section 7.2.3)

The “general linear model” in R is a multivariate technique (identical to that used in Section 5; see also Figure 5-1) that allows the use of multiple continuous variables and a categorical variable (in this case atypical preferential pathway). This is an analysis of covariance technique.

7.2.1 Atypical Preferential Pathway Effects on Subslab Soil Gas Concentrations – Exploratory Graphical Analyses

As shown on Figure 7-1 for TCE, the atypical preferential pathway cases may exhibit a higher subslab soil gas concentration for a given distance to primary release within the first 100 feet. The difference in concentration, if any, is essentially negligible beyond 100 feet. Note that the r^2 values for the dataset from which atypical preferential pathways have been removed is low (0.05), which indicates that distance to primary release is not the primary factor controlling subslab soil gas concentrations. The r^2 value associated with the data for which the strict preferential pathway = “true” is stronger (0.50), suggesting that strict preferential pathways are affected by distance to primary release.

As shown on Figure 7-2, PCE concentrations in subslab soil gas do not appear to decrease with distance to the point of primary release when an atypical preferential pathway is present. The number of cases/distances represented in the dataset is small and there is no reasonable physical mechanism why concentrations would actually increase with distance to the point of primary release; therefore, this finding is likely an artifact of small sample size. The PCE cases studied with atypical preferential pathways do not generally exhibit subslab soil gas concentrations sufficient to lead to indoor air concentrations above screening levels (Venable et al., 2015).

7.2.2 Atypical Preferential Pathway Effects on Indoor Air Concentrations – Visualization/Regression

Figures 7-3 through 7-6 show plots of indoor air concentration versus distance to primary release for TCE (Figures 7-3 and 7-4) and PCE (Figures 7-5 and 7-6). Figures 7-3 and 7-5 use a semi-log scale with a linear scale for distance to primary release, whereas Figures 7-4 and 7-6 use a log-log scale. Each (a) part of the figures corresponds to indoor air data remaining after applying the 1,000X background source screen to paired subslab soil gas data. Each (b) part of the figures corresponds to indoor air data remaining after applying the 5,000X background source screen to paired groundwater vapor data.

When TCE is plotted on a semi-log scale (Figure 7-3), the slope of the relationship between indoor air concentration with distance to primary release is statistically significant ($p < 0.05$) when atypical preferential pathways are present (strict preferential pathway = "true"). The slope is more steeply negative than when atypical preferential pathways are absent (strict preferential pathway = "false"), although the slope is not significant when they are absent ($p > 0.05$). This holds true whether the data is screened on the basis of subslab soil gas concentration (Figure 7-3a) or screened on the basis of groundwater concentration (Figure 7-3b). However, it should be noted that the r^2 values in Figure 7-3 are low, which indicates that the distance to primary release only explains a minority of the variance in indoor air concentration. This can be seen visually in Figure 7-3 by the variety of indoor air concentrations associated with some of the shortest distances to primary release.

When TCE is plotted on a log-log scale (Figure 7-4), the relationship between indoor air concentration with distance to primary release for TCE is not statistically significant if screening is done using subslab soil gas data (Figure 7-4a), either for the cases where the strict preferential pathway = "false" or for the cases where it is "true". The slope is somewhat steeper for the cases where strict preferential pathway = "true". The r^2 values in Figure 7-4 are low, which indicates that the distance to primary release only explains a minority of the variance in indoor air concentration.

The results are different when using groundwater data for screening (Figure 7-4b). The relationship between indoor air concentration with distance to primary release for TCE is statistically significant for both the case where strict preferential pathway = "false" and the case where strict preferential pathway = "true". In this dataset, the indoor air concentration decreases more rapidly with increasing distance if atypical preferential pathways are present.

There is an insufficient number of indoor air data points for PCE with strict preferential pathway = "true" to fit a regression line in either the semi-log or the log-log plot (Figures 7-5 and 7-6). The few data points where the pathway is "true" are for an indoor air concentration below 10 $\mu g/m^3$.

7.2.3 Atypical Preferential Pathway Effects on Indoor Air Concentration in General Linear Model

The results of the general linear model are provided in tabular form. Figure 7-7 provides an example of R-generated results along with annotations explaining how to read them.

7.2.3.1 Atypical Preferential Pathway Effects on Indoor Air Concentration as a Function of Groundwater Concentration in General Linear Model –Results Using Unscreened Data

Without screening to remove potential background source effects, there were no significant terms in the general linear model for TCE, suggesting that preferential pathways are not significant (Figure 7-7). Moreover, although the term falls short of significance for TCE ($p = 0.072$), the coefficient is negative; this suggests that if there was any effect associated with the strict preferential pathway, then a "true" case would reduce the indoor air concentration on average.

In the general linear model for PCE (Figure 7-8), only the distance to primary release term is significant, and indicates that indoor air concentration decreases with distance to primary release. This result is similar to the results of the single variate analysis in Section 4.5.

7.2.3.2 Atypical Preferential Pathway Effects on Indoor Air Concentration as a Function of Subslab Soil Gas Concentration in General Linear Model – Results Using Unscreened Data

Without screening to remove potential background source effects, there were no statistically significant terms in the general linear models for either PCE or TCE (Figures 7-9 and 7-10, respectively). Moreover, although the term falls short of significance for TCE ($p = 0.071$), the coefficient is negative; this suggests that if there was any effect associated with the strict preferential pathway, then a "true" case would reduce the indoor air concentration on average. Although this result would not be expected, the negative coefficient suggests that the atypical preferential pathways in this small dataset are not significantly exacerbating VI.

7.2.3.3 Atypical Preferential Pathway Effects on Indoor Air Concentration as a Function of Groundwater Concentration – Results Using Data Screened with Groundwater 5,000X Background Source Strength Screen

The 5,000X background source strength screen for groundwater vapor was used consistent with the main analysis in Section 4. There were no significant terms in the TCE general linear model after screening (Figure 7-11), suggesting that the effect of atypical preferential pathways was not significant overall.

There was insufficient data for the R software to be able to calculate the general linear model for PCE with this screening.

7.2.3.4 Atypical Preferential Pathway Effects on Indoor Air Concentration as a Function of Subslab Soil Gas Concentration in General Linear Model – Results Using Data Screened with Subslab Soil Gas 1,000X Background Source Strength Screen

The 1,000X background source strength screen for subslab soil gas was used consistent with the main analysis in Section 4. The increase of indoor air concentration with increasing subslab soil gas concentration (Figure 7-12) is highly significant ($p < 0.001$), as would be expected. In addition, indoor air concentration decreases with increasing distance to primary release ($p = 0.043$). Indoor air concentration is also reduced overall in the presence of an atypical preferential pathway ($p = 0.020$).

The finding that atypical preferential pathways decrease indoor air concentration is at first counterintuitive. When interpreting this finding, it may be helpful to understand it as follows: after controlling for subslab source strength and for distance to primary release, atypical preferential pathways reduced indoor air concentration. One possible mechanism is that some of the features characterized as atypical preferential pathways, such as tunnels, could provide substantial air exchange. In the Sun Devil manor study, shutting a land drain with a valve decreased the TCE concentration but may have increased radon (Guo, 2015). Studies in the radon literature suggest that visually observable large penetrations in the building envelope do not increase indoor air concentrations in most instances, because the available small penetrations in most buildings are sufficient to supply as much advective flow as the subslab soil can deliver (Nazaroff and Nero, 1988; Robinson and Sextro, 1995). Given the small sample size, this finding should not be interpreted to indicate that preferential pathways never increase VI.

There are no remaining data points for PCE associated with cases where strict preferential pathways = “true” after the source strength screening step, so the analysis is not presented.

7.3 Atypical Preferential Pathway Conclusions

There is not a clear and consistent relationship between the presence of an atypical preferential pathways and subslab soil gas concentrations in this dataset. Based on the graphical analysis and the general linear model, there is insufficient evidence to conclude that atypical preferential pathways as a class systematically increase indoor air concentrations. There are some indications in these data analyses that the presence of these preferential pathways could actually decrease indoor air concentrations in some circumstances. However, this does not eliminate the possibility that in some individual instances, atypical preferential pathways would contribute to higher indoor air concentrations, as supported in other studies (e.g., McHugh and Beckley, 2018).

Quantitative Decision Framework

This section provides an overview of the QDF and associated flow charts, score card, and interpretation graphs, as previously introduced in prior documentation (Venable et al., 2015; Lund et al., 2018), as well as changes that were made to the QDF scorecard as a result of the updated analyses presented in this report. The version of the scorecard presented herein is intended to supersede the most recent version (Lund et al., 2018).

8.1 Quantitative Decision Framework Overview

A decision framework is an "evidence-based, practical" structure to guide the making of decisions (Ottawa Hospital Research Institute, 2014). It describes the information gathered as inputs to the decision and how the inputs are evaluated or weighted to arrive at the decision. To prepare a QDF based on the results of this research, several possible technology transfer formats were considered. A combination of a flowchart with an embedded scoring approach was ultimately selected and is described in Venable et al. (2015). An interim update to the QDF was completed in 2018 (Lund et al., 2018); the 2018 version will be considered in this report as the version being updated.

The QDF flowchart (and embedded scoring system) is similar to the format used in the Interstate Technology and Regulatory Council (ITRC) petroleum VI guidance document (ITRC, 2014). This format was selected because:

- The QDF flowchart shows the overall step-by-step process and provides "off ramps" for clear-cut cases. Harder cases requiring a more nuanced analysis lead the user to a scoring box.
- The scoring scheme allows a more in-depth evaluation of "grey zone" cases using multiple lines of evidence leading to a "vapor intrusion prioritization score."
- The range of weights in the scoring system are tailored to emphasize the importance of certain predictor variables.
- A default score is specified for the absence of information to indicate mid-range risk. Thus, the same scorecard can be used with different amounts of data.
- Point totals are used to prioritize sites for further VI investigation or pre-emptive mitigation.
- A separate, additional uncertainty score is then computed based on the number of missing lines of evidence.

The unit of analysis chosen for the scoring system is the sample zone, because sample zones are the primary units of analysis used in this project. However, the scoring system can be used to prioritize buildings by considering the highest scoring, regularly occupied zone within each building. Similarly, sites could be prioritized by evaluating the buildings at or proximate to that site individually and considering the number of high-priority buildings for each site.

In the DoD VI Industrial Database, the size of some of the enclosed areas (sample zones)[54] is quite large. For example, of the 299 sample zones in the database:

- 159 sample zones have surface areas equal to or below 1,000 square feet
- 99 sample zones have areas ranging from 1,001 to 10,000 square feet
- 36 sample zones have areas ranging from 10,001 to 100,000 square feet

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[54] As noted in Section 2.3, the sample zone concept in the DoD VI Industrial Database represents an enclosed location within a building where at least one indoor air sample has been collected. The conceptual idea that best represents sample zone is a box. A sample zone should have limited air mixing with other sample zones.

- 3 sample zones have areas greater than 100,001 square feet
- 2 sample zones have an unknown surface area

The key outcome of this project is a VI decision framework, which is intended to allow the Navy (and DoD as a whole) to apply the results of the data analysis to management of VI sites at multiple stages in the project lifecycle. The current project will focus on updating the scorecard element of the decision framework from the 2018 version (Lund et al., 2018). The flowchart from the 2018 version is still useful and information describing it will be reprinted here for the convenience of the reader. Readers desiring a "user manual" level presentation of the framework should refer to the user's quick start guide (Venable et al., 2015, Appendix H; Lund et al., 2018). This section describes the development of the framework as it emerged from the data analysis in some detail.

This decision framework is conceptually related to the Navy VI Decision Process Tool (Caldwell, 2012), which is a computerized "expert system" that guides the user through the analysis of VI data and facilitates a weighted evaluation of multiple lines of evidence. A related approach to sitewide VI building prioritization was previously outlined by Lund (2013). In that previous prioritization approach, quantitative scores were assigned for factors such as distance to VOC source, magnitude of concentration exceedance, occupancy, building area, and air exchange characteristics.

This QDF is presented as a flowchart showing the overall step-by-step process of the VI site investigation (Figure 8-1). The first step requires minimum trigger conditions to initiate a VI evaluation. An initial screening for acute/rapid response conditions is included in the flow chart, along with follow-on procedures if a rapid response is necessary. The QDF flowchart then leads to a scorecard for all buildings that satisfy the initial trigger condition and do not need a rapid response.

The scorecard allows a more in-depth evaluation of "grey zone" cases using multiple lines of evidence and leading to a VI potential prioritization score. The range of weights in the scoring system are tailored to emphasize the importance of certain predictor variables identified in the data analysis: average subslab soil gas concentration, average groundwater concentration, depth to groundwater, soil type, presence of atypical preferential pathways, distance to the point at which the chemicals were originally released, and building age. The factors highlighted in the QDF are either those well accepted in the VI field or derived from the data analysis efforts in this project.

More information about how the factors and weightings were originally derived is available in Section 6 (results of the data analysis) and Section 7 (derivation of factors and weighting) of the NESDI #476 report (Venable et al., 2015). The results of the reanalysis are included in the current report.

Two different scorecards are provided (Figure 8-2)—one for use when only groundwater data are available and one for when both groundwater and subslab soil gas data are available. Certain predictor variables are not used in the scorecard when subslab soil gas data are available due to the higher weight of importance placed on subslab soil gas data. Additionally, the subslab soil gas data would be expected to capture the effects of the omitted predictor variables (e.g., depth to groundwater).

Each scorecard generates two scores:

- A VI potential score that can be used as a relative predictor of VI potential for a given industrial or commercial building
- An uncertainty score that rates the relative amount of information available and potentially provides insight into the confidence of the prediction (Figure 8-2)

The VI potential score can then be applied using any of three graphical keys (Figure 8-3):

- For prioritization decisions for initial investigation (Figure 8-4)
- Evaluations of whether indoor air results are reasonably consistent with other lines of evidence (Figure 8-5)
- Recommendations on the degree of vigilance needed in long-term stewardship (Figure 8-6)

Figure 8-3 shows graphically how Figures 8-4 to 8-6 are applied throughout the project lifecycle to interpret the scorecard results.

There is not a strict correspondence of a VI potential prioritization score to a recommendation in Figures 8-4 to 8-6. Rather, recommendations are shown for zones that shade into one another. This reflects the degree of uncertainty associated with the current understanding of VI and the need to apply professional judgment to site-specific decision making.

It is important to note that the QDF scoring system should not be used indiscriminately—buildings being evaluated for VI should be within 100 feet of a release or a subsurface concentration of VOCs (consistent with regulatory and DoD recommendations in the DoD VI handbook [TSERAWG, 2009]) unless a significant atypical preferential vapor transport pathway external to the building is present.

8.2 Linkage Between Data Analysis and Decision Framework

The factors highlighted in the QDF are either those well accepted in the field or derived from the data analysis efforts in this project.

8.2.1 Flowchart Overview and Basis

The flow chart begins with "consider a site" (Figure 8-1). The industrial/commercial QDF can be applied in projects with different legal or program objectives, in which the term "a site" could be defined as:

1. A site where groundwater and/or soil VOC contamination has been characterized and is from a known source(s). Example: a contaminated groundwater plume originating from known historical disposal practices from an industrial operation or building.
2. A site where the observed groundwater and/or soil VOC contamination is from an unknown source(s) but is assumed to originate in the general area of the highest concentrations and appears to be well delineated. Example: a contaminated groundwater plume of unknown source(s) where the highest concentrations emanate from an area comprised of buildings used in the past for industrial activities and hazardous materials storage or usage.
3. Widespread, diffuse known groundwater and/or soil VOC contamination emanating from one or more potential undefined sources.

The boxes on the flow chart (Figure 8-1) are numbered and used below to summarize the steps in the VI investigation lifecycle process:

Box 1: An anthropogenic subsurface source (release) with a minimum concentration greater than or equal to a VI risk-based screening level is used as a trigger for proceeding to the next step in the flowchart.

It is also necessary to determine whether a significant atypical preferential pathway connects the source to the building. A significant atypical preferential pathway is defined as those features that: 1) intercept a site-related subsurface volatile source area (high concentration); 2) provide limited resistance to vapor migration; 3) are not found in most buildings; and 4) provide a vapor migration pathway into a current or future building for site-related volatile chemicals. The potential for an acute hazard (e.g., explosivity or acute toxicity) to be present is also a trigger. Additional information regarding atypical preferential pathways is provided later in this section.

Box 2: Determine whether an acute exposure or rapid response condition may be reasonably expected to be present. Conditions potentially posing an acute exposure condition or one meriting rapid response include concentrations sufficient to cause acute toxicity or create the potential for explosive conditions. Further information on this topic is provided in the DoD VI handbook (TSERAWG, 2009, Section 5.1) and USEPA VI guidance (USEPA, 2015, Section 7.5). Proceed to the Rapid Response Flowchart (Figure 8-1) if an acute exposure or rapid response condition is present.

Box 3: Assemble a preliminary VI CSM. A key element of the CSM is specifying the spot or specific area where a release of volatile contaminants to the ground surface may have occurred (the *primary release).* In many cases the primary solvent release areas are associated with the following: underground solvent storage tank, landfill, disposal pit/dry well, drum storage area, fire/crash training area, surface impoundment/lagoon, burn area, waste line, waste treatment plant, sewage treatment plant, oil/water separator, maintenance yard, chemical disposal, plating shop, vapor degreasers and dip tank (USEPA, 2004). The objective of the primary release evaluation is to provide as much relevant information as possible about how close a vadose zone source may be to the buildings in question. The location of the primary release may be described in Preliminary Assessment/Site Inspection reports or Remedial Investigation reports at Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)-regulated sites. At Resource Conservation and Recovery Act (RCRA)-regulated sites this information may be in reports such as RCRA Facility Assessments or RCRA Facility Investigations. In some cases, the approximate location of the primary release can be inferred from maps of groundwater concentrations or exterior soil gas concentrations. If contamination is not well characterized and the source is unknown, clues indicating potential vadose zone sources can also be provided by the historical name of a building or its known functions. If necessary, interviews with building managers can provide information on past use or disposal of solvents.

Also, as part of Box 3, the relevant groundwater and/or soil gas data are obtained and organized. To estimate the groundwater concentration under the building, only analytical data that represent concentrations at or near (e.g., 10 feet below) the water table should be considered. Use of deeper groundwater introduces substantial uncertainty to the analysis since only the water at the water table can directly supply VOCs for VI. If a clean water lens overlies the deeper impacted groundwater, the potential for VI could be substantially overestimated. Conversely, if shallower groundwater concentrations were higher, the potential for VI would be underestimated. The approximate groundwater concentration of the analyte under the building undergoing VI evaluation can often be determined by interpolation from isoconcentration maps that are frequently found in remedial investigation, RCRA facility investigation, or groundwater monitoring reports. Groundwater concentrations can then be converted into groundwater vapor concentrations using Henry's law.[55] Groundwater vapor concentrations can then be used in AF-based analyses that predict indoor air concentrations.

Information on atypical preferential pathways is also used when developing the CSM. It is also important to identify actual or potential future receptors, i.e., those individuals who may be exposed to VOCs in the indoor environment. USEPA recommends an inclusion zone[56] of 100 feet be initially considered (USEPA, 2015, Section 6.2.1) as a rule of thumb, which is also recognized in the DoD VI handbook (TSERAWG, 2009). Buildings to be evaluated are typically only those that are fully enclosed. For example, a bus stop shelter, carport, or gazebo would not normally be evaluated. Buildings not occupied and not intended to be occupied by persons for a significant period of time such as a shed would also not normally be evaluated (USEPA, 2015). Coordinate with the local oversight agencies to clarify their understanding of significant occupancy. Future risk would, however, be considered for buildings suitable for regular occupancy that are currently vacant.

If no currently occupied buildings exist, or risks are not expected to be significant in the existing buildings then the flowchart shows that potential for VI into future buildings also needs to be considered and appropriately managed (see box to the right of Box 3 on flowchart).

Box 4: The VI potential of a building is first scored using the VI potential scorecard and those scores interpreted according to Figures 8-4 to 8-6 (see Section 8.3). Data gaps may be present, which can be addressed in subsequent steps. The scorecard should be revisited when additional information is obtained (see Boxes 7 through 11).

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[55] Henry's law calculators are available in stand-alone websites (https://www3.epa.gov/ceampubl/learn2model/part-two/onsite/esthenry.html) or as part of the widely used Johnson & Ettinger model (https://www.epa.gov/vaporintrusion/epa-spreadsheet-modeling-subsurface-vapor-intrusion).

[56] "Inclusion zone" is defined in USEPA (2015) as "Land area within which EPA recommends assessing the vapor intrusion pathway, which extends beyond the aggregate boundaries of the site-specific source(s) of vapor-forming chemicals."

Box 5: It may be desirable to narrow the preliminary investigative area depending on how many buildings fall within the inclusion zone and available resources using the "worst first" principle (USEPA, 2015). For example, if only 10 small buildings fall within a 100-foot inclusion zone at a given site, the decision may be to proceed to Box 6 for all 10 buildings. If, as an example, 100 large buildings are within the inclusion zone at a site with a large diffuse plume, it may be necessary to define a more tractable preliminary investigative area using the worst first principle. The initial scoring reference in Box 4 can provide a guide for selecting those worst-case or higher priority buildings.

Box 6: A standard building survey is prepared during a site visit with the primary purposes of:

- Defining occupancy patterns,
- Evaluating the condition of the building envelope,
- Identifying atypical preferential pathways, and
- Identifying potential or likely indoor VOC sources.

Refer to the DoD VI handbook (TSERAWG, 2009, Appendices E and H), ITRC VI guidance (ITRC, 2007, Appendix G), and USEPA VI guidance (USEPA, 2015, Sections 6.3.5 and 6.4.1) for additional building survey considerations. Expected near term changes, such as ongoing new construction, major building renovations, or occupancy changes should also be considered.

Since understanding of atypical preferential pathways continues to evolve at a rapid rate, the available survey forms (which were prepared several years ago) do not provide adequate guidance for identifying atypical preferential pathways. Moreover, not all atypical preferential pathways are visible, since many are hidden in wall cavities. Case studies suggest that the presence of atypical preferential pathways connecting an occupied building to a distant point of release or mass source are associated with many of the highest observed indoor air concentrations that are linked to VI.

Box 7: The VI potential of a building should be updated using results from the scorecard, with the scores interpreted according to Figures 8-4 to 8-6. Data gaps that may be present can be addressed in subsequent steps. The scorecard will also be revisited with additional information obtained in subsequent steps.

Box 8: Data needs are identified in preparation for field sampling, beginning with the highest priority buildings. This may involve collection of samples closer to the point of potential exposure. For example, if only groundwater data are available, a potential data gap may be identified that can be addressed through collection of exterior soil gas, subslab soil gas, indoor air, and/or sewer gas sampling. A DoD companion document "Matrix for Selecting Vapor Intrusion Investigation Technologies" (TSERAWG, 2019) provides more details about how the available sampling and analysis technologies can be used to address various study questions.

The VI CSM is also revisited and updated using building-specific information collected during the field surveys. Elements of a VI CSM are discussed in USEPA VI guidance (USEPA, 2015, Section 5.4) and the DoD VI handbook (TSERAWG, 2009, Section 2.3). Filling the identified data gaps are objectives in the development of the Uniform Federal Policy – Quality Assurance Project Plan (UFP-QAPP) and Sampling and Analysis Plan (SAP).

Box 9: Data needs identified in Box 8 are collected consistent with the UFP-QAPP/SAP.

Box 10: Data are reviewed using a multiple lines of evidence approach to determine if additional data are needed. The new data and previously collected data are evaluated together for consistency with the overall CSM to determine if the information is sufficient to support building-level decision making. This process is described in the USEPA VI guidance (USEPA, 2015, Section 7.2).

Box 11: Information may be sufficient for a reasonable building-specific decision at this point as to whether:

- The VI pathway is complete, and concentrations are reasonably expected to exceed a regulatory target, potentially leading to mitigation and/or remediation.

- The VI pathway is complete, but concentrations are not currently above regulatory targets, which may lead to preemptive mitigation, remediation, and/or long-term stewardship/monitoring.
- The VI pathway is currently incomplete and not expected to be complete in the future, which may lead to no further action.

In cases where indoor air data have been collected, a review of the VI potential score and the observed indoor air concentrations (Figure 8-5) will aid in determining if the data are suggestive of a subsurface (i.e., VI) or background (indoor or outdoor) vapor source. Information on building-specific decision making is provided in the USEPA VI guidance (USEPA, 2015, Section 7) and the DoD VI handbook (TSERAWG, 2009, Section 5).

Box 12: Results of the VI investigation need to be incorporated into the overall CERCLA process (e.g., remedial investigation and risk assessment, feasibility study, decision documents, or five-year reports as appropriate). Further details on conducting a VI risk assessment are provided in the USEPA VI guidance (USEPA, 2015, Section 7.4).

8.2.2 Scoring System Basis

The parameters used in the scoring system were those judged most relevant after the quantitative data analysis. The relative weights assigned to the parameters reflect professional judgment, informed by the data analysis presented in Sections 3 to 7, about the parameters' relative importance in influencing indoor air concentrations. The following bullets provide information about the basis used in development of the scoring system (VI scorecard; Figure 8-2):

- Average Subslab Soil Gas Concentration:
  - Data analysis shows that concentrations above a minimum value in subslab soil gas (inflection point) are needed to observe any corresponding increase in indoor air concentrations. Revised data analysis continues to show a strong correlation between subslab soil gas concentration and indoor air concentration. However, the analyses conducted as part of this project—along with other studies—show that indoor air concentration does not increase directly proportionally to subslab soil gas concentration. Thus, the point scores increase more slowly than subslab soil gas concentration. Additional information is provided in Section 8.4.
- Average Groundwater Vapor Concentration:
  - Data analysis shows that concentrations above a minimum value in groundwater (inflection point) are needed to observe any corresponding increase in indoor air concentrations. Revised data analysis continues to show a strong correlation between groundwater vapor concentration and indoor air concentration. However, in this and other studies, indoor air concentration does not increase directly proportionally to groundwater vapor concentration. Thus, the point scores increase more slowly than groundwater vapor concentration. Additional information is provided in Section 8.4.
- Sample Zone Area:
  - Although it was part of prior scorecards (Venable et al., 2015, Figure 7-2; Lund et al., 2018), the sample zone area was eliminated from the current scorecard. The rationale for this update is provided in Section 8.4.
- Soil Type and Solvent Use History:
  - For the purpose of preparation of the scorecard, the variables of soil type and solvent use in the building were associated. The reason for this association is that many of the mechanisms that explain the observed soil type effects would be expected to apply primarily near the point of release. Because the data were analyzed using adjectival categories (fine versus coarse), only three scoring categories could be created.

  - Based on the analyses, the effect of soil type, while often significant, was relatively less than the effect of subslab soil gas concentration. Therefore, the weight assigned to subslab soil gas concentration was greater than that of soil type and solvent use history.

- Atypical Preferential Pathways:
  - Atypical preferential pathways and scoring based on the analyses presented in Section 7 are discussed in Section 8.4.
- Distance to Primary Release Point:
  - Data analysis shows an association between proximity to the primary release and higher subslab soil gas and indoor air concentrations.
  - The total weight range was assigned to distance to primary release based on the strength of the observed relationships, the statistical significance of the observed relationships, and the agreement of the observed relationships to mechanistic expectations.
- Depth to Impacted Groundwater:
  - Considerations related to groundwater depth and the resulting scoring approach based on the DoD VI Industrial Database analyses are presented in Section 8.4.
- Presence of Engineered HVAC System
  - This is a new category proposed based on the results of the data analyses; the rationale and scoring are discussed in Section 8.4.
- Year of Building's Original Construction
  - The building age (i.e., the year of original construction) is a new category proposed based on the results of the analyses; the rationale and scoring are discussed in Section 8.4.

8.3 Using the Scoring System and Keys in Different Situations

8.3.1 Interpretation of Vapor Intrusion Potential Scores During Initial Site Assessment

After the scorecard has been completed and totaled, evaluate the results for each sample zone or building using Figure 8-4, which provides recommendations for prioritization based on the relative scores. The scorecard also recommends calculating a simple index of the uncertainty of the determination, where each question in the scorecard that could not be definitively answered is assigned one point, and the total number of uncertainty points is interpreted according to Figure 8-2. When scoring results in high or very high uncertainty, the remedial project manager may elect to collect additional information and re-score the building or sample zone.

The flowcharts and scoring systems are designed to be used on a single building at a time. The prioritization score for each building would be the highest score for any occupied zone within the building. The tool can also be used on a sitewide basis as further discussed in the next section.

8.3.2 Basewide or National Applications

As noted in the preceding section, the flowcharts and scoring systems are designed to be used on a single building level. This is because the data analysis for this project was conducted on the single building or sample zone level. These tools, however, can easily be adapted to be used on a sitewide basis, by evaluating buildings individually against the scoring system and collating the results. Alternately, where multiple buildings of an essentially repetitive design and use are present, they can be evaluated as a group. Prioritizing buildings for investigation according to their risk for VI can be useful when it is desirable to first evaluate the "worst-case" buildings to determine whether risks are likely for the site as a whole. To date, most efforts to identify "worst-case" buildings have been based only on plume maps, but this scoring system could allow such choices to consider both environmental concentrations and building characteristics. The results of this tool can be used to integrate multiple lines of evidence when selecting sampling locations within or between buildings in accordance with USEPA (2015).

Ultimately, it may be possible to interface this scoring system with Navy Installation Restoration Information Solution (NIRIS) and with databases of Navy facilities to allow a more automated, nationwide prioritization effort to be pursued.

8.3.3 Interpretation of Vapor Intrusion Potential Scores During a Detailed Vapor Intrusion Study

The prioritization score can provide useful information at sites where indoor air data have been collected. Per the DoD VI handbook (TSERAWG, 2009), measured concentrations of VOCs in indoor air consist of three components:

- VOCs from subsurface VI
- VOCs from indoor air background sources
- VOCs from outdoor air background sources

The contributions from each of the above sources need to be evaluated when determining whether VI is impacting the building. It is recommended that co-located and concurrent groundwater, near-slab or subslab soil gas, and outdoor air sampling be performed when indoor air sampling is conducted so that the potential sources/confounding factors (e.g., background concentrations) can be evaluated.

In practice, it is difficult to completely inventory all chemical uses and storage in a building without a costly and disruptive inspection, using a field instrument and having full access to all locked storage areas, closets, desks, etc. Furthermore, ongoing mission critical uses can preclude removal of VOCs from the building. Thus, the multiple lines of evidence (e.g., groundwater, subslab soil gas, and indoor air concentrations) must frequently be weighed together to evaluate whether an observed indoor air concentration is attributable to VI. Regulatory agencies frequently seek “concordance” among these lines of evidence but have provided little detail in how the inter-comparison of lines of evidence should be performed. The scoring system presented here can be helpful in evaluating whether observed indoor air concentrations are reasonably attributable to the subslab soil gas or groundwater concentrations. The scoring system (interpreted according to Figure 8-5) provides a way to put observed indoor air concentrations in a context relative to their source and significance.

In a case where the total prioritization score is relatively low, but the indoor air concentration is high (represented by the orange box on Figure 8-5), additional steps to determine if a background indoor or outdoor source may be present are recommended. Those additional steps could include:

- A more exhaustive review and verification of the chemical inventory information
- Building pressurization/depressurization tests
- Analysis of the spatial pattern of VOC concentration ratios (e.g., PCE/TCE, etc.) in subslab soil gas and indoor air
- Use of tracers (i.e., radon) to determine a building-specific AF
- Use of a VOC-specific, field portable, gas chromatography or GC/MS instrument to search the building for indoor sources and/or vapor entry points

Cases with a high prioritization score but low indoor air concentrations (blue box on Figure 8-5) are expected to occur and may be attributable to:

- Temporal variability due to meteorology during sampling causing VI not to be observed or
- A high-quality floor system in good condition that provides a better than average resistance to intrusion, coupled with

- A high amount of air exchange

Such a dataset might suggest that substantial indoor- or building envelope-specific evidence may be required to allay concerns about VI. That evidence might include multiple rounds of indoor air sampling, longer-term indoor air sampling, building pressurization/depressurization tests, or long-term monitoring of subslab-indoor differential pressure or radon concentrations (as a tracer of VI).

The green box on Figure 8-5 represents a situation where an indoor air concentration above screening level is observed and a high VI potential prioritization score suggest concentrations may be due to VI. Under those circumstances:

- Consider confirming exceedances and that they are due to VI (not background sources)
- Decide whether to mitigate
- Consider conducting multiple sampling events if averaging over exposure time is allowed

In evaluating these options, consideration should be given to the placement of the situation within the green box. For example, if a concentration in indoor air is observed many orders of magnitude above the screening level with only a moderately high VI potential score, that would suggest that additional effort may be needed to rule out potential background sources. Conversely, if an indoor air concentration many orders of magnitude above screening levels was observed with a very high VI potential score, less exhaustive efforts to identify potential background sources may be needed. In such a situation, the mitigation option may be given higher emphasis.

The purple box in Figure 8-5 represents the case where low indoor air concentration results are in agreement with relatively low risk expectations from other lines of evidence, which are expressed by a low VI potential score. Situations close to the bottom left corner of the purple box are those with the strongest case for no further VI assessment.

8.3.4 Application for Long-Term Stewardship to Avoid Future Vapor Intrusion Risks

The QDF can also be useful for determining the type of activities that may be necessary in the future, at locations where multiple lines of evidence analysis indicate that current exposures are less than regulatory targets. Note that this document does not address long-term stewardship requirements for buildings with VI mitigation systems. The potential applications without mitigation are also somewhat different for long-term stewardship of existing buildings and for future building construction and thus are described separately in this section although they are shown in one basic figure (Figure 8-6).

8.3.5 Long-term Stewardship of Existing Buildings

USEPA (2015) states:

> "EPA recommends that risk management and response action decisions for the vapor intrusion pathway generally consider reasonably expected future conditions, which may differ from current conditions due to changes in land use, building and infrastructure construction and conditions, and vadose zone hydrology and oxygenation, among other factors. (…) EPA recommends that risk management decisions also consider whether the vapor intrusion pathway is 'potentially complete' under reasonably expected future conditions. The vapor intrusion pathway is referred to as 'potentially complete' for a building when:
>
> - A subsurface source of vapor-forming chemicals is present underneath or near an existing building or a building that is reasonably expected to be constructed in the future
> - Vapors can form from this source(s) and have a route along which to migrate (be transported) toward the building; and

> - Three additional conditions are reasonably expected to all be met in the future, which may not all be met currently; i.e.
>   - the building is susceptible to soil gas entry, which means openings exist for the vapors to enter the building and driving forces exist to draw the vapors from the subsurface through the openings into the building
>   - one or more vapor-forming chemicals comprising the subsurface vapor source(s) is (or will be) present in the indoor environment (see sections 6.3.4 and 6.4.1)
>   - the building is or will be occupied by one or more individuals when the vapor-forming chemical(s) is (or are) present indoors (…)
>
> When the vapor intrusion pathway is determined to be incomplete, then vapor intrusion mitigation is not generally warranted under current conditions. EPA recommends that site managers also evaluate whether subsurface vapor sources that remain have the potential to pose a complete vapor intrusion pathway and unacceptable human health risk due to vapor intrusion in the future if site conditions were to change. For example, potentially unpredictable changes in the transitory soil characteristics (e.g., soil moisture) and soil gas concentrations may occur as a result of constructing a new building or supporting infrastructure. Either type of change could result in the potential for unacceptable human health risk due to vapor intrusion in the future.
>
> Response actions may, therefore, be warranted to protect human health wherever and as long as subsurface vapor sources remain that have the potential to pose unacceptable human health risk in the future due to vapor intrusion. These response actions (…) may include institutional controls (…)."

Such regulatory recommendations are often made because of concerns about the gradual deterioration of the building slab, building renovations, the potential for building or HVAC system modifications (see USEPA, 2015, Section 6.3.3), or continued contaminant migration. There are few good studies to support how frequently this occurs.

It will be assumed here that the release to the environment in question occurred 15 or more years ago, that the plume has been stable or declining for at least 5 years, and, therefore, that the soil gas concentrations can be assumed to be at quasi-equilibrium (Carr et al., 2010). A guide to the levels of long-term stewardship activity that may be appropriate with different VI prioritization scores is provided as Figure 8-5. Under these circumstances, an elevated VI potential combined with indoor air concentrations that are close to action levels will likely result in a requirement that frequent ongoing monitoring be conducted.

In situations with frequent monitoring requirements, cost-benefit analysis can be applied to determine if mitigation to reduce monitoring costs is merited. In mitigated structures, it is generally accepted that differential pressure monitoring can substitute for some or all the ongoing indoor air monitoring that may be required. All monitoring plans should include a provision for the eventual cessation of monitoring—for example, a period of long-term stewardship monitoring may provide sufficient evidence that aging of the building is not increasing the indoor air concentrations. Alternatively, where feasible (e.g., adequate concentrations of radon in soil gas), long-term monitoring of radon as an indicator and tracer of VI should be considered.

8.3.6 Long-Term Stewardship of Future Buildings

The USEPA guidance states (USEPA, 2015):

> "Common scenarios where ICs [Institutional Controls] may be a useful instrument for fostering protectiveness at a site involving vapor intrusion threats include, but are not limited to, the following: (…)
>
> - Future construction is planned or is reasonably anticipated on a site that overlies subsurface contamination with vapor-forming chemicals; (…)"

The scorecard developed here can be used for a multiple lines of evidence analysis for future construction at or near DoD sites. A guide to the levels of long-term stewardship activity that may be appropriate with different VI prioritization scores is provided as Figure 8-5. New construction provides a unique opportunity for cost effective mitigation. In certain cases of moderate VI potential, building features intended for other purposes, such as moisture management, can provide adequate protection against VI (USEPA, 2008). The greater the VI potential, the more monitoring may be required after a new building is constructed. Also, the greater the VI potential, the more ICs may be required on future modifications of the new building that might affect its resistance to VI. This scoring system can also be used to help select sites for new construction when a choice of a location that meets other requirements exists.

8.4 Update to Quantitative Decision Framework Based on the Updated Analyses

This section summarizes updates made to the QDF on the basis of the updated analyses conducted as part of this project. The updates are reflected on the QDF scorecard presented in Figure 8-2.

There is ample evidence to support retaining subslab soil gas concentrations and groundwater vapor concentrations in the QDF. Based on the updated analyses presented in this report, there continues to be evidence that indoor air concentration does not rise linearly with the subslab soil gas or groundwater vapor concentration, as theory would predict. In other words, the paired indoor air-subslab or indoor air-groundwater vapor data are not falling on a 1:1 slope on a log scale (nor on a numerical scale), but generally rise more slowly.[57] This is illustrated on Figures 8-7 and 8-8, which show indoor air concentration data as a function of subslab soil gas and groundwater vapor data, respectively. The data on these figures are identical to Figures 4-18 and 4-54, respectively, but also include power curve fits (corresponding to linear fits in the log-log space). These fits show that indoor air concentrations rise more slowly than theory would project. For subslab soil gas, the slope or exponent is 0.4759 (versus 1 if the increase was linear or on a 1:1 slope in the log scale), meaning that the indoor air concentration doubles each time the subslab soil gas concentration increases by a factor of about 4.3.[58] Similarly, for groundwater vapor, the slope or exponent is 0.1873 (versus 1 if the rise was linear or on a 1:1 slope in the log scale), meaning that the indoor air concentration doubles each time the groundwater vapor concentration increases by a factor of about 40.5.[59] Previously, the subslab soil gas and groundwater were scored based on a sliding scale from 0 to +8, with the highest concentrations assigned the highest score (Venable et al., 2015, Figure 7-2; Lund et al., 2018). The QDF scoring was changed such that the score is consistent with the subsurface concentration rise coefficients (Figure 8-2). For subslab soil gas, this means doubling the score when subslab soil gas concentration buckets change by a factor of about 4.3. Similarly, for groundwater vapor the bucket should increase by a factor of about 40.5.

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[57] Note also that the linkage between groundwater concentrations and subslab soil gas concentrations was found to be relatively weak.

[58] Using the equation $IA = 0.0101\ SS^{0.4759}$ (Figure 8-7), IA doubles when SS increases by a factor of 10^(log 2/0.4759), which is equal to about 4.29.

[59] Using the equation $IA = 0.0841\ GW^{0.1873}$ (Figure 8-8), IA doubles when GW increases by a factor of 10^(log 2/0.1873), which is equal to about 40.5.

There is sufficient evidence from both the single variable analyses with subslab soil gas concentration as the outcome variable and the single variable analyses with indoor air concentration as the outcome variable to retain the use of distance to primary release as a significant element of the QDF. It is appropriate that this variable continue to be scored based on a sliding scale, where the highest score (+8 if subslab soil gas data are available or +12 if only groundwater data are available) is assigned to a release closest to the building or sample zone (less than 10 feet), and the lowest score (0) is assigned to release furthest from the building (greater than 200 feet) (Figure 8-2). The range of distance is based on the range observed in the DoD VI Industrial Database.

The single variable analysis with subslab soil gas concentration as the outcome variable showed higher concentrations with fine soil for several lower chlorinated VOCs (Section 3.4). It should be emphasized that the buildings analyzed as part of this project are primarily near the point at which the chlorinated solvents were released and thus do not fit a conventional groundwater-sourced VI model. The analysis with subslab soil gas concentration as the outcome also showed higher PCE concentrations at the upper percentiles. In the single variable analysis with indoor air concentration as the outcome (Section 4.5), variable fine soils were associated with substantially higher indoor air concentrations of PCE and TCE. The multivariate analysis suggested that fine soil contributes to higher indoor air concentrations as a function of groundwater concentration (considering the full range of distances to primary release). The multivariate analysis (Sections 5.1 and 5.2) also suggested that fine soils can be associated with unusually high indoor air concentrations (even beyond the 30-foot radius from the point of primary release), and that the protective effect of fine soils from VI is absent in this dataset. Taken together, the emphasis in the QDF on vadose zone sources and the presence of fine soils continue to be appropriate with a score of 0 to +8 (or 0 to +6 for the scorecard when only groundwater data are available), where 0 reflects the absence of a source and the maximum score (+8 or +6) reflects a known or suspected release of solvent in a fine soil setting (Figure 8-2).

In the single variable analysis with subslab soil gas concentration as the outcome variable, the general pattern is of reducing concentrations with increasing depth to groundwater with the exception of the data from one site, which has a strong soil source (Section 3.5). In the single variable analysis with indoor air concentration as the outcome variable, indoor air concentrations unexpectedly increase with increasing depth to groundwater in many cases. Potential explanations were advanced in Section 4.6 for why this behavior is possible in buildings near the point of primary release. In the multivariate analysis (Sections 5.1 and 5.2), the effect of depth is clearest when the coarse soil cases are analyzed separately; in those cases, shallow depths are associated with higher indoor air concentrations. The QDF was revised to limit the points contribution for shallow groundwater to coarse soils only. Previously, the groundwater data-only scorecard[60] provided a score of 0 to +4 for depth of impacted groundwater, with the highest score (+4) assigned to shallow groundwater (less than 1.5 meter or 4.9 feet) and the lowest score (0) assigned to deep groundwater (more than 5 meters or 16.4 feet). This score was modified to apply to coarse soil only, with fine soil given a score of +4 regardless of depth to groundwater if the building being assessed is close to the point of suspected release (Figure 8-2).

The single variable analysis of sample zone area as a predictor of indoor air concentration did not show statistically significant results supporting the hypothesis that indoor air concentrations would decrease in larger sample zones (Section 4.3). The multivariate analysis also casts doubt on the use of the sample zone area criteria in the QDF (Sections 5.4 to 5.6). While there are good physical reasons to expect sample zone area to have an effect if air exchange rate was held constant and source size was held constant, sample zone area does not appear to be a consistent monotonic predictor in our dataset. Air exchange rates vary both by design and practice in ways that are not simply predictable from an observation of zone area. Air exchange rate data were not provided in the database and are generally not measured as part of VI investigations. It is also likely that the VI mass discharge increases in some cases with increasing sample zone area. Previously, the scorecard assigned a score of 0 to +4 for sample zone area, with the greatest score assigned to the smallest area (less than 100 square feet) and the smallest score (0) assigned to the greatest area (more than 100,000 square feet) (Venable et al., 2015, Figure 7-2;

[60] There is no scoring related to depth to water when both groundwater and subslab soil gas data are available.

Lund et al., 2018). Based on the results of the analyses, the sample zone area was dropped from the QDF scorecard (Figure 8-2).

An alternative to the hypothesis of dilution within sample zones is the hypothesis of dilution throughout buildings, using either building area or building volume as the predictor variable. Building volume is a function of building area and height. Like sample zone area, however, a clear and consistent relationship between building area (or building volume) and indoor air concentration could not be established, even after controlling for building use or subslab soil gas concentration in the multivariate analyses (Sections 5.7 and 5.8).

The capping effects on soil gas concentrations predicted from theory for large buildings is not visible in the single variable analysis with subslab soil gas concentration as the outcome variable with a possible exception from small datasets for degradation products trans-1,2-DCE and 1,1-DCA (Section 3.2).

The single variable analysis with subslab soil gas concentration as the outcome variable (Section 3.6) does not provide strong support for retaining exterior wall as a line of evidence in its prior form in the QDF. The single variable analysis of indoor air concentration as the outcome variable suggests that zones on exterior walls are associated with more variable indoor air concentrations. Thus, the presence of an exterior wall does not raise the median indoor air concentration, but it may raise the 90th percentile values in some cases (Section 4.4). Conversely, it is more likely to have a detectable, but modest indoor air concentration when an exterior wall is absent. These observations fit the current understanding that VI exterior walls are known to play the following roles:

- As the common location of wall/floor cracks, which can be major entry routes (USEPA, 2012b; Hallberg et al., 2020)
- As the location where wind-driven differential pressures across the slab can be greater than in a zone with no exterior wall (USEPA, 2012b)
- As a location where fresh air exchange occurs

Thus, the presence of an exterior wall was removed as a scoring factor in the QDF (Figure 8-2), although practitioners should be made aware that both data and theory suggest that more VI variability can be expected in zones with exterior walls as compared to building interior zones. Previous versions of the scorecard factored in the presence of exterior walls in the score (Venable et al., 2015, Figure 7-2; Lund et al., 2018).

Based on the data presented in this report, the presence of an engineered HVAC system was included in the QDF scorecard as a modestly weighted protective factor (score of +3) because of the following (Figure 8-2):

- The VOC with the largest sample size (TCE) showed a statistically significant effect (Section 6.2).
- Although not reaching statistical significance, the data for many of the other VOCs suggested a protective effective of engineered HVAC.
- There are physically plausible mechanisms discussed in Section 6.2 by which engineered HVAC system could provide a protective effect.
- As discussed in Section 6.3, the effect for TCE was again significant when the dataset was limited to winter only.

Based on the results of the analyses, building age was added to the QDF scorecard with the highest scores (+3) applied to the buildings built between 1939 and 1959 (Figure 8-2). The strongest evidence of greater risk in these years comes from the subslab soil gas concentration data. The AF data, however, suggest that more subsurface to indoor air attenuation is occurring in these buildings, probably because of poor weatherization and high air exchange rates. As a result, the indoor air data tend to reflect more variability as a function of building age. Overall, the data would suggest that WWII-era buildings often have strong subslab sources and could also have elevated indoor air concentrations if they were renovated in a way that would increase weatherization or reduce ventilation, but not decrease infiltration exposure. The date of original construction of DoD buildings is generally known, such that it should be a feasible criterion to apply.

Evidence suggests that office building/zone uses may be somewhat predictive of higher indoor air concentrations, and that warehouse uses may be somewhat predictive of lower indoor air concentrations (Sections 5.5 to 5.8 and 6.1). Given that offices are generally more densely occupied than warehouses, it may be appropriate to prioritize sampling in offices over warehouses when other factors are similar. However, because of the limited number of data points supporting this result, using building or zone use as a scoring criterion is not recommended for inclusion in the QDF.

Evidence from the single variable zone use analysis also suggested that warehouses had higher indoor air concentrations than industrial/shop uses (Section 6.1). However, in the multivariate analyses that controlled for source strength, the warehouse uses had somewhat lower indoor air concentrations than would have been predicted for some other uses (Section 5.5). These findings could have a physical mechanism related to the amount of exhaust ventilation present in different building types. However, the statistical analysis is not sufficiently persuasive to merit changing the QDF for this factor at this time.

Analysis of preferential pathways in the dataset indicated that there was not a clear and consistent relationship between the presence of atypical preferential pathways and subslab soil gas concentrations (Section 7). There was insufficient evidence to conclude that atypical preferential pathways as a class systematically increase indoor air concentrations. In some circumstances, there were even some indications that their presence was associated with decreased concentrations. Still, this does not eliminate the possibility that atypical preferential pathways could contribute to higher indoor air concentrations in some instances. Some studies do support a role for them in cases where transport occurs from a distant source to a building (e.g., McHugh and Beckley, 2018). Data analyzed as part of this project was primarily composed of locations near the point of primary release, which may have made the presence (or absence) of identifiable preferential pathways less diagnostic, because almost all buildings have some route for advective soil gas entry. Previously, the scorecard assigned a score of 0 to +4 for the presence of an atypical preferential pathway, with the highest score when such pathway is present. This scoring was kept unchanged on the basis of the potential role played by these pathways (Figure 8-2).

Recommendations for Additional Analyses and Further Work

9.1 Refine the Understanding and Application of the Attenuation Factor Concept

The most applied results from the previous DoD VI Industrial Database analysis were the recommended AFs for subslab soil gas and groundwater presented in the prior QDF report (Venable et al., 2015). As basis for its recommendation, the QDF report, as well as the USEPA VI database report (USEPA, 2012a), used compilations of AF measurements obtained from many buildings collected at a small number of time intervals. Most sample zones in the DoD VI Industrial Database have only one to three sampling events—with the maximum being 13 sampling events. Sampling dates are generally selected based either on convenience or on rules of thumb about when the greatest indoor air concentrations are expected (often believed to be during the heating season). Therefore, both the DoD VI Industrial Database and the USEPA VI database primarily represent the spatial variation in AFs, but also include some of the temporal variability because the sampling dates at any one location are either convenience-based or biased toward higher concentrations. Thus, the upper bound percentile AFs estimated from these database studies represent an upper bound in both space and time.

Studies in which larger datasets were acquired (i.e., greater than 50 samples at one location) have shown that AFs range over two or more orders of magnitude over time (USEPA, 2012c; Johnson et al., 2012). In estimating chronic risks, it is desirable that information about a realistic distribution of AFs over time be included, not just an upper bound estimate. Studies have been conducted that provide further information about realistic distributions of concentrations and AFs in industrial buildings over a full year period (e.g., Levy et al., 2021).

Ideally, the spatial (i.e., variability between buildings) and temporal aspects of AF variability would be fully separated through additional studies. Thus, a practitioner could use the "mean annual AF for a building at 95th percentile of vulnerability to VI" to estimate long-term cancer exposure. The current practice involves using the 95th percentile AF derived from randomly-timed measurements in a series of buildings. If the current sampling guidance has effectively led, as intended, to reasonable worst-case sampling timing, the "mean annual AF for an industrial building at 95th percentile of vulnerability to VI" should be less conservative than the 95th percentile AF from randomly-timed short-term samples.

9.2 Cross-Check Database Attenuation Factor Estimates with Alternate Methodology

Both the approach used for this project and that in the USEPA database study (USEPA, 2012a) rely on screening methodologies to remove the influence of background sources in datasets collected from multiple occupied buildings. These screening methodologies involve tradeoffs as they seek to exclude all data points heavily influenced by background sources while not excluding data points controlled by true VI processes. These tradeoffs can produce either overestimation or underestimation biases for AFs.

Alternate approaches to identify and limit the impact of background sources have now been developed as follows:

- Use of controlled pressure methods to verify or refute the occurrence of VI under controlled test conditions.

- Analysis of datasets after the importance of a VI pathway has been either confirmed or refuted by installation of mitigation technologies specific to VI (such as subslab depressurization or pathway sealing).
- Direct identification of background source locations using room-to-room and drawer-to-drawer searches with field portable, sensitive, and selective instrumentation.
- Sampling and analysis in buildings relatively devoid of background sources—either experimental or newly constructed buildings.
- AF measurements with either natural or introduced tracers of soil gas impacts.

Although each of the above methods (a-e) has only been applied at a limited number of structures, together they would provide enough data, if compiled, to check the results of the database screenings performed by USEPA (2012), Venable et al. (2015), and others.

9.3 Improve Zone Definitions for More Efficient Sampling

This project (and most practical VI assessment work inside buildings) is built around the concept of the sample zone within a building. Typically, indoor air and subslab samples are co-located, "paired," and used to represent a sample zone. The divisions within above-ground spaces (based on partition walls, floors, and HVAC systems) often do not correspond to the divisions of subslab spaces. Subslab spaces can be divided by grade beams, grid/raft foundations, or divisions between sequential building additions. While air within a single enclosed space or HVAC zone above grade is theoretically well mixed, low permeability subsurface zones frequently have highly variable VOC concentrations. HVAC systems in older DoD buildings often consist of a combination of centralized "engineered" systems and systems installed for small group comfort, such as window unit air conditioners and evaporative coolers ("swamp coolers"). Understanding of these issues is critical to devising efficient sampling strategies.

Examples drawn from the DoD VI Industrial Database could be re-examined to determine how to optimally divide a building both above and below grade into zones to avoid either over or under sampling a building.

9.4 Improve the Definition of the Source Zone and Conceptual Site Model in Vapor Intrusion Dataset Analysis

VI studies are most often initiated after VOCs are observed in groundwater. However, contaminant release most frequently occurred to the vadose zone and not directly to groundwater. Going back to the USEPA database—on which aspects of this DoD VI Industrial Database were built—the source term in the dataset is incompletely incorporated into the database (USEPA, 2012a). Thus, while there is information available in the appendix of the USEPA database report from which the CSM can be visualized, the USEPA analysis was not subdivided based on whether the primary mass storage was in soil or groundwater. Most—but not all—of the buildings in the USEPA database analysis are expected to be controlled by groundwater sources. The analysis approach used in the residential database report assumed general mass transport through groundwater (USEPA, 2012a). USEPA did not perform a separate analysis for commercial, industrial, or mixed-use buildings, although some were included in their database.

In the prior QDF report (Venable et al., 2015, Section 5.3.7), attempts were made to divide the cases based on the CSM (i.e., based on where the mass was stored). However, these attempts were not successful and the approach was not continued in this expansion of the database analysis. In this project, certain information was inferred based on the criteria of whether the distance to primary release was greater than 30 feet. However, the concept of "point of primary release" is limited in that VOC releases sometimes occur at multiple locations or over an area.

Not all environmental investigations accurately map the source zone. Frequently, the emphasis is on delineating the edges of a groundwater plume or boundaries of soil gas impact above screening levels. Detailed information about mass storage is often acquired late in the project when high-resolution site characterization methods (e.g., membrane interface probes) are used to support remedial actions or when source mass is excavated. Detailed retrospective analysis of VI datasets where the source was later mapped in detail could be valuable to better understand VI in DoD industrial buildings.

9.5 Build on the DoD VI Industrial Database with Future Data from the Navy VI Electronic Data Deliverable

The analytical data for this project was populated from the NIRIS database, but extensive additional information had to be added specific to this project to permit analysis. The Navy has now developed and rolled out a VI-specific NIRIS electronic data deliverable (NEDD). General training sessions that provided an overview of the VI NEDD were offered in 2019 and 2020, but these sessions were limited in detail with a focus on information related to the logic behind the VI NEDD and the overall structure of the NEDD. Entry of data in the VI NEDD format by most Navy contractors is, to the authors' knowledge, just beginning. After several years of data entry using this tool, a significant dataset will be assembled that could be analyzed to draw further insights into VI processes at a national level; this will be done using a larger dataset of buildings and a greater range of contaminants. Because the structure of the VI NEDD draws significantly from the database developed under this project, it would be feasible to blend the database assembled for this project (which includes data from 2008 to 2017) with VI NEDD data being loaded into NIRIS in 2020 and later.

9.6 Integrate the Quantitative Decision Framework with the Navy Vapor Intrusion Electronic Data Deliverable

To make the QDF easier to use, data processing and reporting tools using the QDF could be developed to interpret and assess VI NEDD data (at a project level). These new tools would support project teams and remedial project managers during the evaluation of project data and the preparation of reports. These tools could also support rapid decision-making. Project-level subtasks could also be used to assess data across multiple buildings, investigation areas, and facilities.

The proposed task would involve developing tools that use data in the VI NEDD, along with other NIRIS data (e.g., analytical), to process the data in standardized ways to support assessment and report production. Examples include calculating AFs, VOC concentration ratios, standardized line charts, graphical comparisons with screening levels, standardized tables, and assessment of next steps using the QDF.

9.7 Improve Indoor Air Quality Management in DoD Buildings Constructed Pre-1960

This report identified buildings constructed during WWII and the early Cold War as potentially being at greater risk for VI. There is a need to proactively manage the Navy's aging building stock, especially WWII and early Cold War buildings for optimum energy efficiency and indoor air quality. Currently, energy efficiency and indoor air quality are not always considered together. Energy audits, efficiency studies, and HVAC retro-commissioning efforts are infrequent—often decades apart. Indoor air quality problems are often addressed only on a complaint basis or when mandated by regulatory agencies. It is common to find Navy buildings with locally improvised HVAC systems for occupant comfort—relying, for example, on window unit air conditioners operated on interior walls or evaporative coolers. This most frequently occurs in warehouse-style or hangar buildings where office spaces have been retrofitted locally under a piecemeal approach. These systems are not optimum for energy use and overall occupant comfort or safety.

References

AECOM, US Army Corps of Engineers. 2012. *Interim Vapor Intrusion Data Report for the Cold Regions Research and Engineering Laboratory Hanover, New Hampshire.* July.

ASHRAE American Society of Heating Refrigerating and Air-conditioning Engineers Inc. 2003. *Ventilation for Acceptable Indoor Air Quality.* Addendum to Standard 62-2001.

Bennett, D.H., W. Fisk, M.G. Apte, X. Wu, A. Trout, D. Faulkner, and D. Sullivan. 2012. "Ventilation, temperature, and HVAC characteristics in small and medium commercial buildings in California." *Indoor Air.* Vol. 22. pp. 309–320. Abstracted in USEPA Exposure Factors Handbook, Chapter 19, July 2018.

Bradley, P.M. 2003. "History and ecology of chloroethene biodegradation: a review." *Bioremediation Journal.* Vol. 7, No. 2. pp. 81-109.

Brewer, R., J. Nagashima, M. Rigby, M. Schmidt, and H. O'Neill. 2014. "Estimation of Generic Subslab Attenuation Factors for Vapor Intrusion Investigations." *Groundwater Monitoring & Remediation.* Vol. 34, No. 4. pp. 79-92.

Brusseau, M.L. 1995. "Sorption and Transport of Organic Chemicals." In *Handbook of vadose zone characterization & monitoring.* Wilson, L. Gray, Lorne G. Everett, and Stephen J. Cullen, eds. CRC Press.

Caldwell, D. 2012. "Navy Vapor Intrusion Evaluation Tool." Environmental Monitoring and Data Quality (EMDQ) 2012 Workshop.

Carr, D.B., L.C. Levy, and A.H. Horneman. 2010. "Vadose Zone Profiling to Better Understand Vadose Zone Processes Related to Vapor Intrusion." Paper presented at 2010 AEHS, 20th Annual Conference on Soils, Sediments, Water and Energy, San Diego, California. March. https://clu-in.org/download/contaminantfocus/vi/vadose%20zone%20profiling%20to%20better.pdf.

CH2M HILL, Inc., P. Venable, T. Chaundry, I. Rivera-Duarte, and D. Caldwell. 2017. *NESDI Vapor Intrusion Database User's Guide.* January.

CH2M HILL, Inc. (CH2M). 2018. *User's Quick Start Guide, Residential Quantitative Decision Framework.* March.

Cox, C. "New Techniques for Assessing the Age, Location and VI Potential of VOC Sources Beneath Buildings." Presented at USEPA Vapor Intrusion Workshop at AEHS Conference San Diego March 2013. https://iavi.rti.org/assets/docs/WorkshopsAndConferences/05_Cox_AEHS_VI_2013.pdf.

Cwiertny, D.M. and M.M. Scherer. 2010. "Abiotic Processes affecting the remediation of chlorinated solvents." In *In Situ Remediation of Chlorinated Solvent Plumes.* pp. 69-108. New York: Springer.

Davis, A.D., Deputy Assistant Secretary, Department of the Army. 2009. Personal communication (letter) with Assistant Chief of Staff for Installation Management. Jan 28.

Department of Defense (DoD). 2010. *Department of Defense Strategic Sustainability Performance Plan, FY 2010.* August 26. https://www.acq.osd.mil/eie/Downloads/IE/DoD%20SSPP-PUBLIC-26Aug10.pdf.

Doherty, R.E. 2010a. "A History of the Production and Use of Carbon Tetrachloride, Tetrachloroethylene, Trichloroethylene and 1,1,1-trichloroethane in the United States: Part 1--Historical background; Carbon Tetrachloride and Tetrachloroethylene." *Environmental Forensics.* Vol. 1, No. 2. pp. 69-81.

Doherty, R.E. 2010b. "A History of the Production and Use of Carbon Tetrachloride, Tetrachloroethylene, Trichloroethylene and 1, 1, 1-Trichloroethane in the United States: Part 2--Trichloroethylene and 1, 1, 1-Trichloroethane." *Environmental Forensics.* Vol. 1, No. 2. pp. 83-93.

Doherty, R.E. 2012. "The Manufacture, Use, and Supply of Chlorinated Solvents in the United States During World War II." *Environmental Forensics.* Vol. 13, No. 1. pp. 7-26.

Doucette, W.J., A.J. Hall, and K.A. Gorder. 2010. “Emissions of 1,2-Dichloroethane from Holiday Decorations as a Source of Indoor Air Contamination.” *Groundwater Monitoring & Remediation.* Vol. 30, No. 1. pp. 65-71. Accessed on November 1, 2019.
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1013.1487&rep=rep1&type=pdf.

Environmental Quality Management, Inc. (EQM). 1997. *User’s Guide for the Johnson and Ettinger (1991) Model for Subsurface Vapor Intrusion into Buildings.* Prepared for the United States Environmental Protection Agency. September. Accessed on December 11, 2020 at https://rais.ornl.gov/epa/je/guide.pdf.

Folkes, D. and D. Tripp. 2016. “The Value of an Iterative Approach to VI Evaluation and Mitigation: Lessons Learned at the CRREL Facility in Hanover NH.” Presented at Battelle Conference. May.

Guo, Y. 2015. *Vapor Intrusion at a Site with an Alternative Pathway and a Fluctuating Groundwater Table.* Ph.D. Thesis. Arizona State University, 2015.

Hallberg, K., L. Lund, C. Lutes, L. Levy, D. Caldwell, and T. Lewis. 2020. “Putting Spatial and Temporal Variation Together: DoD Virginia Site A – Climate Zone 4.” Presented at Spring 2020 USEPA Vapor Intrusion Workshop: Why (When, Where, and How) You Should Continuously Monitor Indoor Radon, Differential Temperature and Pressure During Chlorinated Vapor Intrusion Assessments. March 17.

He, Y.T., J.T. Wilson, C. Su, and R.T. Wilkin. 2015. "Review of abiotic degradation of chlorinated solvents by reactive iron minerals in aquifers." *Groundwater Monitoring & Remediation.* Vol. 35, No. 3. pp. 57-75.

Hochberg, Y. 1988. “A Sharper Bonferroni Procedure for Multiple Tests of Significance.” *Biometrika.* Vol. 75. pp. 800–802.

Holton, C. 2018. “Indicators, Tracers and Surrogates of Chlorinated Vapor Intrusion – Pressure and Wind as Indicators.” USEPA VI Workshop March 20, 2018. Accessed July 18, 2018.
https://iavi.rti.org/assets/docs/WorkshopsAndConferences/06_Holton_EPA_VI_Workshop_2018.pdf.

Interstate Technology Regulatory Council (ITRC). 2007. *Vapor Intrusion Pathway: A Practical Guideline.* January.

ITRC. 2014. *Petroleum Vapor Intrusion Fundamentals of Screening, Investigation, and Management.* October.

Jacoby, B. Undated. *Regression III: Advanced Methods.* Michigan State University Department of Political Science. Accessed December 3, 2020.
https://www.researchgate.net/profile/David_Booth14/post/I_have_1_dependent_variable_and_3_independent_variables_and_was_wondering_what_would_be_the_best_non-parametric_test_to_use/attachment/5aa4ac824cde266d58909801/AS%3A602847724978176%401520741506114/download/15.Loess.pdf.

Johnson, P.C., E. Luo, C. Holton, P. Dahlen, Y. Guo, K. Gorder, and E. Dettenmaier. 2012. “Vapor Intrusion Above a Dilute CHC Plume: Lessons-Learned from Two Years of Monitoring.” Presented at USEPA Workshop, 22nd Annual International Conference on Soil, Water, Energy, and Air, San Diego, CA, March 19-22. Accessed December 17, 2020.
https://iavi.rti.org/assets/docs/WorkshopsAndConferences/09_P%20Johnson%20AEHS%20Talk%20032112.pdf.

LaMorte, W.W. 2017. *Mann Whitney U Test (Wilcoxon Rank Sum Test).* Boston University School of Public Health. Accessed July 18, 2018. http://sphweb.bumc.bu.edu/otlt/mph-modules/bs/bs704_nonparametric/BS704_Nonparametric4.html.

Lawrence, S.J. 2006. *Description, Properties, and Degradation of Selected Volatile Organic Compounds Detected in Ground Water—A Review of Selected Literature.* USGS Open File Report No. 2006-1338.

Levy, L.C., V.H. Boyd, C.C. Lutes, K.E. Hallberg, L.G. Lund, and T.B. Lewis. 2021. *Findings Report: Assessing Temporal Variability in Industrial Buildings during Vapor Intrusion Evaluations.* Draft, Navy Environmental Sustainability Development to Integration (NESDI) Program Project 554, January.

Lund, L.G. 2013. "Vapor Intrusion: Where Are We Today." Navy Remediation Innovative Technology Seminar. http://www.navfac.navy.mil/content/dam/navfac/Specialty%20Centers/Engineering%20and%20Expeditionary%20Warfare%20Center/Environmental/Restoration/er_pdfs/rits/RITS2013_VI_Where_are_we_today_final_20140415.pdf.

Lund, L. and A. Lind. 2016. HAPSITE, "Pressure Control, and Forensics to Identify Atypical VI Preferential Pathways." Presented at USEPA Vapor Intrusion Workshop, AEHS 26th Conference on Soil, Water, Energy, and Air, San Diego, CA. March 22.

Lund, L., C. Lutes, K. Hallberg, D. Caldwell, T. Venable, and T. Chaudhry. 2018. "Vapor Intrusion (VI): Quantitative Decision Framework Tool." Presented at the 11th International Conference on the Remediation of Chlorinated and Recalcitrant Compounds, Palm Springs, CA, April 8-12.

McGill, R., J.W. Tukey, and W.A. Larsen. 1978. "Variations of box plots." *The American Statistician.* Vol. 32, No. 1. pp. 12-16.

McHugh, T., and L. Beckley. 2018. *Sewers and Utility Tunnels as Preferential Pathways for Volatile Organic Compound Migration into Buildings: Risk Factors and Investigation Protocol*. Environmental Security Technology Certification Program (ESTCP), Project ER-201505. Final. November. Accessed December 14, 2020. https://www.serdp-estcp.org/content/download/48600/462543/file/ER-201505%20Final%20Report.pdf.

Montana Department of Environmental Quality (MDEQ). 2012. *Typical Indoor Air Concentrations of Volatile Organic Compounds in Non-Smoking Montana Residences Not Impacted by Vapor Intrusion.* August. Accessed October 31, 2019. https://deq.mt.gov/Portals/112/Land/StateSuperfund/Documents/VI_guide/CompleteIndoorVOCReport.pdf.

Nazaroff, W.W., and A.V. Nero. 1988. *Radon and its Decay Products in Indoor Air.* New York: John Wiley & Sons.

Oregon Department of Environmental Quality. 2010. *Guidance for Assessing and Remediating Vapor Intrusion in Buildings Appendix A: Determination of Screening Level Attenuation Factors and Soil Vapor Risk-Based Concentrations.* March.

Ottawa Hospital Research Institute. 2014. *Ottawa Decision Support Framework (ODSF).* https://web.archive.org/web/20150413002118/https://decisionaid.ohri.ca/odsf.html.

New York State Department of Health (NYSDOH). 2006. *Guidance for Evaluating Soil Vapor Intrusion in the State of New York.* Center for Environmental Health, Bureau of Environmental Exposure Investigation. Final. October. Accessed October 29, 2019. https://www.health.ny.gov/environmental/investigations/soil_gas/svi_guidance/.

Rago, R.J. 2015. "Background Indoor Air Levels of Volatile Organic Compounds and Air Phase Petroleum Hydrocarbons in Office Buildings and Schools." Presented at the Environmental Business Council of New England, Inc. (EBC) Site Remediation & Redevelopment Program "Vapor Intrusion – What's in the Air These Days," Woburn, MA. June 26. Accessed October 31, 2019. https://www.haleyaldrich.com/Portals/0/Downloads/vapor-intrusion-ebcne-june-2015.pdf.

R. Christopher Goodwin and Associates, Inc. 1997. *Historic Context for Department of Defense Facilities World War II Permanent Construction.* Prepared for U.S. Army Corps of Engineers Baltimore District. Final. June. https://fas.org/man/dod-101/fac/ww2_pc1.htm.

R Core Team. 2018. R: *A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria. Accessed September 19, 2020. https://www.R-project.org/.

Robinson, A.L., and R.G. Sextro. 1995. "The influence of a subslab gravel layer and open area on soil-gas and radon entry into two experimental basements." *Health Physics.* Vol. 69, No. 3. pp. 367-377.

RStudio Team. 2019. *RStudio: Integrated Development for R.* https://www.rstudio.com/.

Song, S., F. Ramacciotti, B. Schnorr, M. Bock, C. Stubbs, M.J. Bock, M.E. Portland, and C.M. Stubbs. 2011. "Evaluation of EPA's Empirical Attenuation Factor Database." Air Waste and Management Association. *EM Magazine.* February. pp. 16-21.

Song, S., B.A. Schnorr, and F.C. Ramacciotti. 2014. "Quantifying the Influence of Stack and Wind Effects on Vapor Intrusion." *Hum. Ecol. Risk Assess.* Vol. 20, No. 5. pp.1345-1358. Accessed June 19, 2020. https://www.tandfonline.com/doi/abs/10.1080/10807039.2013.858530.

Stroo, H.F., D.W. Major, and J.M. Gossett. 2010. "Bioaugmentation for anaerobic bioremediation of chlorinated solvents." In *In situ remediation of chlorinated solvent plumes*, pp. 425-454. New York: Springer.

Tichenor, B.A., Z. Guo, J.E. Dunn, L.E. Sparks, and M.A. Mason. 1991. "The interaction of vapour phase organic compounds with indoor sinks." *Indoor Air*. Vol. 1, No. 1. pp. 23-35.

Tri-Service Environmental Risk Assessment Workgroup (TSERAWG). 2009. *DoD Vapor Intrusion Handbook.* January. Accessed May 27, 2020. https://clu-in.org/download/char/dodvihdbk200901.pdf.

TSERAWG. 2019. *Matrix for Selecting Vapor Intrusion Investigation Techniques.* DoD Vapor Intrusion Handbook, Fact Sheet Update No. 007. July. Accessed on April 19, 2021. https://denix.osd.mil/irp/vaporintrusion/unassigned/fact-sheet-matrix-selecting-vapor-intrusion-investigation-technologies/.

TSERAWG. 2020. *Vapor Intrusion Preferential Pathways.* DoD Vapor Intrusion Handbook, Fact Sheet Update No. 010. September. Accessed April 19, 2021. https://denix.osd.mil/irp/vaporintrusion/unassigned/vipp-fact-sheet/.

Turk, B.H., J.T. Brown, K. Geisling-Sobotka, D.A. Froehlich, D.T. Grimsrud, J. Harrison, J.F. Koonce, R.J. Prill, and K.L. Revzan. 1987. *Indoor air quality and ventilation measurements in 38 Pacific Northwest commercial buildings. Volume 1: measurement results and interpretation*. Final report. Prepared for U.S. DOE. DE–AC03–76SF00098 by Lawrence Berkeley Laboratory, University of California, Berkeley CA. https://escholarship.org/uc/item/6f71j748.

Unified Facilities Criteria (UFC). 2004. *Protective Coatings and Paints.* UFC 3-190-06. January 16.

United States Environmental Protection Agency (USEPA). 1994. *Contaminants and Remedial Options at Solvent-Contaminated Sites*. EPA/600/R-94/203. November.

USEPA. 2004. *Cleaning Up the Nation's Waste Sites: Markets and Technology Trends*. EPA 542-R-04-015. September.

USEPA. 2008. *Engineering Issue: Indoor Air Vapor Intrusion Mitigation Approaches*. EPA/600/R-08-115. October.

USEPA. 2011. *Background Indoor Air Concentrations of Volatile Organic Compounds in North American Residences (1990-2005): A Compilation of Statistics for Assessing Vapor Intrusion*. Office of Solid Waste and Emergency Response (OSWER), EPA 530-R-10-001. June. Accessed February 18, 2019. https://www.epa.gov/sites/production/files/2015-09/documents/oswer-vapor-intrusion-background-report-062411.pdf.

USEPA. 2012a. *EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings*. Office of Solid Waste and Emergency Response (OSWER), EPA 530-R-10-002. March 16. Accessed September 19, 2019. https://www.epa.gov/sites/production/files/2015-09/documents/oswer_2010_database_report_03-16-2012_final_witherratum_508.pdf.

USEPA. 2012b. *Conceptual Model Scenarios for the Vapor Intrusion Pathway.* Office of Solid Waste and Emergency Response (OSWER), EPA 530-R-10-003. February. Accessed May 26, 2020. https://www.epa.gov/sites/production/files/2015-09/documents/vi-cms-v11final-2-24-2012.pdf.

USEPA. 2012c. *Fluctuation of Indoor Radon and VOC Concentrations Due to Seasonal Variability.* Office of Research and Development, EPA/600/R-12/673. September. Accessed June 22, 2020. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100KK1J.PDF?Dockey=P100KK1J.PDF.

USEPA. 2013. *3-D Modeling of Aerobic Biodegradation of Petroleum Vapors: Effect of Building Area Size on Oxygen Concentration Below the Slab*. EPA 510-R-13-002. June.

USEPA. 2015. *OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air*. Office of Solid Waste and Emergency Response (OSWER), OSWER Publication 9200.2-154. June. Accessed March 12, 2019. https://www.epa.gov/sites/production/files/2015-09/documents/oswer-vapor-intrusion-technical-guide-final.pdf.

USEPA. 2017. *Overview of the Building Assessment Survey and Evaluation Study*. Office of Radiation and Indoor Air, Indoor Environments Division. February 22. Accessed September 17, 2020. https://www.epa.gov/indoor-air-quality-iaq/overview-building-assessment-survey-and-evaluation-study.

USEPA. 2018. *Update for Chapter 19 of the Exposure Factors Handbook: Building Characteristics.* Office of Research and Development, EPA/600/R-18/121F. July. Accessed June 19, 2019. http://ofmpub.epa.gov/eims/eimscomm.getfile?p_download_id=536396.

USEPA. 2019. *Ambient Concentrations of Selected Air Toxics*. September 12. Accessed September 17, 2020. https://cfpub.epa.gov/roe/indicator.cfm?i=90.

USEPA. 2020. *Summarized Data of the Building Assessment Survey and Evaluation Study*. Office of Radiation and Indoor Air, Indoor Environments Division. July 16. Accessed September 17, 2020. https://www.epa.gov/indoor-air-quality-iaq/summarized-data-building-assessment-survey-and-evaluation-study.

USEPA. 2021. *Vapor Intrusion Screening Level (VISL) Calculator.* Accessed on July 22, 2021 at https://epa-visl.ornl.gov/cgi-bin/visl_search.

Venable, P., T. Chaudhry, D. Caldwell, I. Rivera-Duarte, C. Lutes, L. Lund, and K. Hallberg. 2015. *A Quantitative Decision Framework for Assessing Navy Vapor Intrusion Sites*. Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC), TR-NAVFAC-EXWC-EV-1603. June. Accessed September 19, 2019. https://clu-in.org/download/issues/vi/TR-NAVFAC-EXWC-EV-1603.pdf.

Venables, W.T., D.M. Smith, and the R Core Team. 2018. *An Introduction to R. Notes on R: A Programming Environment for Data Analysis and Graphics*. Version 3.5.1. July 7.

Wickham, H. 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer.

Wilcox, R.R., D.M. Erceg-Hurn, F. Clark, and M. Carlson. 2014. "Comparing two Independent Groups via the Lower and Upper Quantiles." *Journal of Statistical Computation and Simulation*. Vol. 84, No. 7. pp. 1543-1551.

Xie, S., and E. Suuberg. 2019. "Trichloroethylene (TCE) Sorption on Various Building Materials at Low Concentration." Presented at AEHS conference, Amherst MA.

Yao, Y., R. Shen, K.G. Pennell, and E.M. Suuberg. 2013a. "Examination of the US EPA's Vapor Intrusion Database based on Models." *Environmental Science & Technology*. Vol. 47. No. 3. pp. 1425-1433.

Yao, Y., R. Shen, K.G. Pennell, and E.M. Suuberg. 2013b. "Examination of the influence of environmental factors on contaminant vapor concentration attenuation factors using the US EPA's vapor intrusion database." *Environmental Science & Technology*. Vol. 47, No. 2. pp. 906-913

Tables

Table 2-1. Source Strength Screens Used for Filtering DoD VI Industrial Database Records

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Analyte	Selected background value for the purpose of this project and for indoor air screening	Source strength database screen for subslab soil gas data								Source strength database screen for groundwater data							
		10X selected background value[a]	50X selected background value[a]	100X selected background value[a]	500X selected background value[a]	1,000X selected background value[a]	Fixed common value[a] of 100 µg/m³	Fixed common value[a] of 500 µg/m³	Fixed common value[a] of 1,000 µg/m³	100X selected background value[a]	500X selected background value[a]	1,000X selected background value[a]	5,000X selected background value[a]	Fixed common value[a] of 1,000 µg/m³	Fixed common value[a] of 10,000 µg/m³	Fixed common value[a] of 100,000 µg/m³	Henry's Constant at 25°C[b]
	BGRD	SS10X BGRD	SS50X BGRD	SS100X BGRD	SS500X BGRD	SS1000X BGRD	SS100 CV	SS500 CV	SS1000 CV	GW100X BGRD	GW500X BGRD	GW1000X BGRD	GW5000X BGRD	GW1000 CV	GW10000 CV	GW100000 CV	
1,1,1-Trichloroethane	10.3	103	515	1,030	5,150	10,300	100	500	1,000	1,030	5,150	10,300	51,500	1,000	10,000	100,000	0.703
1,1-Dichloroethane	<RL	<RL	<RL	<RL	<RL	<RL	100	500	1,000	<RL	<RL	<RL	<RL	1,000	10,000	100,000	0.230
cis-1,2-Dichloroethene	<RL	<RL	<RL	<RL	<RL	<RL	100	500	1,000	<RL	<RL	<RL	<RL	1,000	10,000	100,000	0.167
trans-1,2-Dichloroethene	<RL	<RL	<RL	<RL	<RL	<RL	100	500	1,000	<RL	<RL	<RL	<RL	1,000	10,000	100,000	0.167
Tetrachloroethene	8.0	80	400	800	4,000	8,000	100	500	1,000	800	4,000	8,000	40,000	1,000	10,000	100,000	0.724
Trichloroethene	2.1	21	105	210	1,050	2,100	100	500	1,000	210	1,050	2,100	10,500	1,000	10,000	100,000	0.403
Vinyl Chloride	0.01	0.1	0.5	1	5	10	100	500	1,000	1	5	10	50	1,000	10,000	100,000	1.14
1,1-Dichloroethene	0.8	8	40	80	400	800	100	500	1,000	80	400	800	4,000	1,000	10,000	100,000	1.07
1,2-Dichloroethane	0.34	3.4	17	34	170	340	100	500	1,000	34	170	340	1,700	1,000	10,000	100,000	0.0482

Source: Henry's law dimensionless constants at 25°C based on USEPA (2012a, Table D-1). See also USEPA Chemical Specific Parameters table (https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables).

Consistent with USEPA VI database, the Henry's law constants are corrected to the appropriate site temperature to derive the groundwater concentrations corresponding to a given source strength screen (USEPA, 2012a, Section 5.2, Appendix D).

[a] All values reported in micrograms per cubic meter (µg/m³)

[b] Unitless

DoD = Department of Defense

RL = reporting limit

USEPA = United States Environmental Protection Agency

VI = vapor intrusion

Table 2-2. Number of Indoor Air Concentration Data Remaining After Each Screening Step (Subslab Soil Gas-Indoor Air Data Pairs)
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Dataset	Screening Step	TCE	PCE	cis-1,2-DCE	trans-1,2-DCE	1,2-DCA	1,1-DCA	1,1,1-TCA	1,1-DCE	VC
All Data (whether paired or unpaired with subslab soil gas data)	Indoor Air Data	764	647	674	592	539	502	480	407	718
	Detected in Indoor Air	509	332	209	141	180	98	213	50	44
	Proportion of Detectable Data	67%	51%	31%	24%	33%	20%	44%	12%	6%
Indoor Air Data Paired with Subslab Soil Gas Data (can be one or more subslab soil gas data points)	Indoor Air Data	520	463	433	385	366	354	344	241	467
	Detected in Indoor Air	322	208	106	69	24	37	121	18	12
	Proportion of Detectable Data	62%	45%	24%	18%	7%	10%	35%	7%	3%
	Baseline Screen (Steps 1 through 4)	487	396	272	246	93	177	243	59	97
	Baseline Screen + Source Strength Screen (Steps 1 through 4 plus Step 6)	166	59	74	27	21	38	31	16	12
	Baseline Screen + Preferential Pathway (Steps 1 through 5)	483	391	271	246	93	177	239	59	97
	Baseline Screen + Preferential Pathway + Source Strength Screen (Steps 1 through 6)	166	59	74	27	21	38	31	16	12
	Baseline Screen + Source Strength Screen + Preferential Pathway (Detected in Indoor Air)	142	45	58	5	2	21	26	4	4
	Baseline Screen + Source Strength Screen + Preferential Pathway (Not Detected in Indoor Air)	24	14	16	22	19	17	5	12	8

Indoor air concentration data presented in this table are from 76 buildings in the DoD VI Industrial Database (3 buildings among 79 were excluded due to the presence of atypical preferential VI pathways; 5 sample zones within 2 other buildings were excluded based on upper floor locations; see Section 2.1).

Source strength screen applied is 1,000 times (1,000X) background for VOCs with background values (TCE, PCE, 1,1,1-TCA, 1,1-DCE, 1,2-DCA, and VC) and 1,000 micrograms per cubic meter (µg/m^3) for VOCs without background values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE).

1,1,1-TCA = 1,1,1-trichloroethane
1,1-DCA = 1,1-dichloroethane
1,1-DCE = 1,1-dichloroethene
1,2-DCA = 1,2-dichloroethane
cis-1,2-DCE = cis-1,2-dichloroethene
PCE = tetrachloroethene
TCE = trichloroethene
trans-1,2-DCE = trans-1,2-dichloroethene
VC = vinyl chloride
VOC = volatile organic compound

Table 2-3. Number of Indoor Air Concentration Data Remaining After Each Data Screening Step (Groundwater-Indoor Air Data Pairs)

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Dataset	Screening Step	TCE	PCE	cis-1,2-DCE	trans-1,2-DCE	1,2-DCA	1,1-DCA	1,1,1-TCA	1,1-DCE	VC
All Data (whether paired or unpaired with groundwater data)	Indoor Air Data	764	647	674	592	539	502	480	407	718
	Detected in Indoor Air	509	332	209	141	180	98	213	50	44
	Proportion of Detectable Data	67%	51%	31%	24%	33%	20%	44%	12%	6%
Indoor Air Data Paired with Groundwater Data	Indoor Air Data	454	135	122	34	10	23	0	15	138
	Detected in Indoor Air	293	84	36	6	2	2	0	0	18
	Proportion of Detectable Data	65%	62%	30%	18%	20%	9%	--	0%	13%
	Subsurface Non-Detects Screen (Groundwater) (Step 1)	454	135	122	34	8	23	0	15	138
	Subsurface Non-Detect Screen (Groundwater + Subslab Soil Gas) (Steps 1 and 2)	451	135	122	34	4	23	0	12	66
	Subsurface Non-detects Screen (Steps 1 and 2) + Background Source Screen (Step 3)	449	135	122	34	4	23	0	12	66
	Subsurface Non-detects Screen + Background Source Screen + Ratio Screen (Steps 1 to 4)	448	124	118	34	4	23	0	12	66
	Subsurface Non-detects + Background Source + Ratio Screen + Outdoor Air Screen (Steps 1 to 5)	448	124	118	34	4	23	0	12	66
	Baseline Screen (Steps 1 to 5) + Preferential Pathway Screen (Step 6)	439	123	111	34	4	23	0	12	59
	Baseline Screen + Preferential Pathway Screen + Source Strength Screen (Steps 1 to 7)	241	58	102	17	4	5	0	0	59
	Baseline Screen + Preferential Pathway Screen + Source Strength Screen (Detected in Indoor Air)	171	42	28	5	1	2	0	0	11
	Baseline Screen + Preferential Pathway + Source Strength Screen (Not Detected in Indoor Air)	70	16	74	12	3	3	0	0	48

Indoor air concentration data presented in this table are from 76 buildings in the DoD VI Industrial Database (3 buildings among 79 were excluded due to the presence of atypical preferential VI pathways; 5 sample zones within 2 other buildings were excluded based on upper floor locations; see Section 2.1).

Source strength screen applied is 5,000 times (5,000X) background for VOCs with background values (TCE, PCE, 1,1,1-TCA, 1,1-DCE, 1,2-DCA, and VC) and 1,000 micrograms per cubic meter (µg/m^3) for VOCs without background values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE).

1,1-DCA = 1,1-dichloroethane
1,2-DCA = 1,2-dichloroethane
1,1-DCE = 1,1-dichloroethene
1,1,1-TCA = 1,1,1-trichloroethane
cis-1,2-DCE = cis-1,2-dichloroethene
PCE = tetrachloroethene TCE = trichloroethene
trans-1,2-DCE = trans-1,2-dichloroethene
VC = vinyl chloride
VOC = volatile organic compound

Table 3-1. Wilcoxon-Mann-Whitney – Two-Tailed Significance Test: Subslab Soil Gas Concentration per Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Analyte	Median (Fine) µg/m³	Median (Coarse) µg/m³	U Statistic	P-Value	Sample Number (Fine)	Sample Number (Coarse)
PCE	16.0	38.7	12800	0.0394	127	177
TCE	75.9	155	19600	0.0559	204	172
cis-1,2-DCE	43.6	4.40	2110	0.384	45	103
1,1,1-TCA	9.00	27.0	4330	0.0113	84	84
1,1-DCA	97.1	1.75	855	0.00054	44	64
1,1-DCE	101	7.10	33.0	0.0504	30	5
1,2-DCA	0.512	0.400	6.00	1.00	4	3
VC	3.70	0.500	3.00	0.030	6	5
trans-1,2-DCE	2.90	2.35	1460	0.528	47	58

Detectable Data Only.

U is the test statistic, as defined at https://sphweb.bumc.bu.edu/otlt/mph-modules/bs/bs704_nonparametric/bs704_nonparametric4.html (LaMorte, 2017).

Table 3-2. Quantiles for PCE Comparison of Two Independent Groups of Subslab Soil Gas Concentrations by Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 Coarse	n2 Fine	est1 Coarse	est2 Fine	est1-est2	p.crit	p.value
0.1	177	127	4.05	0.756	3.29	0.008	0.000
0.2	177	127	5.83	1.40	4.43	0.007	0.000
0.3	177	127	9.57	2.10	7.47	0.006	0.000
0.4	177	127	16.4	4.47	11.89	0.012	0.060
0.5	177	127	37.3	20.6	16.7	0.025	0.448
0.6	177	127	70.2	113	-42.5	0.050	0.552
0.7	177	127	200.	830.	-630.	0.017	0.108
0.8	177	127	651	12400	-11700	0.010	0.008
0.9	177	127	11400	134000	-122000	0.006	0.008

Detected Values Only.

est1 = estimated percentiles of the distribution for the first group
est2 = estimated percentiles of the distribution for the second group
n1 = number of samples in the first group
n2 = number of samples in the second group
p.crit = adjusted p-value required for the finding of significance
p.value = calculated for the difference in percentiles between the n1 and n2 groups

Table 3-3. Quantiles for TCE Comparison of Two Independent Groups of Subslab Soil Gas Concentrations by Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 Coarse	n2 Fine	est1 Coarse	est2 Fine	est1-est2	p.crit	p.value
0.1	172	204	2.99	2.24	0.749	0.050	0.556
0.2	172	204	15.5	8.67	6.82	0.017	0.196
0.3	172	204	37.1	20.3	16.8	0.006	0.036
0.4	172	204	81.9	40.6	41.3	0.007	0.068
0.5	172	204	159	78.8	80.5	0.008	0.064
0.6	172	204	427	202	226	0.010	0.200
0.7	172	204	1320	673	648	0.012	0.224
0.8	172	204	10400	3640	6720	0.025	0.180
0.9	172	204	176000	23900	152000	0.006	0.008

Detected Values Only.

est1 = estimated percentiles of the distribution for the first group
est2 = estimated percentiles of the distribution for the second group
n1 = number of samples in the first group
n2 = number of samples in the second group
p.crit = adjusted p-value required for the finding of significance
p.value = calculated for the difference in percentiles between the n1 and n2 groups

Table 3-4. Quantiles for 1,1-DCE Comparison of Two Independent Groups of Subslab Soil Gas Concentrations by Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 Coarse	n2 Fine	est1 Coarse	est2 Fine	est1-est.2	p.crit	p.value
0.1	5	30	2.18	2.47	-0.281	0.050	0.916
0.2	5	30	3.54	10.2	-6.71	0.025	0.424
0.3	5	30	6.02	36.1	-30.1	0.017	0.144
0.4	5	30	10.2	73.1	-62.9	0.012	0.032
0.5	5	30	16.8	125	-109	0.010	0.008
0.6	5	30	25.9	251	-225	0.008	0.000
0.7	5	30	36.9	560	-523	0.007	0.000
0.8	5	30	48.4	1470	-1420	0.006	0.000
0.9	5	30	57.8	9860	-9800	0.006	0.000

Detected Values Only.

est1 = estimated percentiles of the distribution for the first group
est2 = estimated percentiles of the distribution for the second group
n1 = number of samples in the first group
n2 = number of samples in the second group
p.crit = adjusted p-value required for the finding of significance

p.value = calculated for the difference in percentiles between the n1 and n2 groups

Table 3-5. Quantiles for VC Comparison of Two Independent Groups of Subslab Soil Gas Concentrations by Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 Coarse	n2 Fine	est1 Coarse	est2 Fine	est1-est.2	p.crit	p.value
0.1	5	6	0.102	1.16	-1.06	0.007	0.000
0.2	5	6	0.142	6.42	-6.28	0.006	0.000
0.3	5	6	0.218	44.5	-44.3	0.006	0.008
0.4	5	6	0.332	246	-246	0.025	0.004
0.5	5	6	0.491	1060	-1060	0.008	0.028
0.6	5	6	0.713	3570	-3570	0.017	0.004
0.7	5	6	1.02	9470	-9470	0.012	0.008
0.8	5	6	1.40	19700	-19700	0.010	0.012
0.9	5	6	1.77	31800	-31800	0.050	0.012

Detected Values Only.

est1 = estimated percentiles of the distribution for the first group
est2 = estimated percentiles of the distribution for the second group
n1 = number of samples in the first group
n2 = number of samples in the second group
p.crit = adjusted p-value required for the finding of significance

p.value = calculated for the difference in percentiles between the n1 and n2 groups

Table 3-6. Wilcoxon-Mann-Whitney Test – Two-Tailed Significance Test: Subslab Soil Gas Concentration per Exterior Wall Presence, Detectable Data Only

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

	Median (No Exterior Wall) µg/m³	**Median (Exterior Wall) µg/m³**	**U Statistic**	**P-Value**	**Sample Number (No Exterior Wall)**	**Sample Number (Exterior Wall)**
PCE	20.2	57.0	15300	0.103	90	382
TCE	105	180.	20700	0.244	100	447
cis-12-DCE	650	13.0	5480	0.00039	37	217
111-TCA	43.0	36.0	3740	0.415	39	209
11-DCA	215	19.5	2130	0.0225	20	162
11-DCE	117	151	110.	0.754	4	61
12-DCA	0.620	0.405	4.00	1.00	1	7
VC	NA	NA	NA	NA	NA	NA
trans-12-DCE	8.06	2.60	2670	0.0156	30	139

An explanation of the calculation of the test statistic, U in the Wilcoxon-Mann-Whitney test can be found at https://sphweb.bumc.bu.edu/otlt/mph-modules/bs/bs704_nonparametric/bs704_nonparametric4.html (LaMorte, 2017).

NA = Not available

Table 3-7. Quantiles PCE Comparison of Two Independent Groups of Subslab Soil Gas Concentrations by Exterior Wall Presence

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 (No Exterior Wall)	n2 (Exterior Wall)	est1 (No Exterior Wall)	est2 (Exterior Wall)	est1-est.2	p.crit	p.value
0.1	17	91	266	188	77.6	0.025	0.664
0.2	17	91	1440	387	1050	0.008	0.248
0.3	17	91	4710	1440	3280	0.010	0.320
0.4	17	91	10200	5540	4630	0.012	0.464
0.5	17	91	16000	13000	2990	0.050	0.712
0.6	17	91	20500	25100	-4620	0.017	0.516
0.7	17	91	23600	56200	-32599	0.007	0.060
0.8	17	91	28900	149000	-120000	0.006	0.024
0.9	17	91	58200	387000	-328000	0.006	0.000

Detected Values Only.

est1 = estimated percentiles of the distribution for the first group
est2 = estimated percentiles of the distribution for the second group
n1 = number of samples in the first group
n2 = number of samples in the second group
p.crit = adjusted p-value required for the finding of significance

p.value = calculated for the difference in percentiles between the n1 and n2 groups

Table 3-8. Quantiles TCE Comparison of Two Independent Groups of Subslab Soil Gas Concentrations by Exterior Wall Presence
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 (No Exterior Wall)	n2 (Exterior Wall)	est1 (No Exterior Wall)	est2 (Exterior Wall)	est1-est.2	p.crit	p.value
0.1	29	196	461	33.3	427	0.006	0.000
0.2	29	196	1960	303	1660	0.010	0.048
0.3	29	196	4070	870	3190	0.008	0.004
0.4	29	196	7050	2040	5010	0.012	0.028
0.5	29	196	15000	5530	9430	0.025	0.080
0.6	29	196	68500	11600	56900	0.050	0.136
0.7	29	196	385000	26800	358000	0.017	0.076
0.8	29	196	1360000	64300	1290000	0.007	0.016
0.9	29	196	3520000	299000	3220000	0.006	0.000

Detected Values Only.

est1 = estimated percentiles of the distribution for the first group
est2 = estimated percentiles of the distribution for the second group
n1 = number of samples in the first group
n2 = number of samples in the second group
p.crit = adjusted p-value required for the finding of significance

p.value = calculated for the difference in percentiles between the n1 and n2 groups

Table 3-9. Quantiles 1,1,1-TCA Comparison of Two Independent Groups of Subslab Soil Gas Concentrations by Exterior Wall Presence

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 (No Exterior Wall)	n2 (Exterior Wall)	est1 (No Exterior Wall)	est2 (Exterior Wall)	est1-est.2	p.crit	p.value
0.1	13	68	1450	10.4	1430	0.050	0.000
0.2	13	68	6970	42.5	6930	0.025	0.000
0.3	13	68	33000	297	32700	0.017	0.004
0.4	13	68	114000	1070	113000	0.012	0.000
0.5	13	68	271000	2750	268000	0.010	0.004
0.6	13	68	461000	4960	456000	0.008	0.000
0.7	13	68	618000	10400	608000	0.007	0.000
0.8	13	68	746000	33100	713000	0.006	0.000
0.9	13	68	921000	168000	753000	0.006	0.008

Detected Values Only.

est1 = estimated percentiles of the distribution for the first group
est2 = estimated percentiles of the distribution for the second group
n1 = number of samples in the first group
n2 = number of samples in the second group
p.crit = adjusted p-value required for the finding of significance

p.value = calculated for the difference in percentiles between the n1 and n2 groups

Table 3-10. Quantiles 1,1-DCA Comparison of Two Independent Groups of Subslab Soil Gas Concentrations by Exterior Wall Presence
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 (No Exterior Wall)	n2 (Exterior Wall)	est1 (No Exterior Wall)	est2 (Exterior Wall)	est1-est.2	p.crit	p.value
0.1	12	68	131	3.28	128	0.006	0.012
0.2	12	68	753	55.9	697	0.012	0.064
0.3	12	68	2870	177	2700	0.025	0.088
0.4	12	68	7470	364	7110	0.017	0.012
0.5	12	68	14000	908	13100	0.010	0.016
0.6	12	68	20400	1910	18500	0.008	0.012
0.7	12	68	25000	3130	21800	0.007	0.000
0.8	12	68	28400	5090	23300	0.006	0.004
0.9	12	68	32800	12500	20300	0.050	0.216

Detected Values Only.

est1 = estimated percentiles of the distribution for the first group
est2 = estimated percentiles of the distribution for the second group
n1 = number of samples in the first group
n2 = number of samples in the second group
p.crit = adjusted p-value required for the finding of significance

p.value = calculated for the difference in percentiles between the n1 and n2 groups

Table 4-1. Subslab Soil Gas-to-Indoor Air AF Descriptive Statistics for TCE Using Building Sample Zone Averages for Individual Sampling Events

Source Strength Screen (TCE Background = 2.1 μg/m³)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
10x Background (21 μg/m³)	145	8.52E-06	8.94E-05	1.78E-03	1.07E-02	5.35E-02	8.46E-02
100 μg/m³	105	3.95E-06	5.42E-05	3.28E-04	3.14E-03	1.14E-02	1.82E-02
50x Background (105 μg/m³)	103	3.82E-06	5.23E-05	2.70E-04	2.88E-03	1.16E-02	1.83E-02
100x Background (210 μg/m³)	87	3.67E-06	4.57E-05	1.40E-04	1.15E-03	4.04E-03	1.55E-02
500 μg/m³	76	3.58E-06	4.14E-05	9.28E-05	6.58E-04	2.90E-03	3.95E-03
1,000 μg/m³	67	3.46E-06	3.81E-05	6.82E-05	3.79E-04	2.16E-03	3.61E-03
500x Background (1,050 μg/m³)	66	3.45E-06	3.71E-05	6.74E-05	3.65E-04	2.24E-03	3.63E-03
1000x Background (2,100 μg/m³)	58	3.19E-06	3.46E-05	6.39E-05	1.88E-04	1.45E-03	3.19E-03

Pairs with an indoor air concentration below detection limit are not included.

%ile = percentile

AF = attenuation factor

TCE = trichloroethene

μg/m³ = microgram per cubic meter

Table 4-2. Subslab Soil Gas-to-Indoor Air AF Descriptive Statistics for PCE Using Building Sample Zone Averages for Individual Sampling Events

Source Strength Screen (PCE Background = 8.0 μg/m^3)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
10x Background (80 μg/m^3)	62	5.24E-06	5.58E-05	5.60E-04	3.91E-03	9.64E-01	1.14E+00
100 μg/m^3	58	4.63E-06	5.16E-05	4.92E-04	3.74E-03	9.39E-01	1.14E+00
50x Background (400 μg/m^3)	36	1.31E-06	2.34E-05	7.58E-05	5.17E-04	1.89E-03	1.66E-02
500 μg/m^3	33	1.20E-06	2.20E-05	5.65E-05	4.23E-04	9.46E-04	1.73E-03
100x Background (800 μg/m^3)	29	1.05E-06	1.82E-05	5.02E-05	2.88E-04	6.36E-04	9.21E-04
1,000 μg/m^3	29	1.05E-06	1.82E-05	5.02E-05	2.88E-04	6.36E-04	9.21E-04
500x Background (4,000 μg/m^3)	24	8.55E-07	1.45E-05	3.76E-05	2.02E-04	5.00E-04	5.81E-04
1000x Background (8,000 μg/m^3)	21	7.40E-07	1.71E-05	2.92E-05	1.90E-04	5.68E-04	5.83E-04

Pairs with an indoor air concentration below detection limit are not included.
%ile = percentile
AF = attenuation factor
PCE = tetrachloroethene
μg/m^3 = microgram per cubic meter

Table 4-3. Subslab Soil Gas-to-Indoor Air AF Descriptive Statistics for cis-1,2-DCE Using Building Sample Zone Averages for Individual Sampling Events

Source Strength Screen (cis-1,2-DCE Background = N/A)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
All data	44	2.81E-06	2.20E-05	2.55E-04	3.42E-03	5.54E-02	6.95E-02
100 µg/m^3	30	2.58E-06	7.65E-06	4.28E-05	2.63E-04	9.87E-04	1.64E-03
500 µg/m^3	29	2.58E-06	7.43E-06	3.90E-05	2.37E-04	9.40E-04	1.69E-03
1,000 µg/m^3	27	2.58E-06	7.21E-06	3.00E-05	1.62E-04	5.12E-04	1.64E-03

Pairs with an indoor air concentration below detection limit are not included.

%ile = percentile

AF = attenuation factor

cis-1,2-DCE = cis-1,2-dichloroethene

N/A = not applicable

µg/m^3 = microgram per cubic meter

Table 4-4. Subslab Soil Gas-to-Indoor Air AF Descriptive Statistics for 1,1-DCA Using Building Sample Zone Averages for Individual Sampling Events

Source Strength Screen (1,1-DCA Background = N/A)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
All data	26	3.77E-06	7.61E-05	1.84E-04	1.21E-03	1.84E-02	3.69E-02
100 µg/m^3	22	3.15E-06	4.76E-05	1.40E-04	5.37E-04	1.52E-03	2.35E-03
500 µg/m^3	16	2.95E-06	1.44E-05	9.41E-05	1.76E-04	8.97E-04	1.76E-03
1,000 µg/m^3	13	2.92E-06	1.02E-05	7.33E-05	1.19E-04	1.61E-04	1.81E-04

Pairs with an indoor air concentration below detection limit are not included.

%ile = percentile

1,1-DCA = 1,1-dichloroethane

AF = attenuation factor

N/A = not applicable

µg/m^3 = microgram per cubic meter

Table 4-5. Subslab Soil Gas-to-Indoor Air AF Descriptive Statistics for VOCs Using Building Sample Zone Averages for Individual Sampling Events

Analyte	Number of Data Pairs and AFs	Minimum	5%	25%	50%	75%	90%	95%	Maximum	Mean	Strd Dev
All VOCs	142	1.60E-07	2.15E-06	1.09E-05	4.61E-05	1.44E-04	5.82E-04	1.82E-03	1.27E-02	3.38E-04	1.22E-03
1,1-DCA	13	2.80E-06	2.92E-06	1.02E-05	7.33E-05	1.19E-04	1.61E-04	1.81E-04	2.00E-04	7.38E-05	6.76E-05
1,1-DCE	3	1.45E-04	1.52E-04	1.76E-04	2.07E-04	2.87E-04	3.35E-04	3.51E-04	3.67E-04	2.40E-04	1.14E-04
1,1,1-TCA	11	1.62E-06	2.53E-06	4.40E-06	9.20E-06	3.00E-05	2.22E-04	5.24E-04	8.26E-04	1.05E-04	2.48E-04
cis-1,2-DCE	27	1.23E-06	2.58E-06	7.21E-06	3.00E-05	1.62E-04	5.12E-04	1.64E-03	2.33E-03	2.53E-04	5.85E-04
PCE	21	3.45E-07	7.40E-07	1.71E-05	2.92E-05	1.90E-04	5.68E-04	5.83E-04	1.09E-03	1.59E-04	2.75E-04
TCE	58	1.60E-07	3.19E-06	3.46E-05	6.39E-05	1.88E-04	1.45E-03	3.19E-03	1.27E-02	6.01E-04	1.83E-03
trans-1,2-DCE	5	9.29E-06	1.05E-05	1.53E-05	2.54E-05	2.85E-05	4.52E-05	5.07E-05	5.63E-05	2.69E-05	1.81E-05
VC	4	8.68E-07	3.24E-06	1.27E-05	1.85E-05	2.05E-05	2.10E-05	2.12E-05	2.13E-05	1.48E-05	9.49E-06

Source strength screen applied is 1,000 times background for VOCs with background values (TCE, PCE, 1,1,1-TCA, 1,1-DCE, and VC) and 1,000 µg/m^3 for VOCs without background values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE).

There were no pairs meeting the various filtering criteria for 1,2-dichloroethane (1,2-DCA).

Pairs with an indoor air concentration below detection limit are not included.

1,1,1-TCA = 1,1,1-trichloroethane
1,1-DCA = 1,1-dichloroethane
1,1-DCE = 1,1-dichloroethene
AF = attenuation factor
cis-1,2-DCE = cis-1,2-dichloroethene
PCE = tetrachloroethene
Strd Dev = standard deviation
TCE = trichloroethene
trans-1,2-DCE = trans-1,2-dichloroethene
VC = vinyl chloride
VOC = volatile organic compound
µg/m^3 = microgram per cubic meter

Table 4-6. Subslab Soil Gas-to-Indoor Air AF Descriptive Statistics for TCE Using Building Sample Zone Averages for All Sampling Events

Source Strength Screen (TCE Background = 2.1 µg/m³)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
10x Background (21 µg/m³)	80	8.04E-06	6.90E-05	8.09E-04	5.92E-03	1.92E-02	5.07E-02
100 µg/m³	63	7.37E-06	5.98E-05	2.08E-04	1.74E-03	6.52E-03	1.06E-02
50x Background (105 µg/m³)	61	7.29E-06	5.88E-05	2.00E-04	1.68E-03	6.37E-03	1.07E-02
100x Background (210 µg/m³)	54	5.98E-06	5.46E-05	1.38E-04	7.64E-04	3.57E-03	6.43E-03
500 µg/m³	47	4.68E-06	4.74E-05	8.30E-05	4.34E-04	2.20E-03	4.14E-03
1,000 µg/m³	42	3.74E-06	4.14E-05	7.46E-05	4.09E-04	2.21E-03	4.30E-03
500x Background (1,050 µg/m³)	41	3.56E-06	4.03E-05	6.92E-05	3.77E-04	2.35E-03	4.39E-03
1000x Background (2,100 µg/m³)	37	3.44E-06	3.61E-05	6.67E-05	1.82E-04	6.83E-04	2.86E-03

Pairs with an indoor air concentration below detection limit are not included.

%ile = percentile

AF = attenuation factor

TCE = trichloroethene

µg/m³ = microgram per cubic meter

Table 4-7. Subslab Soil Gas-to-Indoor Air AF Descriptive Statistics for PCE Using Building Sample Zone Averages for All Sampling Events

Source Strength Screen (PCE Background = 8.0 µg/m³)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
10x Background (80 µg/m³)	48	7.45E-06	4.92E-05	7.56E-04	8.62E-02	1.02E+00	1.72E+00
100 µg/m³	44	7.00E-06	4.18E-05	5.34E-04	4.18E-02	9.56E-01	1.14E+00
50x Background (400 µg/m³)	29	5.77E-06	2.39E-05	8.09E-05	5.68E-04	2.94E-03	3.43E-02
500 µg/m³	26	5.55E-06	2.35E-05	5.34E-05	4.03E-04	9.09E-04	2.25E-03
100x Background (800 µg/m³)	22	5.25E-06	1.95E-05	3.76E-05	2.14E-04	7.25E-04	8.43E-04
1,000 µg/m³	22	5.25E-06	1.95E-05	3.76E-05	2.14E-04	7.25E-04	8.43E-04
500x Background (4,000 µg/m³)	18	4.52E-06	1.74E-05	2.79E-05	1.20E-04	4.10E-04	5.94E-04
1000x Background (8,000 µg/m³)	15	3.86E-06	1.77E-05	2.67E-05	9.55E-05	4.36E-04	6.20E-04

Pairs with an indoor air concentration below detection limit are not included.

%ile = percentile

AF = attenuation factor

PCE = tetrachloroethene

µg/m³ = microgram per cubic meter

Table 4-8. Subslab Soil Gas-to-Indoor Air AF Descriptive Statistics for cis-1,2-DCE Using Building Sample Zone Averages for All Sampling Events

Source Strength Screen (cis-1,2-DCE Background = N/A)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
All data	30	5.17E-06	2.27E-05	1.66E-04	5.88E-03	4.62E-02	6.18E-02
100 µg/m^3	20	3.64E-06	8.11E-06	4.73E-05	1.39E-04	5.60E-04	1.13E-03
500 µg/m^3	20	3.64E-06	8.11E-06	3.45E-05	1.39E-04	5.60E-04	1.13E-03
1,000 µg/m^3	20	3.64E-06	8.11E-06	3.45E-05	1.17E-04	3.53E-04	1.13E-03

Pairs with an indoor air concentration below detection limit are not included.
%ile = percentile
AF = attenuation factor
cis-1,2-DCE = cis-1,2-dichloroethene
N/A = not applicable
µg/m^3 = microgram per cubic meter

Table 4-9. Subslab Soil Gas-to-Indoor Air AF Descriptive Statistics for 1,1-DCA Using Building Sample Zone Averages for All Sampling Events

Source Strength Screen (1,1-DCA Background = N/A)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
All data	21	3.00E-06	7.05E-05	2.00E-04	8.60E-04	3.19E-02	3.86E-02
100 µg/m^3	17	2.96E-06	1.58E-05	1.45E-04	4.88E-04	1.47E-03	2.92E-03
500 µg/m^3	13	2.92E-06	1.02E-05	7.76E-05	2.00E-04	3.75E-04	1.20E-03
1,000 µg/m^3	11	2.90E-06	8.14E-06	7.05E-05	1.12E-04	1.68E-04	1.84E-04

Pairs with an indoor air concentration below detection limit are not included.
%ile = percentile
1,1-DCA = 1,1-dichloroethane
AF = attenuation factor
N/A = not applicable
µg/m^3 = microgram per cubic meter

Table 4-10. Comparison of Subslab Soil Gas-to-Indoor Air AF Descriptive Statistics Using Different Averaging Methods

Analyte	Approach[a]	Number of Data Pairs and AFs	5%	25%	50%	75%	90%	95%
TCE	Per Event	58	3.19E-06	3.46E-05	6.39E-05	1.88E-04	1.45E-03	3.19E-03
	Per Sample Zone	37	3.44E-06	3.61E-05	6.67E-05	1.82E-04	6.83E-04	2.86E-03
	Per Building	20	8.89E-06	4.55E-05	7.58E-05	1.36E-04	7.77E-04	3.07E-03
PCE	Per Event	21	7.40E-07	1.71E-05	2.92E-05	1.90E-04	5.68E-04	5.83E-04
	Per Sample Zone	15	3.86E-06	1.77E-05	2.67E-05	9.55E-05	4.36E-04	6.20E-04
	Per Building	9	5.50E-06	2.00E-05	2.67E-05	5.02E-05	2.80E-04	5.12E-04
cis-1,2-DCE	Per Event	27	2.58E-06	7.21E-06	3.00E-05	1.62E-04	5.12E-04	1.64E-03
	Per Sample Zone	20	3.64E-06	8.11E-06	3.45E-05	1.17E-04	3.53E-04	1.13E-03
	Per Building	10	7.46E-06	9.25E-06	3.82E-05	1.21E-04	4.55E-04	1.28E-03
1,1-DCA	Per Event	13	2.92E-06	1.02E-05	7.33E-05	1.19E-04	1.61E-04	1.81E-04
	Per Sample Zone	11	2.90E-06	8.14E-06	7.05E-05	1.12E-04	1.68E-04	1.84E-04
	Per Building	6	7.71E-06	2.92E-05	9.08E-05	1.15E-04	1.44E-04	1.56E-04

[a] "Per event" refers to building sample zone averages for individual sampling events; "Per sample zone" refers to building sample zone averages for all sampling events; "Per building" refers to building averages for all sampling events of all sample zones. A sampling event needs to pass the source screen zone to be included in the average.

Source strength screen applied is 1,000 times background for VOCs with background values (TCE and PCE) and 1,000 μg/m^3 for VOCs without background values (cis-1,2-DCE and 1,1-DCA).

Pairs with an indoor air concentration below detection limit are not included.

1,1-DCA = 1,1-dichloroethane

AF = attenuation factor

cis-1,2-DCE = cis-1,2-dichloroethene

PCE = tetrachloroethene

TCE = trichloroethene

μg/m^3 = microgram per cubic meter

Table 4-11. Comparison of Subslab Soil Gas-to-Indoor Air AF Descriptive Statistics with and without Indoor Air Detects When Computing Building Sample Zone Averages for Individual Sampling Events

Analyte	Approach	Number of Data Pairs and AFs	5%	25%	50%	75%	90%	95%
TCE	IA Detects Only	58	3.19E-06	3.46E-05	6.39E-05	1.88E-04	1.45E-03	3.19E-03
	IA Non-Detects Taken at DL	62	3.39E-06	3.64E-05	6.18E-05	1.50E-04	1.25E-03	3.15E-03
PCE	IA Detects Only	21	7.40E-07	1.71E-05	2.92E-05	1.90E-04	5.68E-04	5.83E-04
	IA Non-Detects Taken at DL	27	1.90E-06	1.20E-05	2.39E-05	7.72E-05	4.00E-04	5.79E-04
cis-1,2-DCE	IA Detects Only	27	2.58E-06	7.21E-06	3.00E-05	1.62E-04	5.12E-04	1.64E-03
	IA Non-Detects Taken at DL	33	2.58E-06	9.09E-06	4.83E-05	2.37E-04	4.47E-04	5.33E-04
1,1-DCA	IA Detects Only	13	2.92E-06	1.02E-05	7.33E-05	1.19E-04	1.61E-04	1.81E-04
	IA Non-Detects Taken at DL	18	2.97E-06	1.06E-05	4.36E-05	9.91E-05	1.45E-04	1.73E-04

Source strength screen applied is 1,000 times background for VOCs with background values (TCE and PCE) and 1,000 $\mu g/m^3$ for VOCs without background values (cis-1,2-DCE and 1,1-DCA).
1,1-DCA = 1,1-dichloroethane
AF = attenuation factor
cis-1,2-DCE = cis-1,2-dichloroethene
DL = detection limit
IA = indoor air
PCE = tetrachloroethene
TCE = trichloroethene
VOC = volatile organic compound
$\mu g/m^3$ = microgram per cubic meter

Table 4-12. Comparison of Subslab Soil Gas-to-Indoor Air AF Descriptive Statistics Obtained Using Building Sample Zone Average and Maximum Concentrations for Individual Sampling Events

Analyte	Approach[a]	Number of Data Pairs and AFs	5%	25%	50%	75%	90%	95%
TCE	Average Concentrations	58	3.19E-06	3.46E-05	6.39E-05	1.88E-04	1.45E-03	3.19E-03
	Maximum Concentrations	58	3.23E-06	2.90E-05	5.34E-05	2.06E-04	1.28E-03	3.19E-03
PCE	Average Concentrations	21	7.40E-07	1.71E-05	2.92E-05	1.90E-04	5.68E-04	5.83E-04
	Maximum Concentrations	21	3.00E-07	6.62E-06	2.92E-05	1.84E-04	5.68E-04	5.83E-04
cis-1,2-DCE	Average Concentrations	27	2.58E-06	7.21E-06	3.00E-05	1.62E-04	5.12E-04	1.64E-03
	Maximum Concentrations	27	2.21E-06	7.67E-06	3.00E-05	1.79E-04	6.04E-04	1.71E-03
1,1-DCA	Average Concentrations	13	2.92E-06	1.02E-05	7.33E-05	1.19E-04	1.61E-04	1.81E-04
	Maximum Concentrations	13	2.99E-06	1.02E-05	7.33E-05	1.04E-04	1.31E-04	1.61E-04

[a] "Average concentration" refers to approach using building sample zone average subslab soil gas and indoor air concentrations for individual sampling events; "Maximum concentration" refers to approach using building sample zone maximum subslab soil gas and indoor air concentrations for individual sampling events.

Source strength screen applied is 1,000 times background for VOCs with background values (TCE and PCE) and 1,000 $\mu g/m^3$ for VOCs without background values (cis-1,2-DCE and 1,1-DCA).

Pairs with an indoor air concentration below detection limit are not included.

$\mu g/m^3$ = microgram per cubic meter
1,1-DCA = 1,1-dichloroethane
AF = attenuation factor
cis-1,2-DCE = cis-1,2-dichloroethene
PCE = tetrachloroethene
TCE = trichloroethene
VOC = volatile organic compound

Table 4-13. Groundwater-to-Indoor Air AF Descriptive Statistics for TCE Using Building Sample Zone Averages for Individual Sampling Events

Source Strength Screen (TCE Background = 2.1 µg/m^3)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
100x Background (210 µg/m^3)	181	4.49E-08	3.04E-07	1.61E-06	3.71E-05	2.78E-04	1.38E-03
1,000 µg/m^3	165	4.44E-08	2.84E-07	1.24E-06	2.75E-05	1.26E-04	2.73E-04
500x Background (1,050 µg/m^3)	165	4.44E-08	2.84E-07	1.24E-06	2.75E-05	1.26E-04	2.73E-04
1000x Background (2,100 µg/m^3)	148	3.89E-08	2.04E-07	8.10E-07	9.26E-06	4.15E-05	8.51E-05
10,000 µg/m^3	131	3.48E-08	1.76E-07	5.95E-07	3.07E-06	2.68E-05	4.45E-05
5000x Background (10,500 µg/m^3)	130	3.47E-08	1.76E-07	5.89E-07	2.98E-06	2.49E-05	4.24E-05
100,000 µg/m^3	106	3.20E-08	1.55E-07	5.34E-07	1.73E-06	1.04E-05	2.74E-05

Pairs with an indoor air concentration below detection limit are not included.

%ile = percentile

AF = attenuation factor

TCE = trichloroethene

µg/m^3 = microgram per cubic meter

Table 4-14. Groundwater-to-Indoor Air AF Descriptive Statistics for PCE Using Building Sample Zone Averages for Individual Sampling Events

Source Strength Screen (PCE Background = 8.0 µg/m³)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
100x Background (800 µg/m³)	58	1.46E-08	2.63E-07	6.21E-06	6.53E-05	4.43E-04	5.34E-04
1,000 µg/m³	58	1.46E-08	2.63E-07	6.21E-06	6.53E-05	4.43E-04	5.34E-04
500x Background (4,000 µg/m³)	52	1.46E-08	1.41E-07	3.03E-06	4.24E-05	2.63E-04	5.13E-04
1000x Background (8,000 µg/m³)	45	1.46E-08	8.85E-08	2.15E-06	2.07E-05	1.29E-04	2.15E-04
10,000 µg/m³	45	1.46E-08	8.85E-08	2.15E-06	2.07E-05	1.29E-04	2.15E-04
5000x Background (40,000 µg/m³)	37	1.31E-08	4.91E-08	1.16E-06	9.33E-06	1.08E-04	1.54E-04
100,000 µg/m³	27	9.49E-09	4.30E-08	1.46E-07	2.35E-05	1.29E-04	2.05E-04

Pairs with an indoor air concentration below detection limit are not included.
%ile = percentile
AF = attenuation factor
PCE = tetrachloroethene
µg/m³ = microgram per cubic meter

Table 4-15. Groundwater-to-Indoor Air AF Descriptive Statistics for cis-1,2-DCE Using Building Sample Zone Averages for Individual Sampling Events

Source Strength Screen (cis-1,2-DCE Background = N/A)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
All data	28	1.29E-08	1.54E-07	9.52E-07	8.60E-06	3.59E-05	9.32E-05
1,000 $\mu g/m^3$	28	1.29E-08	1.54E-07	9.52E-07	8.60E-06	3.59E-05	9.32E-05
10,000 $\mu g/m^3$	25	1.24E-08	1.25E-07	6.25E-07	4.91E-06	2.09E-05	2.94E-05
100,000 $\mu g/m^3$	13	1.13E-08	5.69E-08	1.63E-07	5.40E-07	1.15E-06	1.55E-06

Pairs with an indoor air concentration below detection limit are not included.

%ile = percentile

AF = attenuation factor

cis-1,2-DCE = cis-1,2-dichloroethene

N/A = not applicable

$\mu g/m^3$ = microgram per cubic meter

Table 4-16. Groundwater-to-Indoor Air AF Descriptive Statistics for VOCs Using Building Sample Zone Averages for Individual Sampling Events

Analyte	Number of Data Pairs and AFs	Minimum	5%	25%	50%	75%	90%	95%	Maximum	Mean	Strd Dev
All VOCs	209	3.55E-09	1.48E-08	1.24E-07	6.25E-07	4.11E-06	2.76E-05	6.22E-05	5.15E-04	1.20E-05	4.41E-05
1,1-DCA	2	1.45E-05	1.55E-05	1.91E-05	2.37E-05	2.83E-05	3.11E-05	3.20E-05	3.29E-05	2.37E-05	1.30E-05
1,2-DCA	1	1.24E-04	1.24E-04	1.24E-04	1.24E-04	1.24E-04	1.24E-04	1.24E-04	1.24E-04	1.24E-04	--
cis-1,2-DCE	25	1.06E-08	1.24E-08	1.25E-07	6.25E-07	4.91E-06	2.09E-05	2.94E-05	4.82E-05	5.87E-06	1.18E-05
PCE	37	3.55E-09	1.31E-08	4.91E-08	1.16E-06	9.33E-06	1.08E-04	1.54E-04	5.15E-04	3.33E-05	9.50E-05
TCE	130	7.41E-09	3.47E-08	1.76E-07	5.89E-07	2.98E-06	2.49E-05	4.24E-05	1.06E-04	7.20E-06	1.79E-05
trans-1,2-DCE	5	5.47E-08	5.93E-08	7.78E-08	9.04E-08	4.07E-07	1.15E-06	1.40E-06	1.64E-06	4.55E-07	6.80E-07
VC	9	8.82E-09	1.20E-08	2.12E-08	3.46E-08	4.66E-06	6.12E-06	6.94E-06	7.77E-06	2.05E-06	3.10E-06

Source strength screen applied is 5,000 times background for VOCs with background values (TCE, PCE, 1,2-DCA, and VC) and 10,000 μg/m^3 for VOCs without background values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE).
Pairs with an indoor air concentration below detection limit are not included.
There were no pairs meeting the various filtering criteria for 1,1,1-trichloroethane (1,1,1-TCA) and 1,1-dichloroethene (1,1-DCE).
%ile = percentile
1,1-DCA = 1,1-dichloroethane
1,2-DCA = 1,2-dichloroethane
AF = attenuation factor
cis-1,2-DCE = cis-1,2-dichloroethene
PCE = tetrachloroethene
Strd Dev = standard deviation
TCE = trichloroethene
trans-1,2-DCE = trans-1,2-dichloroethene
VC = vinyl chloride
VOC = volatile organic compound
μg/m^3 = microgram per cubic meter

Table 4-17. Groundwater-to-Indoor Air AF Descriptive Statistics for TCE Using Building Sample Zone Averages for All Sampling Events

Source Strength Screen (TCE Background = 2.1 µg/m^3)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
100x Background (210 µg/m^3)	83	5.73E-08	9.25E-07	2.68E-05	1.70E-04	8.16E-04	3.44E-03
1,000 µg/m^3	69	4.56E-08	5.56E-07	9.31E-06	5.09E-05	2.52E-04	4.86E-04
500x Background (1,050 µg/m^3)	69	4.56E-08	5.56E-07	9.31E-06	5.09E-05	2.52E-04	4.86E-04
1000x Background (2,100 µg/m^3)	60	3.89E-08	5.17E-07	4.18E-06	3.65E-05	5.98E-05	2.86E-04
10,000 µg/m^3	47	3.38E-08	2.64E-07	1.36E-06	1.64E-05	4.56E-05	5.37E-05
5000x Background (10,500 µg/m^3)	46	3.34E-08	2.50E-07	1.32E-06	1.05E-05	4.46E-05	4.97E-05
100,000 µg/m^3	33	2.60E-08	2.37E-07	1.28E-06	9.31E-06	2.73E-05	4.45E-05

Pairs with an indoor air concentration below detection limit are not included.
%ile = percentile
AF = attenuation factor
TCE = trichloroethene
µg/m^3 = microgram per cubic meter

Table 4-18. Groundwater-to-Indoor Air AF Descriptive Statistics for PCE Using Building Sample Zone Averages for All Sampling Events

Source Strength Screen (PCE Background = 8.0 µg/m^3)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
100x Background (800 µg/m^3)	42	2.52E-08	6.71E-07	3.41E-06	6.06E-05	4.23E-04	6.34E-04
1,000 µg/m^3	42	2.52E-08	6.71E-07	3.41E-06	6.06E-05	4.23E-04	6.34E-04
500x Background (4,000 µg/m^3)	36	2.27E-08	3.32E-07	2.32E-06	3.68E-05	2.81E-04	5.89E-04
1000x Background (8,000 µg/m^3)	31	2.04E-08	1.82E-07	2.06E-06	9.58E-06	7.55E-05	1.85E-04
10,000 µg/m^3	31	2.04E-08	1.82E-07	2.06E-06	9.58E-06	7.55E-05	1.85E-04
5000x Background (40,000 µg/m^3)	26	1.82E-08	9.10E-08	1.57E-06	3.50E-06	7.02E-05	1.57E-04
100,000 µg/m^3	17	1.49E-08	4.76E-08	2.29E-07	3.58E-06	1.19E-04	1.85E-04

Pairs with an indoor air concentration below detection limit are not included.

%ile = percentile

AF = attenuation factor

PCE = tetrachloroethene

µg/m^3 = microgram per cubic meter

Table 4-19. Groundwater-to-Indoor Air AF Descriptive Statistics for cis-1,2-DCE Using Building Sample Zone Averages for All Sampling Events

Source Strength Screen (cis-1,2-DCE Background = N/A)	Number of Data Pairs and AFs	5 %ile	25 %ile	Median (50 %ile)	75 %ile	90 %ile	95 %ile
All data	19	1.31E-08	1.44E-07	6.25E-07	1.32E-05	4.05E-05	1.26E-04
1,000 µg/m^3	19	1.31E-08	1.44E-07	6.25E-07	1.32E-05	4.05E-05	1.26E-04
10,000 µg/m^3	16	1.27E-08	1.13E-07	5.14E-07	2.34E-06	1.32E-05	1.86E-05
100,000 µg/m^3	9	1.17E-08	5.69E-08	1.63E-07	5.40E-07	9.19E-07	1.44E-06

Pairs with an indoor air concentration below detection limit are not included.
%ile = percentile
AF = attenuation factor
cis-1,2-DCE = cis-1,2-dichloroethene
N/A = not applicable
µg/m^3 = microgram per cubic meter

Table 4-20. Comparison of Groundwater-to-Indoor Air AF Descriptive Statistics with and without Indoor Air Detects When Computing Building Sample Zone Averages for Individual Sampling Events

Analyte	Approach	Number of Data Pairs and AFs	5%	25%	50%	75%	90%	95%
TCE	IA Detects Only	130	3.47E-08	1.76E-07	5.89E-07	2.98E-06	2.49E-05	4.24E-05
	IA Non-Detects Taken at DL	186	4.45E-08	2.56E-07	8.77E-07	6.42E-06	2.58E-05	4.31E-05
PCE	IA Detects Only	37	1.31E-08	4.91E-08	1.16E-06	9.33E-06	1.08E-04	1.54E-04
	IA Non-Detects Taken at DL	51	1.10E-08	1.07E-07	2.06E-06	4.22E-06	3.28E-05	1.30E-04
cis-1,2-DCE	IA Detects Only	25	1.24E-08	1.25E-07	6.25E-07	4.91E-06	2.09E-05	2.94E-05
	IA Non-Detects Taken at DL	78	2.96E-08	4.32E-07	4.62E-06	2.08E-05	8.04E-05	1.56E-04

Source strength screen applied is 5,000 times background for VOCs with background values (TCE and PCE) and 10,000 µg/m^3 for VOCs without background values (cis,1-2-DCE).

AF = attenuation factor
cis-1,2-DCE = cis-1,2-dichloroethene
DL = detection limit
IA = indoor air
PCE = tetrachloroethene
TCE = trichloroethene
VOC = volatile organic compound
µg/m^3 = microgram per cubic meter

Table 4-21. Quantiles for Detected PCE – Comparison of Two Independent Groups of Indoor Air Concentrations by Types of Walls

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 (No Exterior Wall)	n2 (Exterior Wall)	est1 (No Exterior Wall)	est2 (Exterior Wall)	est1-est.2	p.crit	p.value
0.1	6	39	0.102	0.049	0.053	0.006	0.000
0.2	6	39	0.158	0.073	0.086	0.008	0.056
0.3	6	39	0.268	0.098	0.171	0.012	0.208
0.4	6	39	0.440	0.171	0.269	0.017	0.436
0.5	6	39	0.686	0.535	0.151	0.050	0.824
0.6	6	39	1.04	1.76	-0.719	0.025	0.580
0.7	6	39	1.56	4.69	-3.13	0.010	0.164
0.8	6	39	2.25	11.6	-9.36	0.007	0.016
0.9	6	39	2.96	48.7	-45.7	0.006	0.000

Detected data only.

Source strength screen: SS1000X Background.

Table 4-22. Quantiles for Detected TCE – Comparison of Two Independent Groups of Indoor Air Concentrations by Types of Walls

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 (No Exterior Wall)	n2 (Exterior Wall)	est1 (No Exterior Wall)	est2 (Exterior Wall)	est1-est.2	p.crit	p.value
0.1	16	126	0.596	0.136	0.460	0.006	0.012
0.2	16	126	1.39	0.278	1.11	0.006	0.008
0.3	16	126	2.47	0.526	1.94	0.007	0.004
0.4	16	126	3.79	1.01	2.78	0.008	0.024
0.5	16	126	5.35	1.91	3.44	0.010	0.024
0.6	16	126	7.10	3.44	3.66	0.017	0.032
0.7	16	126	9.14	5.28	3.86	0.025	0.144
0.8	16	126	12.4	13.7	-1.27	0.050	0.872
0.9	16	126	21.4	49.0	-27.7	0.012	0.036

Detected data only.

Source strength screen: SS1000X Background.

Table 4-23. Quantiles for Detected cis-1,2-DCE – Comparison of Two Independent Groups of Indoor Air Concentrations by Types of Walls

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 (No Exterior Wall)	n2 (Exterior Wall)	est1 (No Exterior Wall)	est2 (Exterior Wall)	est1-est.2	p.crit	p.value
0.1	12	42	0.358	0.190	0.168	0.008	0.040
0.2	12	42	0.693	0.276	0.417	0.012	0.108
0.3	12	42	1.05	0.410	0.644	0.010	0.056
0.4	12	42	1.34	0.581	0.757	0.007	0.028
0.5	12	42	1.56	0.710	0.850	0.006	0.000
0.6	12	42	1.81	0.823	0.983	0.006	0.008
0.7	12	42	2.28	1.14	1.14	0.017	0.112
0.8	12	42	3.29	2.11	1.18	0.025	0.488
0.9	12	42	4.72	5.56	-0.840	0.050	0.720

Detected data only.

Source strength screen:1,000 µg/m^3 constant value.

Table 4-24. Quantiles for Detected trans-1,2-DCE – Comparison of Two Independent Groups of Indoor Air Concentrations by Types of Walls

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 (No Exterior Wall)	n2 (Exterior Wall)	est1 (No Exterior Wall)	est2 (Exterior Wall)	est1-est.2	p.crit	p.value
0.1	4	5	0.077	0.156	-0.079	0.050	0.732
0.2	4	5	0.182	0.681	-0.500	0.025	0.588
0.3	4	5	0.351	2.18	-1.83	0.017	0.460
0.4	4	5	0.603	5.42	-4.81	0.012	0.296
0.5	4	5	0.973	10.9	-9.93	0.010	0.216
0.6	4	5	1.49	18.4	-16.9	0.006	0.152
0.7	4	5	2.15	26.7	-24.5	0.008	0.168
0.8	4	5	2.86	34.2	-31.3	0.006	0.176
0.9	4	5	3.46	39.5	-36.0	0.007	0.144

Detected data only.

Source strength screen:1,000 μg/m^3 constant value.

Table 4-25. Quantiles for Detected 1,1,1-TCA – Comparison of Two Independent Groups of Indoor Air Concentrations by Types of Walls

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 (No Exterior Wall)	n2 (Exterior Wall)	est1 (No Exterior Wall)	est2 (Exterior Wall)	est1-est.2	p.crit	p.value
0.1	8	18	1.11	0.031	1.08	0.006	0.000
0.2	8	18	1.56	0.101	1.45	0.008	0.040
0.3	8	18	1.88	0.409	1.47	0.010	0.144
0.4	8	18	2.14	1.15	0.981	0.025	0.456
0.5	8	18	2.42	2.42	0.005	0.050	0.992
0.6	8	18	2.79	4.32	-1.53	0.017	0.484
0.7	8	18	3.26	7.60	-4.34	0.012	0.116
0.8	8	18	3.87	18.9	-15.0	0.007	0.036
0.9	8	18	4.60	53.2	-48.6	0.006	0.000

Detected data only.

Source strength screen: SS1000X Background.

Table 4-26. Quantiles for Detected 1,1-DCA – Comparison of Two Independent Groups of Indoor Air Concentrations by Types of Walls

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Quantile	n1 (No Exterior Wall)	n2 (Exterior Wall)	est1 (No Exterior Wall)	est2 (Exterior Wall)	est1-est.2	p.crit	p.value
0.1	4	22	0.061	0.041	0.020	0.017	0.156
0.2	4	22	0.064	0.063	0.001	0.050	0.904
0.3	4	22	0.067	0.096	-0.030	0.025	0.248
0.4	4	22	0.070	0.138	-0.068	0.012	0.036
0.5	4	22	0.073	0.182	-0.109	0.010	0.004
0.6	4	22	0.075	0.242	-0.167	0.008	0.000
0.7	4	22	0.078	0.380	-0.303	0.007	0.000
0.8	4	22	0.079	0.657	-0.578	0.006	0.000
0.9	4	22	0.080	1.67	-1.59	0.006	0.000

Detected data only.

Source strength screen:1,000 µg/m^3 constant value.

Table 4-27. Wilcoxon-Mann-Whitney Test – Two-Tailed Significance Test: Indoor Air Concentration per Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

VOC	Median (Fine)	Median (Coarse)	U Statistic	p-Value	Sample No (Fine)	Sample No (Coarse)
PCE	13.6	0.0995	4	0	11	30
TCE	10	1.4	911	0.00001	41	88
cis-1,2-DCE	2.08	0.765	28	0.306	2	50
1,1,1-TCA	1.34	2.6	48	0.68	4	21
1,1-DCA	0.243	0.14	10	0.239	3	13
1,1-DCE	NA	NA	NA	NA	NA	NA
1,2-DCA	NA	NA	NA	NA	NA	NA
trans-1,2-DCE	NA	NA	NA	NA	NA	NA

Detectable data only.

Baseline, atypical preferential pathway, and source strength screens applied at the individual sampling event level.

Source strength screen is 1,000X background or 1,000 µg/m^3 constant value depending on the VOC.

All installations included.

NA = no sufficient data available for comparison.

Table 5-1. Professional Judgment Based Categorization of Primary Zone Use as to Likely Open Doors

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

PRIMARY_USE_CCN	SuspectOpenY1N2	SuspectOpenOC
211-12 - PAINT AND FINISHING HANGAR (NAVAIR DEPOT)	1	Open
211-31 - DEDICATED AIRCRAFT AND ENGINE ACCESS OH -GEN PROC (DEPOT)	2	Closed
211-35 - HYDRAULIC COMPONENTS SHOP (NAVAIR DEPOT)	2	Closed
211-52 - A/C WEAPON OVERHAUL & TEST	2	Closed
211-95 - MATERIAL AND EQUIPMENT STAGING / STORAGE FACILITY (DEPOT)	1	Open
219-10 - PUBLIC WORKS SHOP	2	Closed
610-10 - ADMINISTRATIVE OFFICE	2	Closed
Aircraft Maintenance	1	Open
Bathroom	2	Closed
Break Room	2	Closed
Classroom	2	Closed
Common Area	1	Open
Equipment Storage	2	Closed
Garage	1	Open
Hallway	1	Open
Jet Engine Testing Facility/Office	1	Open
Laboratory	2	Closed
Living Quarters	2	Closed
Locker Room	2	Closed
Machine Shop	2	Closed
Mail Room	2	Closed
Maintenance Shop	2	Closed
Mechanical Room	1	Open
Monitor Room	2	Closed
Office	1	Open
Office/Lounge/Laundry	1	Open
Office/Warehouse	1	Open
Open Equipment Storage area	1	Open
Parking	1	Open
Receiving Room	1	Open
Room	2	Closed
Shop	2	Closed
Short-term residence	2	Closed
Storage	1	Open
Supply Closet	2	Closed
Warehouse	1	Open
Workshop	2	Closed

NAVAIR = Naval Air Systems Command

Figures

Figure 2-1. Location of DoD Installations Part of the DoD VI Database of Commercial and Industrial Buildings
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

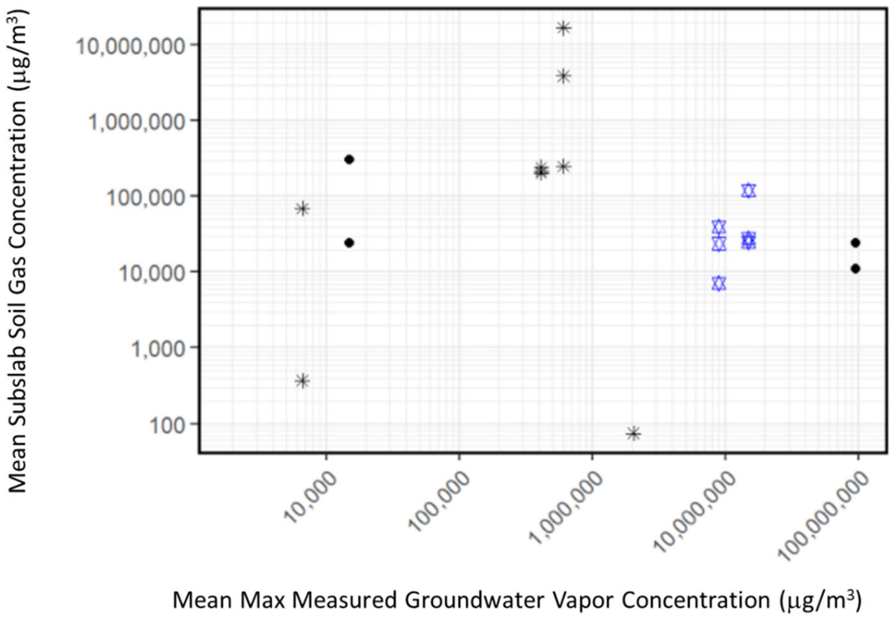


Figure 3-1. PCE Subslab Soil Gas Concentration Versus Max Measured Groundwater Vapor Concentration
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, source strength (100X background on groundwater vapor concentrations), and atypical preferential pathway screens applied to data. Different symbols correspond to data from different DoD installations. R squared [r^2] for the linear fit is 0.01.

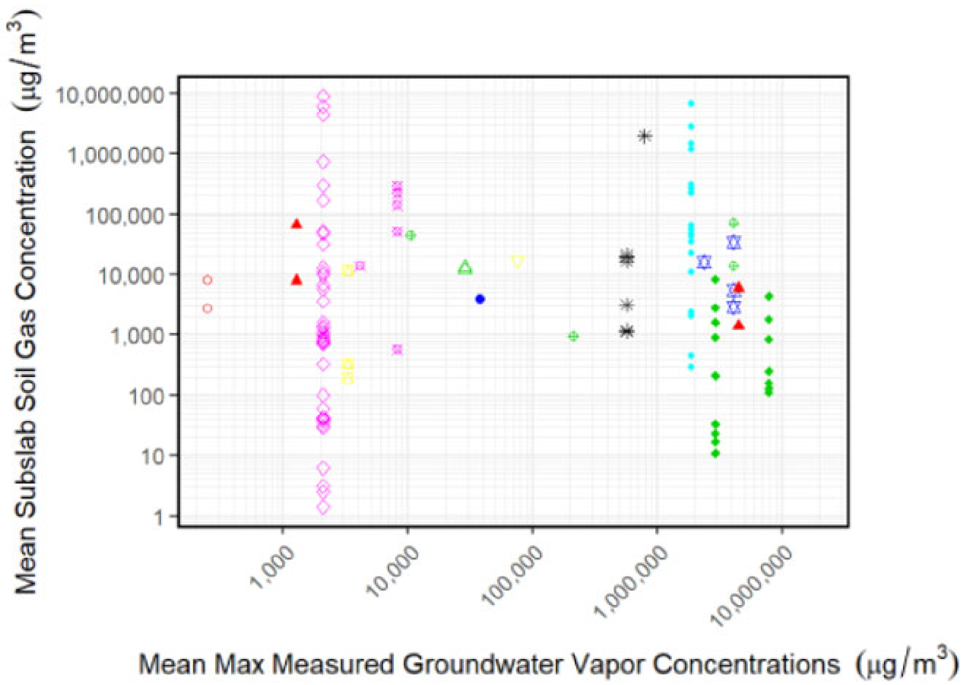


Figure 3-2. TCE Subslab Soil Gas Concentration Versus Max Measured Groundwater Vapor Concentration
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, source strength (100X background on groundwater vapor concentrations), and atypical preferential pathway screens applied to data. Different symbols correspond to data from different DoD installations. R squared [r^2] for the linear fit is 0.08.

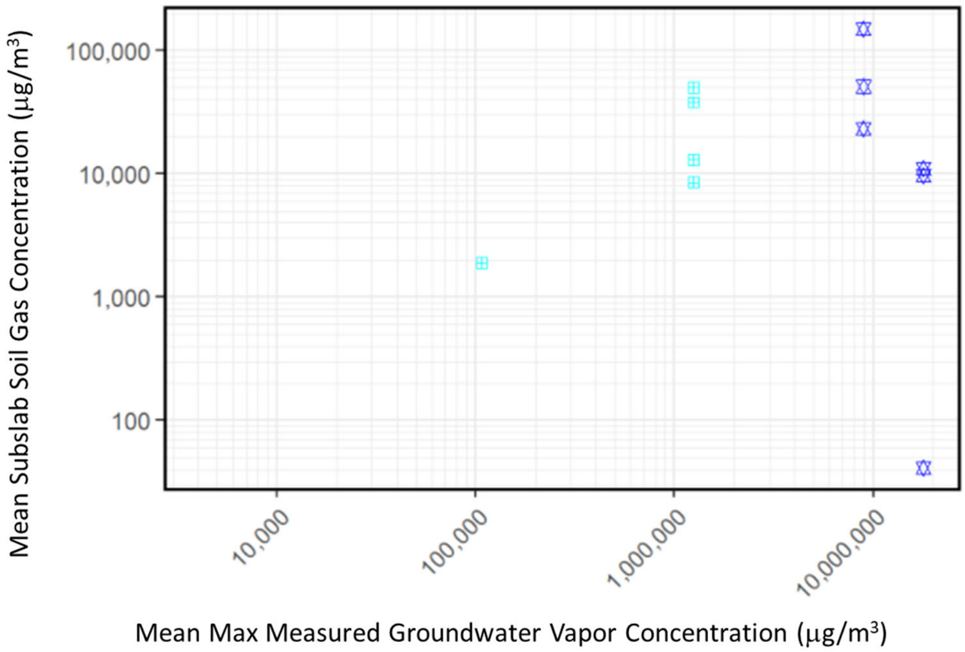


Figure 3-3. cis-1,2-DCE Subslab Soil Gas Concentration Versus Max Measured Groundwater Vapor Concentration
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, source strength (1,000 µg/m³ on groundwater vapor concentrations), and atypical preferential pathway screens applied to data. Different symbols correspond to data from different DoD installations. R squared [r^2] for the linear fit is 0.42.

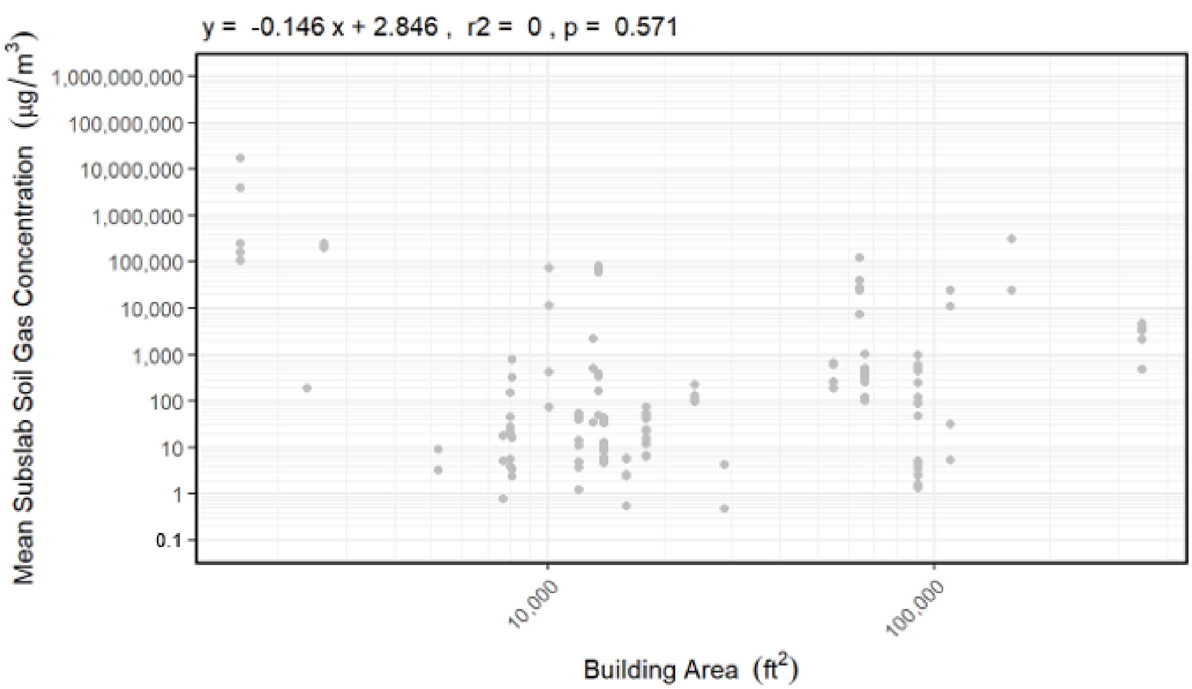


Figure 3-4. PCE Subslab Soil Gas Concentration Versus Building Area
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Atypical preferential pathway screen only. In the equation, x represents the log of the building area and y represents the log of the subslab soil gas concentration.

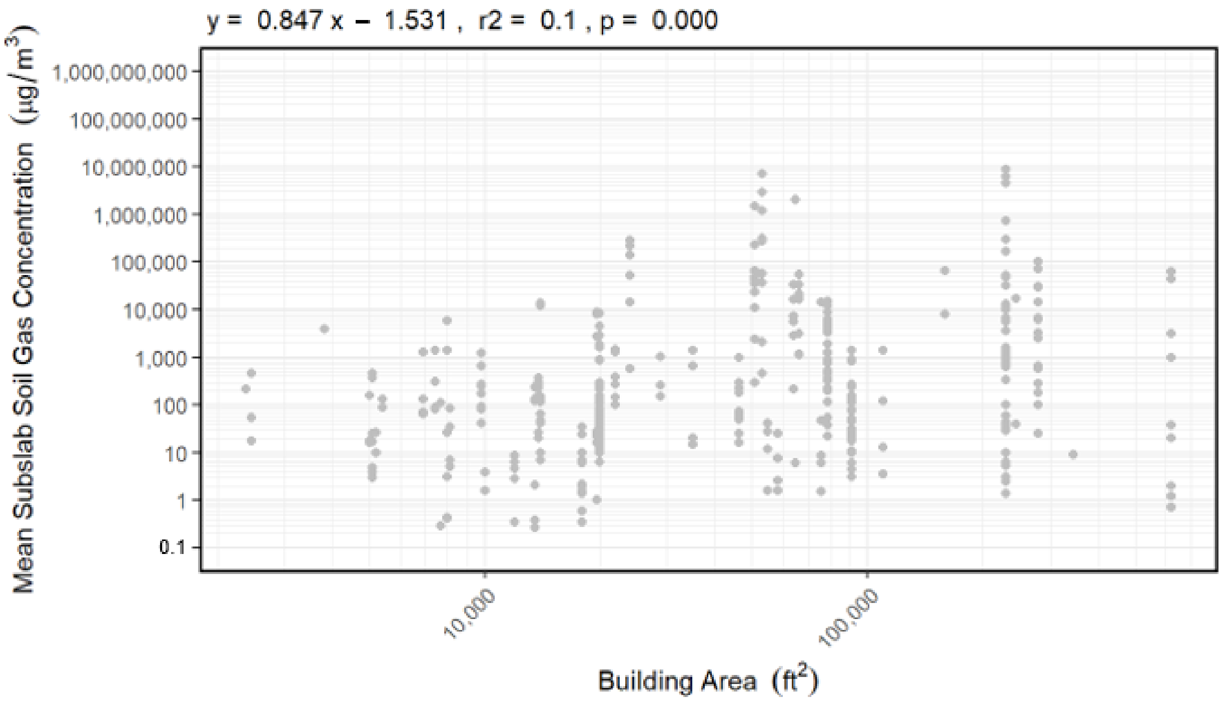


Figure 3-5. TCE Subslab Soil Gas Concentration Versus Building Area
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Atypical preferential pathway screen only. In the equation, x represents the log of the building area and y represents the log of the subslab soil gas concentration.

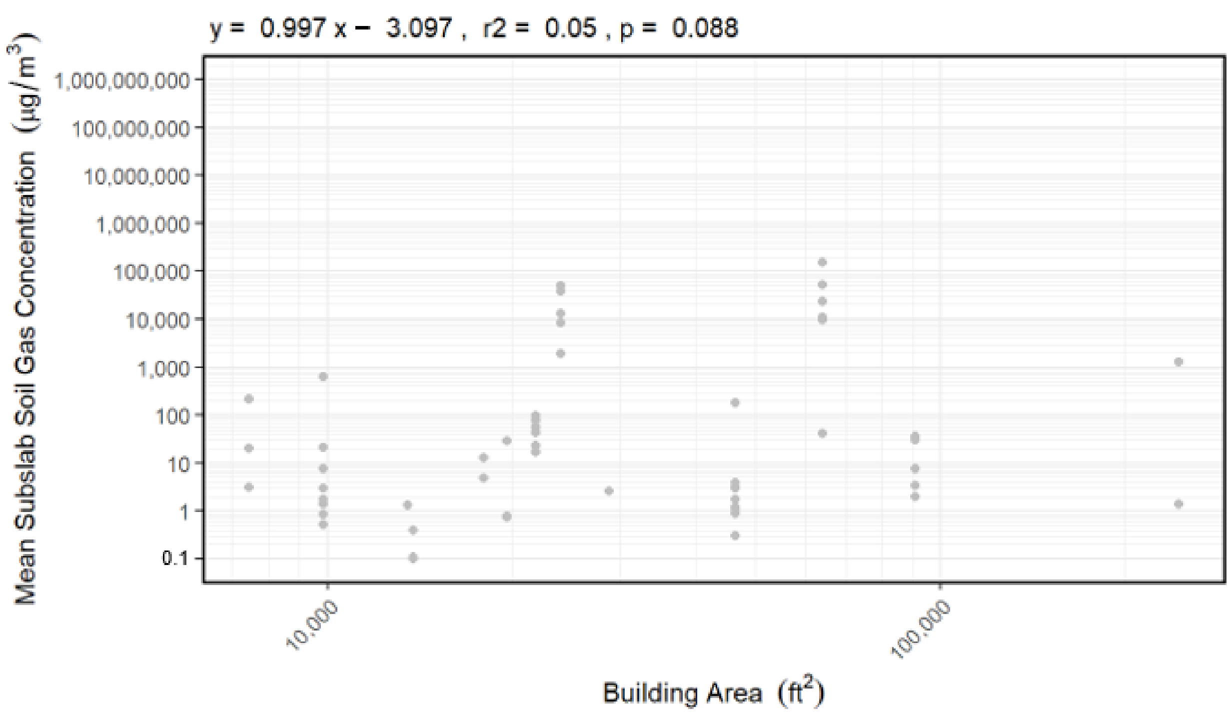


Figure 3-6. cis-1,2-DCE Subslab Soil Gas Concentration Versus Building Area
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Atypical preferential pathway screen only. In the equation, x represents the log of the building area and y represents the log of the subslab soil gas concentration.

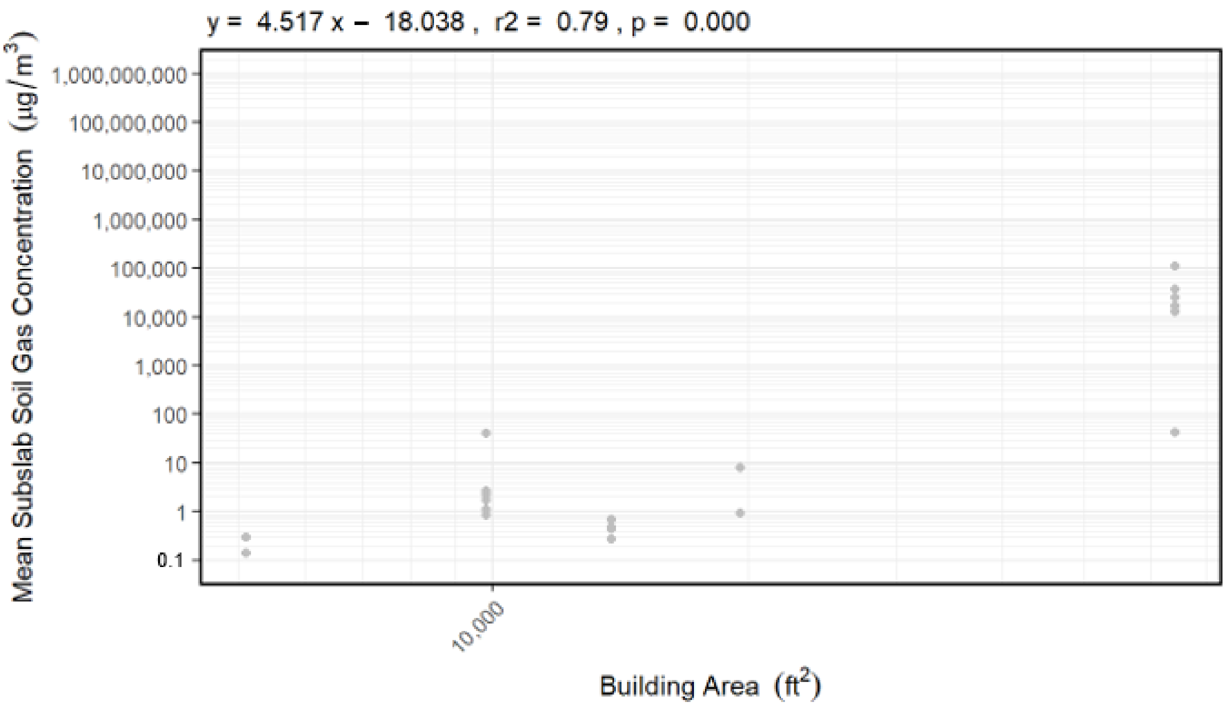


Figure 3-7. trans-1,2-DCE Subslab Soil Gas Concentration Versus Building Area

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Atypical preferential pathway screen only. In the equation, x represents the log of the building area and y represents the log of the subslab soil gas concentration.

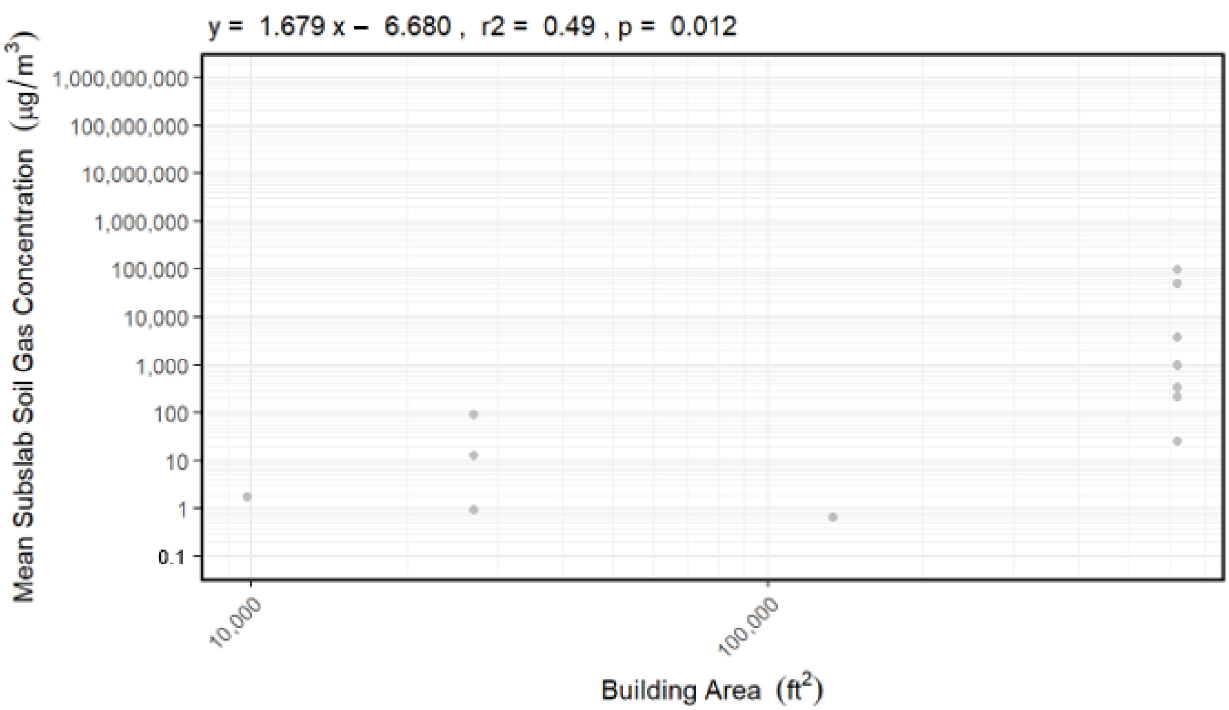


Figure 3-8. 1,1-DCA Subslab Soil Gas Concentration Versus Building Area

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Atypical preferential pathway screen only. In the equation, x represents the log of the building area and y represents the log of the subslab soil gas concentration.

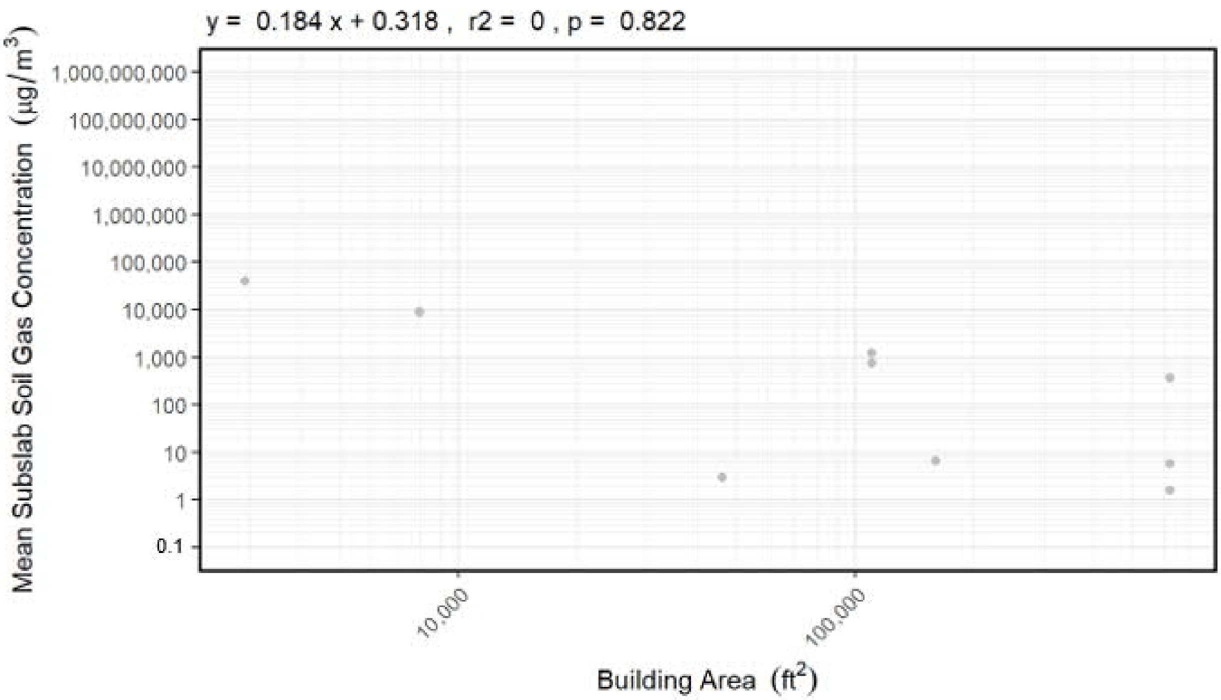


Figure 3-9. VC Subslab Soil Gas Concentration Versus Building Area

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Atypical preferential pathway screen only. In the equation, x represents the log of the building area and y represents the log of the subslab soil gas concentration.

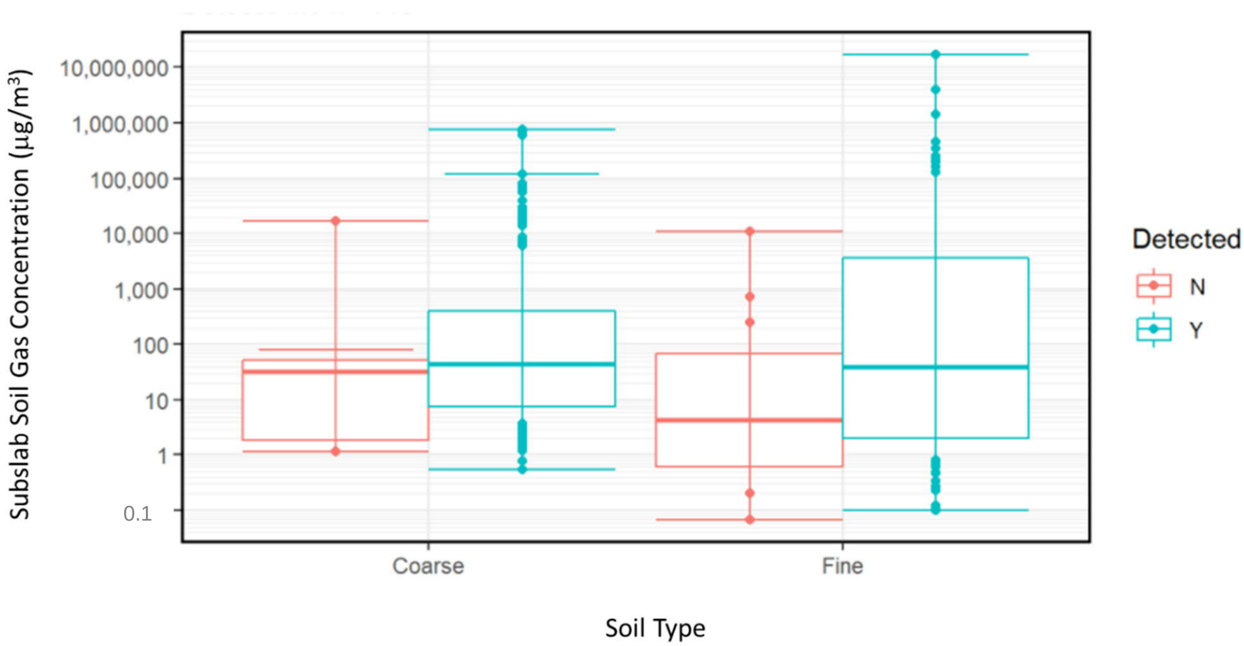


Figure 3-10. PCE Subslab Soil Gas Concentration Versus Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

"Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.

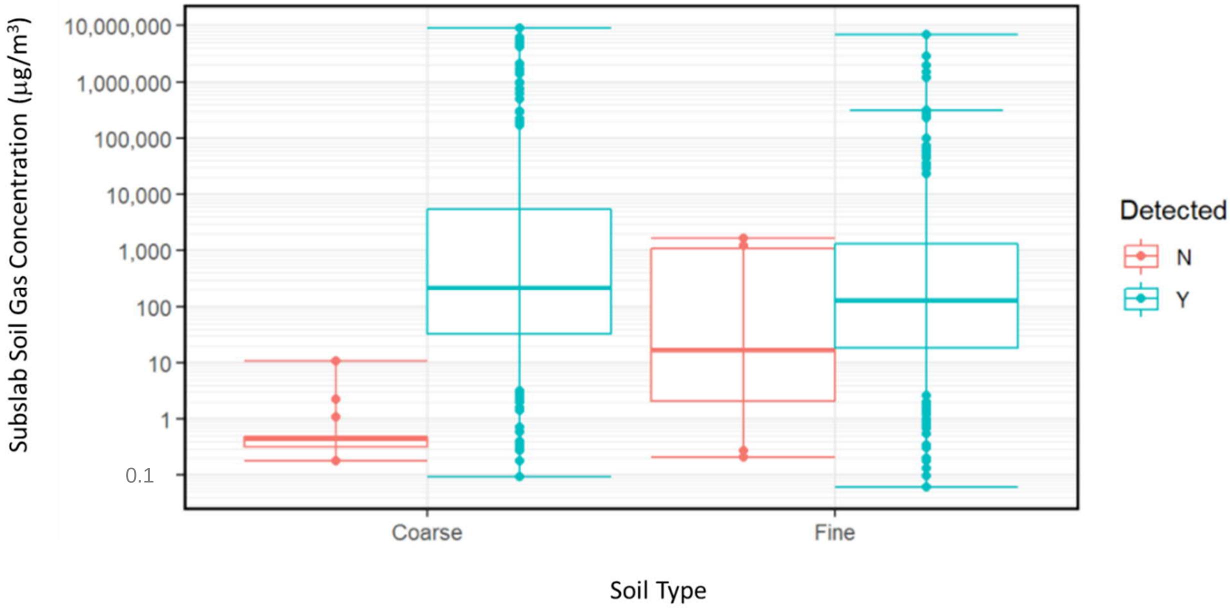


Figure 3-11. TCE Subslab Soil Gas Concentration Versus Soil Type
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.

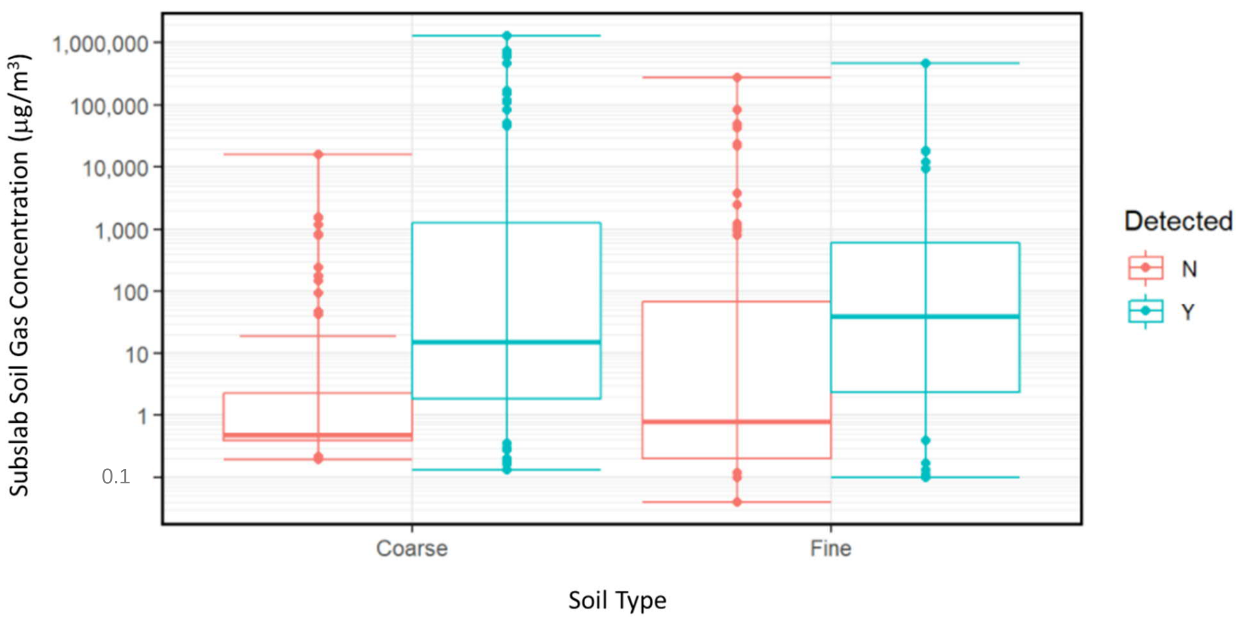


Figure 3-12. cis-1,2-DCE Subslab Soil Gas Concentration Versus Soil Type
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.

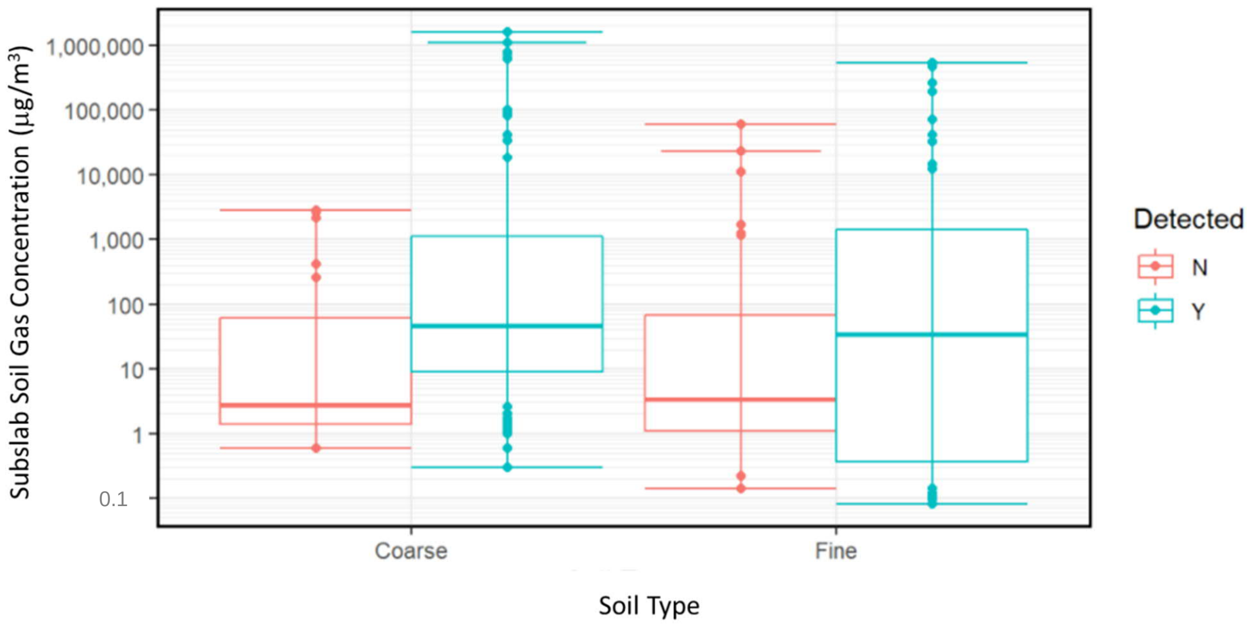


Figure 3-13. 1,1,1-TCA Subslab Soil Gas Concentration Versus Soil Type
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.

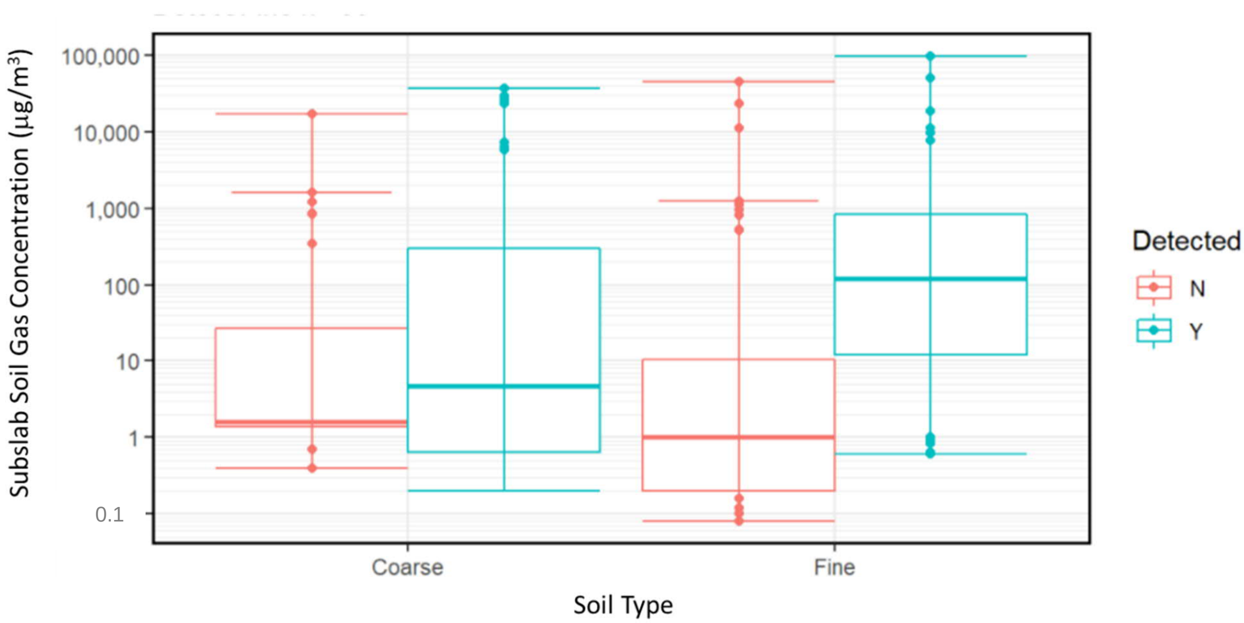


Figure 3-14. 1,1-DCA Subslab Soil Gas Concentration Versus Soil Type
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.

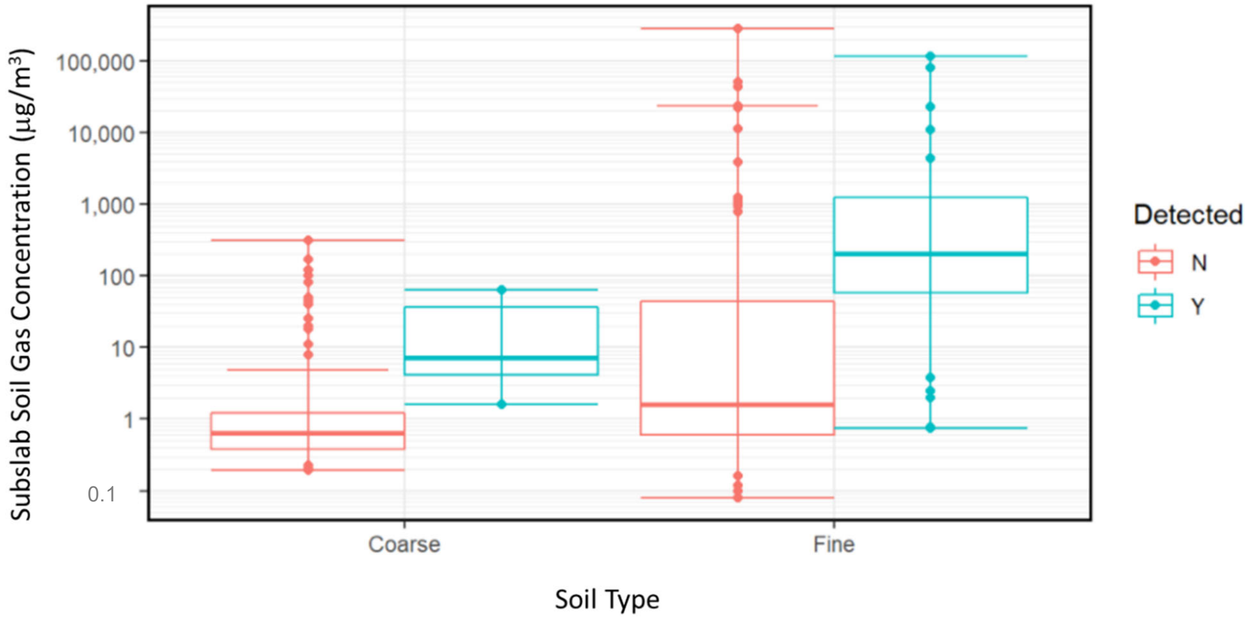


Figure 3-15. 1,1-DCE Subslab Soil Gas Concentration Versus Soil Type
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.

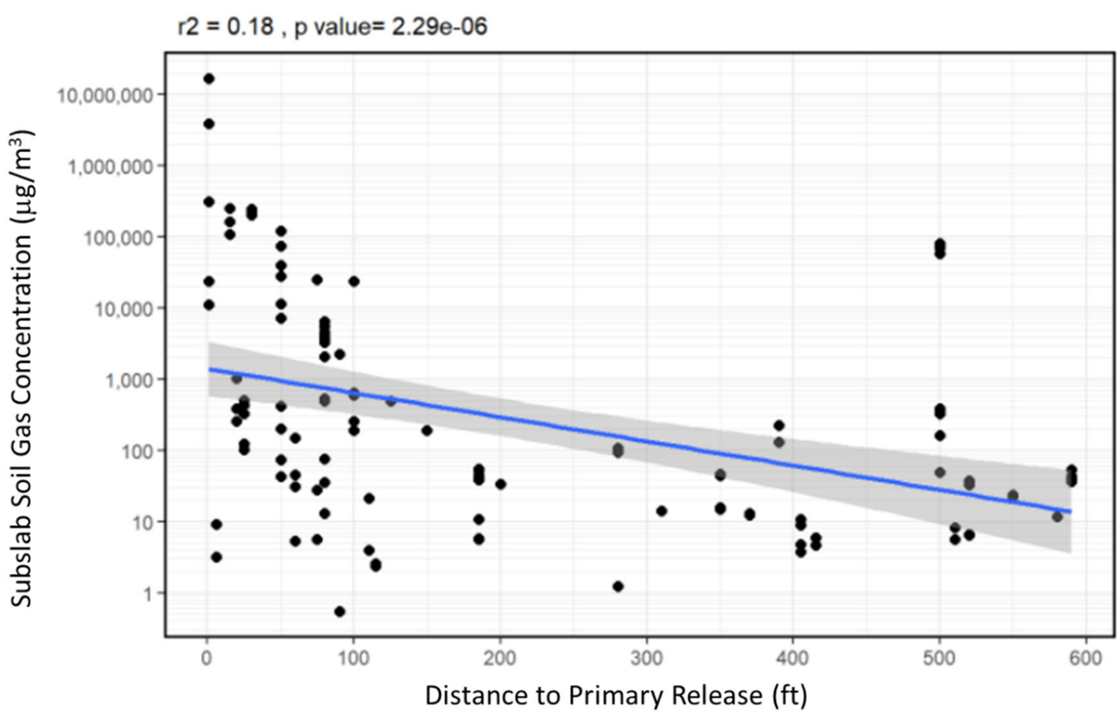


Figure 3-16. PCE Concentration in Subslab Soil Gas Versus Distance to Primary Release, Semi-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Data where an atypical preferential pathway is suspected are not included.

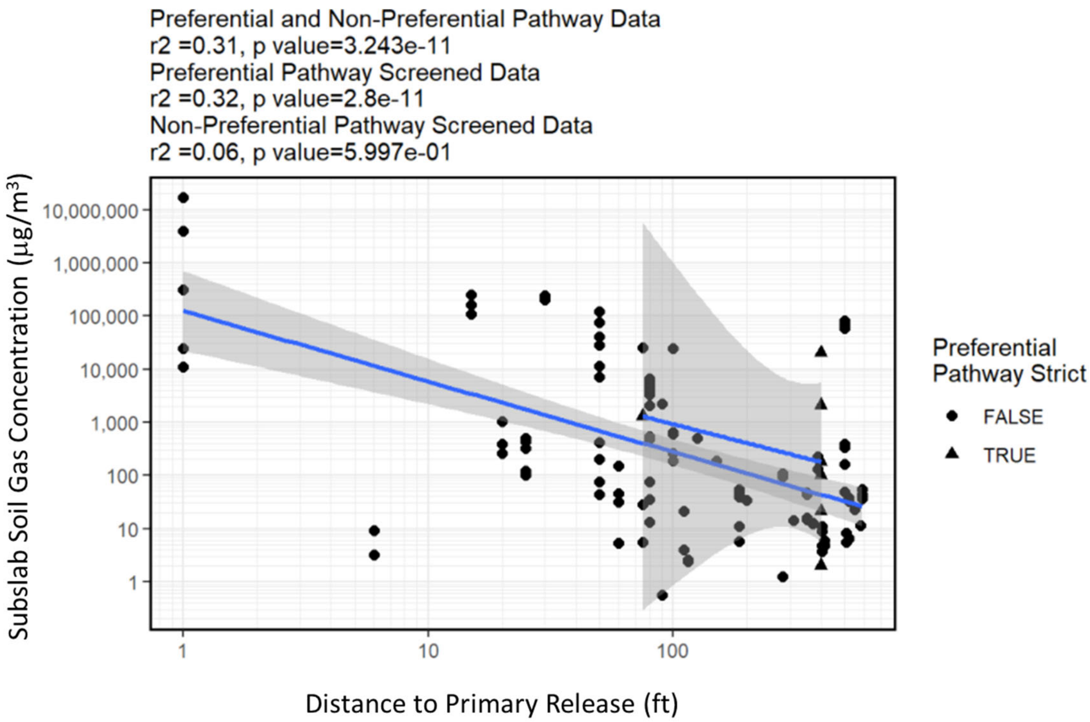


Figure 3-17. PCE Concentration in Subslab Soil Gas Versus Distance to Primary Release, Log-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" refers to data where an atypical ("strict") preferential pathway is not suspected. "True" refers to data where an atypical ("strict") preferential pathway is suspected.

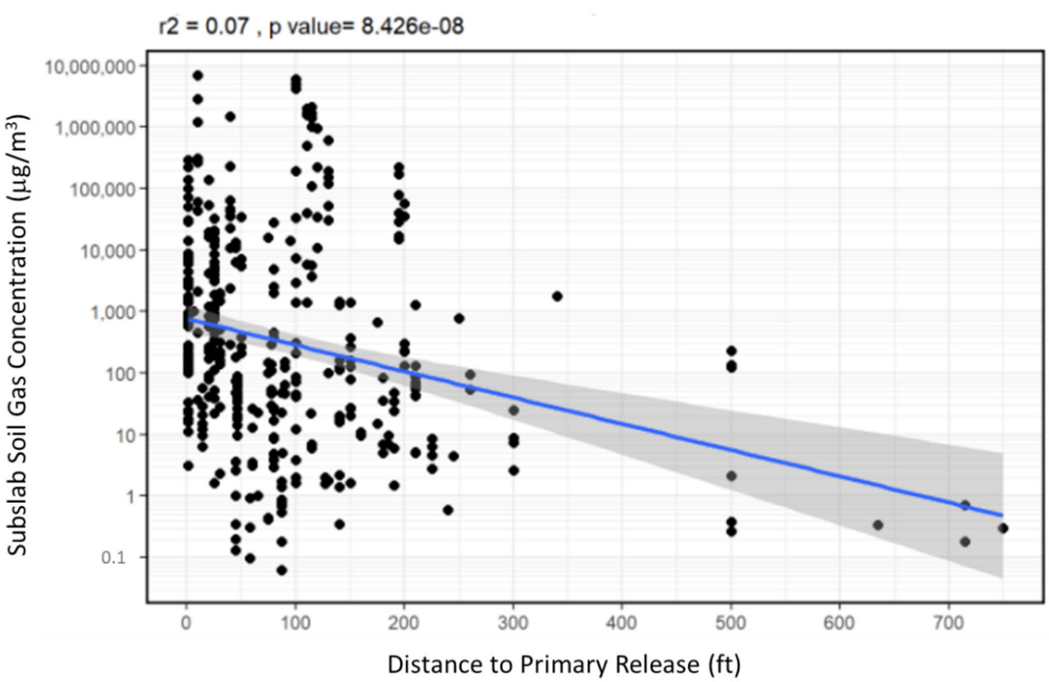


Figure 3-18. TCE Concentration in Subslab Soil Gas Versus Distance to Primary Release, Semi-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Data where an atypical preferential pathway is suspected are not included.

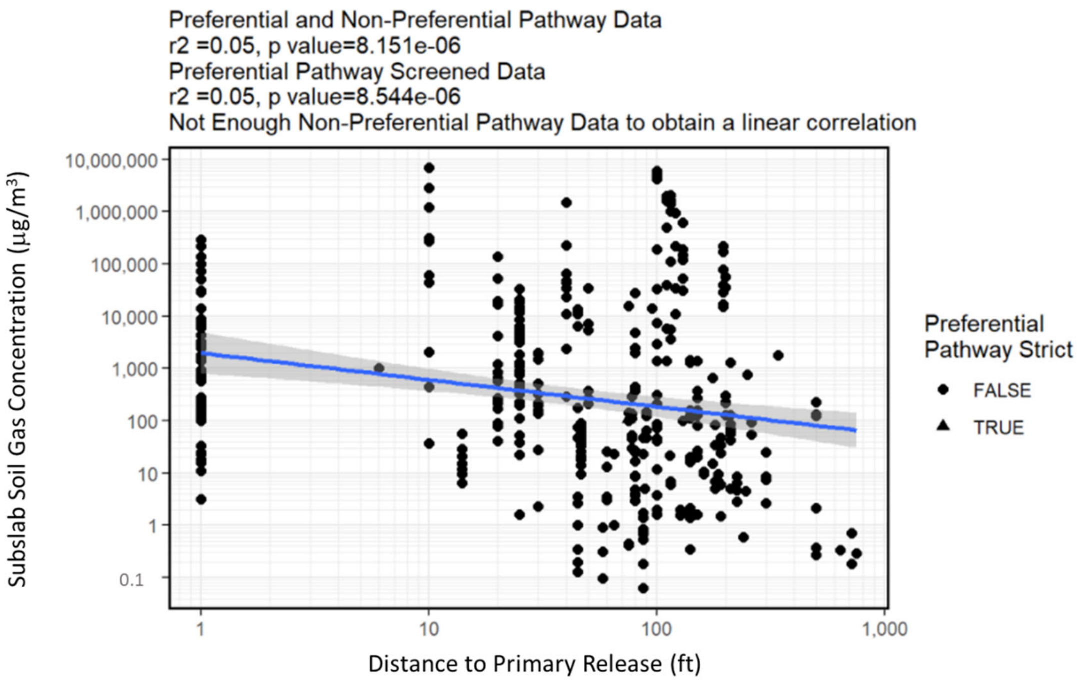


Figure 3-19. TCE Concentration in Subslab Soil Gas vs Distance to Primary Release, Log-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" refers to data where an atypical ("strict") preferential pathway is not suspected. "True" refers to data where an atypical ("strict") preferential pathway is suspected.

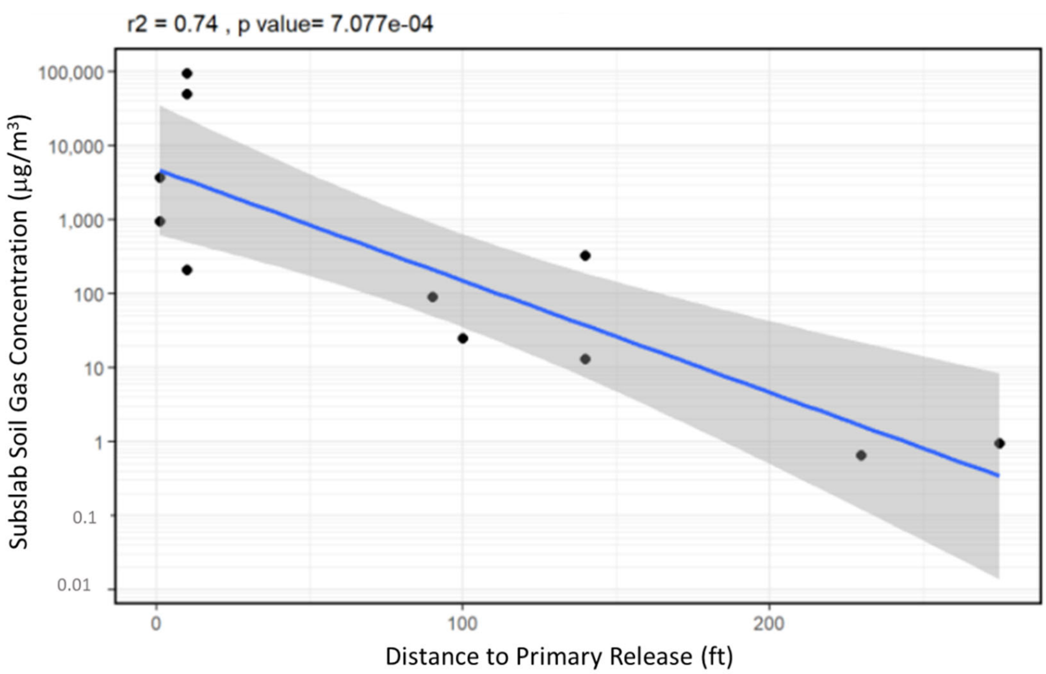


Figure 3-20. 1,1-DCA Subslab Soil Gas Concentration Versus Distance to Primary Release, Semi-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Data where an atypical preferential pathway is suspected are not included.

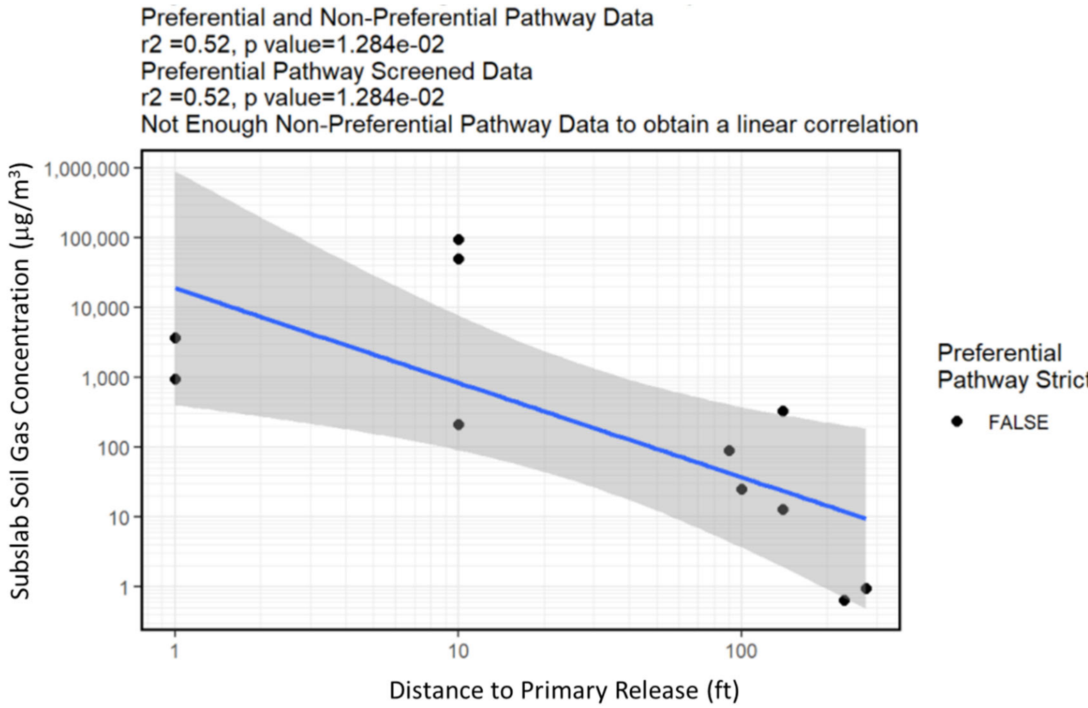


Figure 3-21. 1,1-DCA Subslab Soil Gas Concentration Versus Distance to Primary Release, Log-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" refers to data where an atypical ("strict") preferential pathway is not suspected (there are no data where an atypical preferential pathway is suspected).

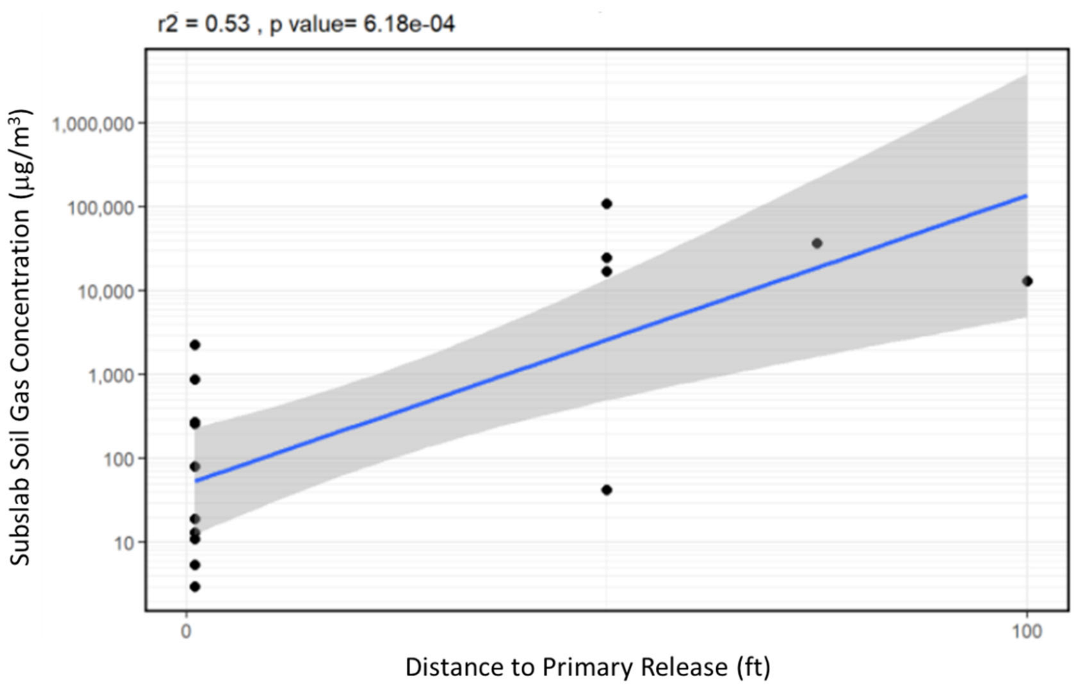


Figure 3-22. trans-1,2-DCE Subslab Soil Gas Concentration Versus Distance to Primary Release, Semi-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Data where an atypical preferential pathway is suspected are not included.

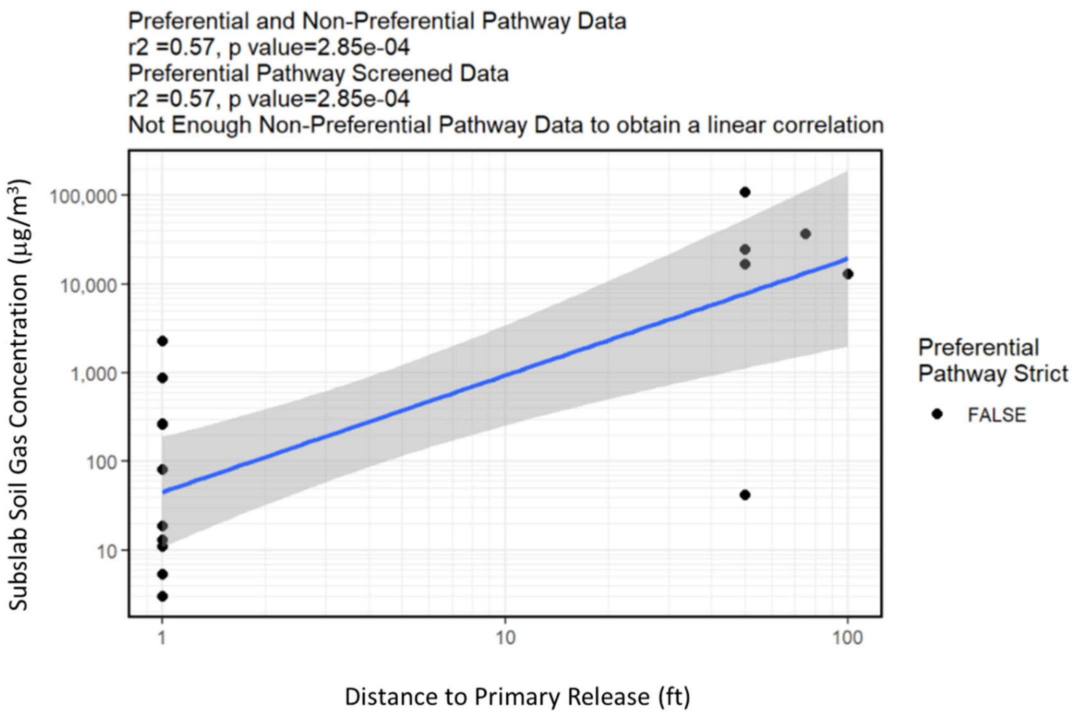


Figure 3-23. trans-1,2-DCE Subslab Soil Gas Concentration Versus distance to Primary Release, Log-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" refers to data where an atypical ("strict") preferential pathway is not suspected (there are no data where an atypical preferential pathway is suspected).

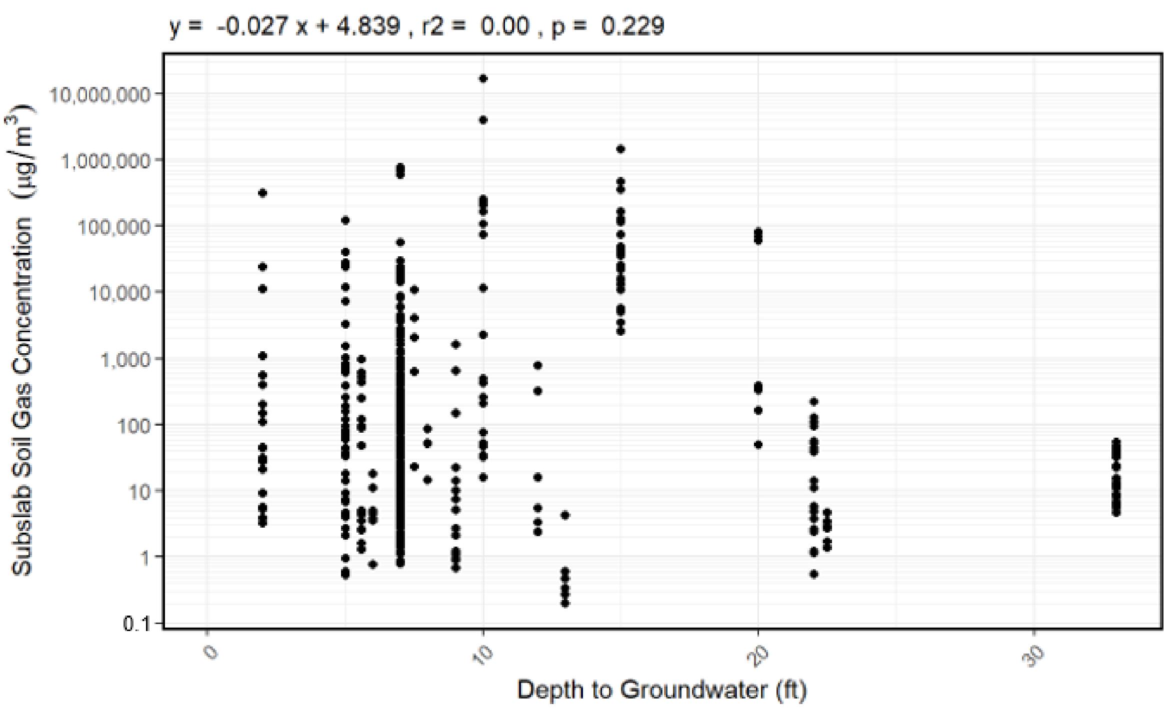


Figure 3-24. PCE Concentration in Subslab Soil Gas as a Function of Depth to Groundwater
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Data where an atypical preferential pathway is suspected are not included. In the equation, x represents the depth to groundwater and y represents the log of the subslab soil gas concentration.

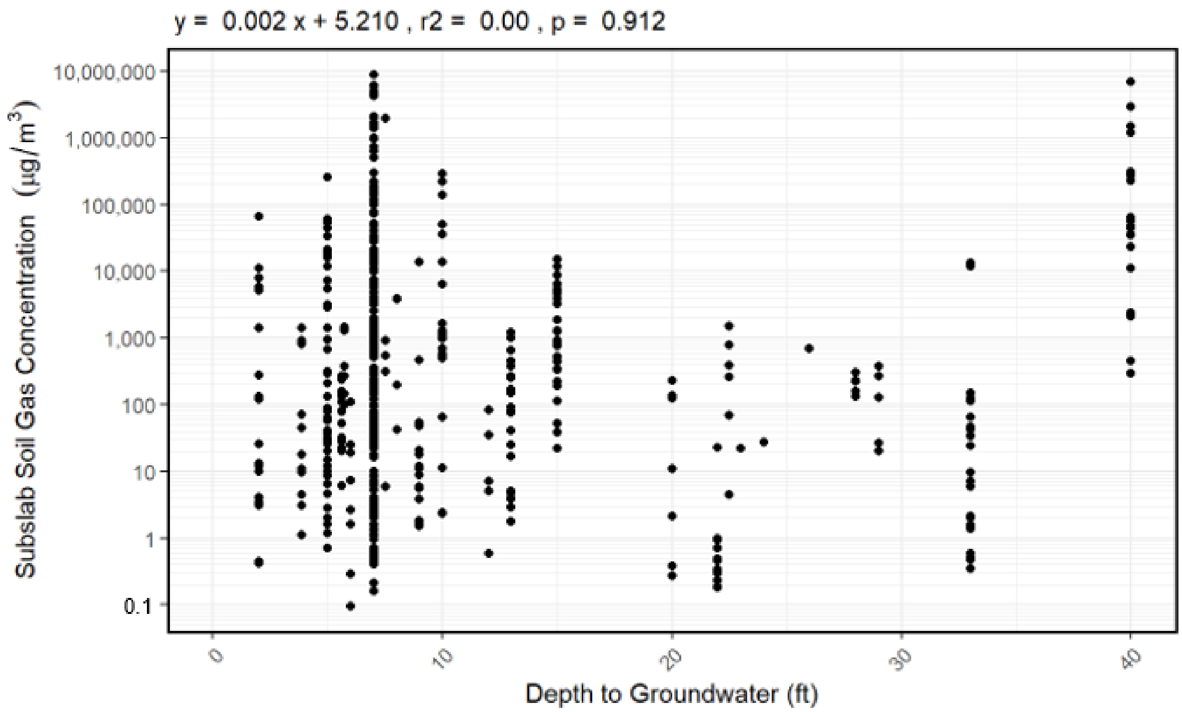


Figure 3-25. TCE Concentration in Subslab Soil Gas as a Function of Depth to Groundwater
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Data where an atypical preferential pathway is suspected are not included. In the equation, x represents the depth to groundwater and y represents the log of the subslab soil gas concentration.

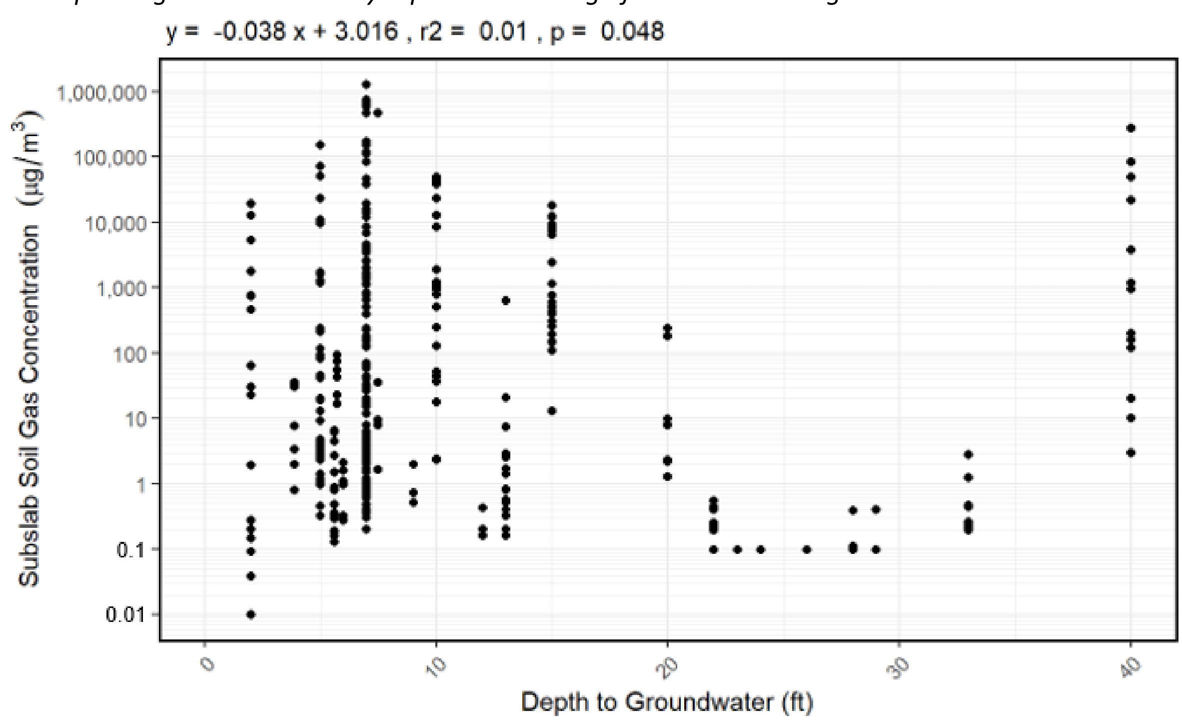


Figure 3-26. cis-1,2-DCE Concentration in Subslab Soil Gas as a Function of Depth to Groundwater
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Data where an atypical preferential pathway is suspected are not included. In the equation, x represents the depth to groundwater and y represents the log of the subslab soil gas concentration.

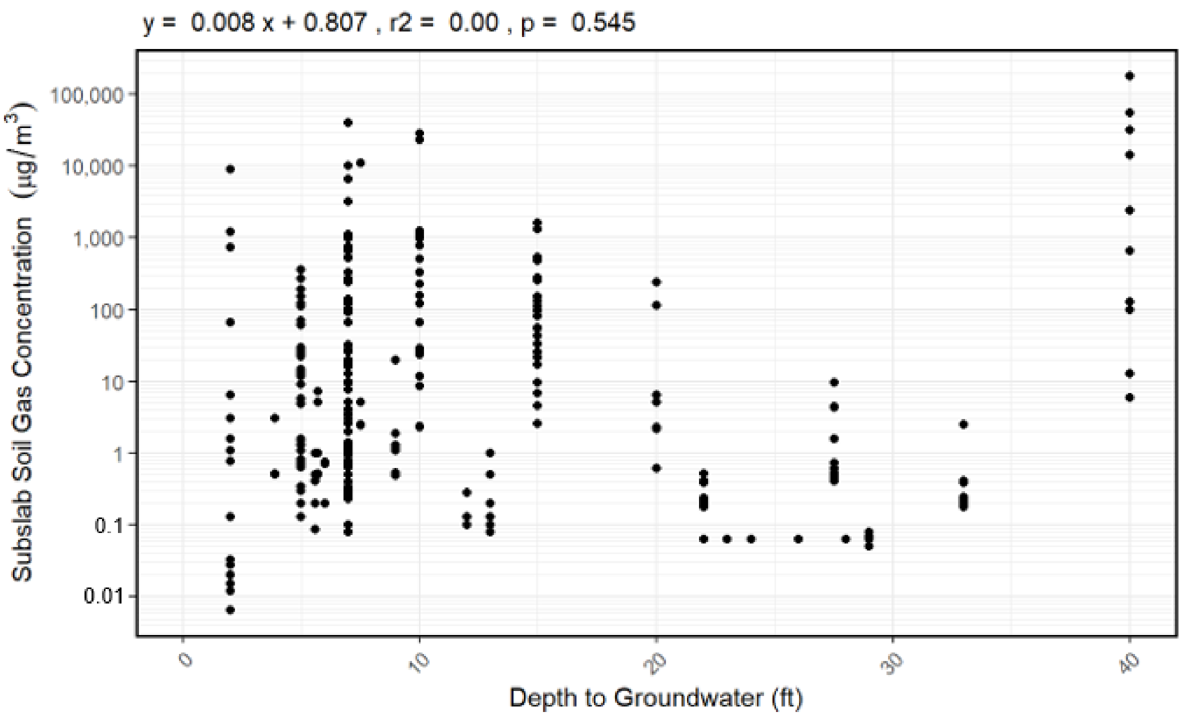


Figure 3-27. VC Concentration in Subslab Soil Gas as a Function of Depth to Groundwater
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Data where an atypical preferential pathway is suspected are not included. In the equation, x represents the depth to groundwater and y represents the log of the subslab soil gas concentration.

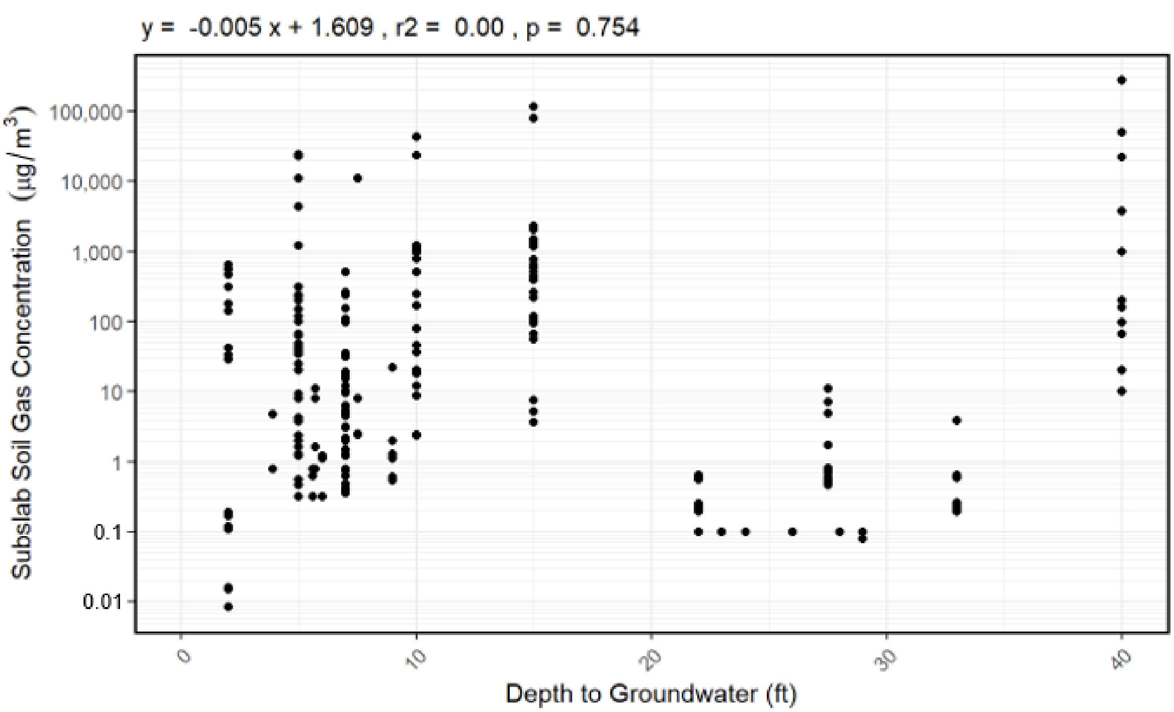


Figure 3-28. 1,1-DCE Concentration in Subslab Soil Gas as a Function of Depth to Groundwater
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Data where an atypical preferential pathway is suspected are not included. In the equation, x represents the depth to groundwater and y represents the log of the subslab soil gas concentration.

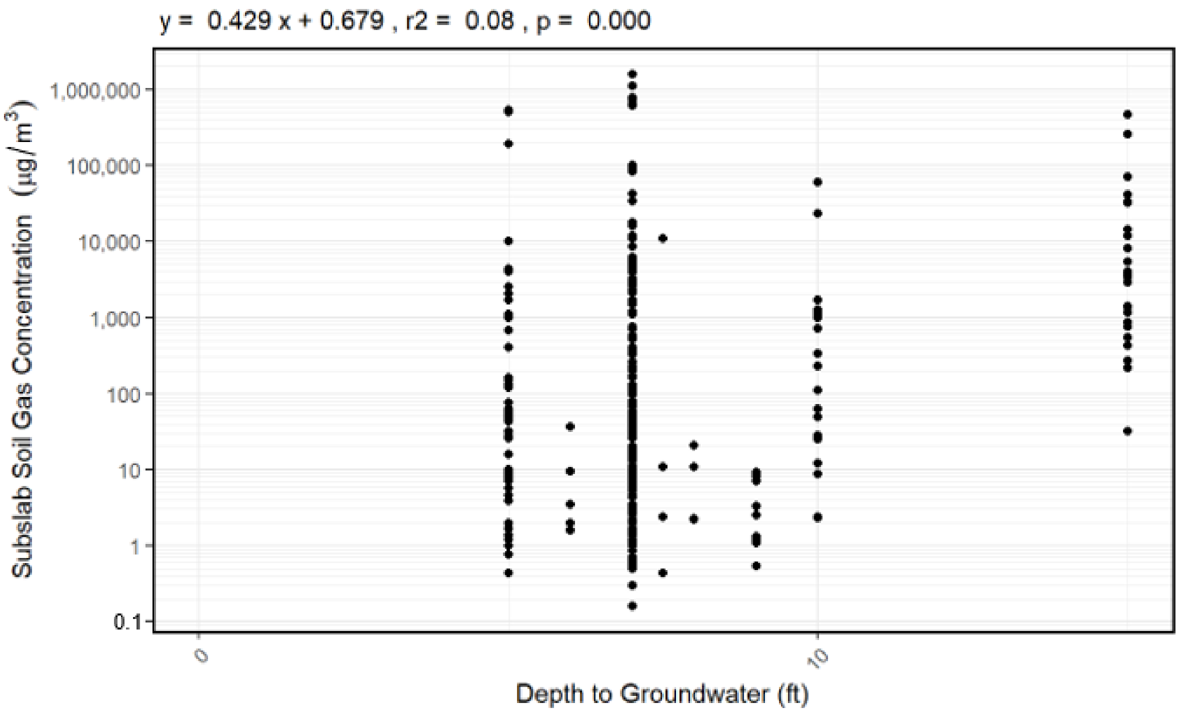


Figure 3-29. 1,1,1-TCA Concentration in Subslab Soil Gas as a Function of Depth to Groundwater
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Data where an atypical preferential pathway is suspected are not included. In the equation, x represents the depth to groundwater and y represents the log of the subslab soil gas concentration.

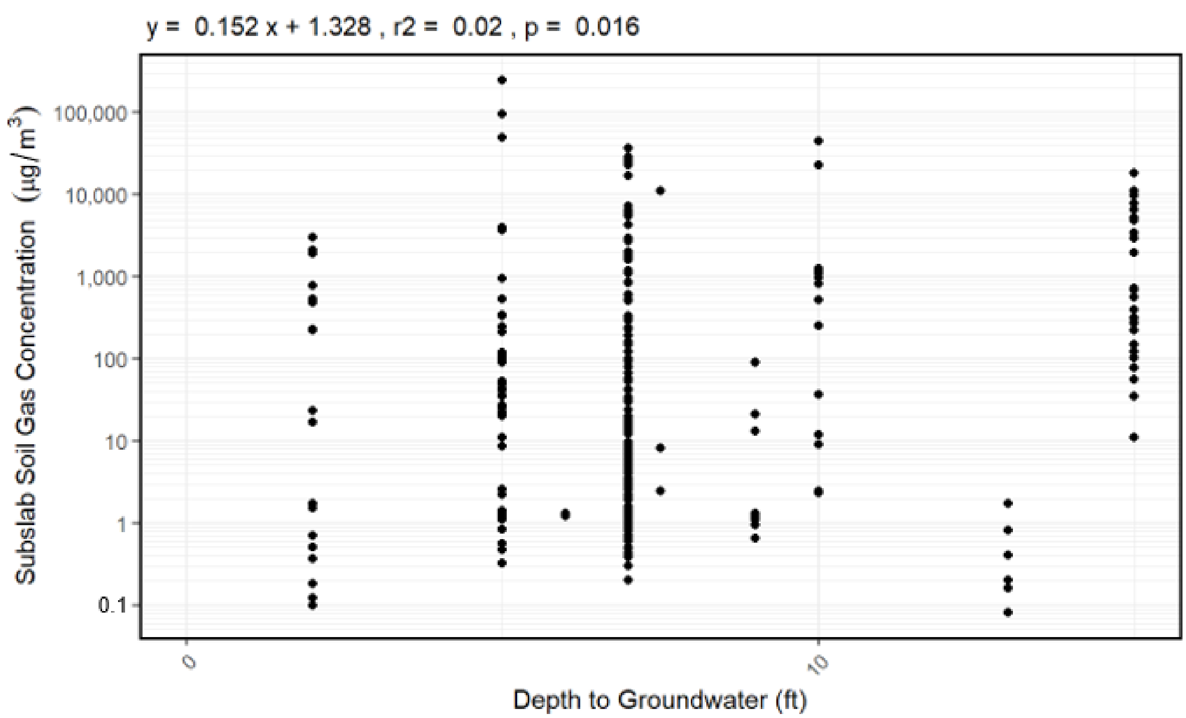


Figure 3-30. 1,1-DCA Concentration in Subslab Soil Gas as a Function of Depth to Groundwater
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Data where an atypical preferential pathway is suspected are not included. In the equation, x represents the depth to groundwater and y represents the log of the subslab soil gas concentration.

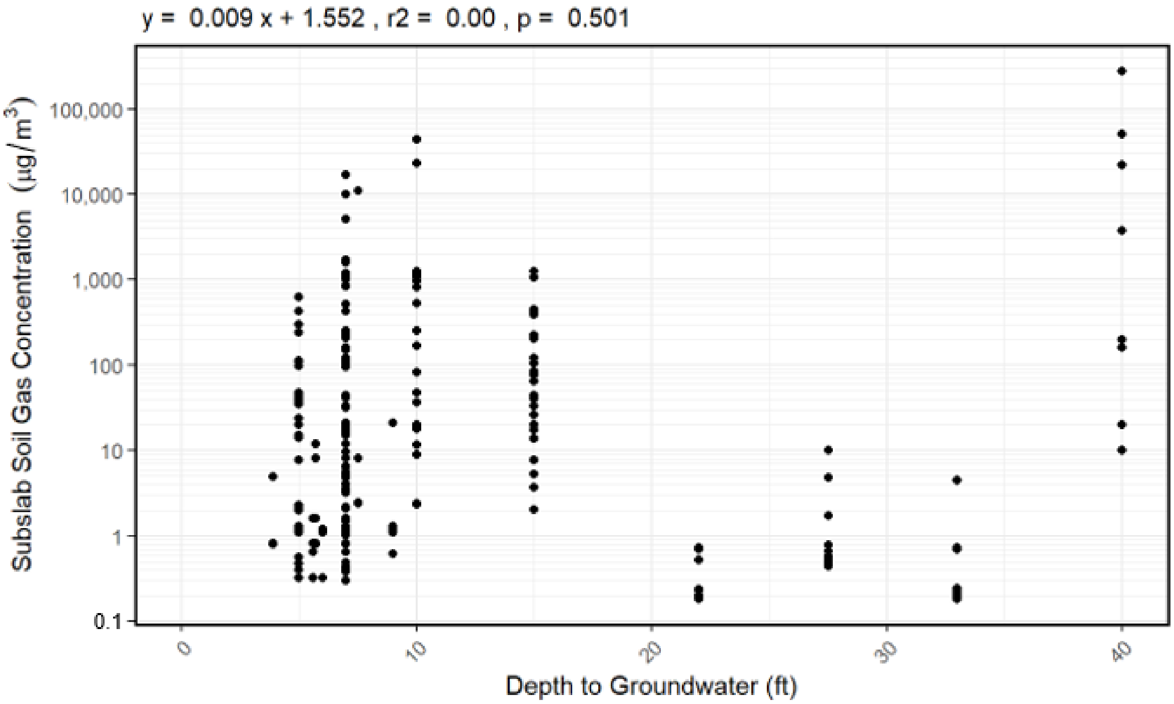


Figure 3-31. 1,2-DCA Concentration in Subslab Soil Gas as a Function of Depth to Groundwater
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Data where an atypical preferential pathway is suspected are not included. In the equation, x represents the depth to groundwater and y represents the log of the subslab soil gas concentration.

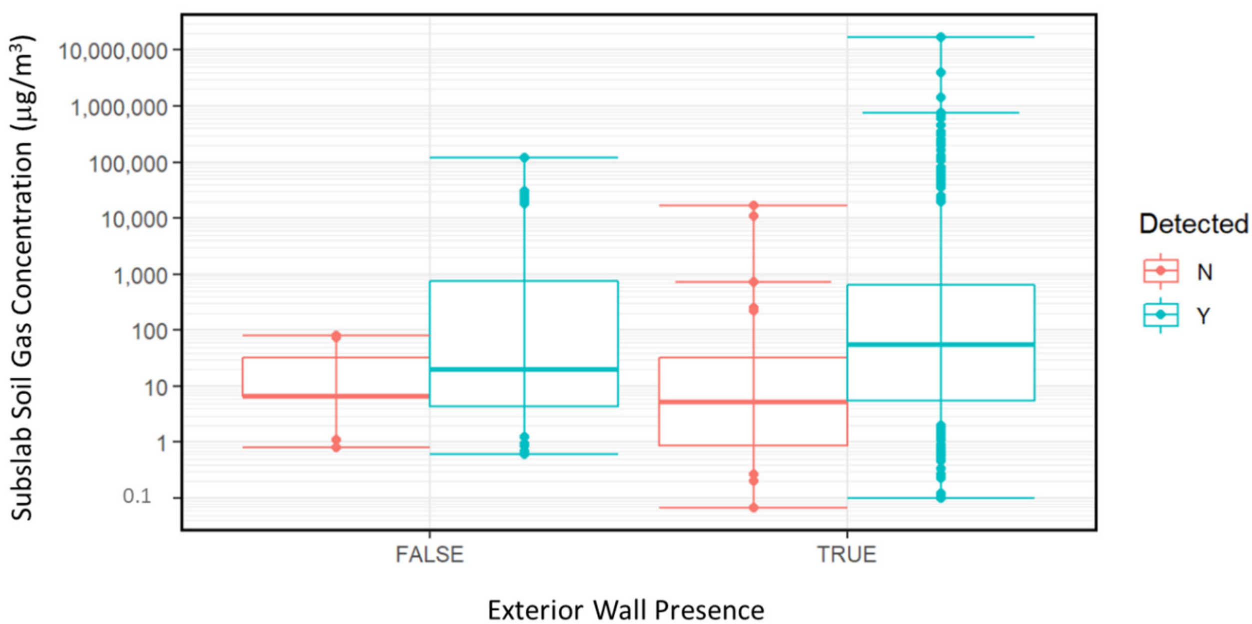


Figure 3-32. PCE Subslab Soil Gas Concentration Versus Exterior Wall Presence
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.

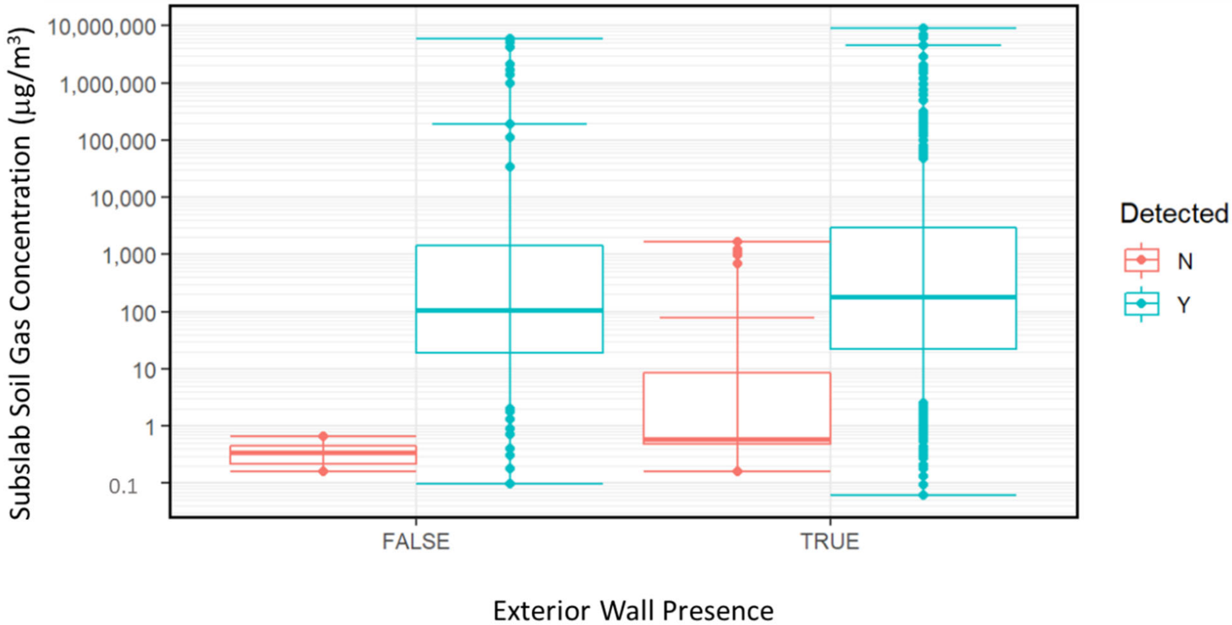


Figure 3-33. TCE Subslab Soil Gas Concentration Versus Exterior Wall Presence
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.

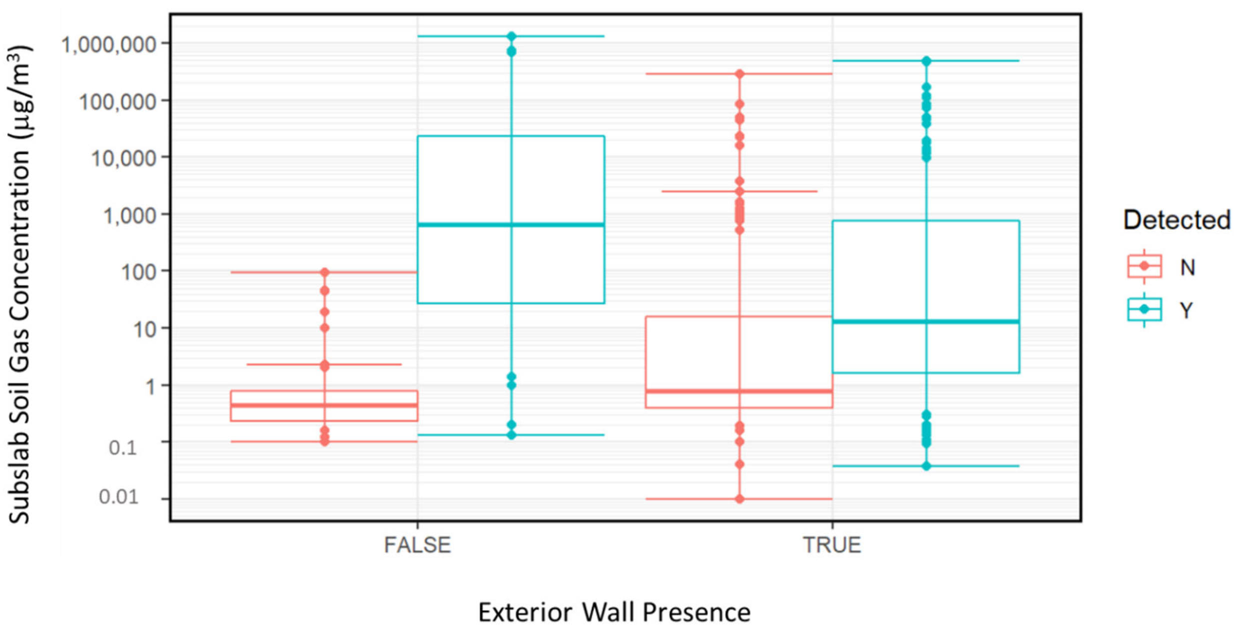


Figure 3-34. cis-1,2-DCE Subslab Soil Gas Concentration Versus Exterior Wall Presence
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.

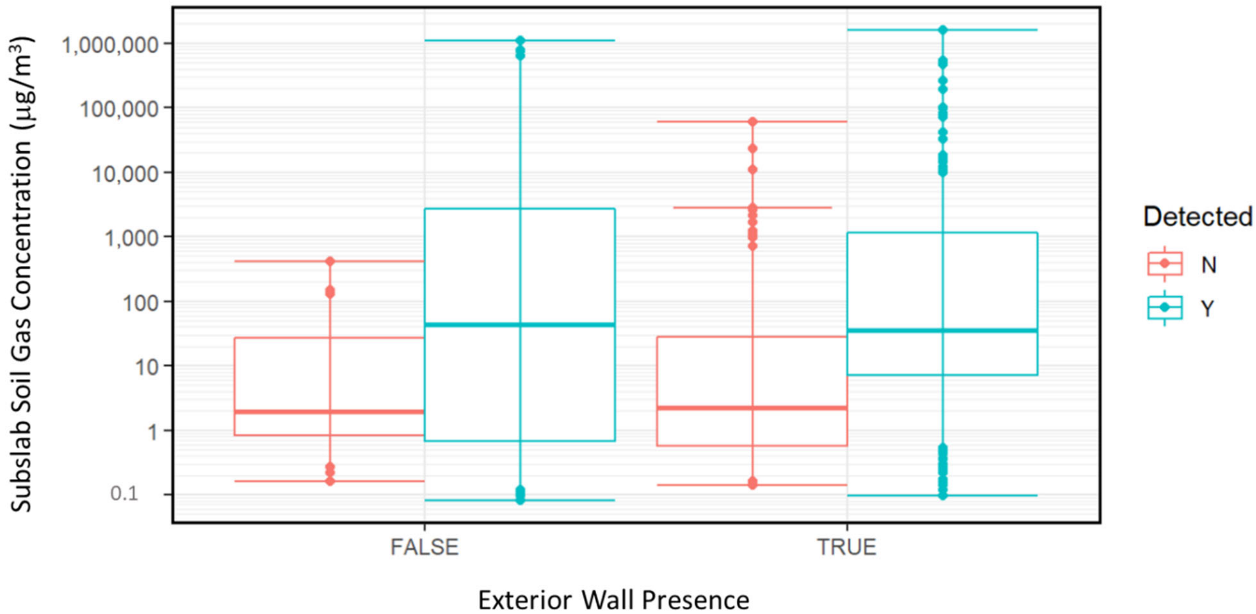


Figure 3-35. 1,1,1-TCA Subslab Soil Gas Concentration Versus Exterior Wall Presence
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.

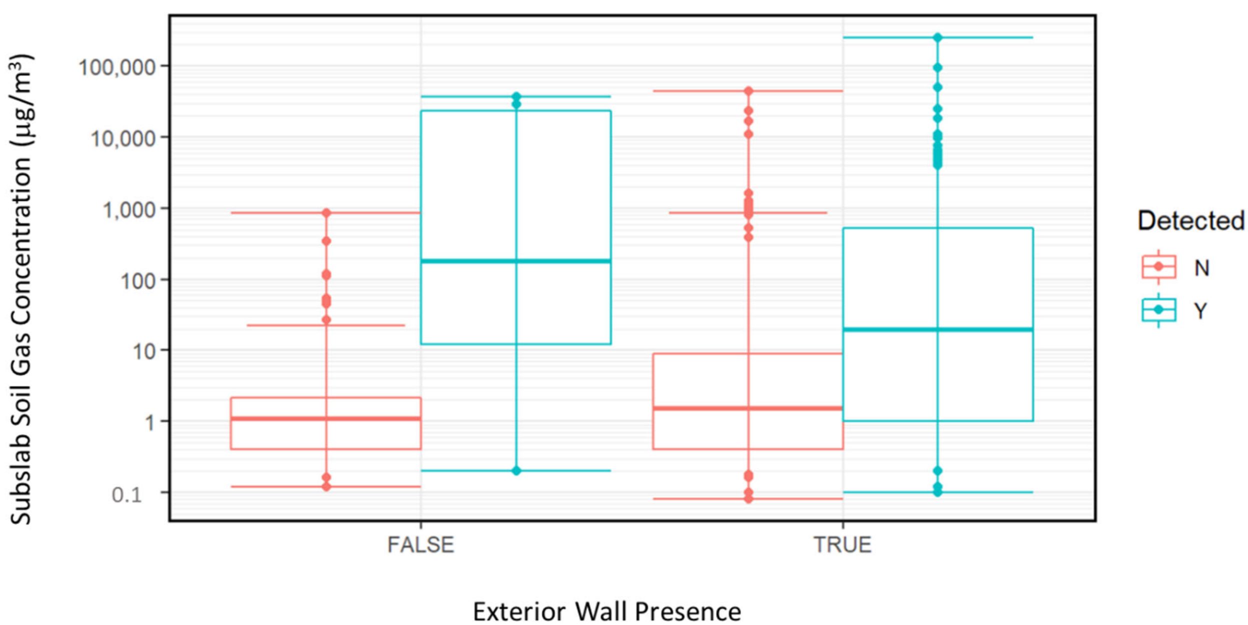


Figure 3-36. 1,1-DCA Subslab Soil Gas Concentration Versus Exterior Wall Presence
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.

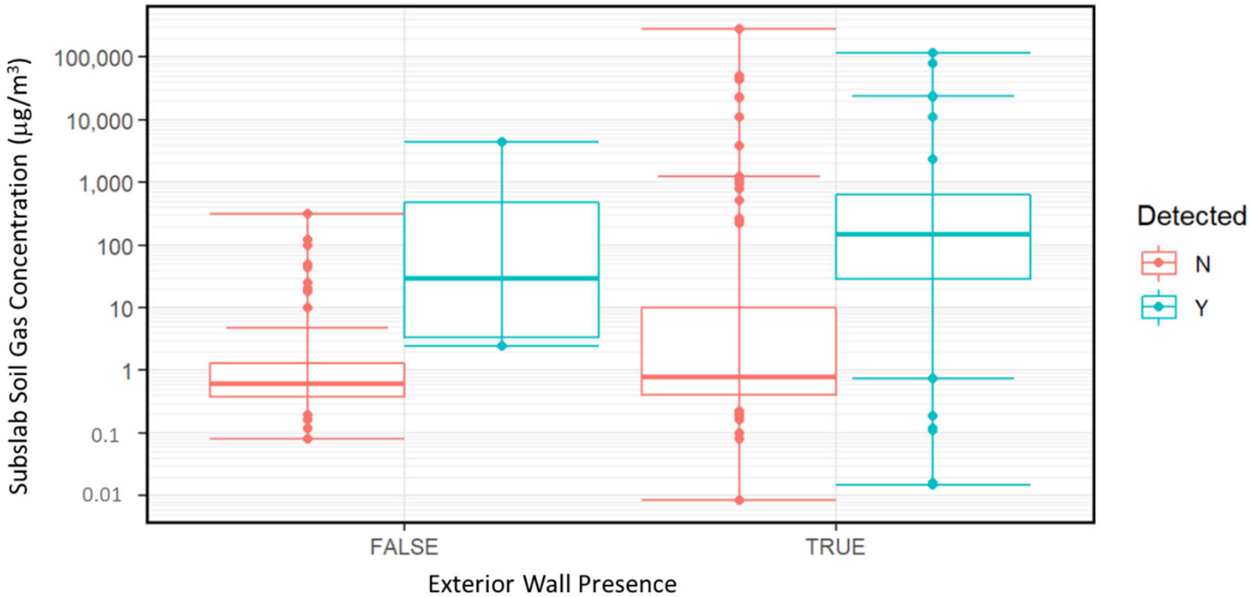


Figure 3-37. 1,1-DCE Subslab Soil Gas Concentration Versus Exterior Wall Presence
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.

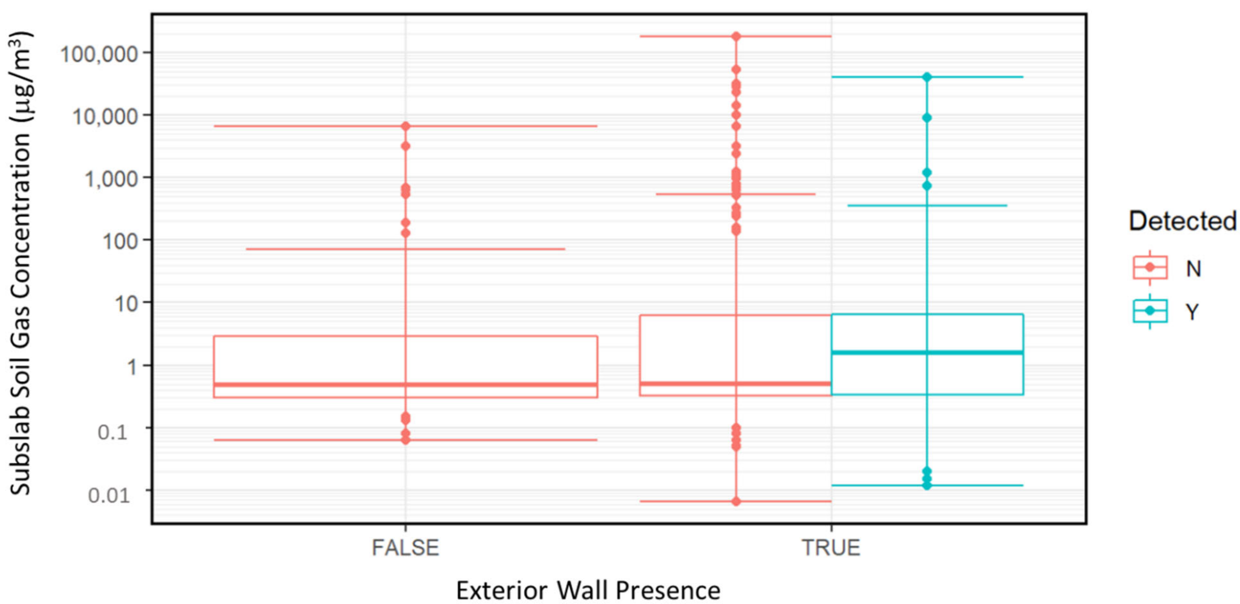
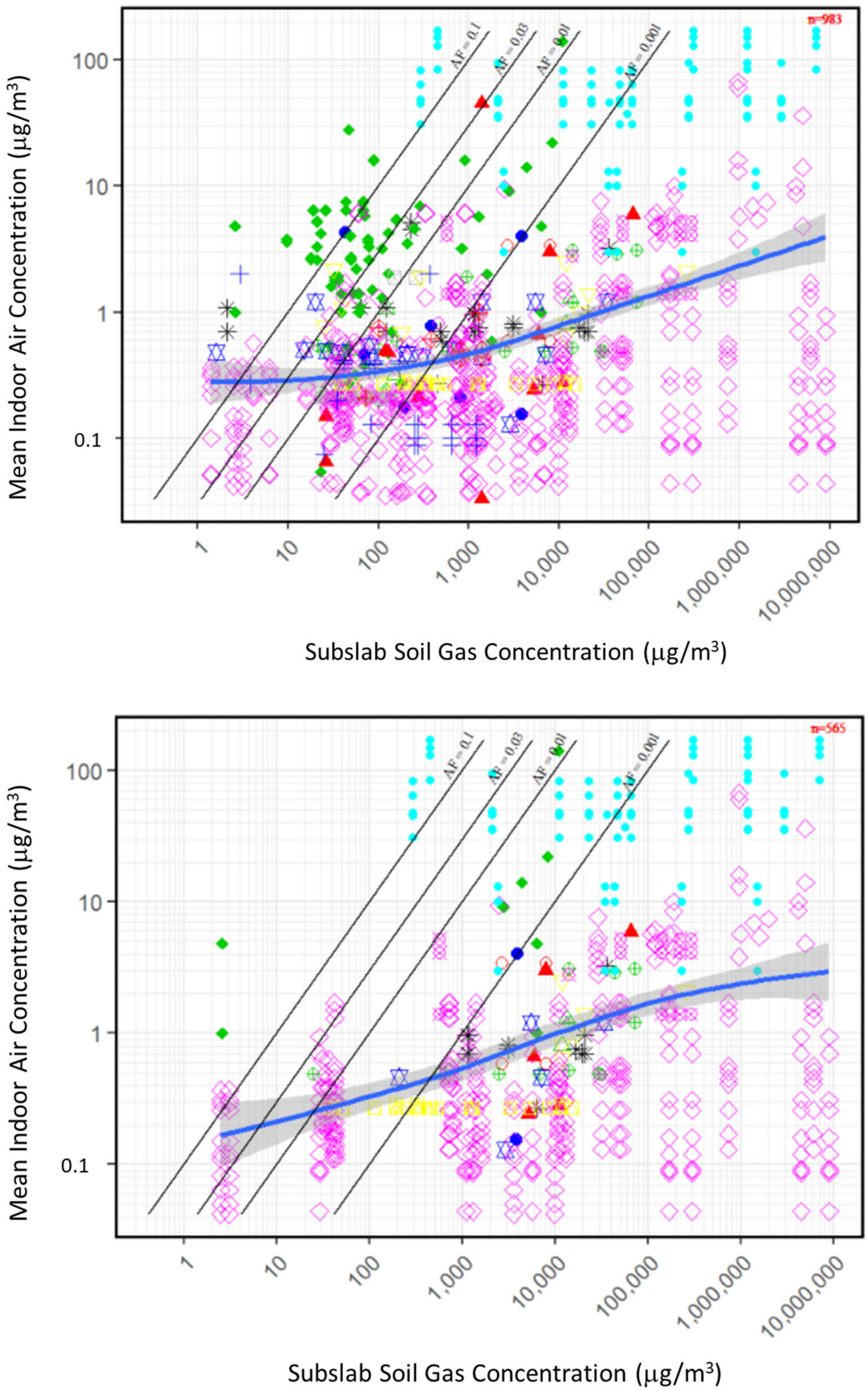


Figure 3-38. VC Subslab Soil Gas Concentration Versus Exterior Wall Presence
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to subslab soil gas detects and non-detects (taken at the detection limit), respectively.



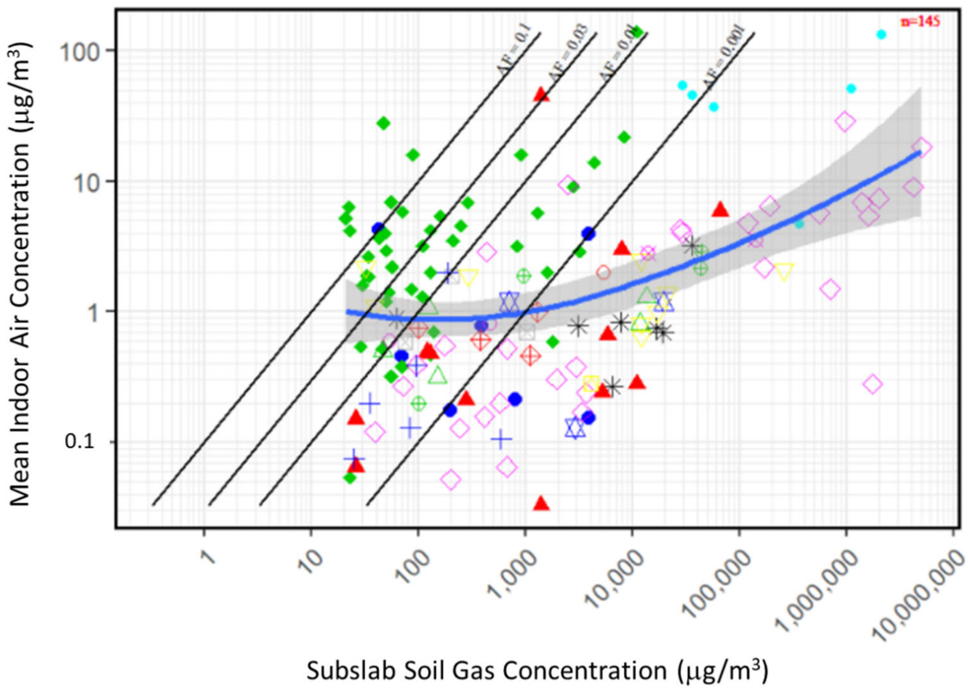
(a)

(b)

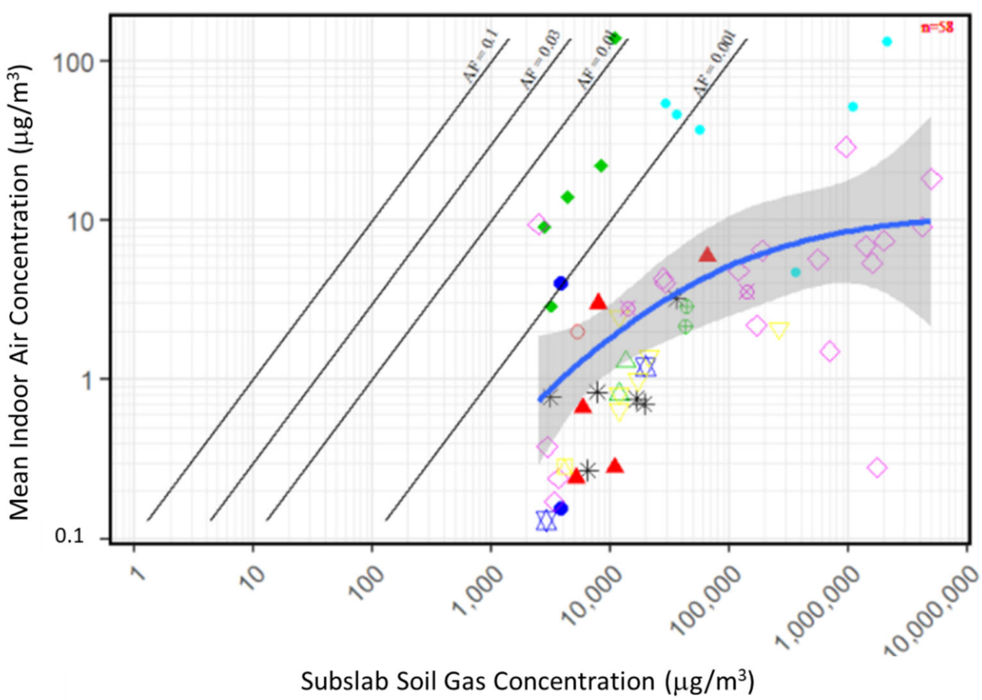
Figure 4-1. Examples of Paired Subslab Soil Gas-Indoor Air Concentration Plots for TCE Showing All Individual Data Pairs Passing the (a) 10X and (b) 1,000X Background Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Different symbols correspond to data from different DoD installations.



(a)

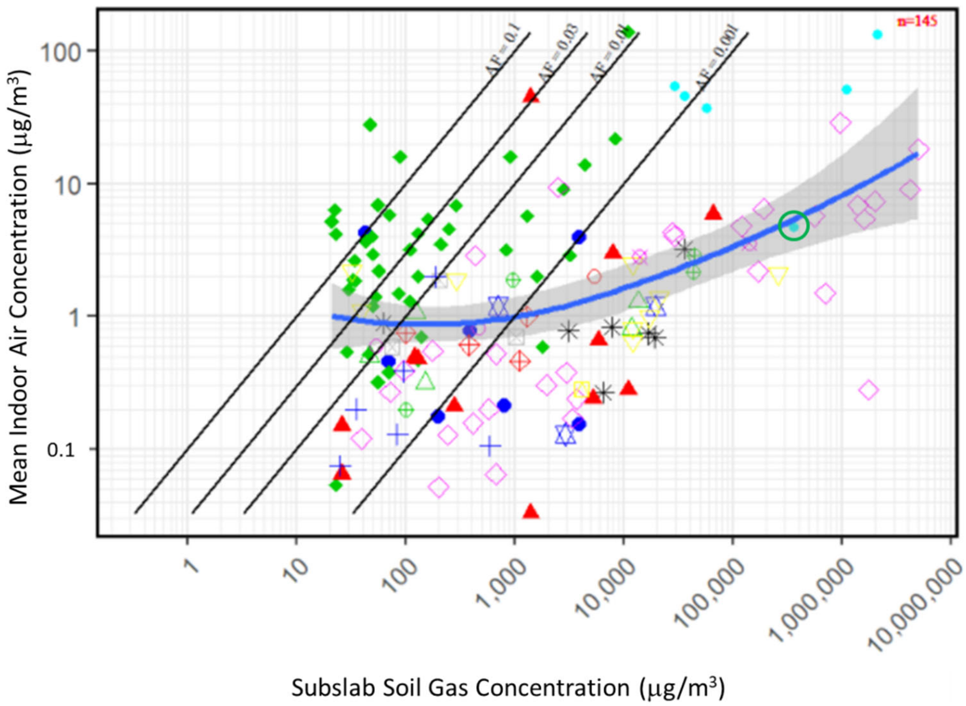


(b)

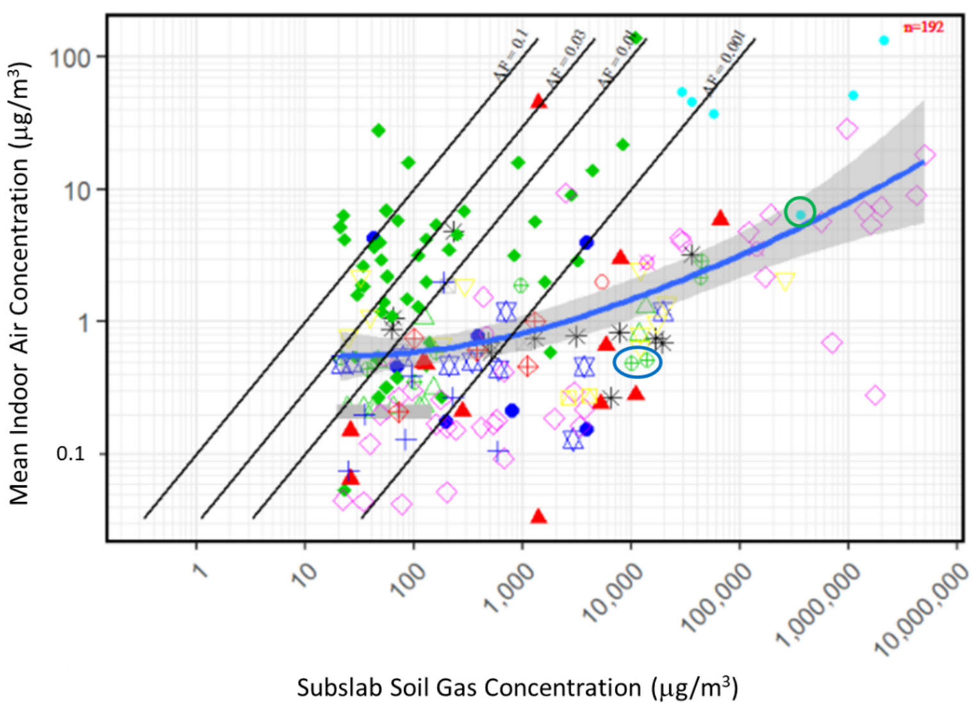
Figure 4-2. Examples of Paired Subslab Soil Gas-Indoor Air Concentration Plots for TCE with Each Data Pair Corresponding to a Building Sample Zone Average for a Given Sampling Event Passing the (a) 10X and (b) 1,000X Background Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.



(a)

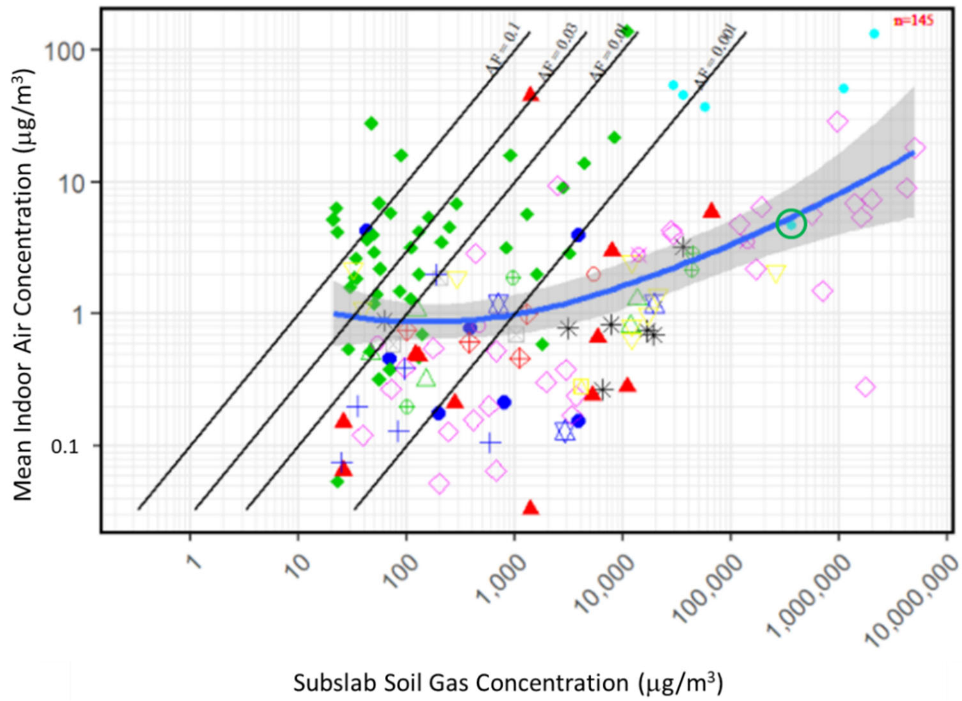


(b)

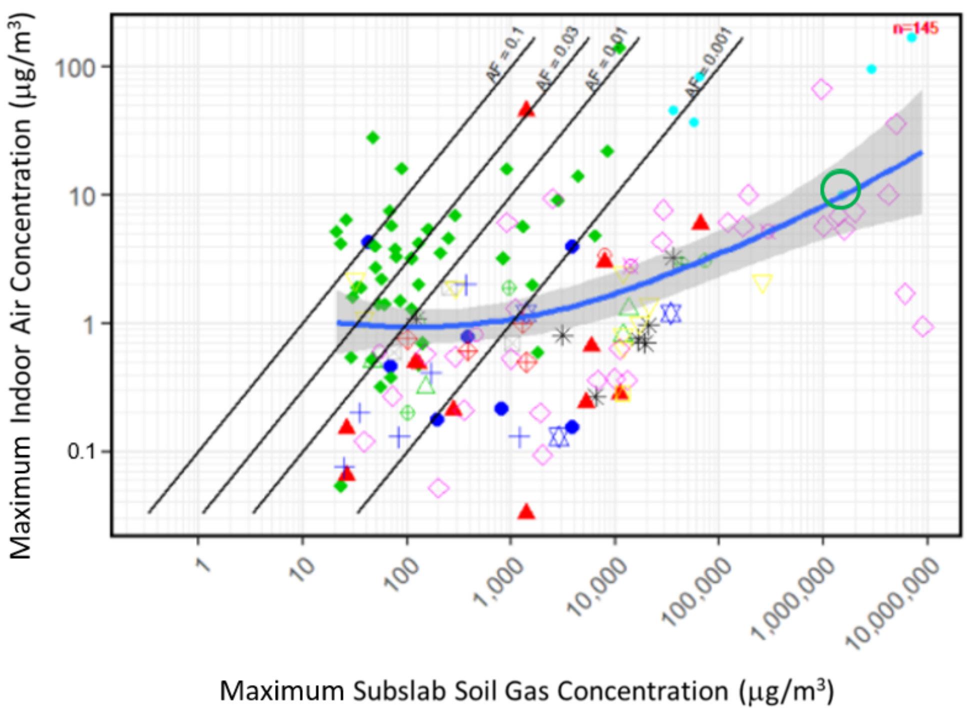
Figure 4-3. Examples of Paired Subslab Soil Gas-Indoor Air Concentration Plots for TCE with Each Data Pair Corresponding to a Building Sample Zone Average for a Given Sampling Event Passing the 10X Background Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between plots that include (a) only detectable concentrations in indoor air (i.e., indoor air non-detects excluded) and (b) non-detects in indoor air plotted at detection limit. Different symbols correspond to data from different DoD installations. Refer to Section 4.1.1.3 for additional discussion regarding the points circled in blue and in green.

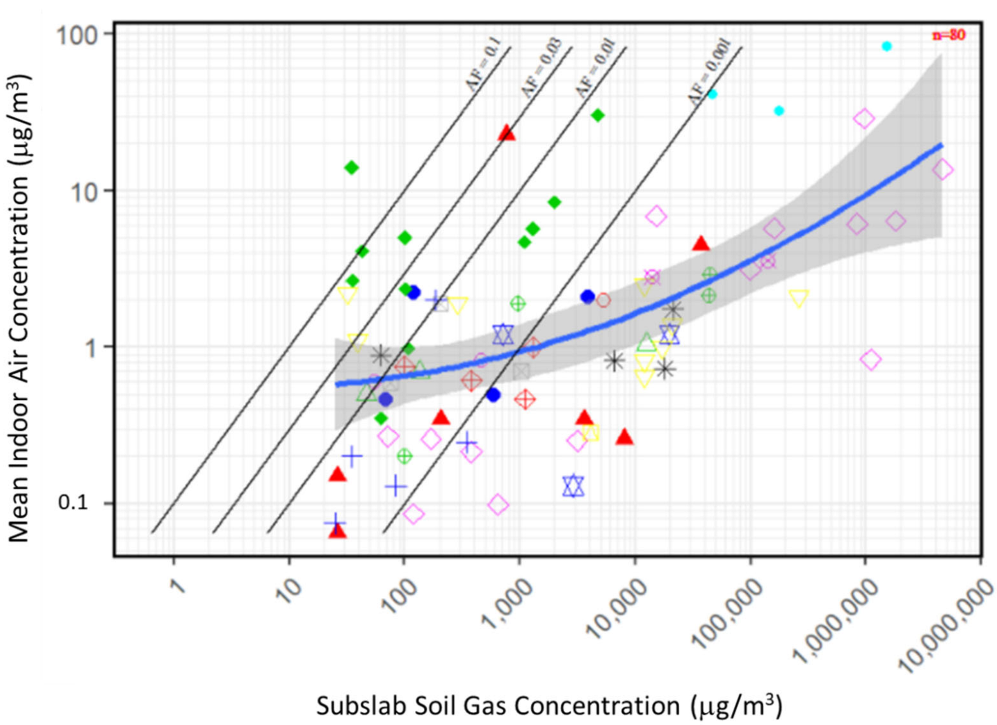


(a)

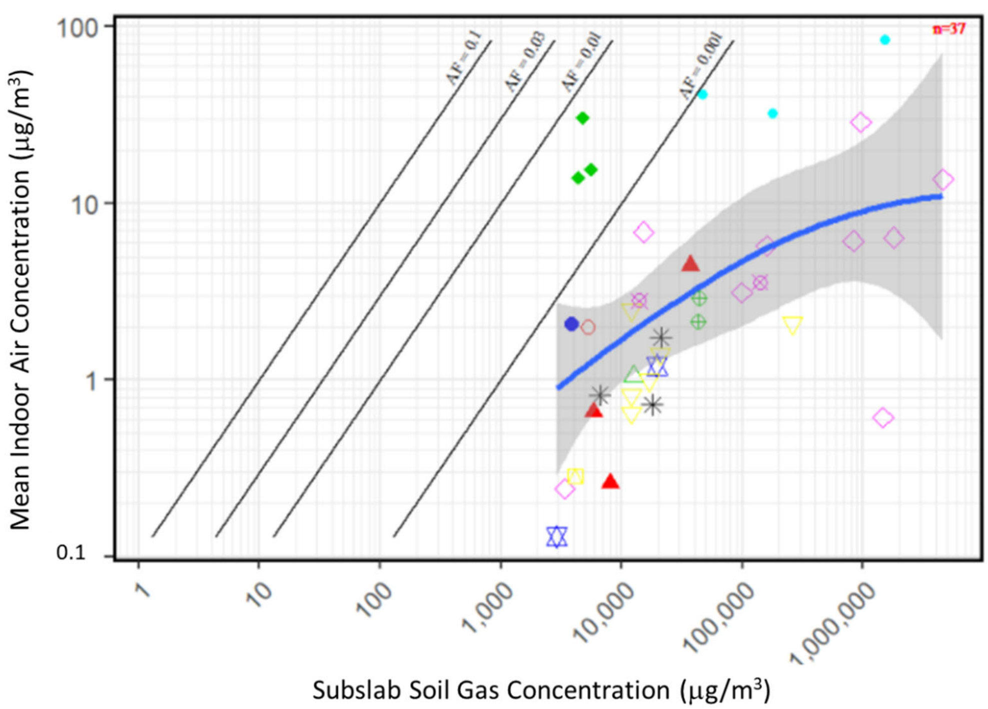


(b)

Figure 4-4. Examples of Paired Subslab-Indoor Air Concentration Plots for TCE with Each Data Pair Corresponding to a Building Sample Zone Average for a Given Sampling Event Passing the 10X Background Source Strength Screen
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Comparison between plots that use (a) average and (b) maximum subslab soil gas and indoor air concentrations. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations. Refer to Section 4.1.1.4 for additional discussion regarding the points circled in green.



(a)

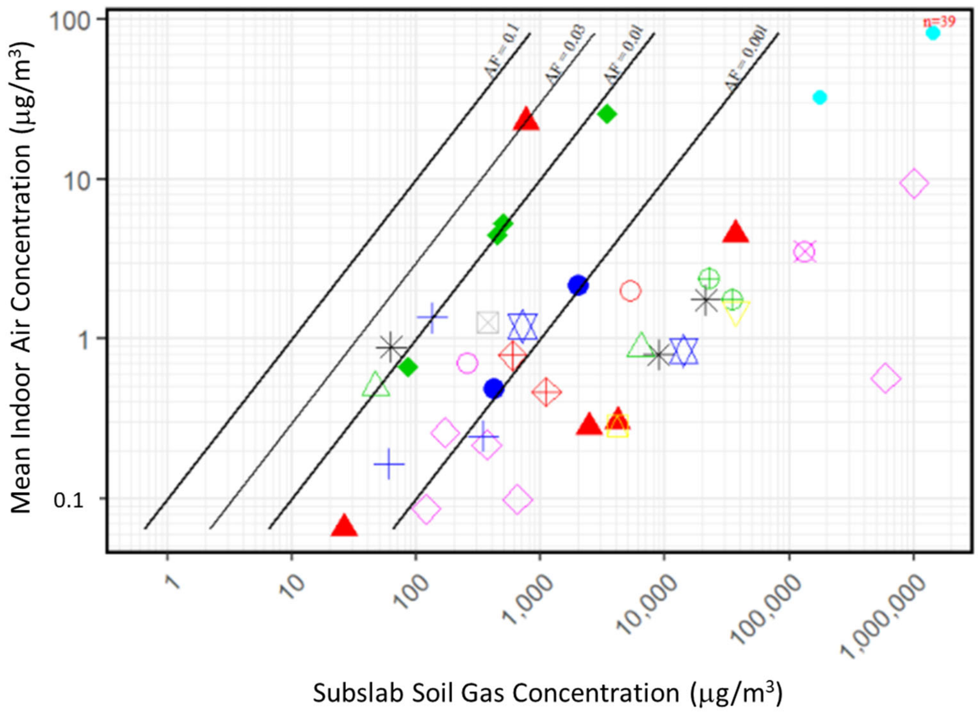


(b)

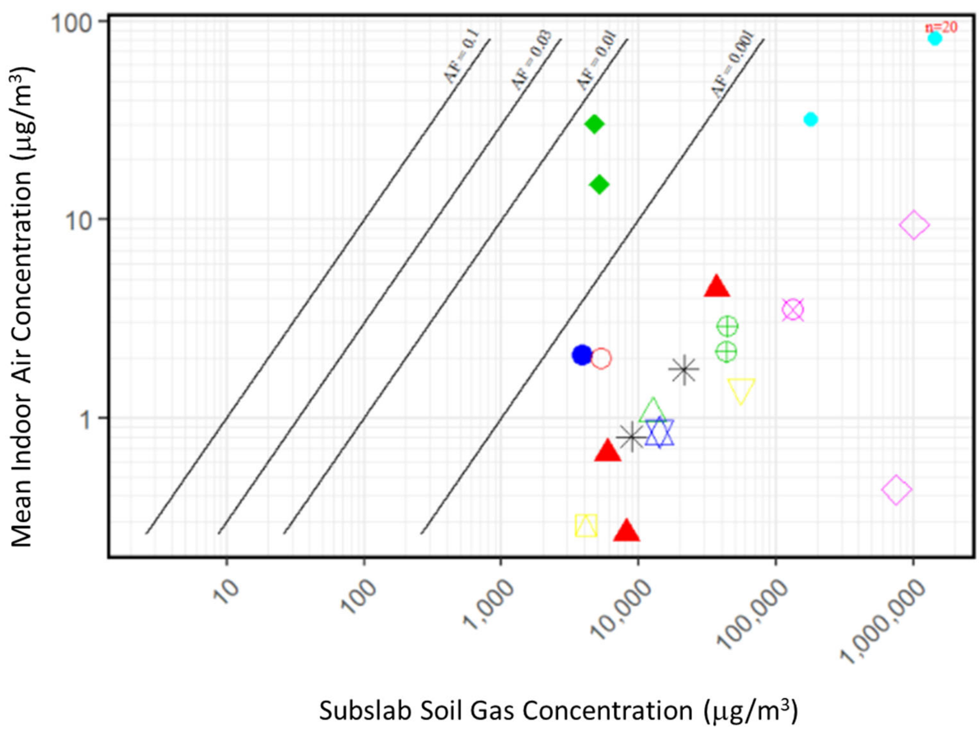
Figure 4-5. Examples of Paired Subslab Soil Gas-Indoor Air Concentration Plots for TCE with Each Data Pair Corresponding to a Building Sample Zone Average for all Sampling Events Passing the (a) 10X and (b) 1,000X Background Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.



(a)



(b)

Figure 4-6. Examples of Paired Subslab Soil Gas-Indoor Air Concentration Plots for TCE with Each Data Pair Corresponding to the Building Average for all Building Zones and Sampling Events Passing the (a) 10X and (b) 1,000X Background Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.

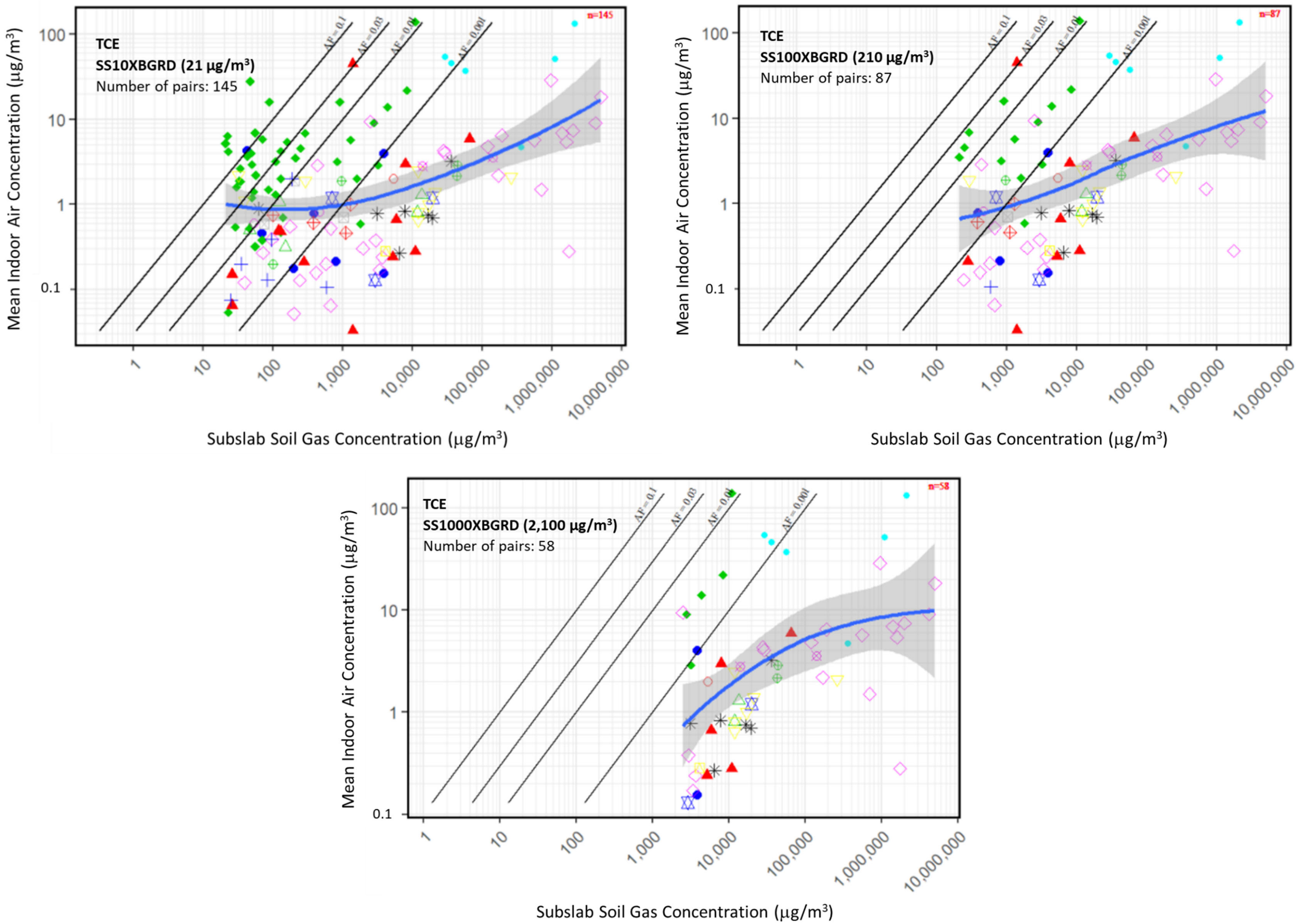


Figure 4-7. Paired Subslab Soil Gas-Indoor Air Concentration Plots for TCE for Increasing Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each data pair corresponds to a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.

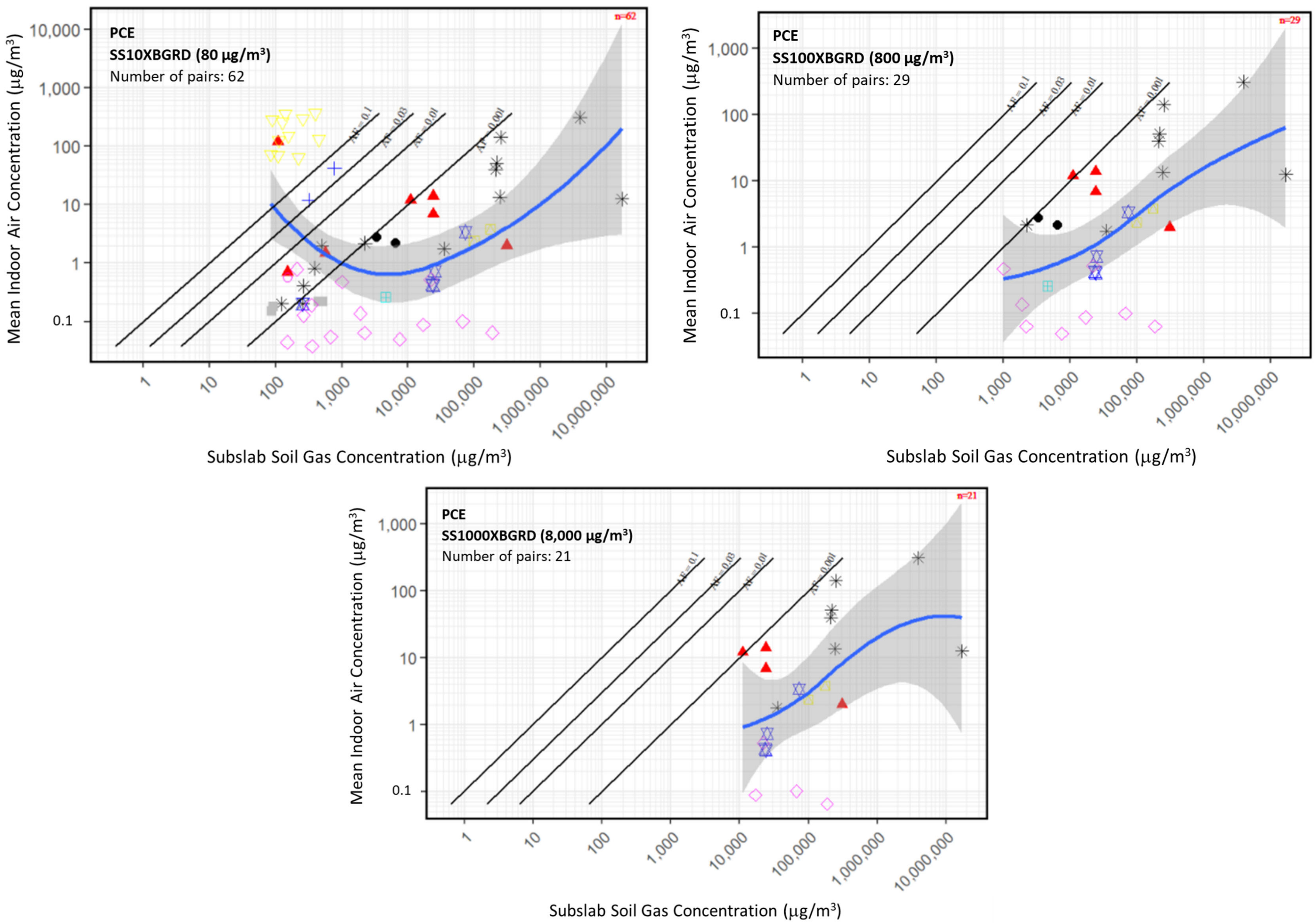


Figure 4-8. Paired Subslab Soil Gas-Indoor Air Concentration Plots for PCE for Increasing Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each data pair corresponds to a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.

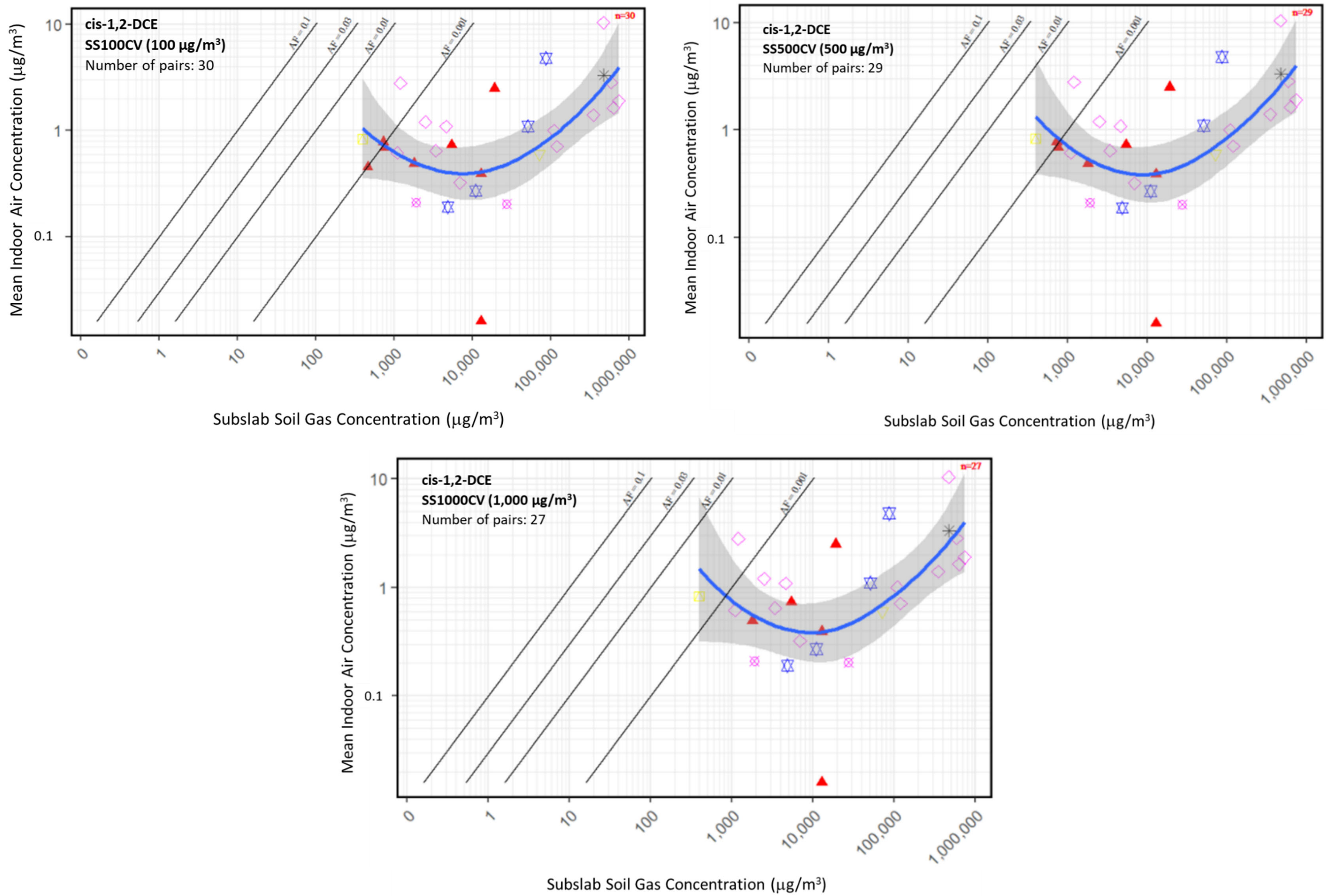


Figure 4-9. Paired Subslab Soil Gas-Indoor Air Concentration Plots for cis-1,2-DCE for Increasing Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each data pair corresponds to a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.

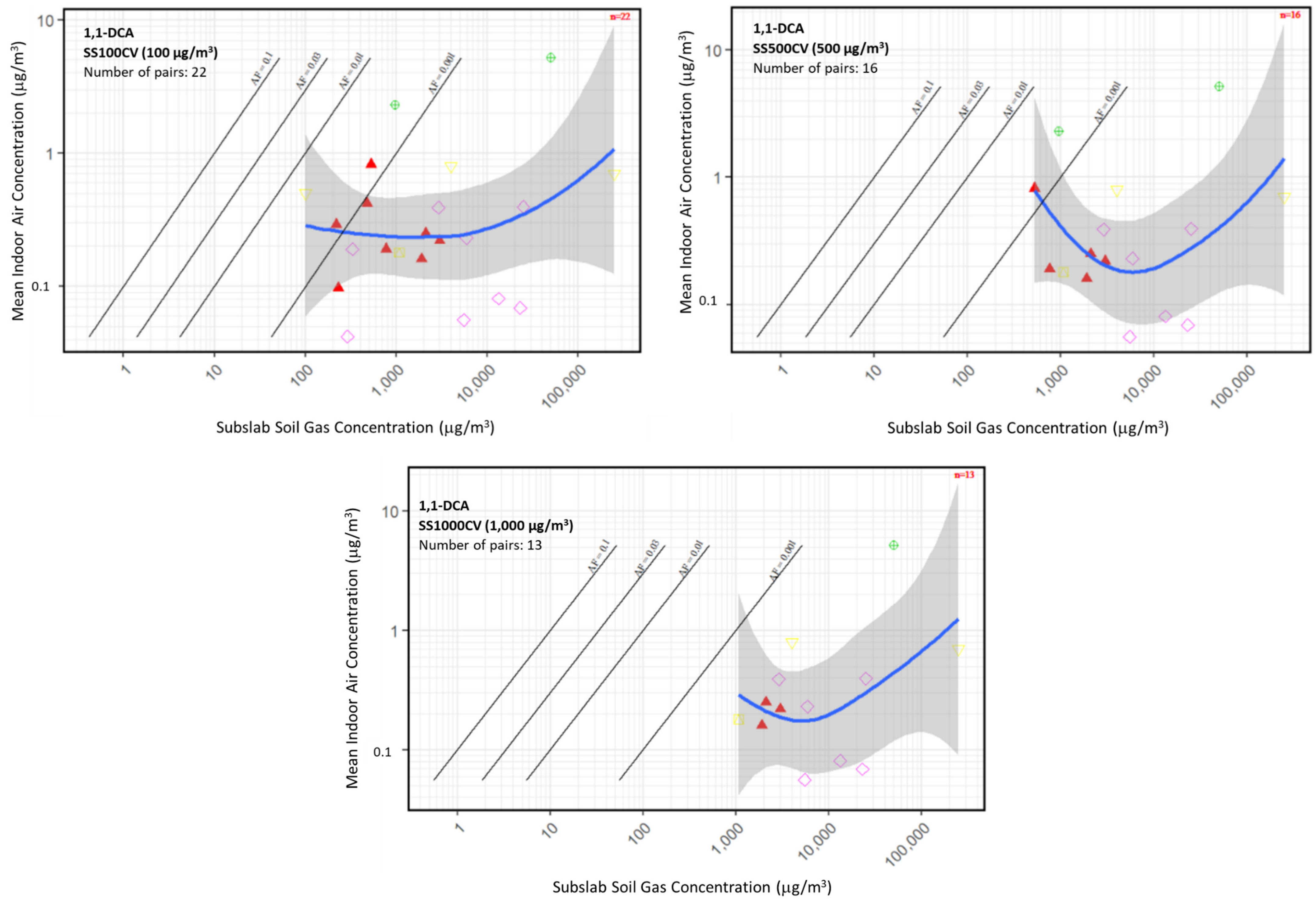


Figure 4-10. Paired Subslab Soil Gas-Indoor Air Concentration Plots for 1,1-DCA for Increasing Source Strength Screen
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Each data pair corresponds to a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.

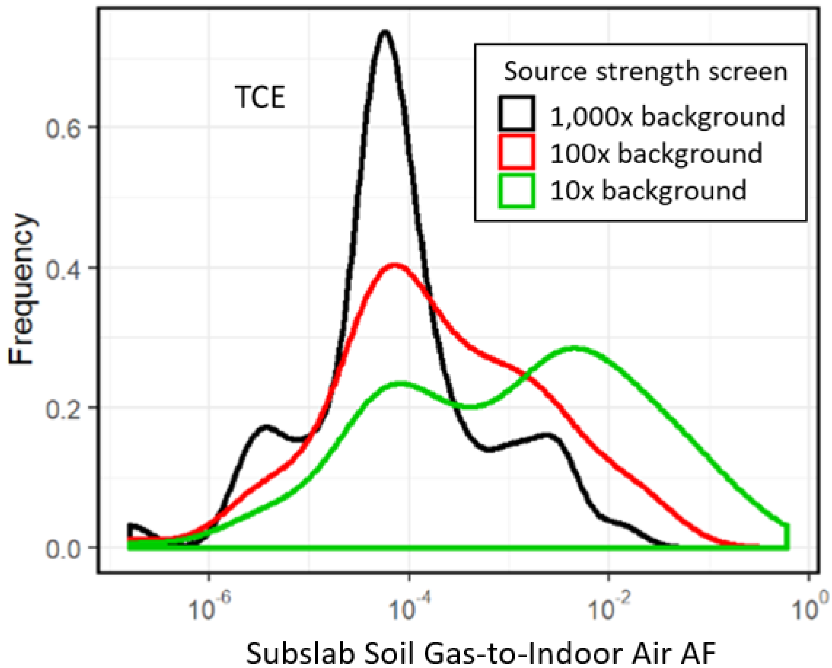


Figure 4-11. Subslab Soil Gas-to-Indoor Air AF Frequency Distribution Plots for TCE After Application of Source Strength Screens Ranging from 10X to 1,000X Background for TCE (21 to 2,100 µg/m^3)

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Data pairs with an indoor air concentration below detection limit are not included.

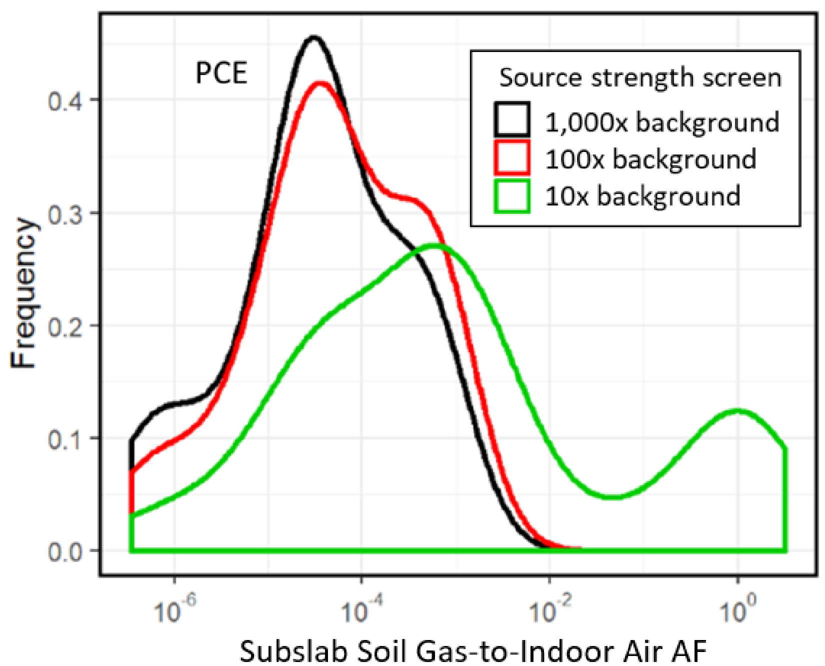


Figure 4-12. Subslab Soil Gas-to-Indoor Air AF Frequency Distribution Plots for PCE After Application of Source Strength Screens Ranging from 10X to 1,000X Background for PCE (80 to 8,000 µg/m^3)

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Data pairs with an indoor air concentration below detection limit are not included.

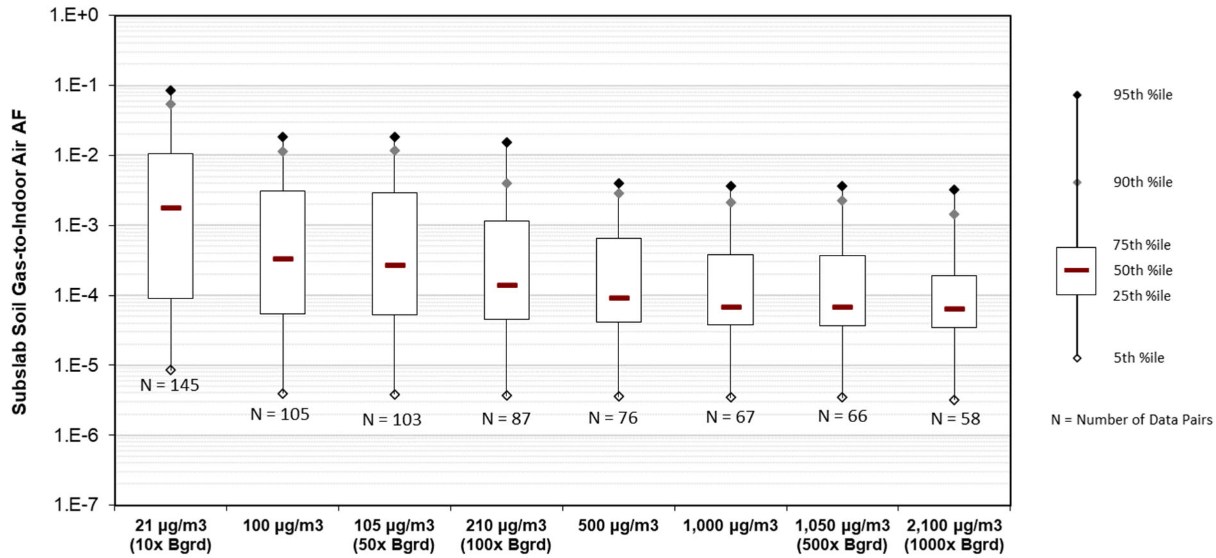


Figure 4-13. Box-and-Whisker Plots Summarizing the Subslab Soil Gas-to-Indoor Air AF Distribution Associated with TCE After Application of the Various Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included.

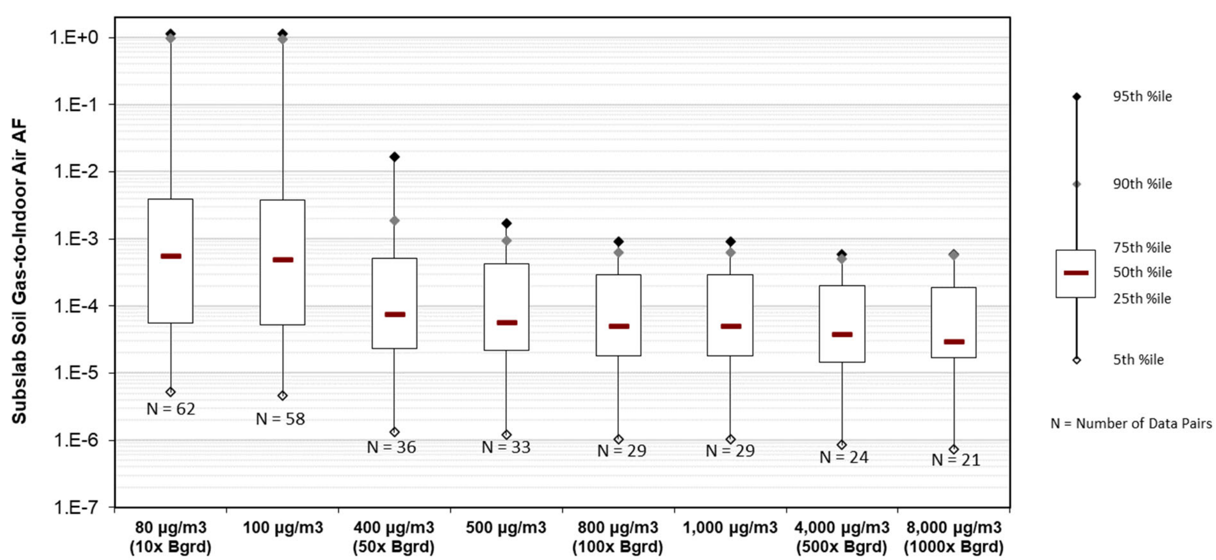


Figure 4-14. Box-and-Whisker Plots Summarizing the Subslab Soil Gas-to-Indoor Air AF distribution Associated with PCE After Application of the Various Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included.

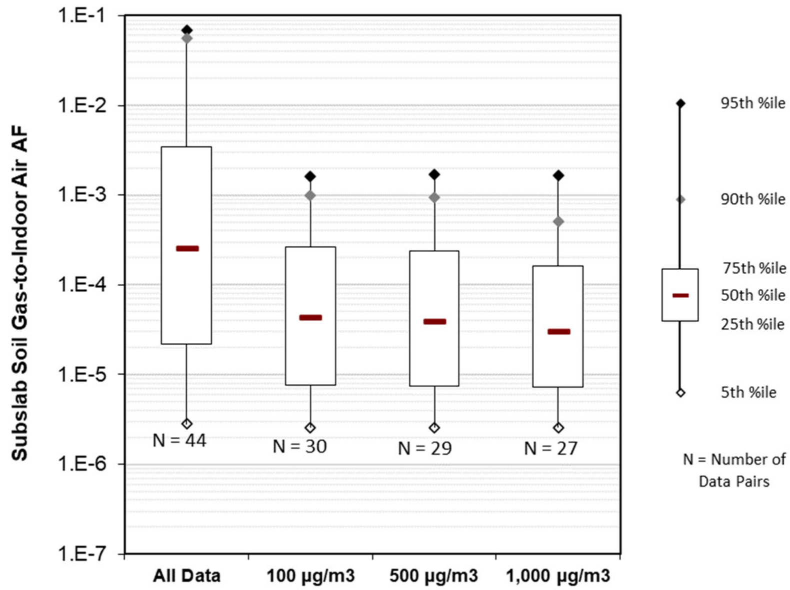


Figure 4-15. Box-and-Whisker Plots Summarizing the Subslab Soil Gas-to-Indoor Air AF Distribution Associated with cis-1,2-DCE After Application of the Various Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included.

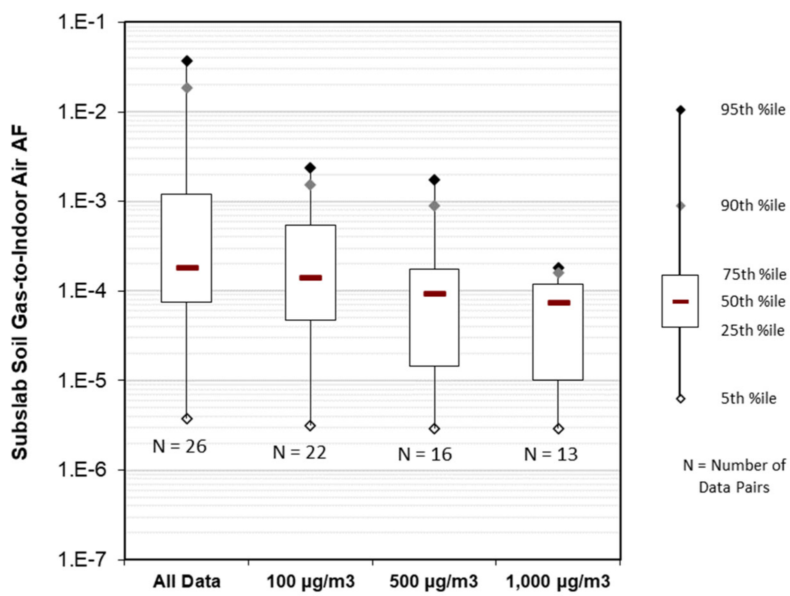


Figure 4-16. Box-and-Whisker Plots Summarizing the Subslab Soil Gas-to-Indoor Air AF Distribution Associated with 1,1-DCA After Application of the Various Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included.

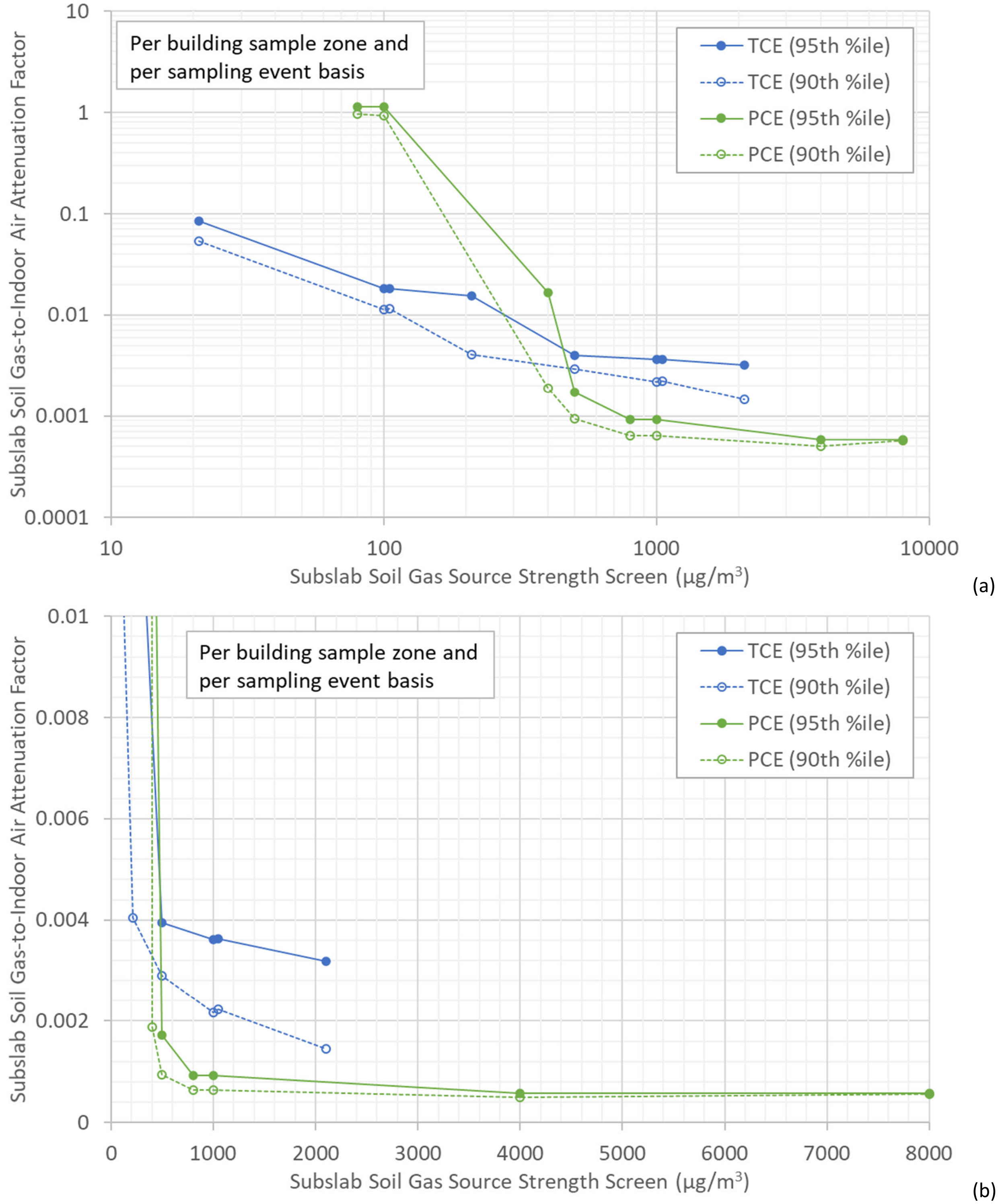


Figure 4-17. Plots of 90th and 95th Percentile Subslab Soil Gas-to-Indoor Air AFs Associated with TCE and PCE as a Function of Source Strength Screen Using (a) Log Scale and (b) Linear Scale

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included.

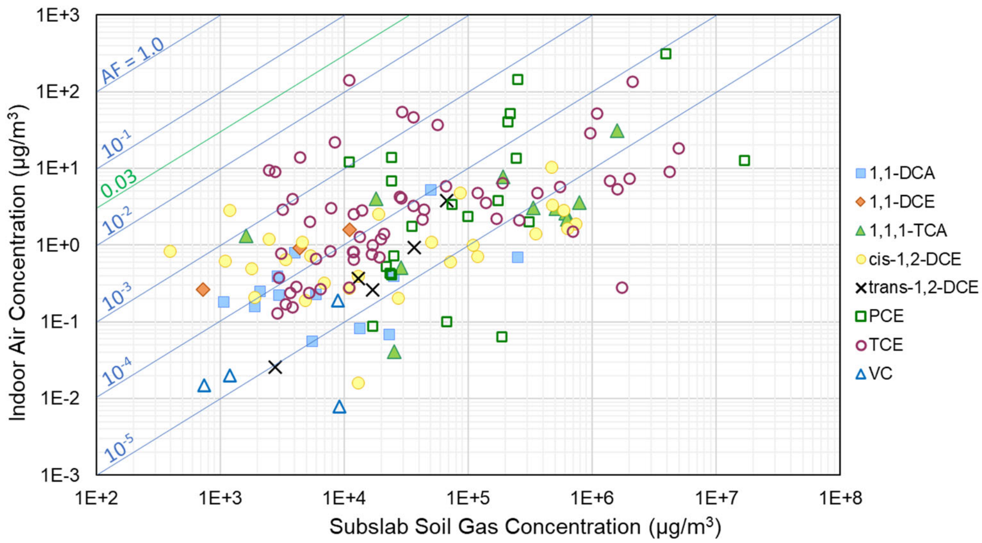


Figure 4-18. Paired Subslab Soil Gas-Indoor Air Concentration Plots for All VOCs in the Analysis

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each data pair represents the average indoor air and subslab soil gas concentrations for a building sample zone for a given sampling event. The pairs on the plots passed either the 1,000X background source strength screen for VOCs with background values (TCE, PCE, 1,1,1-TCA, 1,1-DCE, and VC) or the 1,000 µg/m^3 source strength screen for VOCs without background values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE). Pairs with an indoor air concentration below detection limit are not shown. The blue oblique lines represent subslab soil gas-to-indoor air AF lines ranging from 10^{-5} to 1.0. The green line represents the USEPA default AF of 0.03. There were no pairs meeting the various filtering criteria for 1,2-DCA.

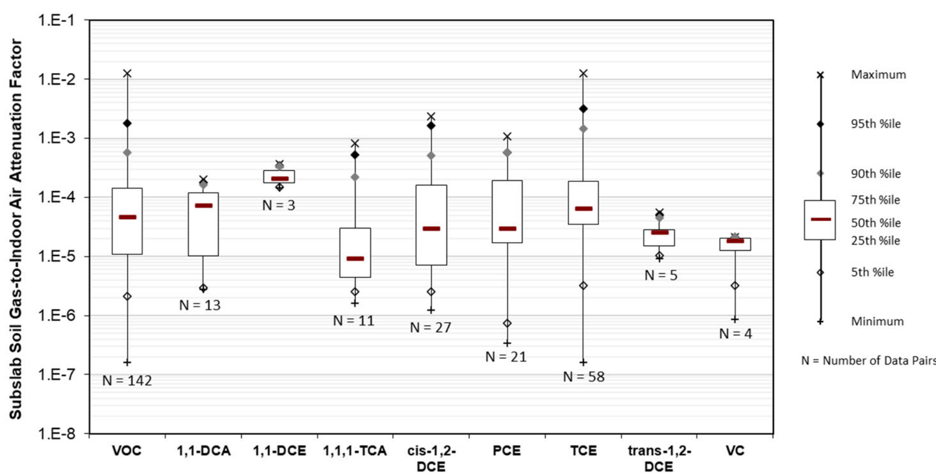


Figure 4-19. Box-and-Whisker Plots Summarizing the Subslab Soil Gas-to-Indoor Air AF Distribution Associated with the VOCs After Application of Either the 1,000X Background Source Strength Screen for VOCs with Background Values (TCE, PCE, 1,1,1-TCA, 1,1-DCE, and VC) or the 1,000 µg/m^3 Source Strength Screen for VOCs without Background Values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE)

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included. There were no pairs meeting the various filtering criteria for 1,2-DCA.

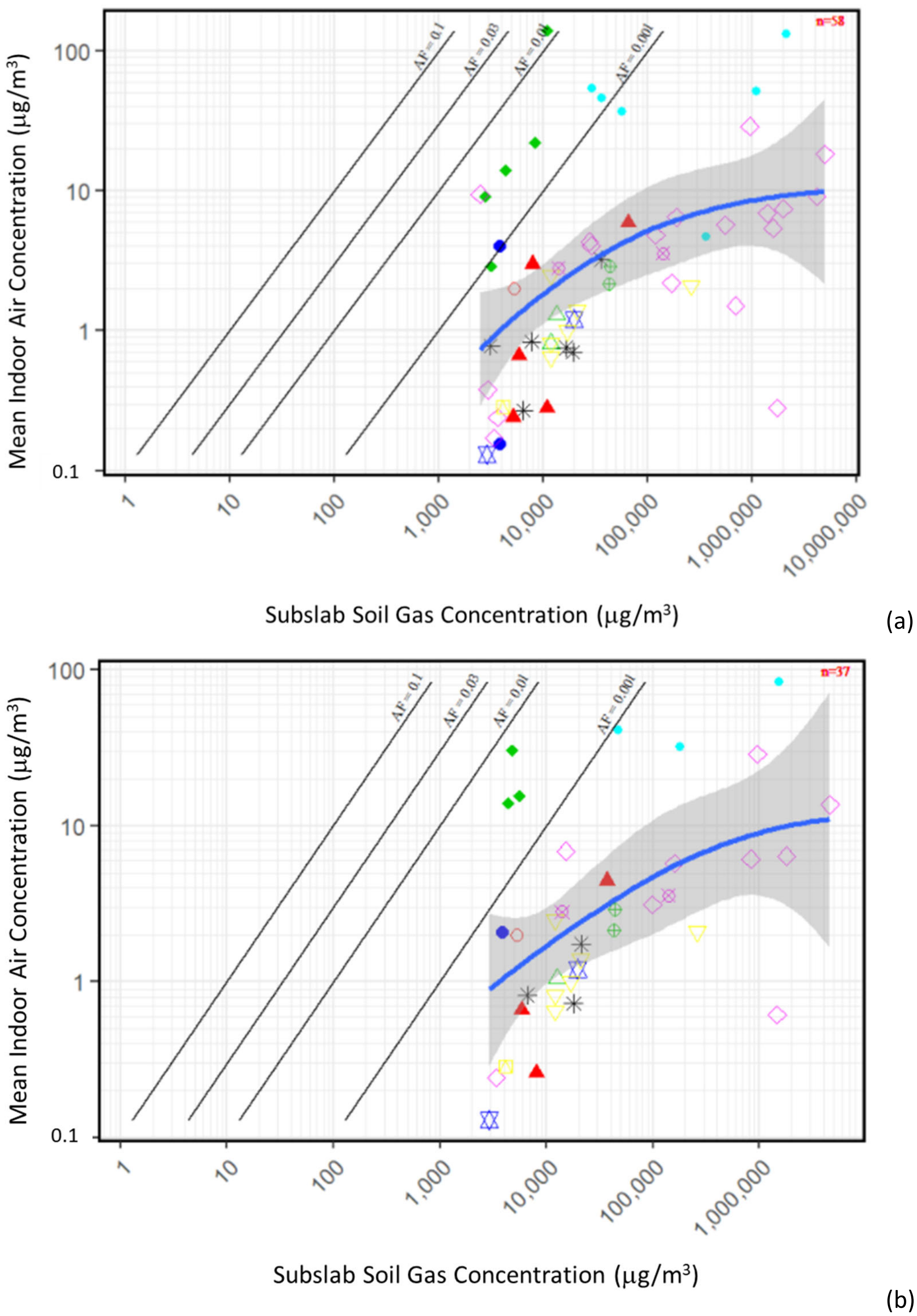
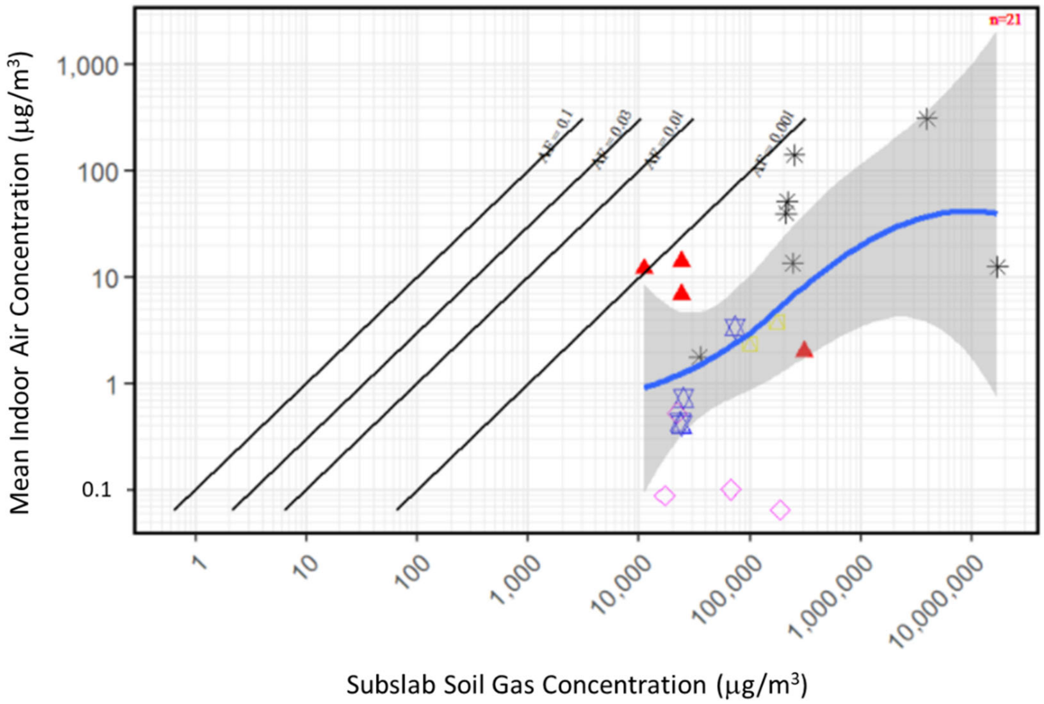


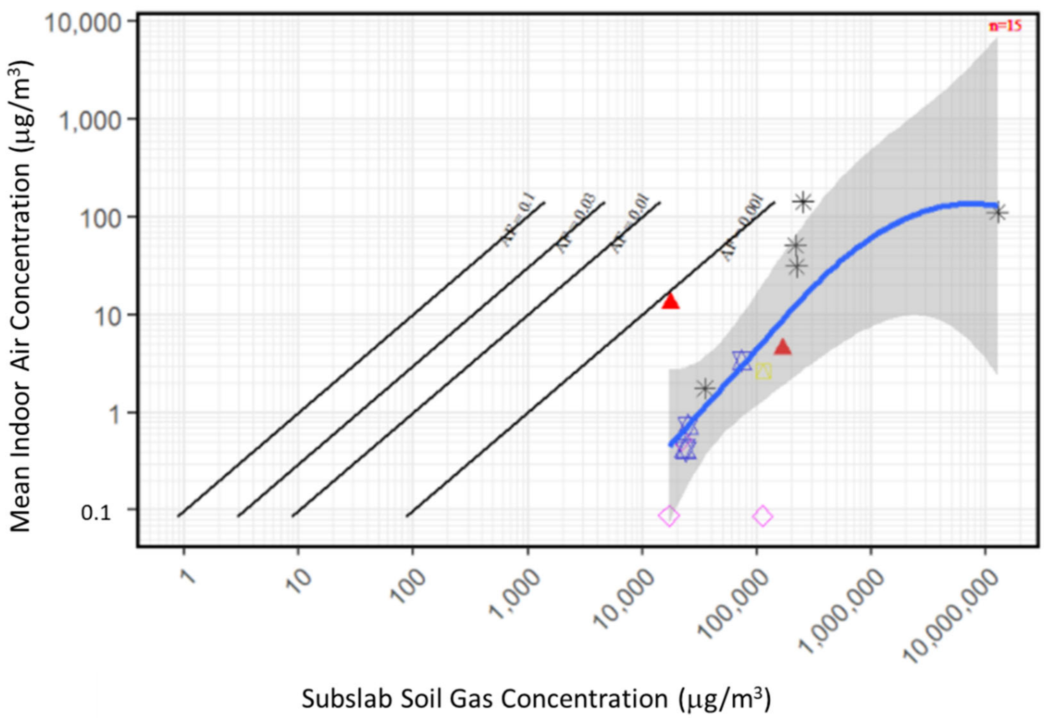
Figure 4-20. Paired Subslab Soil Gas-Indoor Air Concentration Plots for TCE for Data Passing the 1,000X Background Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches using (a) building sample zone averages for individual sampling events and (b) building sample zone averages for all sampling events. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.



(a)

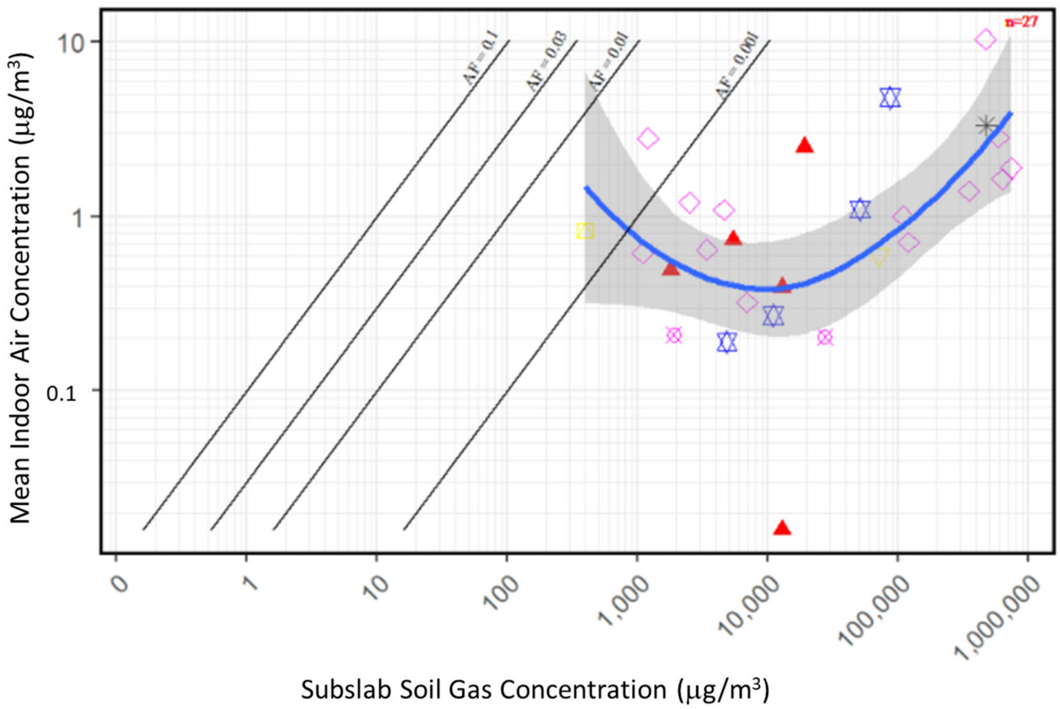


(b)

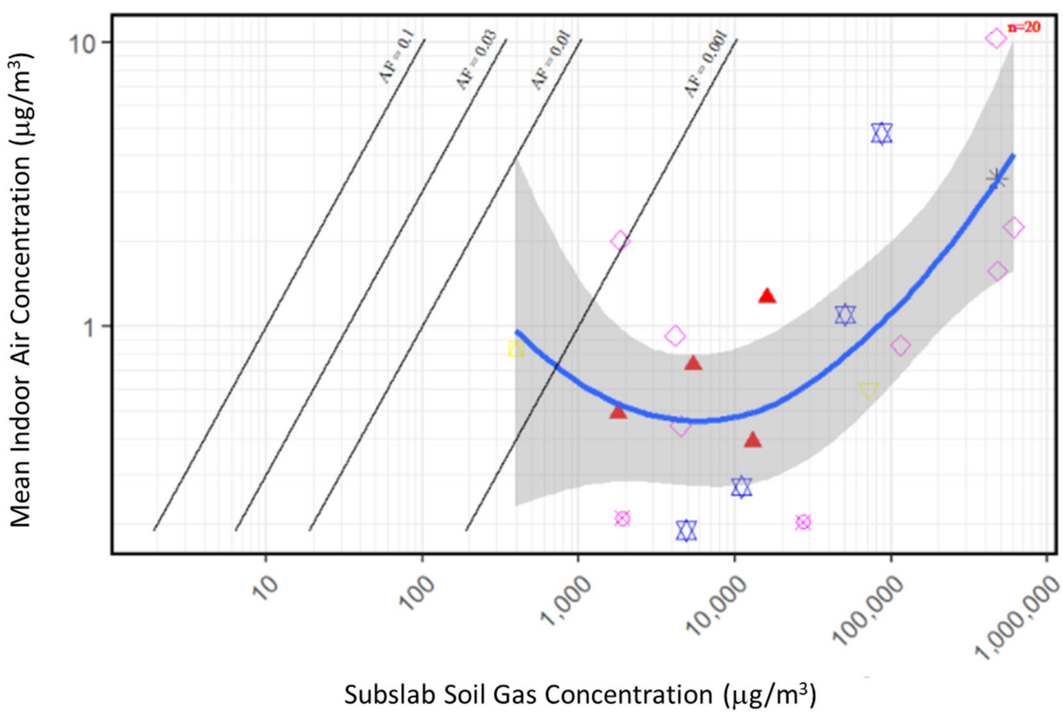
Figure 4-21. Paired Subslab Soil Gas-Indoor Air Concentration Plots for PCE for Data Passing the 1,000X Background Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches using (a) building sample zone averages for individual sampling events and (b) building sample zone averages for all sampling events. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.



(a)

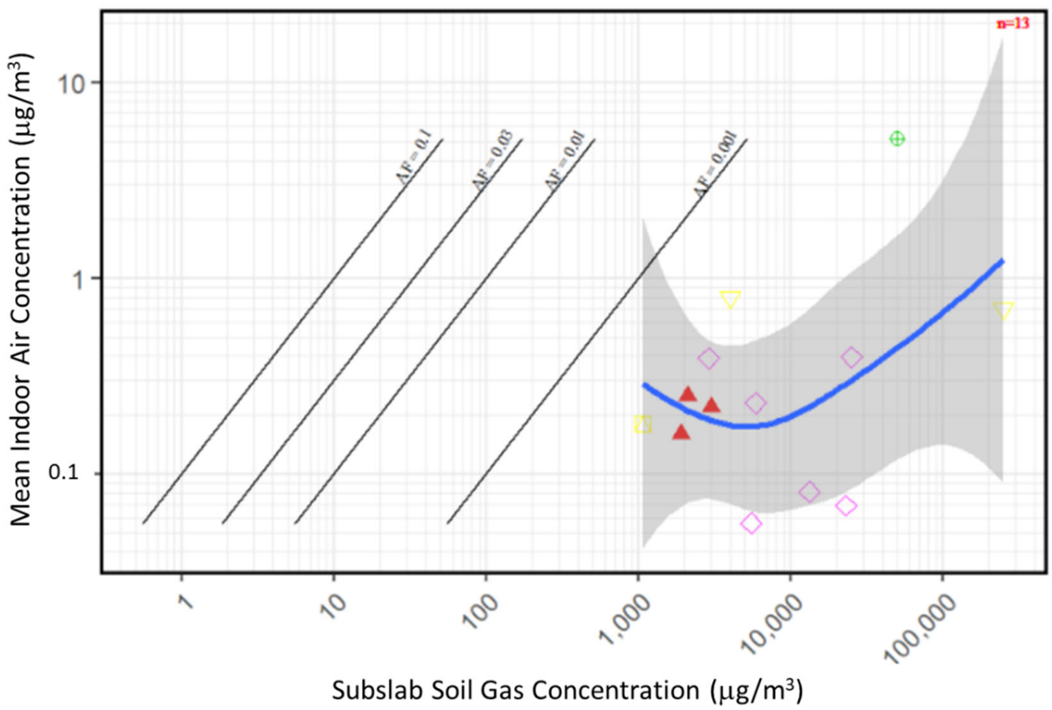


(b)

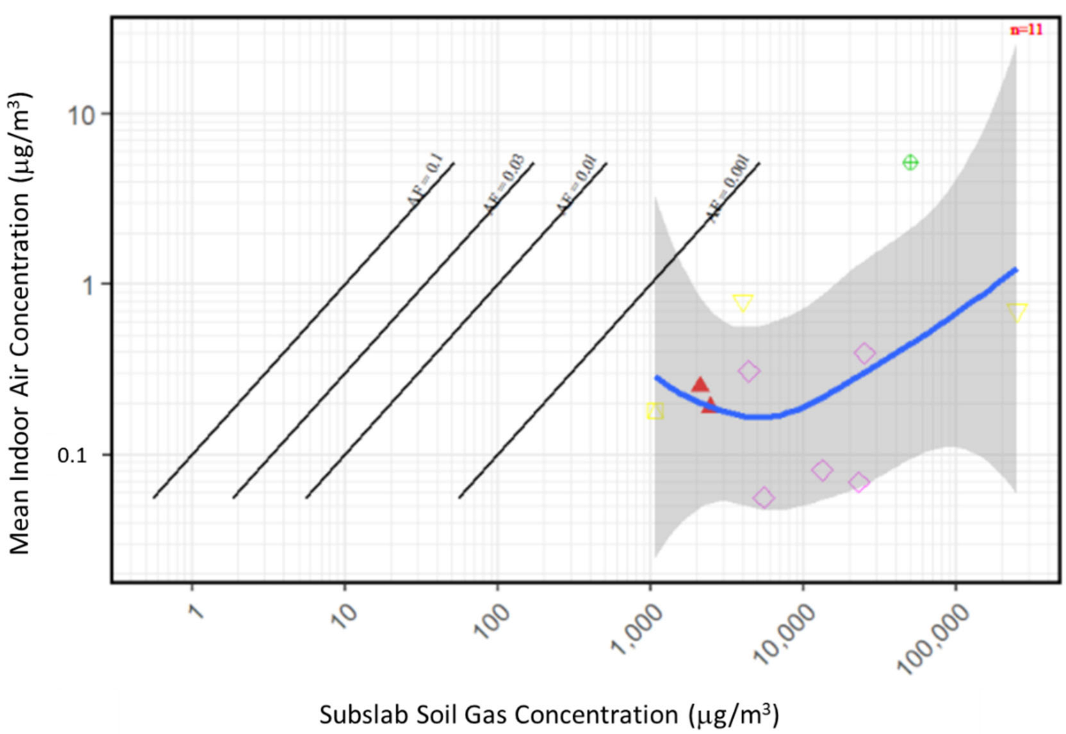
Figure 4-22. Paired Subslab Soil Gas-Indoor Air Concentration Plots for cis-1,2-DCE for Data Passing the 1,000 µg/m³ Fixed Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches using (a) building sample zone averages for individual sampling events and (b) building sample zone averages for all sampling events. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.



(a)

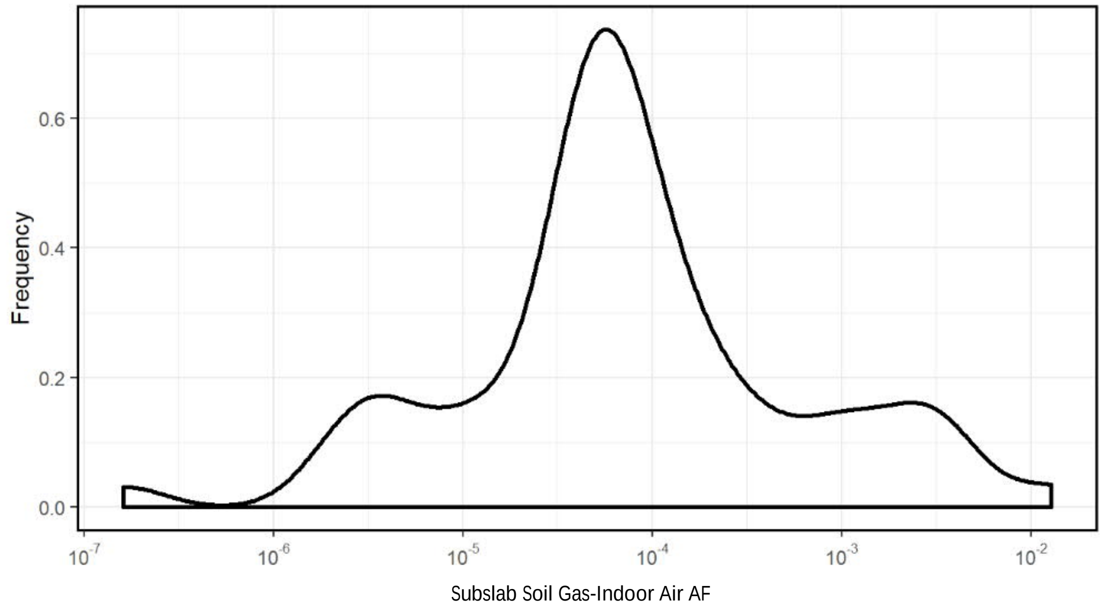


(b)

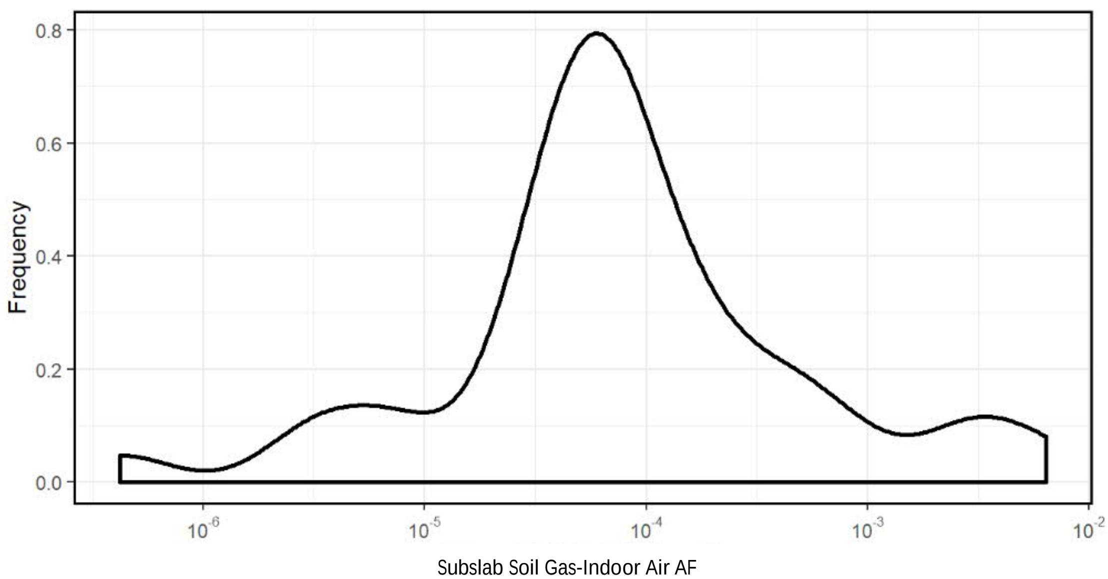
Figure 4-23. Paired Subslab Soil Gas-Indoor Air Concentration Plots for 1,1-DCA for Data Passing the 1,000 µg/m^3 Fixed Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches using (a) building sample zone averages for individual sampling events and (b) building sample zone averages for all sampling events. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.



(a)

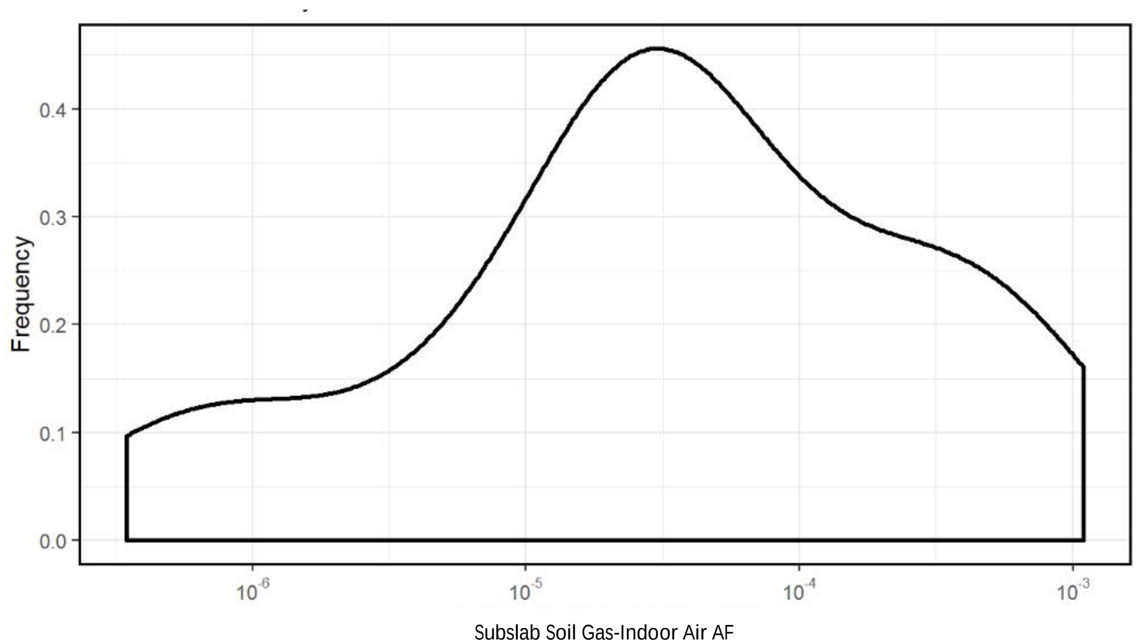


(b)

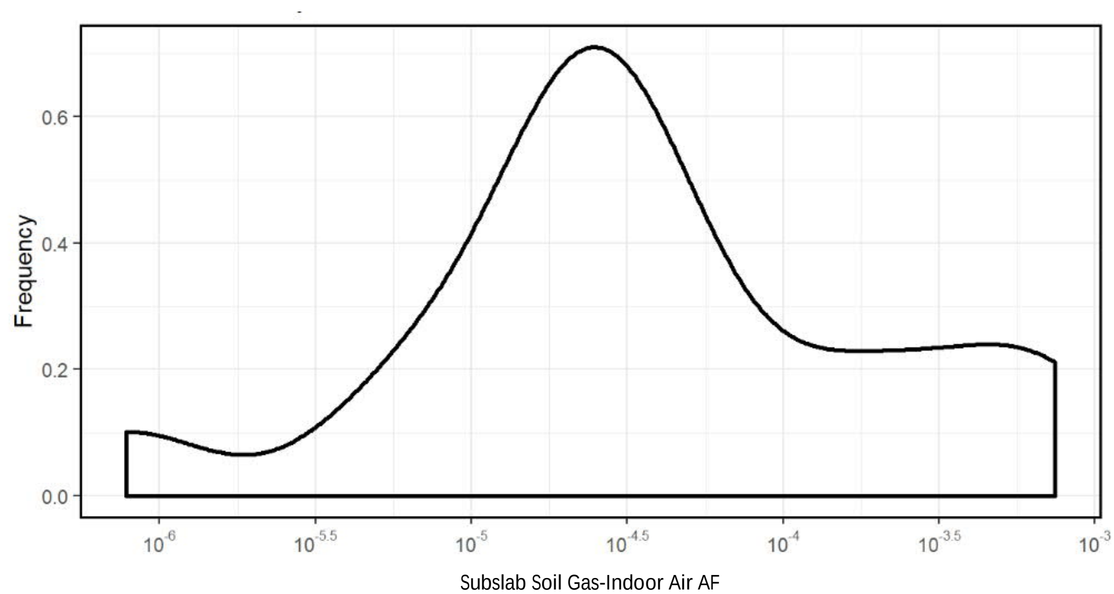
Figure 4-24. Subslab Soil Gas-to-Indoor Air AF Frequency Distribution Plots for TCE for Data Passing the 1,000X Background Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches using (a) building sample zone averages for individual sampling events and (b) building sample zone averages for all sampling events. Data pairs with an indoor air concentration below detection limit are not included.



(a)

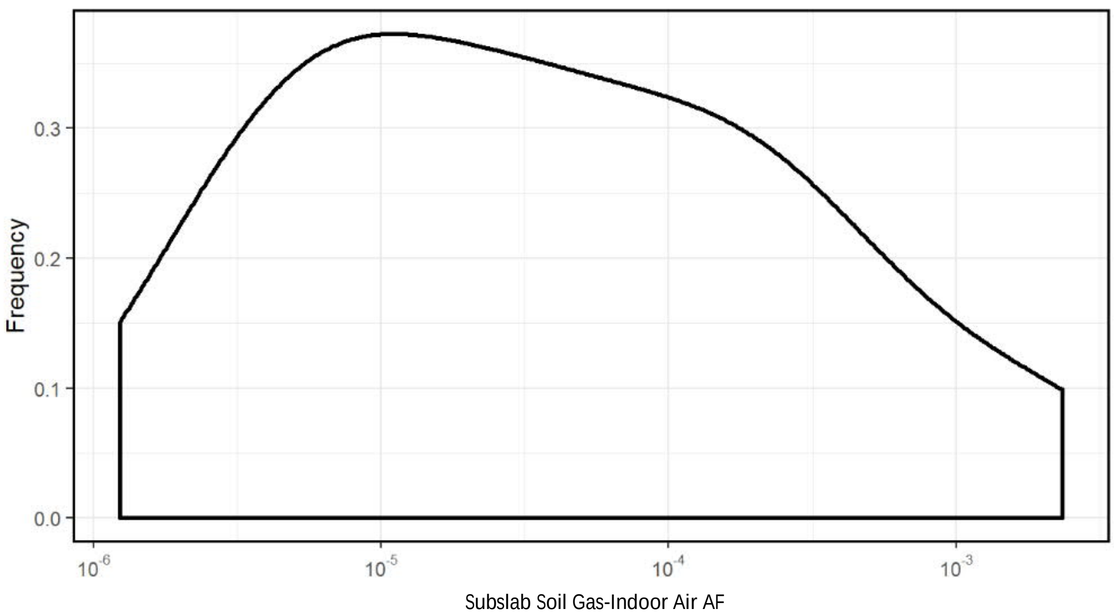


(b)

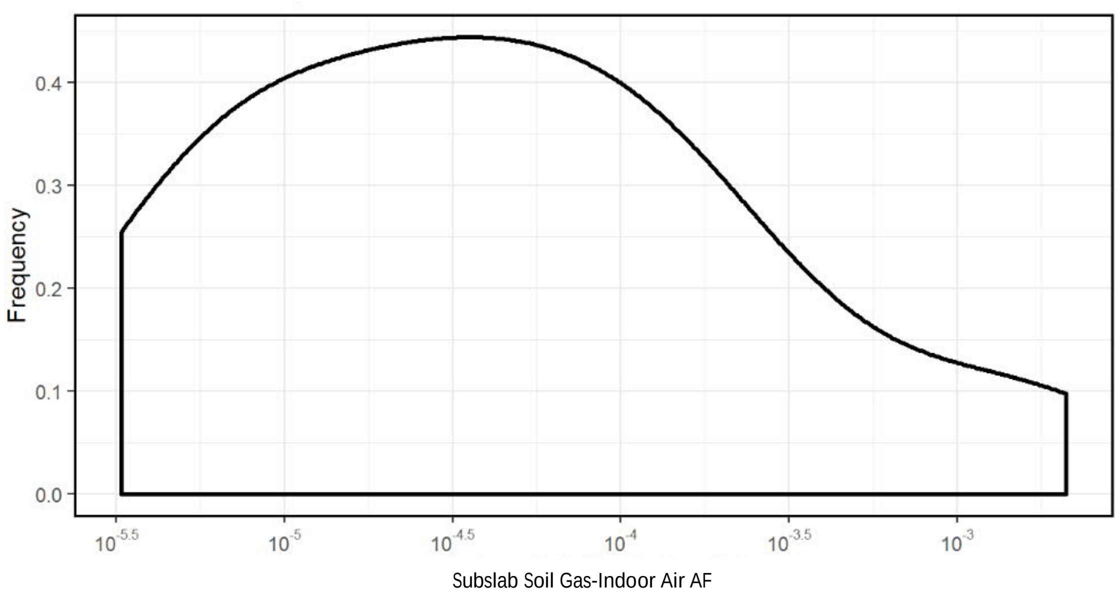
Figure 4-25. Subslab Soil Gas-to-Indoor Air AF Frequency Distribution Plots for PCE for Data Passing the 1,000X Background Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches using (a) building sample zone averages for individual sampling events and (b) building sample zone averages for all sampling events. Data pairs with an indoor air concentration below detection limit are not included.



(a)

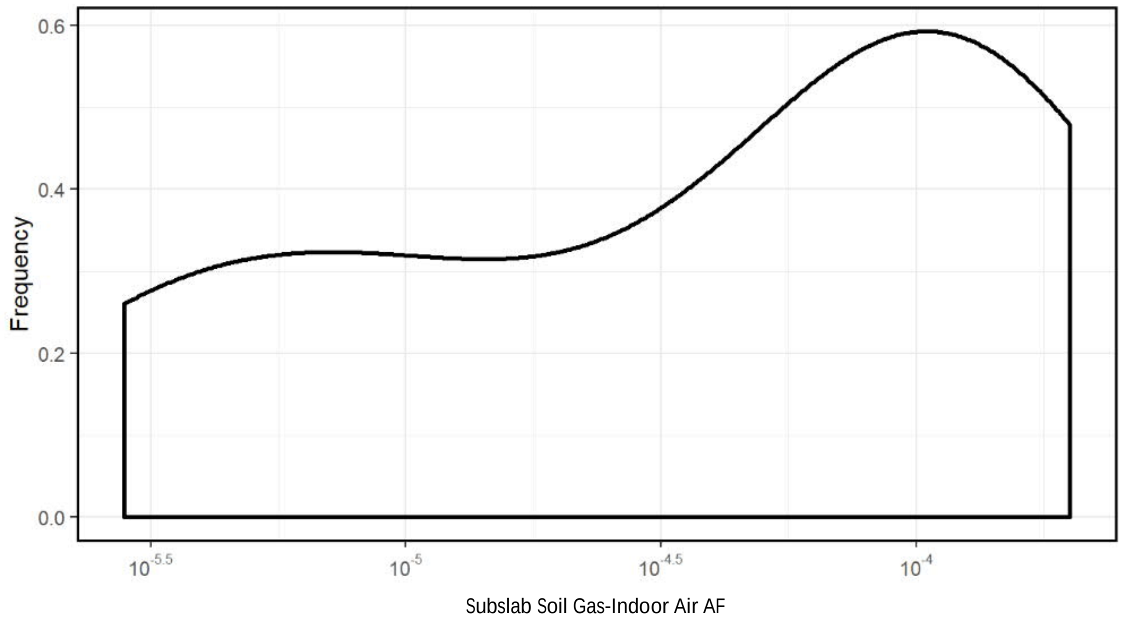


(b)

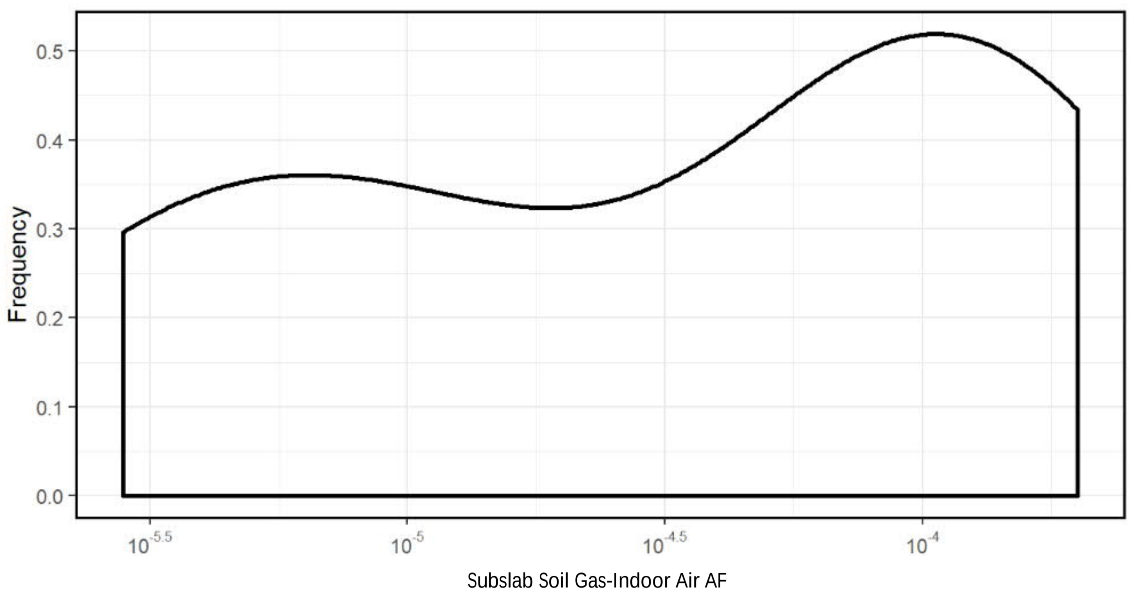
Figure 4-26. Subslab Soil Gas-to-Indoor Air AF Frequency Distribution Plots for cis-1,2-DCE for Data Passing the 1,000 µg/m^3 Fixed Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches using (a) building sample zone averages for individual sampling events and (b) building sample zone averages for all sampling events. Data pairs with an indoor air concentration below detection limit are not included.



(a)



(b)

Figure 4-27. Subslab Soil Gas-to-Indoor Air AF Frequency Distribution Plots for 1,1-DCA for Data Passing the 1,000 µg/m^3 Fixed Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches using (a) building sample zone averages for individual sampling events and (b) building sample zone averages for all sampling events. Data pairs with an indoor air concentration below detection limit are not included.

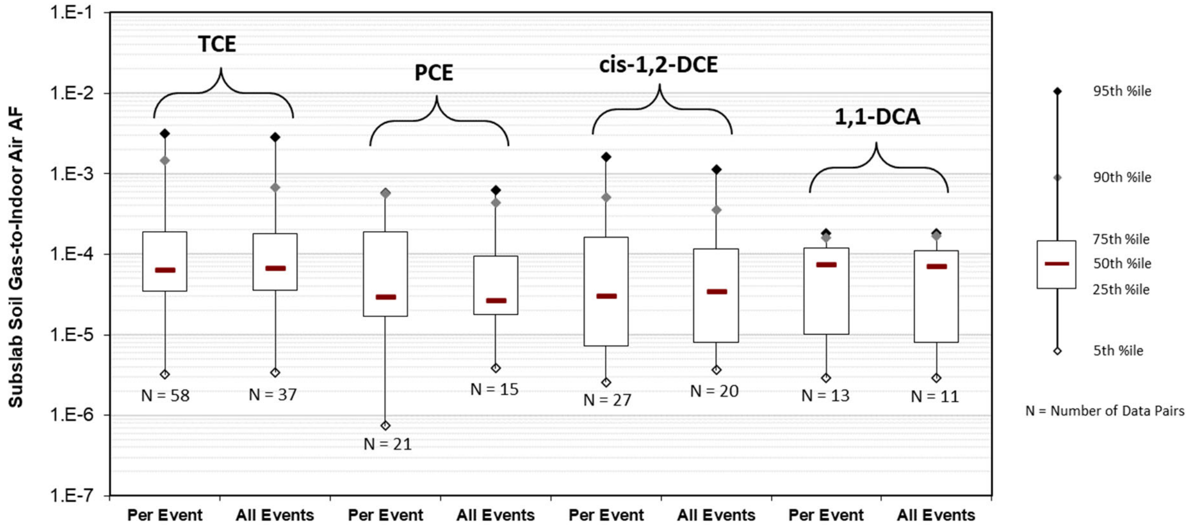
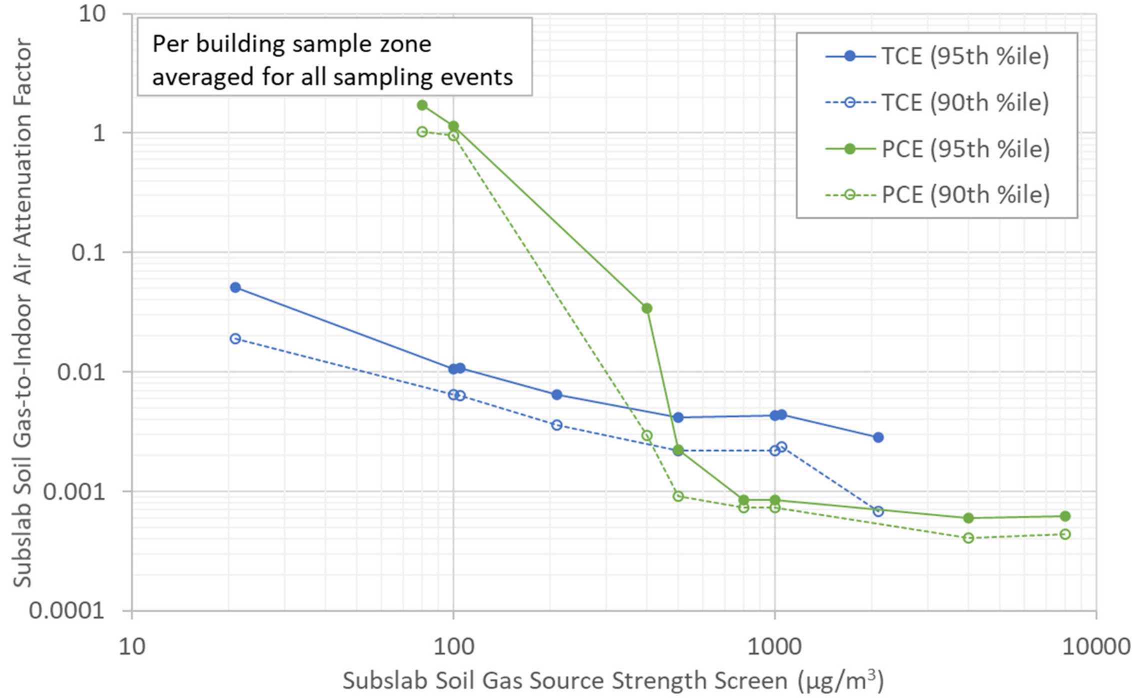


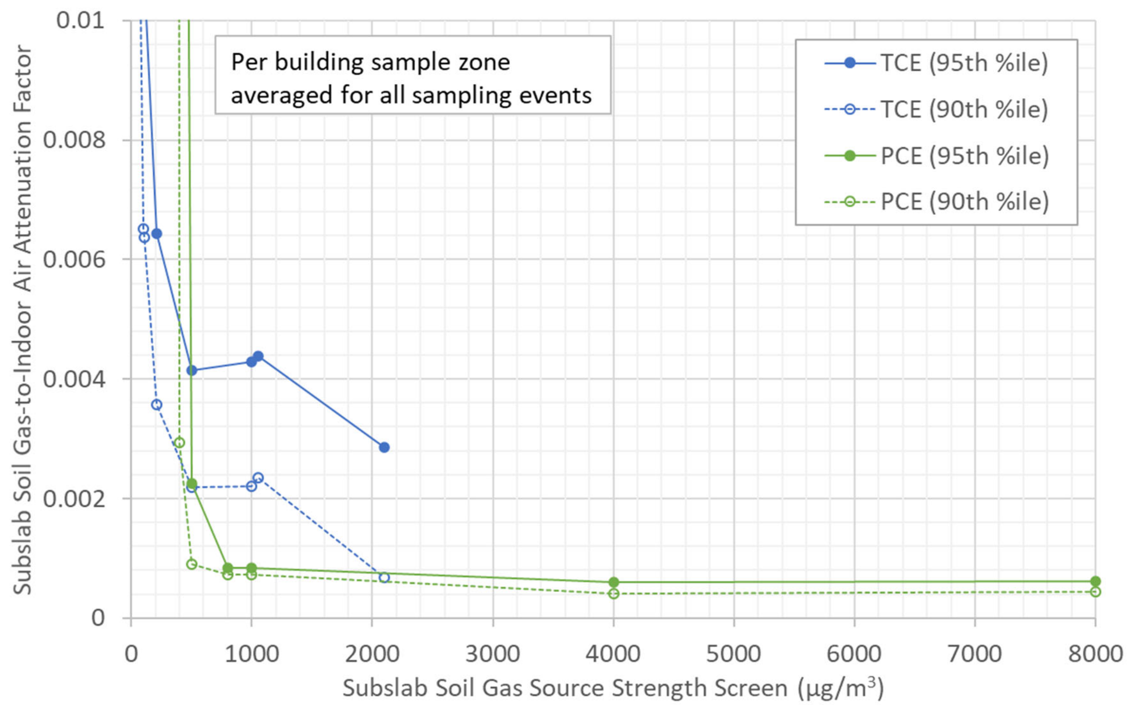
Figure 4-28. Box-and-Whisker Plots Summarizing the Subslab Soil Gas-to-Indoor Air AF Distribution Associated with Selected VOCs after Application of Either the 1,000X Background Source Strength Screen for TCE and PCE or the 1,000 µg/m^3 Fixed Source Strength Screen for cis-1,2-DCE and 1,1-DCA

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between AF distributions derived from building sample zone averages for individual sampling events ("per event") and for all sampling events ("all events"). Pairs with an indoor air concentration below detection limit are not included.



(a)



(b)

Figure 4-29. Plots of 90th and 95th Percentile Subslab Soil Gas-to-Indoor Air AFs Associated with TCE and PCE as a Function of Source Strength Screen Using (a) Log Scale and (b) Linear Scale

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for all sampling events. Pairs with an indoor air concentration below detection limit are not included.

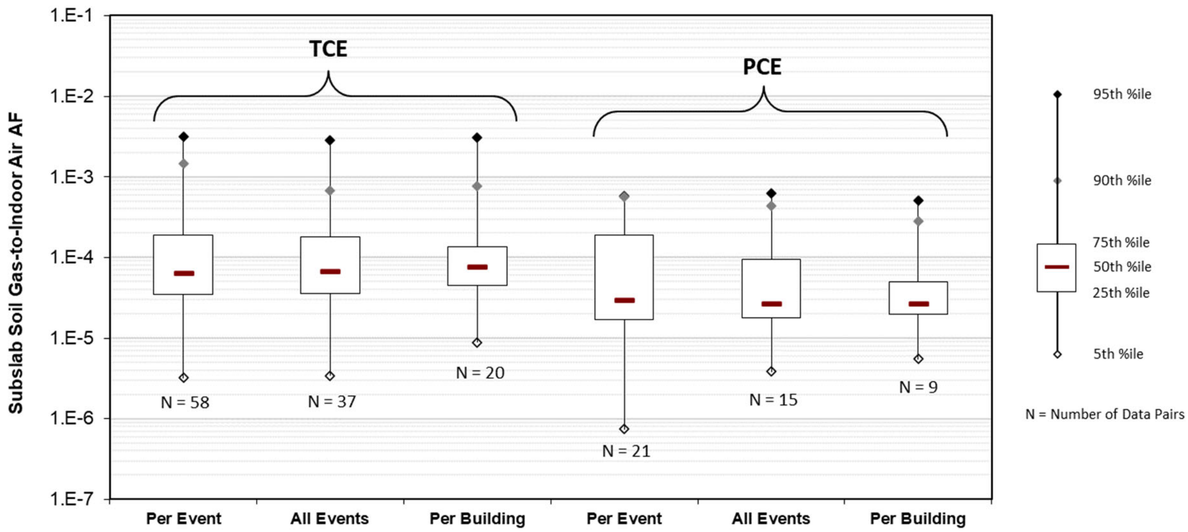


Figure 4-30. Box-and-Whisker Plots Summarizing the Subslab Soil Gas-to-Indoor Air AF Distribution Associated with TCE and PCE After Application of the 1,000X Background Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between AF distributions derived from building sample zone averages for individual sampling events ("per event"), from building sample zone averages for all sampling events ("all events"), and from building averages for all building sample zones and sampling events ("per building"). Pairs with an indoor air concentration below detection limit are not included.

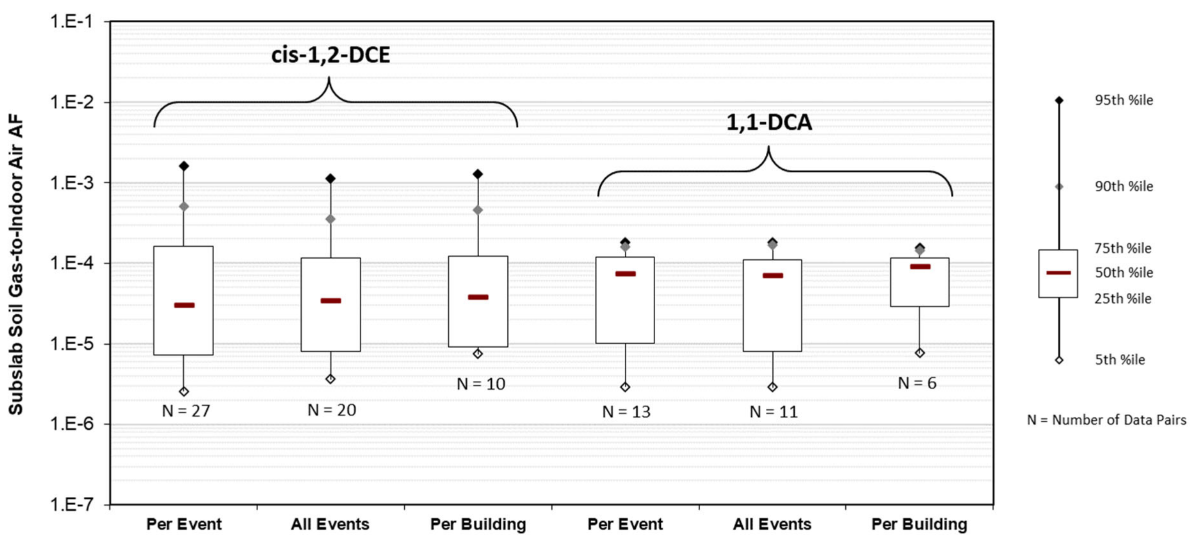
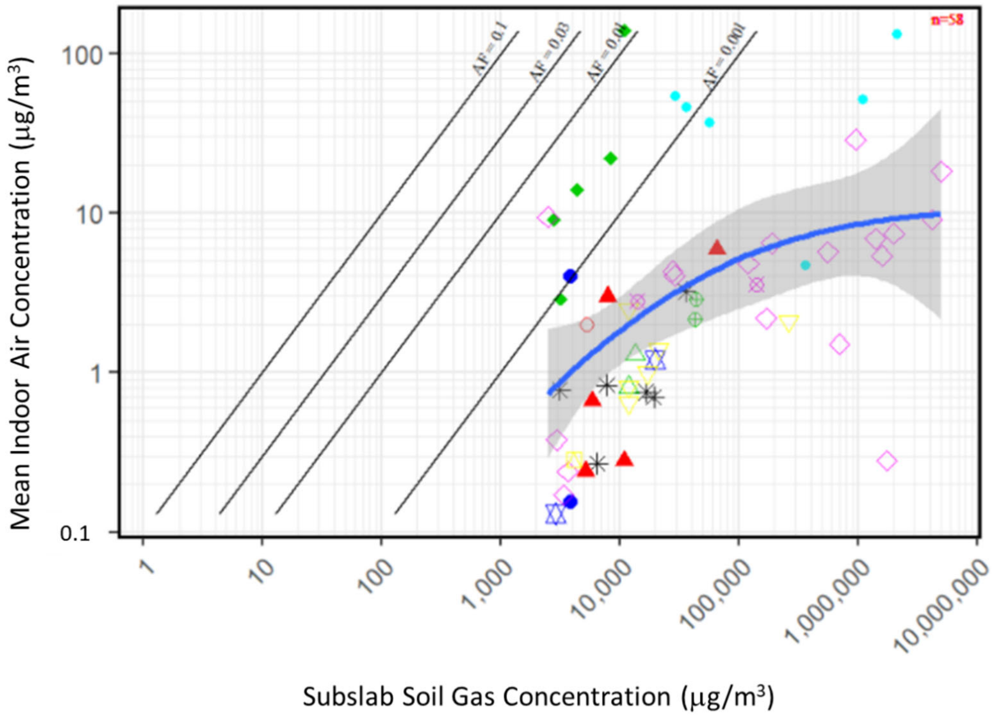


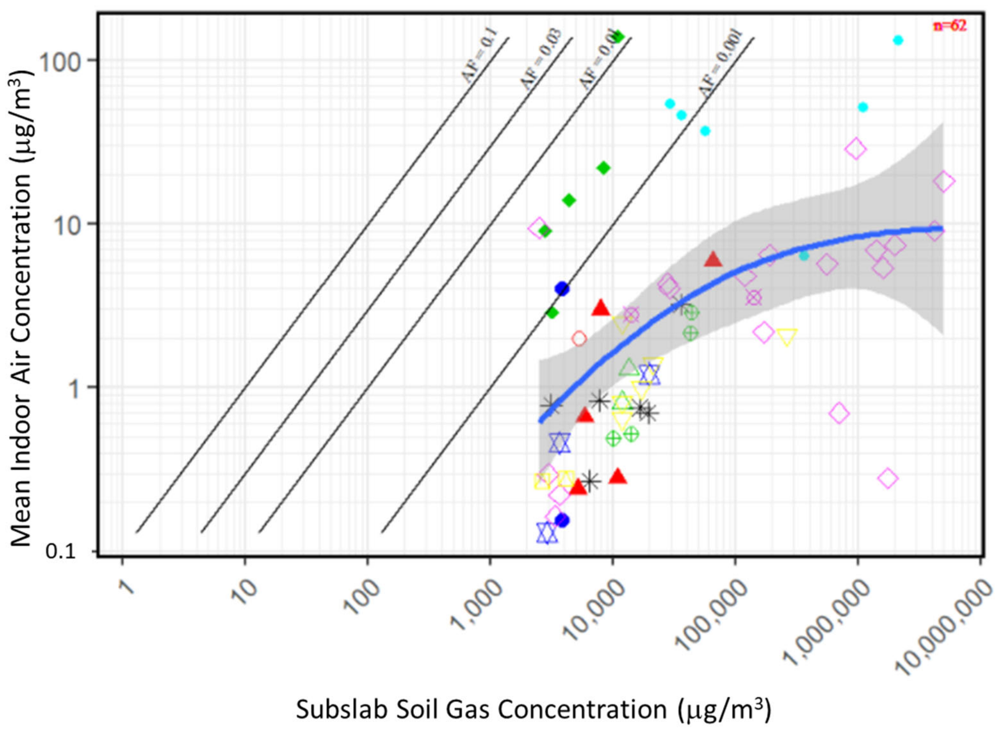
Figure 4-31. Box-and-Whisker Plots Summarizing the Subslab Soil Gas-to-Indoor Air AF Distribution Associated with cis-1,2-DCE and 1,1-DCA After Application of the 1,000 µg/m^3 Fixed Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between AF distributions derived from building sample zone averages for individual sampling events ("per event"), from building sample zone averages for all sampling events ("all events"), and from building averages for all building sample zones and sampling events ("per building"). Pairs with an indoor air concentration below detection limit are not included.

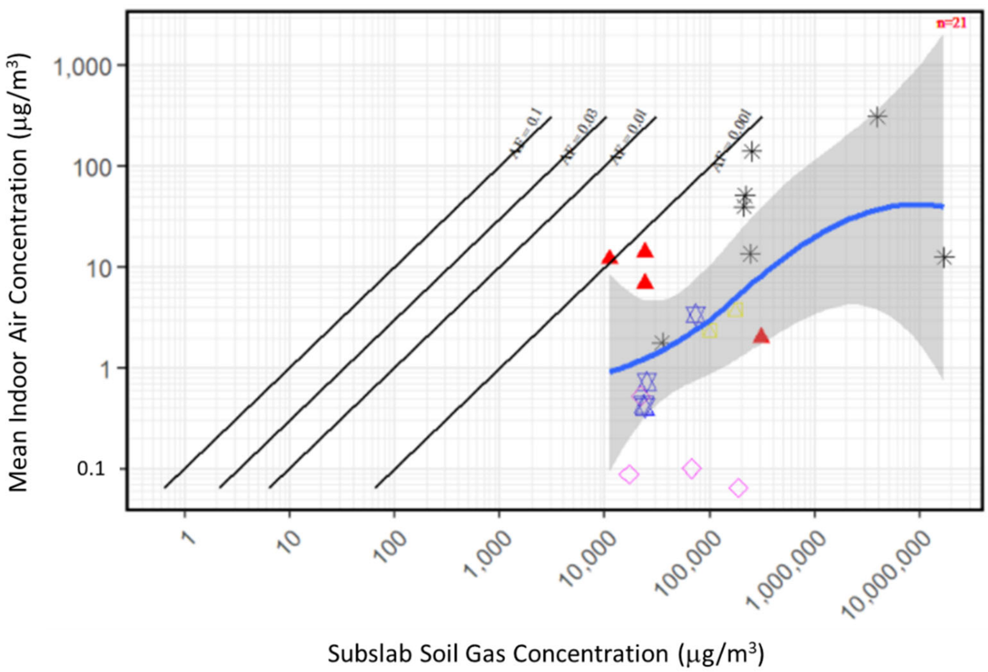


(a)

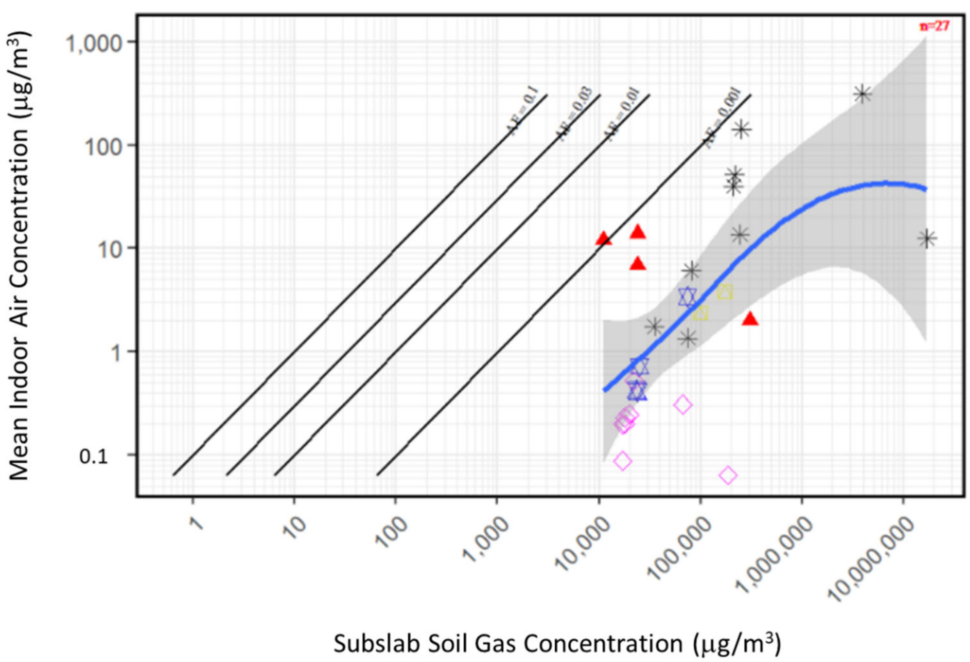


(b)

Figure 4-32. Paired Subslab Soil Gas-Indoor Air Concentration Plots for TCE with Each Data Pair Corresponding to a Building Sample Zone Average for a Given Sampling Event Passing the 1,000X Background Source Strength Screen
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Comparison between the approaches that include (a) only detectable concentrations in indoor air (i.e., indoor air non-detects excluded) and (b) non-detects in indoor air plotted at detection limit. Different symbols correspond to data from different DoD installations.

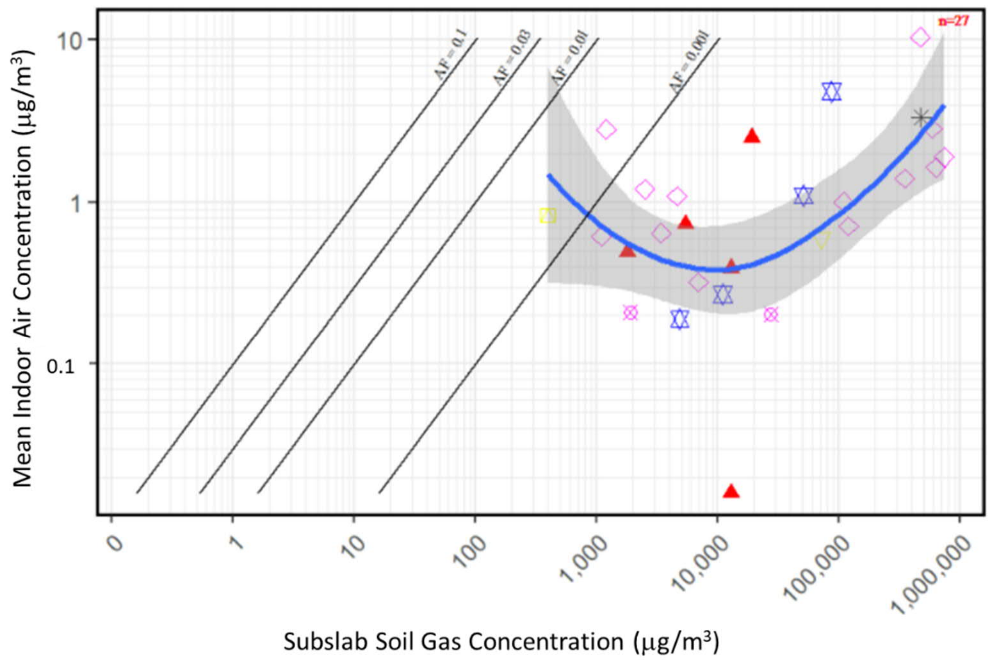


(a)

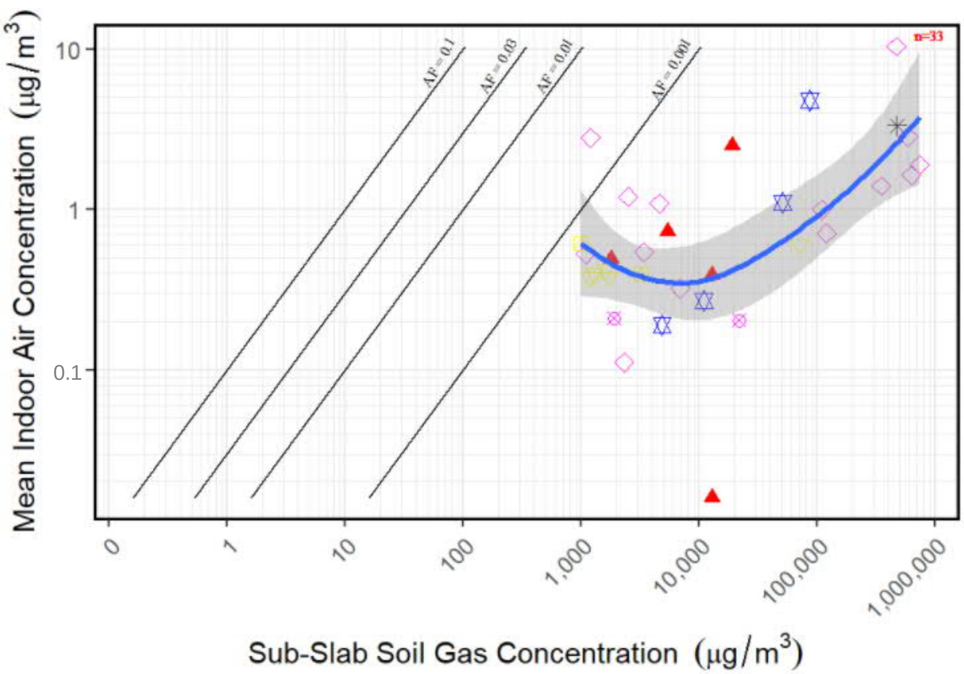


(b)

Figure 4-33. Paired Subslab Soil Gas-Indoor Air Concentration Plots for PCE with Each Data Pair Corresponding to a Building Sample Zone Average for a Given Sampling Event Passing the 1,000X Background Source Strength Screen
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Comparison between the approaches that include (a) only detectable concentrations in indoor air (i.e., indoor air non-detects excluded) and (b) non-detects in indoor air plotted at detection limit. Different symbols correspond to data from different DoD installations.



(a)

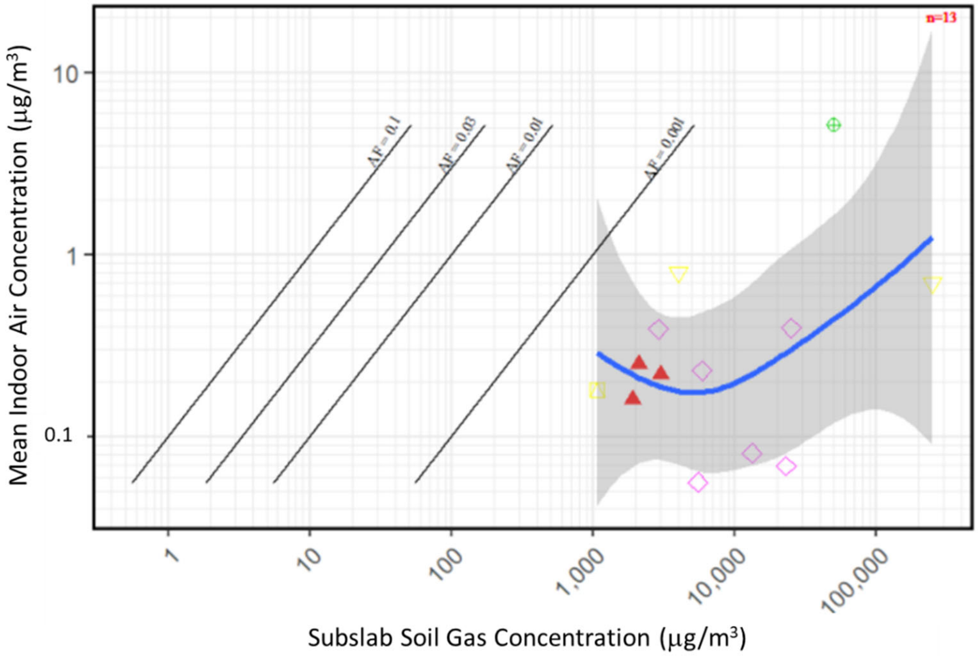


(b)

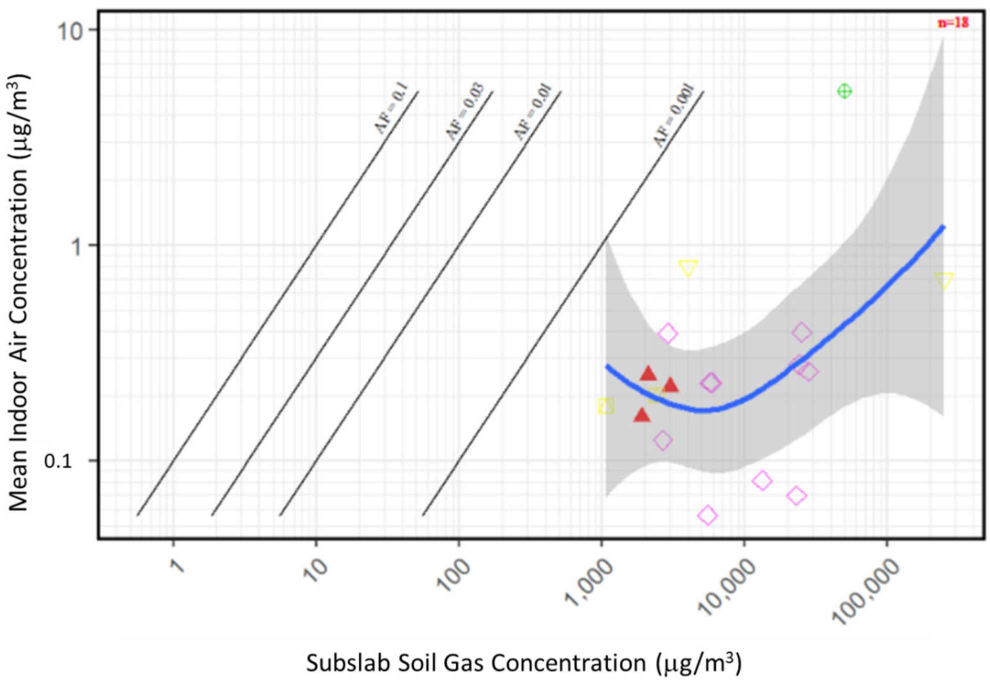
Figure 4-34. Paired Subslab Soil Gas-Indoor Air Concentration Plots for cis-1,2-DCE with Each Data Pair Corresponding to a Building Sample Zone Average for a Given Sampling Event Passing the 1,000 µg/m³ Fixed Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches that include (a) only detectable concentrations in indoor air (i.e., indoor air non-detects excluded) and (b) non-detects in indoor air plotted at detection limit. Different symbols correspond to data from different DoD installations.



(a)



(b)

Figure 4-35. Paired Subslab Soil Gas-Indoor Air Concentration Plots for 1,1-DCA with Each Data Pair Corresponding to a Building Sample Zone Average for a Given Sampling Event Passing the 1,000 µg/m³ Fixed Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches that include (a) only detectable concentrations in indoor air (i.e., indoor air non-detects excluded) and (b) non-detects in indoor air plotted at detection limit. Different symbols correspond to data from different DoD installations.

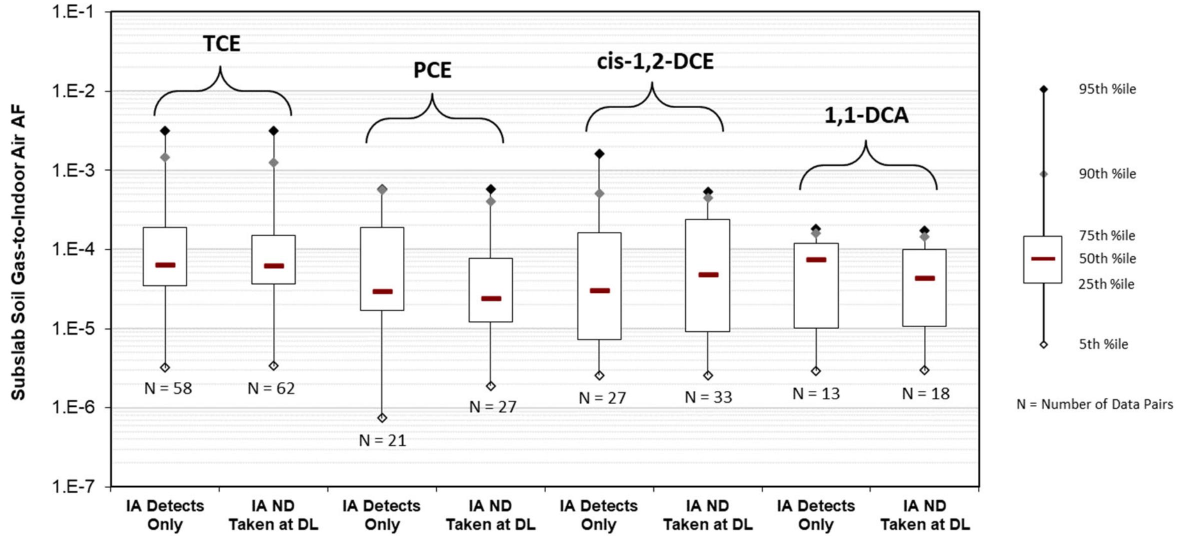


Figure 4-36. Box-and-Whisker Plots Summarizing the Subslab Soil Gas-to-Indoor Air AF Distribution Associated with Selected VOCs After Application of Either the 1,000X Background Source Strength Screen for TCE and PCE or the 1,000 µg/m^3 Fixed Source Strength Screen for cis-1,2-DCE and 1,1-DCA

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

The AF distributions are derived from building sample zone averages for individual sampling events. Comparison between distributions obtained using indoor air (IA) detects only and IA non-detects (ND) taken at detection limit (DL).

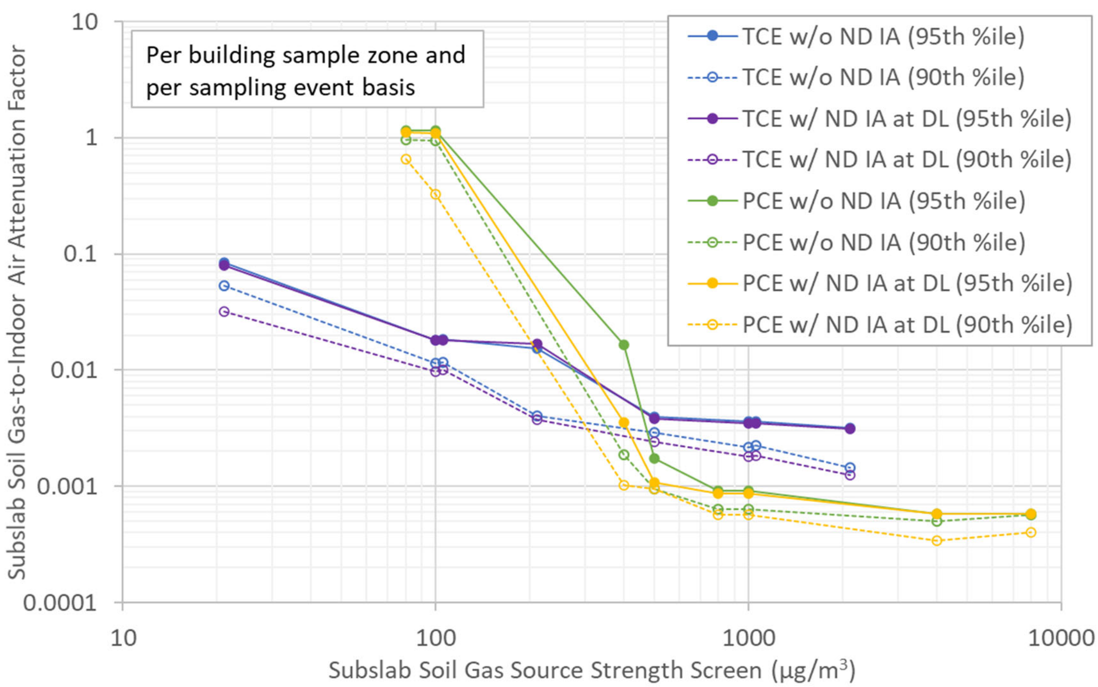


Figure 4-37. Plots of 90th and 95th Percentile Subslab Soil Gas-to-Indoor Air AFs Associated with TCE and PCE as a Function of Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Comparison of analyses using indoor air detects only and indoor air non-detects taken at detection limit.

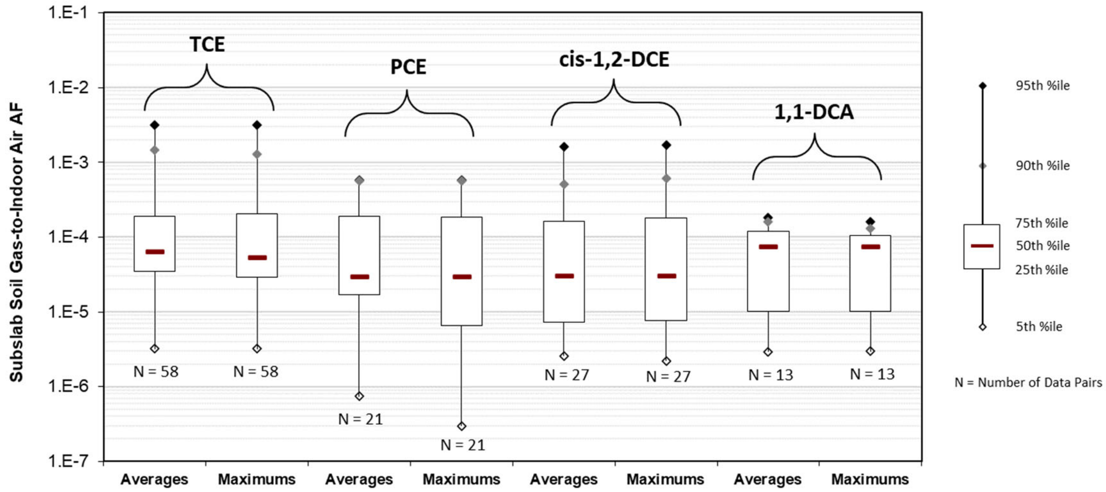


Figure 4-38. Box-and-Whisker Plots Summarizing the Subslab Soil Gas-to-Indoor Air AF Distribution Associated with Selected VOCs After Application of Either the 1,000X Background Source Strength Screen for TCE and PCE or the 1,000 μg/m^3 Fixed Source Strength Screen for cis-1,2-DCE and 1,1-DCA

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

The AF distributions are derived for individual sampling events using either building sample zone average subslab soil gas and indoor air concentrations ("averages") or building sample zone maximum subslab soil gas and indoor air concentrations ("maximums"). Pairs with an indoor air concentration below detection limit are not included.

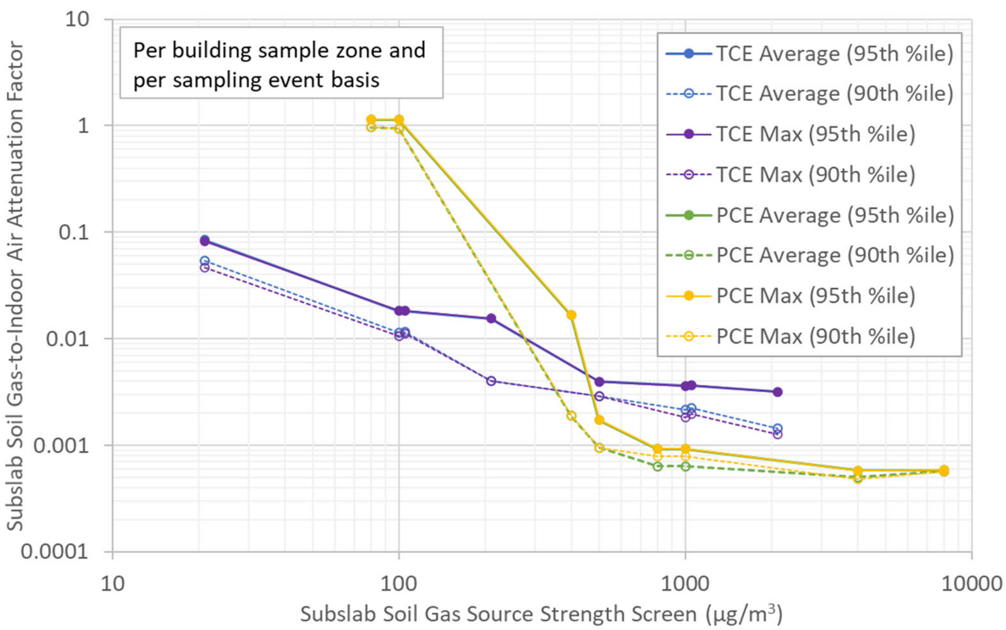


Figure 4-39. Plots of 90th and 95th Percentile Subslab Soil Gas-to-Indoor Air AFs Associated with TCE and PCE as a Function of Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison of analyses using AFs obtained using building sample zone average and maximum concentrations in subslab soil gas and indoor air for a given sampling event. Pairs with an indoor air concentration below detection limit are not included.

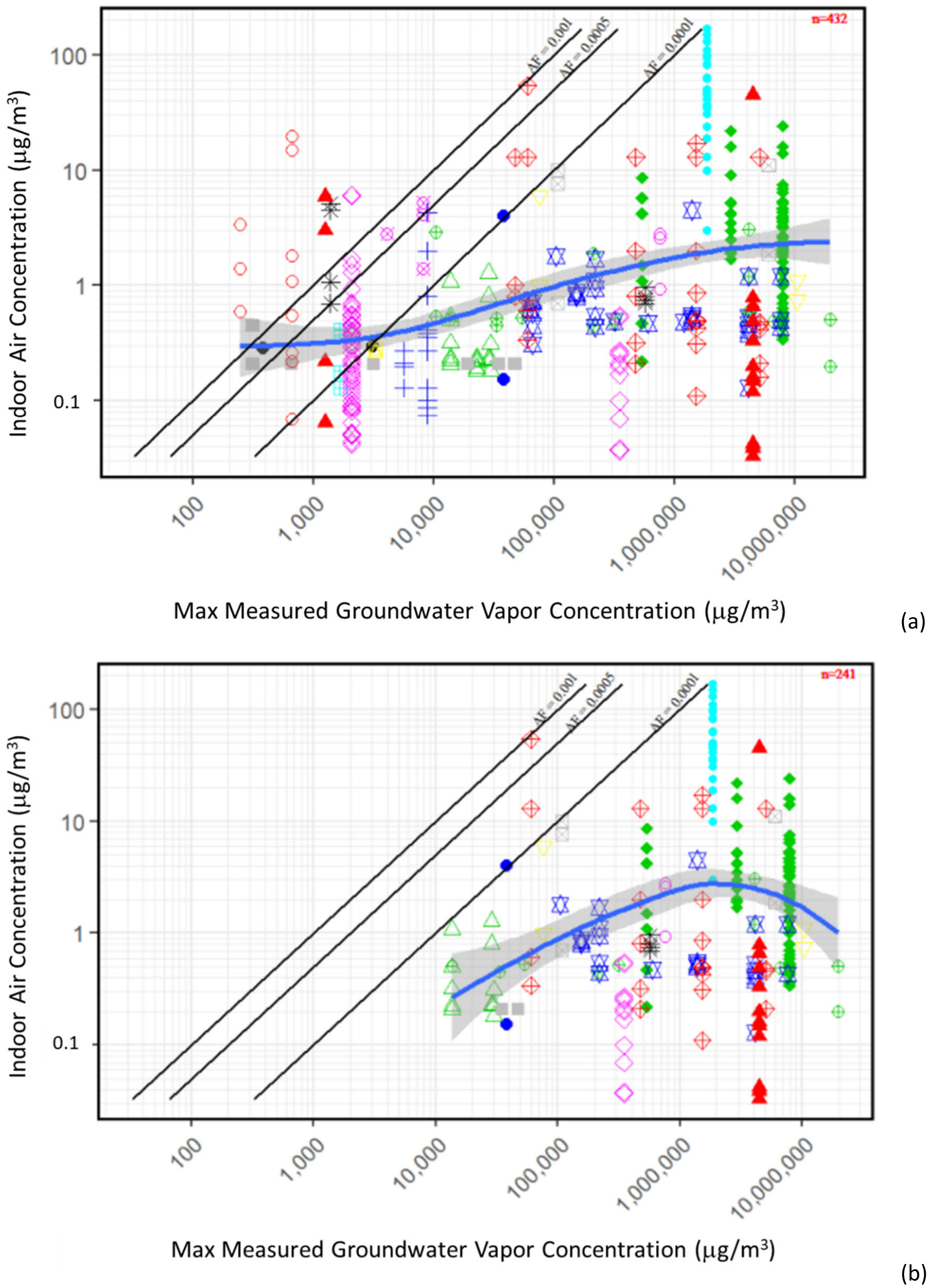
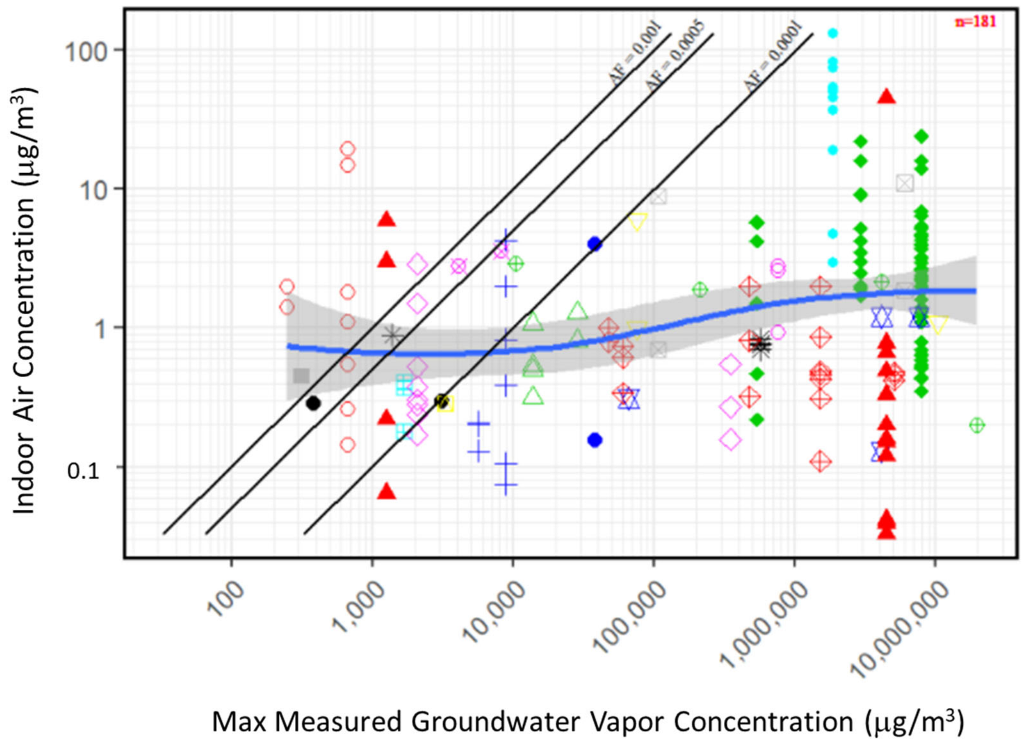


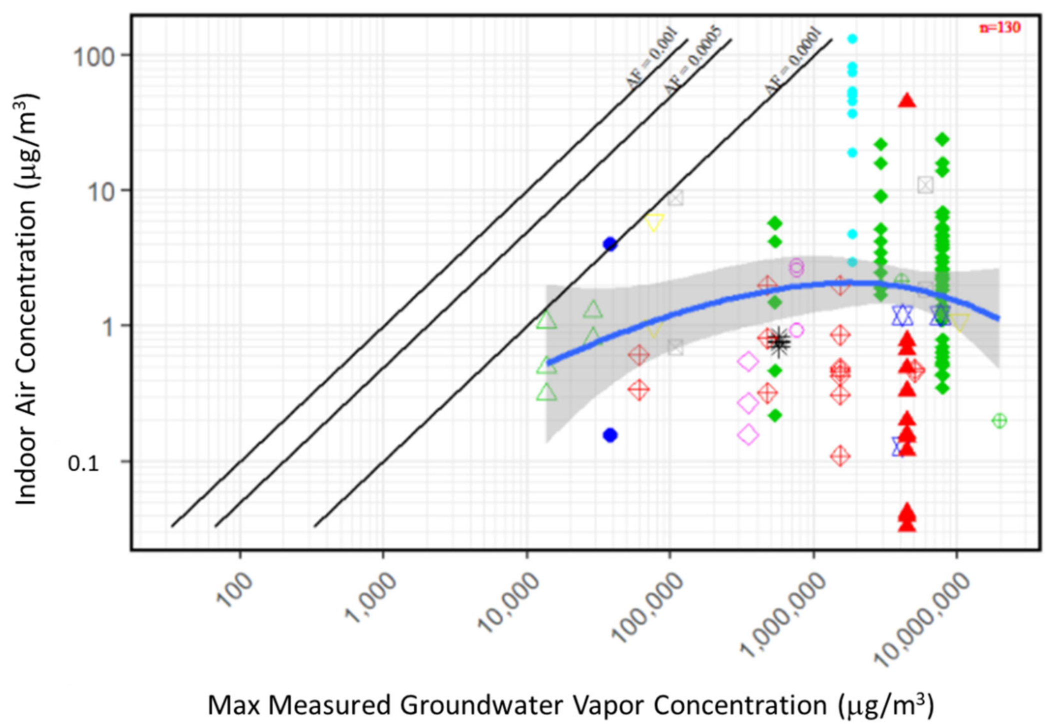
Figure 4-40. Examples of Paired Groundwater-Indoor Air Concentration Plots for TCE Showing All Individual Data Pairs Passing the (a) 100X and (b) 5,000X Background Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Different symbols correspond to data from different DoD installations.



(a)

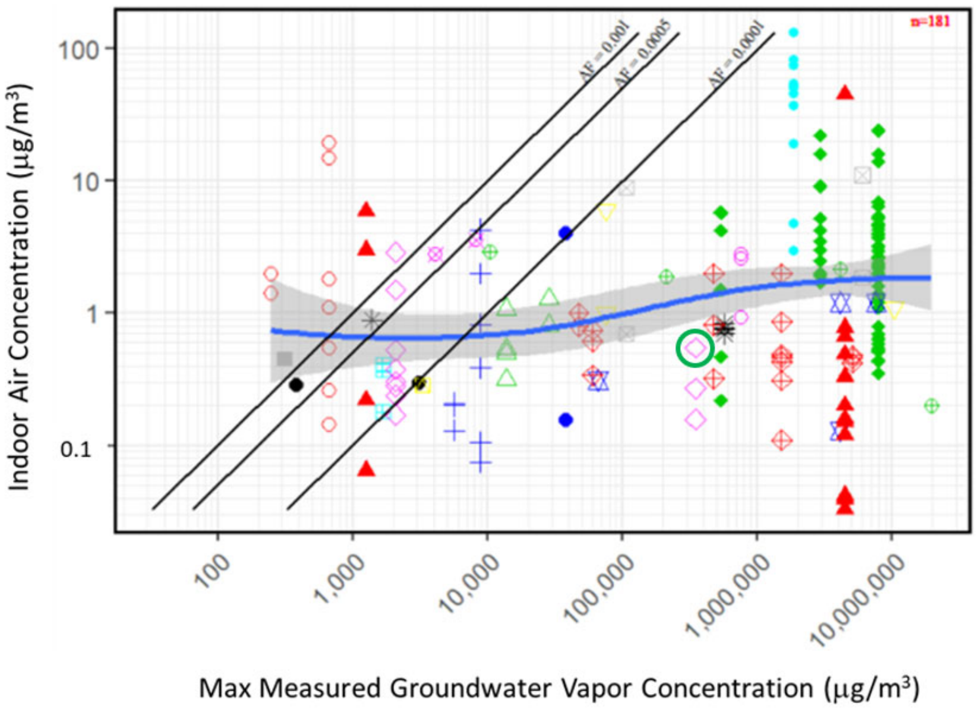


(b)

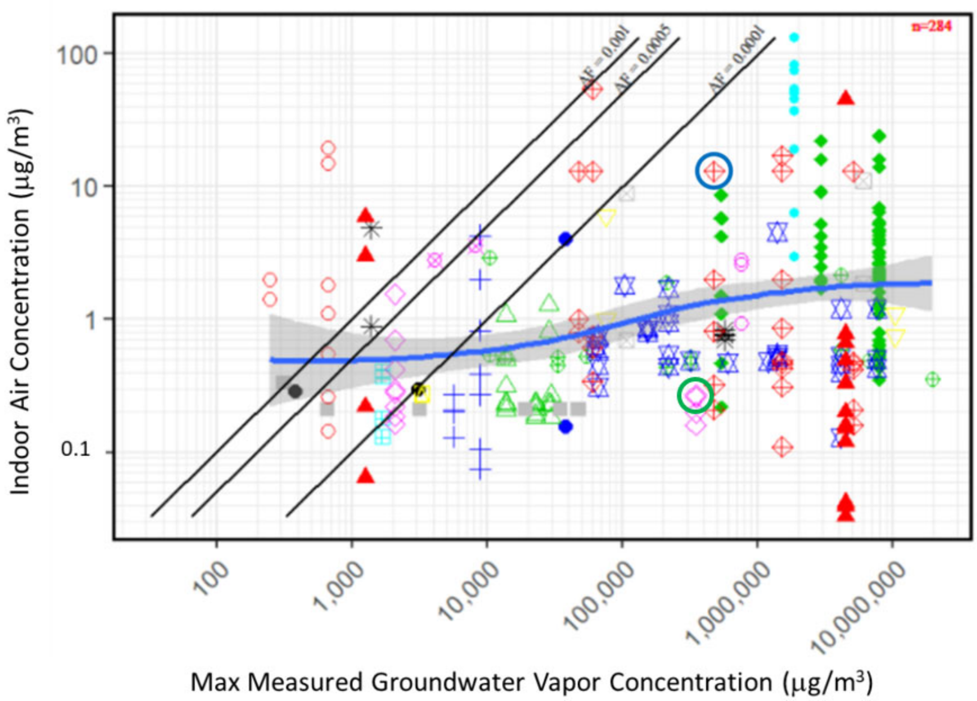
Figure 4-41. Examples of Paired Groundwater-Indoor Air Concentration Plots for TCE with Each Data Pair Corresponding to a Building Sample Zone Average for a Given Sampling Event Passing the (a) 100X (b) 5,000X Background Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.



(a)

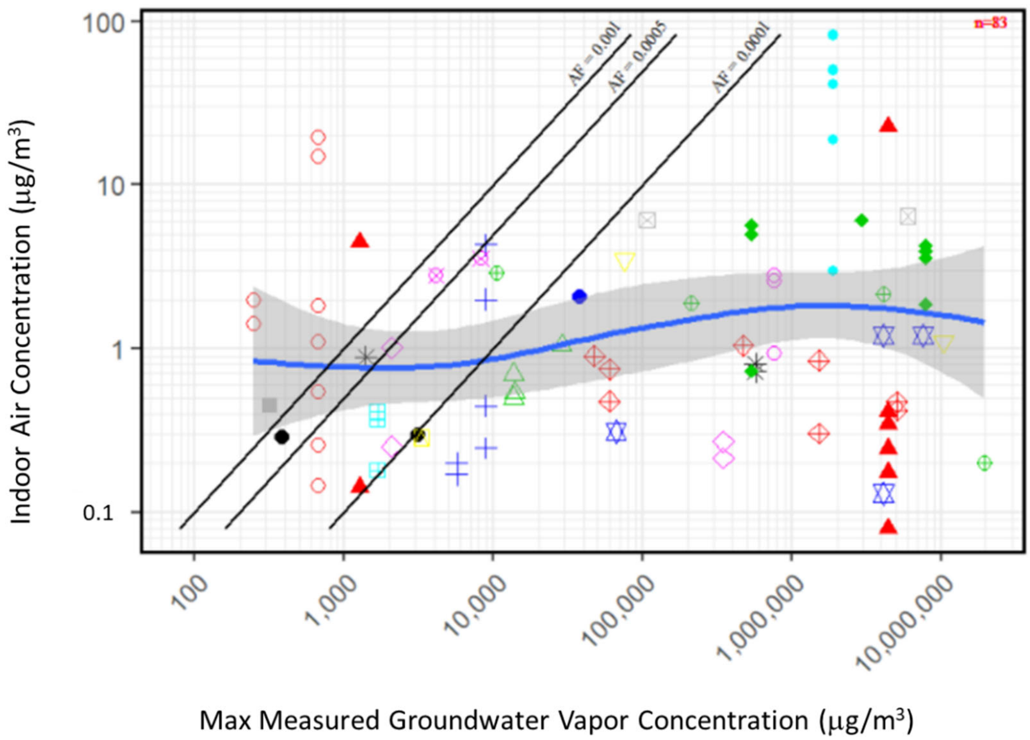


(b)

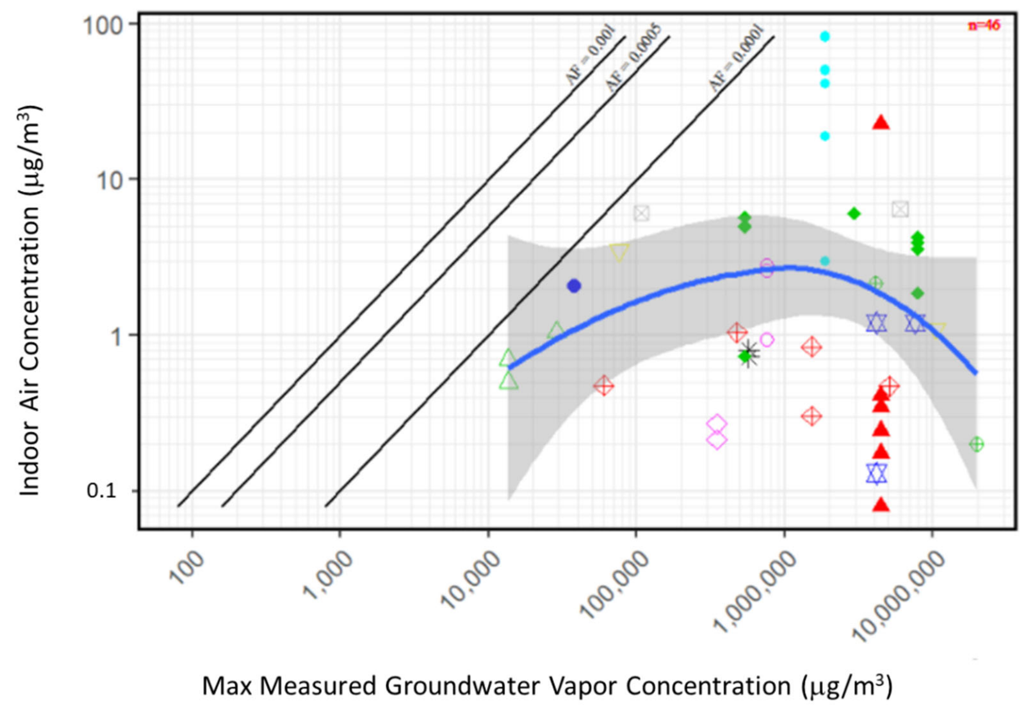
Figure 4-42. Examples of Paired Groundwater-Indoor Air Concentration Plots for TCE with Each Data Pair Corresponding to a Building Sample Zone Average for a Given Sampling Event Passing the 100X Background Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between plots that include (a) only detectable concentrations in indoor air (i.e., indoor air non-detects excluded) and (b) non-detects in indoor air plotted at detection limit. Different symbols correspond to data from different DoD installations. Refer to Section 4.2.1.3 for additional discussion regarding the points circled in blue and in green.



(a)



(b)

Figure 4-43. Examples of Paired Groundwater-Indoor Air Concentration Plots for TCE with each Data Pair Corresponding to a Building Sample Zone Average for all Sampling Events Passing the (a) 100X and (b) 5,000X Background Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.

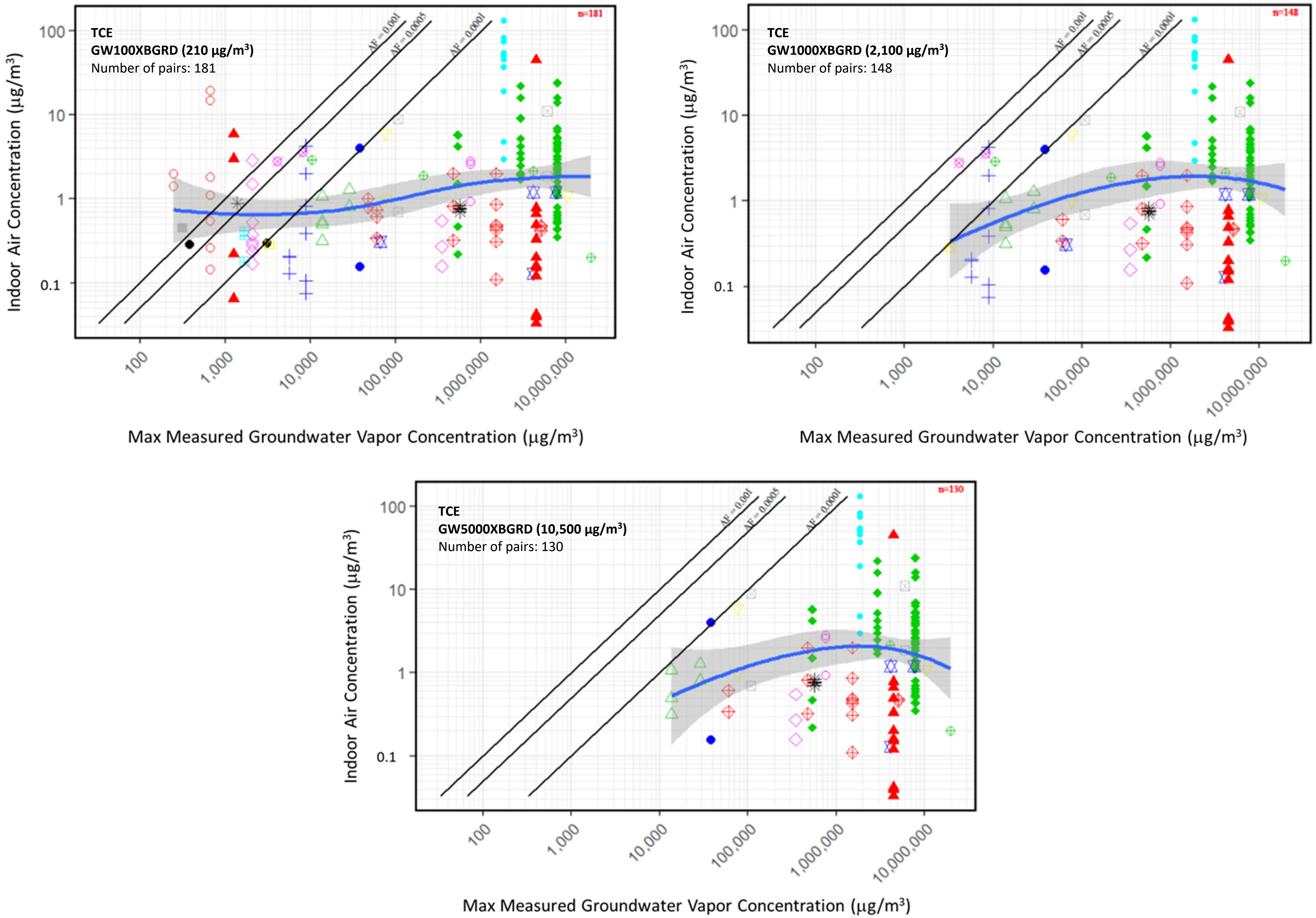


Figure 4-44. Paired Groundwater-Indoor Air Concentration Plots for TCE for Increasing Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each data pair corresponds to a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.

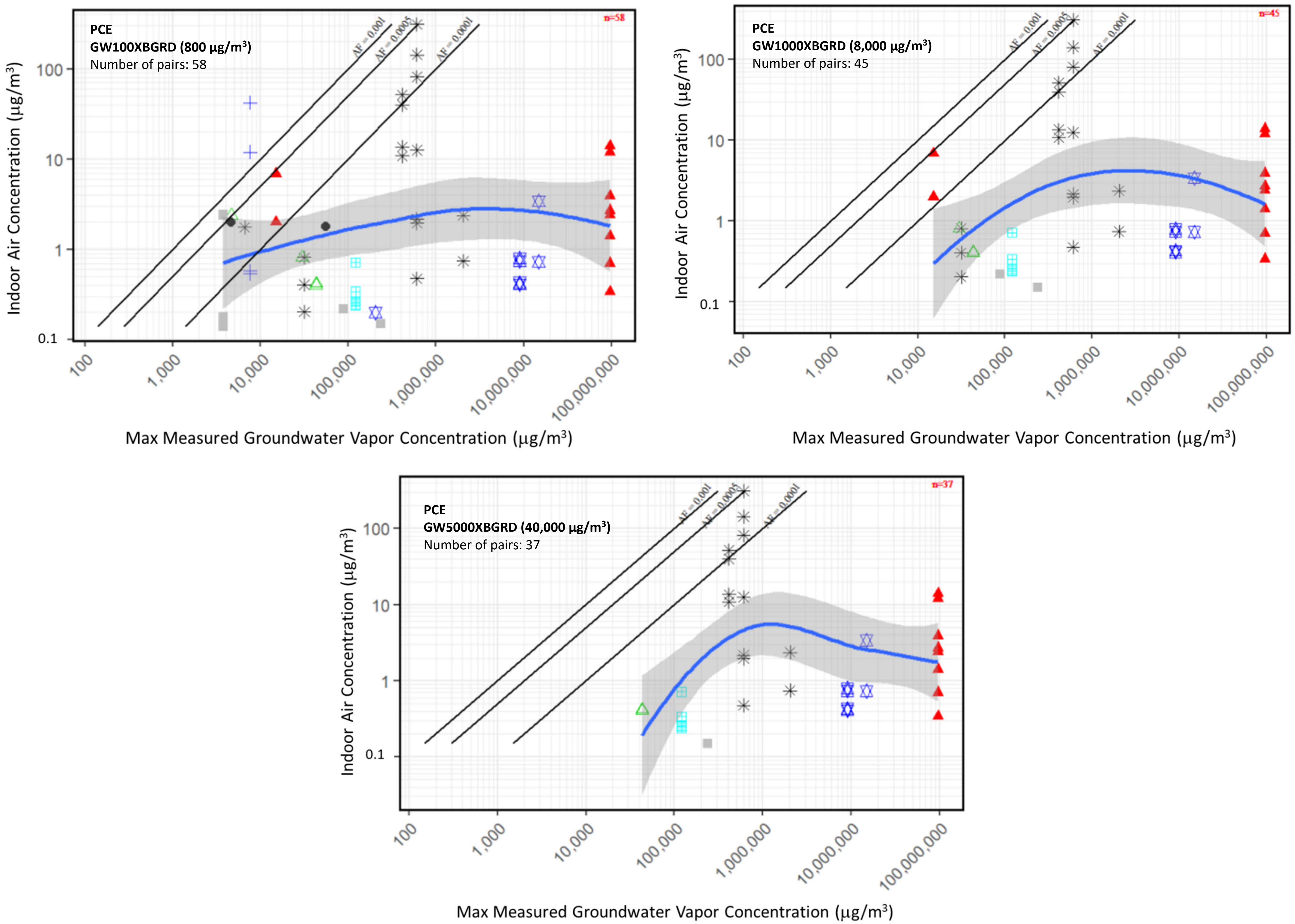


Figure 4-45. Paired Groundwater-Indoor Air Concentration Plots for PCE for Increasing Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each data pair corresponds to a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.

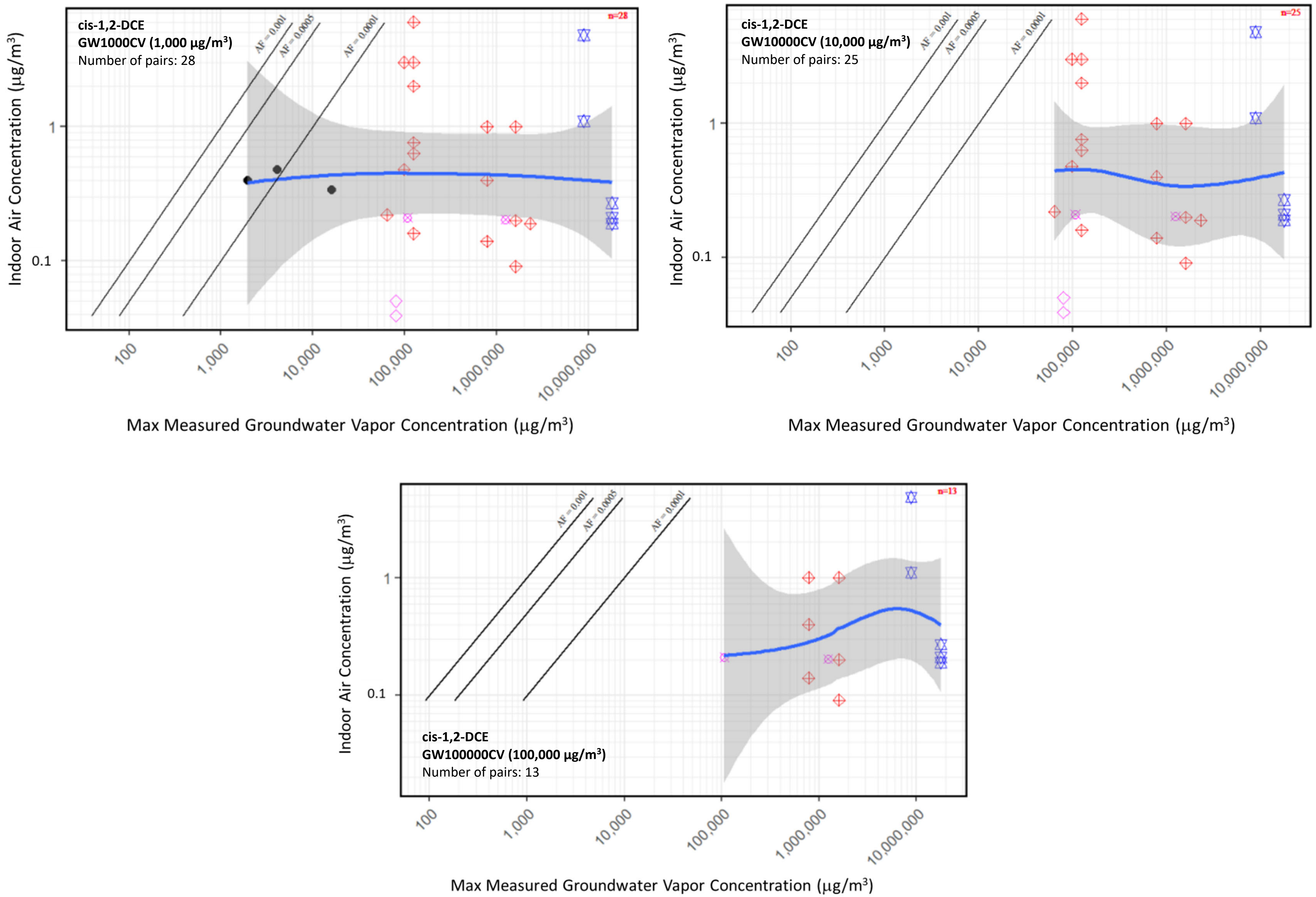


Figure 4-46. Paired groundwater-indoor air concentration plots for cis-1,2-DCE for Increasing Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each data pair corresponds to a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.

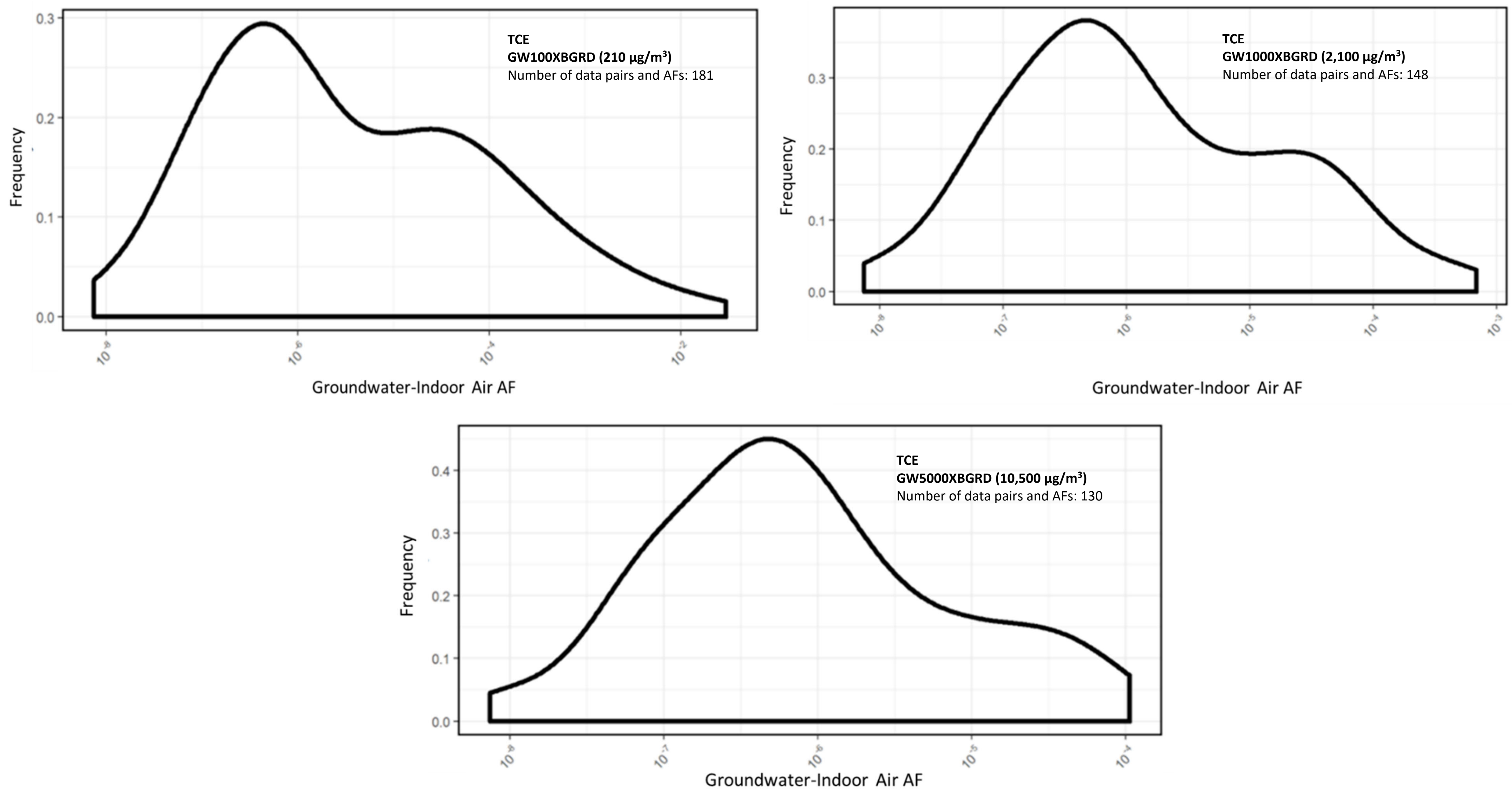


Figure 4-47. Groundwater-to-Indoor Air AF Frequency Distribution Plots for TCE After Application of Source Strength Screens Ranging From 100X to 5,000X Background for TCE (210 to 10,500 µg/m³)

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Data pairs with an indoor air concentration below detection limit are not included.

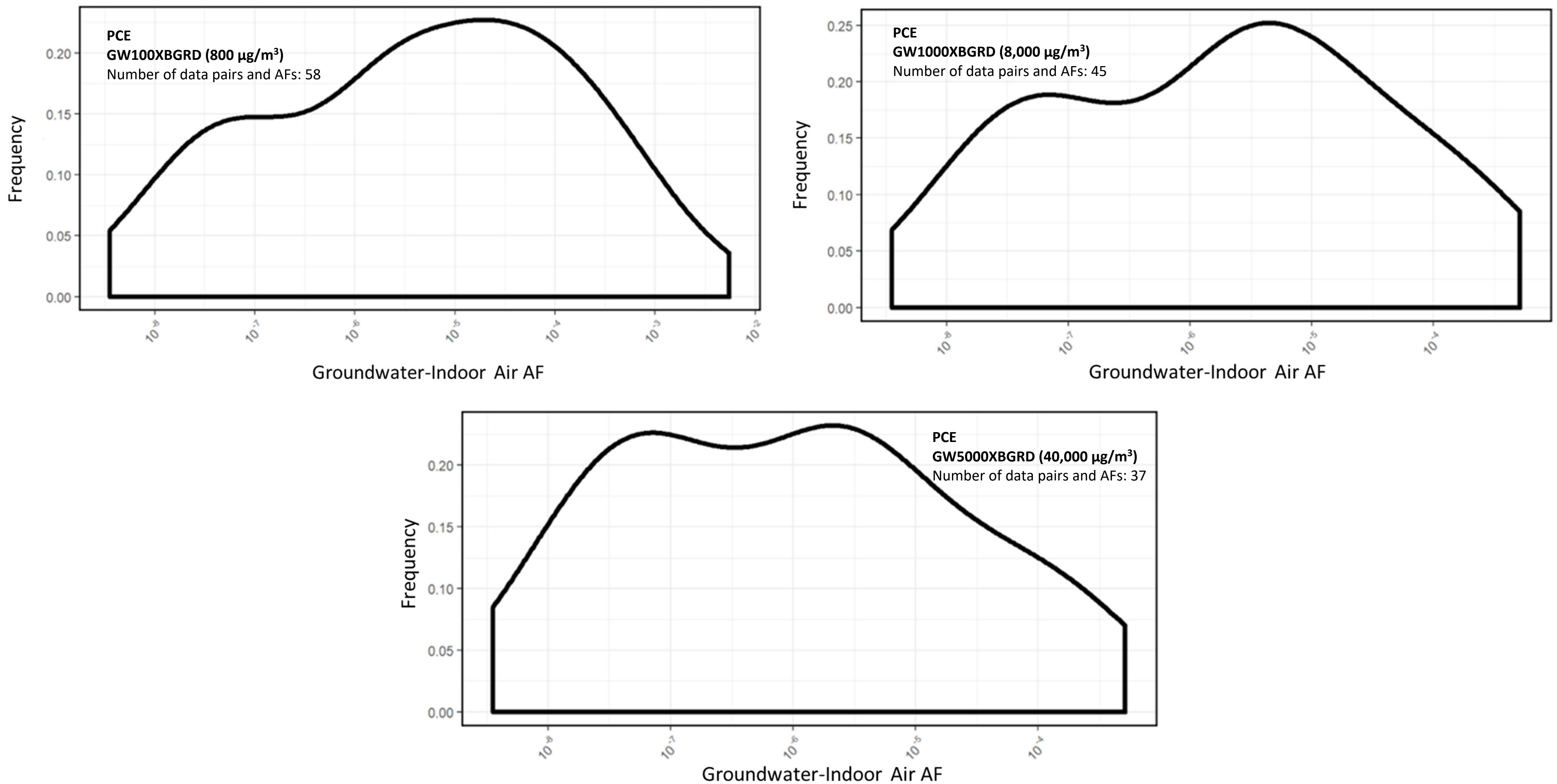


Figure 4-48. Groundwater-to-Indoor Air AF Frequency Distribution Plots for TCE After Application of Source Strength Screens Ranging from 100X to 5,000X Background for PCE (800 to 40,000 µg/m^3)

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Data pairs with an indoor air concentration below detection limit are not included.

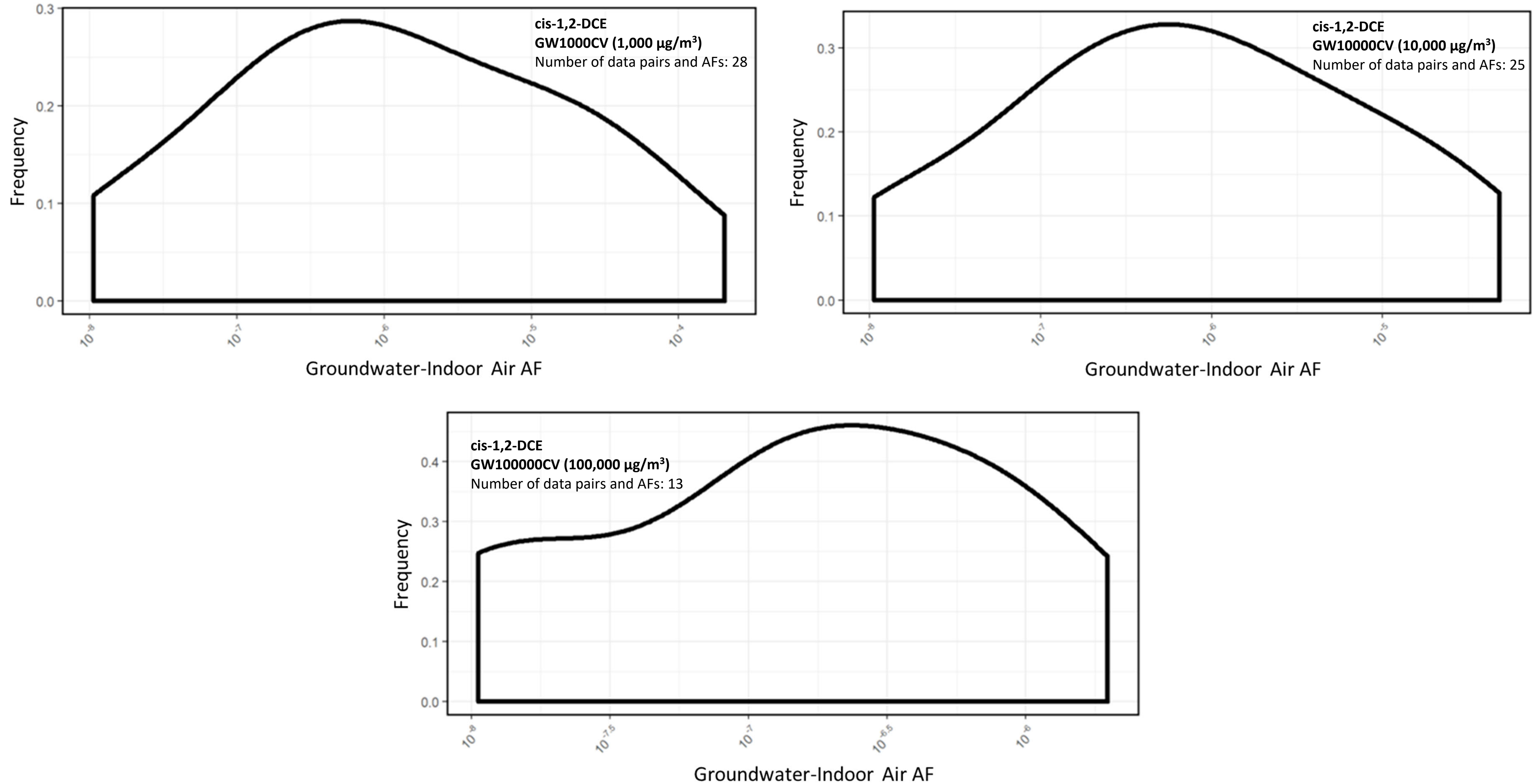


Figure 4-49. Groundwater-to-Indoor Air AF Frequency Distribution Plots for cis-1,2-DCE After Application of Fixed Source Strength Screens Ranging from 1,000 to 100,000 µg/m³

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Data pairs with an indoor air concentration below detection limit are not included.

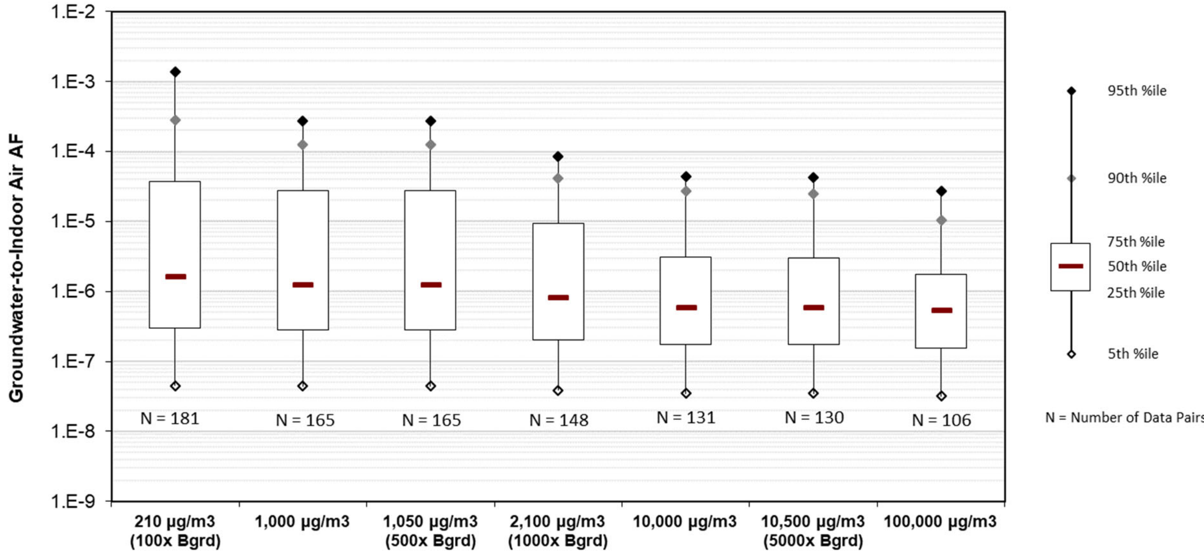


Figure 4-50. Box-and-Whisker Plots Summarizing the Groundwater-to-Indoor Air AF distribution Associated with TCE After Application of the Various Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included.

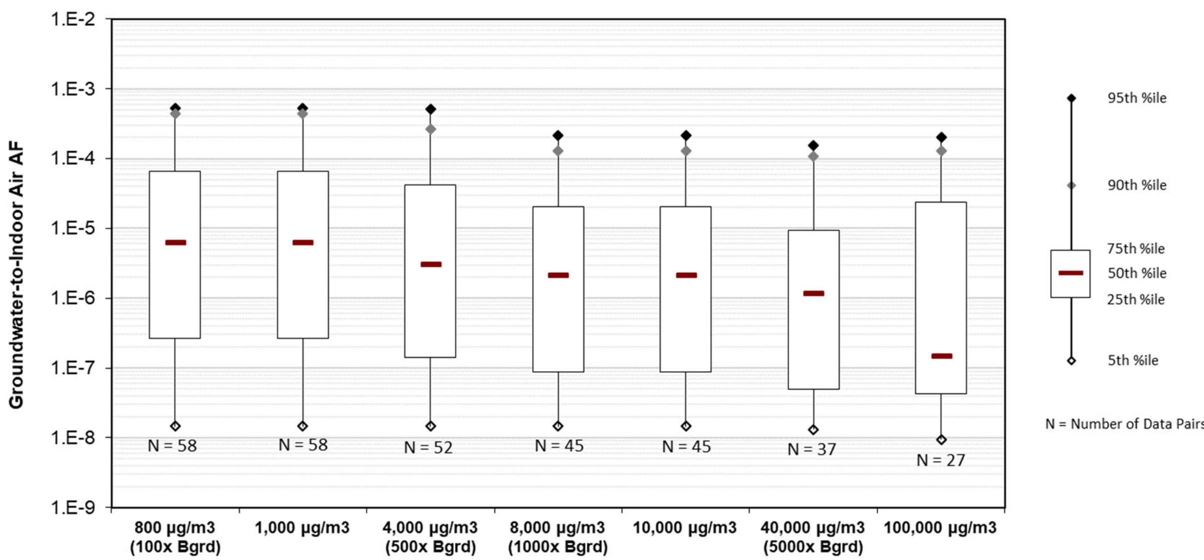


Figure 4-51. Box-and-Whisker Plots Summarizing the Groundwater-to-Indoor air AF Distribution Associated with PCE After Application of the Various Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included.

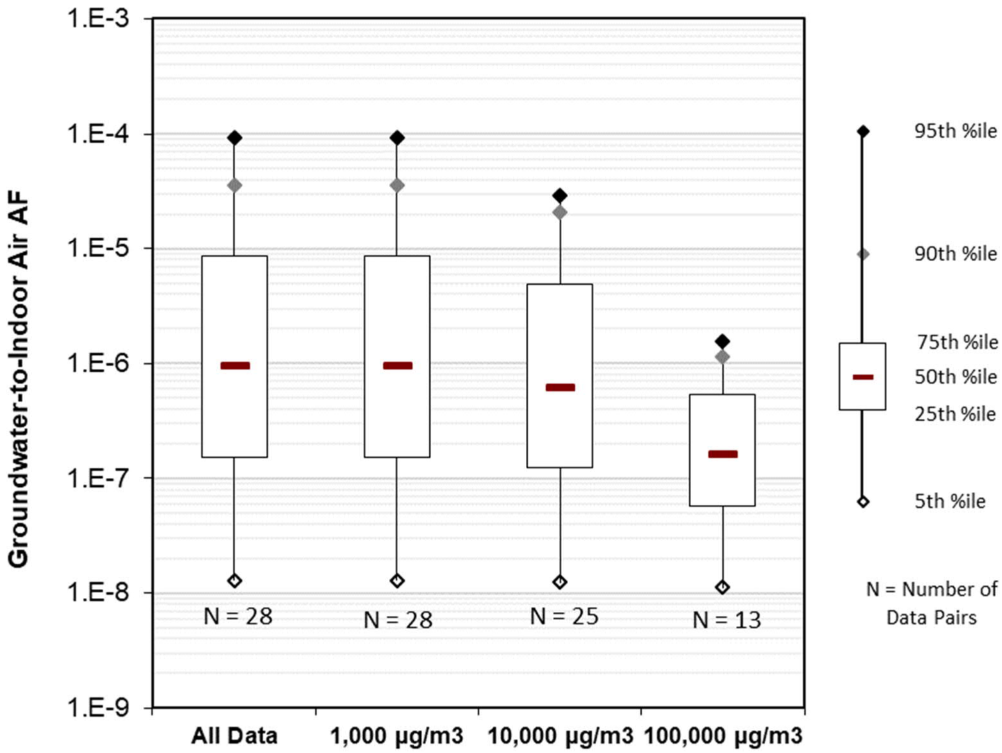
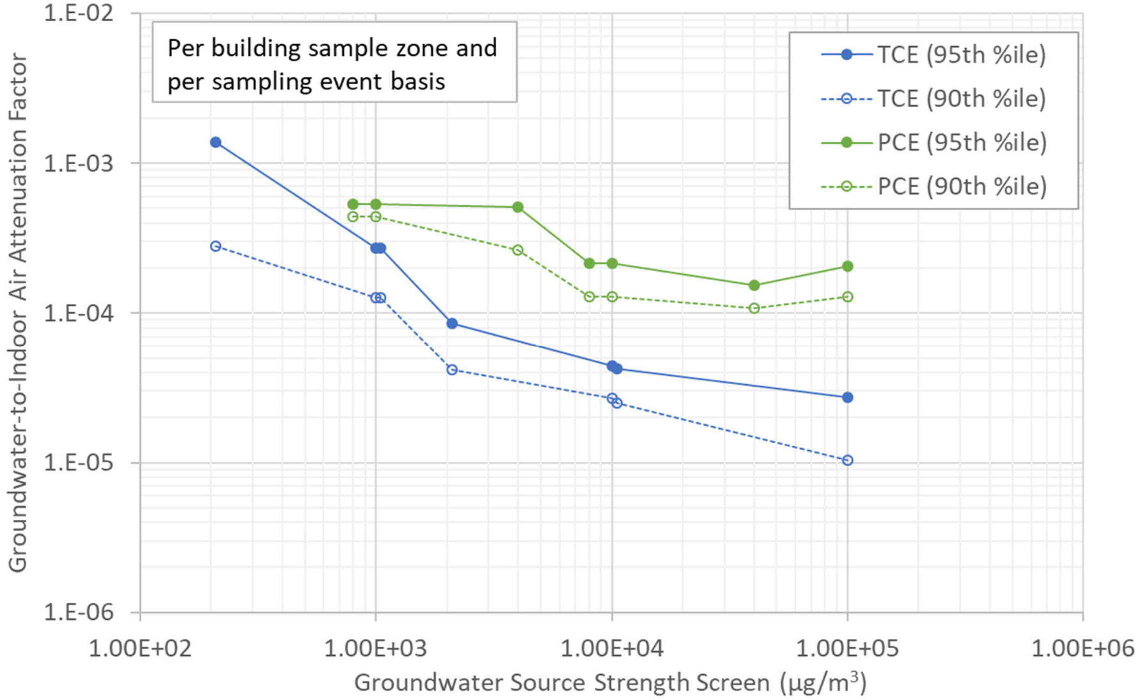


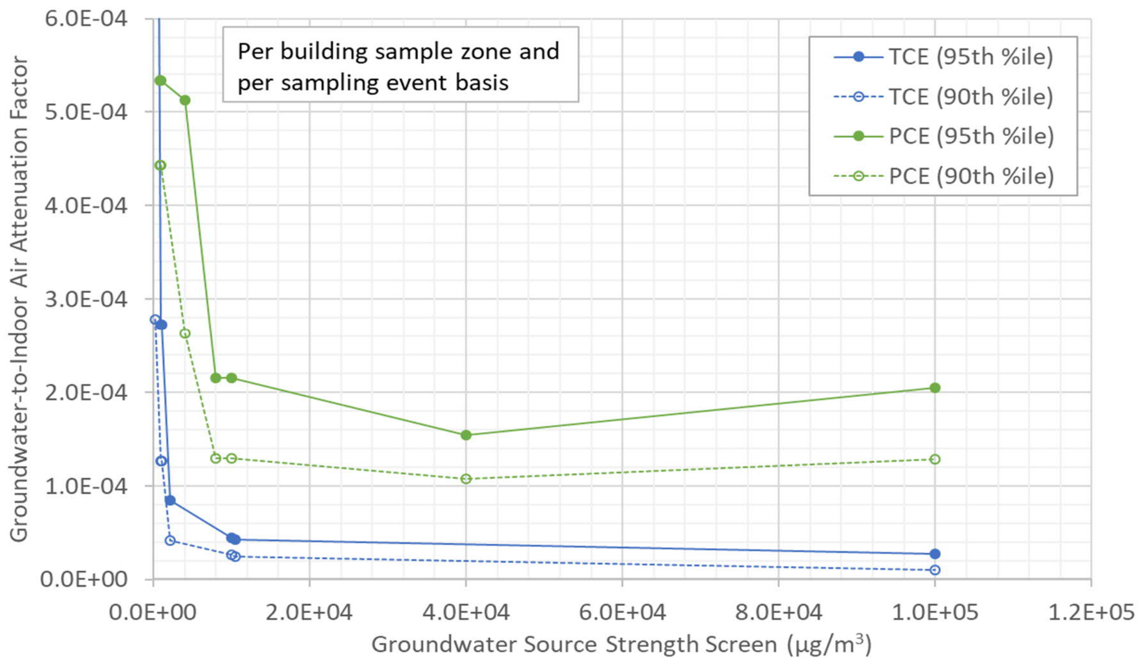
Figure 4-52. Box-and-Whisker Plots Summarizing the Groundwater-to-Indoor Air AF Distribution Associated with cis-1,2-DCE After Application of the Various Source Strength Screens

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included.



(a)



(b)

Figure 4-53. Plots of 90th and 95th Percentile Groundwater-to-Indoor Air AFs Associated with TCE and PCE as a Function of Source Strength Screen Using (a) Log Scale and (b) Linear Scale

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included.

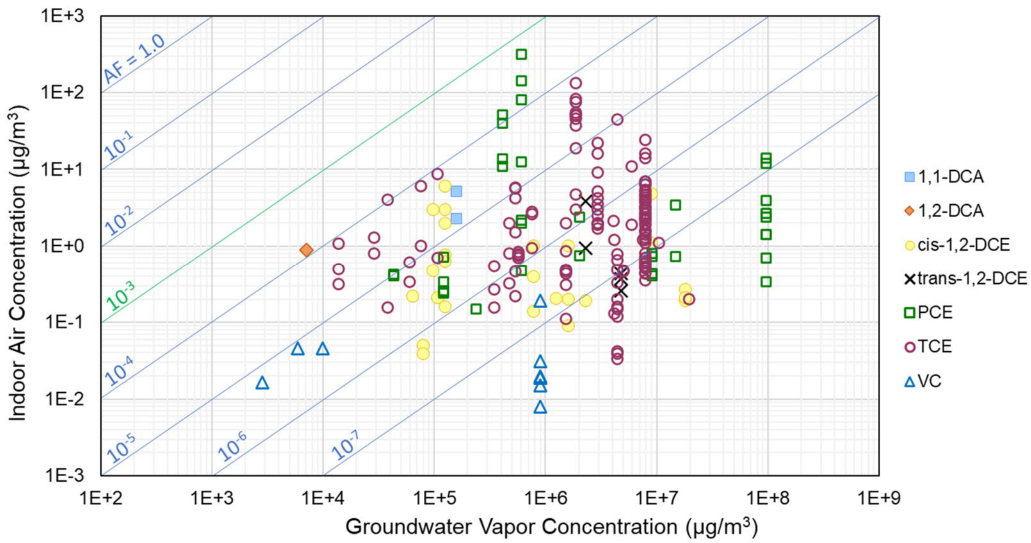


Figure 4-54. Paired Groundwater-Indoor Air Concentration Plots for all VOCs in the Analysis

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each data pair represents the groundwater vapor and average indoor air concentrations for a building sample zone for a given sampling event. The pairs on the plots passed either the 5,000X background source strength screen for VOCs with background values (TCE, PCE, 1,2-DCA, and VC) or the 10,000 µg/m³ source strength screen for VOCs without background values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE). Pairs with an indoor air concentration below detection limit are not shown. The blue oblique lines represent groundwater-to-indoor air AF lines ranging from 10^{-7} to 1.0. The green line represents the USEPA default AF of 10^{-3}. There were no pairs meeting the various filtering criteria for 1,1,1-TCA and 1,1-DCE.

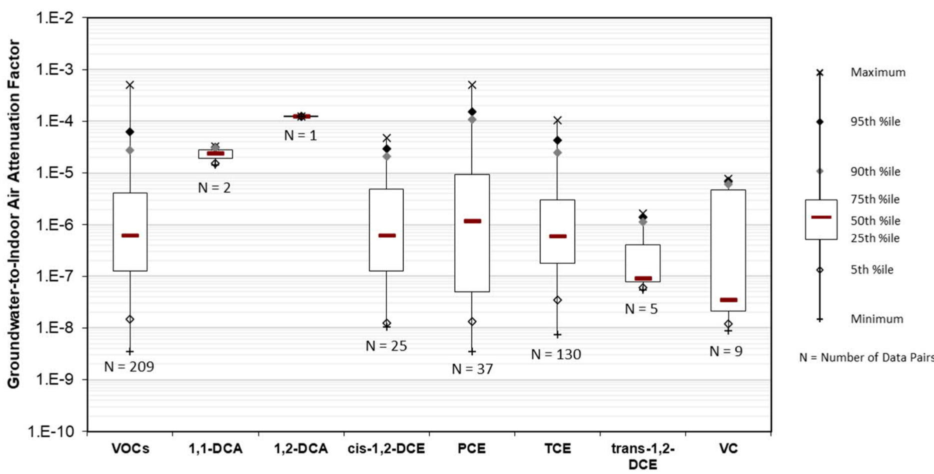
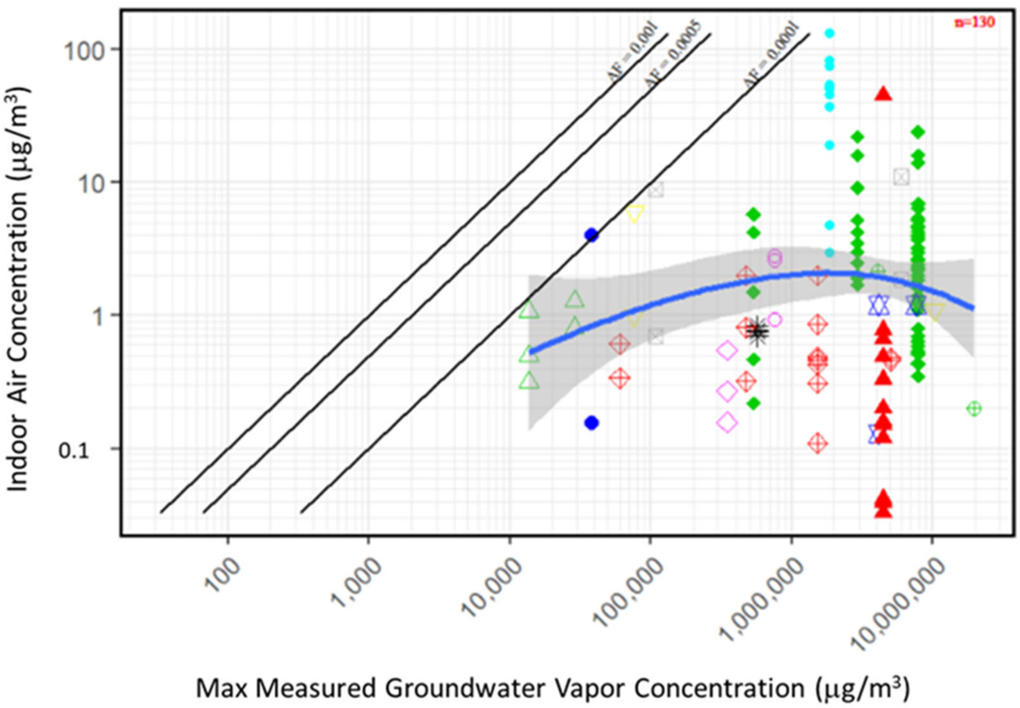


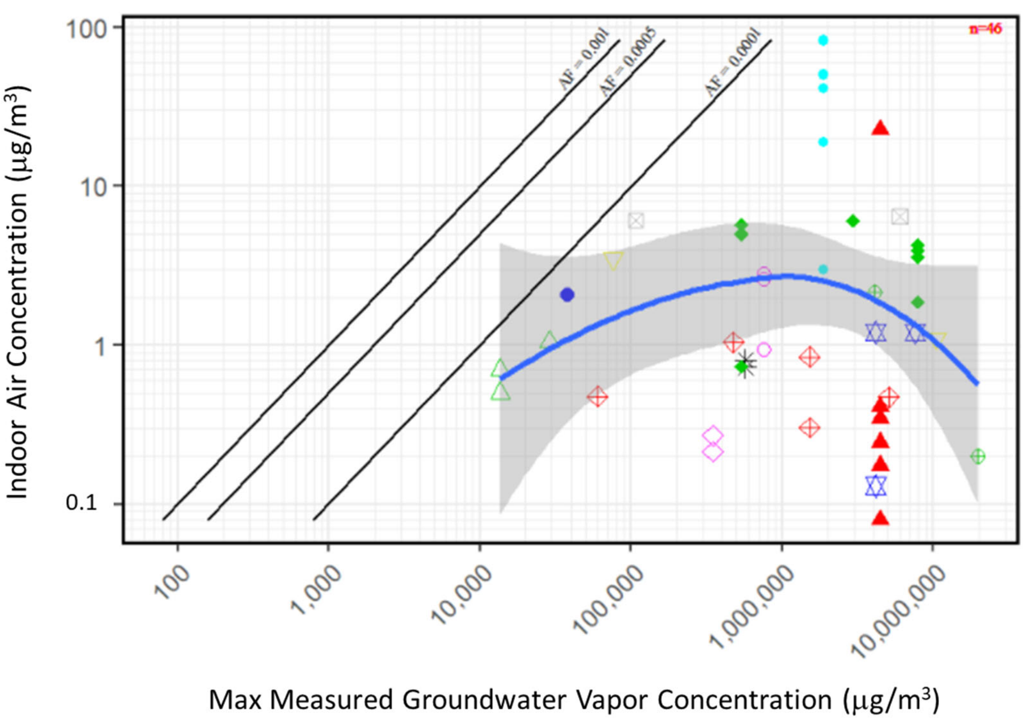
Figure 4-55. Box-and-Whisker Plots Summarizing the Groundwater-to-Indoor Air AF Distribution Associated with the VOCs After Application of Either the 5,000X Background Source Strength Screen for VOCs with Background Values (TCE, PCE, 1,2-DCA, and VC) or the 10,000 µg/m³ Source Strength Screen for VOCs without Background Values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE)

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Pairs with an indoor air concentration below detection limit are not included. There were no pairs meeting the various filtering criteria for 1,1,1-TCA and 1,1-DCE.



(a)

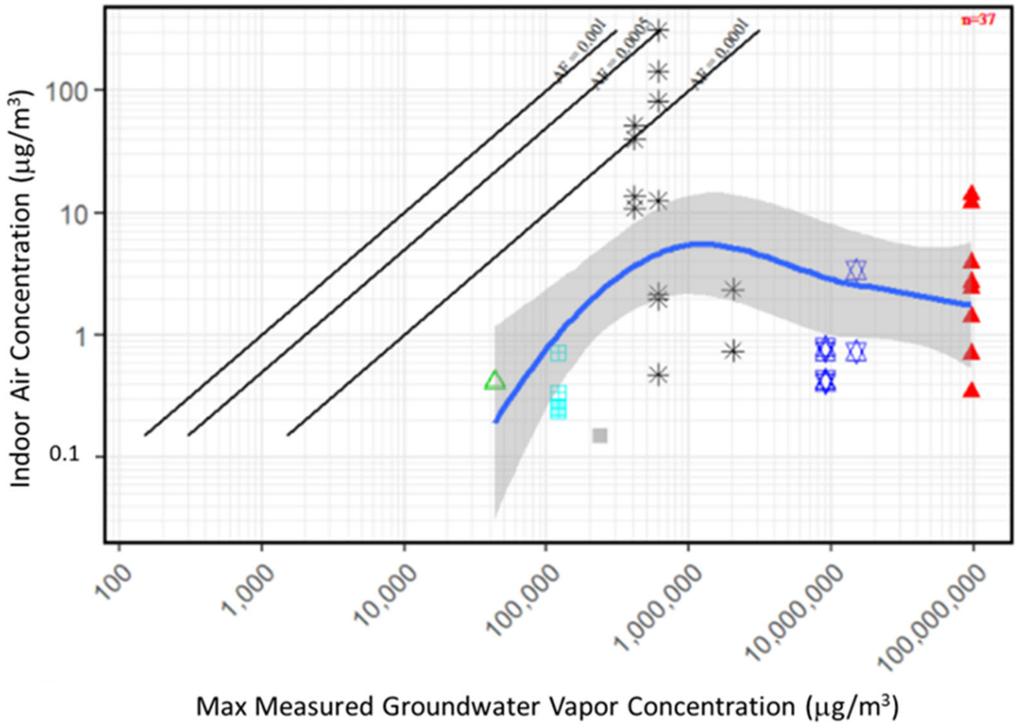


(b)

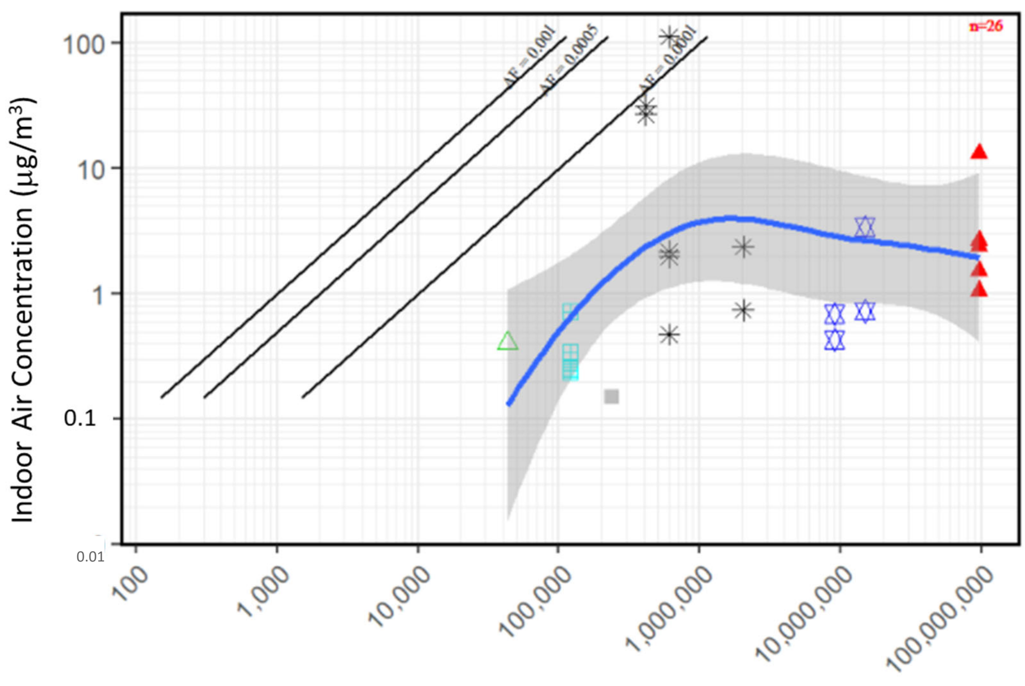
Figure 4-56. Paired Groundwater-Indoor Air Concentration Plots for TCE for Data Passing the 5,000X Background Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches using (a) building sample zone averages for individual sampling events and (b) building sample zone averages for all sampling events. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.



(a)

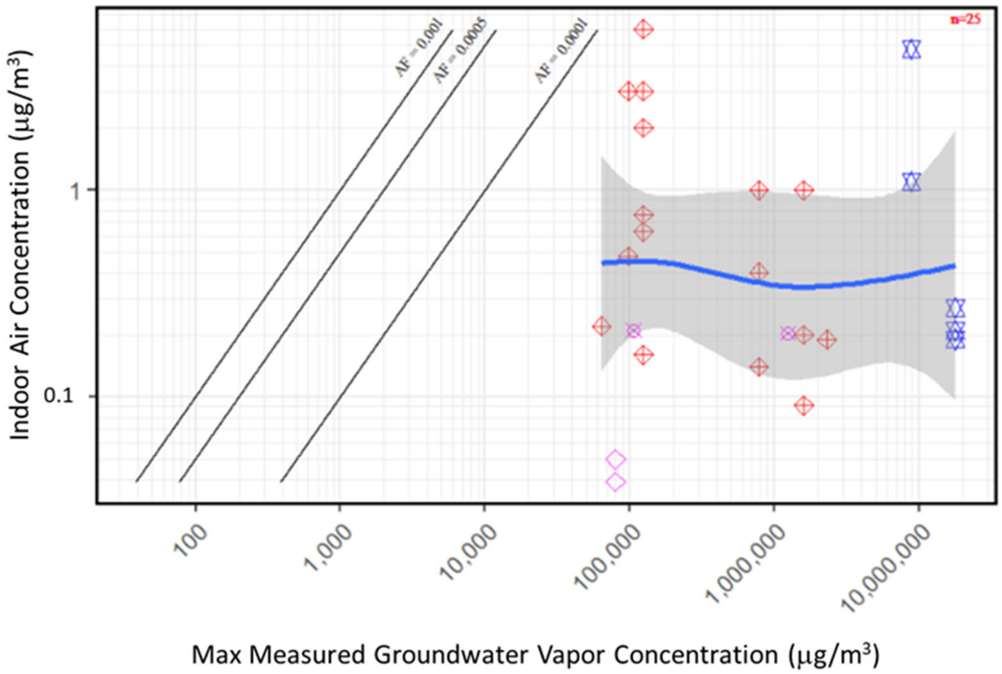


(b)

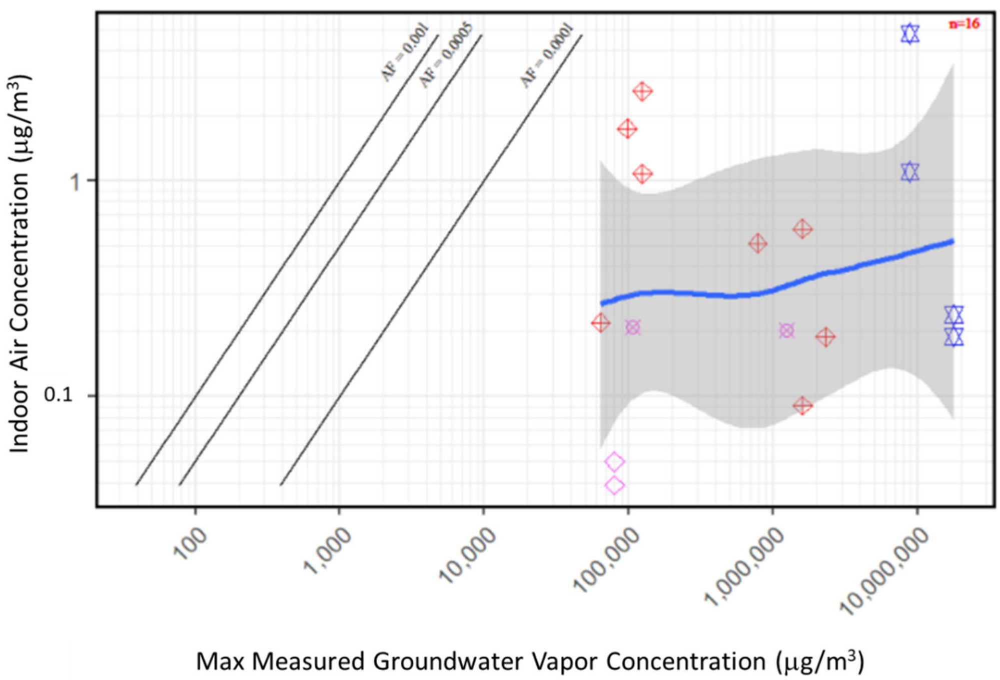
Figure 4-57. Paired groundwater-Indoor Air Concentration Plots for PCE for Data Passing the 5,000X Background Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches using (a) building sample zone averages for individual sampling events and (b) building sample zone averages for all sampling events. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.



(a)



(b)

Figure 4-58. Paired Groundwater-Indoor Air Concentration Plots for cis-1,2-DCE for Data Passing the 10,000 µg/m³ Fixed Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches using (a) building sample zone averages for individual sampling events and (b) building sample zone averages for all sampling events. Pairs with an indoor air concentration below detection limit are not included. Different symbols correspond to data from different DoD installations.

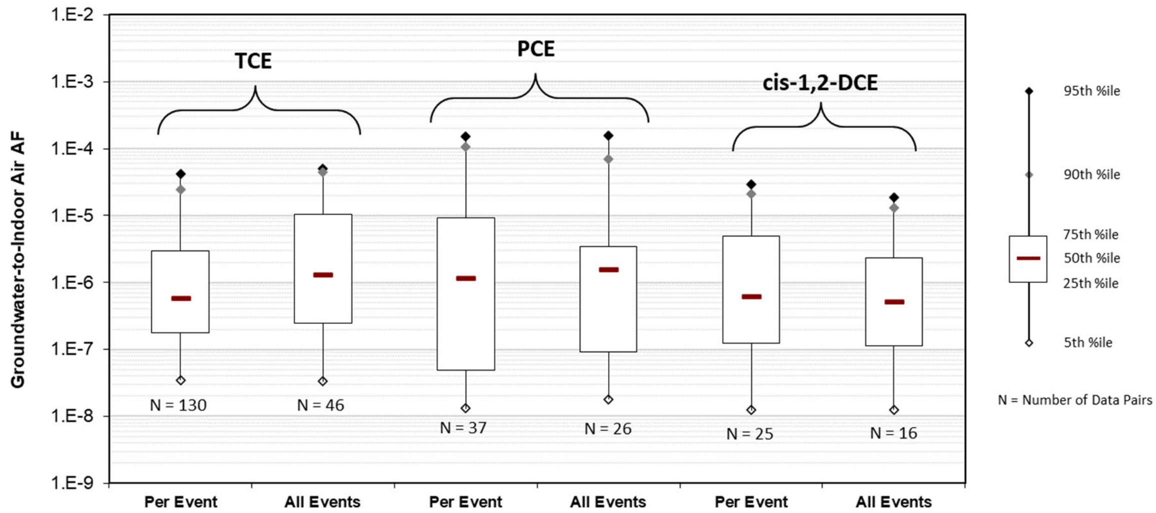


Figure 4-59. Box-and-Whisker Plots Summarizing the Groundwater-to-Indoor Air AF Distribution Associated with Selected VOCs After Application of Either the 5,000X Background Source Strength Screen for TCE and PCE or the 10,000 µg/m^3 Fixed Source Strength Screen for cis-1,2-DCE

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between AF distributions derived from building sample zone averages for individual sampling events ("per event") and for all sampling events ("all events"). Pairs with an indoor air concentration below detection limit are not included.

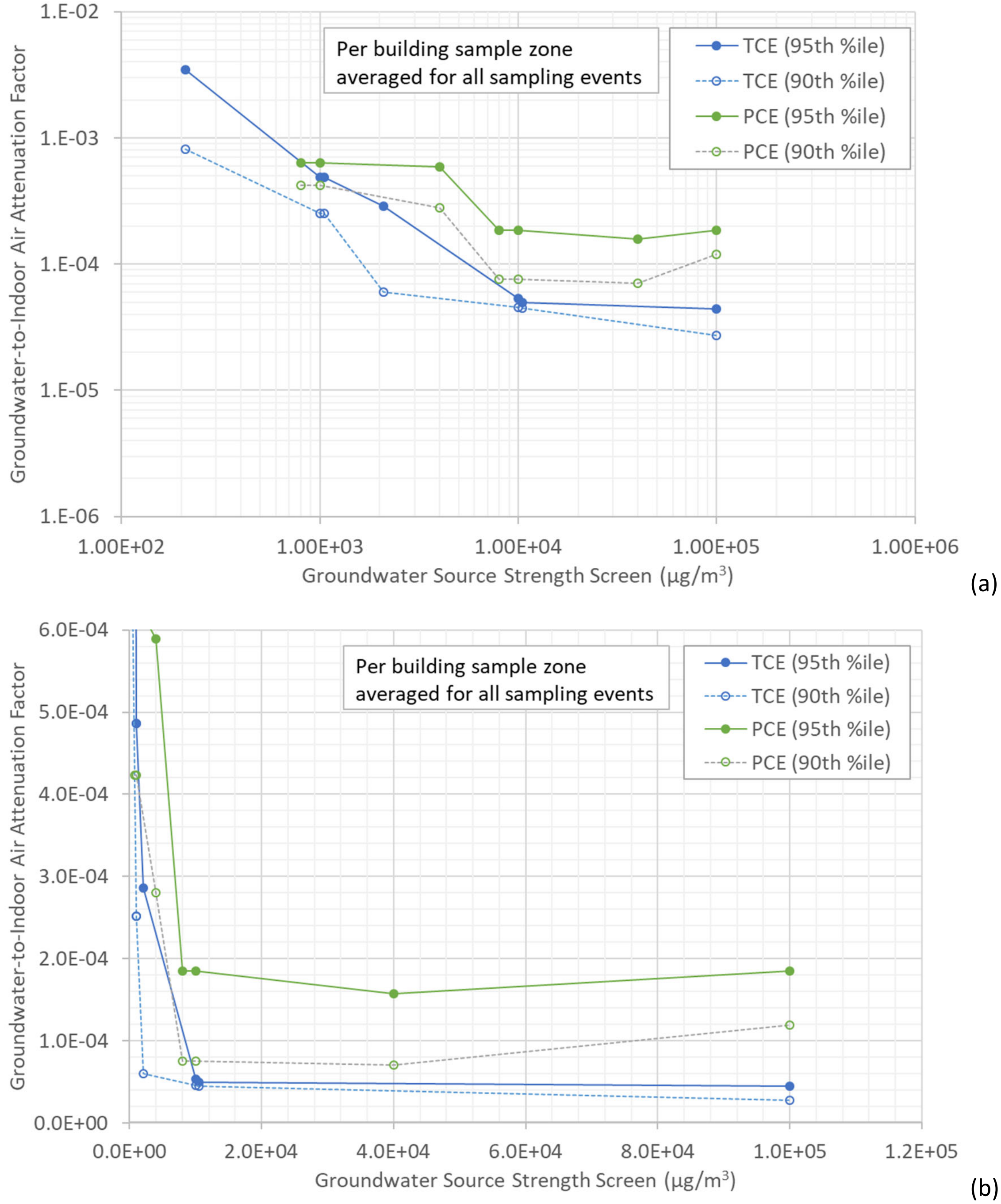
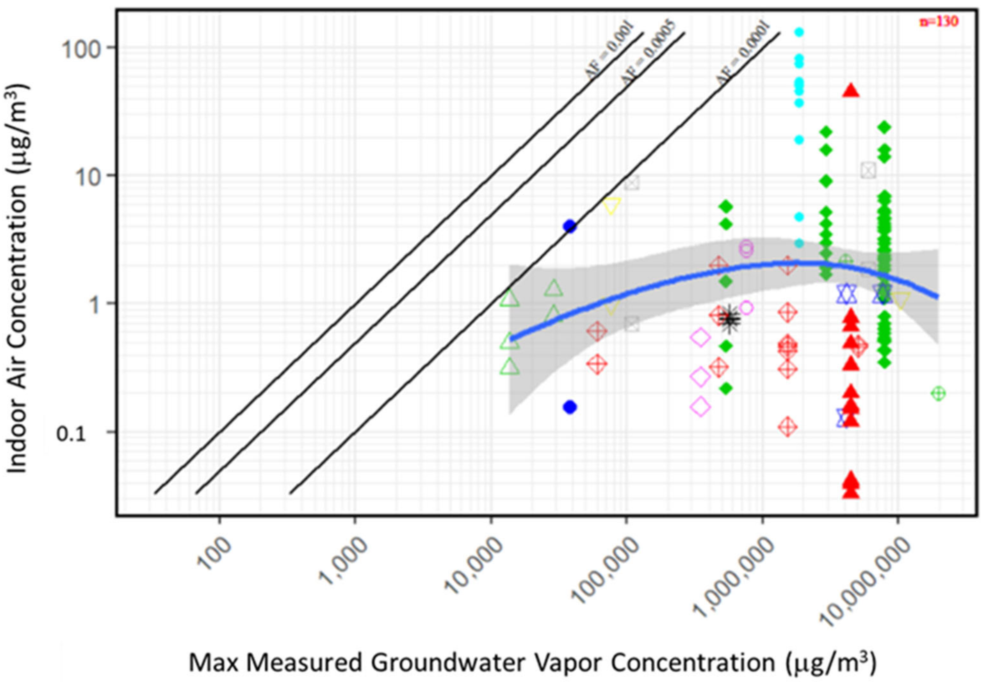


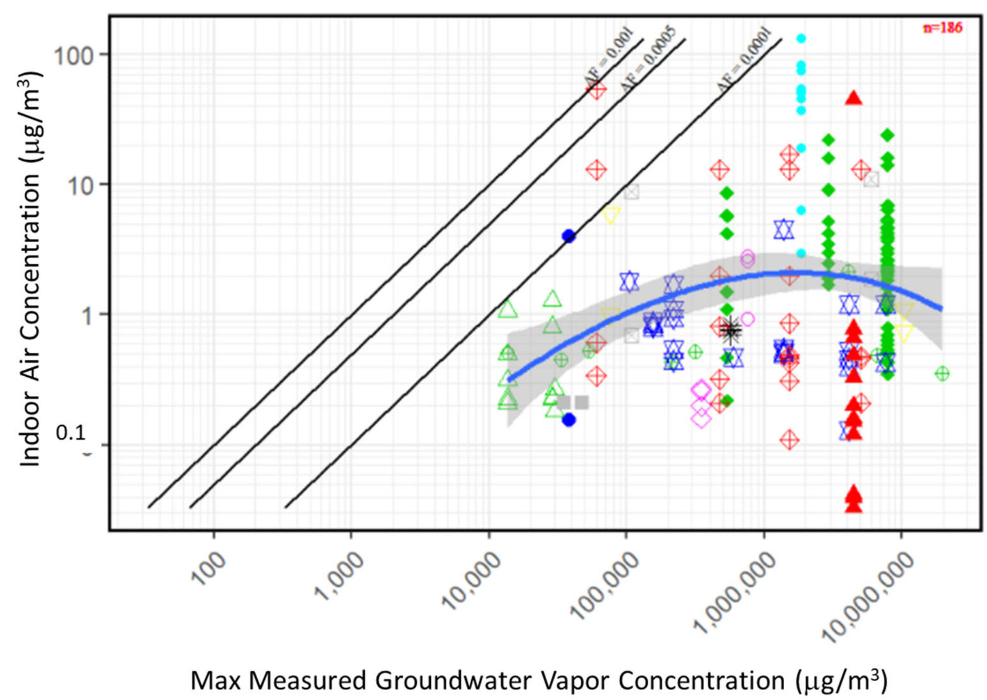
Figure 4-60. Plots of 90th and 95th Percentile Groundwater-to-Indoor Air AFs Associated with TCE and PCE as a Function of Source Strength Screen Using (a) Log Scale and (b) Linear Scale

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for all sampling events. Pairs with an indoor air concentration below detection limit are not included.

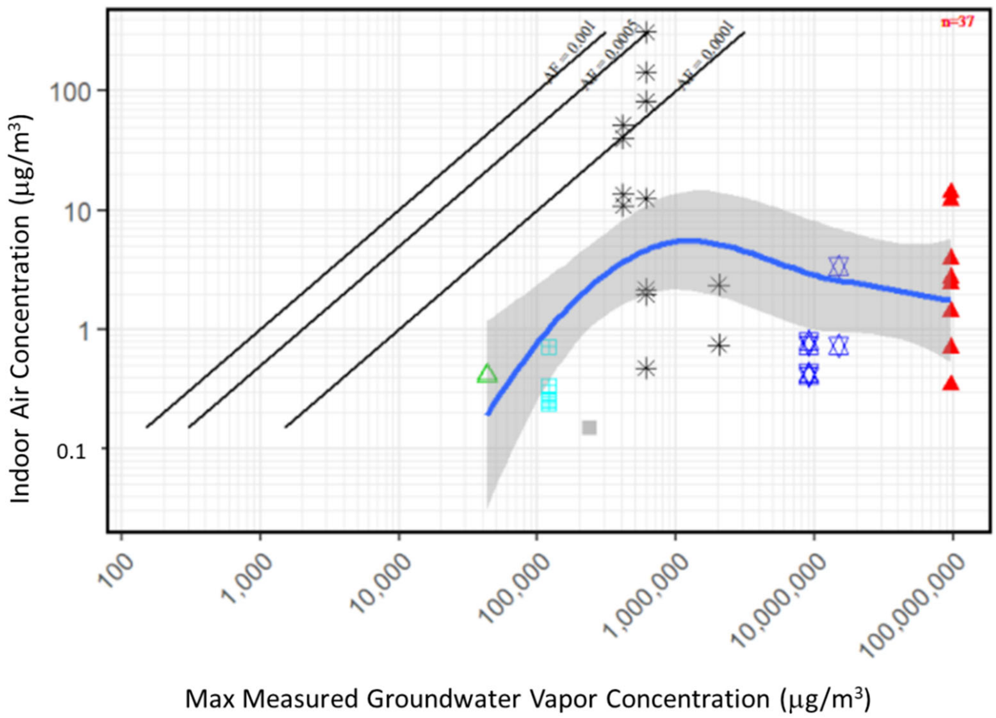


(a)

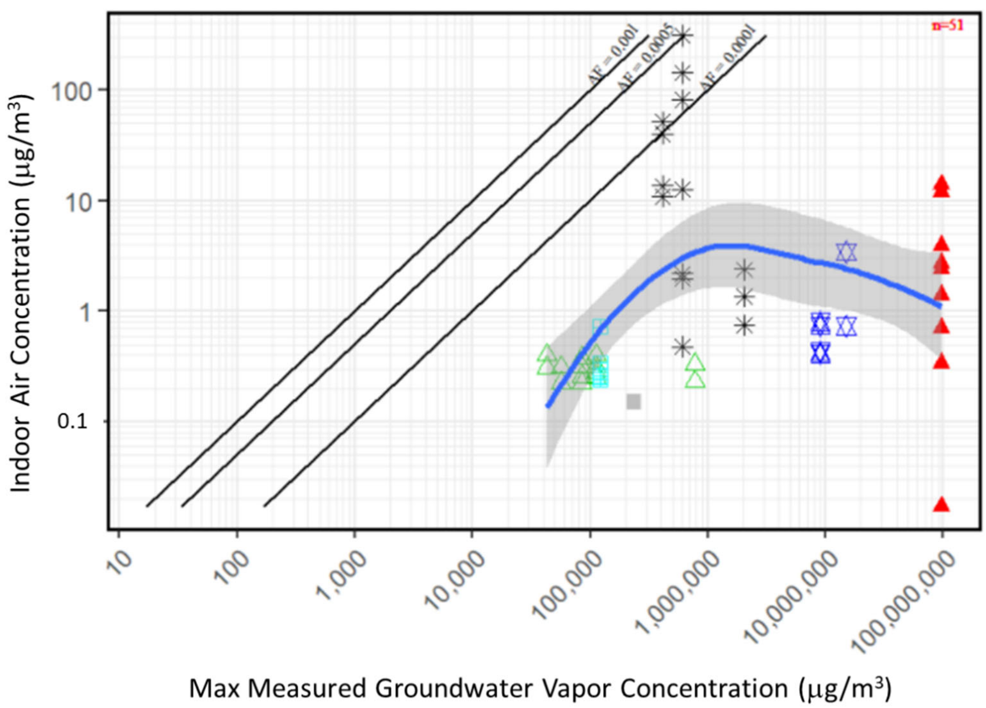


(b)

Figure 4-61. Paired Groundwater-Indoor Air Concentration Plots for TCE with Each Data Pair Corresponding to a Building Sample Zone Average for a Given Sampling Event Passing the 5,000X Background Source Strength Screen
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Comparison between the approaches that include (a) only detectable concentrations in indoor air (i.e., indoor air non-detects excluded) and (b) non-detects in indoor air plotted at detection limit. Different symbols correspond to data from different DoD installations.

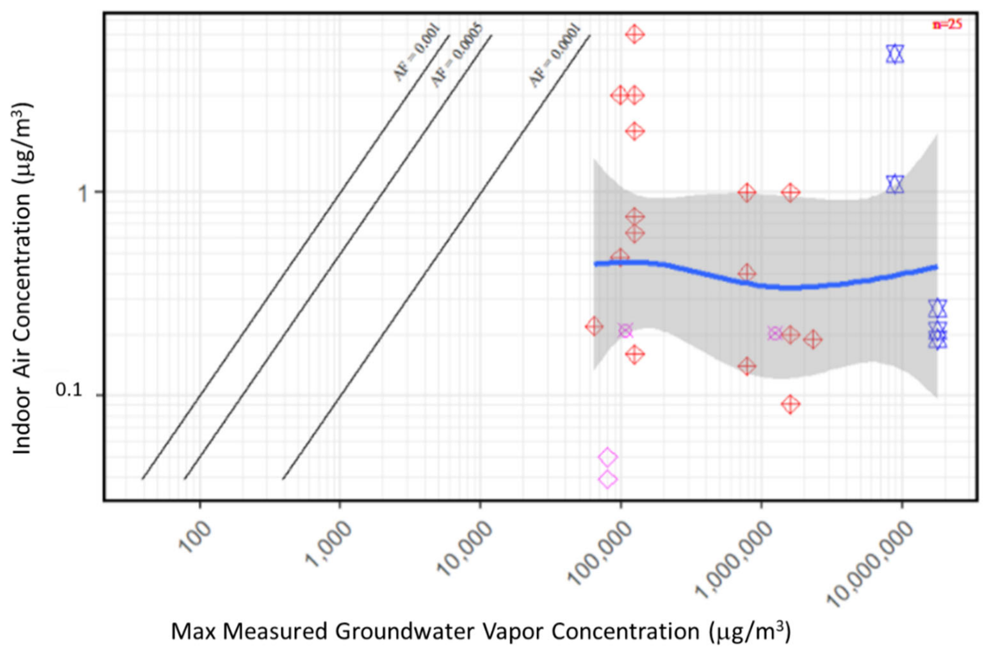


(a)

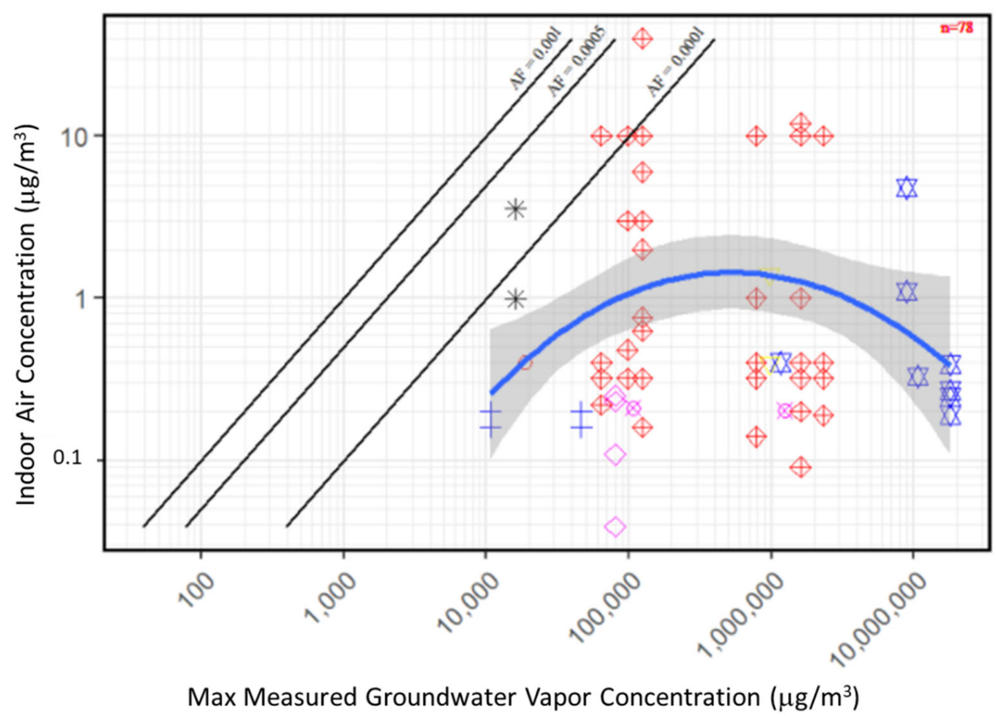


(b)

Figure 4-62. Paired Groundwater-Indoor Air Concentration Plots for PCE with Each Data Pair Corresponding to a Building Sample Zone Average for a Given Sampling Event Passing the 5,000X Background Source Strength Screen
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Comparison between the approaches that include (a) only detectable concentrations in indoor air (i.e., indoor air non-detects excluded) and (b) non-detects in indoor air plotted at detection limit. Different symbols correspond to data from different DoD installations.



(a)



(b)

Figure 4-63. Paired Groundwater-Indoor Air Concentration Plots for cis-1,2-DCE with Each Data Pair Corresponding to a Building Sample Zone Average for a Given Sampling Event Passing the 10,000 µg/m³ Fixed Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Comparison between the approaches that include (a) only detectable concentrations in indoor air (i.e., indoor air non-detects excluded) and (b) non-detects in indoor air plotted at detection limit. Different symbols correspond to data from different DoD installations.

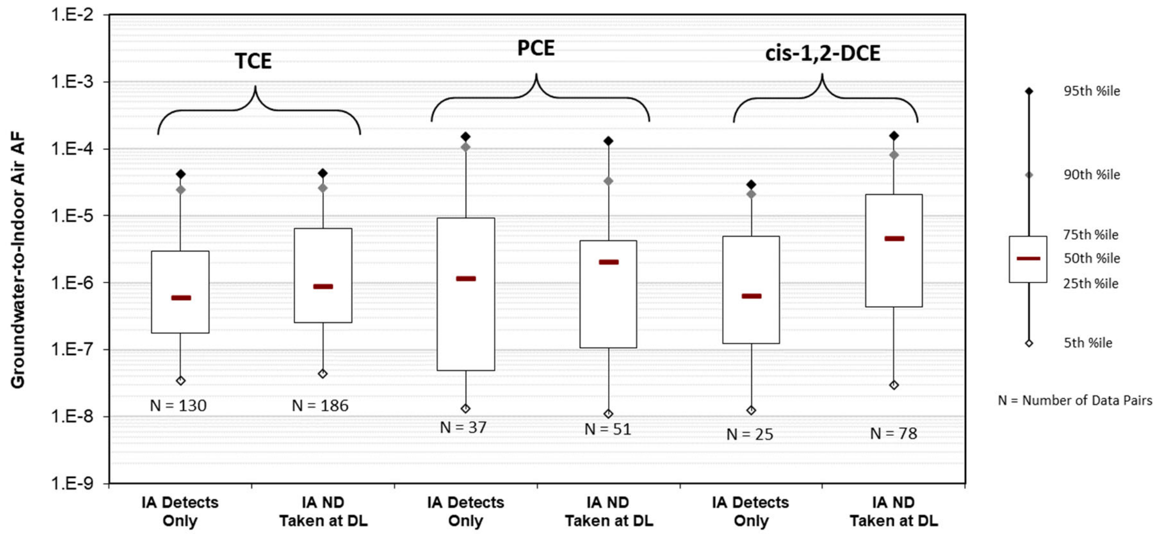


Figure 4-64. Box-and-Whisker Plots Summarizing the Groundwater-to-Indoor Air AF Distribution Associated with Selected VOCs After Application of Either the 5,000X Background Source Strength Screen for TCE and PCE or the 10,000 µg/m^3 Fixed Source Strength Screen for cis-1,2-DCE

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

The AF distributions are derived from building sample zone averages for individual sampling events. Comparison between distributions obtained using indoor air (IA) detects only and IA non-detects (ND) taken at detection limit (DL).

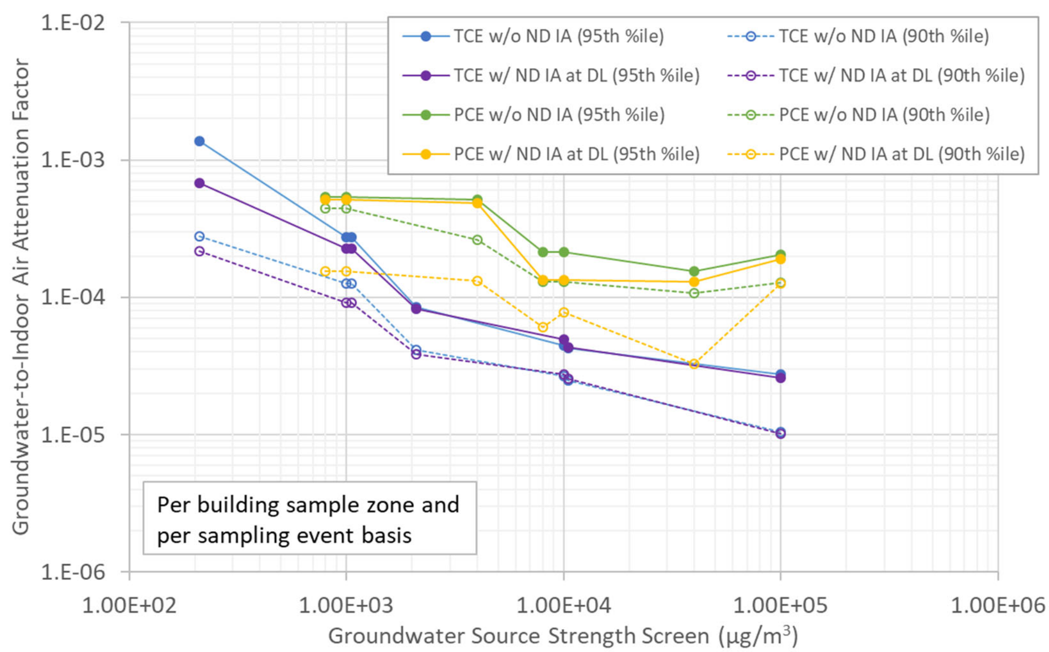


Figure 4-65. Plots of 90th and 95th Percentile Groundwater-to-Indoor Air AFs Associated with TCE and PCE as a Function of Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each AF represents a building sample zone average for a given sampling event. Comparison of analyses using indoor air detects only and indoor air non-detects taken at detection limit.

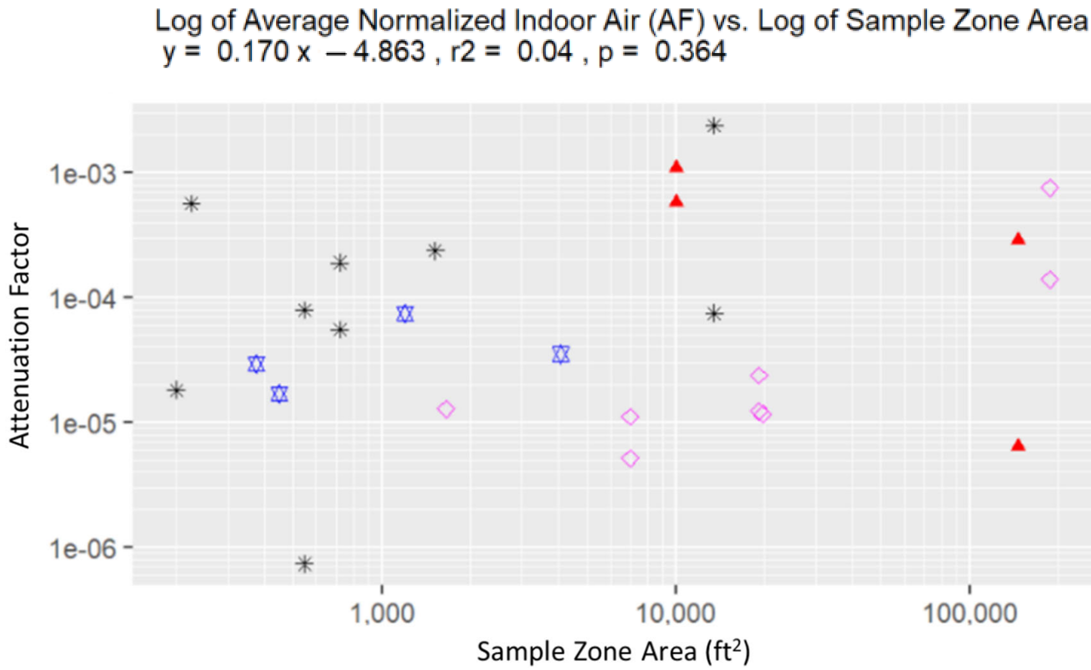


Figure 4-66. Sample Zone Area Versus PCE Normalized Indoor Air Concentration

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Averages for individual sampling events with non-detects taken at detection limit; 1,000X background source strength screen. Different symbols correspond to data from different DoD installations. In the equation, x represents the log of the sample zone area and y represents the log of the AF.

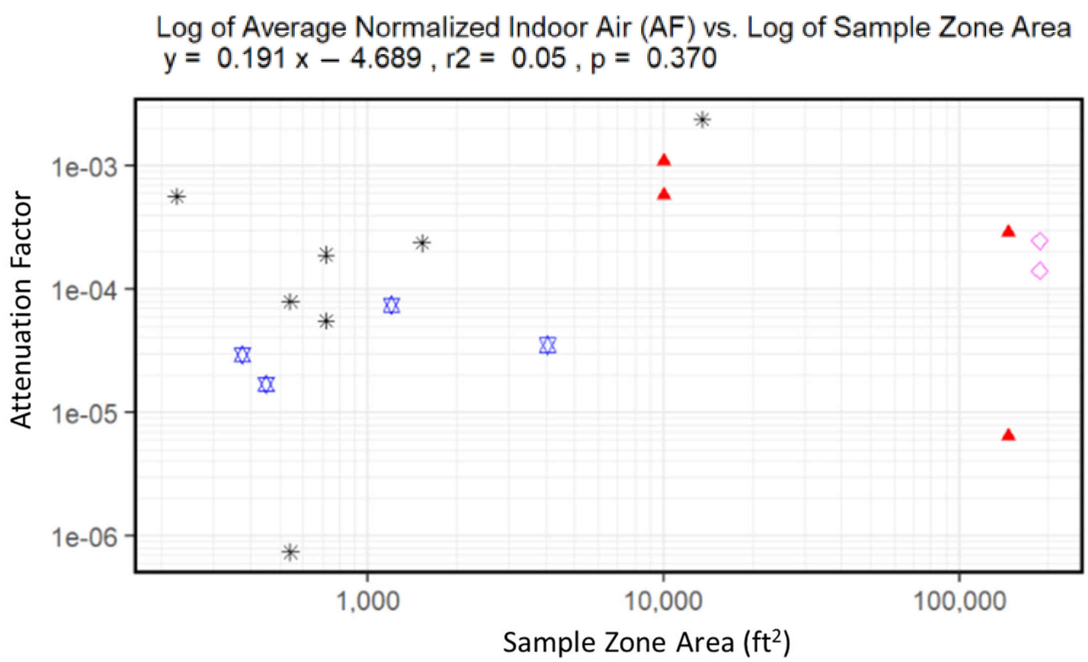


Figure 4-67. Sample Zone Area Versus PCE Normalized Indoor Air Concentration

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Averages for individual sampling events with detectable data only; 1,000X background source strength screen. Different symbols correspond to data from different DoD installations. In the equation, x represents the log of the sample zone area and y represents the log of the AF.

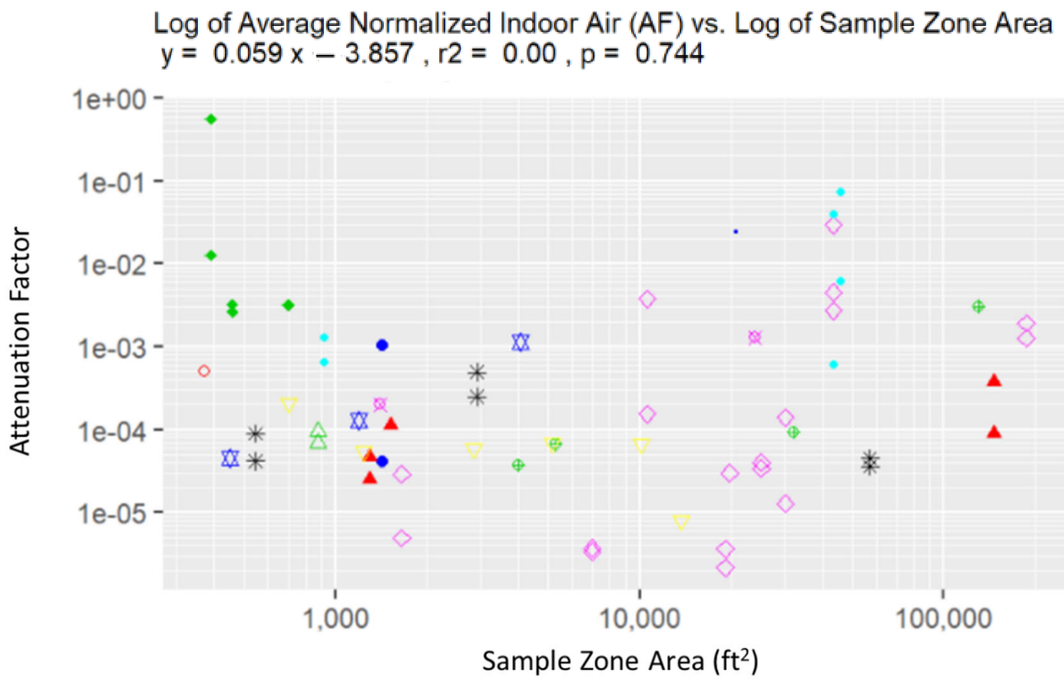


Figure 4-68. Sample Zone Area Versus TCE Normalized Indoor Air Concentration
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Averages for individual sampling events with non-detects taken at detection limit; 1,000X background source strength screen. Different symbols correspond to data from different DoD installations. In the equation, x represents the log of the sample zone area and y represents the log of the AF.

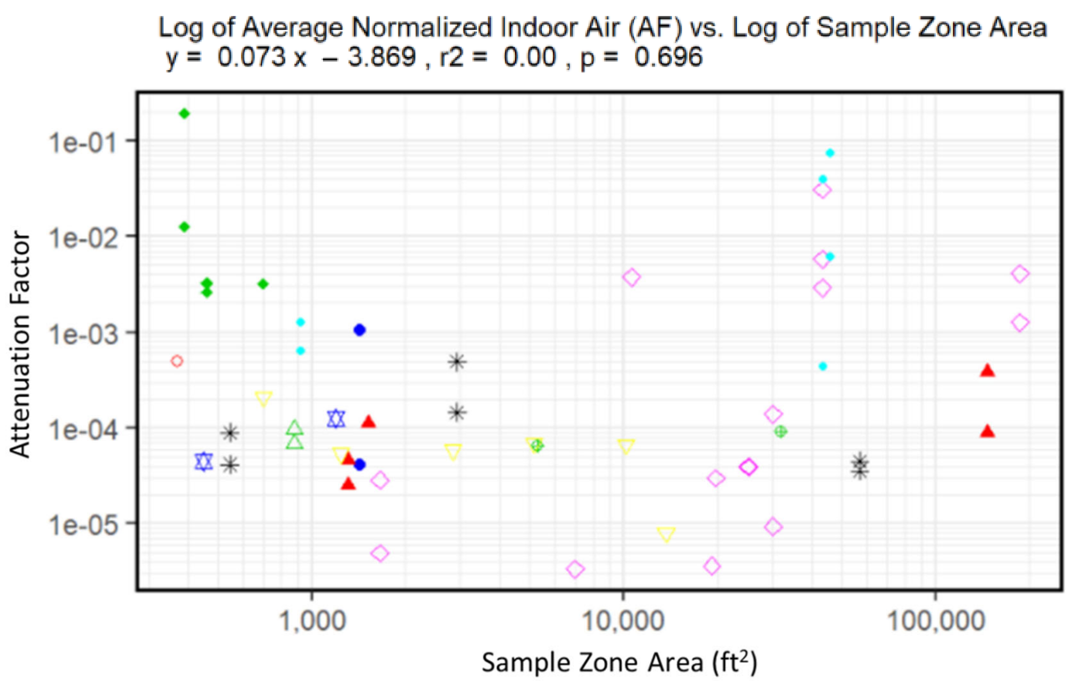


Figure 4-69. Sample Zone Area Versus TCE Normalized Indoor Air Concentration
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Averages for individual sampling events with detectable data only; 1,000X background source strength screen. Different symbols correspond to data from different DoD installations. In the equation, x represents the log of the sample zone area and y represents the log of the AF.

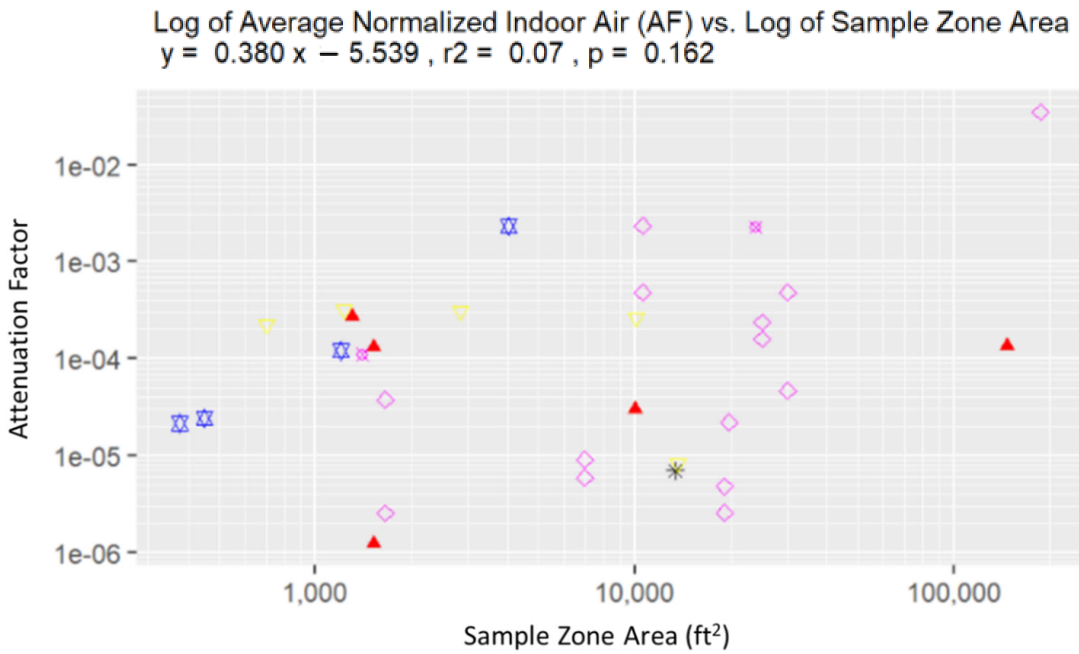


Figure 4-70. Sample Zone Area Versus cis-1,2-DCE Normalized Indoor Air Concentration

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Averages for individual sampling events with non-detects taken at detection limit; 1,000 µg/m³ fixed source strength screen. Different symbols correspond to data from different DoD installations. In the equation, x represents the log of the sample zone area and y represents the log of the AF.

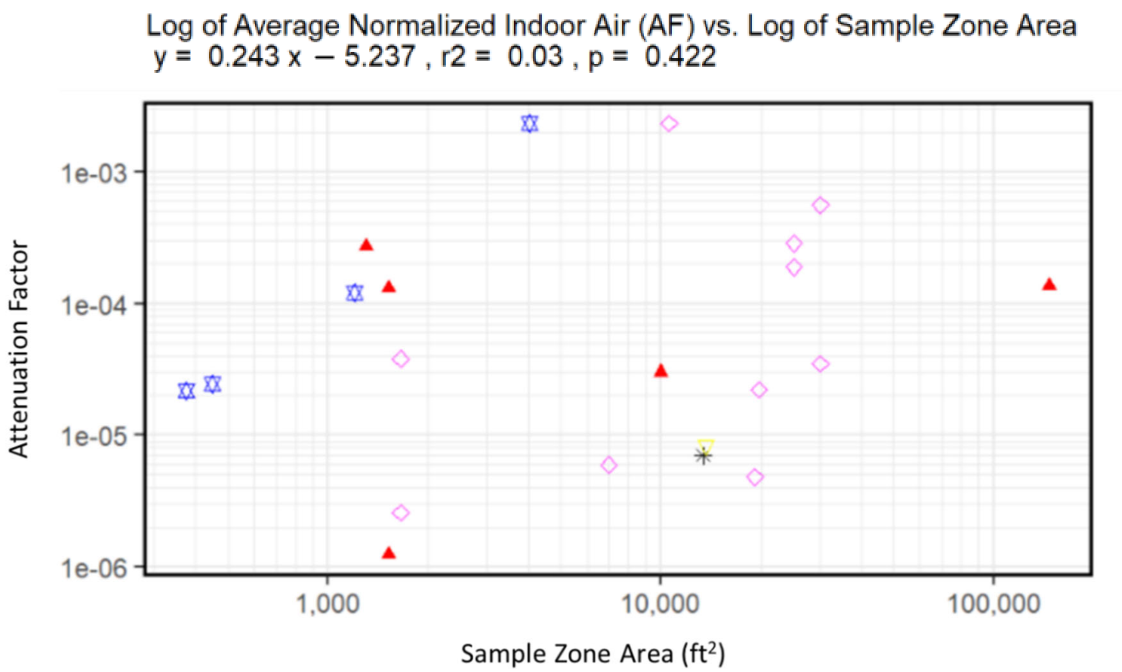


Figure 4-71. Sample Zone Area Versus cis-1,2-DCE Normalized Indoor Air Concentration

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Averages for individual sampling events with detectable data only; 1,000 µg/m³ fixed source strength screen. Different symbols correspond to data from different DoD installations. In the equation, x represents the log of the sample zone area and y represents the log of the AF.

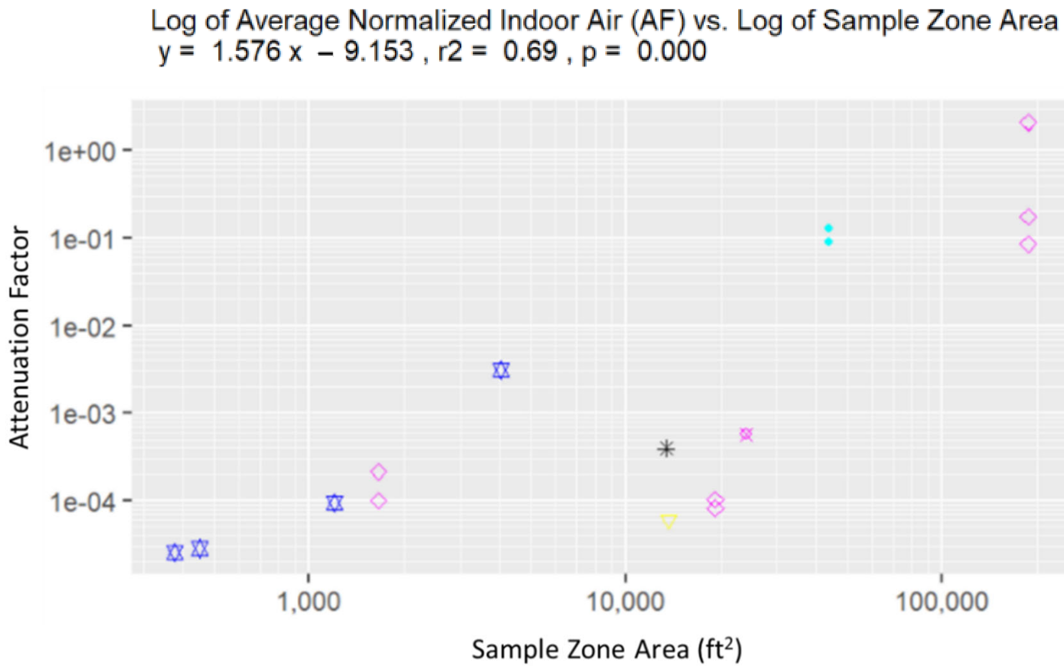


Figure 4-72. Sample Zone Area Versus trans-1,2-DCE Normalized Indoor Air Concentration
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Averages for individual sampling events with non-detects taken at detection limit; 1,000 µg/m³ fixed source strength screen. Different symbols correspond to data from different DoD installations. In the equation, x represents the log of the sample zone area and y represents the log of the AF.

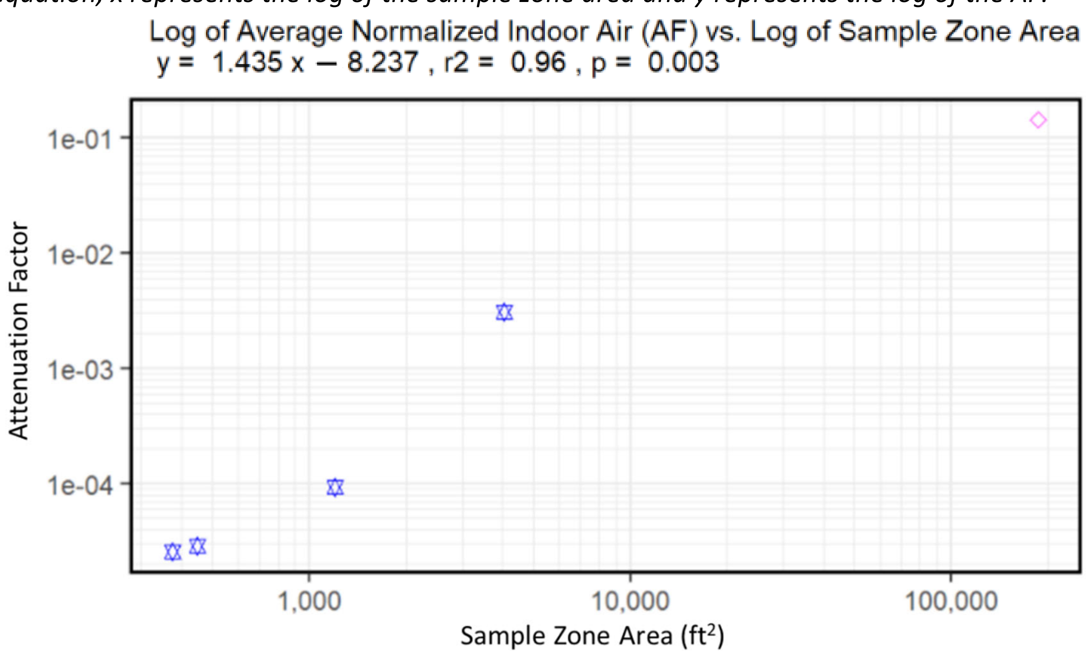


Figure 4-73. Sample Zone Area Versus trans-1,2-DCE Normalized Indoor Air Concentration
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Averages for individual sampling events with detectable data only; 1,000 µg/m³ fixed source strength screen. Different symbols correspond to data from different DoD installations. In the equation, x represents the log of the sample zone area and y represents the log of the AF.

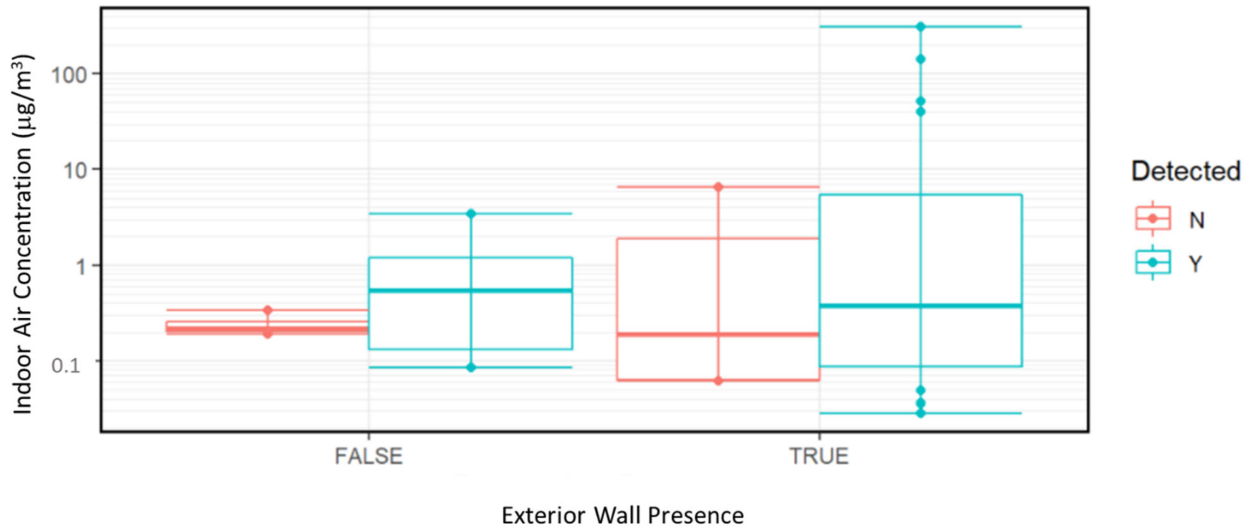


Figure 4-74. PCE Box-and-Whisker Plots of Indoor Air Concentration Versus Exterior Wall Presence in Sample Zone
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to indoor air detects and non-detects (taken at the detection limit), respectively.

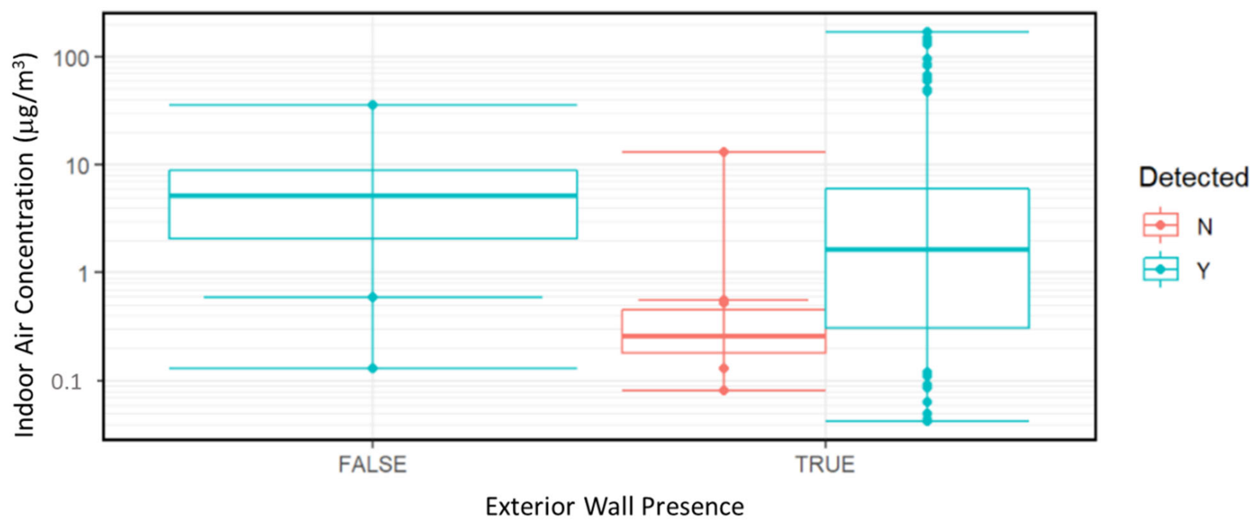


Figure 4-75. TCE Box-and-Whisker Plots of Indoor Air Concentration Versus Exterior Wall Presence in Sample Zone
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to indoor air detects and non-detects (taken at the detection limit), respectively.

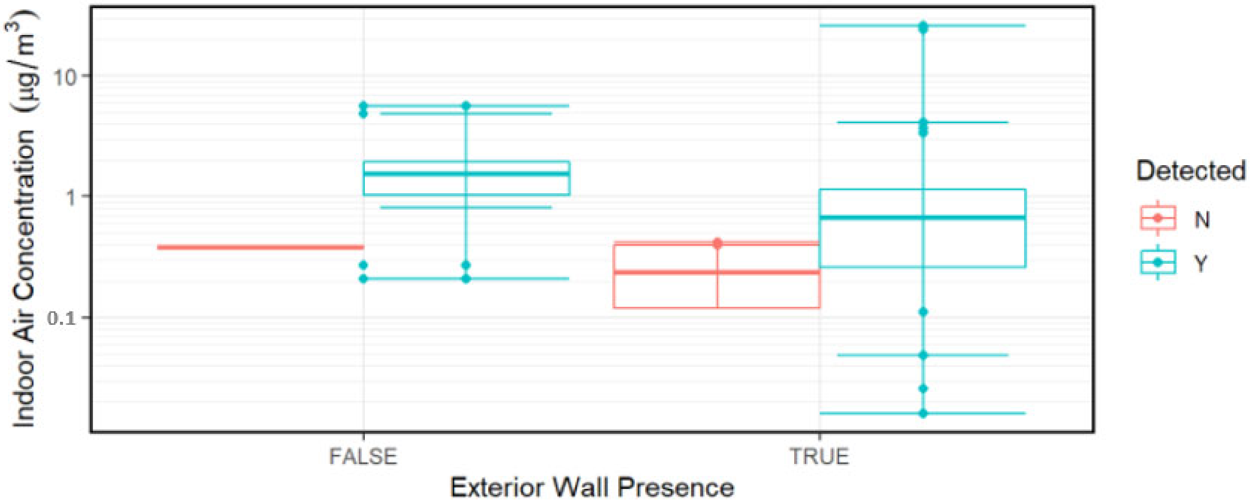


Figure 4-76. cis-1,2-DCE Box-and-Whisker Plots of Indoor Air Concentration Versus Exterior Wall Presence in Sample Zone

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to indoor air detects and non-detects (taken at the detection limit), respectively.

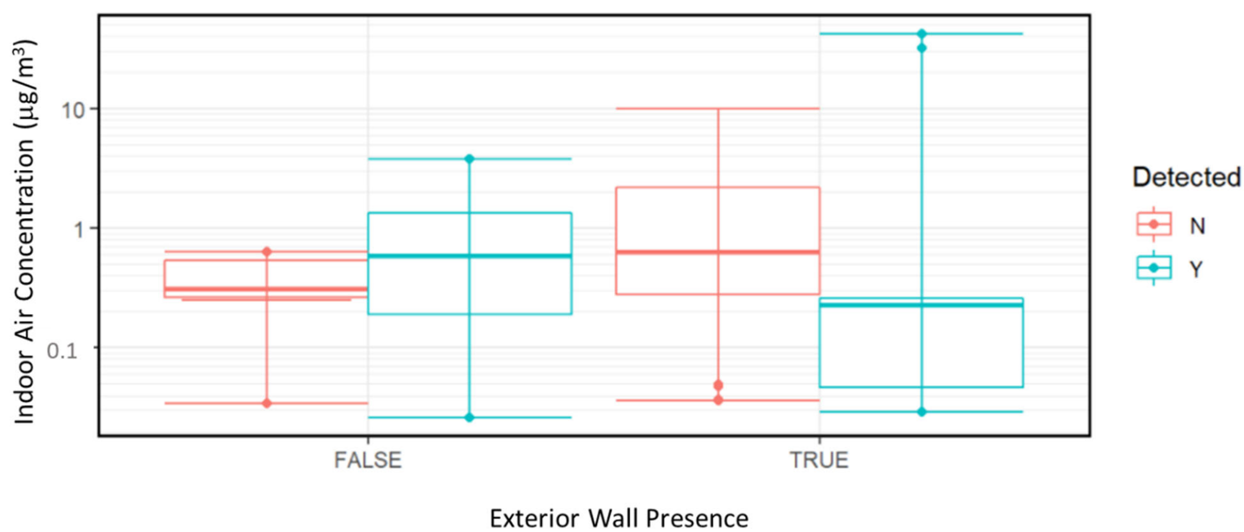


Figure 4-77. trans-1,2-DCE Box-and-Whisker Plots of Indoor Air Concentration Versus Exterior Wall Presence in Sample Zone

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to indoor air detects and non-detects (taken at the detection limit), respectively.

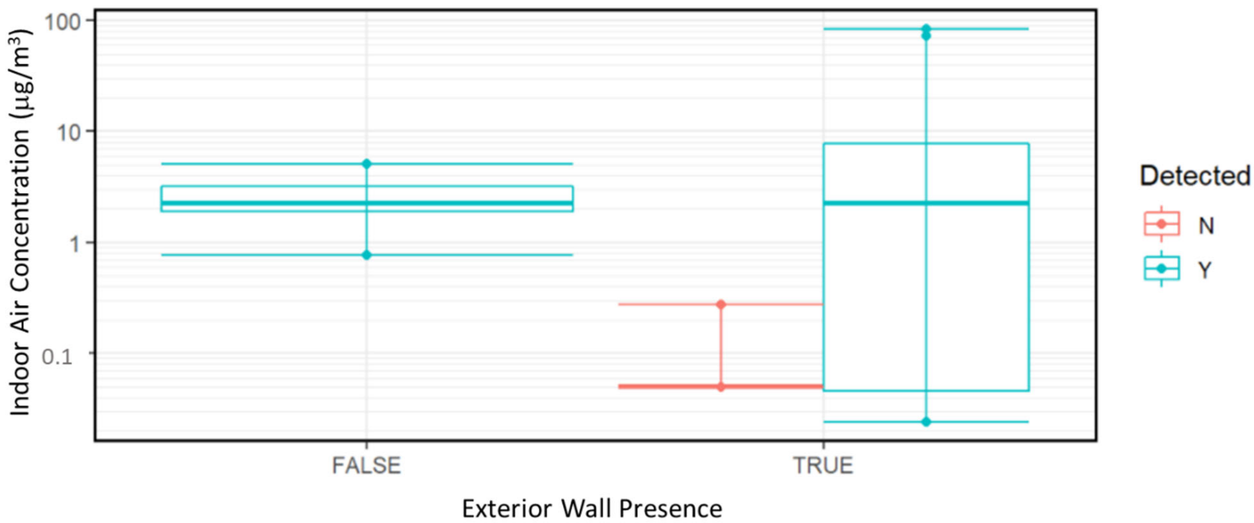


Figure 4-78. 1,1,1-TCA Box-and-Whisker Plots of Indoor Air Concentration Versus Exterior Wall Presence in Sample Zone

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to indoor air detects and non-detects (taken at the detection limit), respectively.

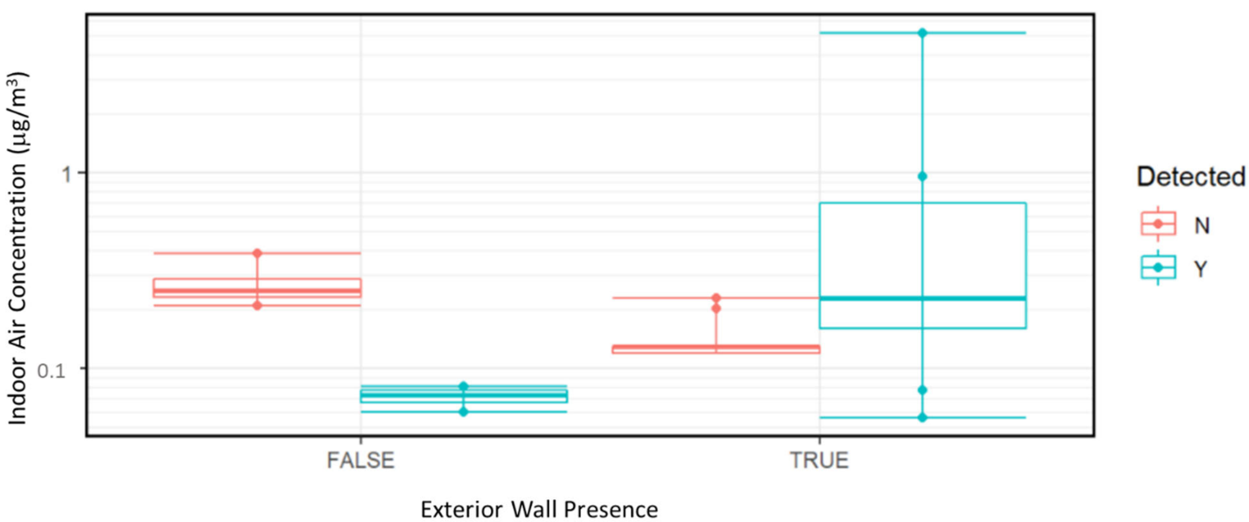


Figure 4-79. 1,1-DCA Box-and-Whisker Plots of Indoor Air Concentration Versus Exterior Wall Presence in Sample Zone

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

"False" indicates that an exterior wall is not present in the sample zone. "True" indicates that an exterior wall is present in the sample zone. "Y" and "N" refer to indoor air detects and non-detects (taken at the detection limit), respectively.

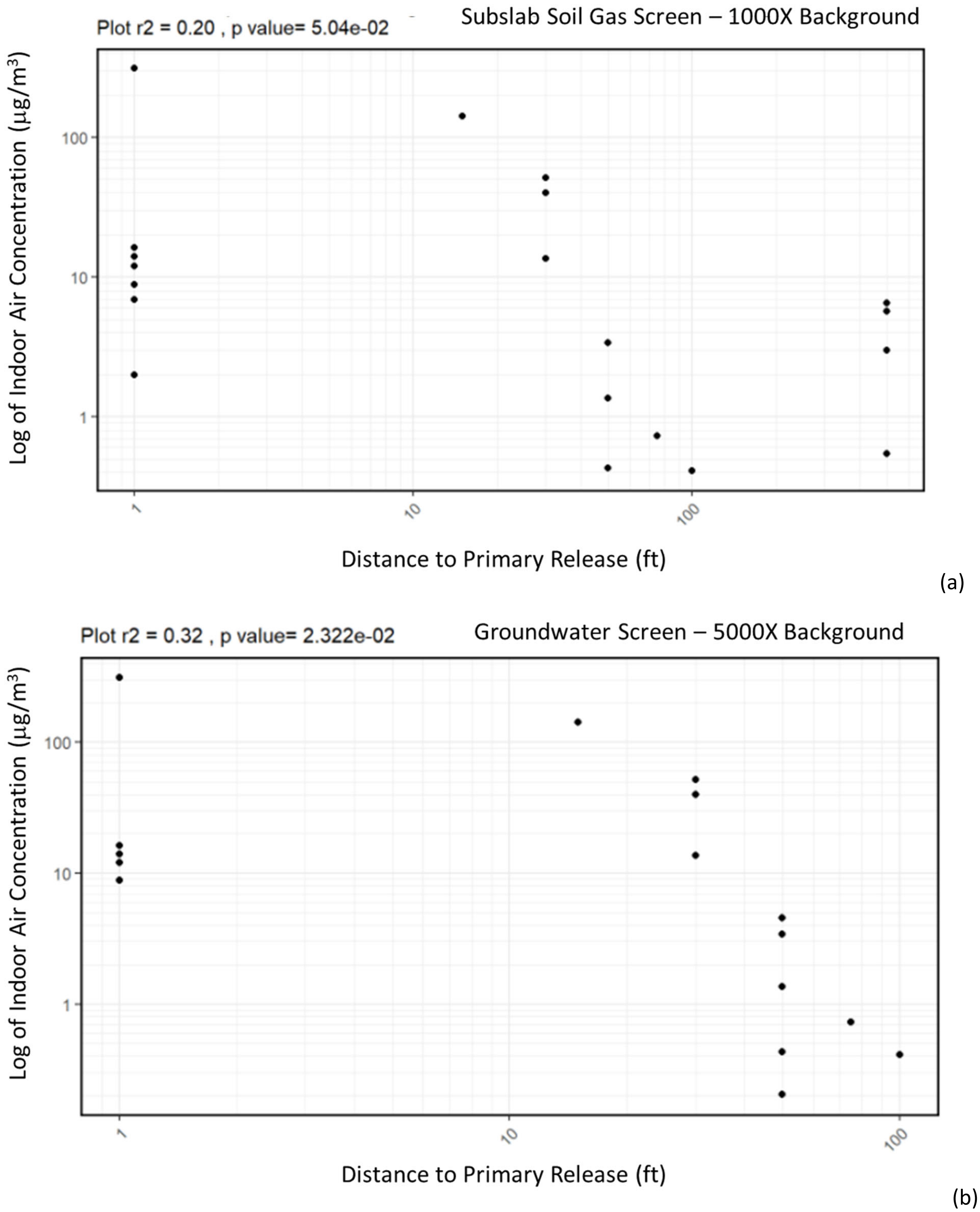


Figure 4-80. PCE Indoor Air Concentration Versus Distance to Primary Release, Log-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength screened data based on (a) subslab soil gas and (b) groundwater.

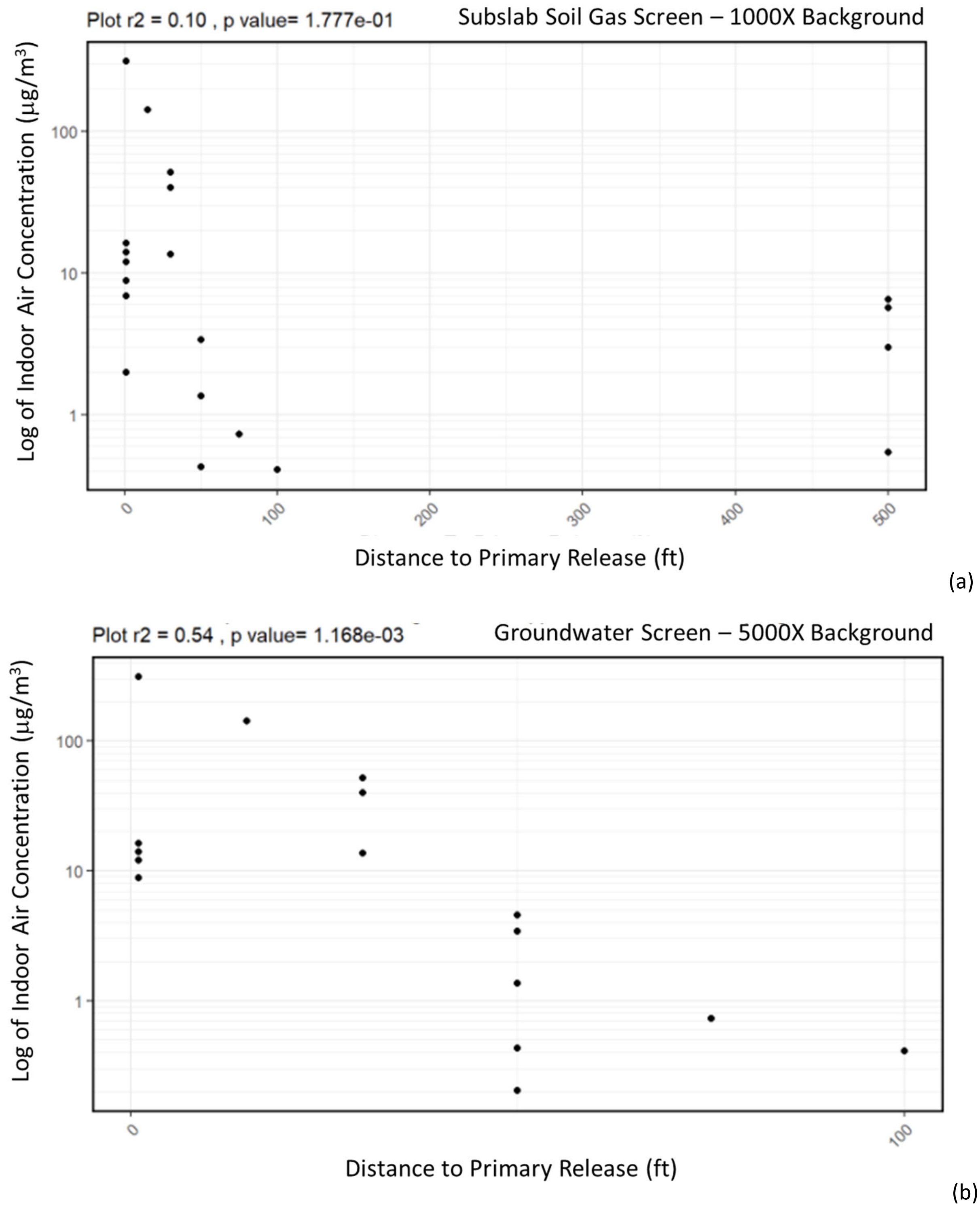
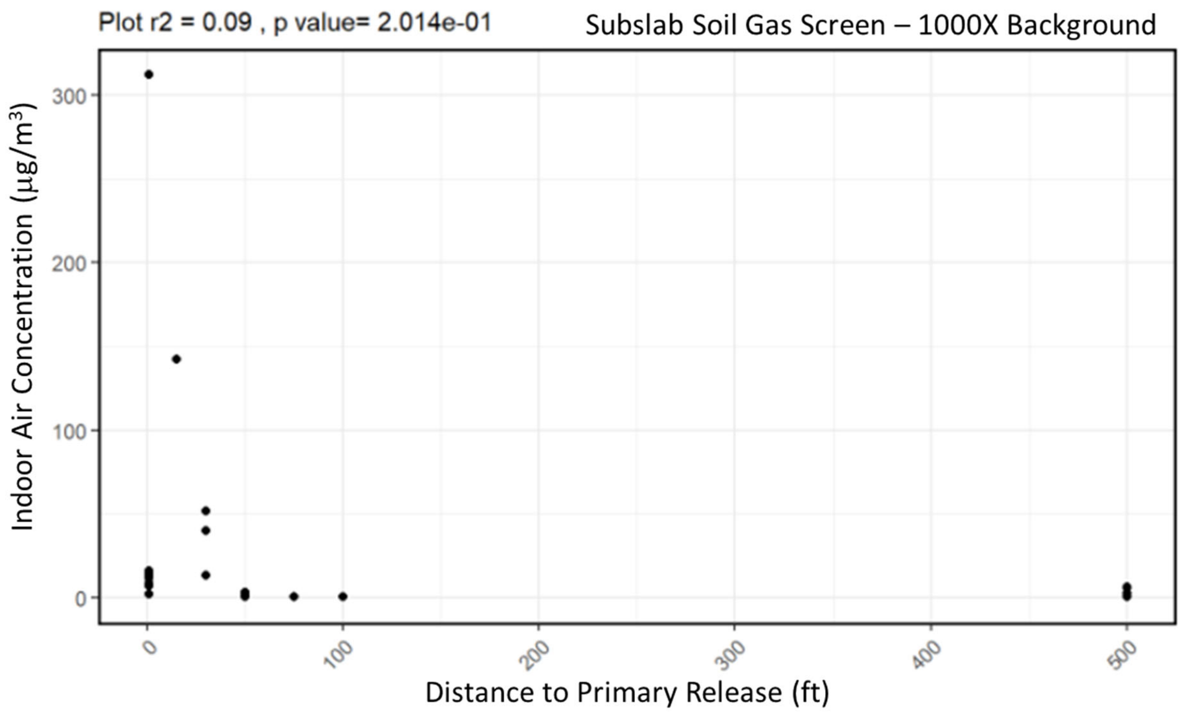
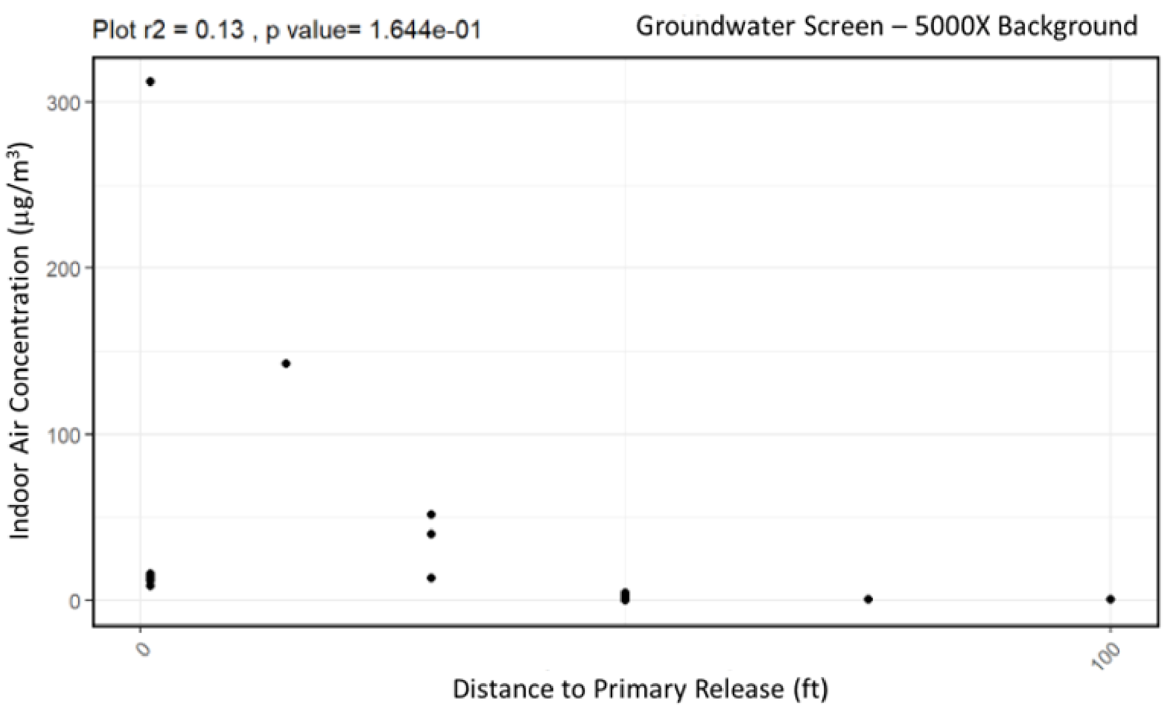


Figure 4-81. PCE Indoor Air Concentration Versus Distance to Primary Release, Semi-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength screened data based on (a) subslab soil gas and (b) groundwater.

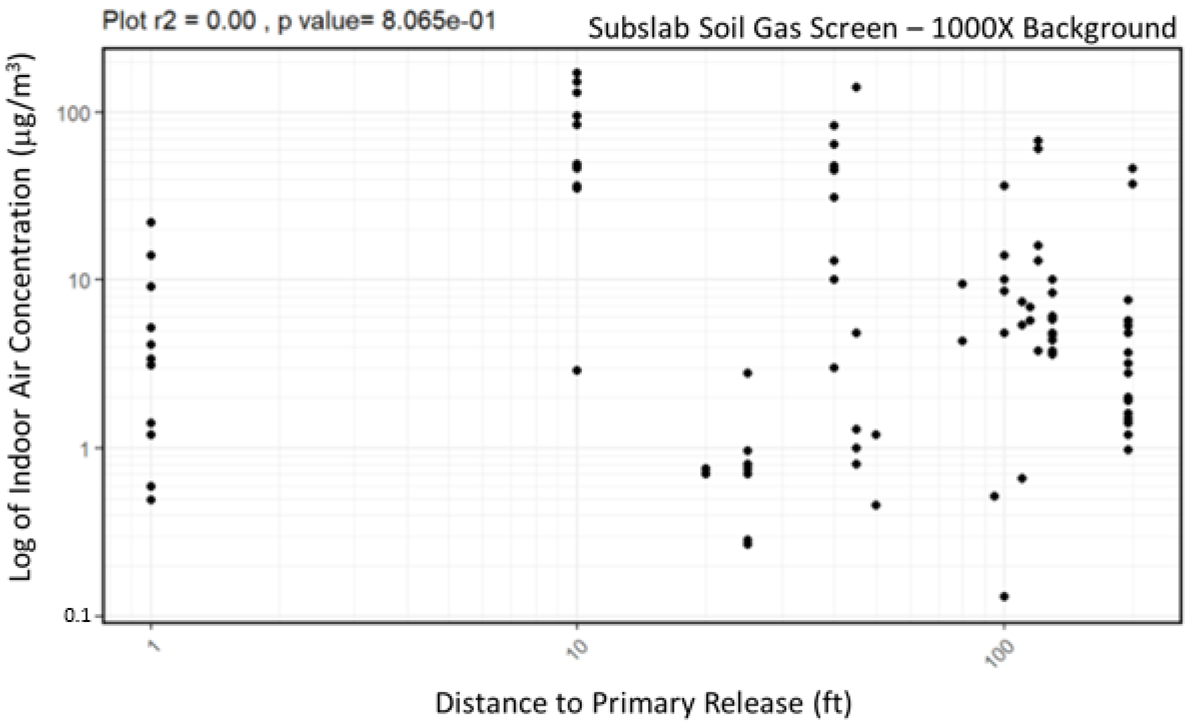


(a)

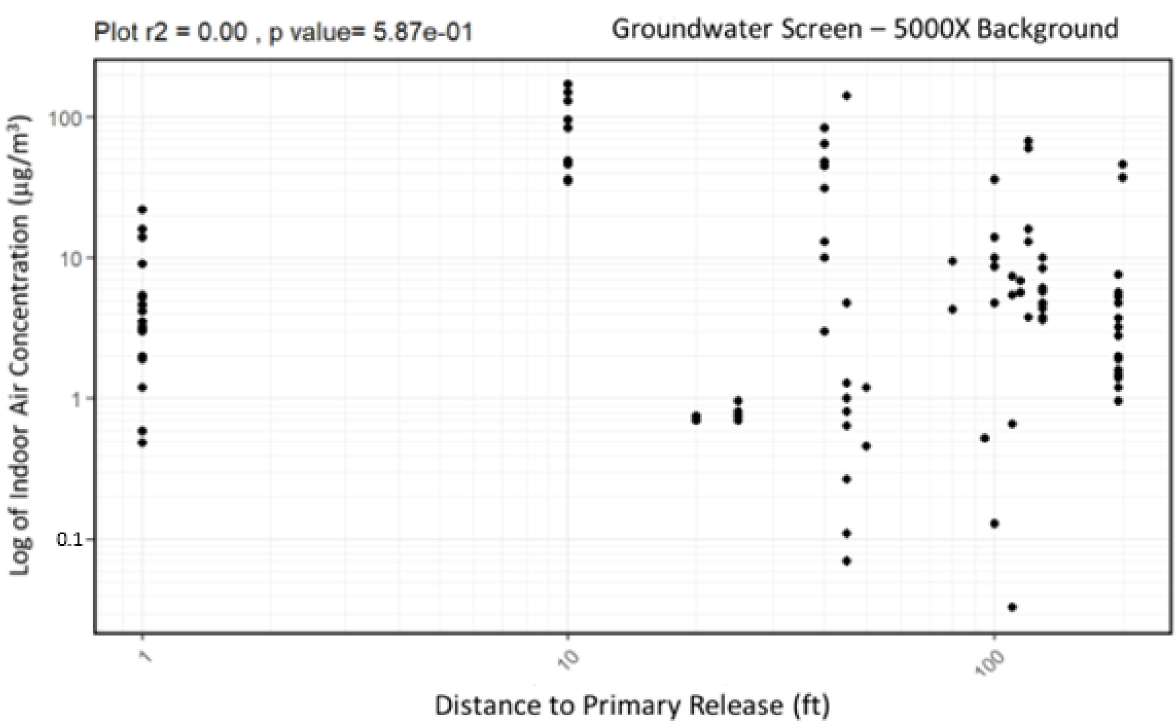


(b)

Figure 4-82. PCE Indoor Air Concentration Versus Distance to Primary Release, Linear Scale Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings Baseline, atypical preferential pathway, and source strength screened data based on (a) subslab soil gas and (b) groundwater.

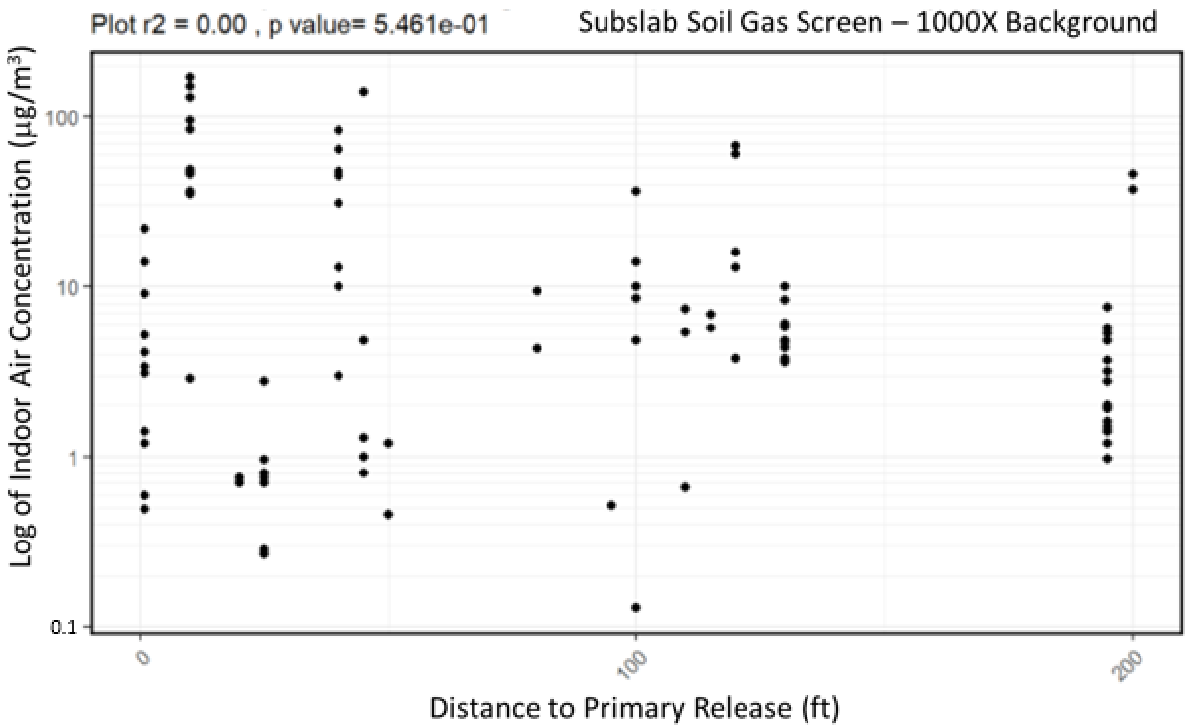


(a)

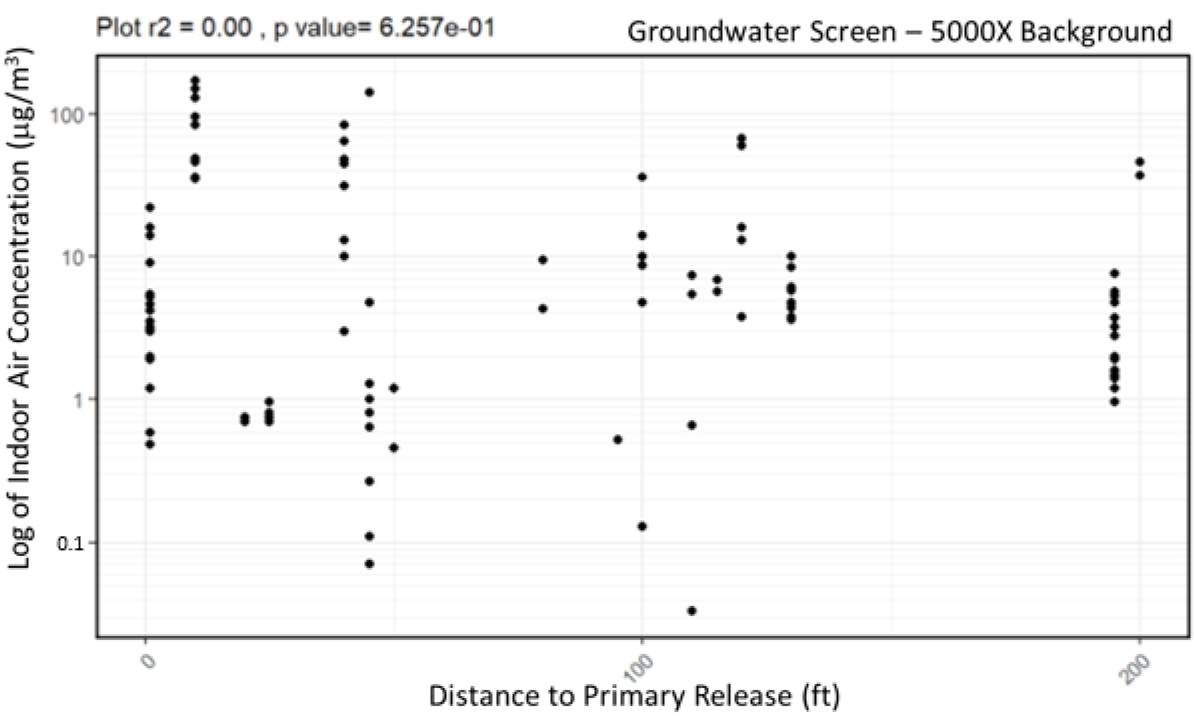


(b)

Figure 4-83. TCE Indoor Air Concentration Versus Distance to Primary Release, Log-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength screened data based on (a) subslab soil gas and (b) groundwater.

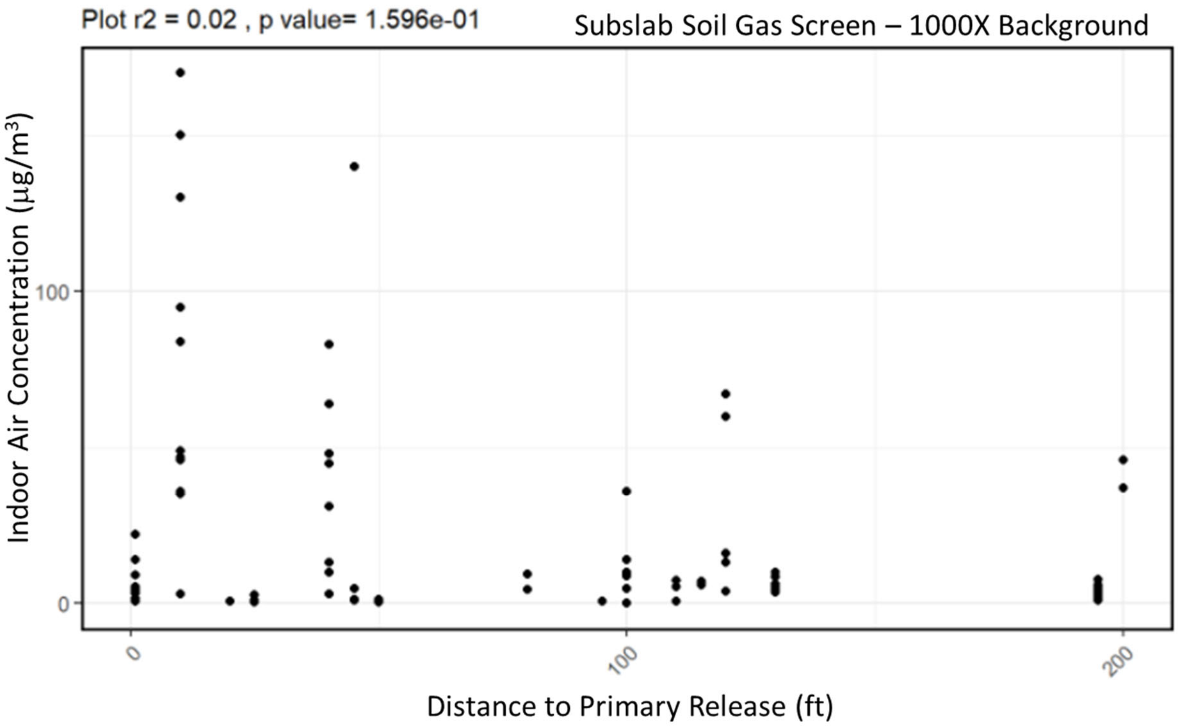


(a)

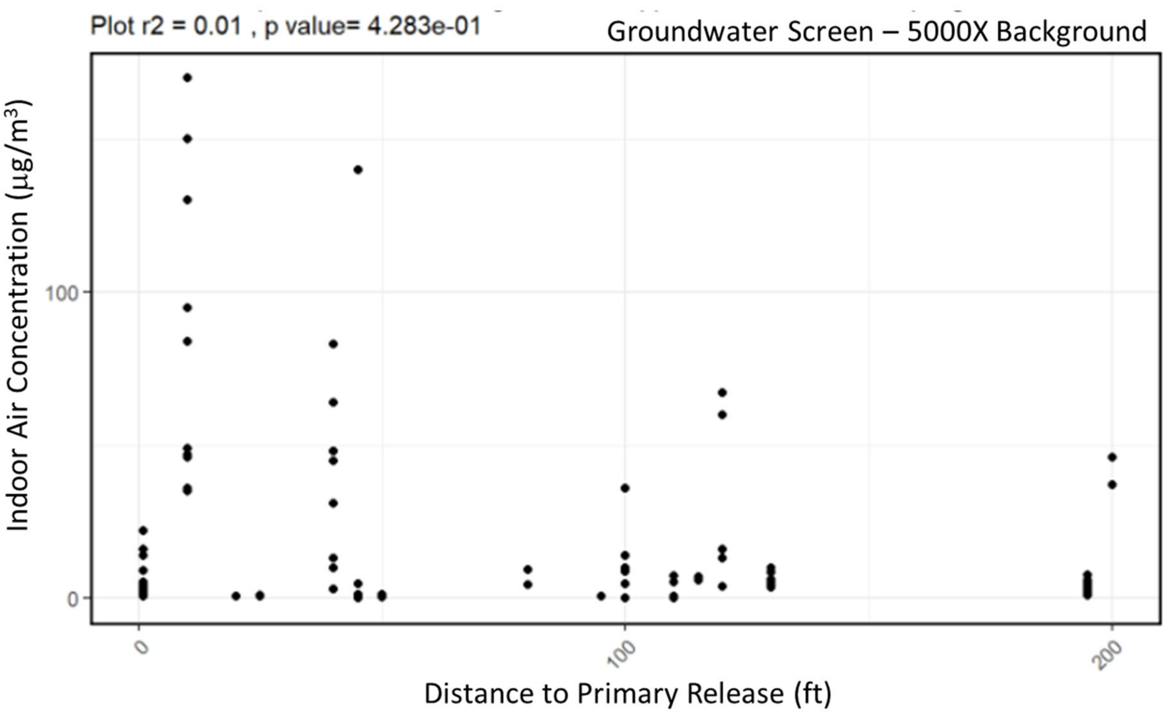


(b)

Figure 4-84. TCE Indoor Air Concentration Versus Distance to Primary Release, Semi-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength screened data based on (a) subslab soil gas and (b) groundwater.

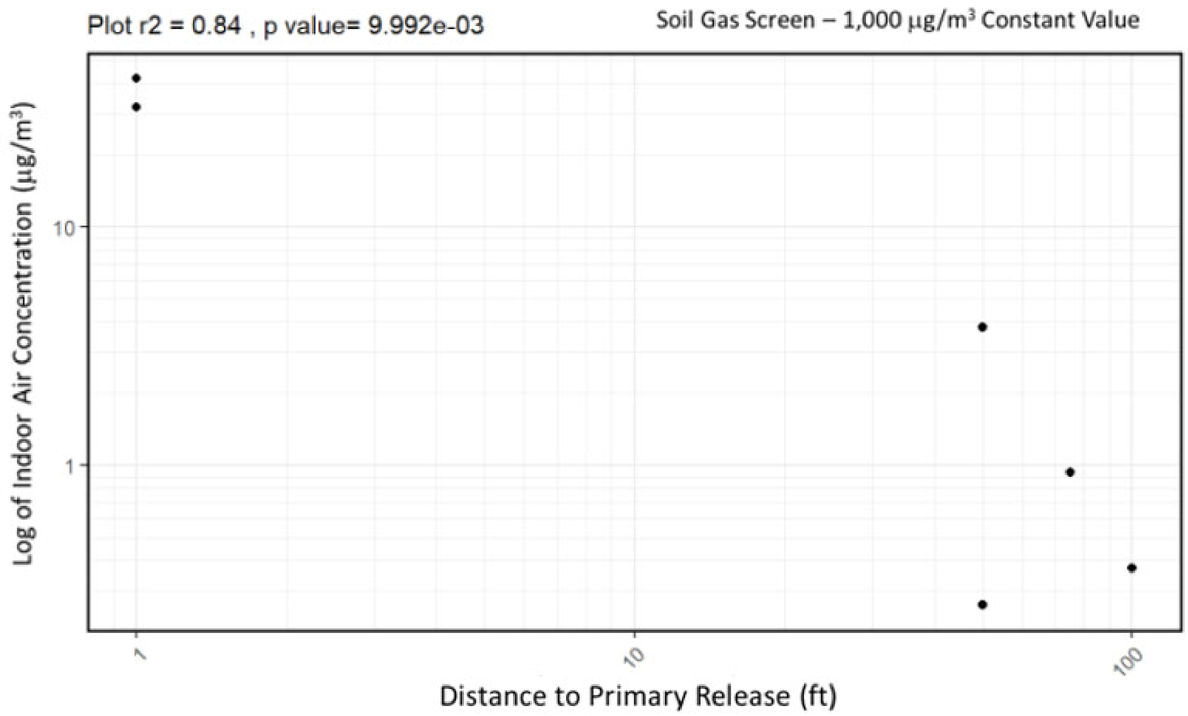


(a)

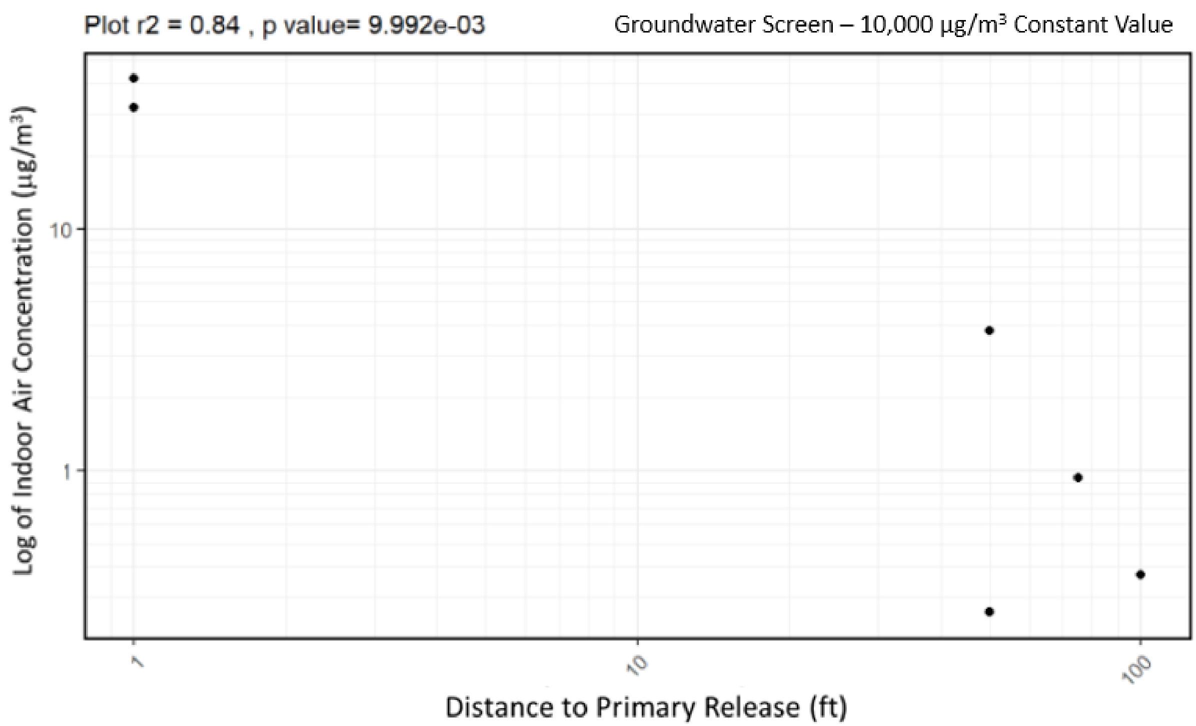


(b)

Figure 4-85. TCE Indoor Air Concentration Versus Distance to Primary Release, Linear Scale Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength screened data based on (a) subslab soil gas and (b) groundwater.



(a)



(b)

Figure 4-86. trans-1,2-DCE Indoor Air Concentration Versus Distance to Primary Release Log-log Plot
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings Baseline, atypical preferential pathway, and source strength screened data based on (a) subslab soil gas and (b) groundwater.

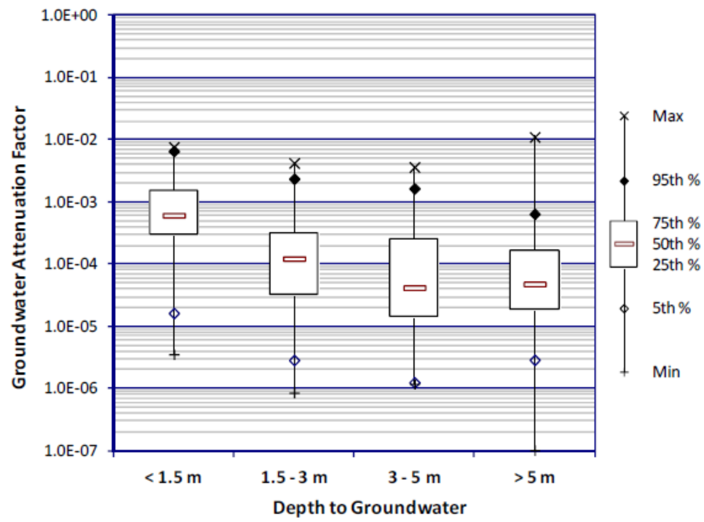


Figure 30. Box-and-whisker plots summarizing groundwater attenuation factor distributions for various depth to groundwater categories after Source Strength Screen.

Figure 4-87. USEPA VI Database Relationship Between Normalized Indoor Air Concentration and Depth to Groundwater for Residential Buildings

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Normalized air concentration = groundwater attenuation factor. Reprinted from USEPA, 2012a.

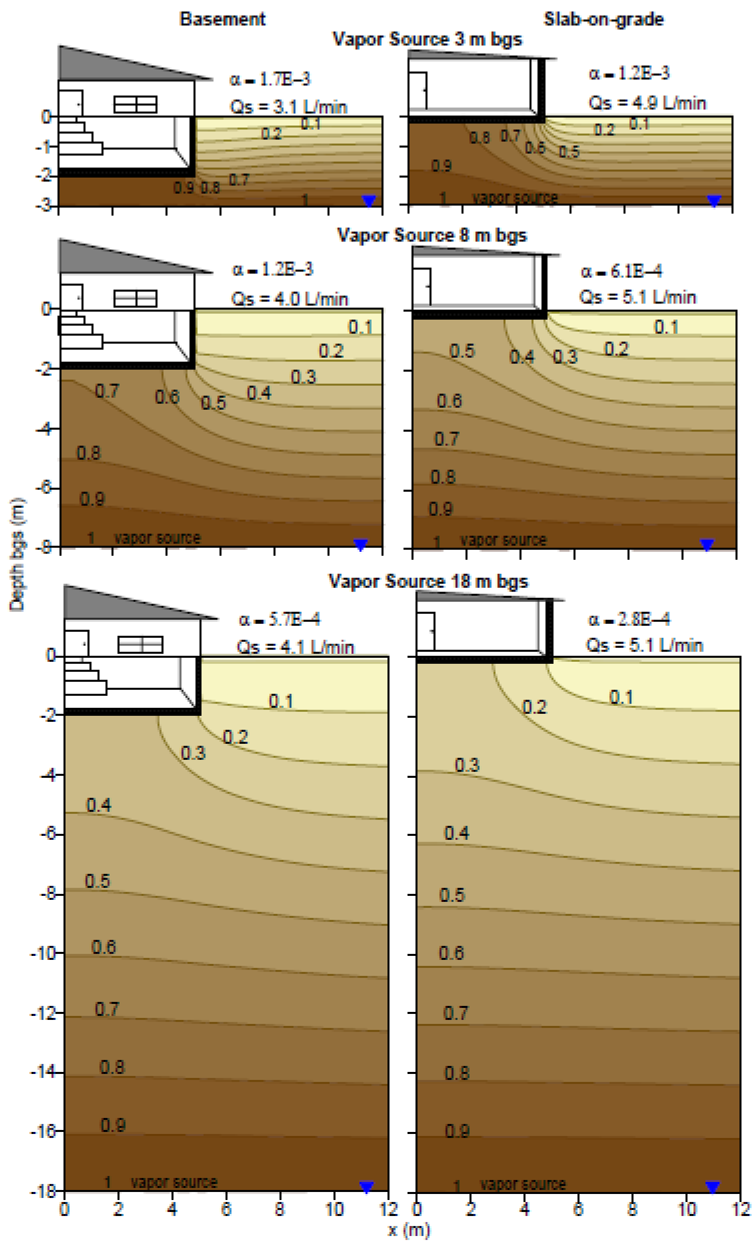


Figure 8. Effect of groundwater source depth on soil vapor distribution and normalized indoor air concentration (α) for two foundation types.

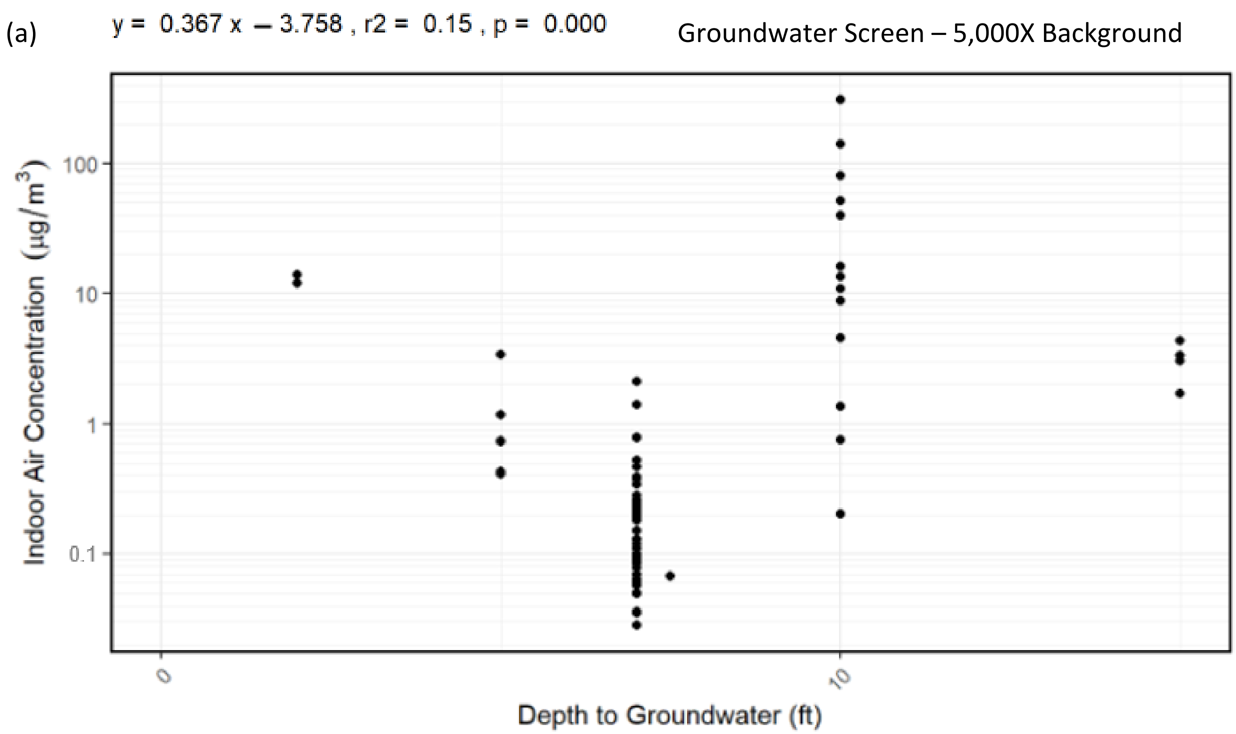
The soil vapor concentration contour lines are normalized by the source vapor concentration. Qs is the soil gas flow rate predicted for building under-pressurized by 5 Pa.

(Abreu, 2005)

Figure 4-88. 3D Equilibrium Modeling of Effect of Groundwater Depth on Normalized Indoor Air Concentration and Soil Gas Flow Rate

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Reprinted from USEPA, 2012b.



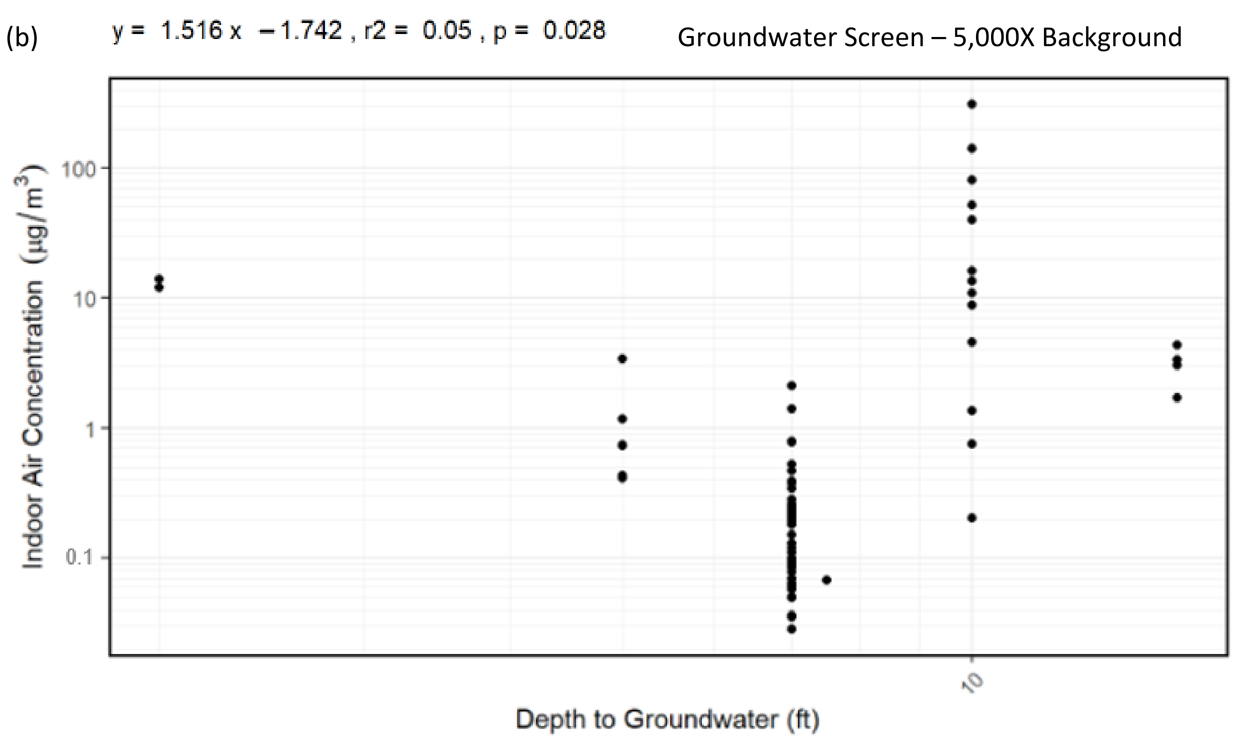
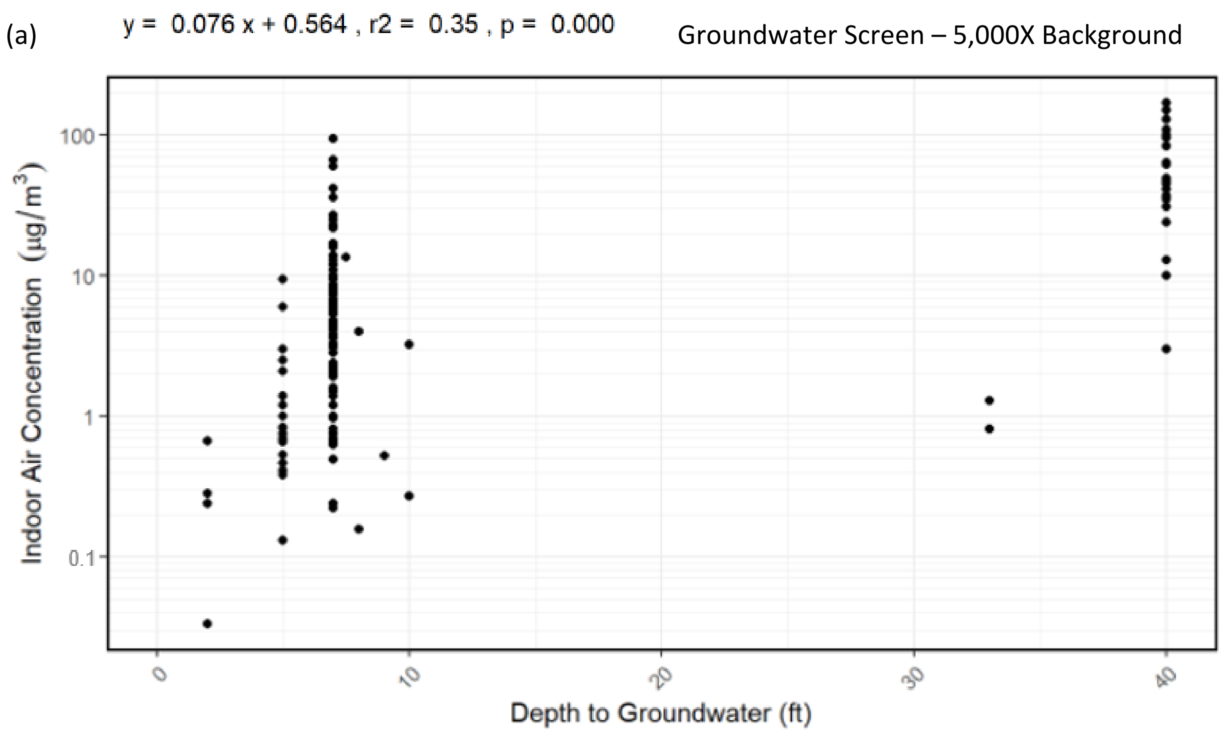


Figure 4-89. PCE in Indoor Air as a Function of Depth to Groundwater
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings Baseline, atypical preferential pathway, and source strength screened data using (a) a semi-log plot and (b) a log-log plot. In the equations, x represents the depth to groundwater (for a) or log of depth to groundwater (for b) and y represents the log of the indoor air concentration (for both a and b).



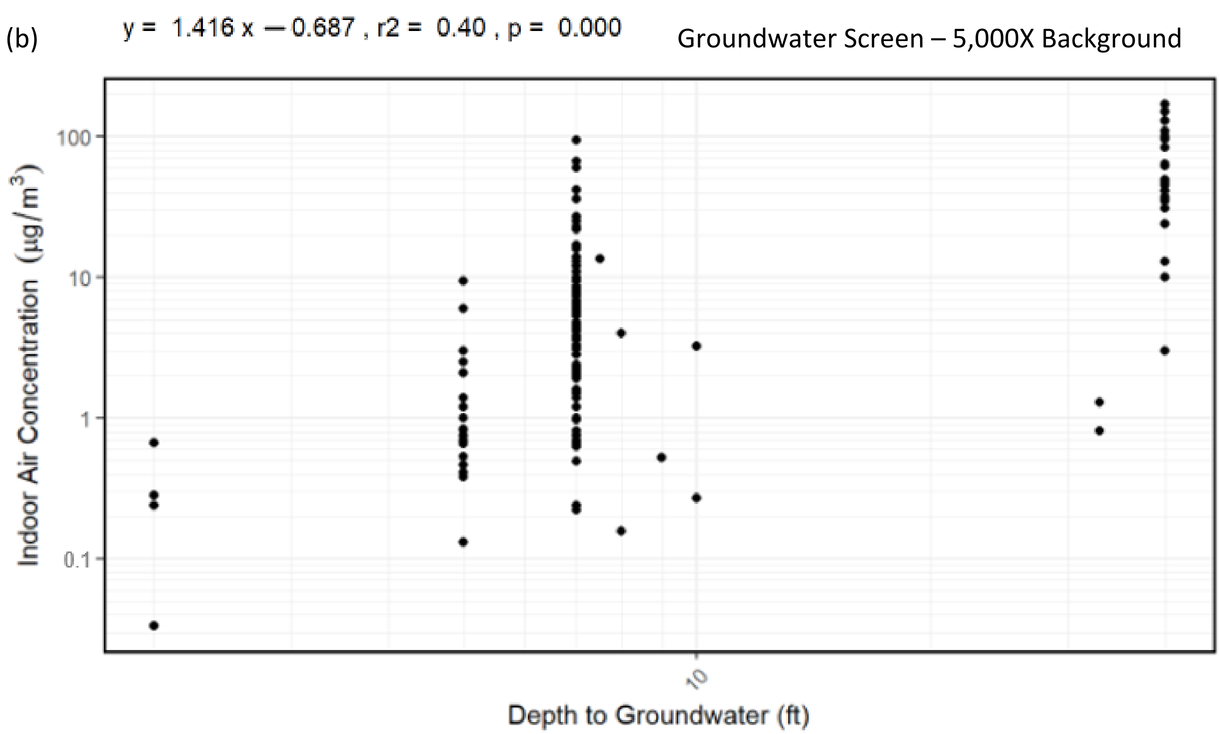


Figure 4-90. TCE in Indoor Air as a Function of Depth to Groundwater
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings Baseline, atypical preferential pathway, and source strength screened data using (a) a semi-log plot and (b) a log-log plot. In the equations, x represents the depth to groundwater (for a) or log of depth to groundwater (for b) and y represents the log of the indoor air concentration (for both a and b).

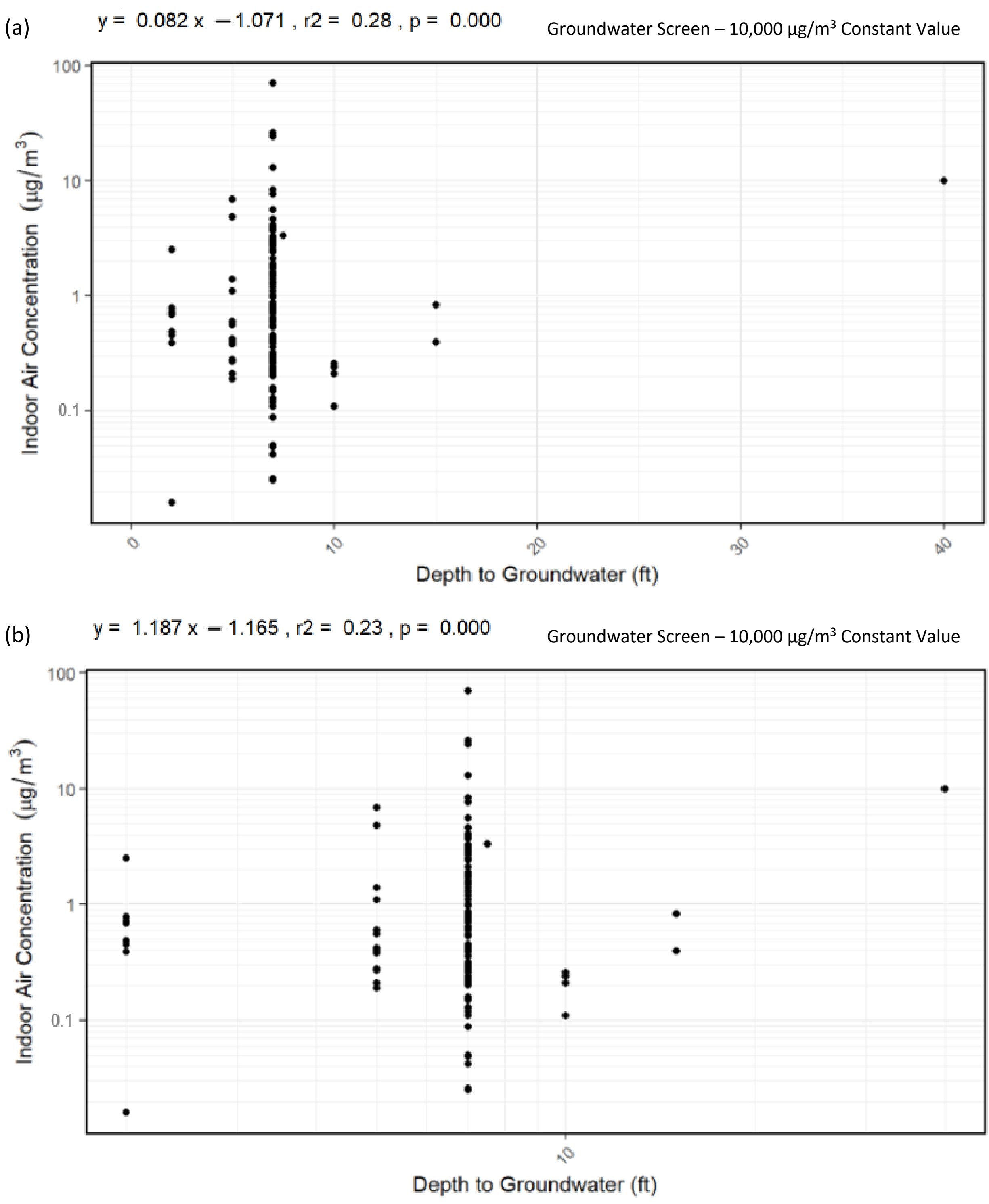
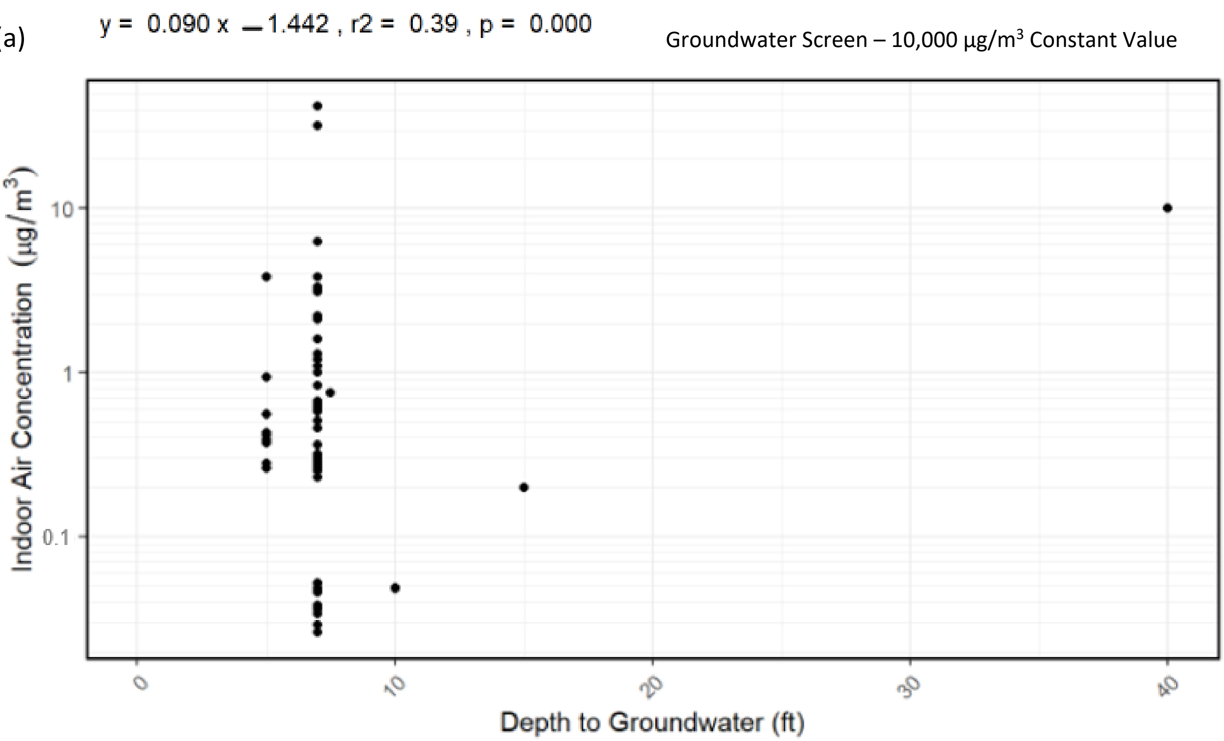


Figure 4-91. cis-1,2-DCE in Indoor Air as a Function of Depth to Groundwater

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings Baseline, atypical preferential pathway, and source strength screened data using (a) a semi-log plot and (b) a log-log plot. In the equations, x represents the depth to groundwater (for a) or log of depth to groundwater (for b) and y represents the log of the indoor air concentration (for both a and b).

(a)



(b)

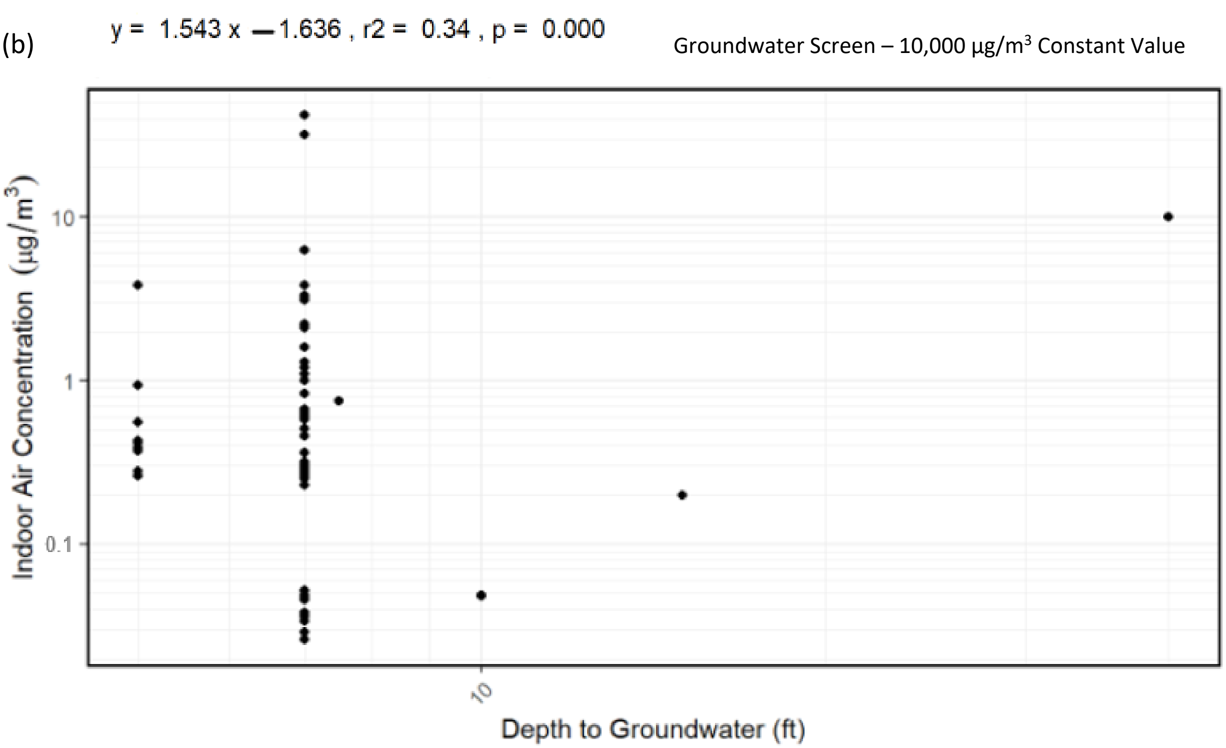
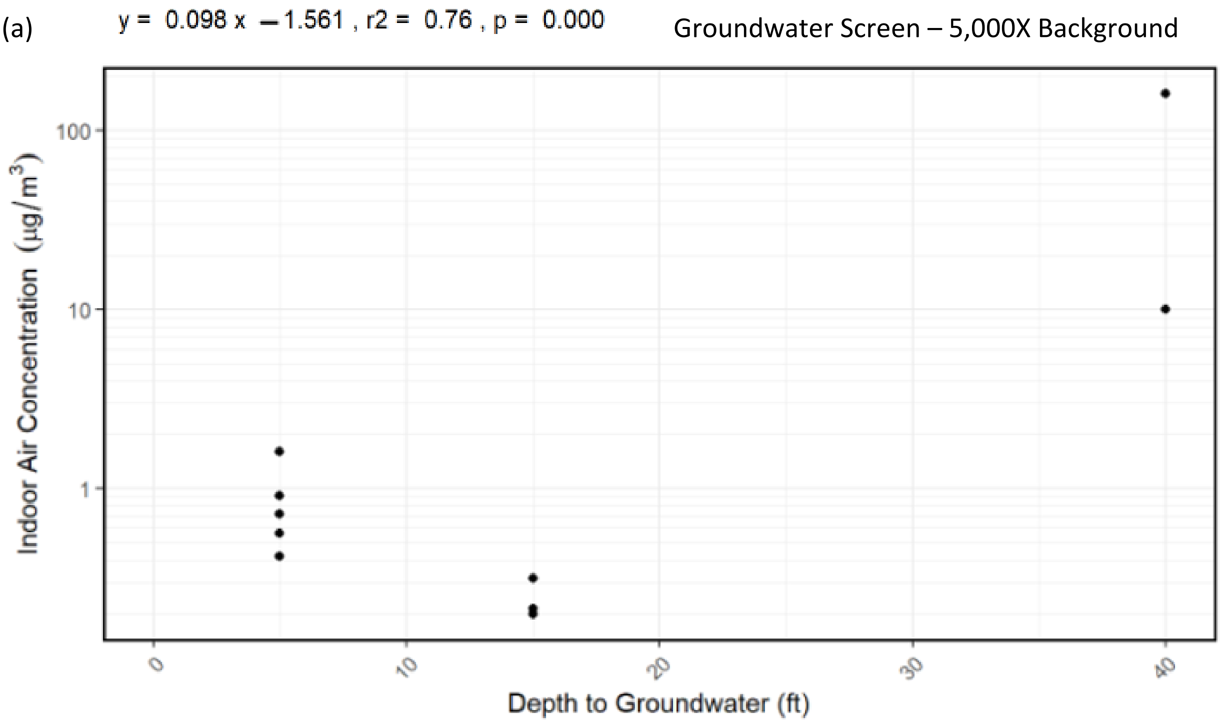


Figure 4-92. trans-1,2-DCE in Indoor Air as a Function of Depth to Groundwater

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings Baseline, atypical preferential pathway, and source strength screened data using (a) a semi-log plot and (b) a log-log plot. In the equations, x represents the depth to groundwater (for a) or log of depth to groundwater (for b) and y represents the log of the indoor air concentration (for both a and b).

(a)



(b)

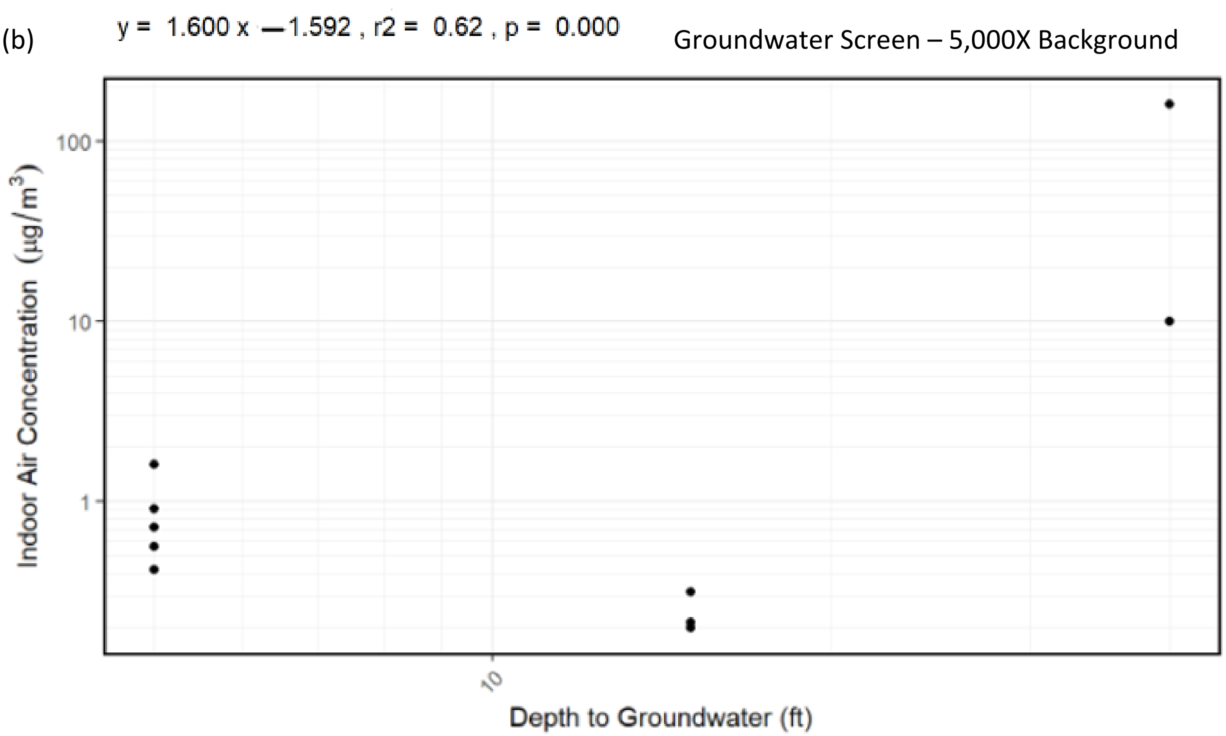
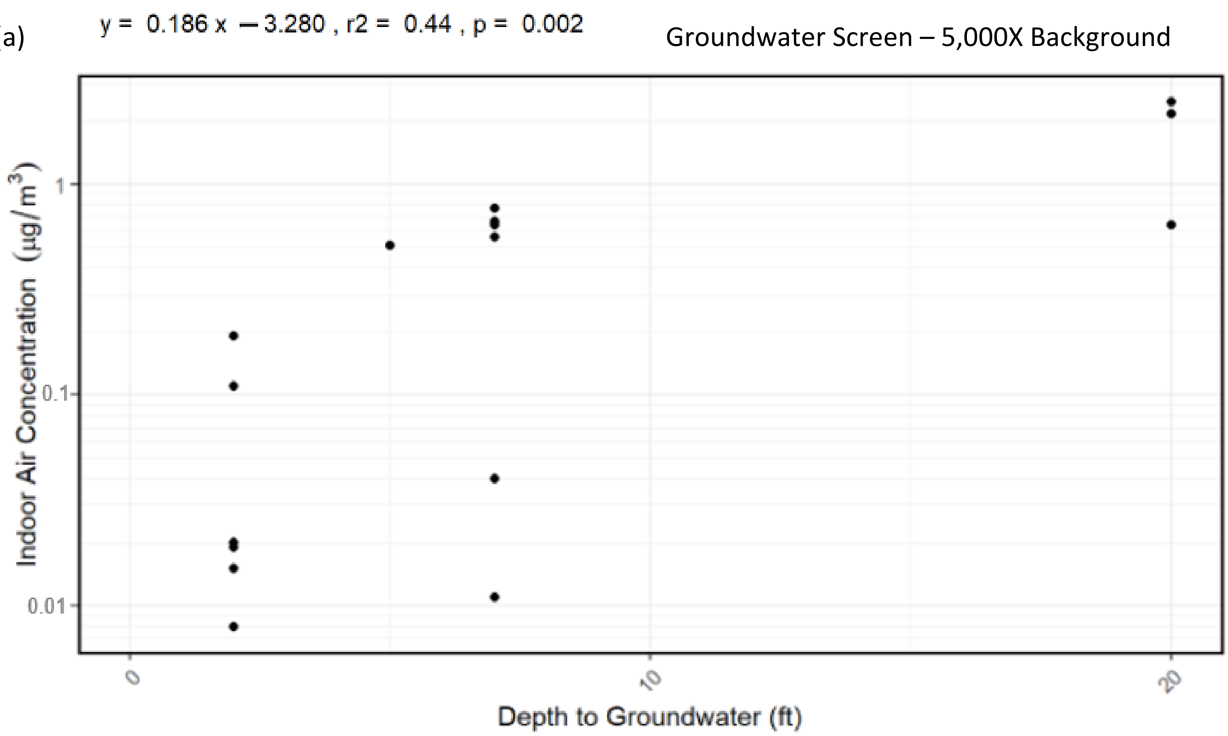


Figure 4-93. 1,1-DCE in Indoor Air as a Function of Depth to Groundwater
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings Baseline, atypical preferential pathway, and source strength screened data using (a) a semi-log plot and (b) a log-log plot. In the equations, x represents the depth to groundwater (for a) or log of depth to groundwater (for b) and y represents the log of the indoor air concentration (for both a and b).

(a)



(b)

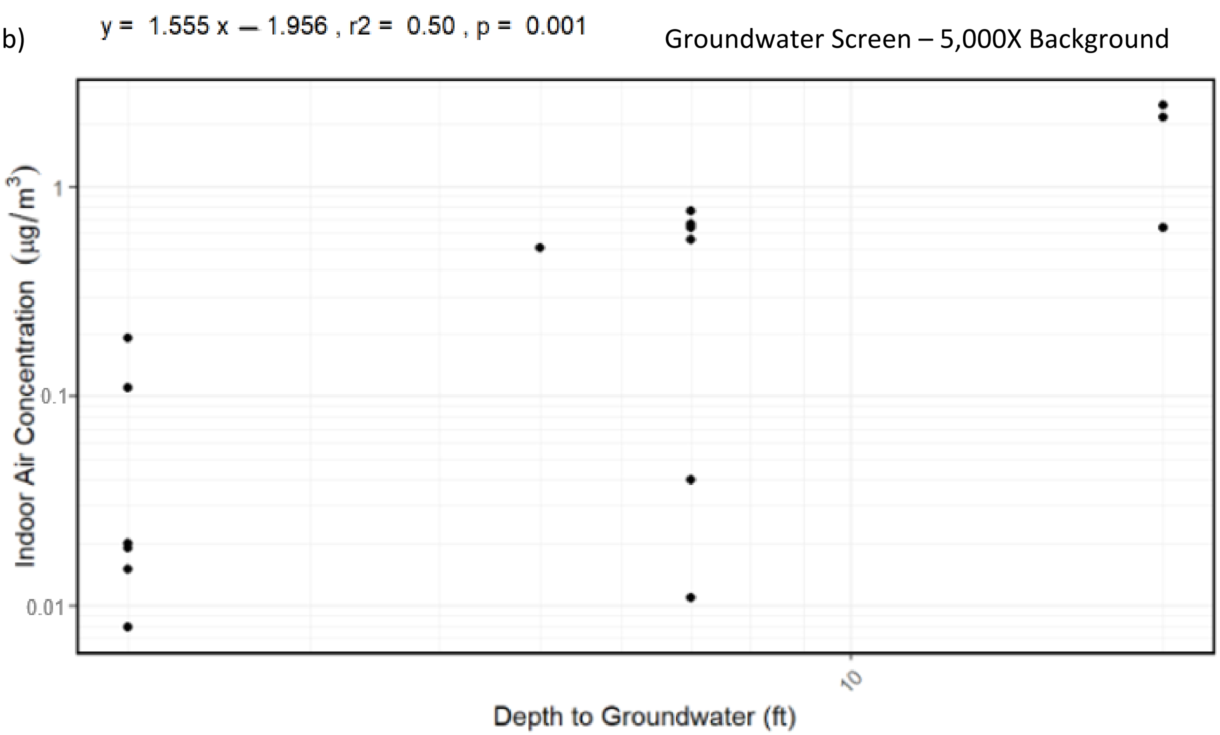


Figure 4-94. VC in Indoor Air as a Function of Depth to Groundwater

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings Baseline, atypical preferential pathway, and source strength screened data using (a) a semi-log plot and (b) a log-log plot. In the equations, x represents the depth to groundwater (for a) or log of depth to groundwater (for b) and y represents the log of the indoor air concentration (for both a and b).

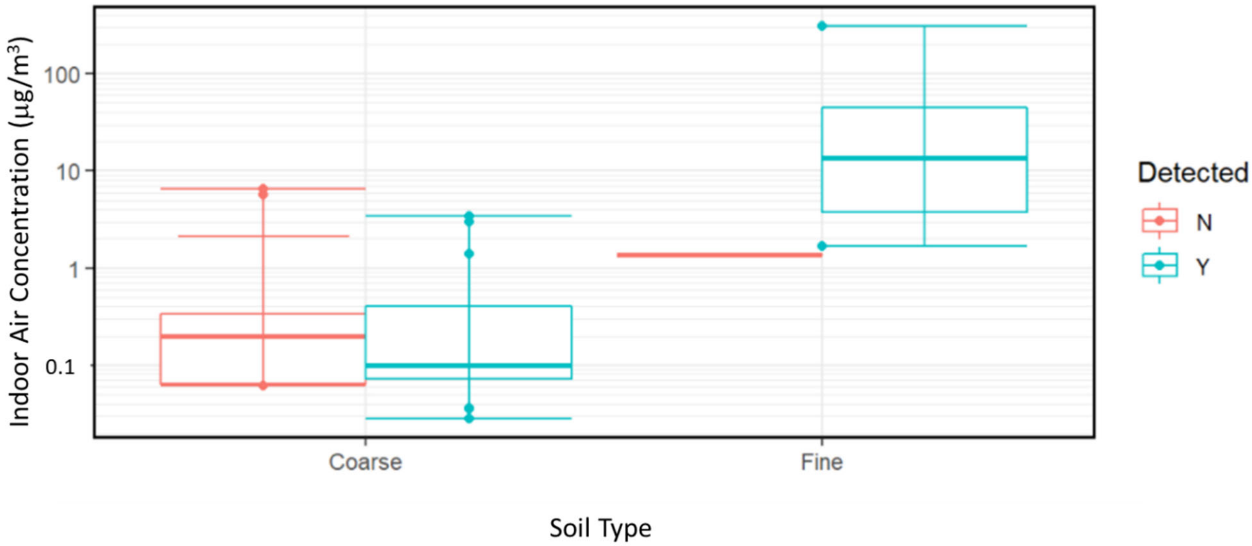


Figure 4-95. PCE Indoor Air Concentration Versus Soil Type
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"Y" and "N" refer to indoor air detects and non-detects (taken at the detection limit), respectively.

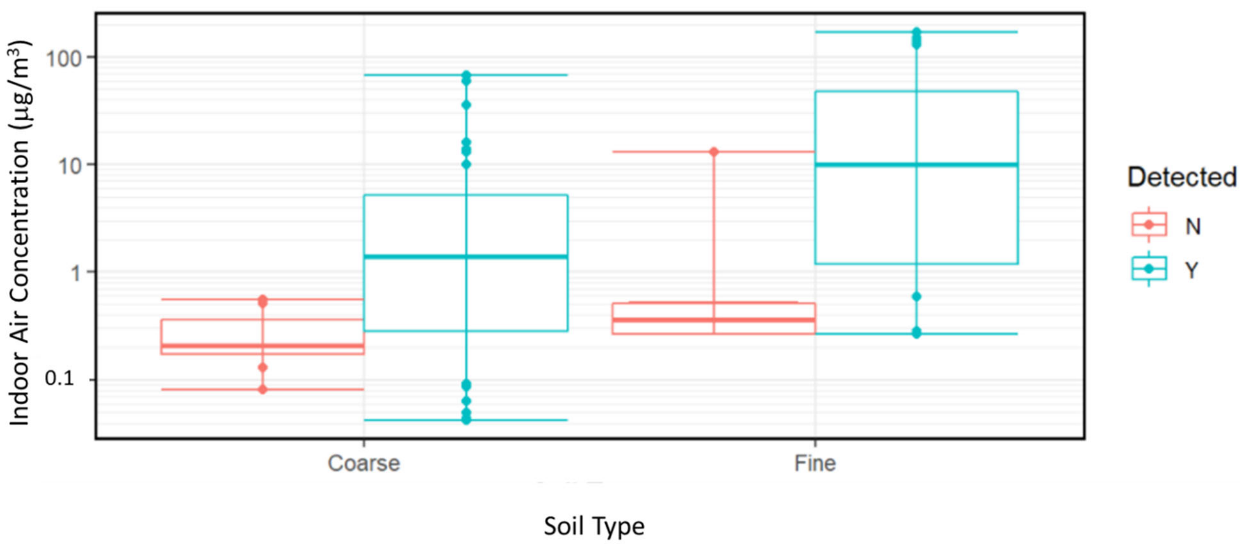


Figure 4-96. TCE Indoor Air Concentration Versus Soil Type
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"Y" and "N" refer to indoor air detects and non-detects (taken at the detection limit), respectively.

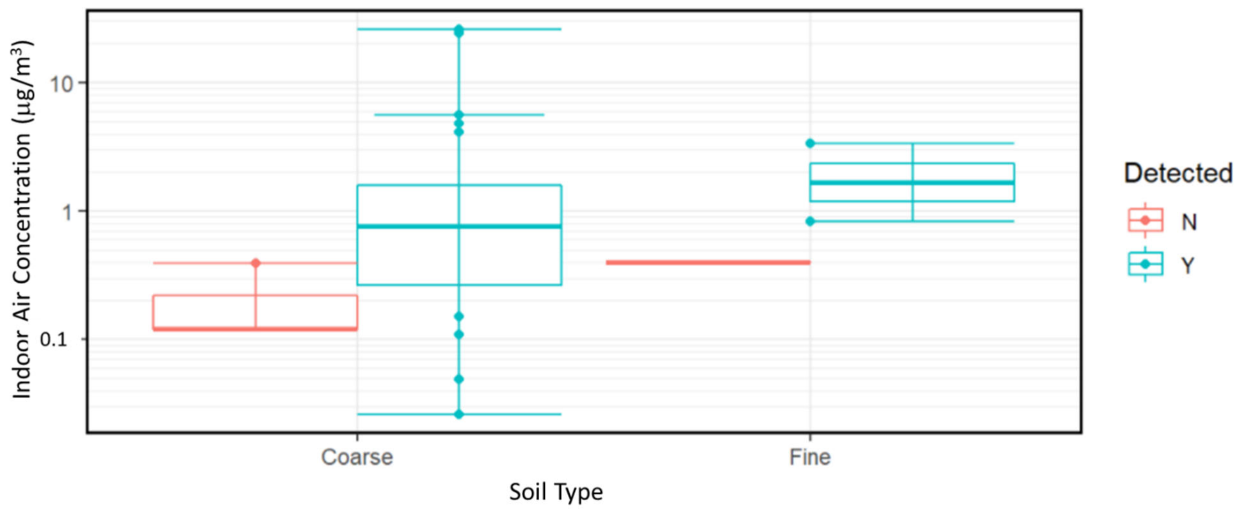


Figure 4-97. cis-1,2-DCE Indoor Air Concentration Versus Soil Type
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"Y" and "N" refer to indoor air detects and non-detects (taken at the detection limit), respectively.

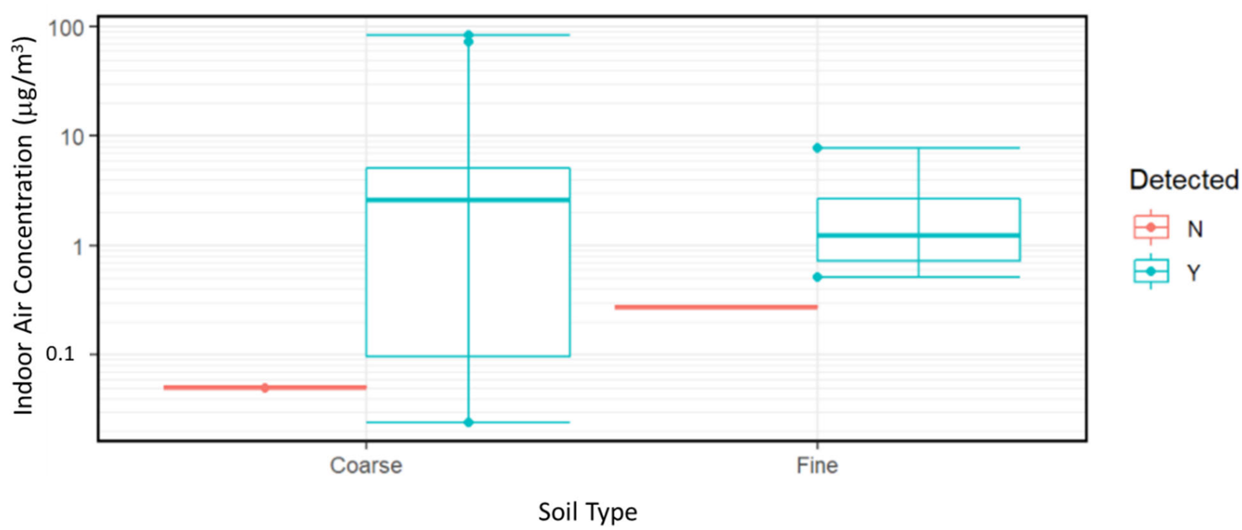


Figure 4-98. 1,1,1-TCA Indoor Air Concentration Versus Soil Type
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"Y" and "N" refer to indoor air detects and non-detects (taken at the detection limit), respectively.

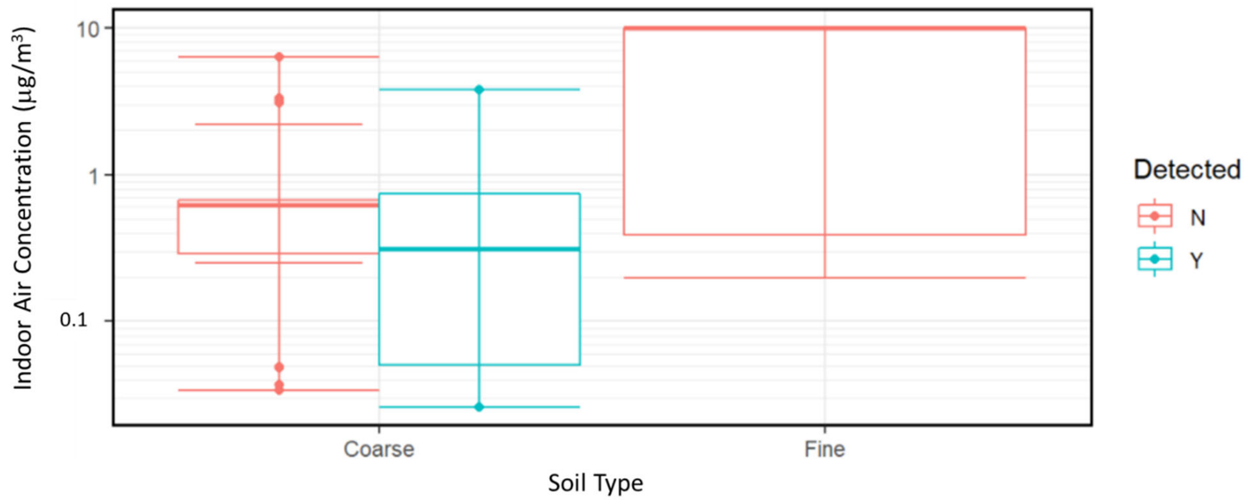


Figure 4-99. trans-1,2-DCE Indoor Air Concentration Versus Soil Type
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"Y" and "N" refer to indoor air detects and non-detects (taken at the detection limit), respectively.

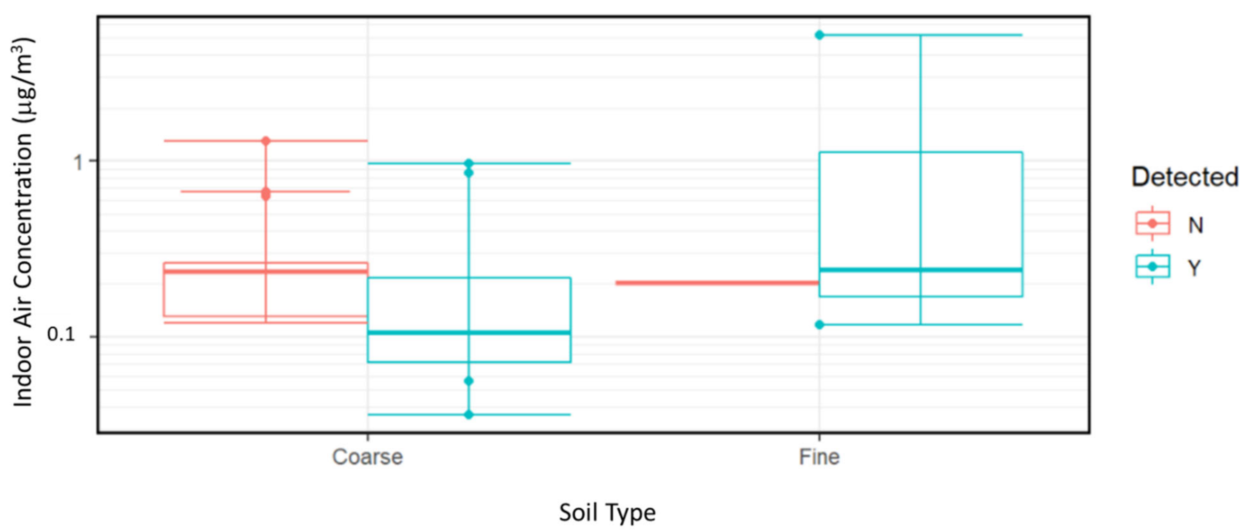


Figure 4-100. 1,1-DCA Concentrations in Indoor Air Versus Soil Type
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
"Y" and "N" refer to indoor air detects and non-detects (taken at the detection limit), respectively.

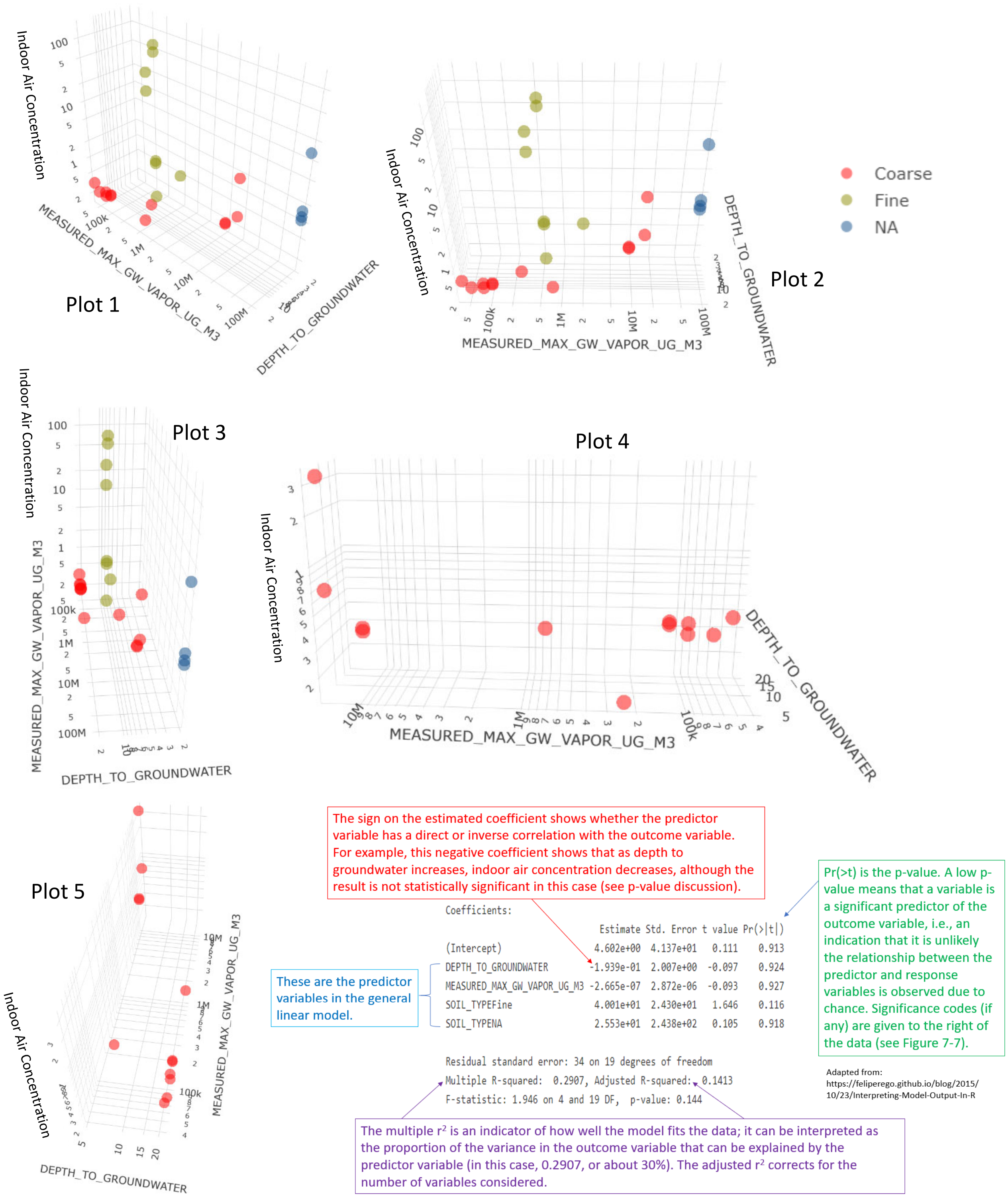


Figure 5-1. PCE Indoor Air Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth and Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plots 4 and 5 show data for coarse soil type only. General linear model results also shown with a key to how to read it.

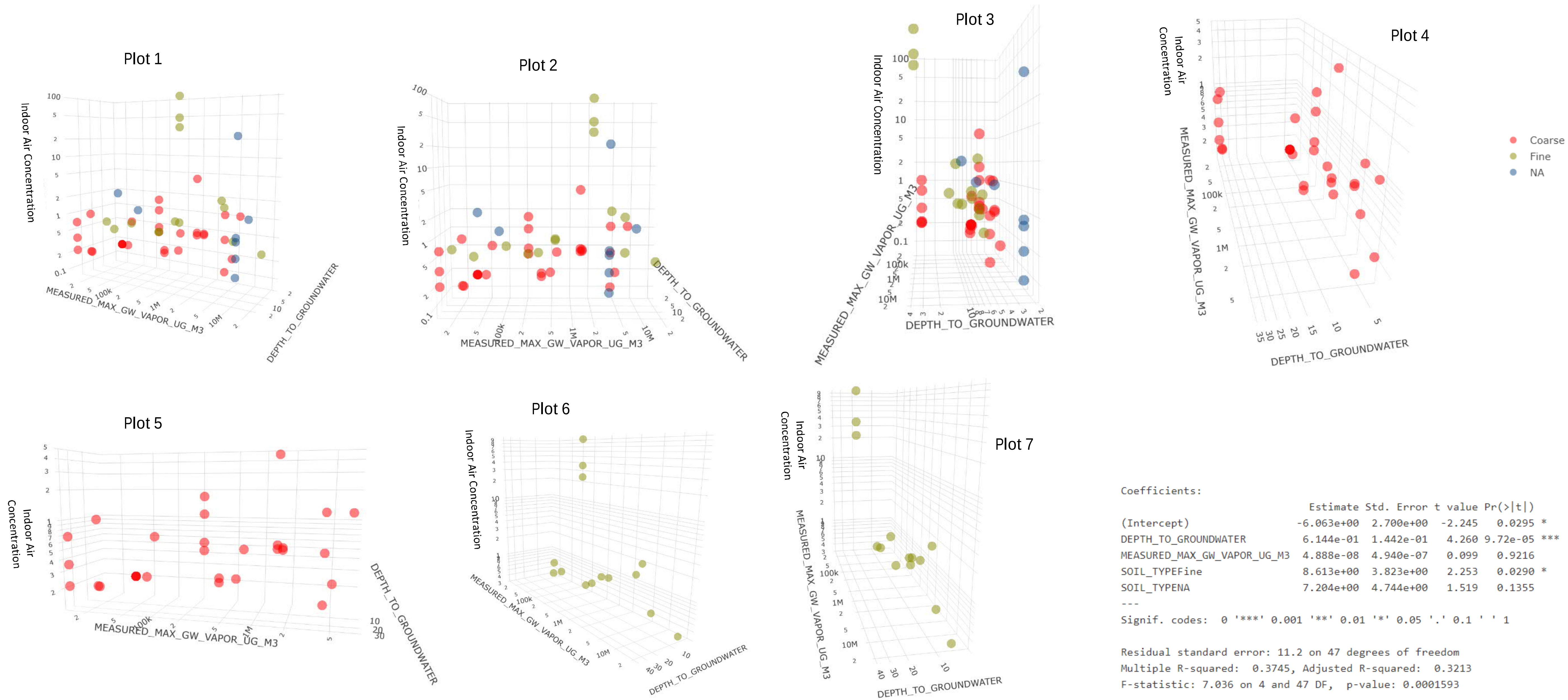
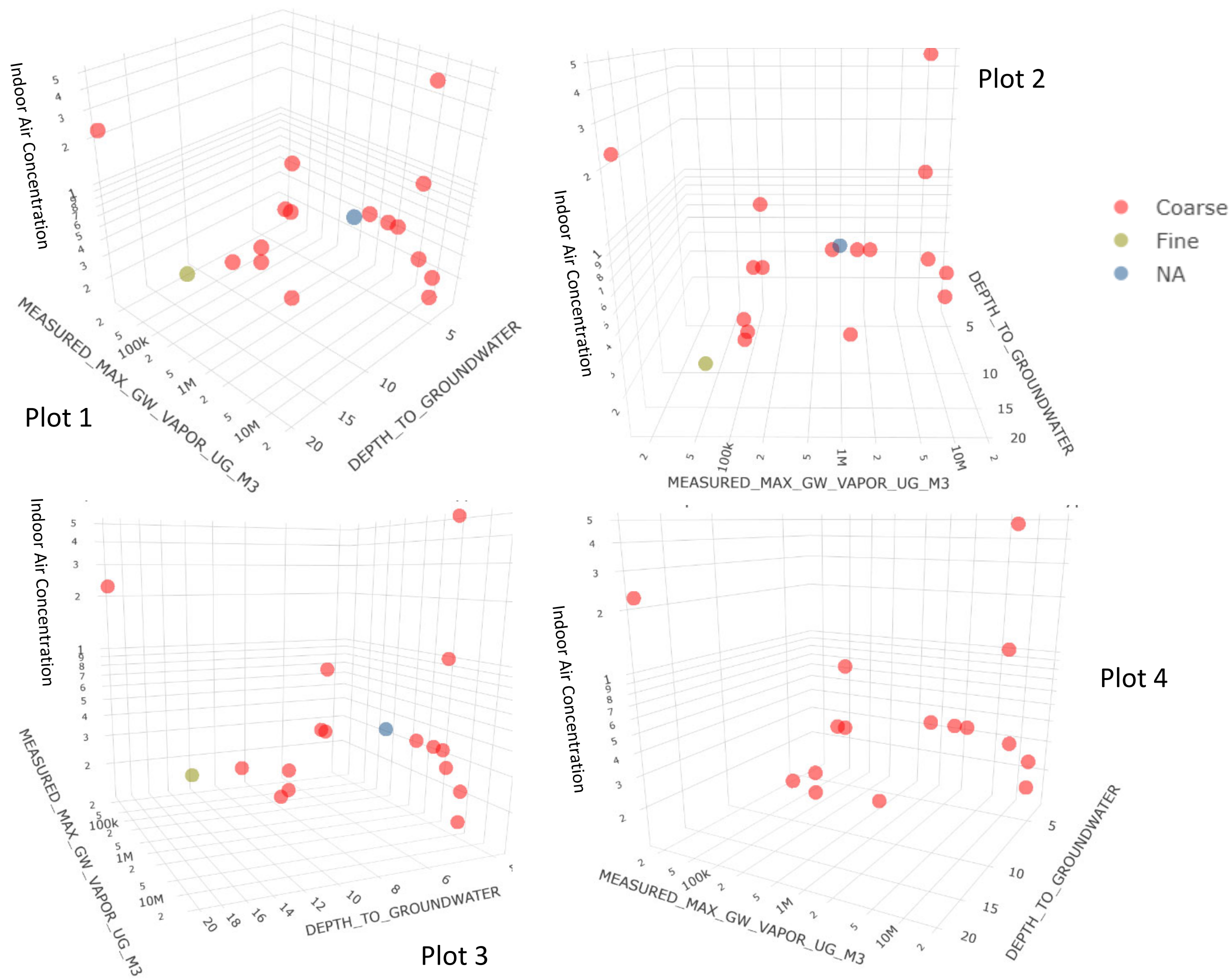


Figure 5-2. TCE Indoor Air Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth and Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plots 4 and 5 show data for coarse soil type only. Plots 6 and 7show data for fine soil type only. Generalized linear model results also shown.




```
Coefficients:
                            Estimate Std. Error t value Pr(>|t|)
(Intercept)                1.417e-02  7.462e-01   0.019    0.985
DEPTH_TO_GROUNDWATER       8.496e-02  8.429e-02   1.008    0.332
MEASURED_MAX_GW_VAPOR_UG_M3 3.765e-08  5.277e-08   0.714    0.488
SOIL_TYPEFine             -9.404e-01  1.374e+00  -0.685    0.506
SOIL_TYPENA               -7.545e-02  1.305e+00  -0.058    0.955

Residual standard error: 1.239 on 13 degrees of freedom
Multiple R-squared:  0.1006, Adjusted R-squared:  -0.1761
F-statistic: 0.3636 on 4 and 13 DF,  p-value: 0.8302
```

Figure 5-3. cis-1,2-DCE Indoor Air Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth, and Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plot 4 shows data for coarse soil type only. General linear model results also shown.

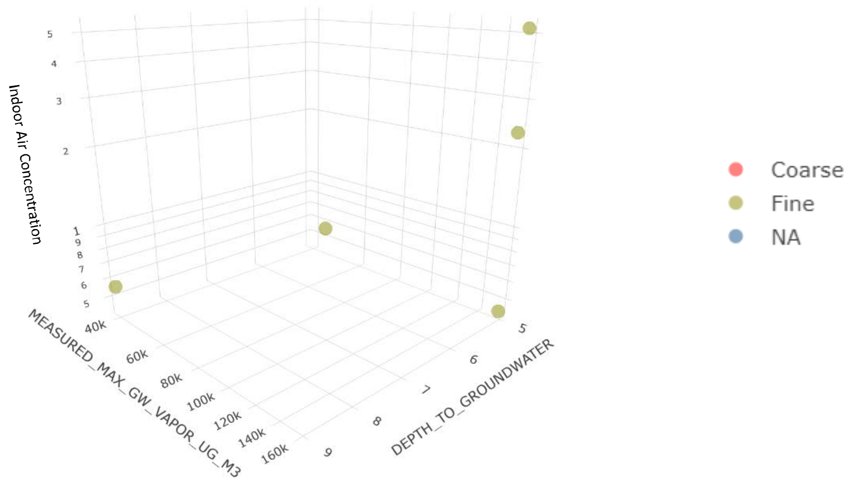
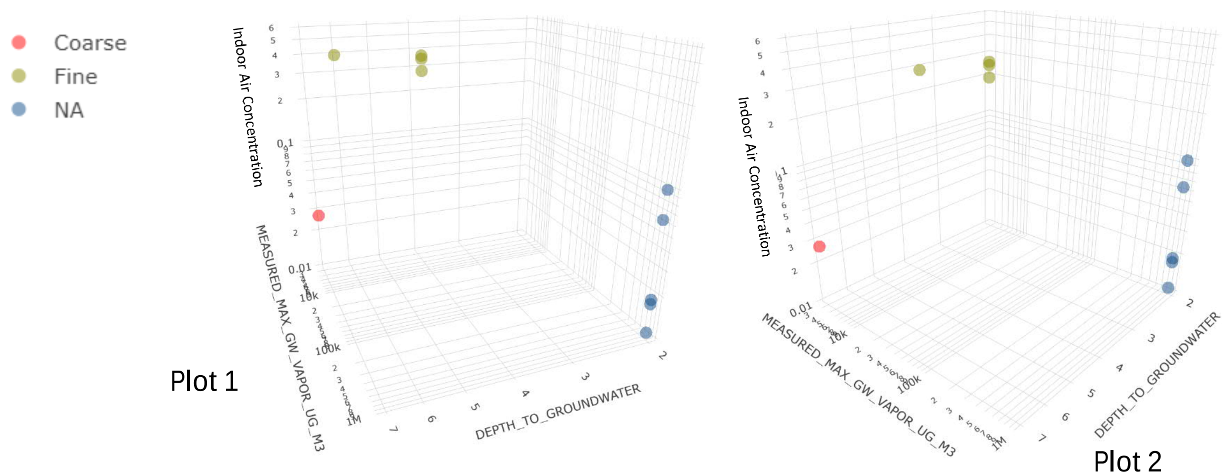


Figure 5-4. 1,1-DCA Indoor Air Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth, and Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

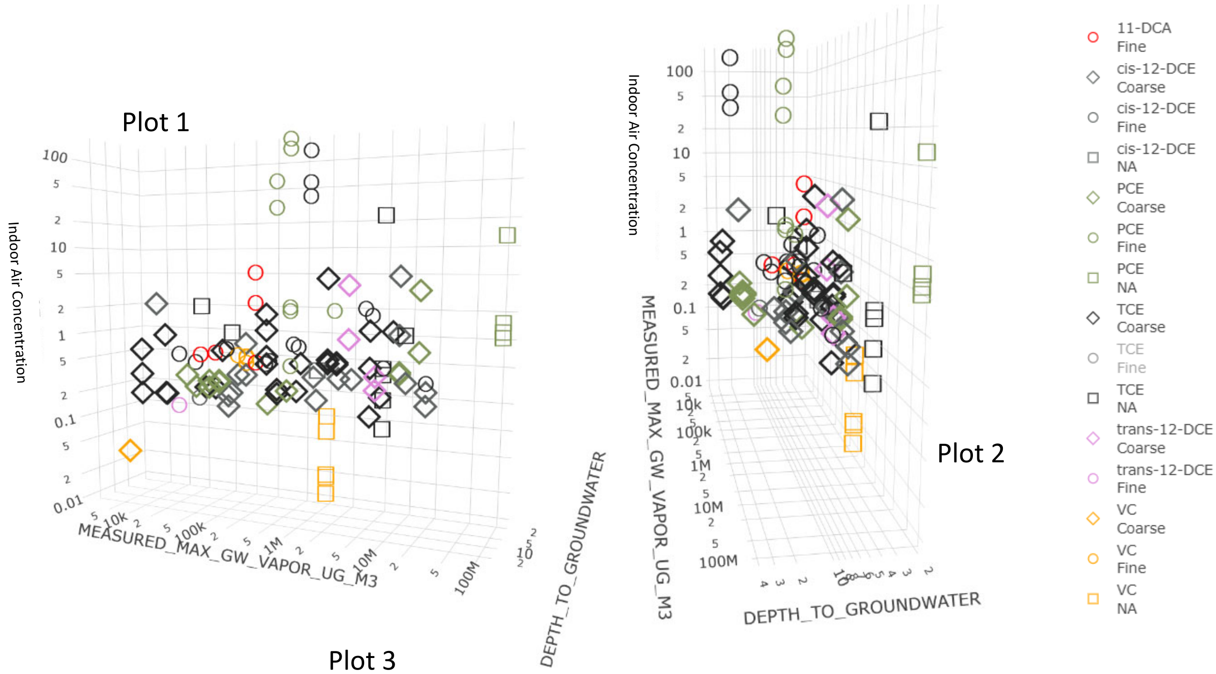


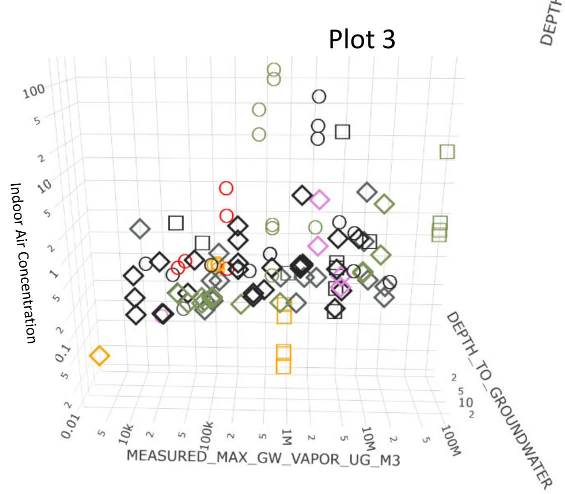

```
Coefficients: (1 not defined because of singularities)
                             Estimate Std. Error t value Pr(>|t|)
(Intercept)                -2.138e-01  1.782e-01  -1.200    0.275
DEPTH_TO_GROUNDWATER        3.437e-02  2.464e-02   1.395    0.212
MEASURED_MAX_GW_VAPOR_UG_M3  2.091e-07  1.476e-07   1.417    0.206
SOIL_TYPEFine               5.106e-01  4.710e-02  10.841 3.65e-05 ***
SOIL_TYPENA                        NA         NA      NA       NA
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.04149 on 6 degrees of freedom
Multiple R-squared:  0.981,	Adjusted R-squared:  0.9716
F-statistic: 103.5 on 3 and 6 DF,  p-value: 1.48e-05
```

Figure 5-5. VC Indoor Air Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth, and Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

General linear model results shown.



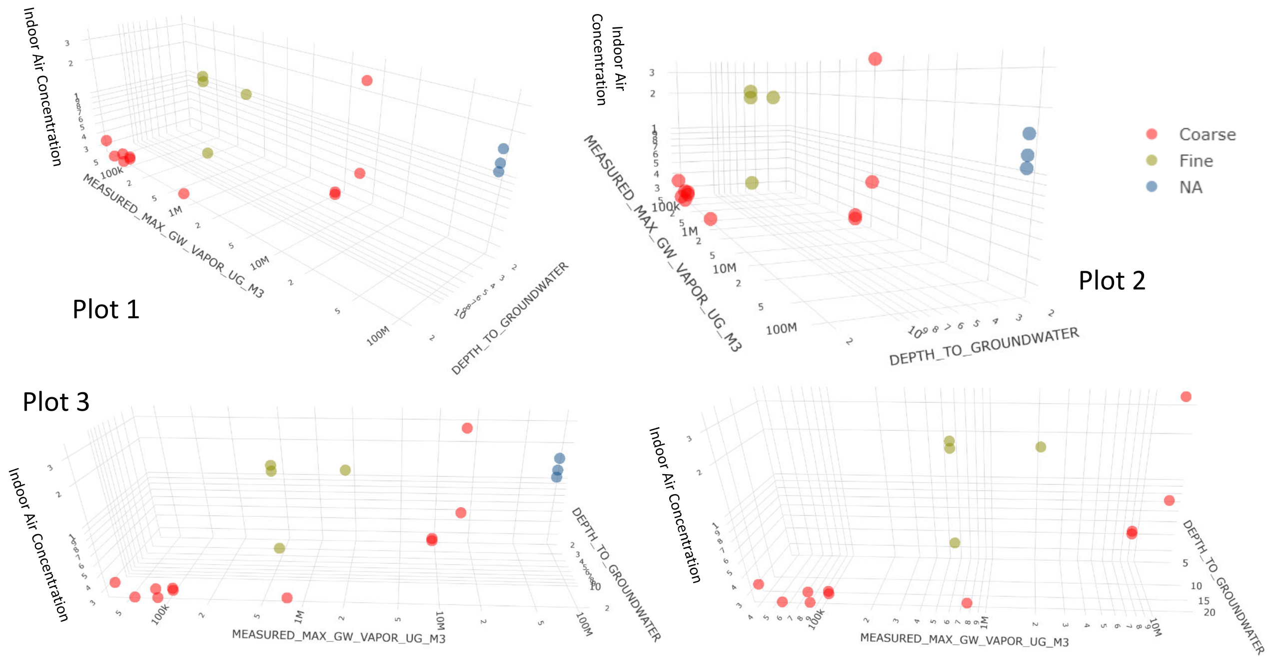



```
Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                 -2.729e+01  1.187e+01  -2.299  0.02267 *
DEPTH_TO_GROUNDWATER         1.114e-01  2.405e-01   0.463  0.64391
MEASURED_MAX_GW_VAPOR_UG_M3 -1.471e-07  1.092e-07  -1.347  0.17969
SOIL_TYPEFine                2.848e+01  4.343e+00   6.556 5.91e-10 ***
SOIL_TYPENA                  1.271e+01  7.877e+00   1.613  0.10850
Analyte_Shortcis-12-DCE      2.551e+01  1.296e+01   1.969  0.05055 .
Analyte_ShortPCE             3.229e+01  1.166e+01   2.769  0.00622 **
Analyte_ShortTCE             2.087e+01  1.188e+01   1.756  0.08086 .
Analyte_Shorttrans-12-DCE    2.238e+01  1.581e+01   1.416  0.15864
Analyte_ShortVC              9.413e+00  1.400e+01   0.672  0.50225
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 24.39 on 176 degrees of freedom
Multiple R-squared:  0.2568, Adjusted R-squared:  0.2188
F-statistic: 6.756 on 9 and 176 DF,  p-value: 2.637e-08
```

Figure 5-6. Indoor Air Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth, and Soil Type – Plots for All VOCs

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

General linear model results shown.

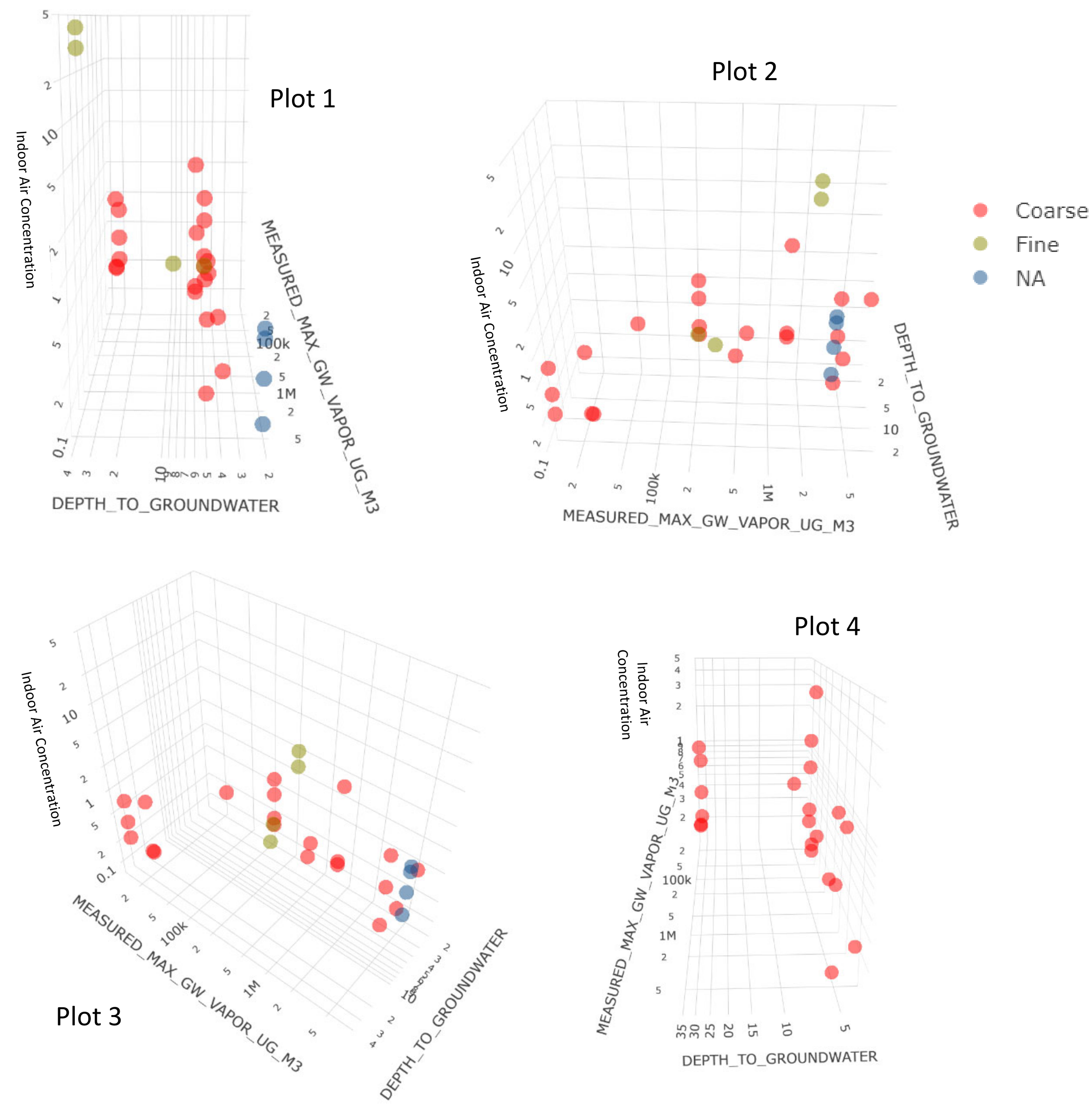



```
Coefficients:
                            Estimate Std. Error t value Pr(>|t|)
(Intercept)               -2.811e+00  1.716e+00  -1.639  0.12526
DEPTH_TO_GROUNDWATER       1.393e-01  7.839e-02   1.777  0.09895 .
MEASURED_MAX_GW_VAPOR_UG_M3  2.808e-07  1.078e-07   2.605  0.02181 *
SOIL_TYPEFine              2.809e+00  9.060e-01   3.101  0.00844 **
SOIL_TYPENA               -2.313e+01  8.838e+00  -2.617  0.02132 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.6474 on 13 degrees of freedom
Multiple R-squared:  0.6068, Adjusted R-squared:  0.4858
F-statistic: 5.016 on 4 and 13 DF,  p-value: 0.01145
```

Figure 5-7. PCE Indoor Air Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth and Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Dataset restricted to distance to primary release greater than 30 feet. Plot 4 excludes data for unknown ("NA") soil types. General linear model results also shown.

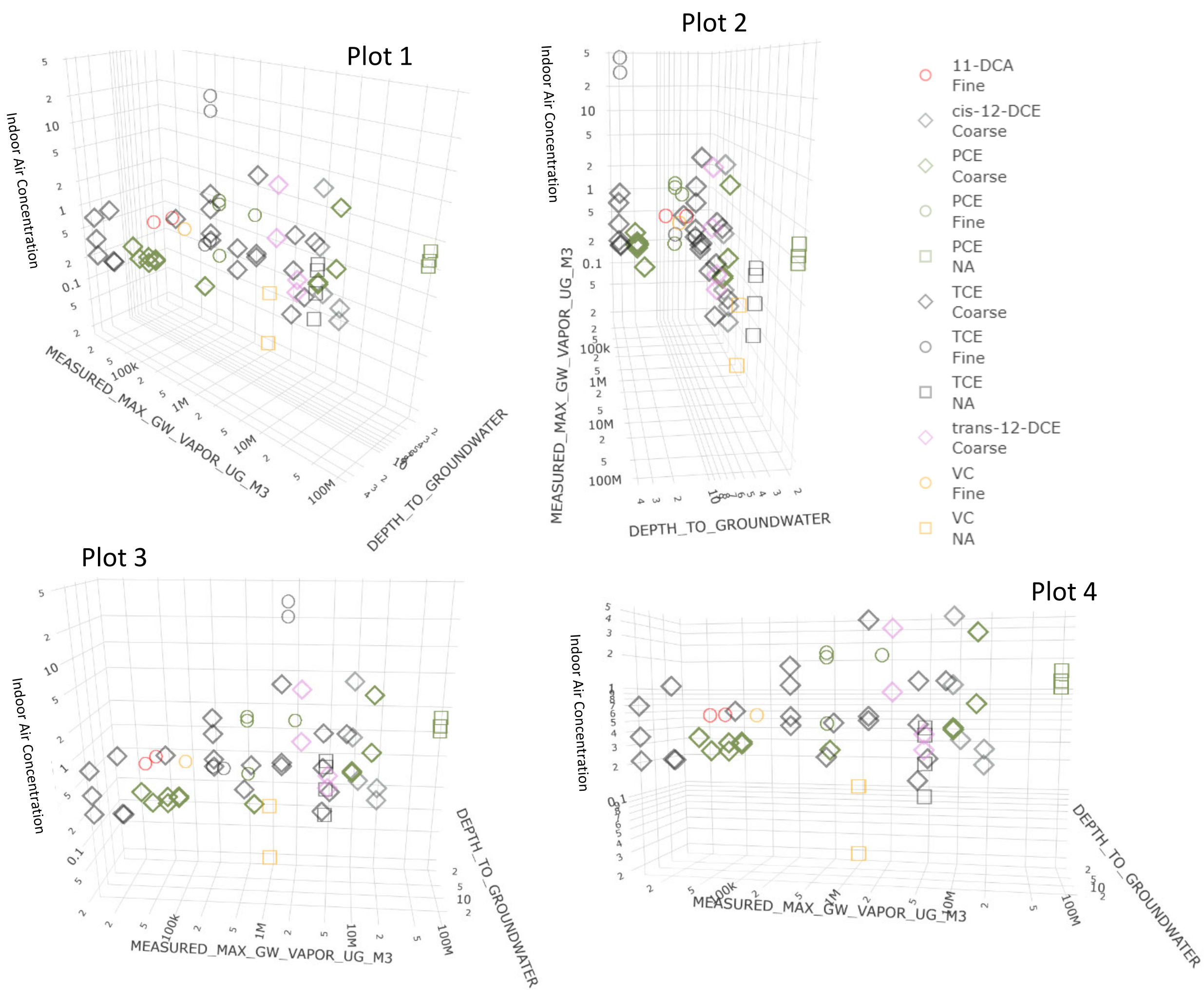



```
Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                 -5.067e+00  2.276e+00  -2.226 0.035666 *
DEPTH_TO_GROUNDWATER         3.071e-01  9.748e-02   3.150 0.004330 **
MEASURED_MAX_GW_VAPOR_UG_M3  1.234e-06  6.602e-07   1.869 0.073827 .
SOIL_TYPEFine                1.473e+01  3.513e+00   4.192 0.000324 ***
SOIL_TYPENA                 -7.932e-01  3.888e+00  -0.204 0.840064
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 6.19 on 24 degrees of freedom
Multiple R-squared:  0.6153, Adjusted R-squared:  0.5512
F-statistic: 9.597 on 4 and 24 DF,  p-value: 8.808e-05
```

Figure 5-8. TCE Indoor Air Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth, and Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Dataset restricted to distance to primary release greater than 30 feet. Plot 4 shows data for coarse soil type only. General linear model results also shown.




```
Coefficients:
                            Estimate Std. Error t value Pr(>|t|)
(Intercept)                -6.161e+00  3.064e+00  -2.011   0.0469 *
DEPTH_TO_GROUNDWATER        2.240e-01  4.544e-02   4.930 3.09e-06 ***
MEASURED_MAX_GW_VAPOR_UG_M3 6.415e-08  2.573e-08   2.493   0.0142 *
SOIL_TYPEFine               5.150e+00  1.034e+00   4.982 2.49e-06 ***
SOIL_TYPENA                -7.243e-01  2.025e+00  -0.358   0.7213
Analyte_Shortcis-12-DCE     5.553e+00  3.543e+00   1.567   0.1200
Analyte_ShortPCE            2.159e+00  3.011e+00   0.717   0.4750
Analyte_ShortTCE            5.640e+00  3.090e+00   1.826   0.0708 .
Analyte_Shorttrans-12-DCE   6.157e+00  3.648e+00   1.688   0.0944 .
Analyte_ShortVC             4.291e+00  3.952e+00   1.086   0.2800
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 4.036 on 105 degrees of freedom
Multiple R-squared:  0.3351, Adjusted R-squared:  0.2781
F-statistic: 5.879 on 9 and 105 DF,  p-value: 1.287e-06
```

Figure 5-9. Indoor Air Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth, and Soil Type – Plots for All VOCs

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings Dataset restricted to distance to primary release greater than 30 feet. Screen selected for each individual compound. Plot 4 excludes TCE data in fine soil type. General linear model results also shown.

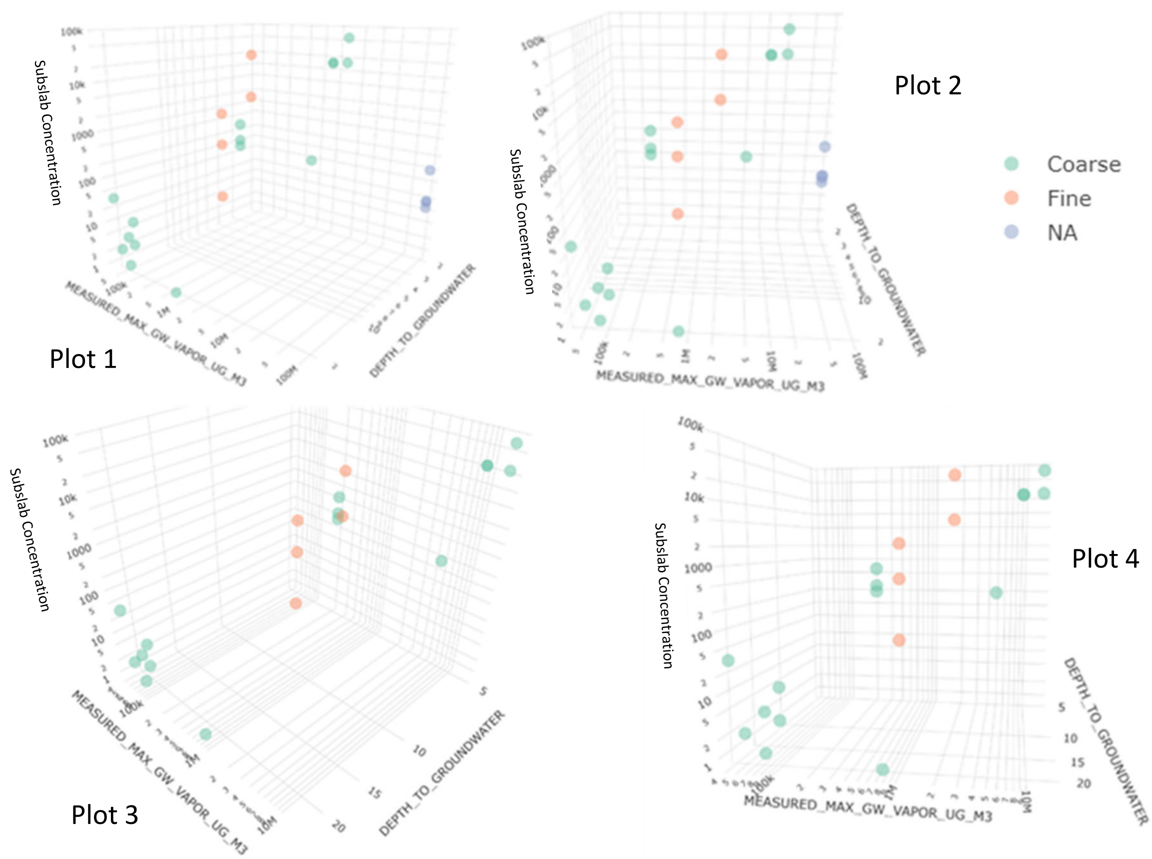


Figure 5-10. PCE Subslab Soil Gas Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth, and Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Dataset restricted to distance to primary release greater than 30 feet. Plots 3 and 4 exclude data for unknown ("NA") soil types.

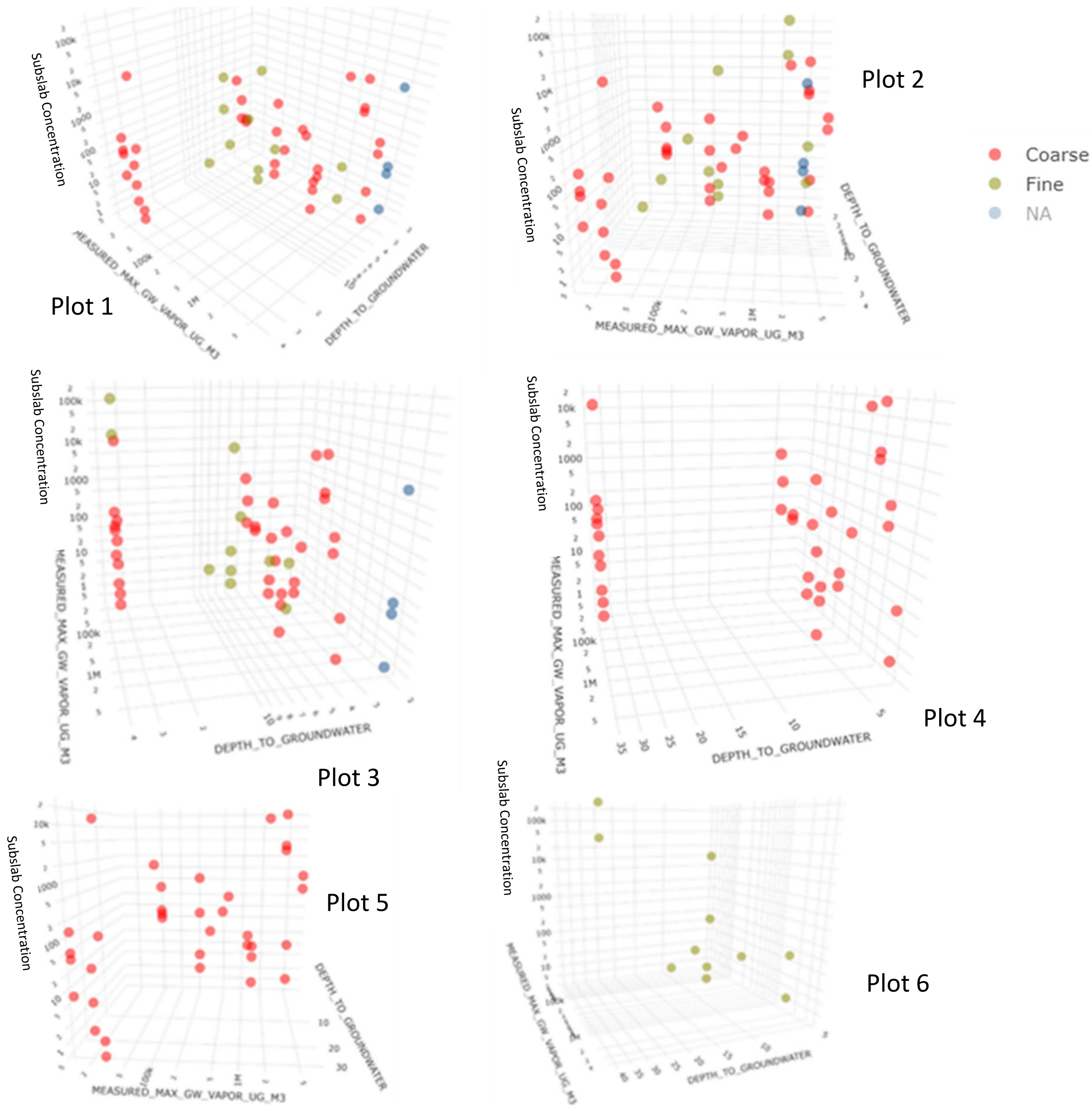


Figure 5-11. TCE Subslab Soil Gas Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth, and Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Dataset restricted to distance to primary release greater than 30 feet. Plots 4 and 5 show data for coarse soil type only. Plot 6 shows data for fine soil type only.

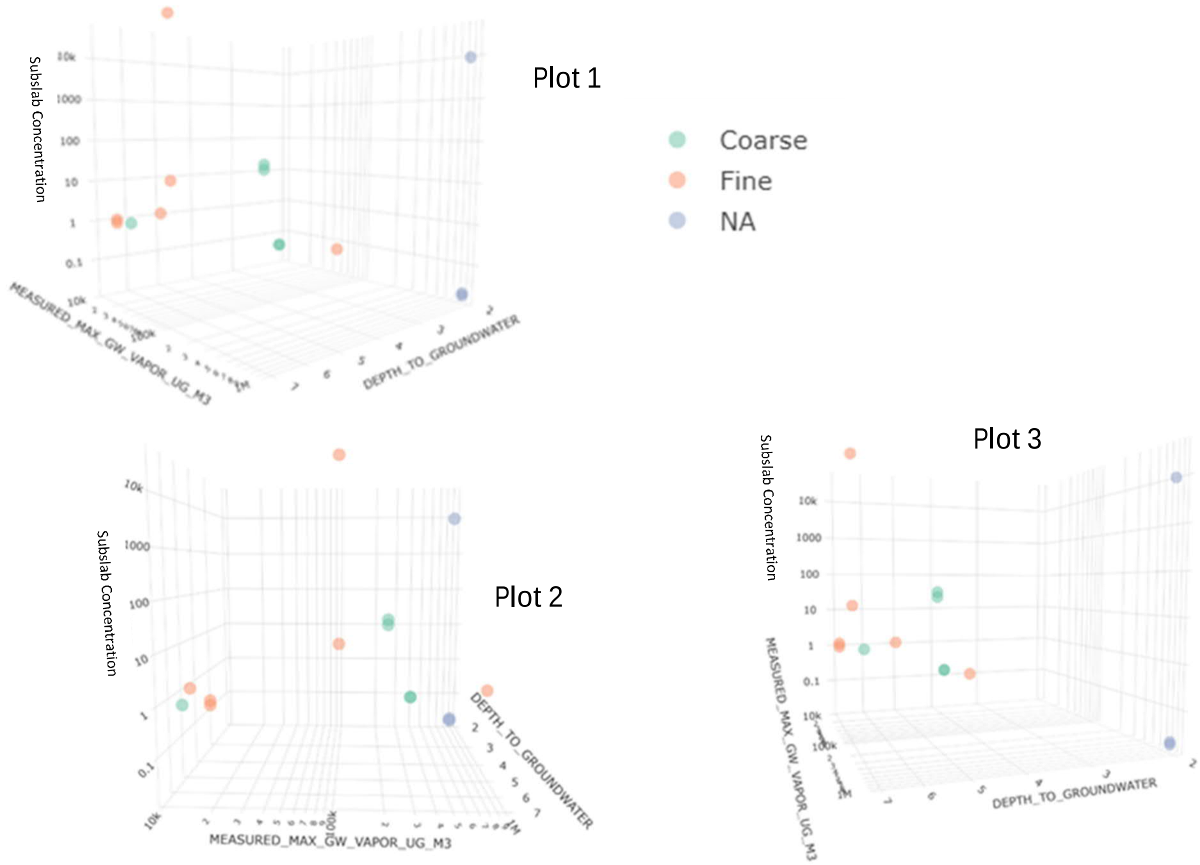
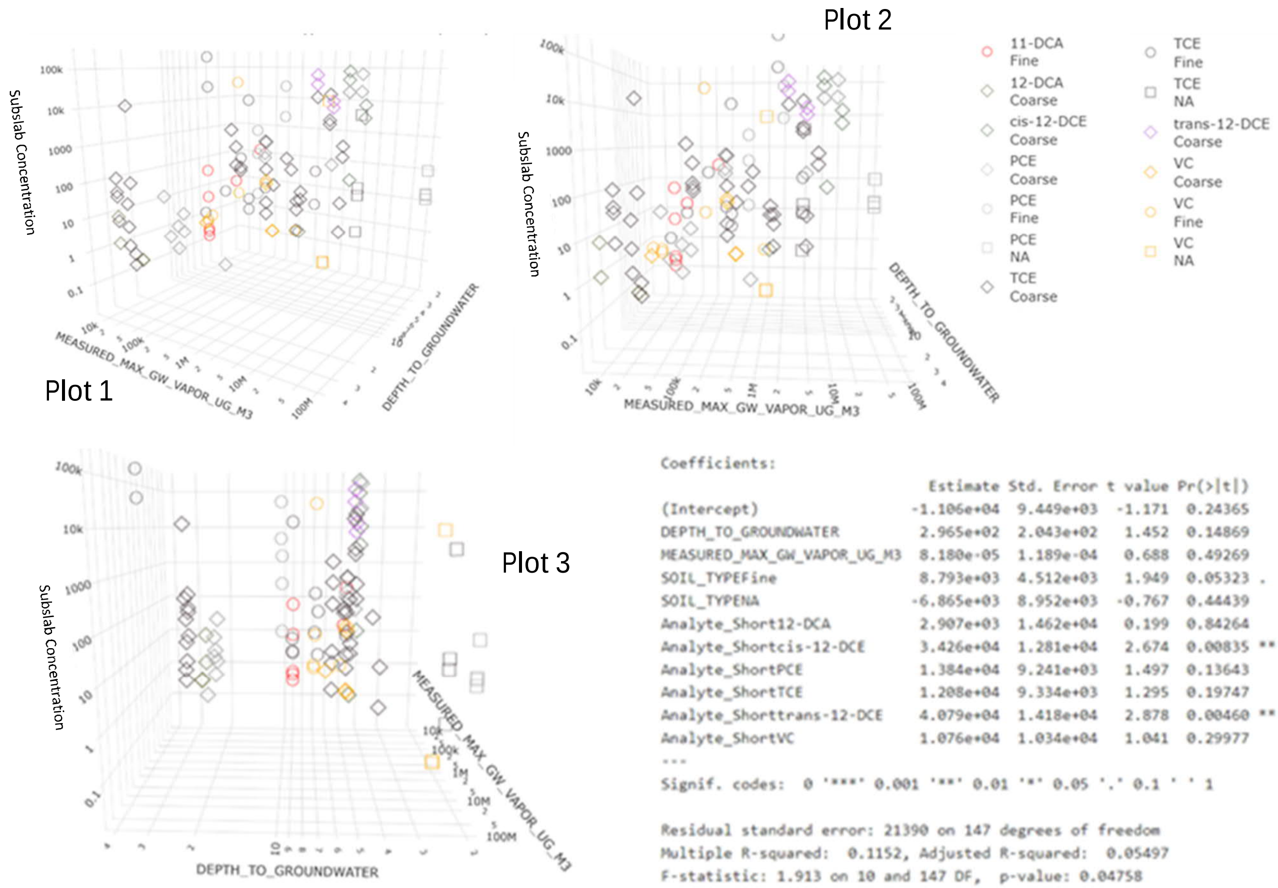


Figure 5-12. VC Subslab Soil Gas Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth, and Soil Type

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings Dataset restricted to distance to primary release greater than 30 feet.




```
Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                 -1.106e+04  9.449e+03  -1.171  0.24365
DEPTH_TO_GROUNDWATER         2.965e+02  2.043e+02   1.452  0.14869
MEASURED_MAX_GW_VAPOR_UG_M3  8.180e-05  1.189e-04   0.688  0.49269
SOIL_TYPEFine                8.793e+03  4.512e+03   1.949  0.05323 .
SOIL_TYPENA                 -6.865e+03  8.952e+03  -0.767  0.44439
Analyte_Short12-DCA          2.907e+03  1.462e+04   0.199  0.84264
Analyte_Shortcis-12-DCE      3.426e+04  1.281e+04   2.674  0.00835 **
Analyte_ShortPCE             1.384e+04  9.241e+03   1.497  0.13643
Analyte_ShortTCE             1.208e+04  9.334e+03   1.295  0.19747
Analyte_Shorttrans-12-DCE    4.079e+04  1.418e+04   2.878  0.00460 **
Analyte_ShortVC              1.076e+04  1.034e+04   1.041  0.29977
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 21390 on 147 degrees of freedom
Multiple R-squared:  0.1152,	Adjusted R-squared:  0.05497
F-statistic: 1.913 on 10 and 147 DF,  p-value: 0.04758
```

Figure 5-13. Subslab Soil Gas Concentration as a Function of Groundwater Vapor Concentration, Groundwater Depth, and Soil Type – Plots for All VOCs

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Dataset restricted to distance to primary release greater than 30 feet. General linear model results also shown.

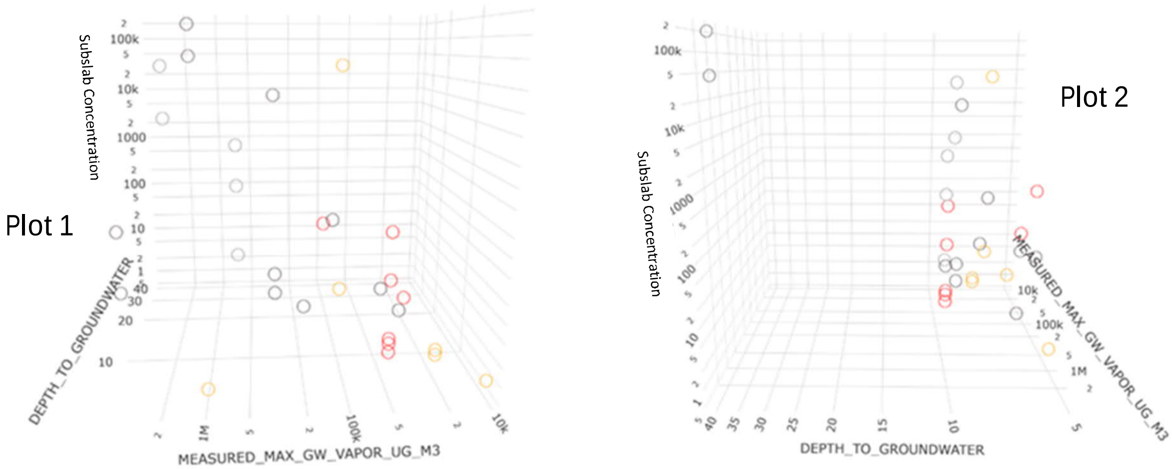


Figure 5-14. Subslab Soil Gas Concentration as a Function of Groundwater Vapor Concentration and Groundwater Depth, Fine Soil Type Only – Plots for All VOCs

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Dataset restricted to distance to primary release greater than 30 feet.

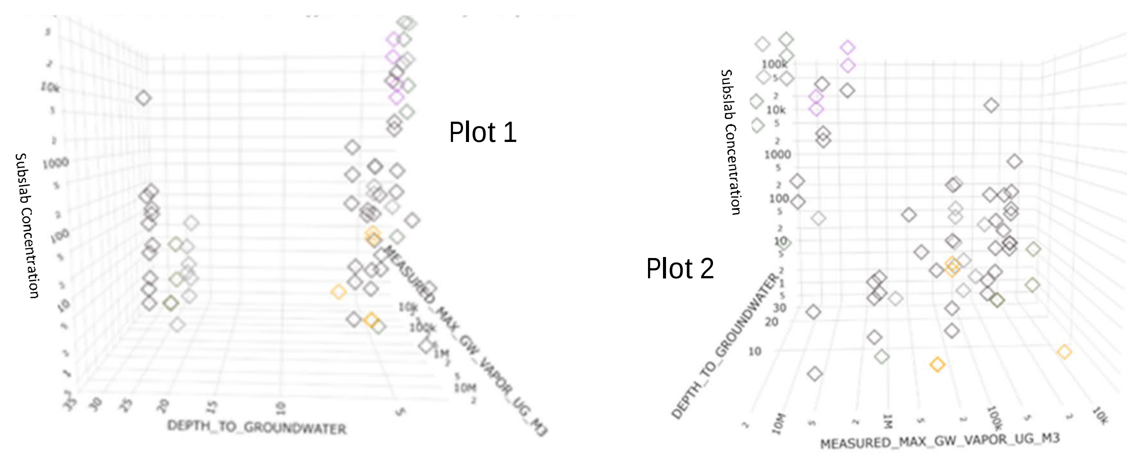
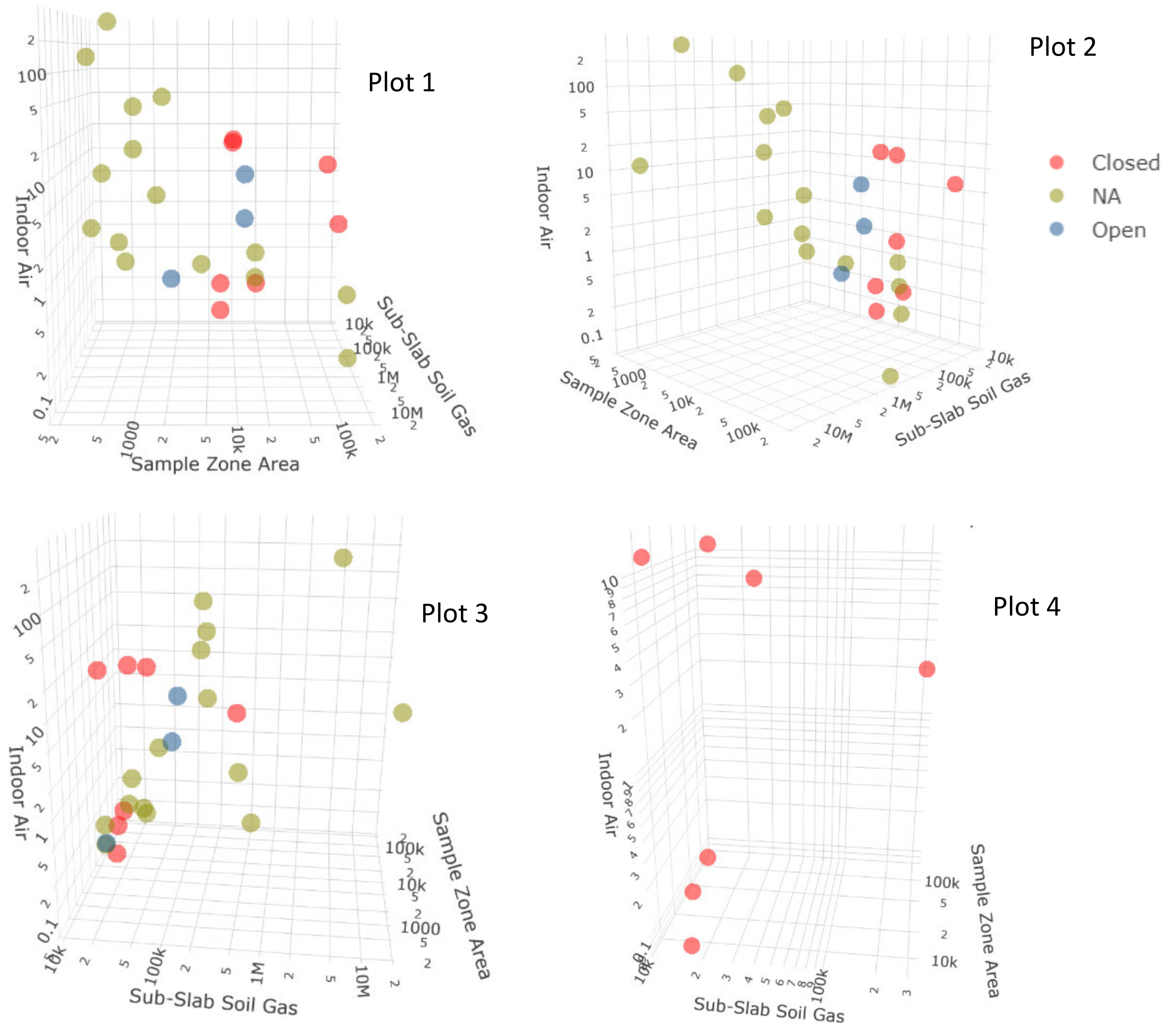


Figure 5-15. Subslab Soil Gas Concentration as a Function of Groundwater Vapor Concentration and Groundwater Depth, Coarse Soil Type Only – Plots for All VOCs

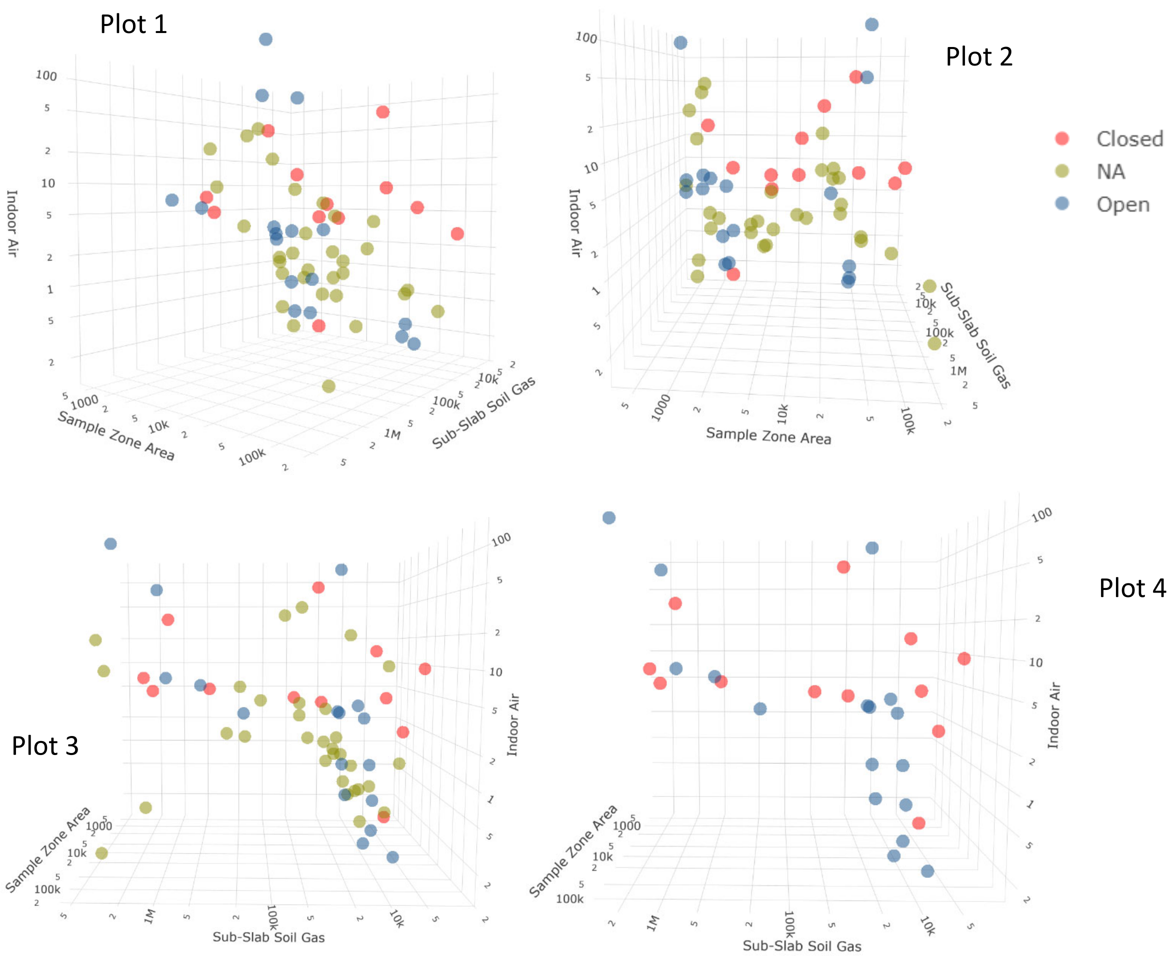
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Dataset restricted to distance to primary release greater than 30 feet.




```
Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)        1.376e+01  2.874e+01   0.479    0.637
SS_Data            1.985e-06  4.246e-06   0.467    0.645
SAMPLE_ZONE_AREA  -1.782e-04  2.386e-04  -0.747    0.464
SuspectOpenOCNA    2.687e+01  3.263e+01   0.823    0.420
SuspectOpenOCOpen -9.468e+00  4.875e+01  -0.194    0.848

Residual standard error: 69.28 on 20 degrees of freedom
  (2 observations deleted due to missingness)
Multiple R-squared:  0.104,  Adjusted R-squared:  -0.07518
F-statistic: 0.5804 on 4 and 20 DF,  p-value: 0.6803
```

Figure 5-16. PCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Presence or Absence of Suspected Open Doors
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Plot 4 shows data for sample zones with closed doors only. General linear model results also shown.

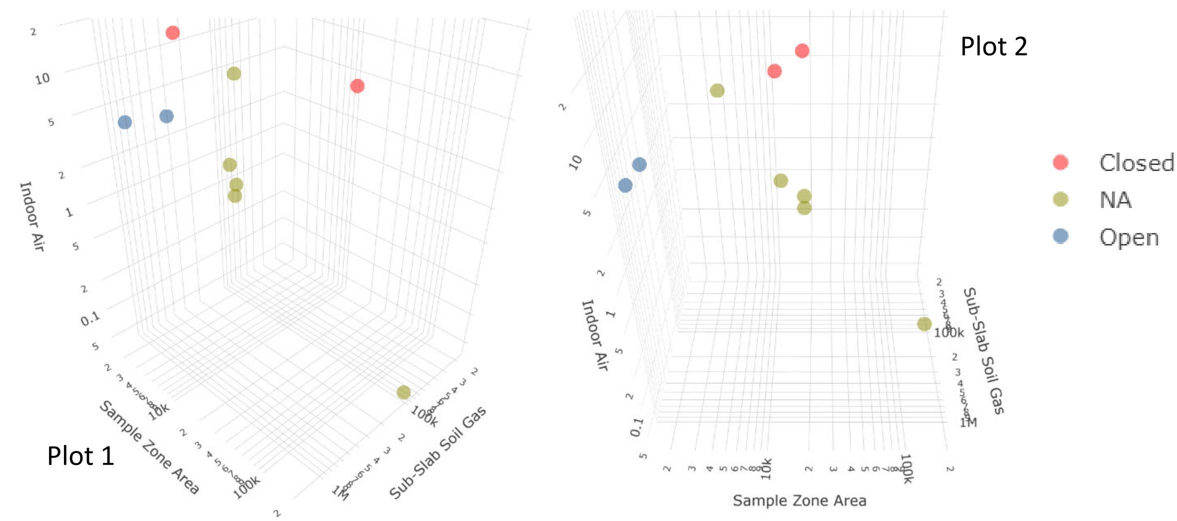


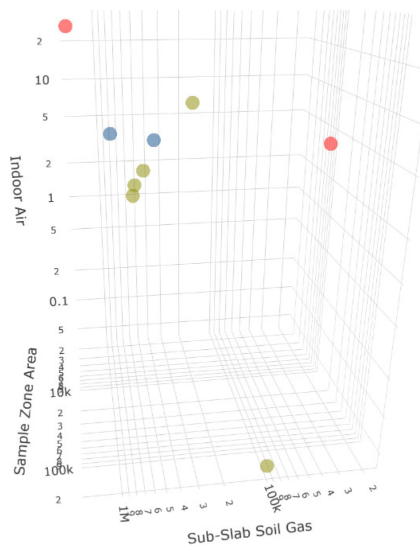

```
Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)       1.047e+01  7.990e+00   1.311   0.1954
SS_Data           6.489e-06  3.392e-06   1.913   0.0609 .
SAMPLE_ZONE_AREA -3.565e-05  7.835e-05  -0.455   0.6509
SuspectOpenOCNA  -6.628e+00  8.785e+00  -0.754   0.4538
SuspectOpenOCOpen 8.520e+00  9.846e+00   0.865   0.3907
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '

Residual standard error: 25.75 on 55 degrees of freedom
  (2 observations deleted due to missingness)
Multiple R-squared:  0.1182, Adjusted R-squared:  0.05405
F-statistic: 1.843 on 4 and 55 DF,  p-value: 0.1338
```

Figure 5-17. TCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Presence or Absence of Suspected Open Doors

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plot 4 excludes data with unknown ("NA") door status. General linear model results also shown.



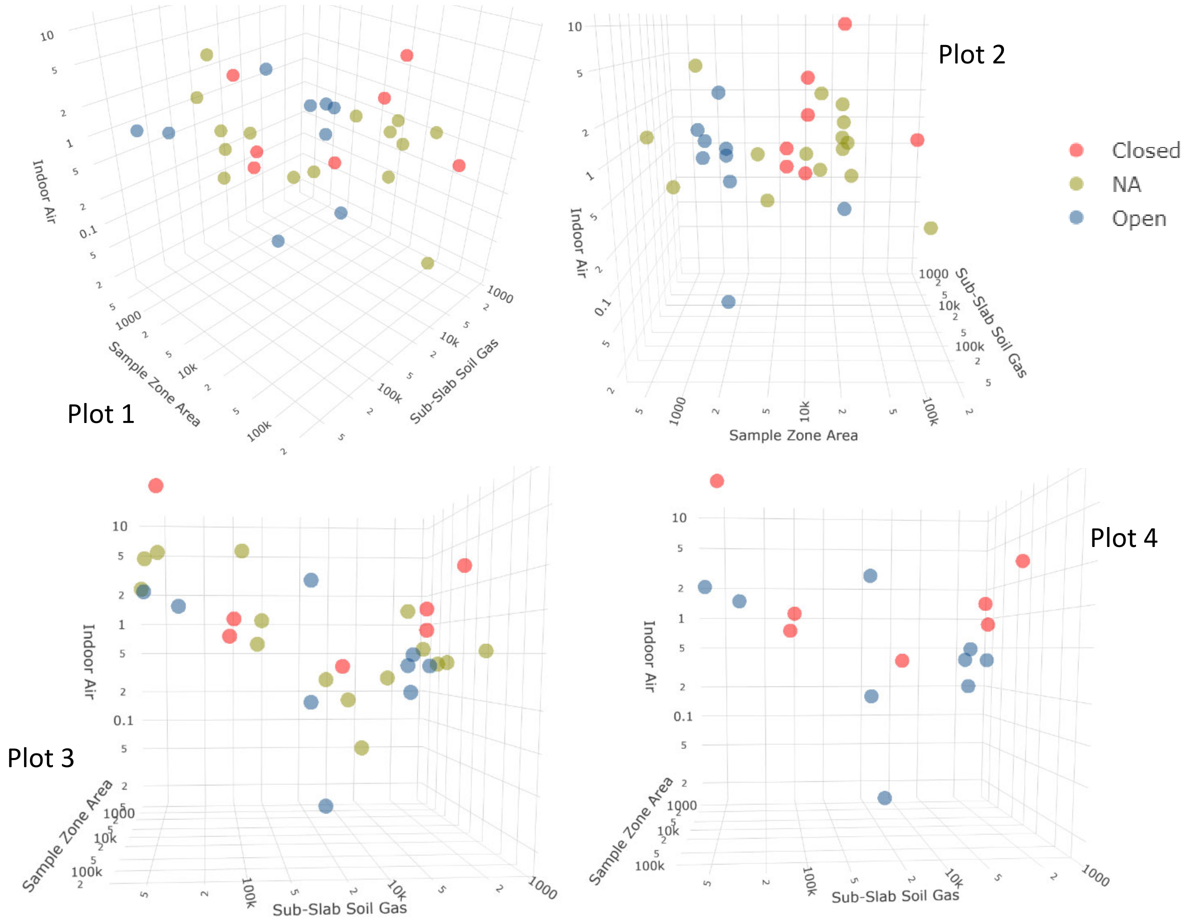


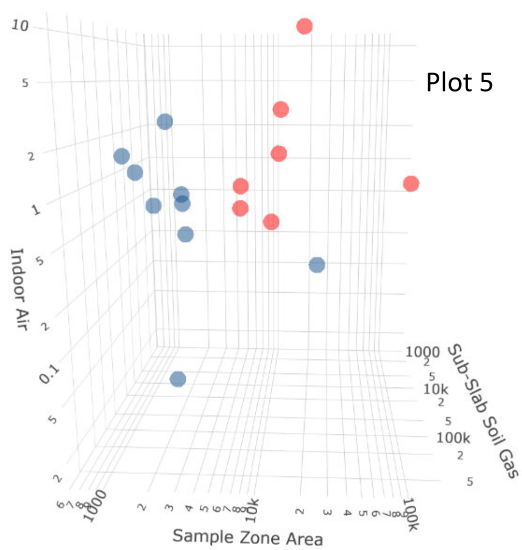

```
Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)        6.656e+00  5.335e+00   1.248   0.2802
SS_Data            1.335e-05  4.393e-06   3.038   0.0385 *
SAMPLE_ZONE_AREA   4.666e-06  3.589e-05   0.130   0.9028
SuspectOpenOCNA   -9.224e+00  4.923e+00  -1.874   0.1343
SuspectOpenOCOpen -1.084e+01  5.571e+00  -1.945   0.1237
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 5.423 on 4 degrees of freedom
  (3 observations deleted due to missingness)
Multiple R-squared:  0.8362, Adjusted R-squared:  0.6724
F-statistic: 5.105 on 4 and 4 DF,  p-value: 0.0717
```

Figure 5-18. 1,1,1-TCA Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Presence or Absence of Suspected Open Doors

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

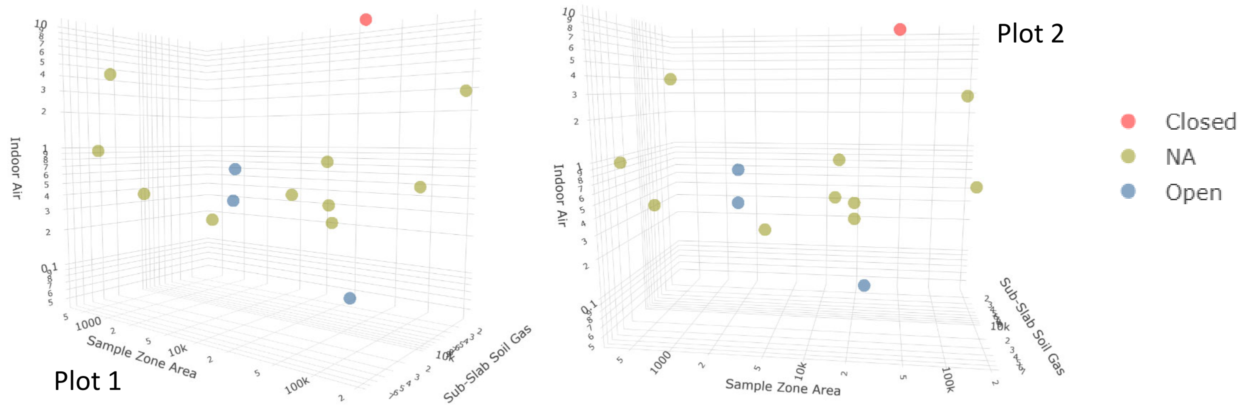
General linear model results shown.

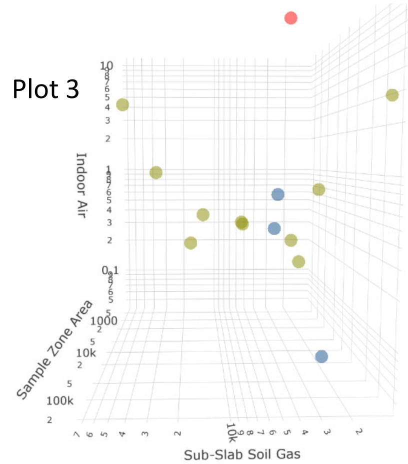





```
Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)        2.156e+00  7.148e-01   3.016  0.00567 **
SS_Data            4.626e-06  1.446e-06   3.198  0.00362 **
SAMPLE_ZONE_AREA  -5.678e-06  8.076e-06  -0.703  0.48828
SuspectOpenOCNA   -1.404e+00  7.880e-01  -1.782  0.08641 .
SuspectOpenOCOpen -1.896e+00  8.911e-01  -2.128  0.04297 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.718 on 26 degrees of freedom
  (10 observations deleted due to missingness)
Multiple R-squared:  0.3685, Adjusted R-squared:  0.2714
F-statistic: 3.793 on 4 and 26 DF,  p-value: 0.0147
```

Figure 5-19. cis-1,2-DCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Presence or Absence of Suspected Open Doors
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Plots 4 and 5 exclude data with unknown ("NA") door status. General linear model results also shown.






```
Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)        9.465e+00  7.959e-01  11.893 8.31e-07 ***
SS_Data            4.699e-05  1.303e-05   3.605   0.0057 **
SAMPLE_ZONE_AREA   8.196e-06  3.633e-06   2.256   0.0505 .
SuspectOpenOCNA   -9.529e+00  8.284e-01 -11.502 1.10e-06 ***
SuspectOpenOCOpen -9.338e+00  9.045e-01 -10.324 2.74e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.7751 on 9 degrees of freedom
  (10 observations deleted due to missingness)
Multiple R-squared:  0.9414, Adjusted R-squared:  0.9154
F-statistic: 36.17 on 4 and 9 DF,  p-value: 1.49e-05
```

Figure 5-20. trans-1,2-DCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Presence or Absence of Suspected Open Doors
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
General linear model results shown.

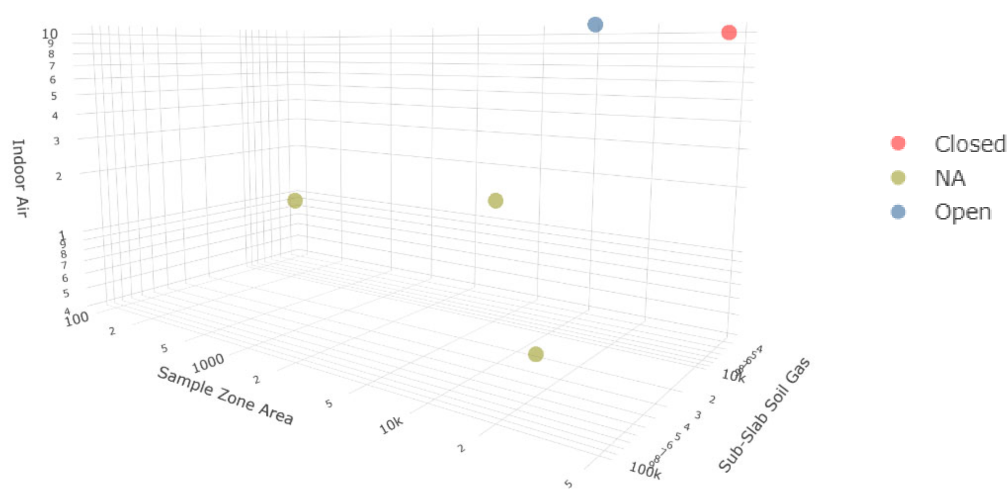


Figure 5-21. 1,1-DCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Presence or Absence of Suspected Open Doors
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

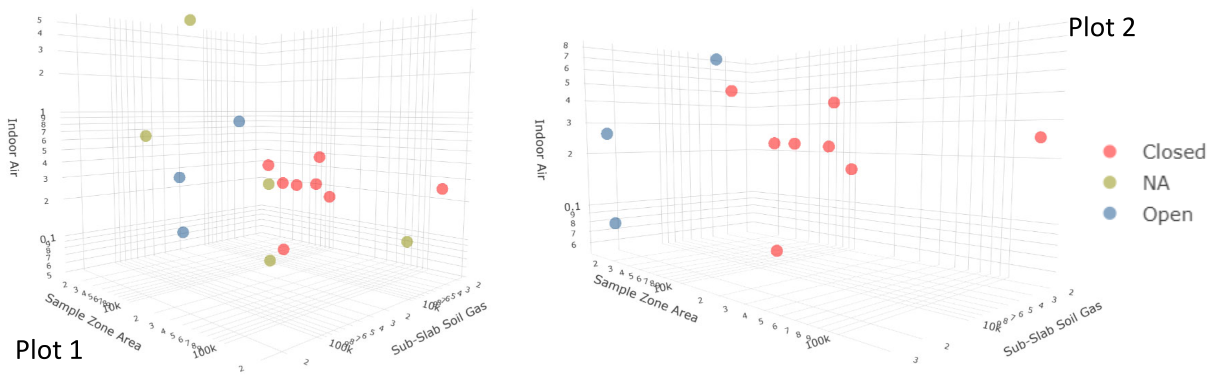


Figure 5-22. 1,1-DCA Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Presence or Absence of Suspected Open Doors

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plot 2 excludes data with unknown ("NA") door status.

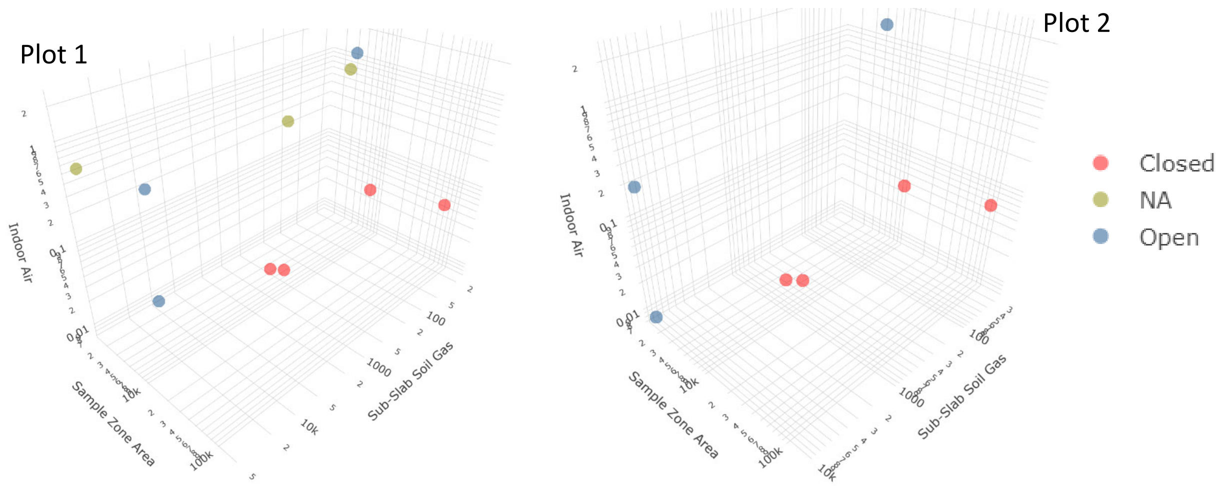
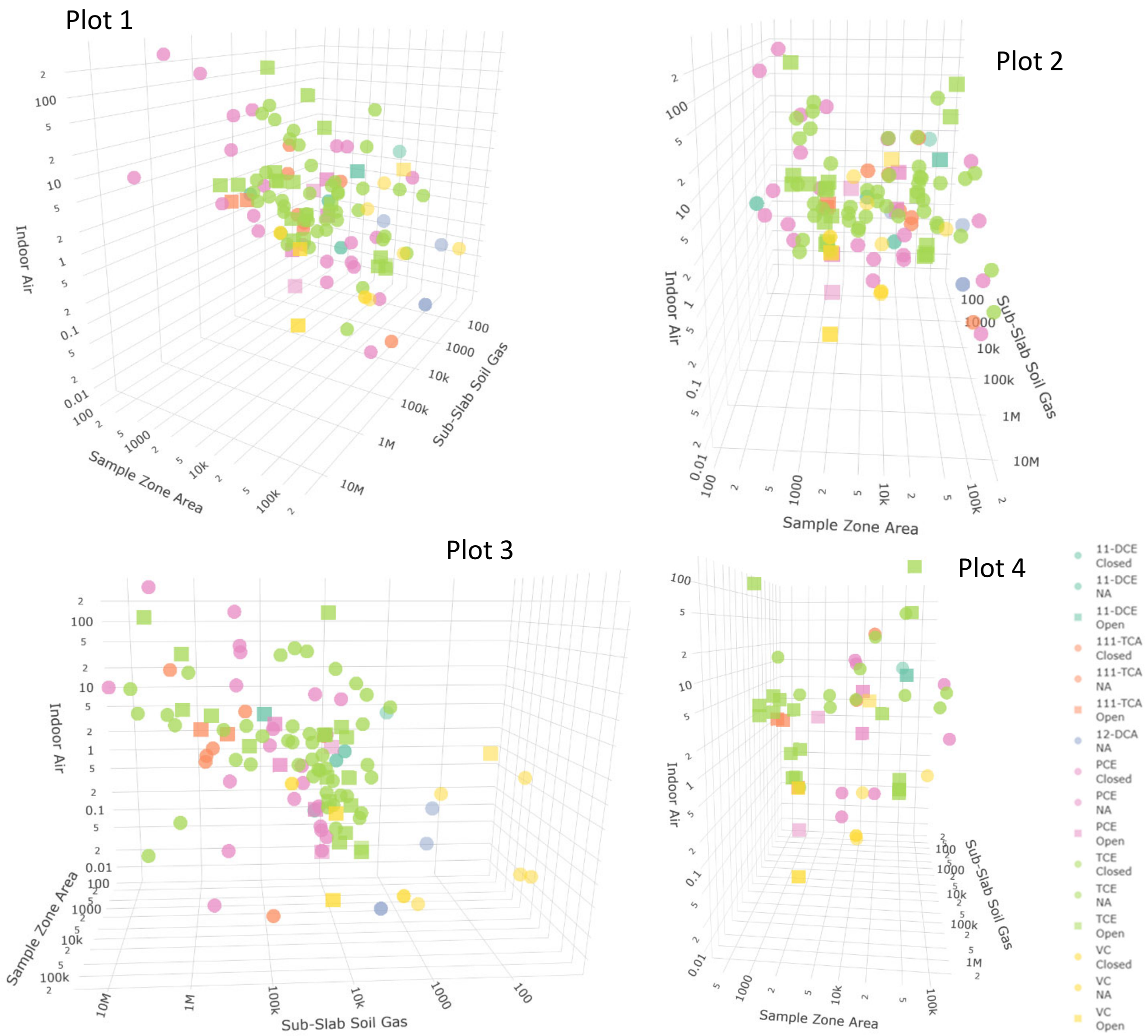
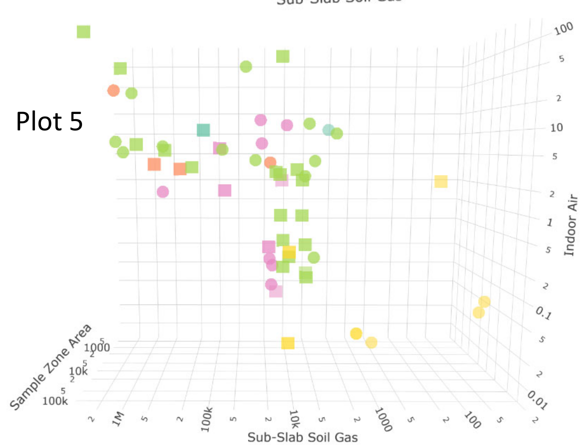


Figure 5-23. VC Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Presence or Absence of Suspected Open Doors

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plot 2 excludes data with unknown ("NA") door status.



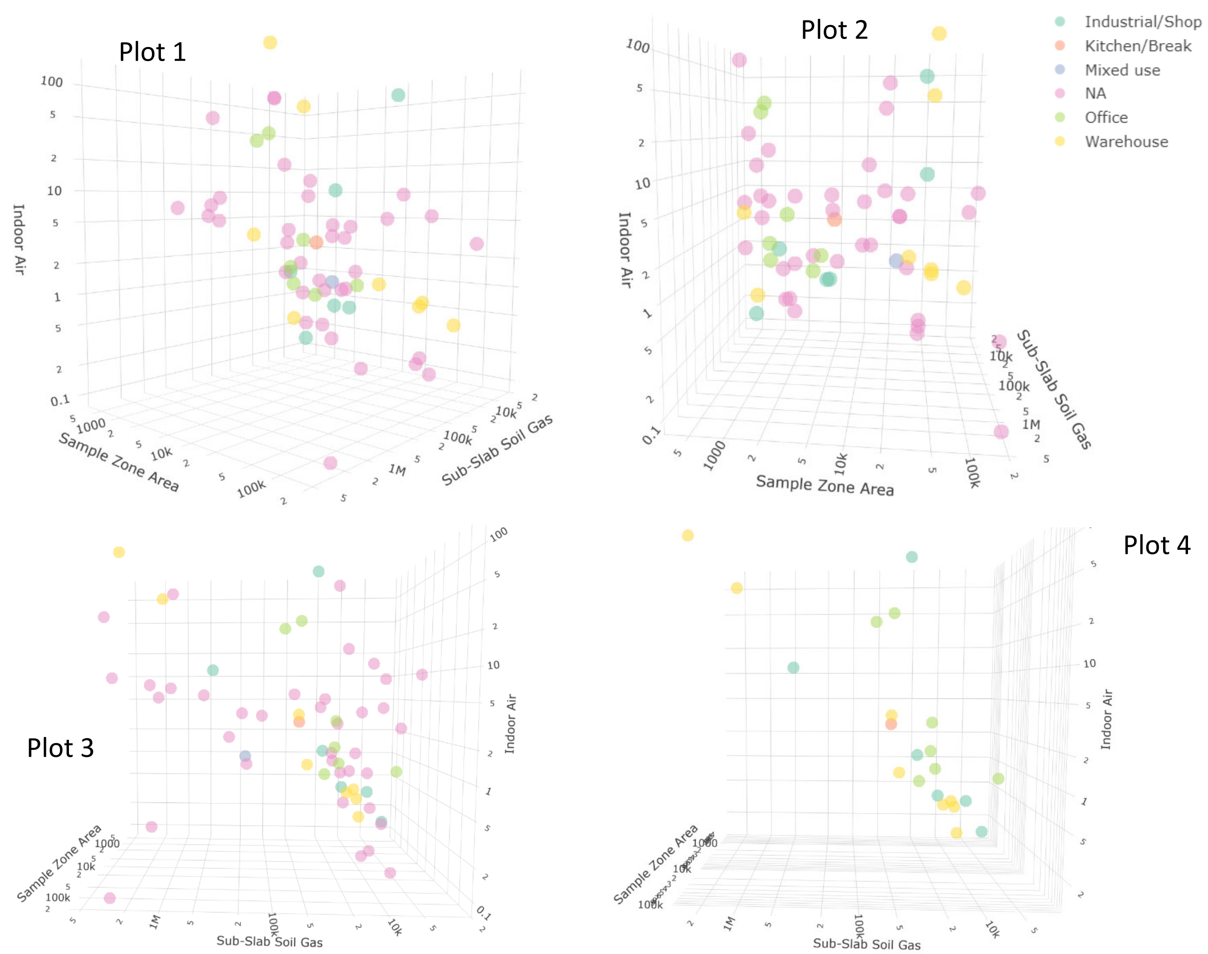


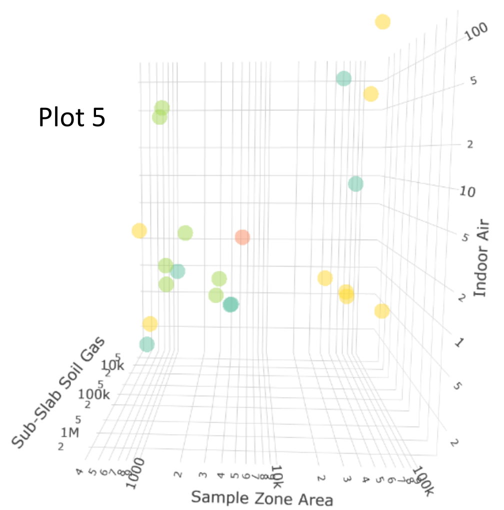

```
Coefficients:
                      Estimate Std. Error t value Pr(>|t|)
(Intercept)          2.636e+00  1.362e+01   0.194  0.84672
SS_Data              3.832e-06  1.420e-06   2.698  0.00755 **
SAMPLE_ZONE_AREA    -7.317e-05  5.263e-05  -1.390  0.16589
SuspectOpenOCNA      2.311e+00  6.504e+00   0.355  0.72275
SuspectOpenOCOpen    4.869e+00  7.527e+00   0.647  0.51842
Analyte_Short111-TCA 1.580e+00  1.518e+01   0.104  0.91723
Analyte_Short12-DCA  5.754e+00  2.326e+01   0.247  0.80486
Analyte_ShortPCE     1.807e+01  1.349e+01   1.340  0.18180
Analyte_ShortTCE     6.268e+00  1.285e+01   0.488  0.62631
Analyte_ShortVC     -3.554e+00  1.597e+01  -0.223  0.82410
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 37.07 on 208 degrees of freedom
  (186 observations deleted due to missingness)
Multiple R-squared:  0.08047,    Adjusted R-squared:  0.04068
F-statistic: 2.022 on 9 and 208 DF,  p-value: 0.03831
```

Figure 5-24. Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Presence or Absence of Suspected Open Doors – Plots for All VOCs

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plots 4 and 5 exclude data with unknown ("NA") door status. General linear model results also shown.



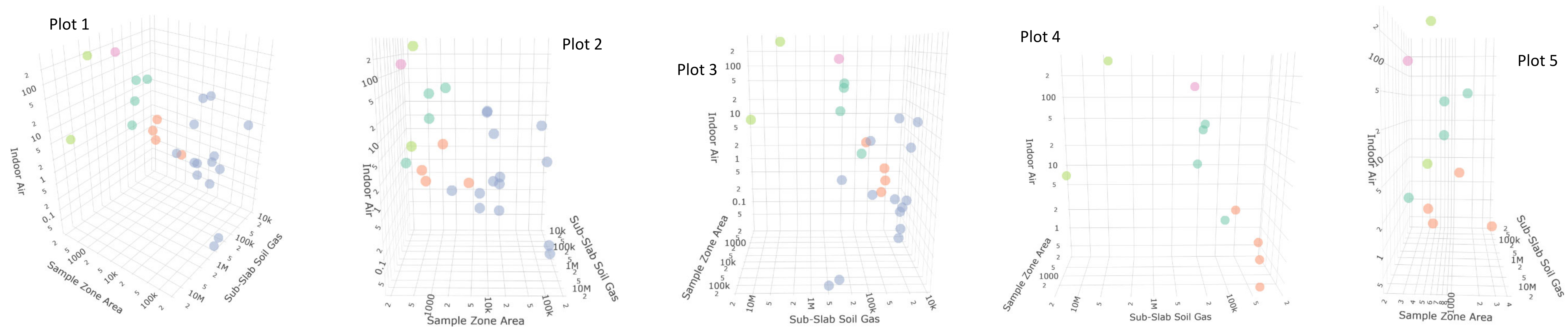



```
Coefficients:
                                    Estimate Std. Error t value Pr(>|t|)
(Intercept)                        1.107e+01  1.097e+01   1.009    0.318
SS_Data                            6.683e-06  3.572e-06   1.871    0.067 .
SAMPLE_ZONE_AREA                  -6.671e-05  8.259e-05  -0.808    0.423
ZONE_USE_STANDARDIZEDKitchen/Break -8.106e+00  2.883e+01  -0.281    0.780
ZONE_USE_STANDARDIZEDMixed use    -7.069e+00  2.882e+01  -0.245    0.807
ZONE_USE_STANDARDIZEDNA           -4.080e+00  1.189e+01  -0.343    0.733
ZONE_USE_STANDARDIZEDOffice        1.675e+00  1.489e+01   0.112    0.911
ZONE_USE_STANDARDIZEDWarehouse     1.267e+01  1.466e+01   0.864    0.391
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 26.68 on 52 degrees of freedom
  (3 observations deleted due to missingness)
Multiple R-squared:  0.1051, Adjusted R-squared:  -0.0154
F-statistic: 0.8722 on 7 and 52 DF,  p-value: 0.5347
```

Figure 5-25. TCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Sample Zone Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plots 4 and 5 exclude data for mixed or unknown ("NA") sample zone use. General linear model results also shown.




```
Coefficients:
                                      Estimate Std. Error t value Pr(>|t|)
(Intercept)                          3.088e+01  5.333e+00   5.789 1.74e-05 ***
SS_Data                             -2.294e-05  1.157e-06 -19.834 1.11e-13 ***
SAMPLE_ZONE_AREA                     3.060e-05  4.030e-05   0.759 0.457491
ZONE_USE_STANDARDIZEDIndustrial/Shop -2.874e+01 7.538e+00  -3.813 0.001273 **
ZONE_USE_STANDARDIZEDNA             -2.702e+01  6.444e+00  -4.193 0.000546 ***
ZONE_USE_STANDARDIZEDOffice          1.173e+02  1.192e+01   9.844 1.14e-08 ***
ZONE_USE_STANDARDIZEDWarehouse       3.710e+02  1.503e+01  24.679 2.49e-15 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 10.66 on 18 degrees of freedom
  (4 observations deleted due to missingness)
Multiple R-squared:  0.9809, Adjusted R-squared:  0.9746
F-statistic: 154.2 on 6 and 18 DF,  p-value: 1.783e-14
```

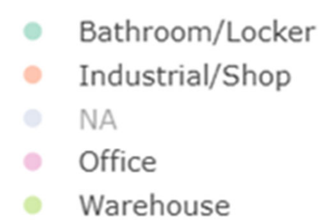
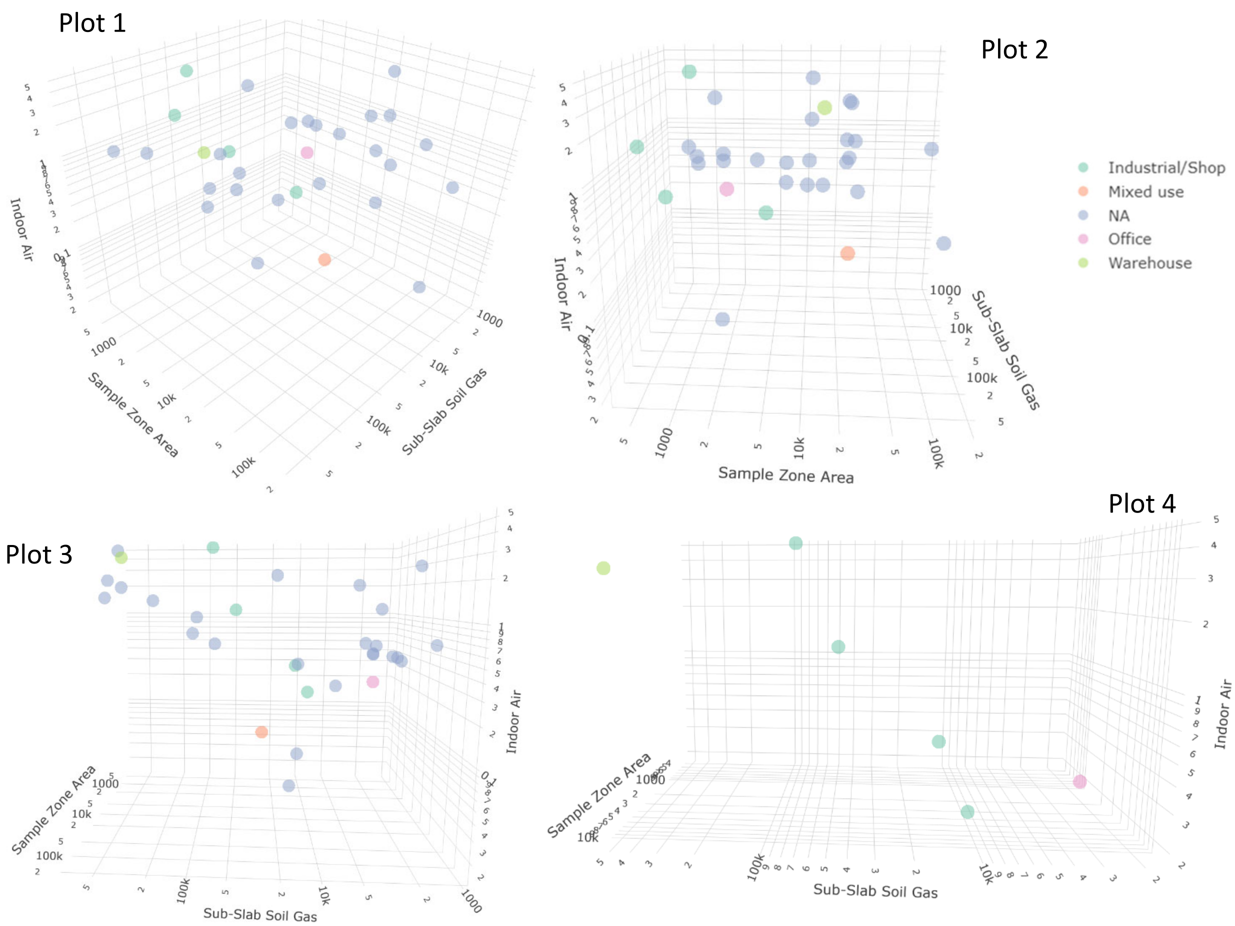
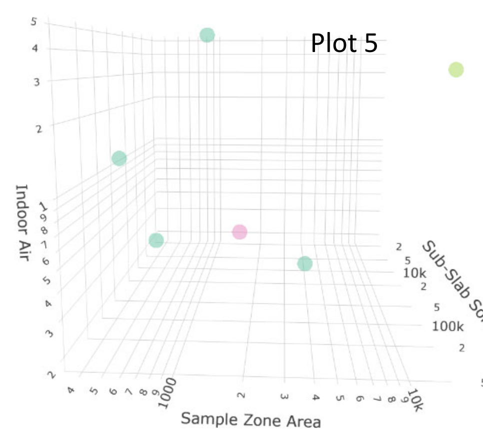


Figure 5-26. PCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Sample Zone Use
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Plots 4 and 5 exclude data for unknown ("NA") sample zone use. General linear model results also shown.






```
Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                  1.414e+00  9.644e-01   1.466   0.1555
SS_Data                      4.501e-06  1.738e-06   2.590   0.0161 *
SAMPLE_ZONE_AREA            -1.499e-06  8.964e-06  -0.167   0.8686
ZONE_USE_STANDARDIZEDMixed use -1.298e+00  2.160e+00  -0.601   0.5534
ZONE_USE_STANDARDIZEDNA     -6.075e-01  1.075e+00  -0.565   0.5773
ZONE_USE_STANDARDIZEDOffice   -1.211e+00  2.151e+00  -0.563   0.5788
ZONE_USE_STANDARDIZEDWarehouse -2.050e-01  2.288e+00  -0.090   0.9294
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.923 on 24 degrees of freedom
  (10 observations deleted due to missingness)
Multiple R-squared:  0.2691, Adjusted R-squared:  0.08641
F-statistic: 1.473 on 6 and 24 DF,  p-value: 0.2295
```

Figure 5-27. cis-1,2-DCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Sample Zone Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plots 4 and 5 exclude data for mixed or unknown ("NA") sample zone use. General linear model results also shown.

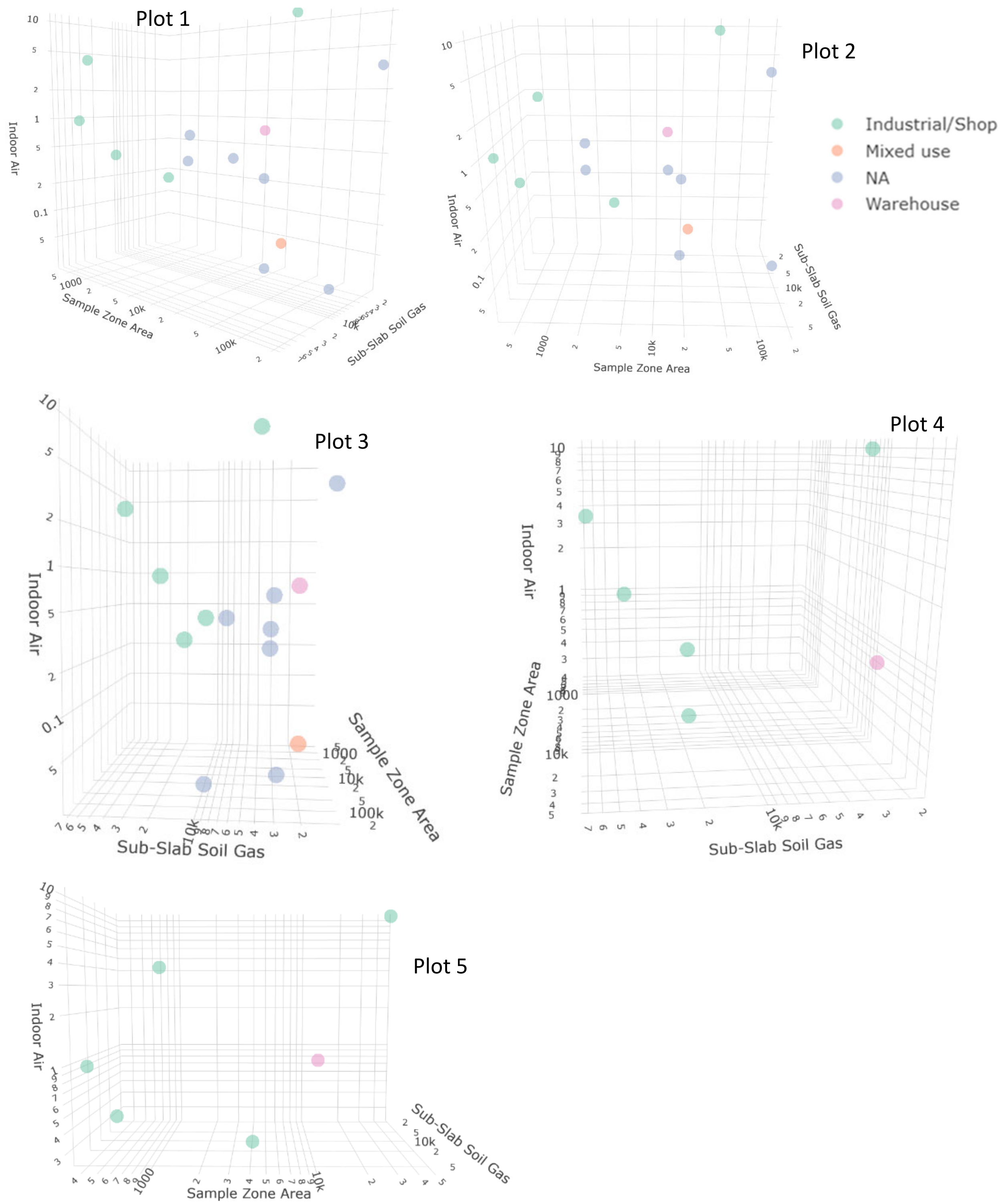


Figure 5-28. trans-1,2-DCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Sample Zone Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plots 4 and 5 exclude data for unknown ("NA") sample zone use.

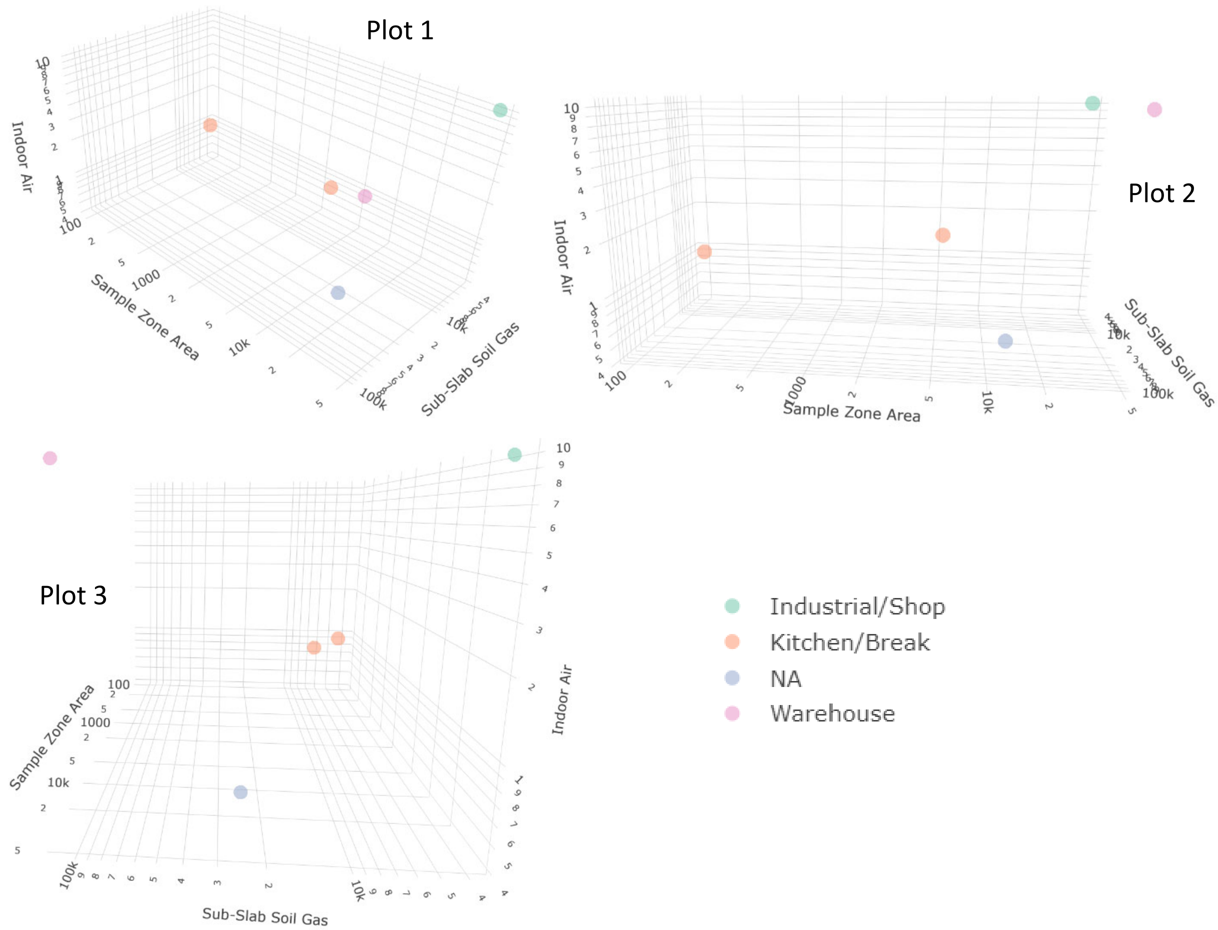


Figure 5-29. 1,1-DCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Sample Zone Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

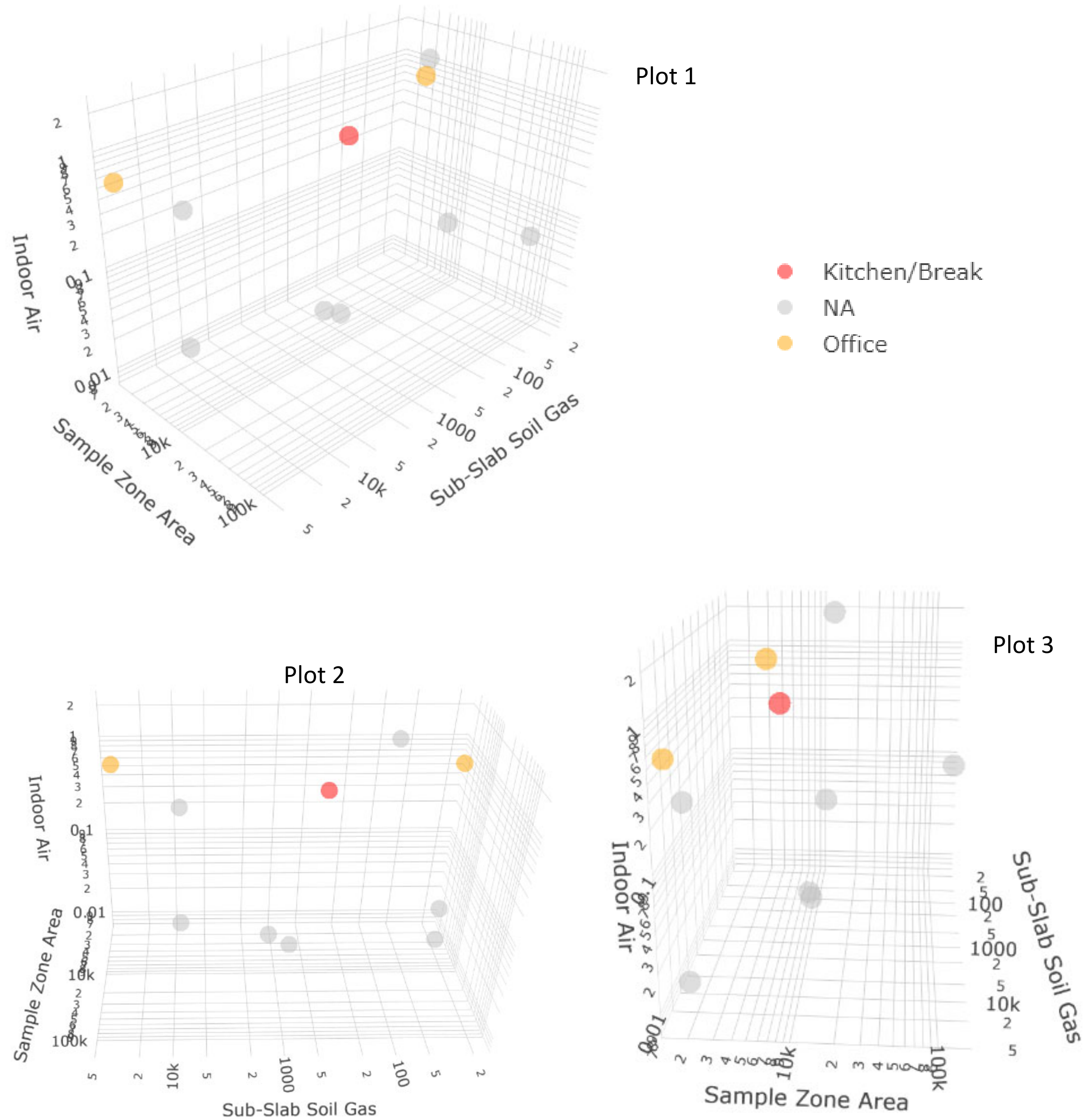
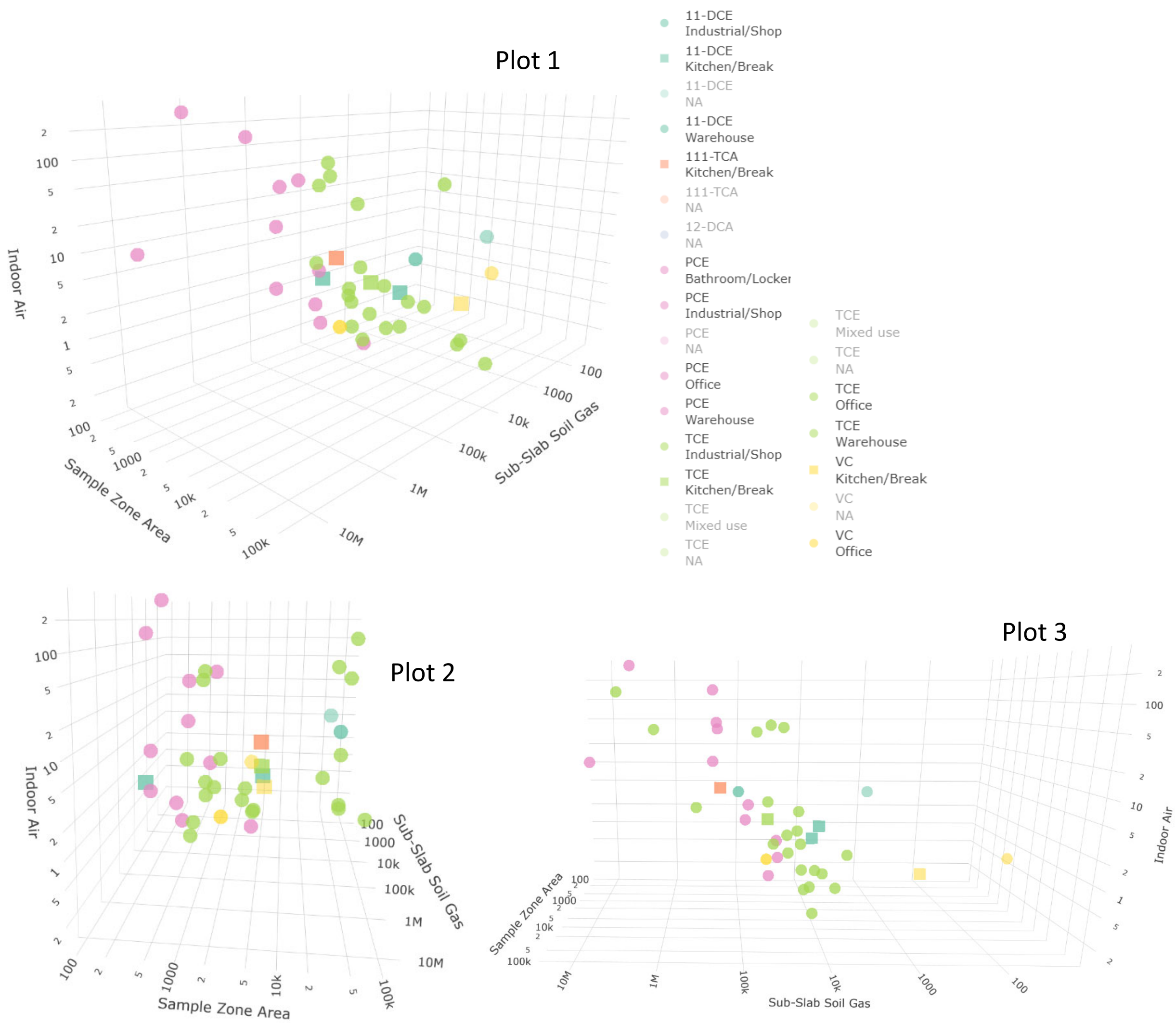


Figure 5-30. VC Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Sample Zone Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings




```
Coefficients:
                                  Estimate Std. Error t value Pr(>|t|)
(Intercept)                      1.554e+00  1.914e+01   0.081   0.9354
SS_Data                          1.740e-06  1.448e-06   1.202   0.2309
SAMPLE_ZONE_AREA                -8.134e-05  5.148e-05  -1.580   0.1157
ZONE_USE_STANDARDIZEDIndustrial/Shop -8.621e+00  1.526e+01  -0.565   0.5726
ZONE_USE_STANDARDIZEDKitchen/Break  -3.219e+00  1.923e+01  -0.167   0.8672
ZONE_USE_STANDARDIZEDMixed use  -5.826e+00  2.877e+01  -0.202   0.8398
ZONE_USE_STANDARDIZEDNA         -5.591e+00  1.396e+01  -0.401   0.6892
ZONE_USE_STANDARDIZEDOffice      1.316e+01  1.599e+01   0.823   0.4112
ZONE_USE_STANDARDIZEDWarehouse   3.405e+01  1.621e+01   2.101   0.0369 *
Analyte_Short111-TCA             1.172e+01  1.546e+01   0.758   0.4492
Analyte_Short12-DCA              1.592e+01  2.304e+01   0.691   0.4904
Analyte_ShortPCE                 2.481e+01  1.451e+01   1.710   0.0889 .
Analyte_ShortTCE                 9.486e+00  1.365e+01   0.695   0.4879
Analyte_ShortVC                  1.476e+00  1.625e+01   0.091   0.9277
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 35.42 on 204 degrees of freedom
  (186 observations deleted due to missingness)
Multiple R-squared:  0.177,	Adjusted R-squared:  0.1245
F-statistic: 3.375 on 13 and 204 DF,  p-value: 0.0001033
```

Figure 5-31. Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Sample Zone Use – Plots for All VOCs

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

The plots exclude data for mixed or unknown ("NA") sample zone use. General linear model results also shown.

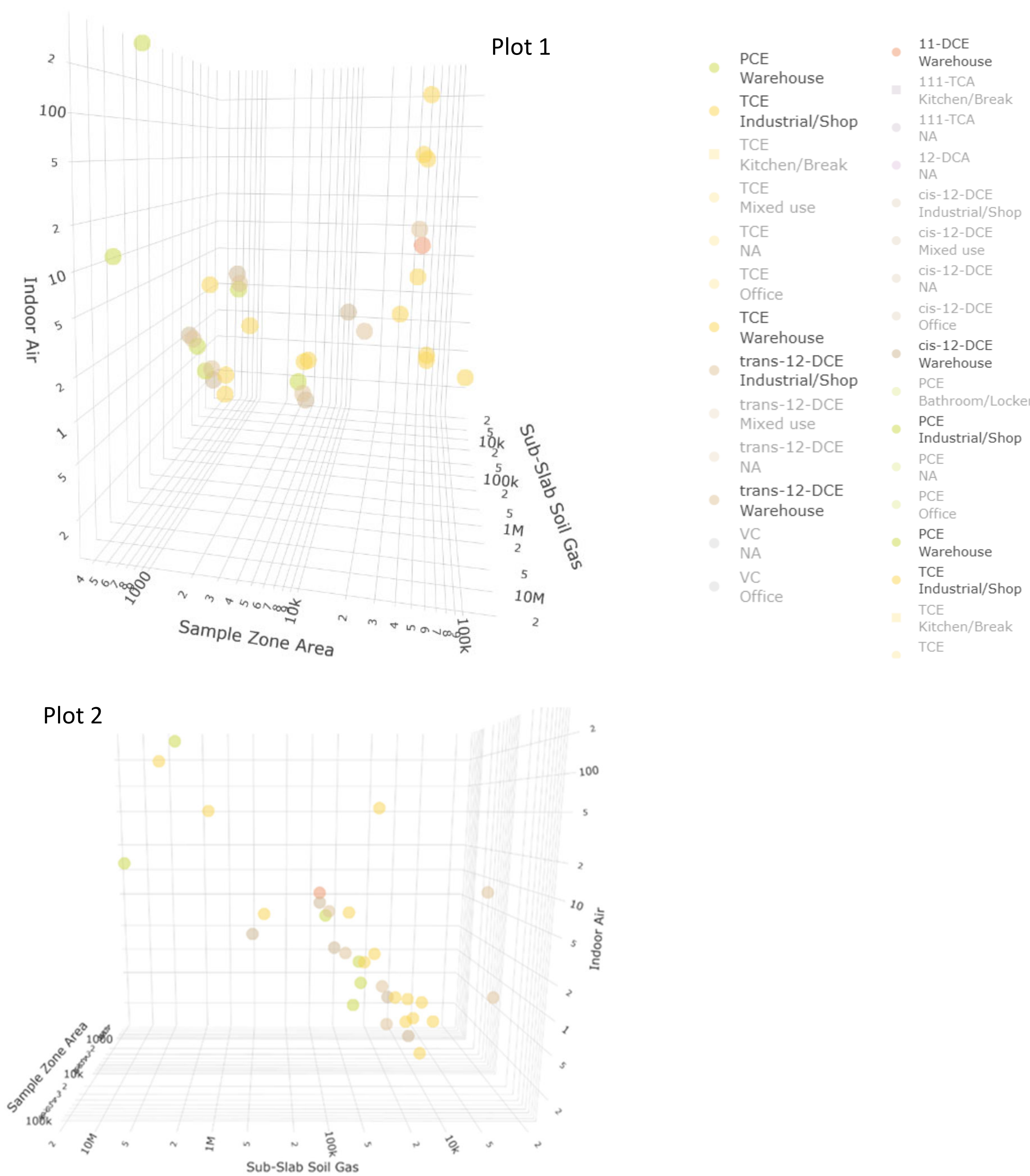
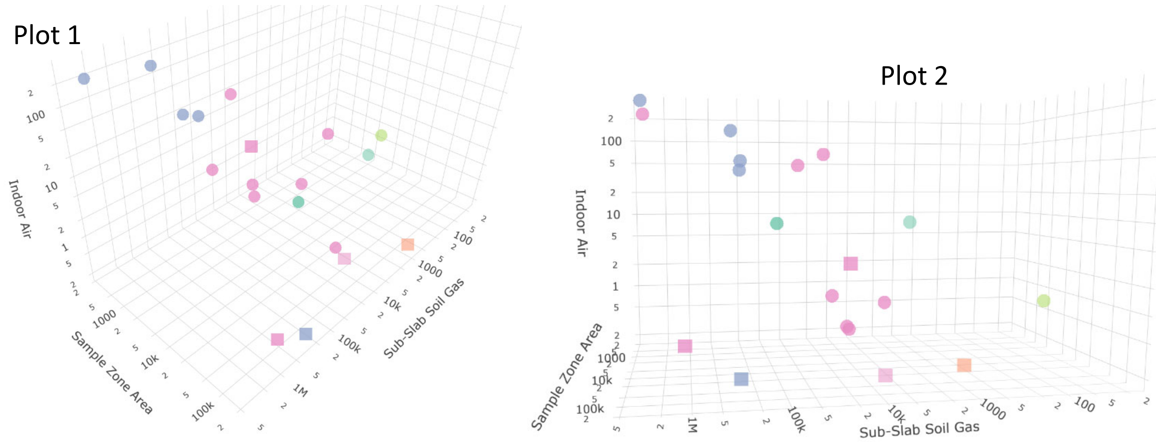


Figure 5-32. Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Sample Zone Use – Plots for All VOCs

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

The plots only include data for sample zones with warehouse and industrial/shop uses.

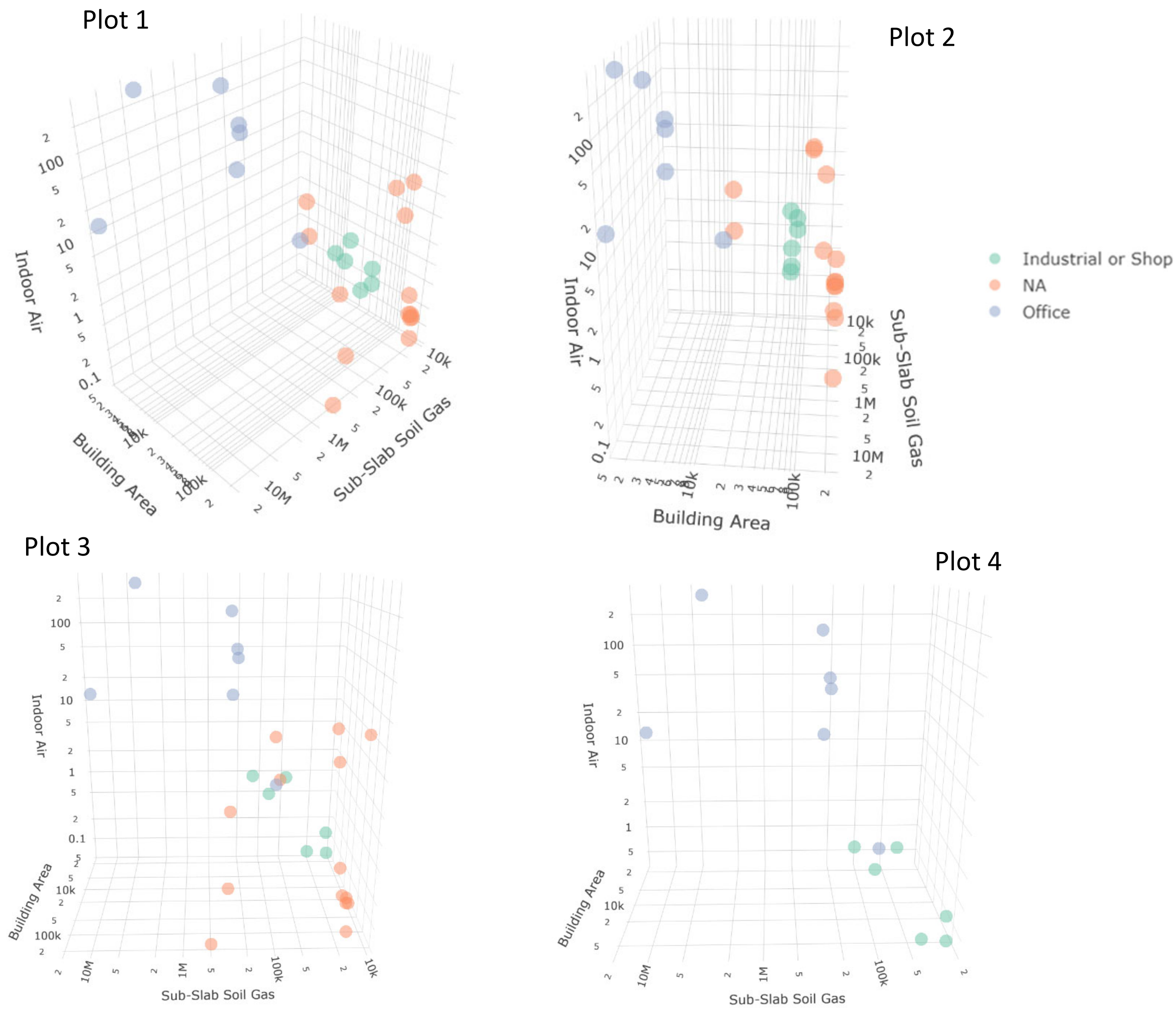


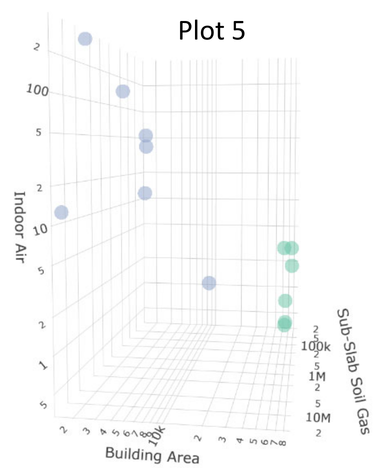

```
Coefficients:
                                     Estimate Std. Error t value Pr(>|t|)
(Intercept)                         -5.443e+01  1.867e+01  -2.915 0.007787 **
SS_Data                              5.307e-05  4.029e-06  13.172 3.37e-12 ***
SAMPLE_ZONE_AREA                    -4.491e-04  7.948e-05  -5.651 9.43e-06 ***
ZONE_USE_STANDARDIZEDIndustrial/Shop 1.097e+02  1.830e+01   5.994 4.12e-06 ***
ZONE_USE_STANDARDIZEDNA              5.525e+01  1.714e+01   3.223 0.003763 **
ZONE_USE_STANDARDIZEDOffice          7.350e+01  1.359e+01   5.410 1.70e-05 ***
ZONE_USE_STANDARDIZEDWarehouse       6.583e+01  1.628e+01   4.044 0.000505 ***
Analyte_Short12-DCA                  8.329e+01  2.432e+01   3.425 0.002314 **
Analyte_ShortPCE                     8.937e+01  1.655e+01   5.399 1.74e-05 ***
Analyte_ShortTCE                     3.518e+00  1.318e+01   0.267 0.791849
Analyte_ShortVC                     -1.705e+01  2.391e+01  -0.713 0.483008
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 18.73 on 23 degrees of freedom
  (60 observations deleted due to missingness)
Multiple R-squared:  0.9623, Adjusted R-squared:  0.946
F-statistic: 58.79 on 10 and 23 DF,  p-value: 5.739e-14
```

Figure 5-33. Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Sample Zone Area, and Sample Zone Use – Plots for All VOCs (Winter Data Only)

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

General linear model results shown.



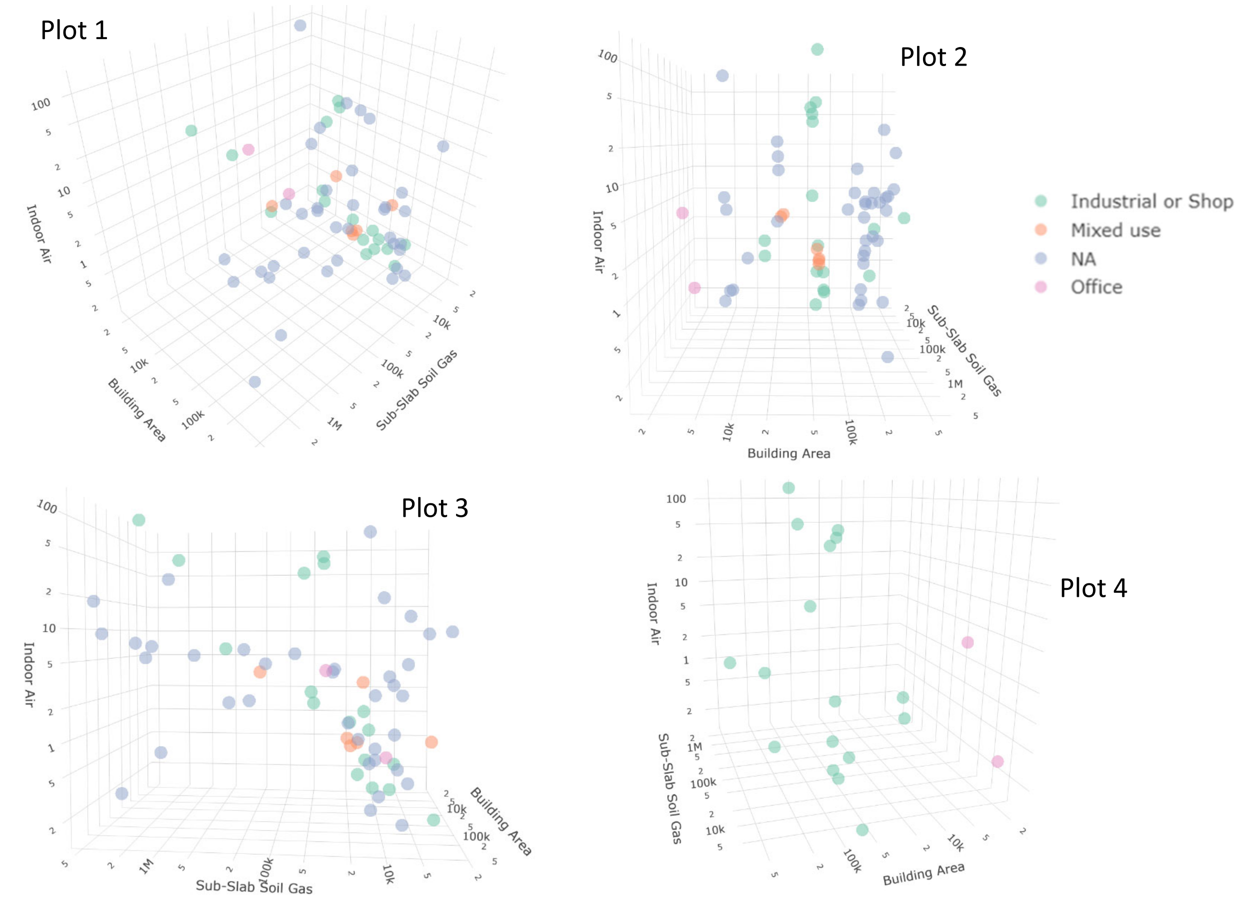


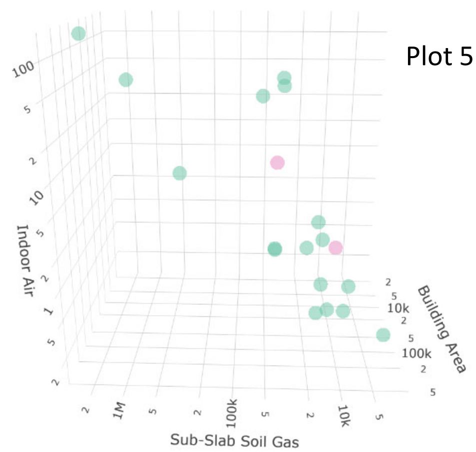

```
Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                  4.908e+00  2.753e+01   0.178   0.8601
SS_Data                     -1.262e-06  3.808e-06  -0.331   0.7434
BUILDING_AREA               -4.281e-05  1.997e-04  -0.214   0.8322
BUILDING_USE_STANDARDIZEDNA  5.765e+00  3.513e+01   0.164   0.8711
BUILDING_USE_STANDARDIZEDOffice 8.110e+01  3.690e+01   2.198   0.0388 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 58.4 on 22 degrees of freedom
  (4 observations deleted due to missingness)
Multiple R-squared:  0.3055, Adjusted R-squared:  0.1793
F-statistic:  2.42 on 4 and 22 DF,  p-value: 0.07901
```

Figure 5-34. PCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Area, and Building Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plots 4 and 5 exclude data for unknown ("NA") building use. General linear model results also shown.






```
Coefficients:
                                   Estimate Std. Error t value Pr(>|t|)
(Intercept)                       2.546e+01  6.803e+00   3.743 0.000431 ***
SS_Data                           7.597e-06  3.268e-06   2.325 0.023734 *
BUILDING_AREA                    -6.625e-05  2.888e-05  -2.294 0.025571 *
BUILDING_USE_STANDARDIZEDMixed use -2.075e+01  1.182e+01  -1.756 0.084529 .
BUILDING_USE_STANDARDIZEDNA      -1.006e+01  7.369e+00  -1.365 0.177760
BUILDING_USE_STANDARDIZEDOffice  -2.377e+01  1.866e+01  -1.274 0.207964
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 24.58 on 56 degrees of freedom
  (3 observations deleted due to missingness)
Multiple R-squared:  0.1863, Adjusted R-squared:  0.1136
F-statistic: 2.564 on 5 and 56 DF,  p-value: 0.03699
```

Figure 5-35. TCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Area, and Building Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plots 4 and 5 exclude data for mixed or unknown ("NA") building use. General linear model results also shown.

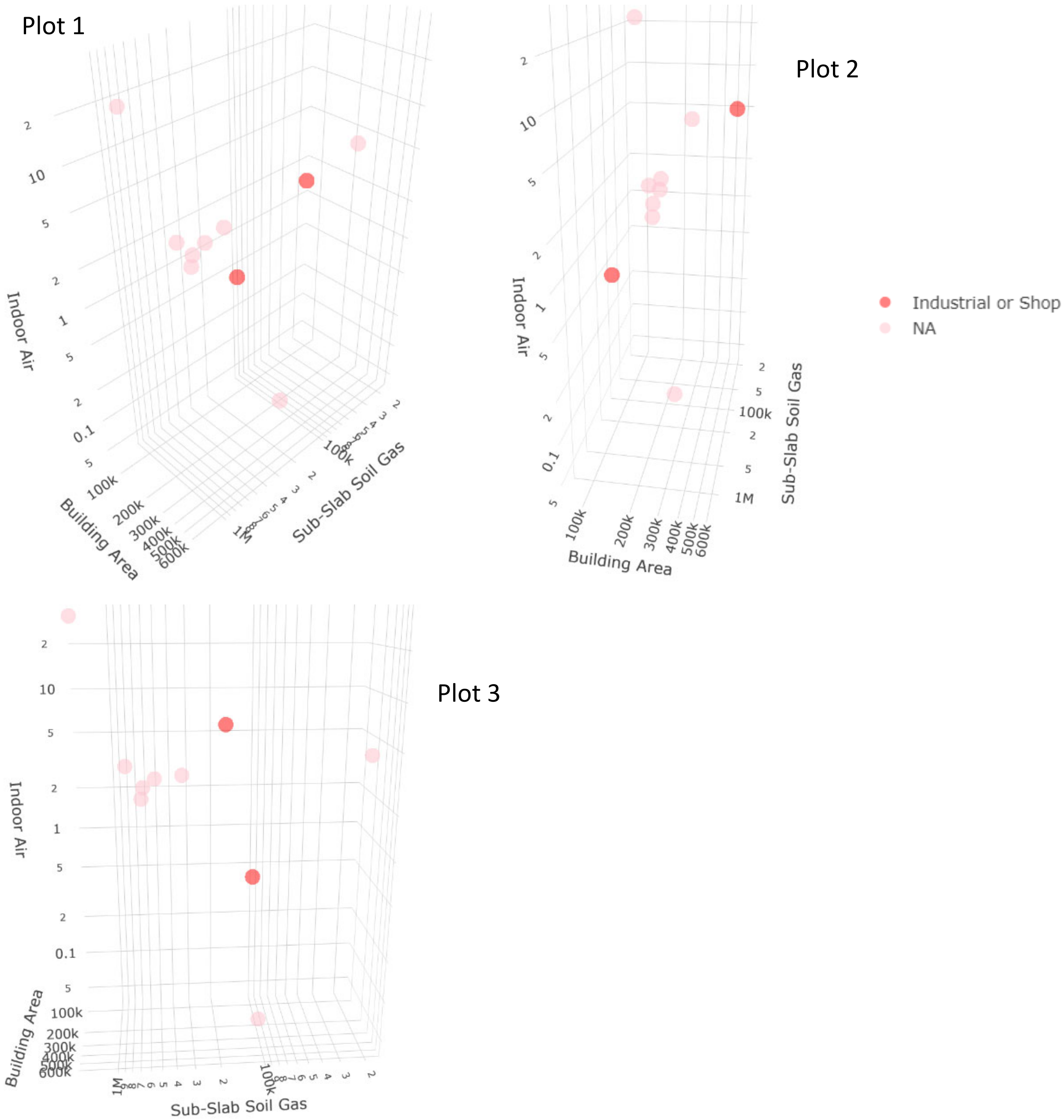
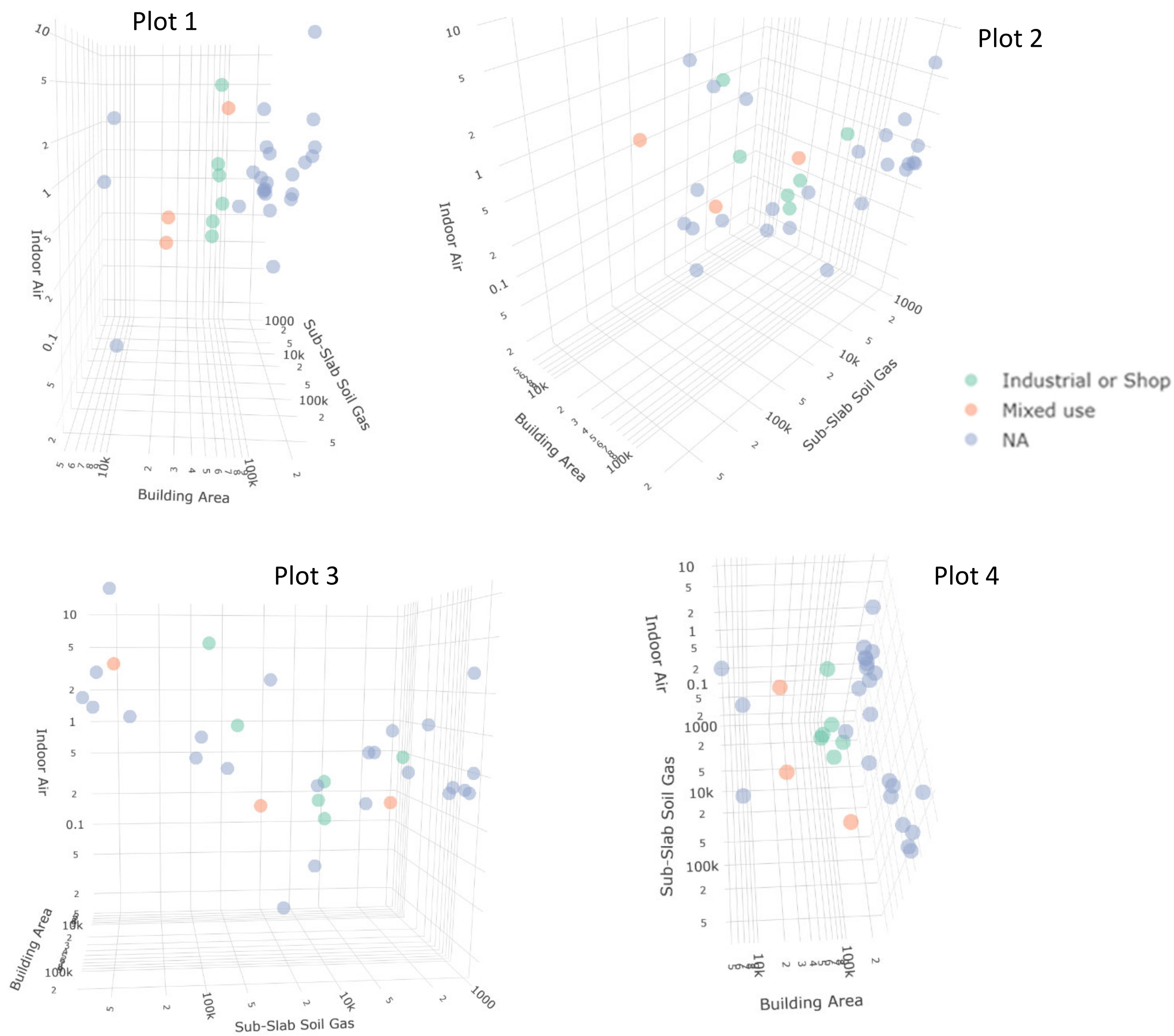


Figure 5-36. 1,1,1-TCA Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Area, and Building Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

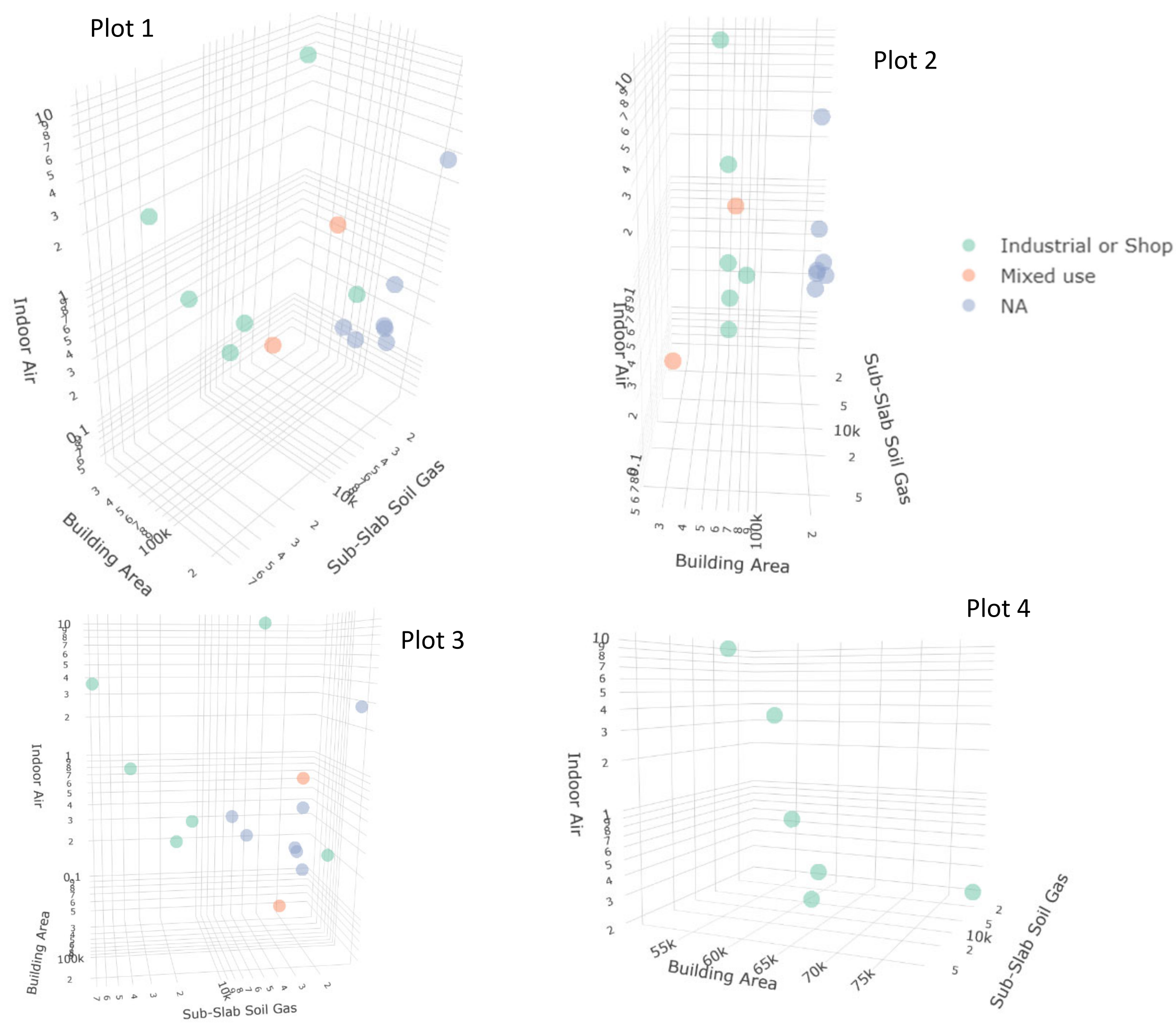



```
Coefficients:
                                   Estimate Std. Error t value Pr(>|t|)
(Intercept)                       1.147e+00  8.040e-01   1.427  0.16474
SS_Data                           4.861e-06  1.568e-06   3.100  0.00437 **
BUILDING_AREA                    -8.295e-07  4.859e-06  -0.171  0.86568
BUILDING_USE_STANDARDIZEDMixed use -6.863e-01  1.306e+00  -0.526  0.60335
BUILDING_USE_STANDARDIZEDNA      -2.608e-01  1.020e+00  -0.256  0.80014
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.799 on 28 degrees of freedom
  (10 observations deleted due to missingness)
Multiple R-squared:  0.263,  Adjusted R-squared:  0.1577
F-statistic: 2.498 on 4 and 28 DF,  p-value: 0.06531
```

Figure 5-37. cis-1,2-DCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Area, and Building Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

General linear model results shown.

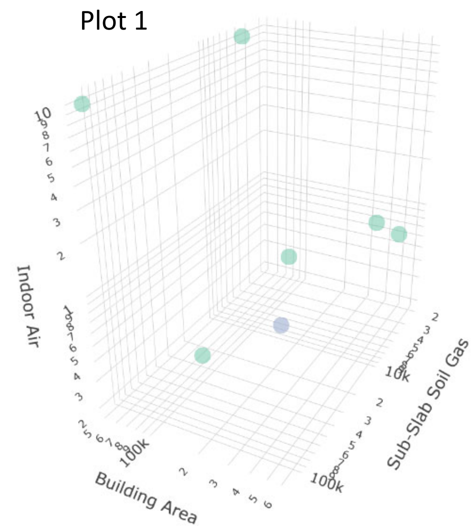


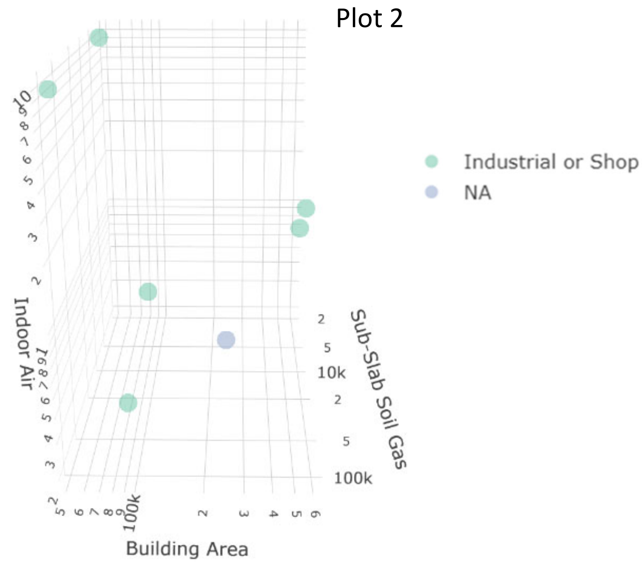

```
Coefficients:
                                   Estimate Std. Error t value Pr(>|t|)
(Intercept)                       8.507e+00  4.770e+00   1.783    0.105
SS_Data                          -9.584e-06  4.656e-05  -0.206    0.841
BUILDING_AREA                    -8.850e-05  7.020e-05  -1.261    0.236
BUILDING_USE_STANDARDIZEDMixed use -4.159e+00  2.752e+00  -1.511    0.162
BUILDING_USE_STANDARDIZEDNA       1.283e+01  1.190e+01   1.079    0.306

Residual standard error: 2.633 on 10 degrees of freedom
  (10 observations deleted due to missingness)
Multiple R-squared:  0.2628, Adjusted R-squared:  -0.03215
F-statistic: 0.891 on 4 and 10 DF,  p-value: 0.5039
```

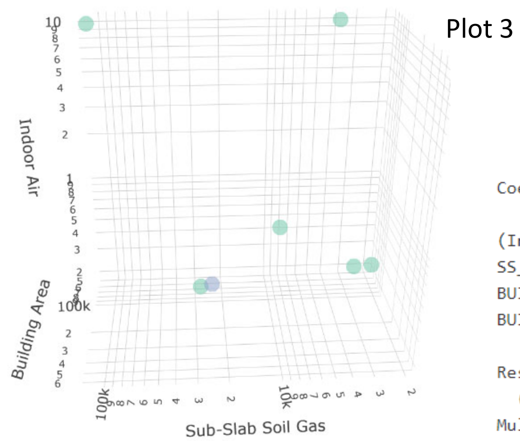
Figure 5-38. trans-1,2-DCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Area, and Building Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plot 4 only includes data for buildings with industrial or shop use. General linear model results also shown.





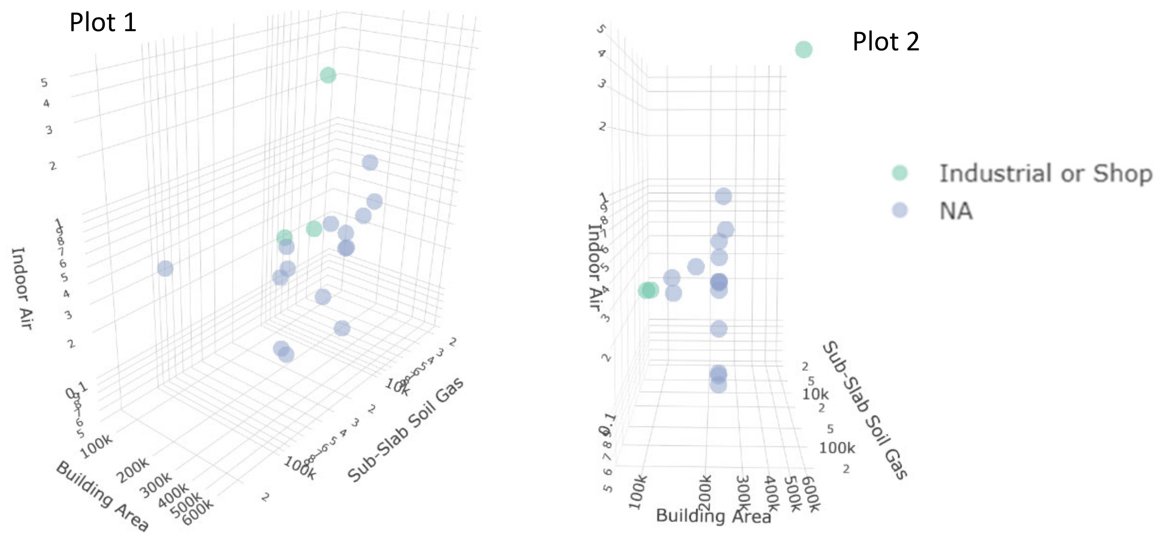


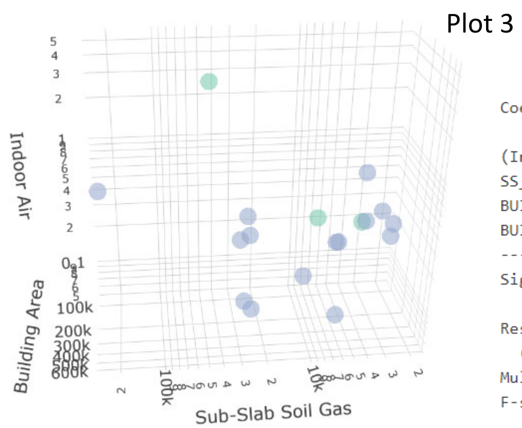

```
Coefficients:
                             Estimate Std. Error t value Pr(>|t|)
(Intercept)                 3.690e+00  3.507e+00   1.052    0.370
SS_Data                     4.862e-05  5.202e-05   0.935    0.419
BUILDING_AREA              -4.824e-06  8.142e-06  -0.592    0.595
BUILDING_USE_STANDARDIZEDNA -3.256e+00  5.266e+00  -0.618    0.580

Residual standard error: 4.871 on 3 degrees of freedom
  (8 observations deleted due to missingness)
Multiple R-squared:  0.4328, Adjusted R-squared:  -0.1344
F-statistic: 0.763 on 3 and 3 DF,  p-value: 0.5853
```

Figure 5-39. 1,1-DCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Area, and Building Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Geneal linear model results shown.



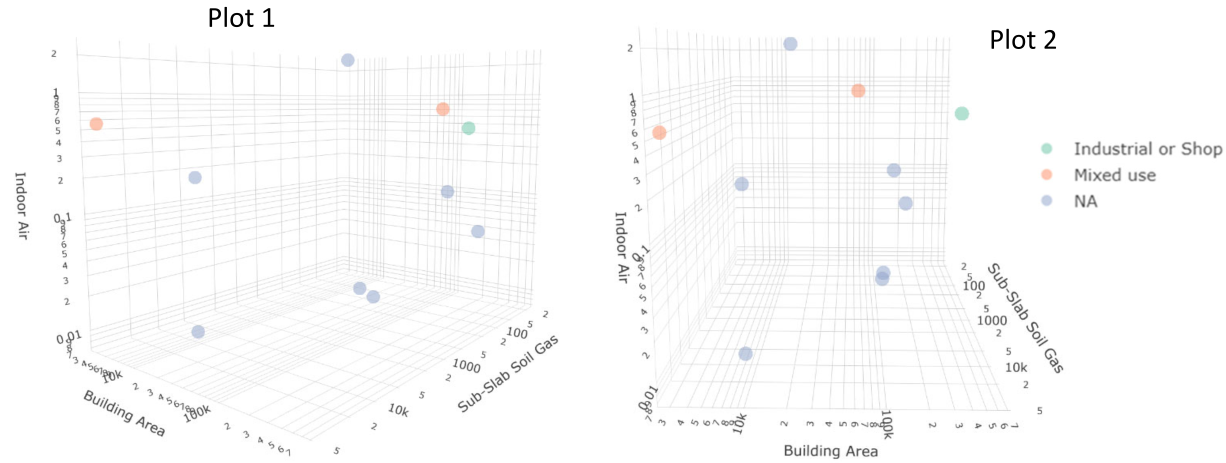


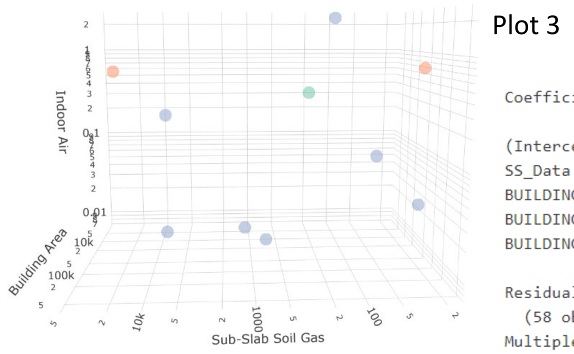

```
Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                  -2.648e-01  3.141e-01  -0.843 0.413482
SS_Data                       4.235e-07  1.722e-06   0.246 0.809303
BUILDING_AREA                 8.170e-06  8.575e-07   9.529 1.69e-07 ***
BUILDING_USE_STANDARDIZEDNA -1.190e+00  2.537e-01  -4.691 0.000347 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3943 on 14 degrees of freedom
  (7 observations deleted due to missingness)
Multiple R-squared:  0.9078, Adjusted R-squared:  0.888
F-statistic: 45.94 on 3 and 14 DF,  p-value: 1.709e-07
```

Figure 5-40. 1,1-DCA Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Area, and Building Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

General linear model results shown.



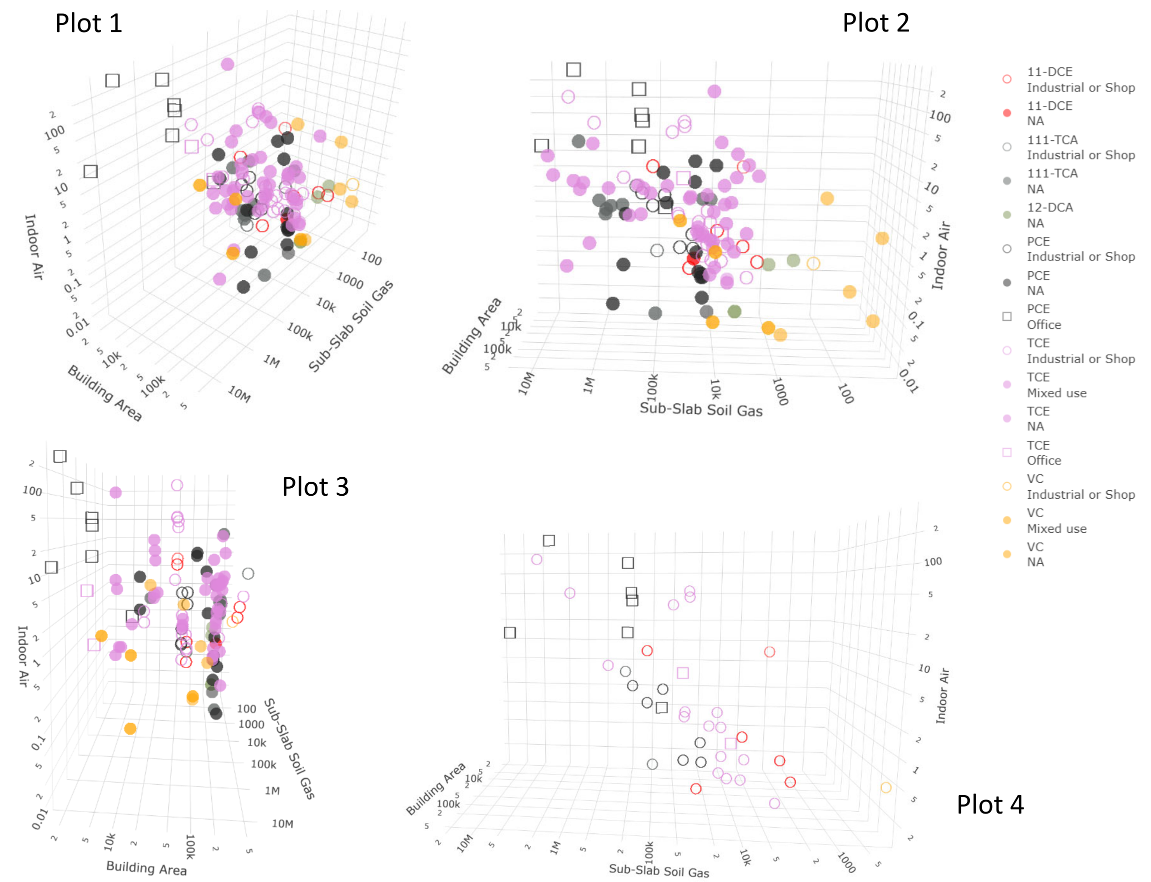


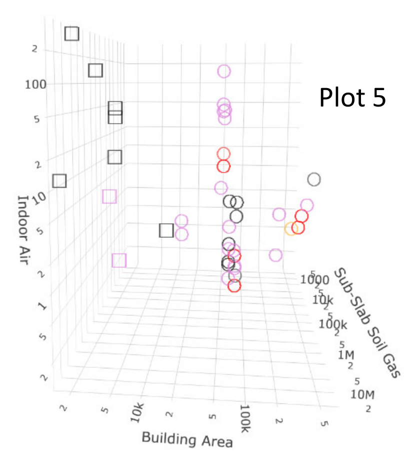

```
Coefficients:
                                      Estimate Std. Error t value Pr(>|t|)
(Intercept)                          3.819e+00  2.654e+00   1.439    0.210
SS_Data                             -2.571e-05  2.918e-05  -0.881    0.419
BUILDING_AREA                       -5.318e-06  4.074e-06  -1.305    0.249
BUILDING_USE_STANDARDIZEDMixed use -2.483e+00  2.414e+00  -1.029    0.351
BUILDING_USE_STANDARDIZEDNA        -2.876e+00  2.290e+00  -1.256    0.265

Residual standard error: 0.7966 on 5 degrees of freedom
  (58 observations deleted due to missingness)
Multiple R-squared:  0.2861, Adjusted R-squared:  -0.2851
F-statistic: 0.5008 on 4 and 5 DF,  p-value: 0.7387
```

Figure 5-41. VC Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Area, and Building Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

General linear model results shown.



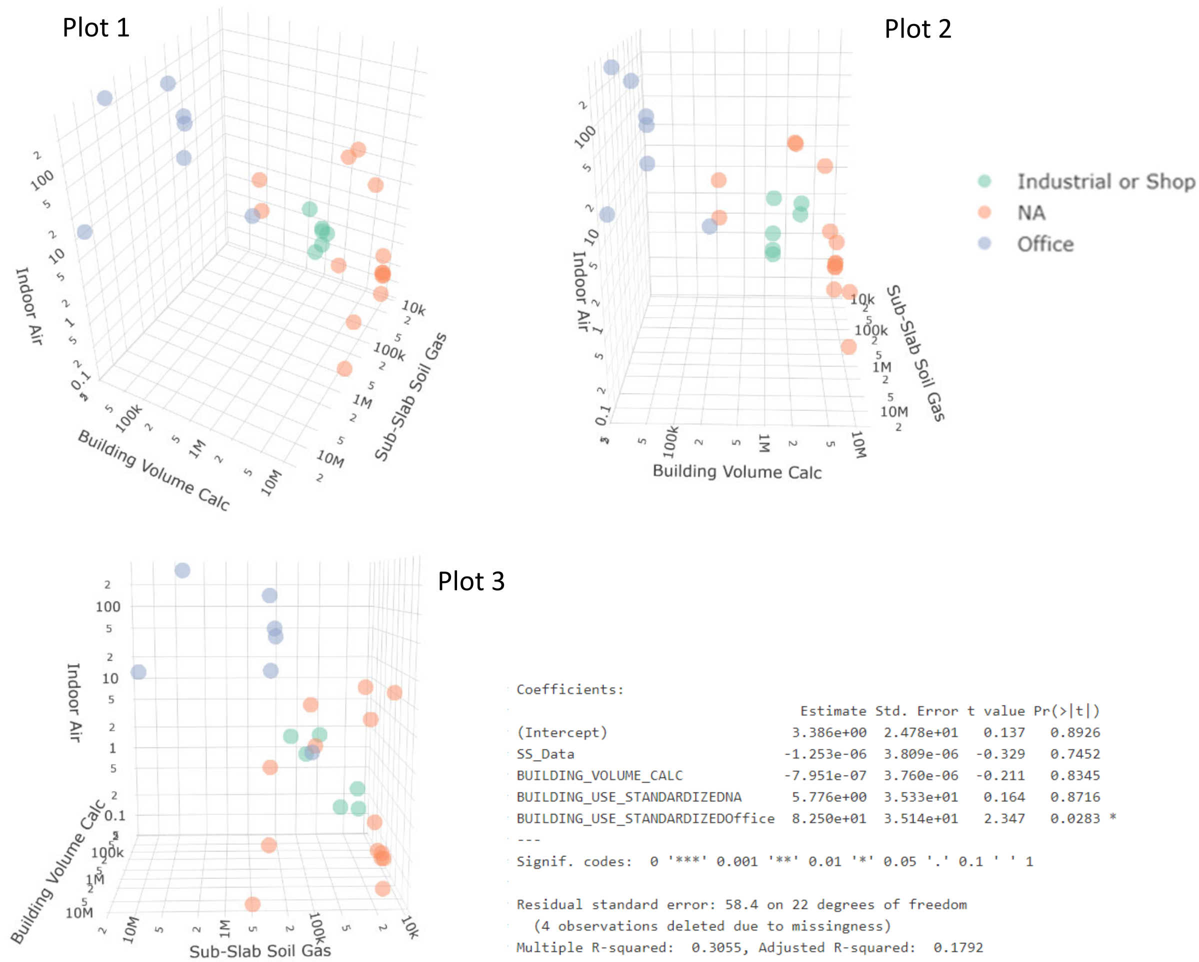



```
Coefficients:
                                   Estimate Std. Error t value Pr(>|t|)
(Intercept)                       1.170e+01  1.057e+01   1.107    0.270
SS_Data                           1.833e-06  1.348e-06   1.359    0.175
BUILDING_AREA                    -2.999e-05  1.870e-05  -1.603    0.110
BUILDING_USE_STANDARDIZEDMixed use -1.386e+01 1.019e+01  -1.359    0.175
BUILDING_USE_STANDARDIZEDNA      -6.379e+00  5.508e+00  -1.158    0.248
BUILDING_USE_STANDARDIZEDOffice   4.259e+01  1.043e+01   4.082 6.23e-05 ***
Analyte_Short111-TCA              5.934e+00  1.253e+01   0.473    0.636
Analyte_Short12-DCA               1.901e+00  1.984e+01   0.096    0.924
Analyte_ShortPCE                  5.202e+00  1.135e+01   0.458    0.647
Analyte_ShortTCE                  6.249e+00  1.059e+01   0.590    0.556
Analyte_ShortVC                  -6.922e-01  1.403e+01  -0.049    0.961
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Figure 5-42. Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Area, and Building Use – Plots for All VOCs

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plots 4 and 5 exclude data for mixed or unknown ("NA") building use. General linear model results also shown.

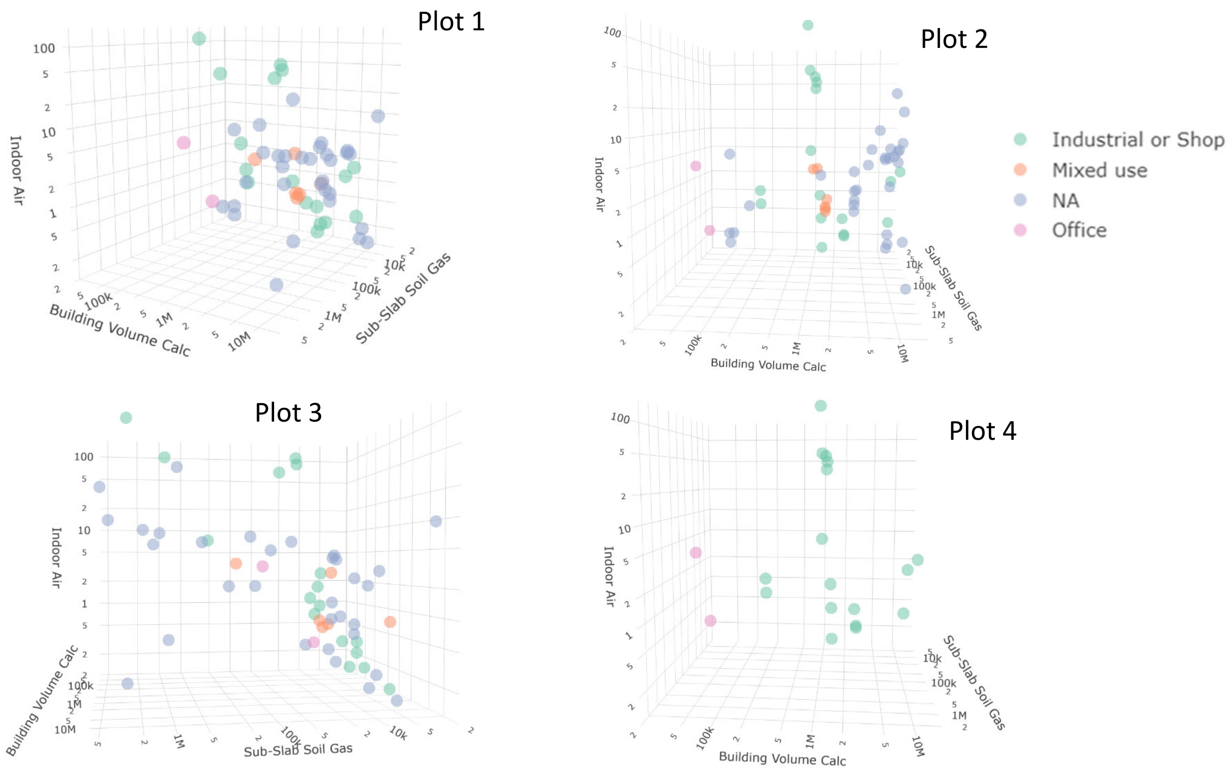



```
Coefficients:
                               Estimate Std. Error t value Pr(>|t|)
(Intercept)                   3.386e+00  2.478e+01   0.137   0.8926
SS_Data                      -1.253e-06  3.809e-06  -0.329   0.7452
BUILDING_VOLUME_CALC         -7.951e-07  3.760e-06  -0.211   0.8345
BUILDING_USE_STANDARDIZEDNA   5.776e+00  3.533e+01   0.164   0.8716
BUILDING_USE_STANDARDIZEDOffice 8.250e+01  3.514e+01   2.347   0.0283 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 58.4 on 22 degrees of freedom
  (4 observations deleted due to missingness)
Multiple R-squared:  0.3055, Adjusted R-squared:  0.1792
F-statistic: 2.419 on 4 and 22 DF,  p-value: 0.07905
```

Figure 5-43. PCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Volume, and Building Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

General linear model results shown.




```
Coefficients:
                                   Estimate Std. Error t value Pr(>|t|)
(Intercept)                       2.100e+01  4.823e+00   4.355 6.44e-05 ***
SS_Data                           9.183e-06  2.476e-06   3.709 0.000514 ***
BUILDING_VOLUME_CALC             -1.036e-06  6.093e-07  -1.701 0.095021 .
BUILDING_USE_STANDARDIZEDMixed use -1.836e+01  8.651e+00  -2.123 0.038645 *
BUILDING_USE_STANDARDIZEDNA      -1.517e+01  5.854e+00  -2.592 0.012424 *
BUILDING_USE_STANDARDIZEDOffice  -1.943e+01  1.363e+01  -1.425 0.160157
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 18.03 on 51 degrees of freedom
  (3 observations deleted due to missingness)
Multiple R-squared:  0.321,  Adjusted R-squared:  0.2545
F-statistic: 4.823 on 5 and 51 DF,  p-value: 0.001097
```

Figure 5-44. TCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Volume, and Building Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plot 4 excludes data for mixed or unknown ("NA") building use. General linear model results also shown.

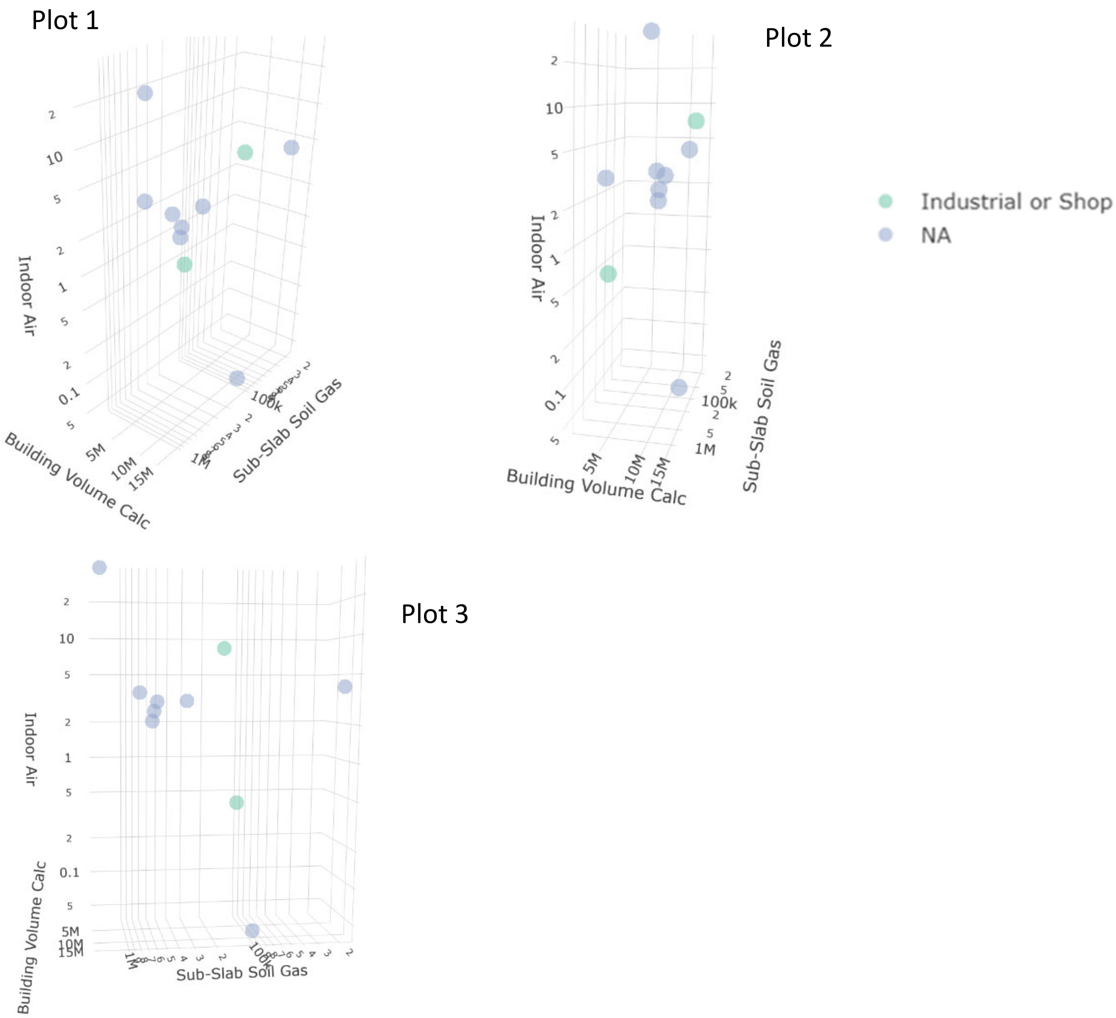
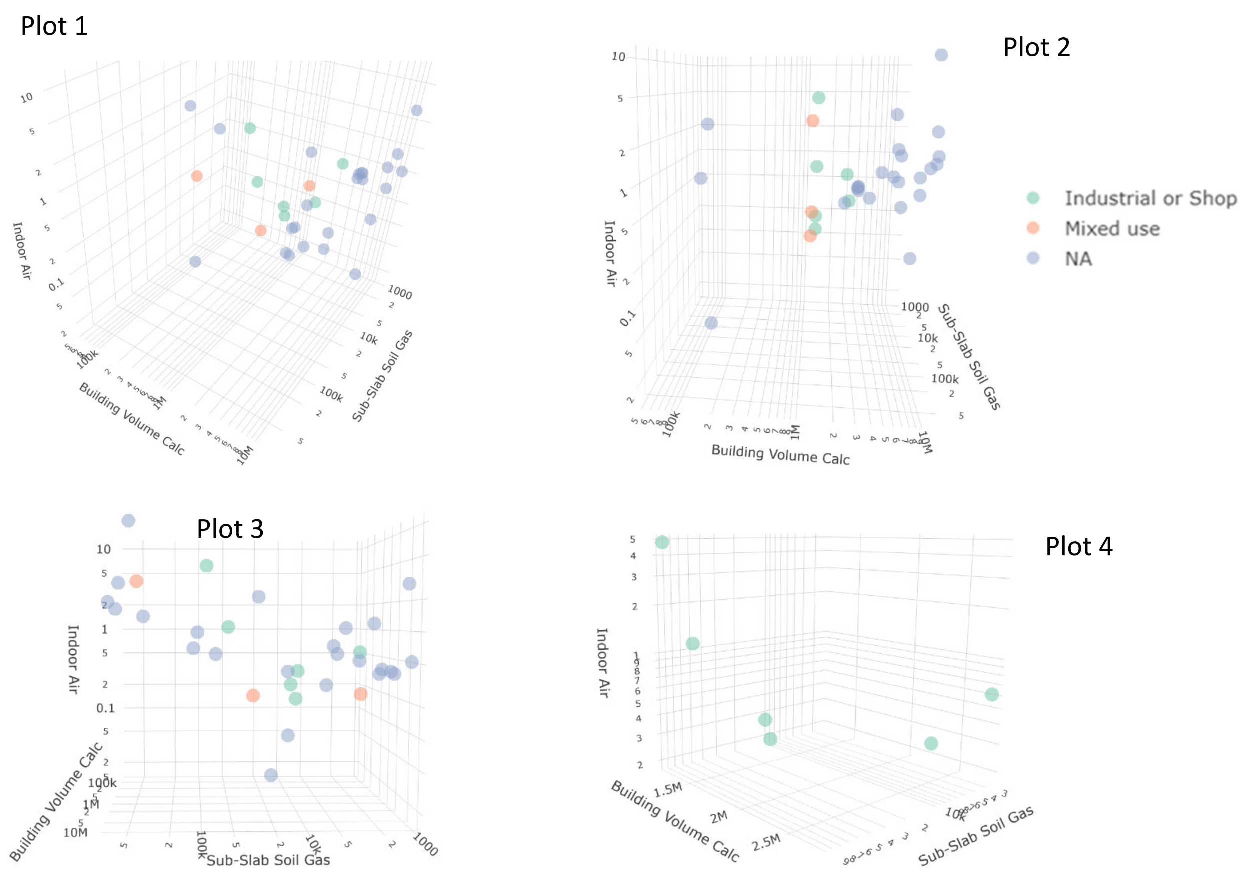


Figure 5-45. 1,1,1-TCA Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Volume, and Building Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

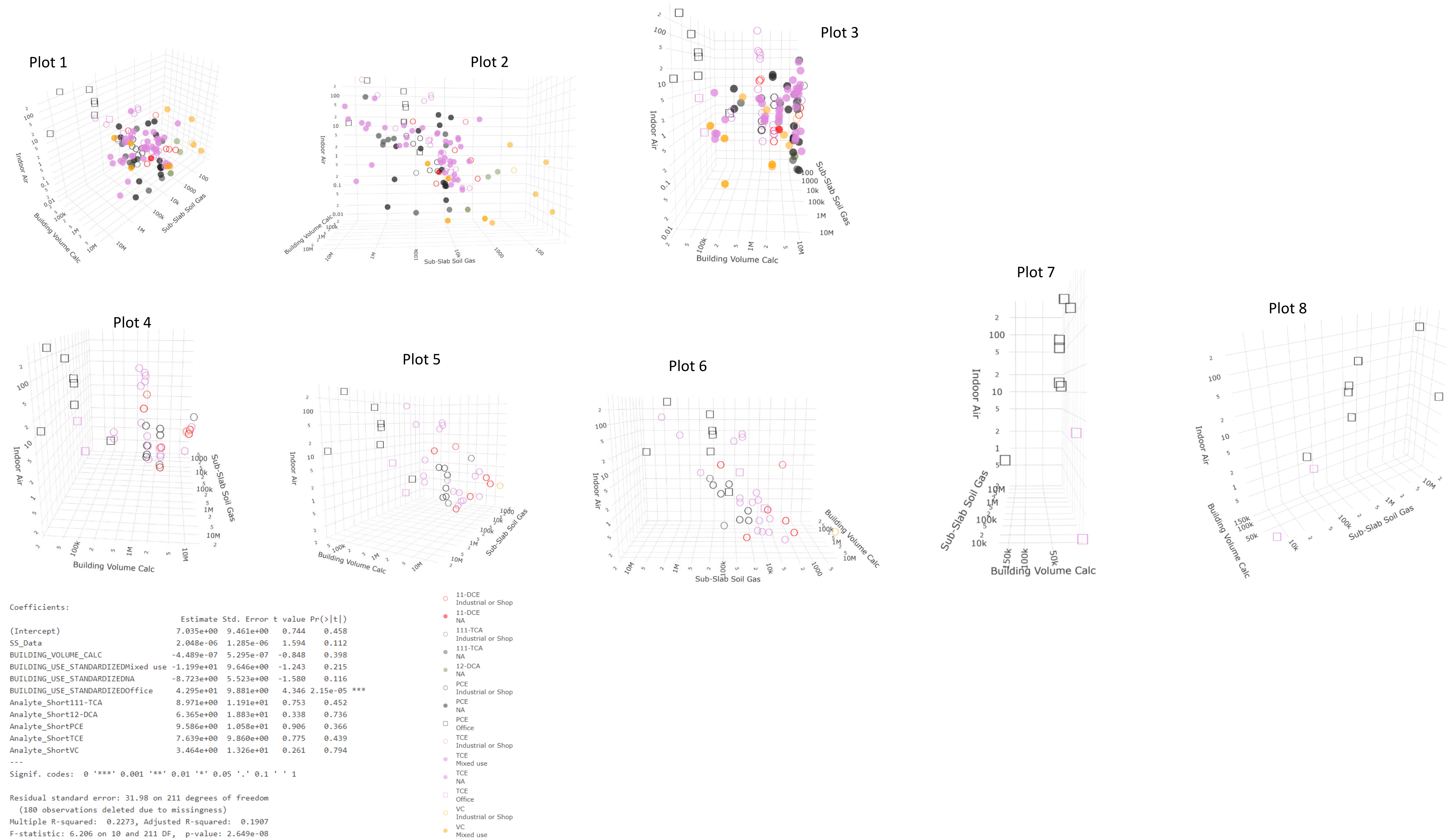



```
Coefficients:
                                   Estimate Std. Error t value Pr(>|t|)
(Intercept)                       1.066e+00  7.540e-01   1.414  0.16842
SS_Data                           4.703e-06  1.640e-06   2.869  0.00776 **
BUILDING_VOLUME_CALC              1.571e-08  1.014e-07   0.155  0.87803
BUILDING_USE_STANDARDIZEDMixed use -6.281e-01  1.299e+00  -0.484  0.63234
BUILDING_USE_STANDARDIZEDNA      -4.353e-01  9.655e-01  -0.451  0.65555
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.799 on 28 degrees of freedom
  (10 observations deleted due to missingness)
Multiple R-squared:  0.2629, Adjusted R-squared:  0.1576
F-statistic: 2.496 on 4 and 28 DF,  p-value: 0.06545
```

Figure 5-46. cis-1,2-DCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Volume, and Building Use

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plot 4 excludes data for mixed or unknown ("NA") building use. General linear model results also shown.

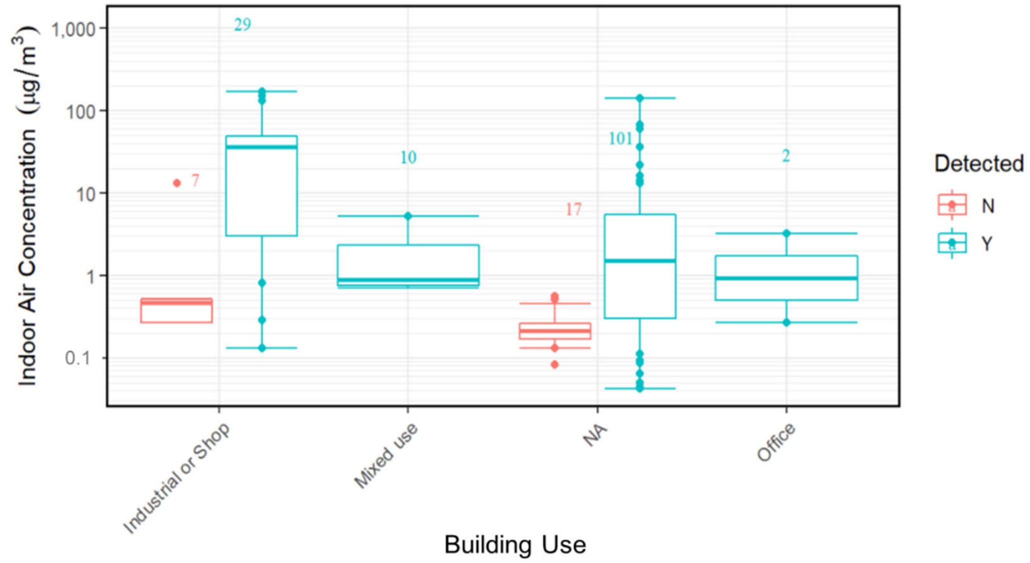



```
Coefficients:
                                    Estimate Std. Error t value Pr(>|t|)
(Intercept)                        7.035e+00  9.461e+00   0.744    0.458
SS_Data                            2.048e-06  1.285e-06   1.594    0.112
BUILDING_VOLUME_CALC              -4.489e-07  5.295e-07  -0.848    0.398
BUILDING_USE_STANDARDIZEDMixed use -1.199e+01  9.646e+00  -1.243    0.215
BUILDING_USE_STANDARDIZEDNA       -8.723e+00  5.523e+00  -1.580    0.116
BUILDING_USE_STANDARDIZEDOffice    4.295e+01  9.881e+00   4.346 2.15e-05 ***
Analyte_Short111-TCA               8.971e+00  1.191e+01   0.753    0.452
Analyte_Short12-DCA                6.365e+00  1.883e+01   0.338    0.736
Analyte_ShortPCE                   9.586e+00  1.058e+01   0.906    0.366
Analyte_ShortTCE                   7.639e+00  9.860e+00   0.775    0.439
Analyte_ShortVC                    3.464e+00  1.326e+01   0.261    0.794
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 31.98 on 211 degrees of freedom
  (180 observations deleted due to missingness)
Multiple R-squared:  0.2273, Adjusted R-squared:  0.1907
F-statistic: 6.206 on 10 and 211 DF,  p-value: 2.649e-08
```

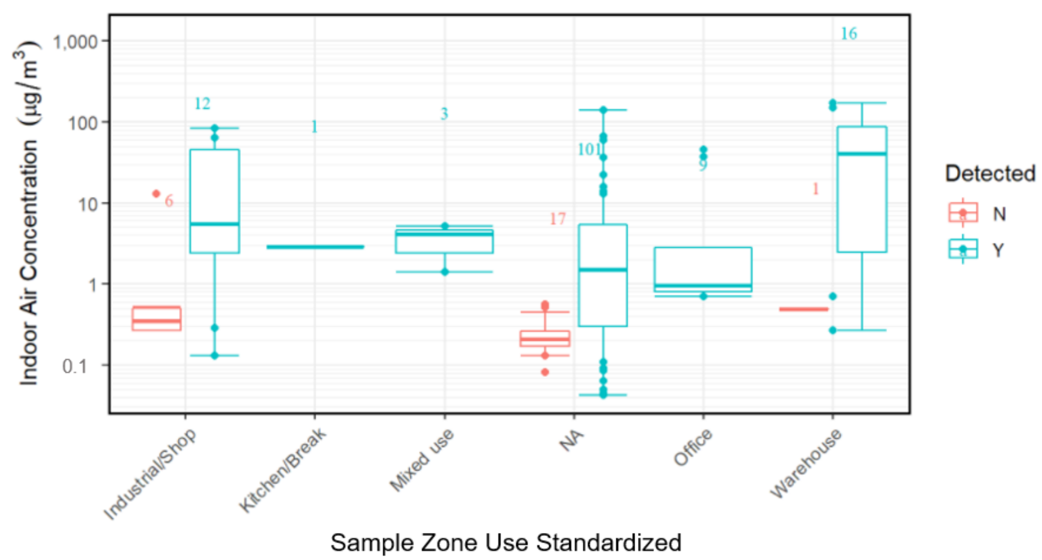
Figure 5-47. Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Building Volume, and Building Use – Plots for All VOCs

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Plots 4 to 6 exclude data for mixed or unknown ("NA") building use. Plots 7 and 8 only include data for buildings with office use. General linear model results also shown.




```
## [1] "ANOVA only includes detected data"
## ANOVA Table (type II tests)
##
##                       Effect DFn DFd      F        p p<.05   ges
## 1 BUILDING_USE_STANDARDIZED   3 138 15.954 5.83e-09     * 0.258
## # A tibble: 6 x 9
##   term  group1 group2 null.value estimate conf.low conf.high   p.adj
## * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>   <dbl>
## 1 BUIL~ Indus~ Mixed~          0 -40.5       -64.8     -16.1  1.67e-4
## 2 BUIL~ Indus~ NA              0 -36.1       -50.1     -22.2  2.53e-9
## 3 BUIL~ Indus~ Office          0 -40.5       -89.0      7.94 1.35e-1
## 4 BUIL~ Mixed~ NA              0   4.32      -17.7      26.3  9.56e-1
## 5 BUIL~ Mixed~ Office          0  -0.0710    -51.4      51.3  1.00e+0
## 6 BUIL~ NA     Office          0  -4.40      -51.7      42.9  9.95e-1
## # ... with 1 more variable: p.adj.signif <chr>
```

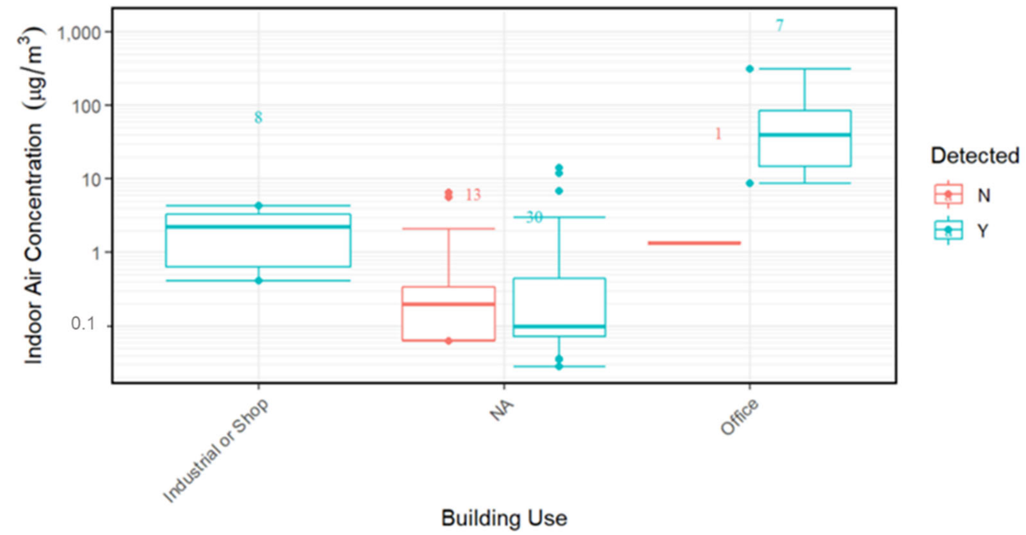



```
## [1] "ANOVA only includes detected data"
## ANOVA Table (type II tests)
##
##                   Effect DFn DFd      F        p p<.05  ges
## 1 ZONE_USE_STANDARDIZED   5 136 10.049 3.34e-08     * 0.27
## # A tibble: 15 x 9
##    term  group1 group2 null.value estimate conf.low conf.high   p.adj
##  * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>   <dbl>
##  1 ZONE~ Indus~ Kitch~          0  -21.4    -98.0       55.2  9.66e-1
##  2 ZONE~ Indus~ Mixed~          0  -20.7    -68.3       26.8  8.05e-1
##  3 ZONE~ Indus~ NA              0  -18.2    -40.6        4.32 1.87e-1
##  4 ZONE~ Indus~ Office          0  -14.2    -46.6       18.3  8.05e-1
##  5 ZONE~ Indus~ Wareh~          0   28.9      0.790     57.0  4.01e-2
##  6 ZONE~ Kitch~ Mixed~          0    0.667  -84.3       85.7  1.00e+0
##  7 ZONE~ Kitch~ NA              0    3.24   -70.7       77.2  1.00e+0
##  8 ZONE~ Kitch~ Office          0    7.22   -70.4       84.8  1.00e+0
##  9 ZONE~ Kitch~ Wareh~          0   50.3    -25.6      126.   3.97e-1
## 10 ZONE~ Mixed~ NA              0    2.58   -40.6       45.7  1.00e+0
## 11 ZONE~ Mixed~ Office          0    6.56   -42.5       55.6  9.99e-1
## 12 ZONE~ Mixed~ Wareh~          0   49.6      3.32      95.9  2.80e-2
## 13 ZONE~ NA     Office          0    3.98   -21.6       29.6  9.98e-1
## 14 ZONE~ NA     Wareh~          0   47.1     27.3       66.9  3.17e-9
## 15 ZONE~ Office Wareh~          0   43.1     12.4       73.8  1.14e-3
## # ... with 1 more variable: p.adj.signif <chr>
```

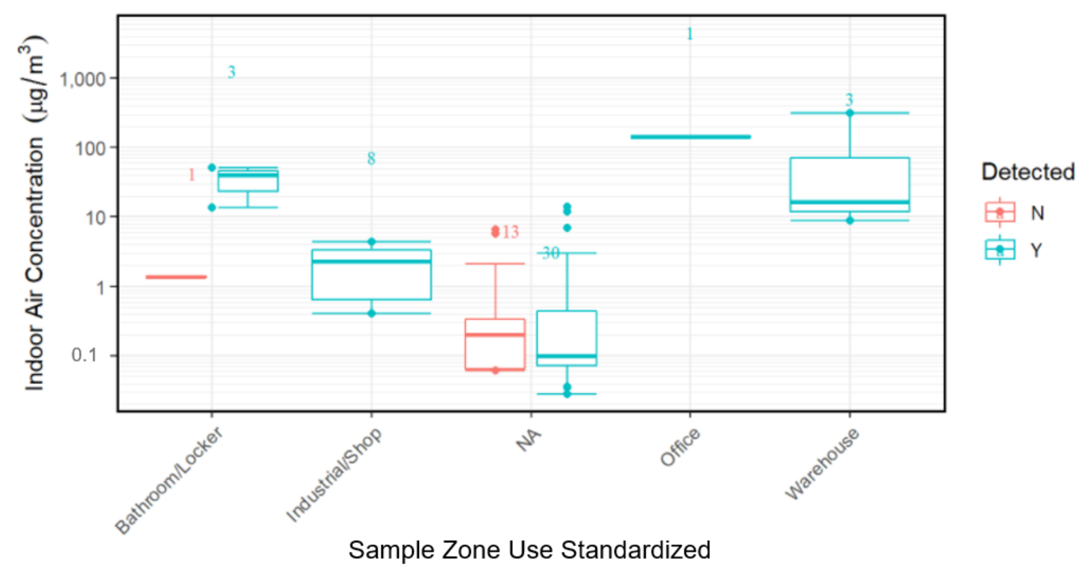
Figure 6-1. TCE Indoor Air Concentration Versus Building Use or Sample Zone Use Standardized

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates use is unknown (not available).




```
## [1] "ANOVA only includes detected data"
## ANOVA Table (type II tests)
##
##                       Effect DFn DFd      F       p p<.05   ges
## 1 BUILDING_USE_STANDARDIZED   2  42 11.275 0.00012     * 0.349
## # A tibble: 3 x 9
##   term  group1 group2 null.value estimate conf.low conf.high   p.adj
## * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>   <dbl>
## 1 BUIL~ Indus~ NA              0   -0.757    -41.3      39.8 9.99e-1
## 2 BUIL~ Indus~ Office          0   81.3       28.6     134.  1.54e-3
## 3 BUIL~ NA     Office          0   82.1       39.3     125.  9.24e-5
## # ... with 1 more variable: p.adj.signif <chr>
```




```
## [1] "ANOVA only includes detected data"
## ANOVA Table (type II tests)
##
##                   Effect DFn DFd     F        p p<.05   ges
## 1 ZONE_USE_STANDARDIZED   4  40 8.652 3.96e-05     * 0.464
## # A tibble: 10 x 9
##    term  group1 group2 null.value estimate conf.low conf.high   p.adj
##  * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>   <dbl>
##  1 ZONE~ Bathr~ Indus~          0  -32.9     -108.       42.6 7.26e-1
##  2 ZONE~ Bathr~ NA              0  -33.6     -101.       33.9 6.17e-1
##  3 ZONE~ Bathr~ Office          0  107.       -21.3     236.  1.41e-1
##  4 ZONE~ Bathr~ Wareh~          0   77.3      -13.7     168.  1.29e-1
##  5 ZONE~ Indus~ NA              0   -0.757    -45.1      43.6 1.00e+0
##  6 ZONE~ Indus~ Office          0  140.        22.0     258.  1.30e-2
##  7 ZONE~ Indus~ Wareh~          0  110.        34.7     186.  1.42e-3
##  8 ZONE~ NA     Office          0  141.        27.7     254.  8.30e-3
##  9 ZONE~ NA     Wareh~          0  111.        43.5     178.  2.88e-4
## 10 ZONE~ Office Wareh~          0  -30.1     -159.       98.6 9.62e-1
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-2. PCE Indoor Air Concentration Versus Building Use or Sample Zone Use Standardized

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates use is unknown (not available).

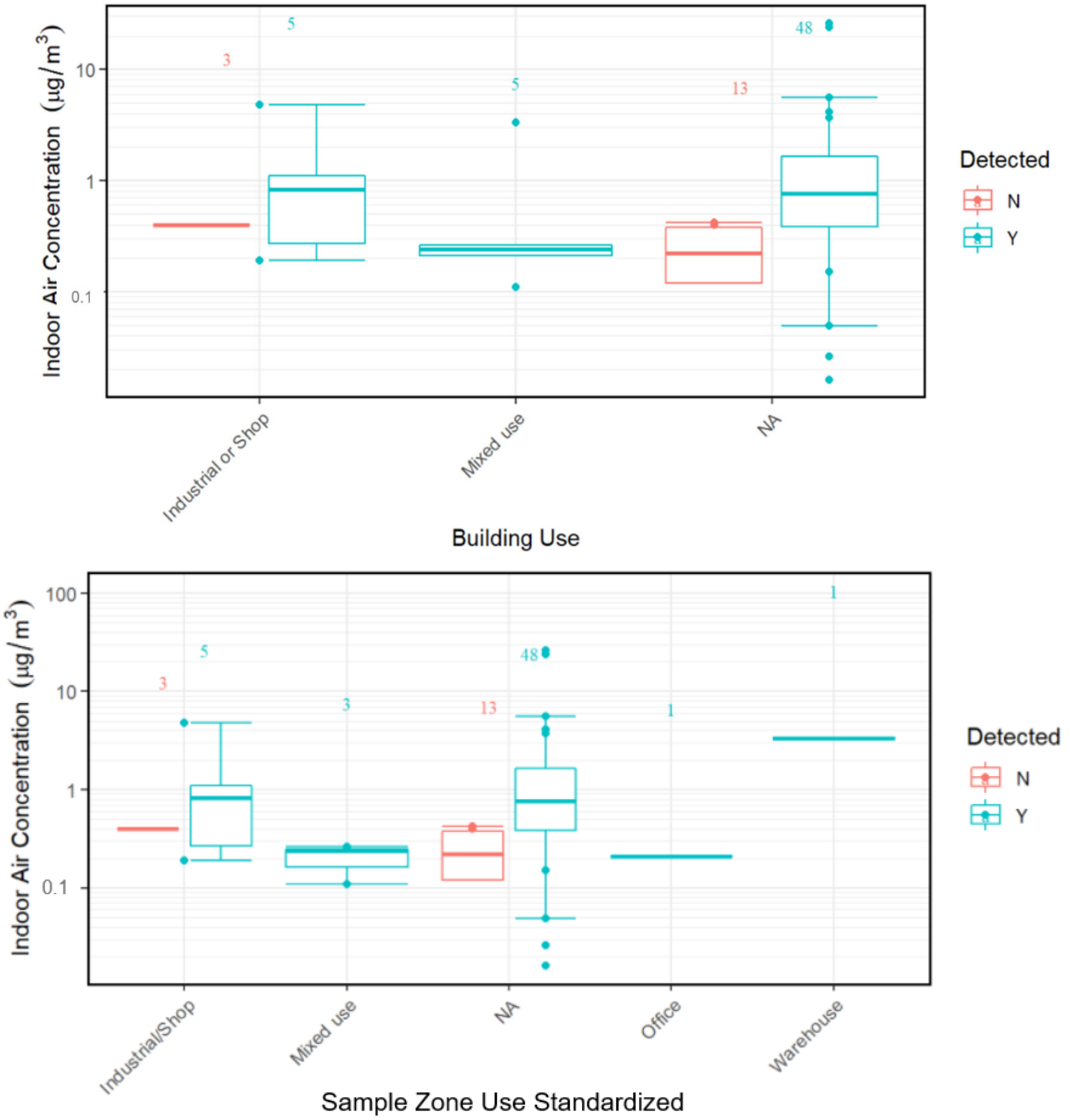
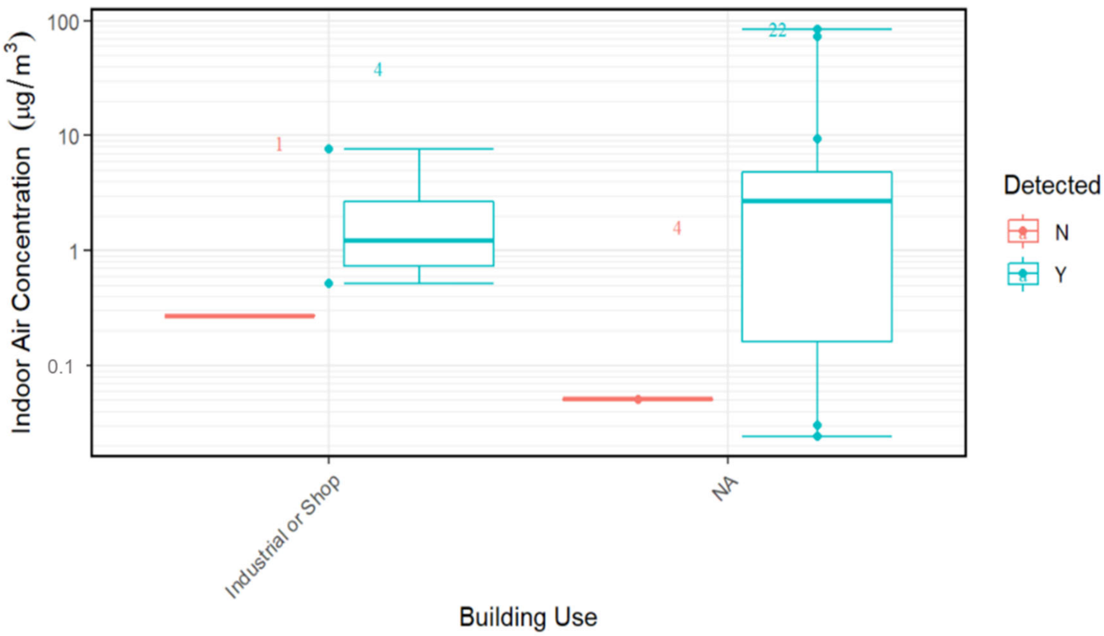


Figure 6-3. cis-1,2-DCE Indoor Air Concentration Versus Building or Sample Zone Use Standardized
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000 µg/m^3) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates use is unknown (not available). No significant ANOVA comparisons in either the building use or sample zone use, so summary table not shown.



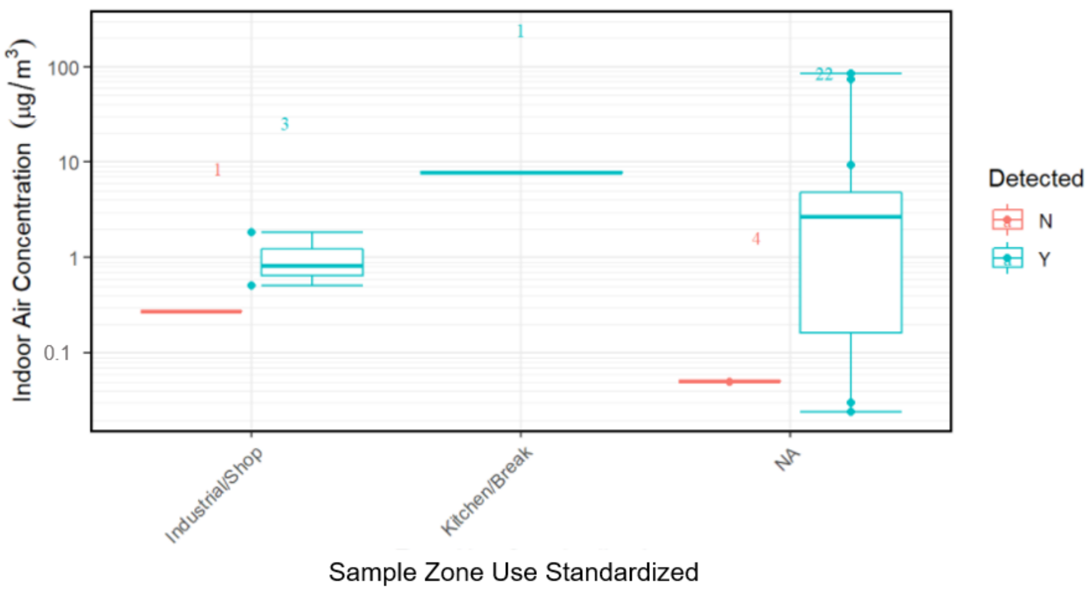


Figure 6-4. 1,1,1-TCA Indoor Air Concentration Versus Building Use or Sample Zone Use Standardized

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates use is unknown (not available). No significant ANOVA comparisons in either the building use or sample zone use, so summary table not shown.

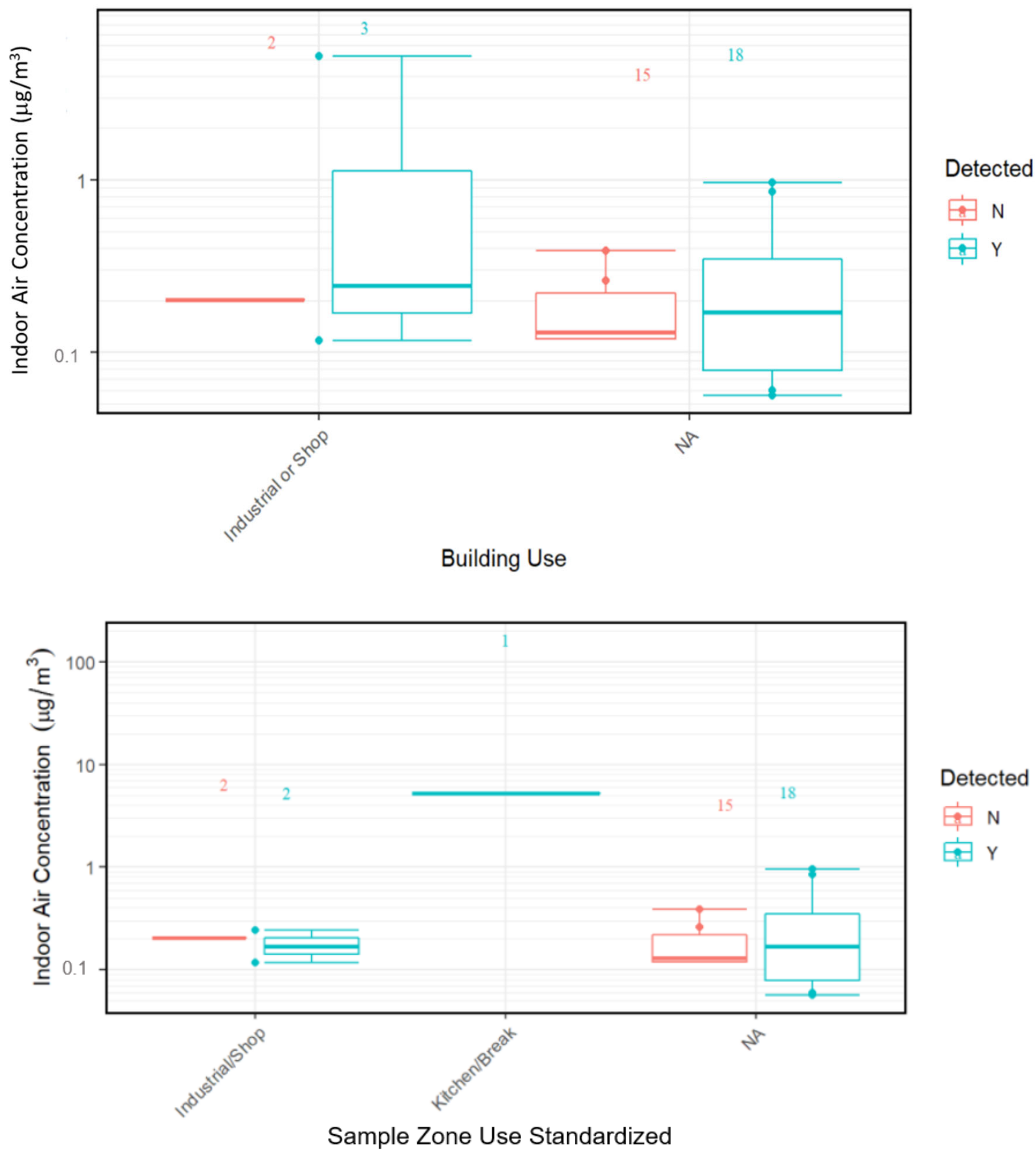
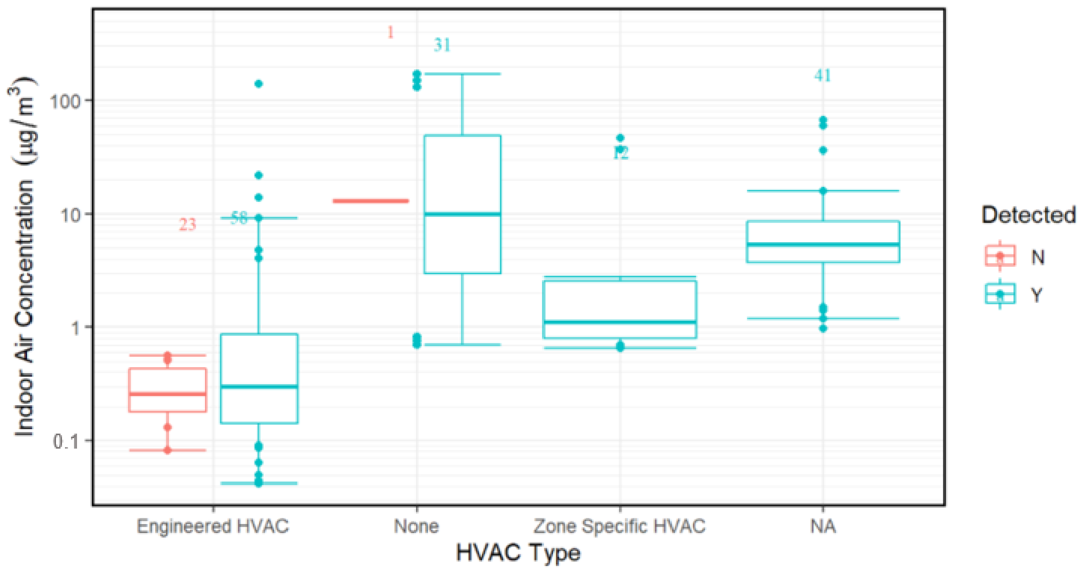
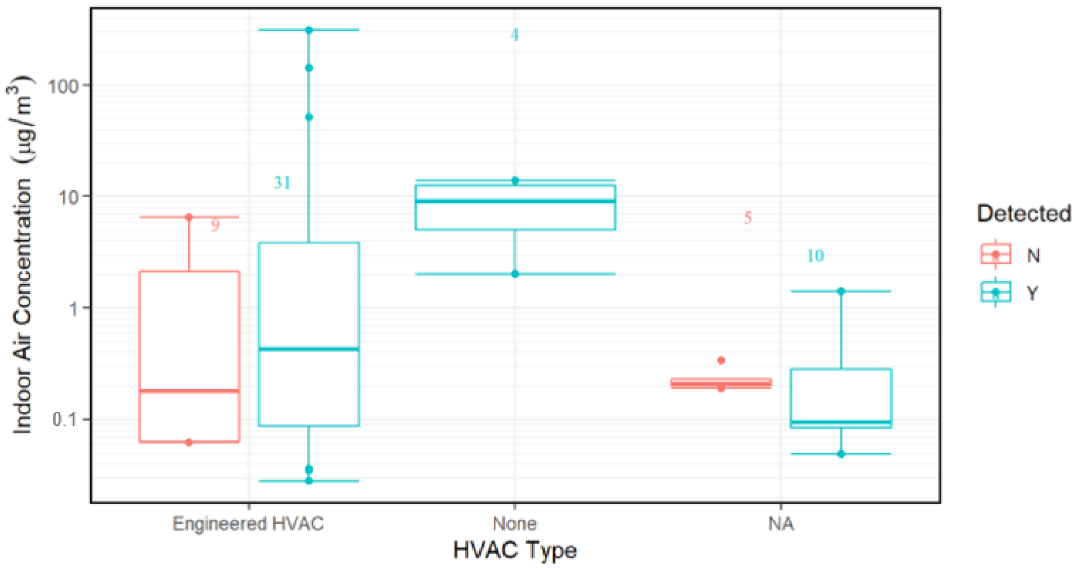


Figure 6-5. 1,1-DCA Indoor Air Concentration Versus Building Sample Zone Use Standardized
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000 µg/m³) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates use is unknown (not available). No significant ANOVA comparisons in either the building use or zone use, so summary table not shown.




```
## ANOVA Table (type II tests)
##
##      Effect DFn DFd      F        p p<.05   ges
## 1 HVAC_TYPE   2 122 18.033 1.38e-07     * 0.228
## # A tibble: 3 x 9
##   term  group1 group2 null.value estimate conf.low conf.high   p.adj
## * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>   <dbl>
## 1 HVAC~ Engin~ None            0    33.9      20.4      47.3  6.80e-8
## 2 HVAC~ Engin~ Zone ~          0     5.15    -14.8      25.1  8.13e-1
## 3 HVAC~ None   Zone ~          0   -28.7     -50.5      -6.94 6.19e-3
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-6. TCE Indoor Air Concentration Versus HVAC Type and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "None" indicates there is no HVAC, whereas "NA" indicates the presence of an HVAC is unknown (not available).

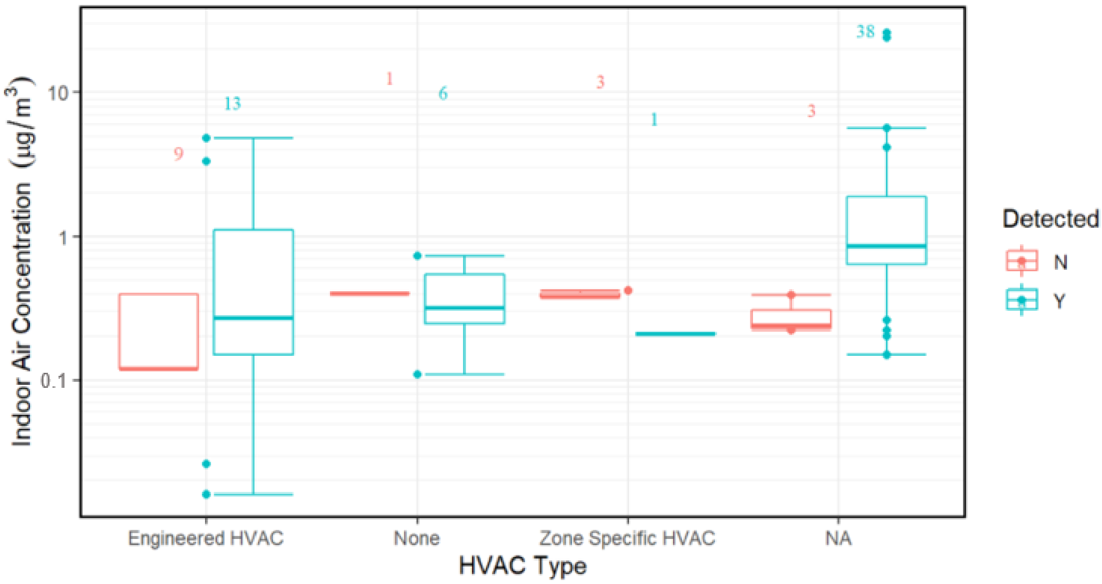



```
## ANOVA Table (type II tests)
##
##      Effect DFn DFd     F     p p<.05   ges
## 1 HVAC_TYPE   1  42 0.063 0.802       0.002
## # A tibble: 1 x 9
##   term    group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>   <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 HVAC_~ Engin~ None            0    -6.85    -61.7      48.0 0.802 ns
```

Figure 6-7. PCE Indoor Air Concentration Versus HVAC Type and ANOVA Results

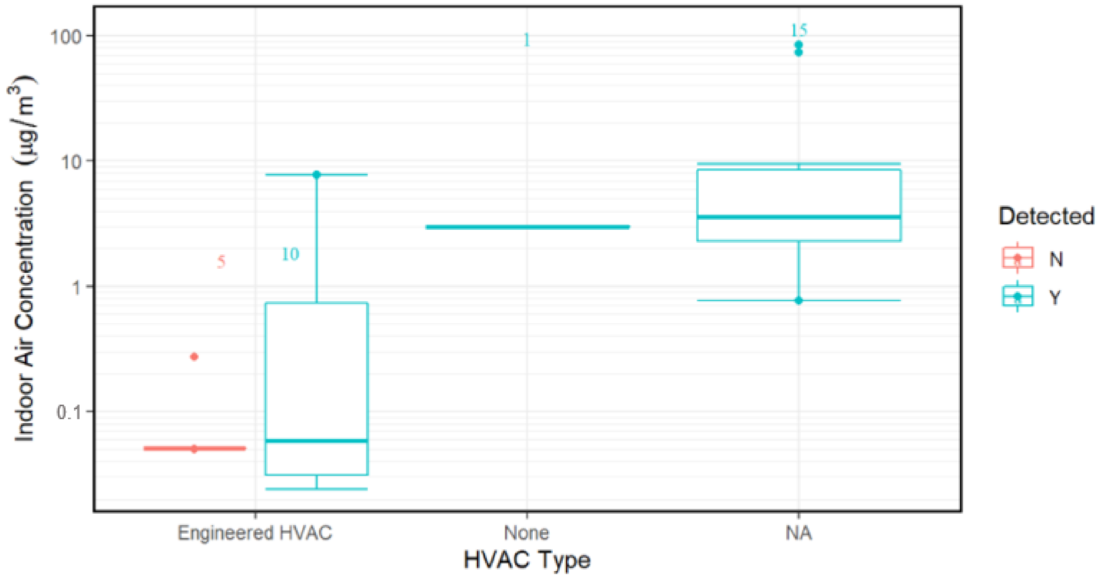
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "None" indicates there is no HVAC, whereas "NA" indicates the presence of an HVAC is unknown (not available).




```
## ANOVA Table (type II tests)
##
##      Effect DFn DFd    F     p p<.05   ges
## 1 HVAC_TYPE   2  30 0.41 0.668       0.027
## # A tibble: 3 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 HVAC_~ Engin~ None            0  -0.330     -1.44     0.778 0.746 ns
## 2 HVAC_~ Engin~ Zone ~          0  -0.372     -1.76     1.02  0.787 ns
## 3 HVAC_~ None   Zone ~          0  -0.0425    -1.64     1.56  0.998 ns
```

Figure 6-8. cis-1,2-DCE Indoor Air Concentration Versus HVAC Type and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings Baseline, atypical preferential pathway, and source strength (1,000 µg/m³) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "None" indicates there is no HVAC, whereas "NA" indicates the presence of an HVAC is unknown (not available).

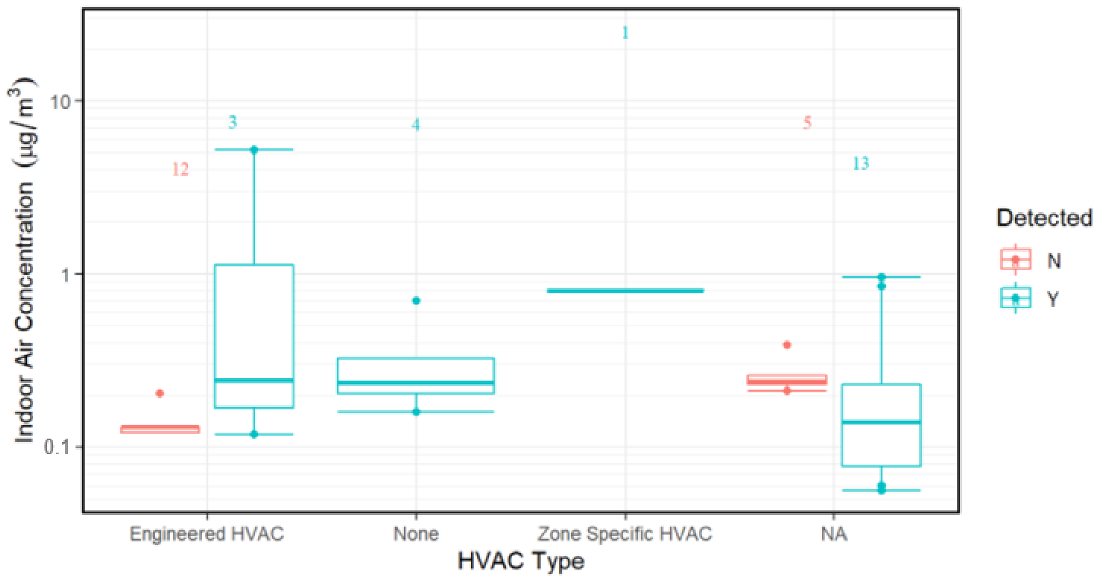



```
## ANOVA Table (type II tests)
##
##      Effect DFn DFd     F     p p<.05   ges
## 1 HVAC_TYPE   1  14 1.187 0.294       0.078
## # A tibble: 1 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 HVAC_~ Engin~ None            0     2.23    -2.16      6.61 0.294 ns
```

Figure 6-9. 1,1,1-TCA Indoor Air Concentration Versus HVAC Type and ANOVA Results

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. “Y” and “N” refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. “None” indicates there is no HVAC, whereas “NA” indicates the presence of an HVAC is unknown (not available).

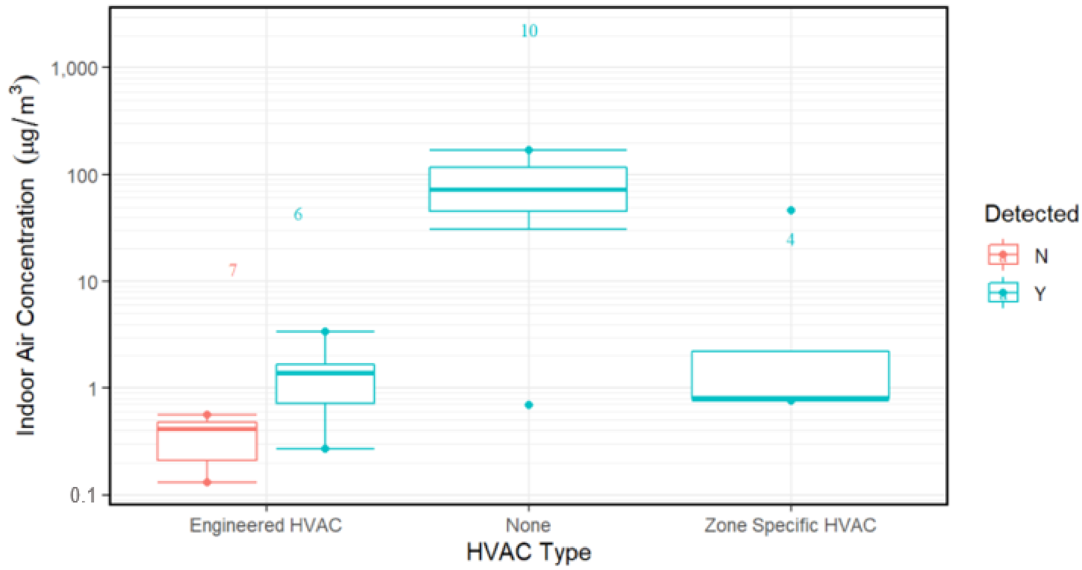



```
## ANOVA Table (type II tests)
##
##      Effect DFn DFd     F     p p<.05   ges
## 1 HVAC_TYPE   2  17 0.066 0.937       0.008
## # A tibble: 3 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 HVAC_~ Engin~ None            0   -0.148    -1.87      1.57 0.973 ns
## 2 HVAC_~ Engin~ Zone ~          0    0.319    -2.83      3.47 0.964 ns
## 3 HVAC_~ None   Zone ~          0    0.468    -2.94      3.88 0.934 ns
```

Figure 6-10. 1,1-DCA Indoor Air Concentration Versus HVAC Type and ANOVA Results

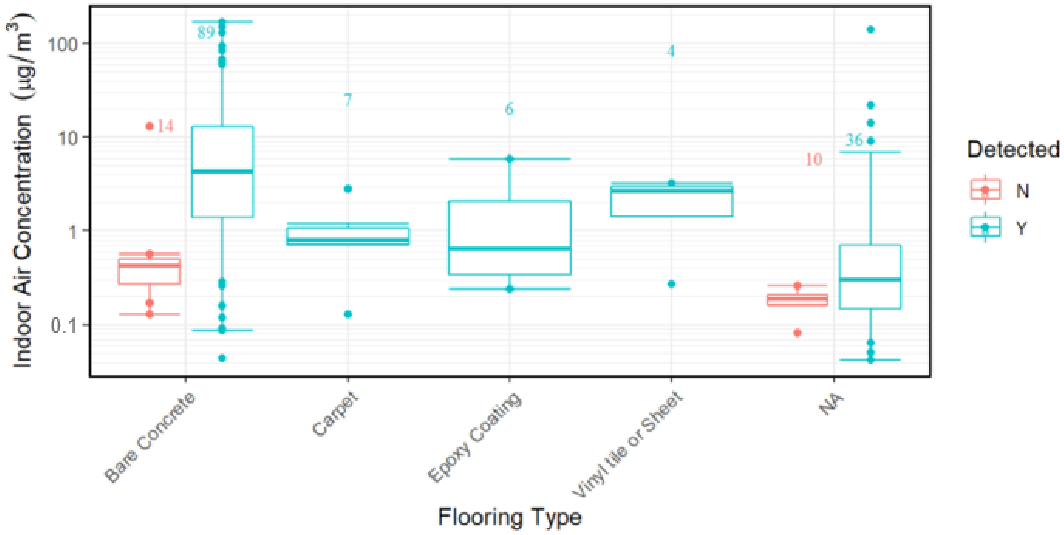
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000 µg/m³) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "None" indicates there is no HVAC, whereas "NA" indicates the presence of an HVAC is unknown (not available).




```
## ANOVA Table (type II tests)
##
##      Effect DFn DFd      F        p p<.05   ges
## 1 HVAC_TYPE   2  24 16.042 3.77e-05     * 0.572
## # A tibble: 3 x 9
##   term  group1 group2 null.value estimate conf.low conf.high   p.adj
## * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>   <dbl>
## 1 HVAC~ Engin~ None            0     79.7     43.7      116.  3.23e-5
## 2 HVAC~ Engin~ Zone ~          0     11.2    -37.8      60.2 8.36e-1
## 3 HVAC~ None   Zone ~          0    -68.5   -119.      -17.8 6.85e-3
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-11. TCE Indoor Air Concentration (Winter Only) Versus HVAC Type and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. “Y” and “N” refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. “None” indicates there is no HVAC.

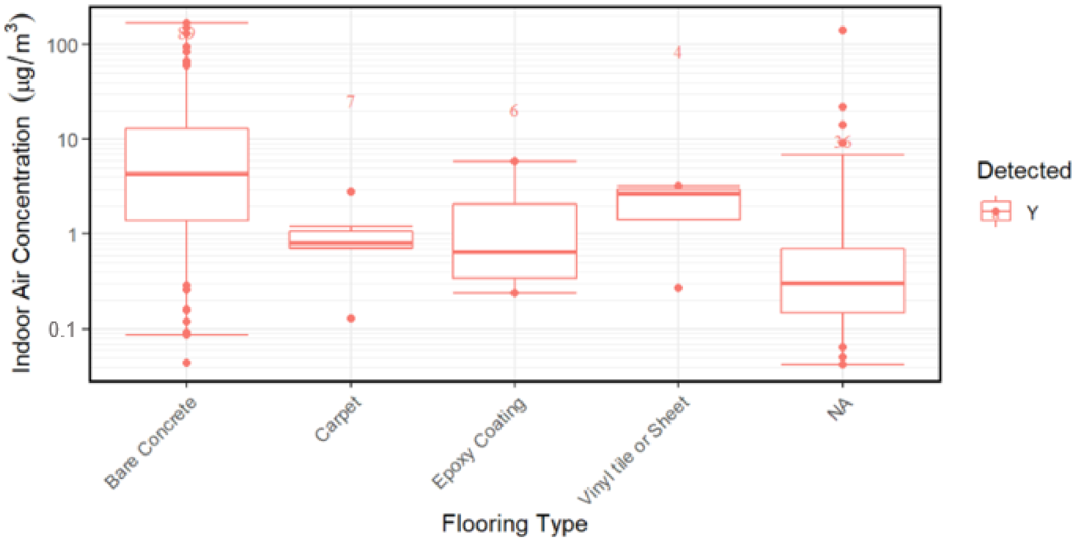



```
## ANOVA Table (type II tests)
##
##         Effect DFn DFd     F     p p<.05  ges
## 1 FLOORING_TYPE   3 116 1.184 0.319       0.03
## # A tibble: 6 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 FLOOR~ Bare ~ Carpet          0  -14.9      -44.6      14.8 0.559 ns
## 2 FLOOR~ Bare ~ Epoxy~          0  -14.2      -46.1      17.8 0.655 ns
## 3 FLOOR~ Bare ~ Vinyl~          0  -13.7      -52.5      25.0 0.792 ns
## 4 FLOOR~ Carpet Epoxy~          0    0.738    -41.6      43.0 1     ns
## 5 FLOOR~ Carpet Vinyl~          0    1.17     -46.5      48.8 1     ns
## 6 FLOOR~ Epoxy~ Vinyl~          0    0.435    -48.7      49.5 1     ns
```

Figure 6-12. TCE Indoor Air Concentrations Versus Flooring Type and ANOVA Results

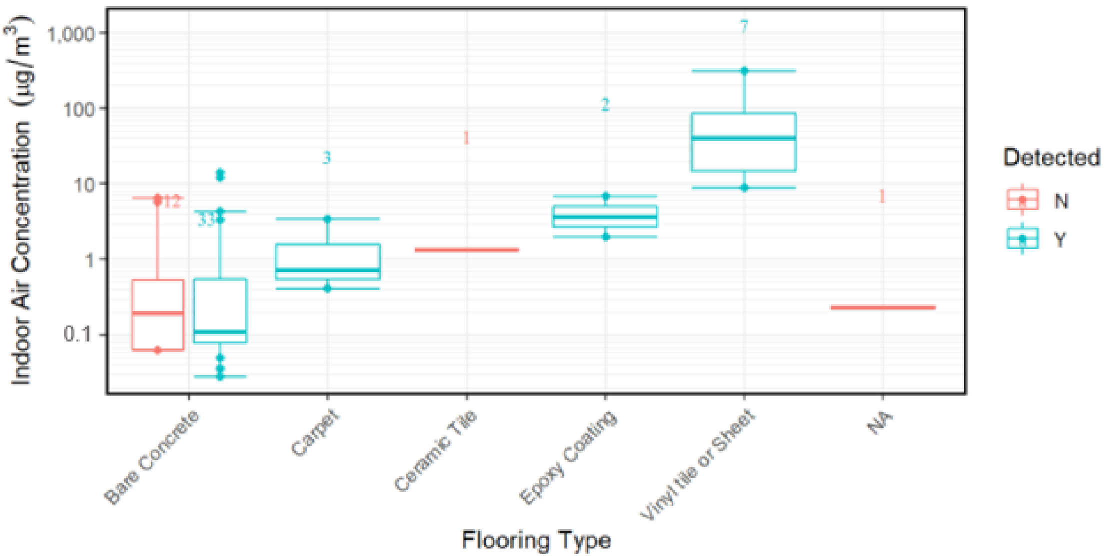
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates floor type is unknown (not available).




```
## ANOVA Table (type II tests)
##
##          Effect DFn DFd     F    p p<.05  ges
## 1 FLOORING_TYPE   3 102 1.424 0.24       0.04
## # A tibble: 6 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 FLOOR~ Bare ~ Carpet          0  -17.2      -48.5      14.1 0.479 ns
## 2 FLOOR~ Bare ~ Epoxy~          0  -16.5      -50.1      17.1 0.577 ns
## 3 FLOOR~ Bare ~ Vinyl~          0  -16.1      -56.8      24.7 0.733 ns
## 4 FLOOR~ Carpet Epoxy~          0    0.738    -43.6      45.1 1     ns
## 5 FLOOR~ Carpet Vinyl~          0    1.17     -48.8      51.2 1     ns
## 6 FLOOR~ Epoxy~ Vinyl~          0    0.435    -51.0      51.9 1     ns
```

Figure 6-13. TCE Indoor Air Concentrations Versus Flooring Type and ANOVA Results (Indoor Air Detects Only)
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. Indoor air detects ("Y") only. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates floor type is unknown (not available).

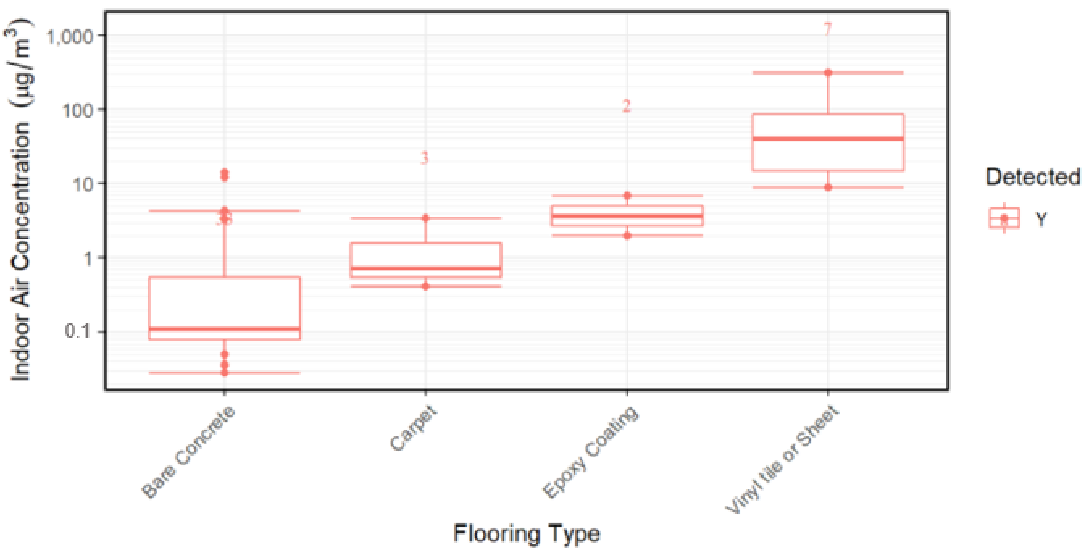



```
## ANOVA Table (type II tests)
##
##          Effect DFn DFd     F        p p<.05   ges
## 1 FLOORING_TYPE   4  53 7.418 8.04e-05     * 0.359
## # A tibble: 10 x 9
##    term  group1 group2 null.value estimate conf.low conf.high   p.adj
##  * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>   <dbl>
##  1 FLOO~ Bare ~ Carpet          0   0.134    -62.8       63.0 1.00e+0
##  2 FLOO~ Bare ~ Ceram~          0  -0.0233  -107.       107.  1.00e+0
##  3 FLOO~ Bare ~ Epoxy~          0   3.07     -73.2       79.3 1.00e+0
##  4 FLOO~ Bare ~ Vinyl~          0  82.1       39.3      125.  1.49e-5
##  5 FLOO~ Carpet Ceram~          0  -0.157   -122.       122.  1.00e+0
##  6 FLOO~ Carpet Epoxy~          0   2.94     -93.4       99.3 1.00e+0
##  7 FLOO~ Carpet Vinyl~          0  82.0        9.20     155.  1.99e-2
##  8 FLOO~ Ceram~ Epoxy~          0   3.09    -126.       132.  1.00e+0
##  9 FLOO~ Ceram~ Vinyl~          0  82.2      -30.6      195.  2.54e-1
## 10 FLOO~ Epoxy~ Vinyl~          0  79.1       -5.52     164.  7.75e-2
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-14. PCE Indoor Air Concentrations Versus Flooring Type and ANOVA Results

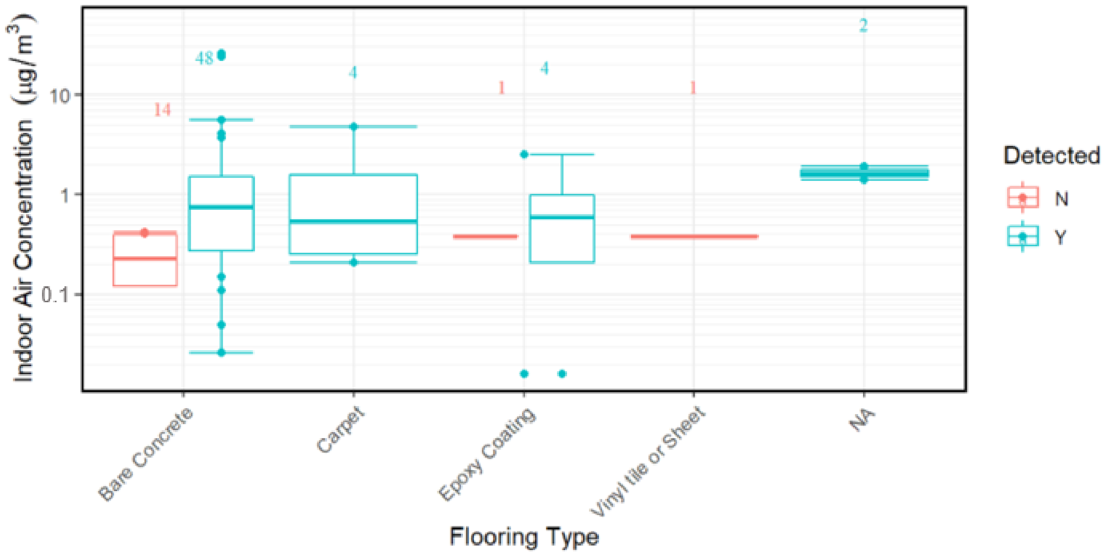
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates floor type is unknown (not available).



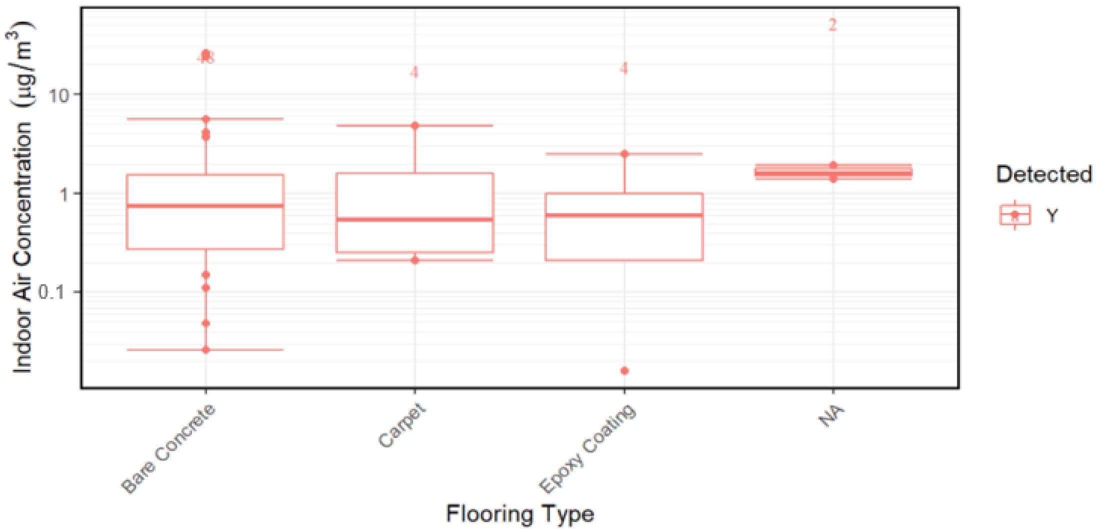

```
## ANOVA Table (type II tests)
##
##          Effect DFn DFd     F        p p<.05   ges
## 1 FLOORING_TYPE   3  41 7.341 0.000476     * 0.349
## # A tibble: 6 x 9
##   term  group1 group2 null.value estimate conf.low conf.high   p.adj
## * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>   <dbl>
## 1 FLOO~ Bare ~ Carpet          0    0.107    -68.5      68.7 1.00e+0
## 2 FLOO~ Bare ~ Epoxy~          0    3.04     -79.8      85.8 1.00e+0
## 3 FLOO~ Bare ~ Vinyl~          0   82.1       34.8     129.  1.97e-4
## 4 FLOO~ Carpet Epoxy~          0    2.94    -101.      107.  1.00e+0
## 5 FLOO~ Carpet Vinyl~          0   82.0        3.55    160.  3.75e-2
## 6 FLOO~ Epoxy~ Vinyl~          0   79.1      -12.1     170.  1.09e-1
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-15. PCE Indoor Air Concentrations Versus Flooring Type and ANOVA Results (Indoor Air Detects Only)
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. Indoor air detects ("Y") only. The number shown above the boxes indicates the number of indoor air data points.




```
## ANOVA Table (type II tests)
##
##          Effect DFn DFd     F     p p<.05   ges
## 1 FLOORING_TYPE   3  68 0.091 0.965       0.004
## # A tibble: 6 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 FLOOR~ Bare ~ Carpet          0  -0.0850    -5.84      5.67 1     ns
## 2 FLOOR~ Bare ~ Epoxy~          0  -0.857     -6.04      4.33 0.972 ns
## 3 FLOOR~ Bare ~ Vinyl~          0  -1.30     -12.5       9.94 0.99  ns
## 4 FLOOR~ Carpet Epoxy~          0  -0.772     -8.25      6.71 0.993 ns
## 5 FLOOR~ Carpet Vinyl~          0  -1.21     -13.7      11.2  0.994 ns
## 6 FLOOR~ Epoxy~ Vinyl~          0  -0.443    -12.7      11.8  1     ns
```

Figure 6-16. cis-1,2-DCE Indoor Air Concentrations Versus Flooring Type and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000 µg/m^3) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates floor type is unknown (not available).

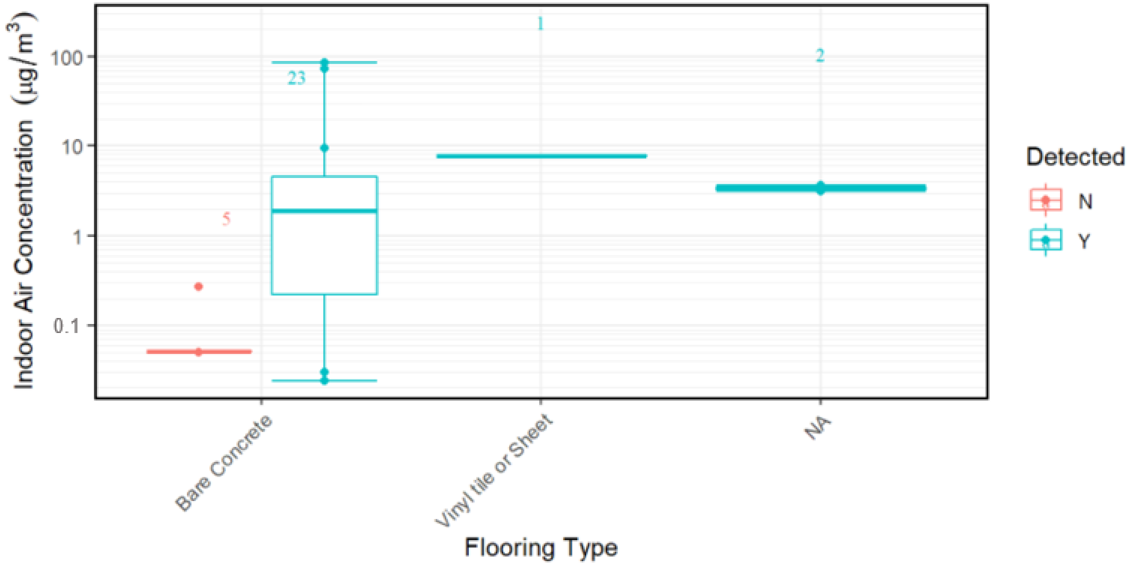



```
## ANOVA Table (type II tests)
##
##          Effect DFn DFd     F     p p<.05   ges
## 1 FLOORING_TYPE   2  53 0.126 0.882       0.005
## # A tibble: 3 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 FLOOR~ Bare ~ Carpet          0   -0.500    -6.42      5.42 0.977 ns
## 2 FLOOR~ Bare ~ Epoxy~          0   -1.16     -7.09      4.76 0.884 ns
## 3 FLOOR~ Carpet Epoxy~          0   -0.661    -8.71      7.39 0.979 ns
```

Figure 6-17. cis-1,2-DCE Indoor Air Concentrations Versus Flooring Type and ANOVA Results (Indoor Air Detects Only)

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000 µg/m³) screens applied. Indoor air detects ("Y") only. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates floor type is unknown (not available).

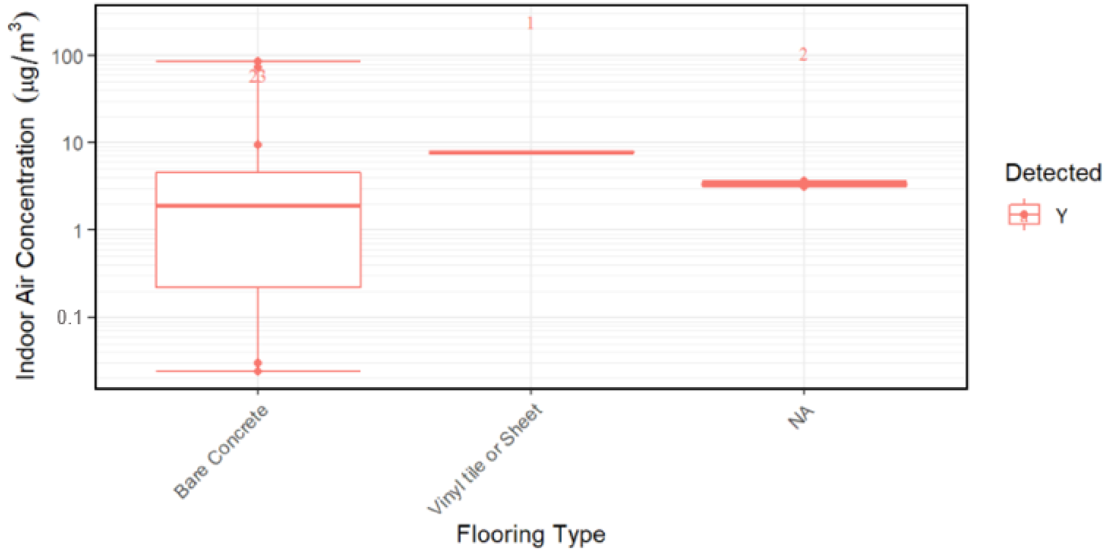



```
## ANOVA Table (type II tests)
##
##          Effect DFn DFd        F     p p<.05      ges
## 1 FLOORING_TYPE   1  27 5.09e-05 0.994       1.89e-06
## # A tibble: 1 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 FLOOR~ Bare ~ Vinyl~          0    0.147    -42.2      42.5 0.994 ns
```

Figure 6-18. 1,1,1-TCA Indoor Air Concentrations Versus Flooring Type and ANOVA Results

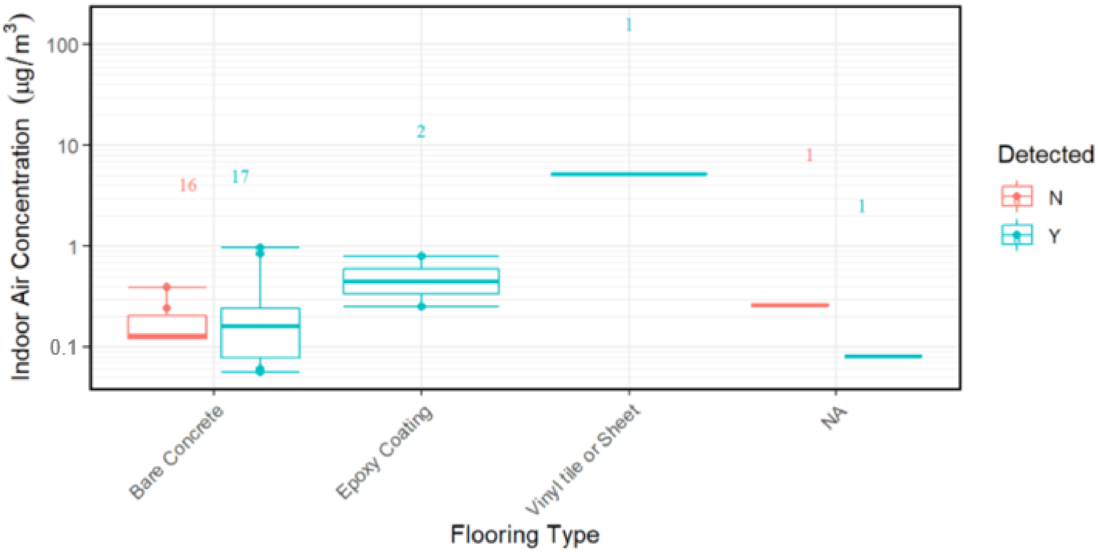
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates floor type is unknown (not available).




```
## ANOVA Table (type II tests)
##
##          Effect DFn DFd     F     p p<.05      ges
## 1 FLOORING_TYPE   1  22 0.004 0.949       0.000193
## # A tibble: 1 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 FLOOR~ Bare ~ Vinyl~          0    -1.47    -48.3      45.4 0.949 ns
```

Figure 6-19. 1,1,1-TCA Indoor Air Concentrations Versus Flooring Type and ANOVA Results (Indoor Air Detects Only)
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. Indoor air detects ("Y") only. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates floor type is unknown (not available).

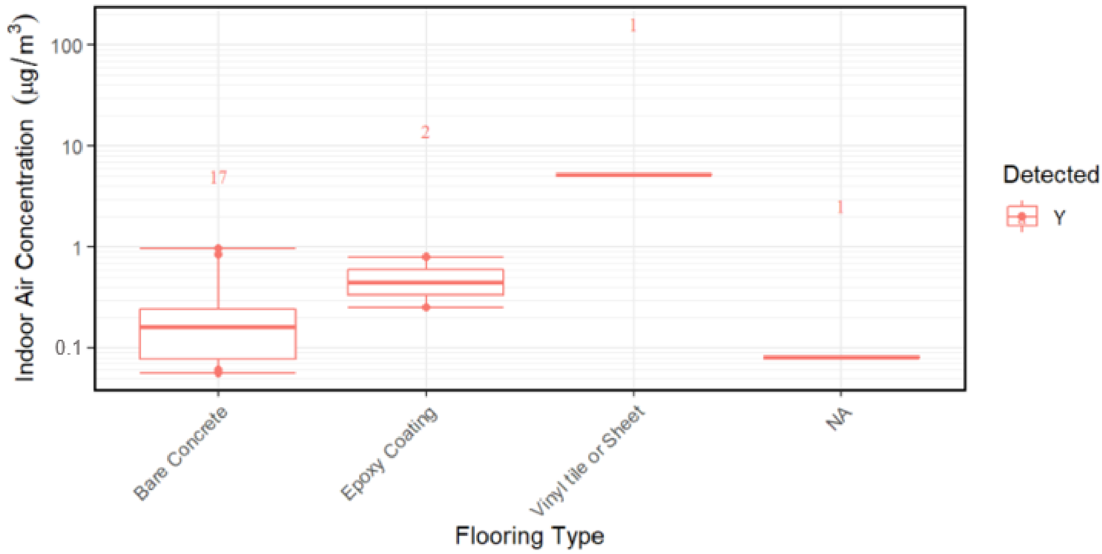



```
## ANOVA Table (type II tests)
##
##          Effect DFn DFd       F        p p<.05   ges
## 1 FLOORING_TYPE   2  33 245.629 1.52e-20     * 0.937
## # A tibble: 3 x 9
##   term  group1 group2 null.value estimate conf.low conf.high    p.adj
## * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>    <dbl>
## 1 FLOO~ Bare ~ Epoxy~          0    0.300  -0.0953     0.696 1.66e- 1
## 2 FLOO~ Bare ~ Vinyl~          0    4.98    4.42       5.53  5.86e-14
## 3 FLOO~ Epoxy~ Vinyl~          0    4.67    4.01       5.34  5.86e-14
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-20. 1,1-DCA Indoor Air Concentrations Versus Flooring Type and ANOVA Results

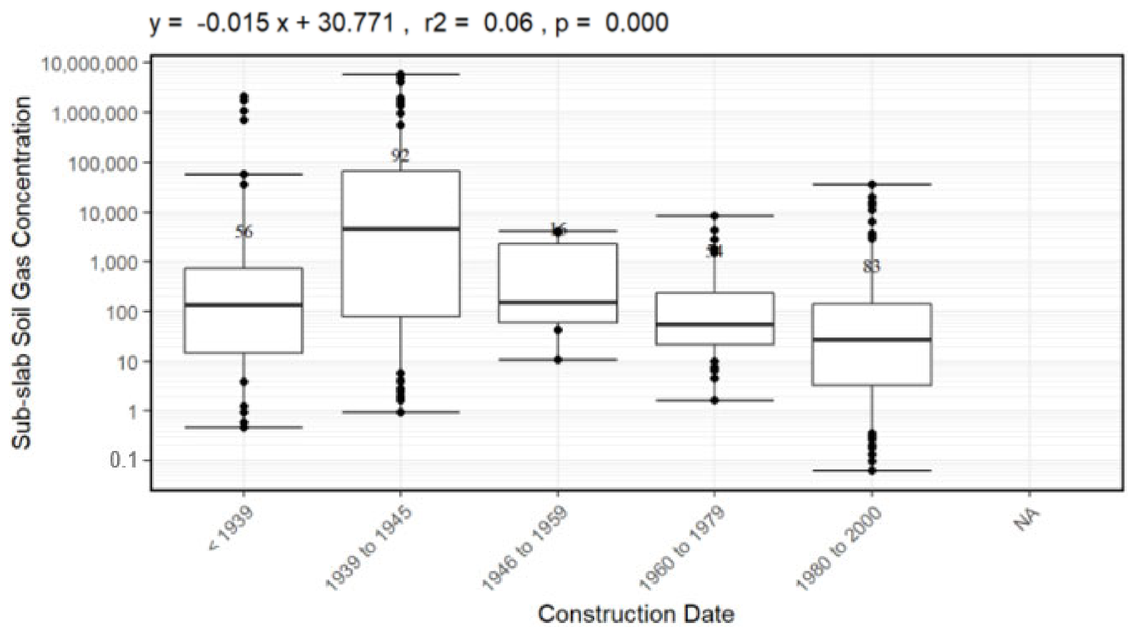
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000 µg/m³) screens applied. "Y" and "N" refer to indoor air detects only and non-detects (taken at the detection limit), respectively. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates floor type is unknown (not available).



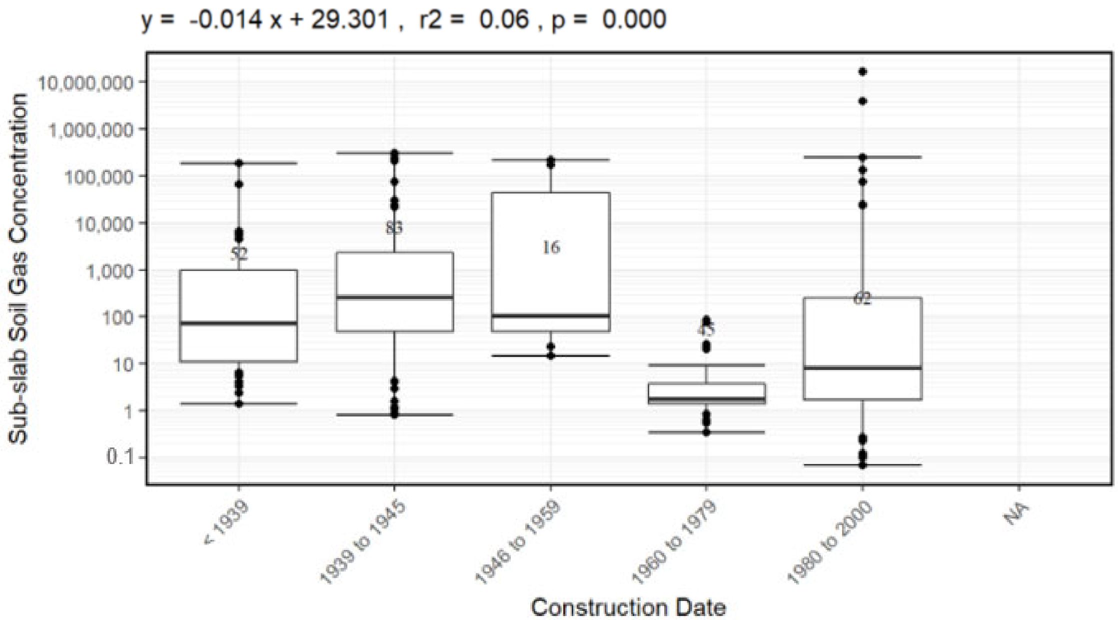

```
## ANOVA Table (type II tests)
##
##          Effect DFn DFd       F        p p<.05   ges
## 1 FLOORING_TYPE   2  17 134.821 3.73e-11     * 0.941
## # A tibble: 3 x 9
##   term  group1 group2 null.value estimate conf.low conf.high    p.adj
## * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>    <dbl>
## 1 FLOO~ Bare ~ Epoxy~          0    0.249   -0.310     0.808 5.02e- 1
## 2 FLOO~ Bare ~ Vinyl~          0    4.92     4.15      5.69  2.07e-11
## 3 FLOO~ Epoxy~ Vinyl~          0    4.68     3.76      5.59  7.63e-10
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-21. 1,1-DCA Indoor Air Concentrations Versus Flooring Type and ANOVA Results (Indoor Air Detects Only)
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000 µg/m³) screens applied. Indoor air detects ("Y") only. The number shown above the boxes indicates the number of indoor air data points. "NA" indicates floor type is unknown (not available).




```
## ANOVA Table (type II tests)
##
##               Effect DFn DFd      F        p p<.05   ges
## 1 CONSTRUCTION_DATE_R   4 296 22.477 3.17e-16     * 0.233
## # A tibble: 10 x 9
##    term  group1 group2 null.value estimate conf.low conf.high    p.adj
##  * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>    <dbl>
##  1 CONS~ < 1939 1939 ~          0    2.83      1.25     4.41  1.44e- 5
##  2 CONS~ < 1939 1946 ~          0    0.383    -2.26     3.03  9.95e- 1
##  3 CONS~ < 1939 1960 ~          0   -0.767    -2.54     1.01  7.61e- 1
##  4 CONS~ < 1939 1980 ~          0   -1.85     -3.46    -0.235 1.56e- 2
##  5 CONS~ 1939 ~ 1946 ~          0   -2.45     -4.97     0.0781 6.26e- 2
##  6 CONS~ 1939 ~ 1960 ~          0   -3.60     -5.19    -2.00  2.14e- 8
##  7 CONS~ 1939 ~ 1980 ~          0   -4.68     -6.09    -3.27  8.69e-13
##  8 CONS~ 1946 ~ 1960 ~          0   -1.15     -3.80     1.50  7.57e- 1
##  9 CONS~ 1946 ~ 1980 ~          0   -2.23     -4.78     0.315 1.17e- 1
## 10 CONS~ 1960 ~ 1980 ~          0   -1.08     -2.71     0.549 3.64e- 1
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-22. TCE Subslab Soil Gas Concentration Versus Construction Date and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline and atypical preferential pathway screens applied. The number shown above the boxes indicates the number of subslab soil gas data points. In the equation, x represents the year of construction and y represents the log of the subslab soil gas concentration.

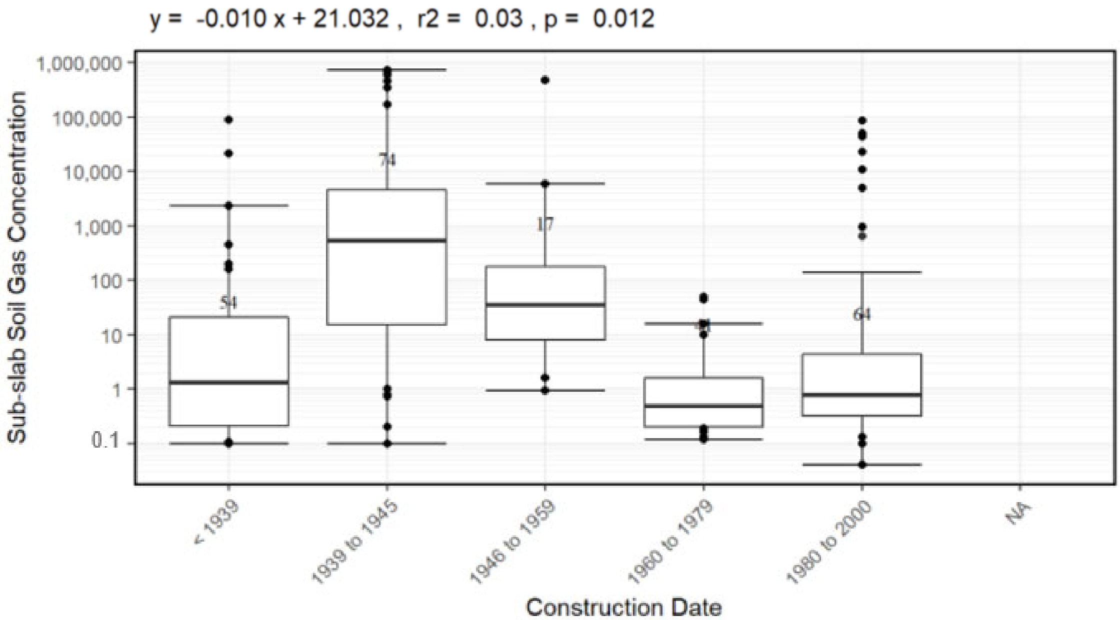



```
## ANOVA Table (type II tests)
##
##                Effect DFn DFd      F        p p<.05   ges
## 1 CONSTRUCTION_DATE_R   4 253 20.775 8.04e-15     * 0.247
## # A tibble: 10 x 9
##    term  group1 group2 null.value estimate conf.low conf.high    p.adj
##  * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>    <dbl>
##  1 CONS~ < 1939 1939 ~          0    1.16    -0.411     2.73  2.56e- 1
##  2 CONS~ < 1939 1946 ~          0    1.93    -0.602     4.47  2.25e- 1
##  3 CONS~ < 1939 1960 ~          0   -3.80    -5.61     -2.00  2.09e- 7
##  4 CONS~ < 1939 1980 ~          0   -1.29    -2.96      0.374 2.10e- 1
##  5 CONS~ 1939 ~ 1946 ~          0    0.777   -1.64      3.20  9.04e- 1
##  6 CONS~ 1939 ~ 1960 ~          0   -4.96    -6.60     -3.32  8.14e-14
##  7 CONS~ 1939 ~ 1980 ~          0   -2.45    -3.94     -0.962 9.14e- 5
##  8 CONS~ 1946 ~ 1960 ~          0   -5.74    -8.32     -3.16  3.79e- 8
##  9 CONS~ 1946 ~ 1980 ~          0   -3.23    -5.71     -0.740 3.94e- 3
## 10 CONS~ 1960 ~ 1980 ~          0    2.51     0.774     4.25  8.79e- 4
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-23. PCE Subslab Soil Gas Concentration Versus Construction Date and ANOVA Results

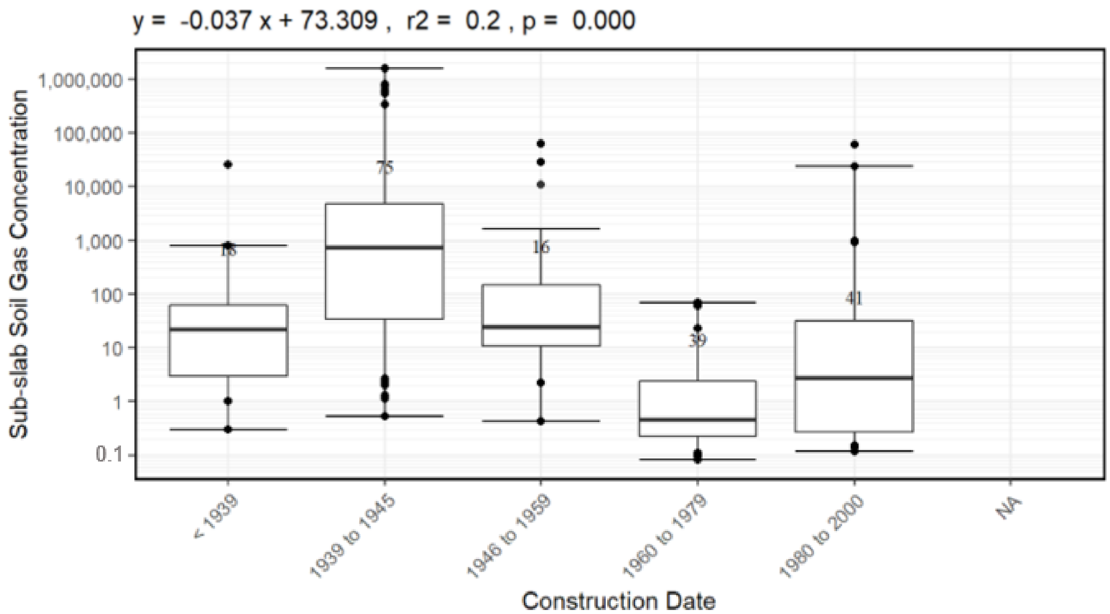
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline and atypical preferential pathway screens applied. The number shown above the boxes indicates the number of subslab soil gas data points. In the equation, x represents the year of construction and y represents the log of the subslab soil gas concentration.



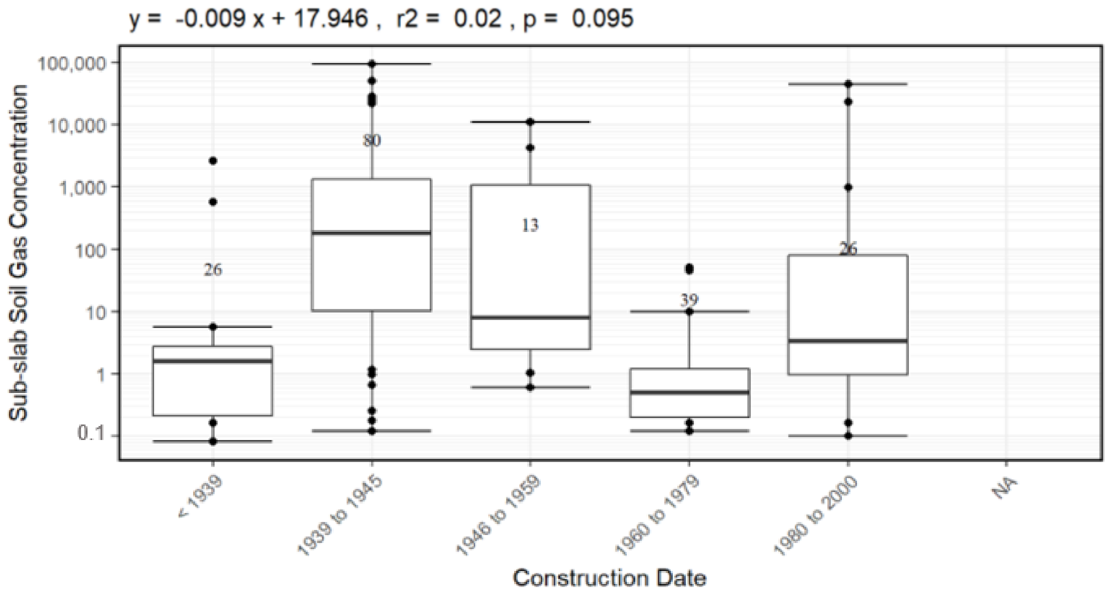

```
## ANOVA Table (type II tests)
##
##                Effect DFn DFd      F       p p<.05   ges
## 1 CONSTRUCTION_DATE_R   4 245 28.904 1.1e-19     * 0.321
## # A tibble: 10 x 9
##    term  group1 group2 null.value estimate conf.low conf.high    p.adj
##  * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>    <dbl>
##  1 CONS~ < 1939 1939 ~          0    4.69     2.97      6.41  1.14e-11
##  2 CONS~ < 1939 1946 ~          0    3.02     0.354     5.69  1.76e- 2
##  3 CONS~ < 1939 1960 ~          0   -1.36    -3.35      0.625 3.28e- 1
##  4 CONS~ < 1939 1980 ~          0   -0.110   -1.88      1.66  1.00e+ 0
##  5 CONS~ 1939 ~ 1946 ~          0   -1.67    -4.25      0.914 3.90e- 1
##  6 CONS~ 1939 ~ 1960 ~          0   -6.05    -7.92     -4.19  4.64e-14
##  7 CONS~ 1939 ~ 1980 ~          0   -4.80    -6.44     -3.16  3.99e-13
##  8 CONS~ 1946 ~ 1960 ~          0   -4.39    -7.16     -1.62  1.90e- 4
##  9 CONS~ 1946 ~ 1980 ~          0   -3.13    -5.75     -0.515 1.01e- 2
## 10 CONS~ 1960 ~ 1980 ~          0    1.25    -0.667     3.17  3.79e- 1
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-24. cis-1,2-DCE Subslab Soil Gas Concentration Versus Construction Date and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline and atypical preferential pathway screens applied. The number shown above the boxes indicates the number of subslab soil gas data points. In the equation, x represents the year of construction and y represents the log of the subslab soil gas concentration.



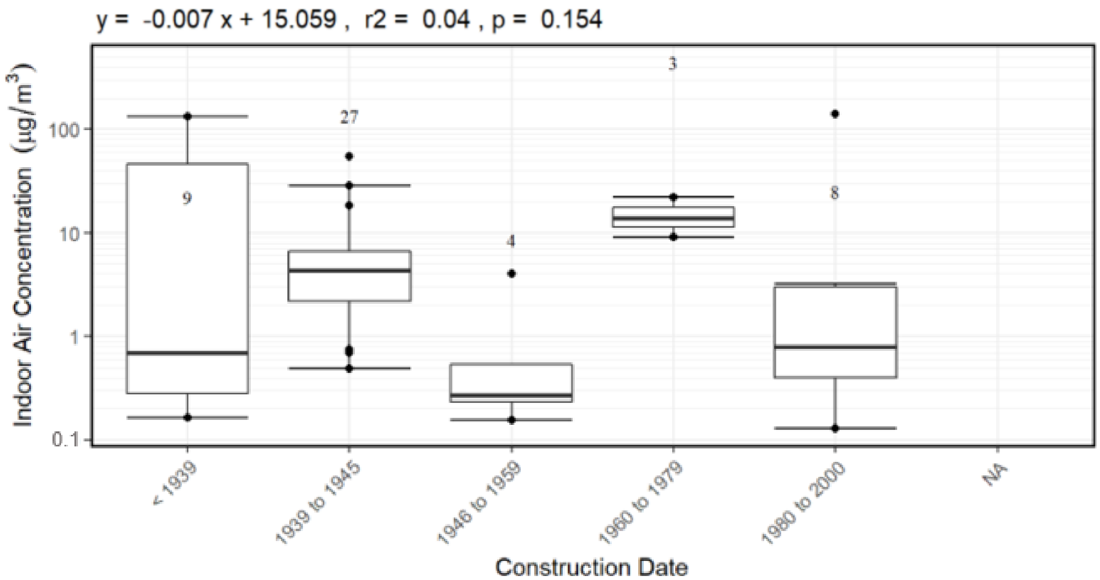

```
## ANOVA Table (type II tests)
##
##               Effect DFn DFd      F        p p<.05   ges
## 1 CONSTRUCTION_DATE_R   4 184 31.265 7.27e-20     * 0.405
## # A tibble: 10 x 9
##    term  group1 group2 null.value estimate conf.low conf.high    p.adj
##  * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>    <dbl>
##  1 CONS~ < 1939 1939 ~          0     3.41    1.09      5.74  7.43e- 4
##  2 CONS~ < 1939 1946 ~          0     1.20   -1.84      4.25  8.13e- 1
##  3 CONS~ < 1939 1960 ~          0    -3.13   -5.66     -0.601 7.07e- 3
##  4 CONS~ < 1939 1980 ~          0    -1.31   -3.82      1.20  6.04e- 1
##  5 CONS~ 1939 ~ 1946 ~          0    -2.21   -4.65      0.233 9.68e- 2
##  6 CONS~ 1939 ~ 1960 ~          0    -6.54   -8.29     -4.79  5.41e-14
##  7 CONS~ 1939 ~ 1980 ~          0    -4.72   -6.44     -3.00  1.95e-11
##  8 CONS~ 1946 ~ 1960 ~          0    -4.33   -6.96     -1.70  1.02e- 4
##  9 CONS~ 1946 ~ 1980 ~          0    -2.51   -5.13      0.102 6.62e- 2
## 10 CONS~ 1960 ~ 1980 ~          0     1.82   -0.164     3.80  8.92e- 2
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-25. 1,1,1-TCA Subslab Soil Gas Concentration Versus Construction Date and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline and atypical preferential pathway screens applied. The number shown above the boxes indicates the number of subslab soil gas data points. In the equation, x represents the year of construction and y represents the log of the subslab soil gas concentration.



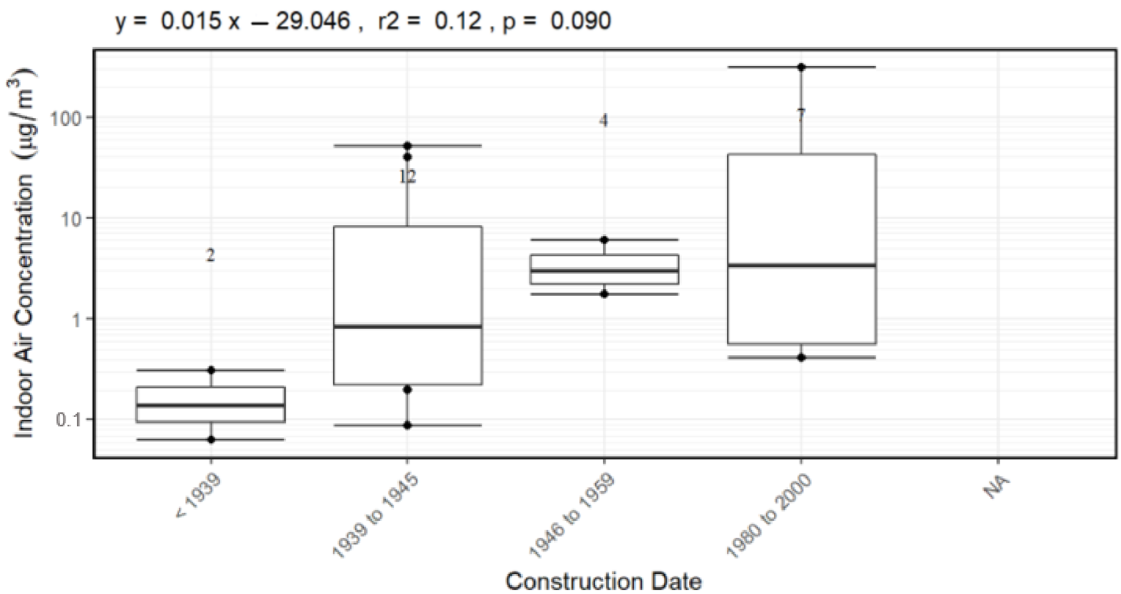

```
## ANOVA Table (type II tests)
##
##                Effect DFn DFd     F        p p<.05   ges
## 1 CONSTRUCTION_DATE_R   4 179 24.56 3.23e-16     * 0.354
## # A tibble: 10 x 9
##    term  group1 group2 null.value estimate conf.low conf.high   p.adj
##  * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>   <dbl>
##  1 CONS~ < 1939 1939 ~          0    4.36     2.53      6.20  5.82e-9
##  2 CONS~ < 1939 1946 ~          0    3.09     0.329     5.85  1.98e-2
##  3 CONS~ < 1939 1960 ~          0   -0.767   -2.83      1.29  8.43e-1
##  4 CONS~ < 1939 1980 ~          0    1.99    -0.268     4.24  1.13e-1
##  5 CONS~ 1939 ~ 1946 ~          0   -1.27    -3.70      1.16  6.01e-1
##  6 CONS~ 1939 ~ 1960 ~          0   -5.13    -6.72     -3.54  0.
##  7 CONS~ 1939 ~ 1980 ~          0   -2.38    -4.21     -0.541 4.16e-3
##  8 CONS~ 1946 ~ 1960 ~          0   -3.86    -6.46     -1.25  6.33e-4
##  9 CONS~ 1946 ~ 1980 ~          0   -1.10    -3.87      1.66  8.06e-1
## 10 CONS~ 1960 ~ 1980 ~          0    2.75     0.696     4.81  2.75e-3
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-26. 1,1-DCA Subslab Soil Gas Concentration Versus Construction Date and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline and atypical preferential pathway screens applied. The number shown above the boxes indicates the number of subslab soil gas data points. In the equation, x represents the year of construction and y represents the log of the subslab soil gas concentration.



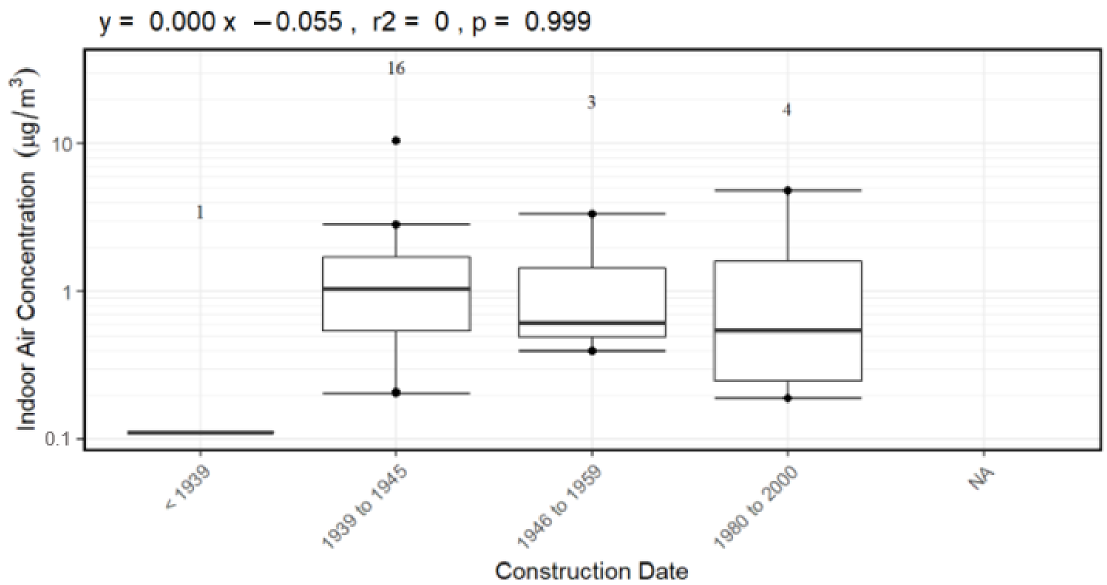

```
## ANOVA Table (type II tests)
##
##                Effect DFn DFd    F    p p<.05   ges
## 1 CONSTRUCTION_DATE_R   4  46 2.33 0.07       0.168
## # A tibble: 10 x 9
##    term  group1 group2 null.value estimate conf.low conf.high  p.adj
##  * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>  <dbl>
##  1 CONS~ < 1939 1939 ~          0    0.245   -1.64      2.13  0.996
##  2 CONS~ < 1939 1946 ~          0   -1.89    -4.84      1.06  0.375
##  3 CONS~ < 1939 1960 ~          0    1.52    -1.75      4.79  0.678
##  4 CONS~ < 1939 1980 ~          0   -0.800   -3.18      1.58  0.874
##  5 CONS~ 1939 ~ 1946 ~          0   -2.13    -4.76      0.494 0.162
##  6 CONS~ 1939 ~ 1960 ~          0    1.28    -1.71      4.26  0.742
##  7 CONS~ 1939 ~ 1980 ~          0   -1.04    -3.02      0.930 0.566
##  8 CONS~ 1946 ~ 1960 ~          0    3.41    -0.333     7.16  0.0898
##  9 CONS~ 1946 ~ 1980 ~          0    1.09    -1.92      4.09  0.841
## 10 CONS~ 1960 ~ 1980 ~          0   -2.32    -5.65      0.997 0.288
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-27. TCE Indoor Air Concentration Versus Construction Date and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. The number shown above the boxes indicates the number of indoor air data points. In the equation, x represents the year of construction and y represents the log of the indoor air concentration.




```
## ANOVA Table (type II tests)
##
##                Effect DFn DFd     F     p p<.05   ges
## 1 CONSTRUCTION_DATE_R   3  21 1.695 0.199       0.195
## # A tibble: 6 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 CONST~ < 1939 1939 ~          0    2.30     -2.39      6.98 0.533 ns
## 2 CONST~ < 1939 1946 ~          0    3.11     -2.20      8.42 0.384 ns
## 3 CONST~ < 1939 1980 ~          0    3.74     -1.18      8.66 0.18  ns
## 4 CONST~ 1939 ~ 1946 ~          0    0.813    -2.73      4.36 0.918 ns
## 5 CONST~ 1939 ~ 1980 ~          0    1.44     -1.48      4.36 0.528 ns
## 6 CONST~ 1946 ~ 1980 ~          0    0.626    -3.22      4.47 0.968 ns
```

Figure 6-28. PCE Indoor Air Concentration Versus Construction Date and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. The number shown above the boxes indicates the number of indoor air data points. In the equation, x represents the year of construction and y represents the log of the indoor air concentration.

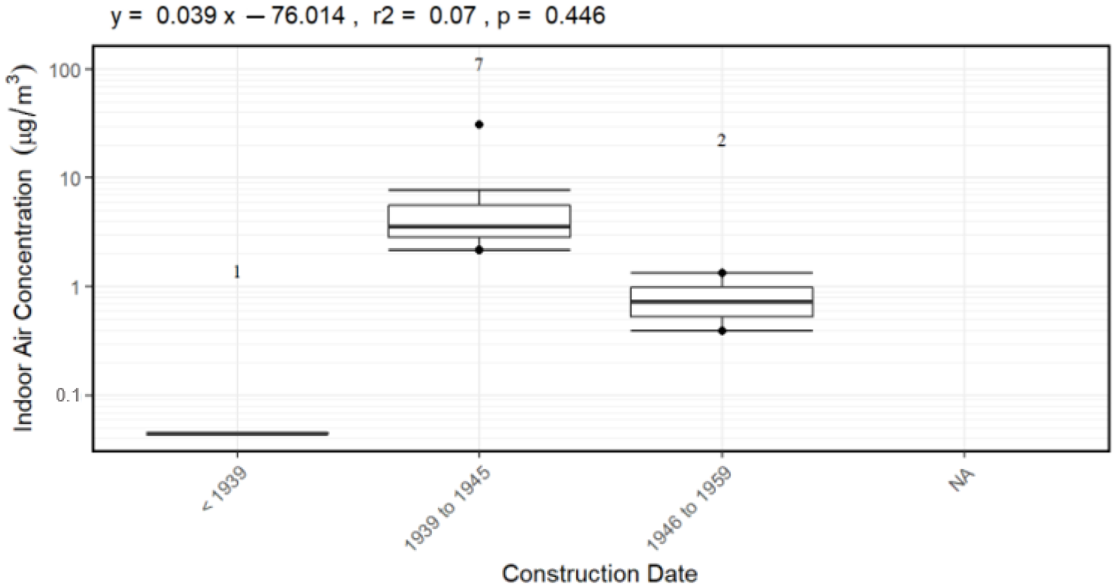



```
## ANOVA Table (type II tests)
##
##                Effect DFn DFd     F     p p<.05   ges
## 1 CONSTRUCTION_DATE_R   3  20 1.257 0.316       0.159
## # A tibble: 6 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 CONST~ < 1939 1939 ~          0   2.19      -1.02      5.40 0.255 ns
## 2 CONST~ < 1939 1946 ~          0   2.12      -1.47      5.72 0.373 ns
## 3 CONST~ < 1939 1980 ~          0   1.87      -1.61      5.35 0.455 ns
## 4 CONST~ 1939 ~ 1946 ~          0  -0.0667    -2.03      1.89 1     ns
## 5 CONST~ 1939 ~ 1980 ~          0  -0.324     -2.06      1.42 0.953 ns
## 6 CONST~ 1946 ~ 1980 ~          0  -0.257     -2.63      2.12 0.99  ns
```

Figure 6-29. cis-1,2-DCE Indoor Air Concentration Versus Construction Date and ANOVA Results

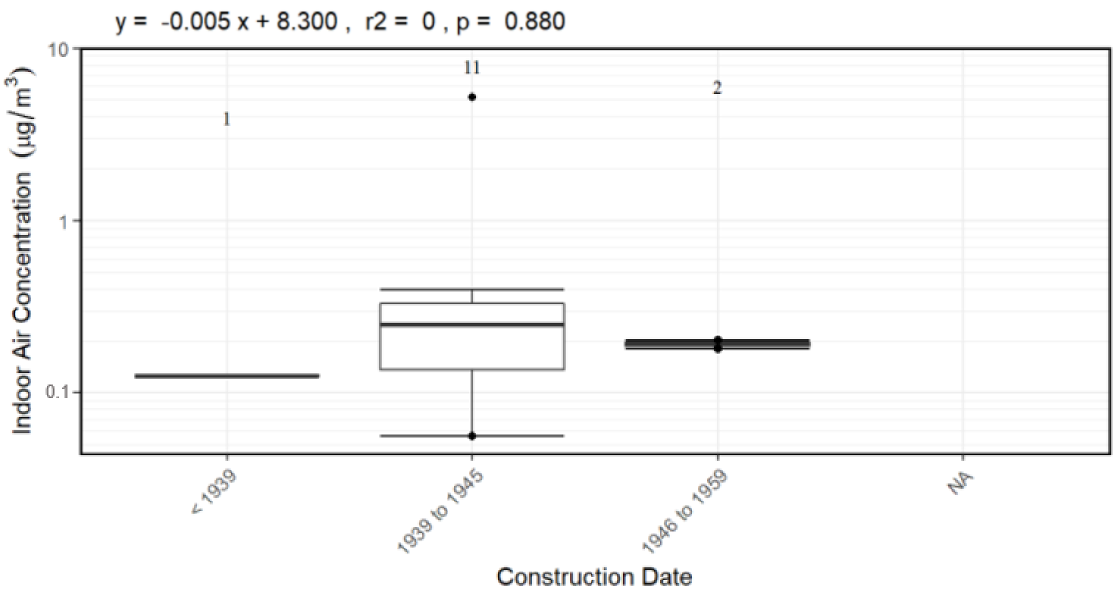
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000 µg/m³) screens applied. The number shown above the boxes indicates the number of indoor air data points. In the equation, x represents the year of construction and y represents the log of the indoor air concentration.



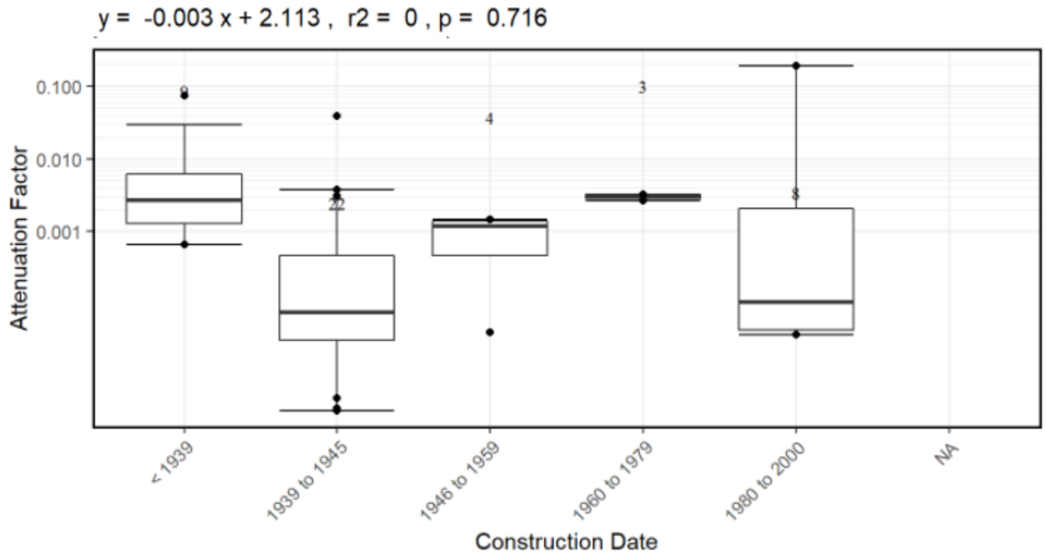

```
## ANOVA Table (type II tests)
##
##               Effect DFn DFd      F     p p<.05   ges
## 1 CONSTRUCTION_DATE_R   2   7 13.262 0.004     * 0.791
## # A tibble: 3 x 9
##   term  group1 group2 null.value estimate conf.low conf.high   p.adj
## * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>   <dbl>
## 1 CONS~ < 1939 1939 ~          0     4.68     1.82      7.54 0.00475
## 2 CONS~ < 1939 1946 ~          0     2.79   -0.492      6.06  0.0917
## 3 CONS~ 1939 ~ 1946 ~          0    -1.89    -4.04     0.252  0.0804
## # ... with 1 more variable: p.adj.signif <chr>
```

Figure 6-30. 1,1,1-TCA Indoor Air Concentration Versus Construction Date and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. The number shown above the boxes indicates the number of indoor air data points. In the equation, x represents the year of construction and y represents the log of the indoor air concentration.



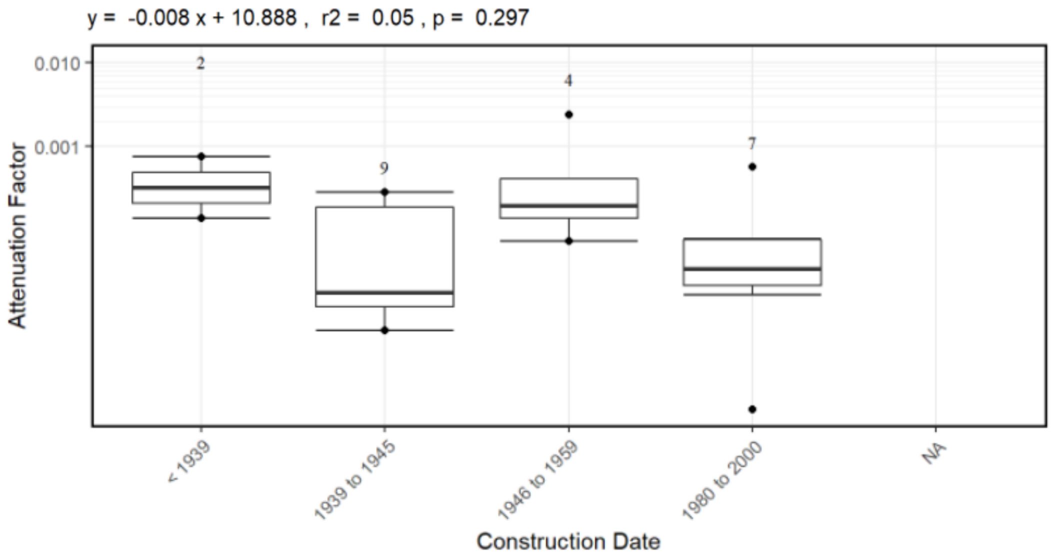

```
## ANOVA Table (type II tests)
##
##               Effect DFn DFd     F     p p<.05   ges
## 1 CONSTRUCTION_DATE_R   2  11 0.193 0.827       0.034
## # A tibble: 3 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 CONST~ < 1939 1939 ~          0    0.694    -2.58      3.97 0.837 ns
## 2 CONST~ < 1939 1946 ~          0    0.424    -3.42      4.26 0.952 ns
## 3 CONST~ 1939 ~ 1946 ~          0   -0.271    -2.68      2.14 0.951 ns
```

Figure 6-31. 1,1-DCA Indoor Air Concentration Versus Construction Date and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000 µg/m³) screens applied. The number shown above the boxes indicates the number of indoor air data points. In the equation, x represents the year of construction and y represents the log of the indoor air concentration.



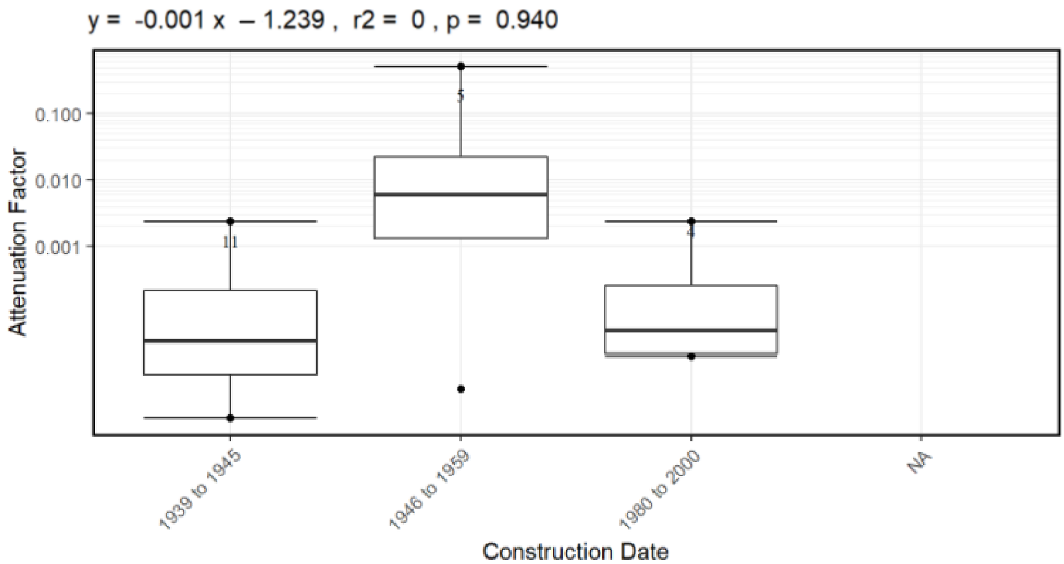

```
## ANOVA Table (type II tests)
##
##               Effect DFn DFd     F     p p<.05  ges
## 1 CONSTRUCTION_DATE_R   4  41 4.833 0.003     * 0.32
## # A tibble: 10 x 9
##    term  group1 group2 null.value estimate conf.low conf.high   p.adj
##  * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>   <dbl>
##  1 CONS~ < 1939 1939 ~          0   -3.66    -6.23     -1.09  0.00193
##  2 CONS~ < 1939 1946 ~          0   -2.04    -5.94      1.87  0.577
##  3 CONS~ < 1939 1960 ~          0   -0.314   -4.65      4.02  1
##  4 CONS~ < 1939 1980 ~          0   -2.18    -5.34      0.980 0.299
##  5 CONS~ 1939 ~ 1946 ~          0    1.62    -1.91      5.16  0.687
##  6 CONS~ 1939 ~ 1960 ~          0    3.34    -0.657     7.35  0.14
##  7 CONS~ 1939 ~ 1980 ~          0    1.48    -1.21      4.16  0.524
##  8 CONS~ 1946 ~ 1960 ~          0    1.72    -3.24      6.69  0.859
##  9 CONS~ 1946 ~ 1980 ~          0   -0.144   -4.13      3.84  1
## 10 CONS~ 1960 ~ 1980 ~          0   -1.87    -6.27      2.54  0.746
## # ... with 1 more variable: p.adj.signif <chr>
## [1] "PCE"
```

Figure 6-32. TCE AF Versus Construction Date and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. The number shown above the boxes indicates the number of AF data points. In the equation, x represents the year of construction and y represents the log of the AF.




```
## ANOVA Table (type II tests)
##
##               Effect DFn DFd     F     p p<.05   ges
## 1 CONSTRUCTION_DATE_R   3  18 2.388 0.103       0.285
## # A tibble: 6 x 9
##   term   group1 group2 null.value estimate conf.low conf.high p.adj p.adj.signif
## * <chr>  <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl> <dbl> <chr>
## 1 CONST~ < 1939 1939 ~          0   -2.16    -5.85      1.53  0.376 ns
## 2 CONST~ < 1939 1946 ~          0   -0.114   -4.20      3.98  1     ns
## 3 CONST~ < 1939 1980 ~          0   -2.28    -6.07      1.50  0.35  ns
## 4 CONST~ 1939 ~ 1946 ~          0    2.04    -0.794     4.88  0.212 ns
## 5 CONST~ 1939 ~ 1980 ~          0   -0.125   -2.51      2.26  0.999 ns
## 6 CONST~ 1946 ~ 1980 ~          0   -2.17    -5.13      0.791 0.2   ns
## [1] "cis-12-DCE"
```

Figure 6-33. PCE AF Versus Construction Date and ANOVA Results
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings
Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. The number shown above the boxes indicates the number of AF data points. In the equation, x represents the year of construction and y represents the log of the AF.

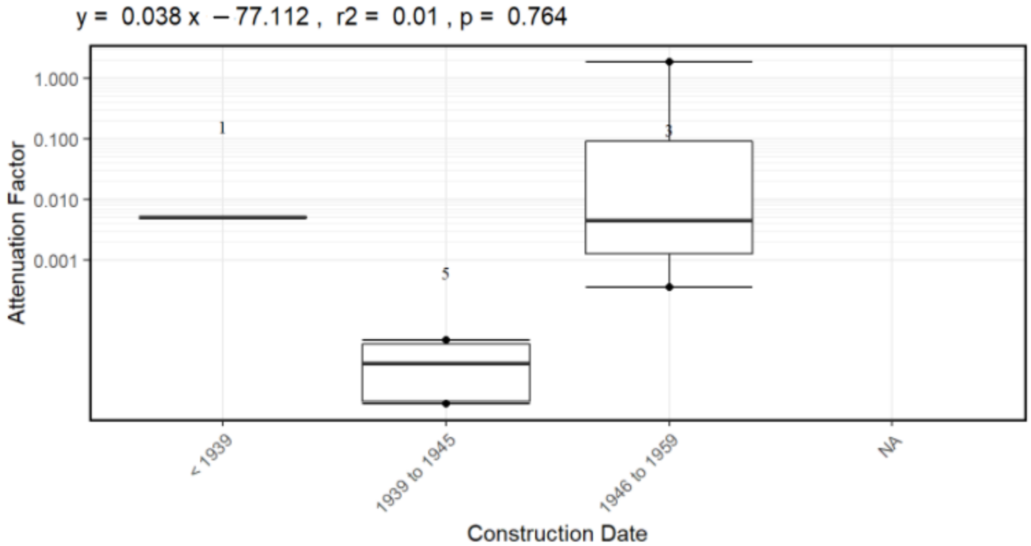



```
## ANOVA Table (type II tests)
##
##               Effect DFn DFd     F     p p<.05   ges
## 1 CONSTRUCTION_DATE_R   2  17 4.101 0.035     * 0.325
## # A tibble: 3 x 9
##   term  group1 group2 null.value estimate conf.low conf.high  p.adj p.adj.signif
## * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>  <dbl> <chr>
## 1 CONS~ 1939 ~ 1946 ~          0    4.18     0.399      7.97 0.0292 *
## 2 CONS~ 1939 ~ 1980 ~          0    0.692   -3.41       4.79 0.902  ns
## 3 CONS~ 1946 ~ 1980 ~          0   -3.49    -8.20       1.22 0.168  ns
## [1] "cis-12-DCE"
```

Figure 6-34. cis-1,2-DCE AF Versus Construction Date and ANOVA Results

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000 µg/m³) screens applied. The number shown above the boxes indicates the number of AF data points. In the equation, x represents the year of construction and y represents the log of the AF.

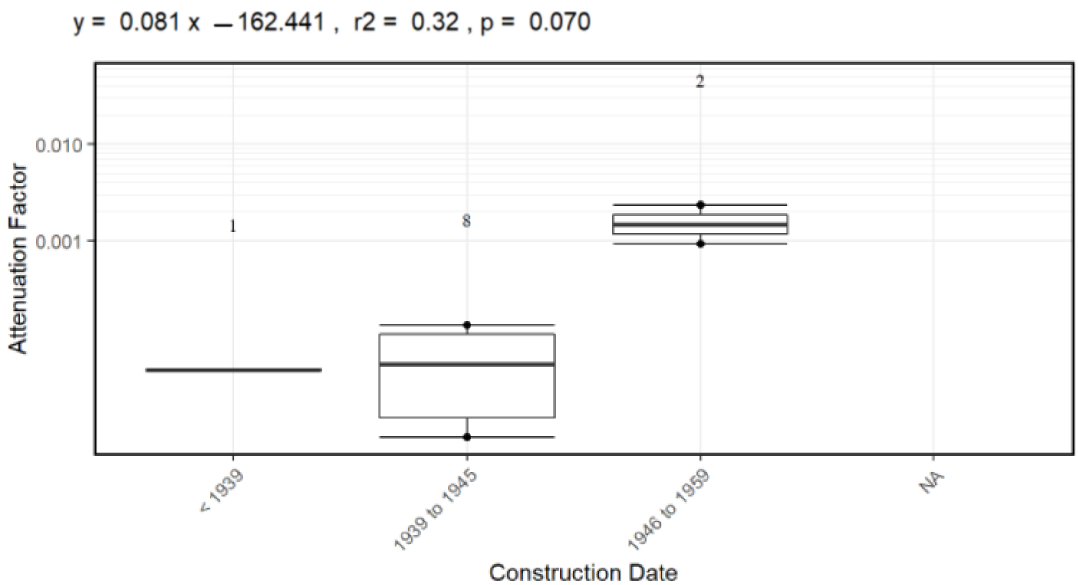



```
## ANOVA Table (type II tests)
##
##                Effect DFn DFd     F    p p<.05   ges
## 1 CONSTRUCTION_DATE_R   2   6 6.661 0.03     * 0.689
## # A tibble: 3 x 9
##   term  group1 group2 null.value estimate conf.low conf.high  p.adj p.adj.signif
## * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>  <dbl> <chr>
## 1 CONS~ < 1939 1939 ~          0    -5.84   -15.0       3.28  0.202  ns
## 2 CONS~ < 1939 1946 ~          0     1.04    -8.58     10.7   0.942  ns
## 3 CONS~ 1939 ~ 1946 ~          0     6.88    0.796     13.0   0.0308 *
## [1] "11-DCA"
```

Figure 6-35. 1,1,1-TCA AF Versus Construction Date and ANOVA Results

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000X background) screens applied. The number shown above the boxes indicates the number of AF data points. In the equation, x represents the year of construction and y represents the log of the AF.




```
## ANOVA Table (type II tests)
##
##               Effect DFn DFd     F     p p<.05   ges
## 1 CONSTRUCTION_DATE_R   2   8 9.473 0.008     * 0.703
## # A tibble: 3 x 9
##   term  group1 group2 null.value estimate conf.low conf.high   p.adj
## * <chr> <chr>  <chr>       <dbl>    <dbl>    <dbl>     <dbl>   <dbl>
## 1 CONS~ < 1939 1939 ~          0   -0.124   -3.30       3.05 0.993
## 2 CONS~ < 1939 1946 ~          0    3.45    -0.213      7.12 0.0639
## 3 CONS~ 1939 ~ 1946 ~          0    3.58     1.21       5.95 0.00637
## # ... with 1 more variable: p.adj.signif <chr>
## [1] "11-DCA"
```

Figure 6-36. 1,1-DCA AF Versus Construction Date and ANOVA Results

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Baseline, atypical preferential pathway, and source strength (1,000 µg/m³) screens applied. The number shown above the boxes indicates the number of AF data points. In the equation, x represents the year of construction and y represents the log of the AF.

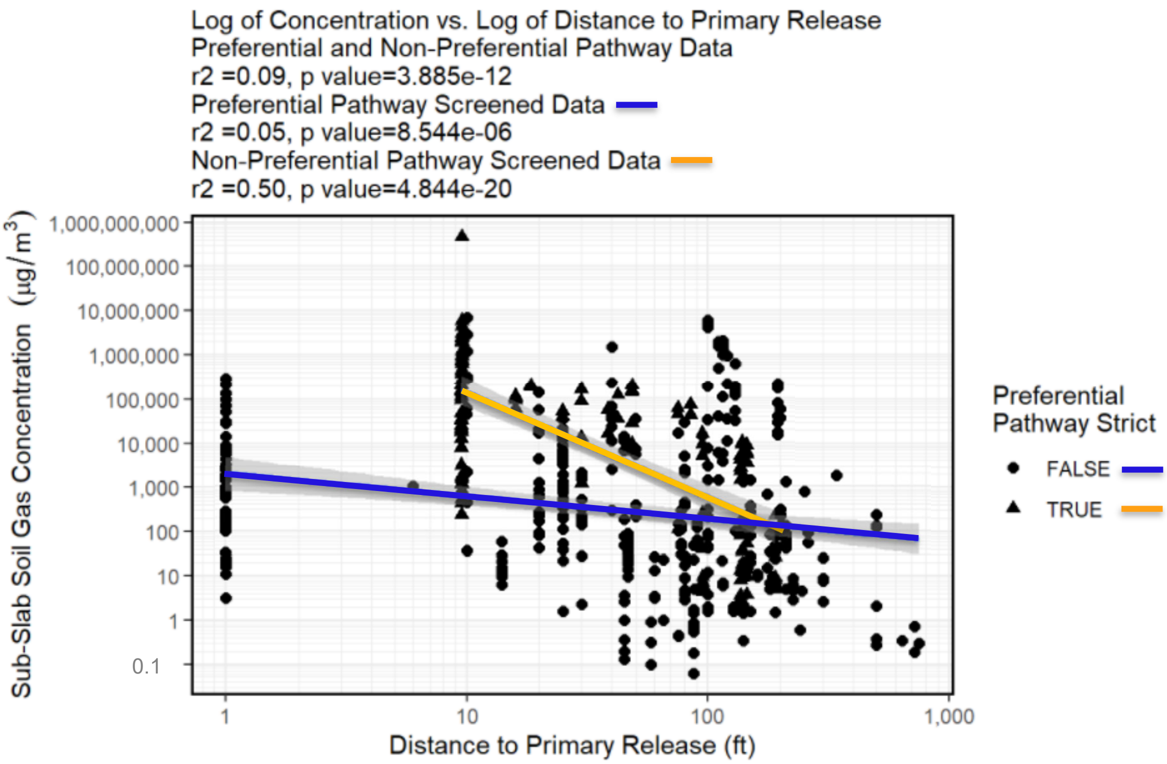


Figure 7-1. TCE Subslab Soil Gas Concentration as a Function of Distance to Primary Release, Showing Effect of Atypical Preferential Pathways

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Three fits: "preferential pathway and non-preferential pathway data" includes all data regardless of preferential pathway status. "Preferential pathway screened data" is the fit represented by the blue line and is only to the data for which "preferential pathway strict" = false (i.e., no atypical preferential pathway present in the data). "Non-preferential pathway screened data" is the the fit represented by the orange line and is only to the data for which "preferential pathway strict" = true (i.e., the data only include data for which there is an atypical preferential pathway).

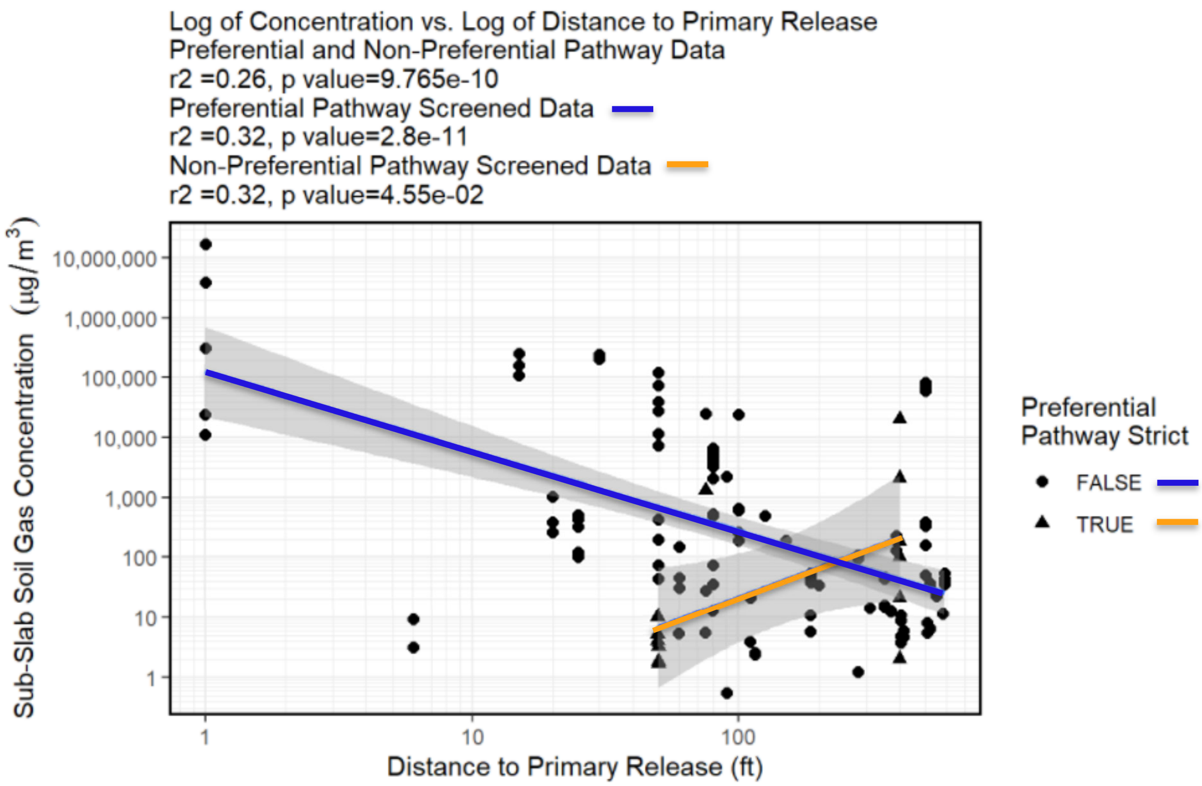
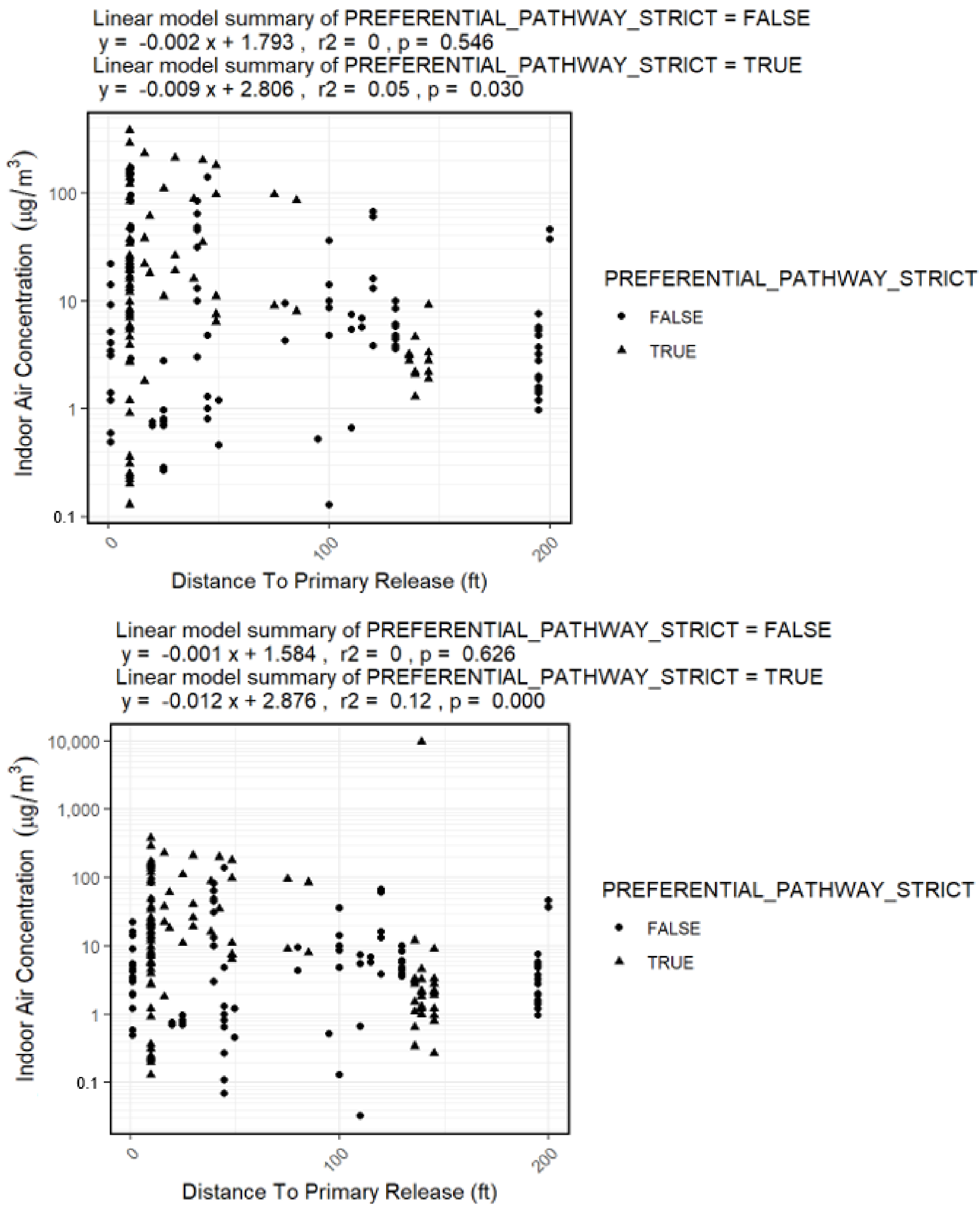


Figure 7-2. PCE Subslab Soil Gas Concentration as a Function of Distance to Primary Release, Showing Effect of Atypical Preferential Pathways

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Three fits: "preferential pathway and non-preferential pathway data" includes all data regardless of preferential pathway status. "Preferential pathway screened data" is the fit represented by the blue line and is only to the data for which "preferential pathway strict" = false (i.e., no atypical preferential pathway present in the data). "Non-preferential pathway screened data" is the the fit represented by the orange line and is only to the data for which "preferential pathway strict" = true (i.e., the data only include data for which there is an atypical preferential pathway).



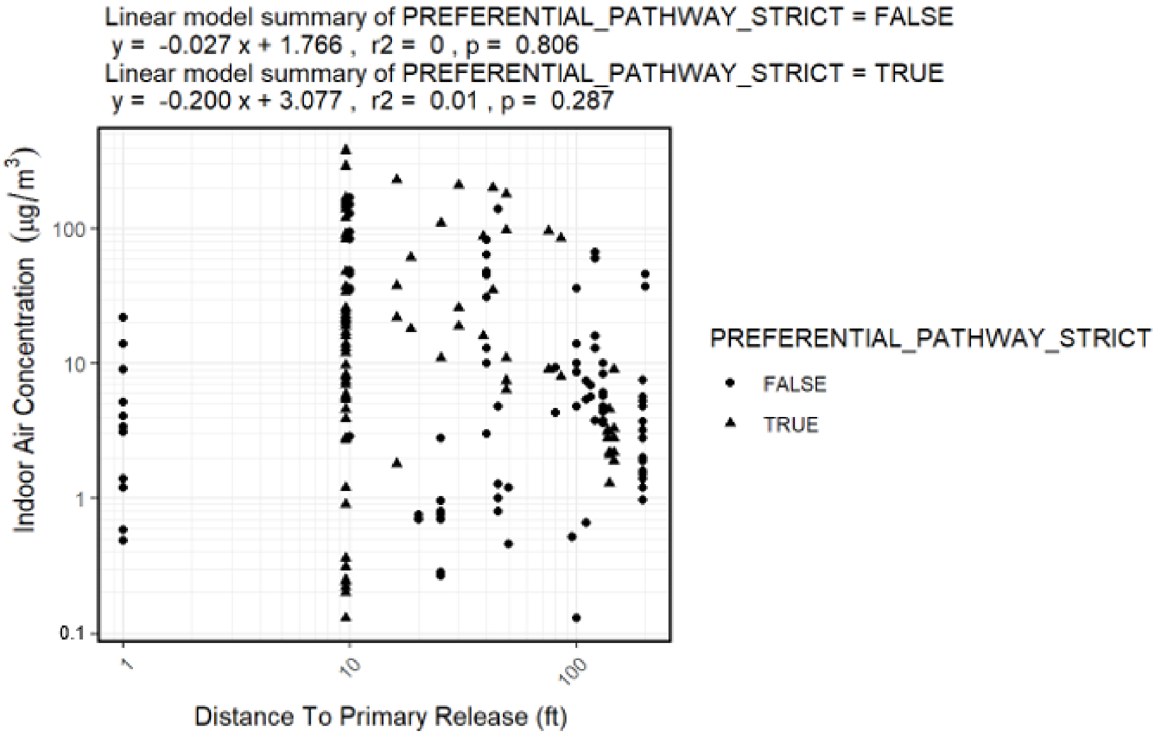
(a)

(b)

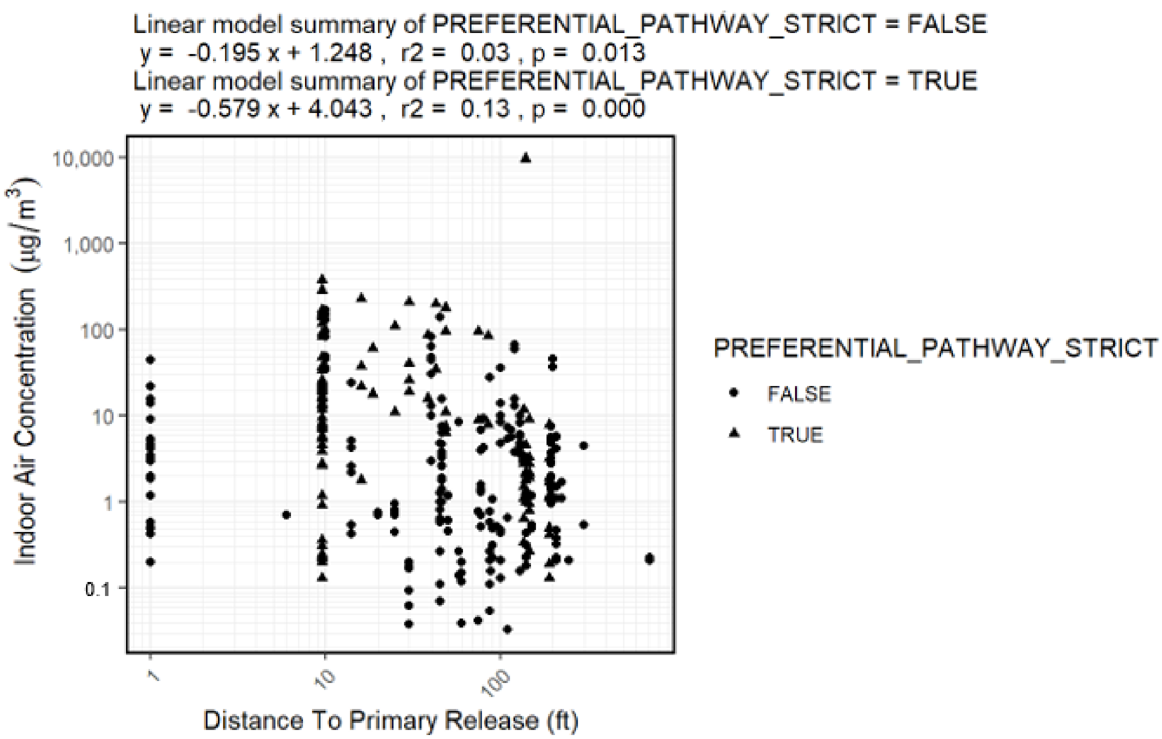
Figure 7-3. TCE Indoor Air Concentration Versus Distance to Primary Release as a Function of Preferential Pathway Status, Semi-log Plots

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Indoor air data screened based on (a) subslab soil gas (1,000X background) and (b) groundwater (5,000X background). In the equation, x represents the distance to primary release and y represents the log of the indoor air concentration.



(a)

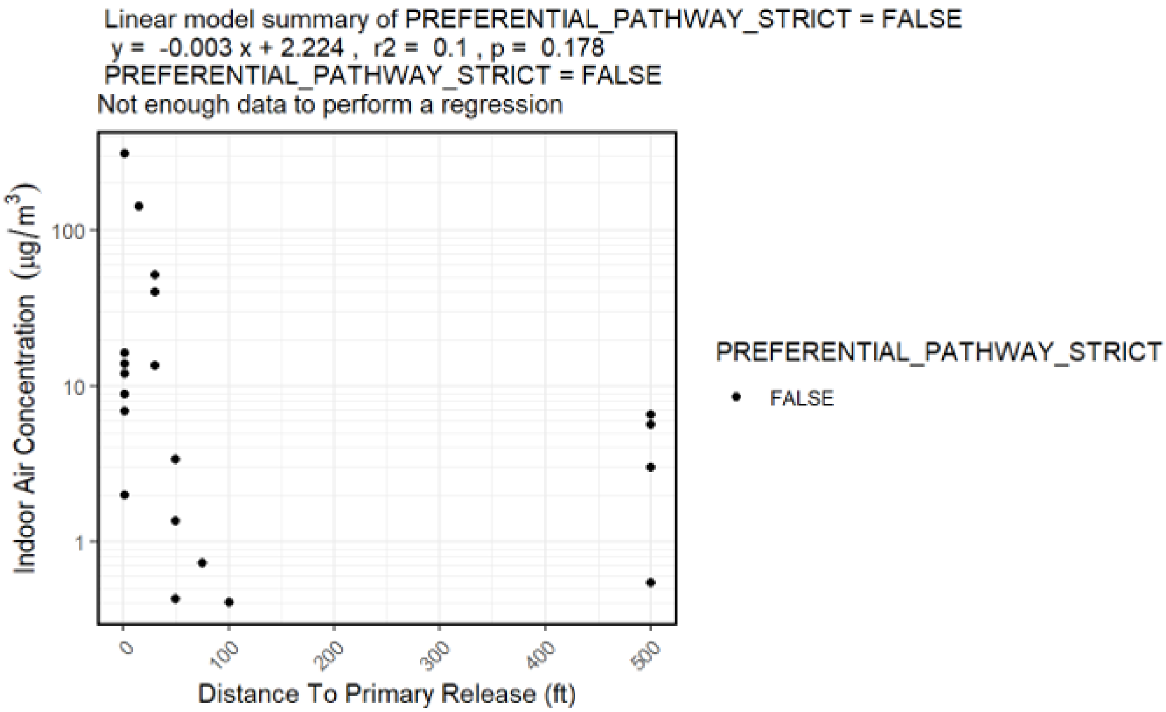


(b)

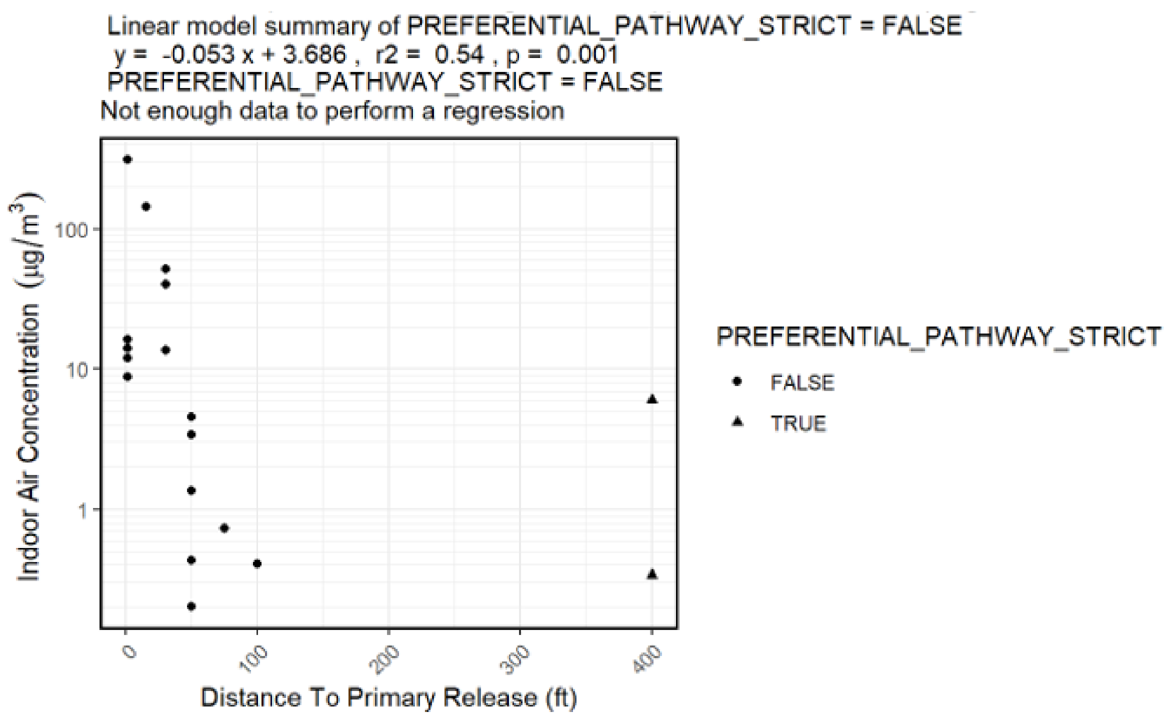
Figure 7-4. TCE Indoor Air Concentration Versus Distance to Primary Release as a Function of Preferential Pathway Status, Log-log Plots

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Indoor air data screened based on (a) subslab soil gas (1,000X background) and (b) groundwater (5,000X background). In the equation, x represents the log of the distance to primary release and y represents the log of the indoor air concentration.



(a)

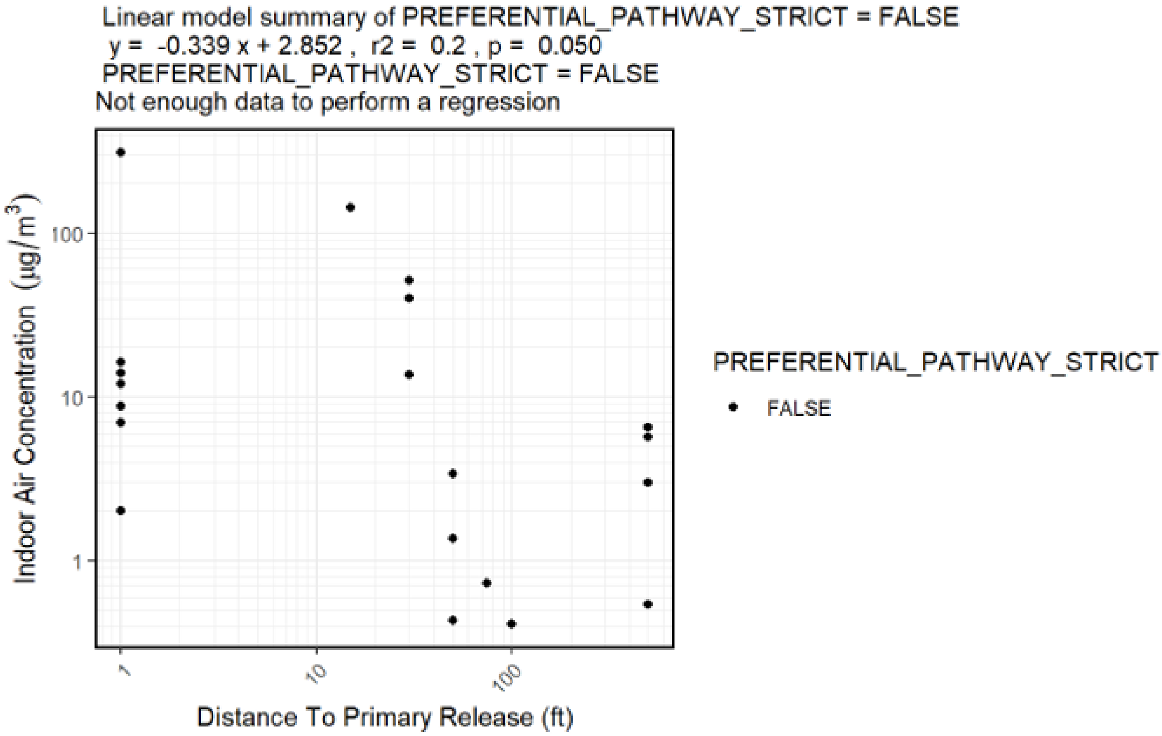


(b)

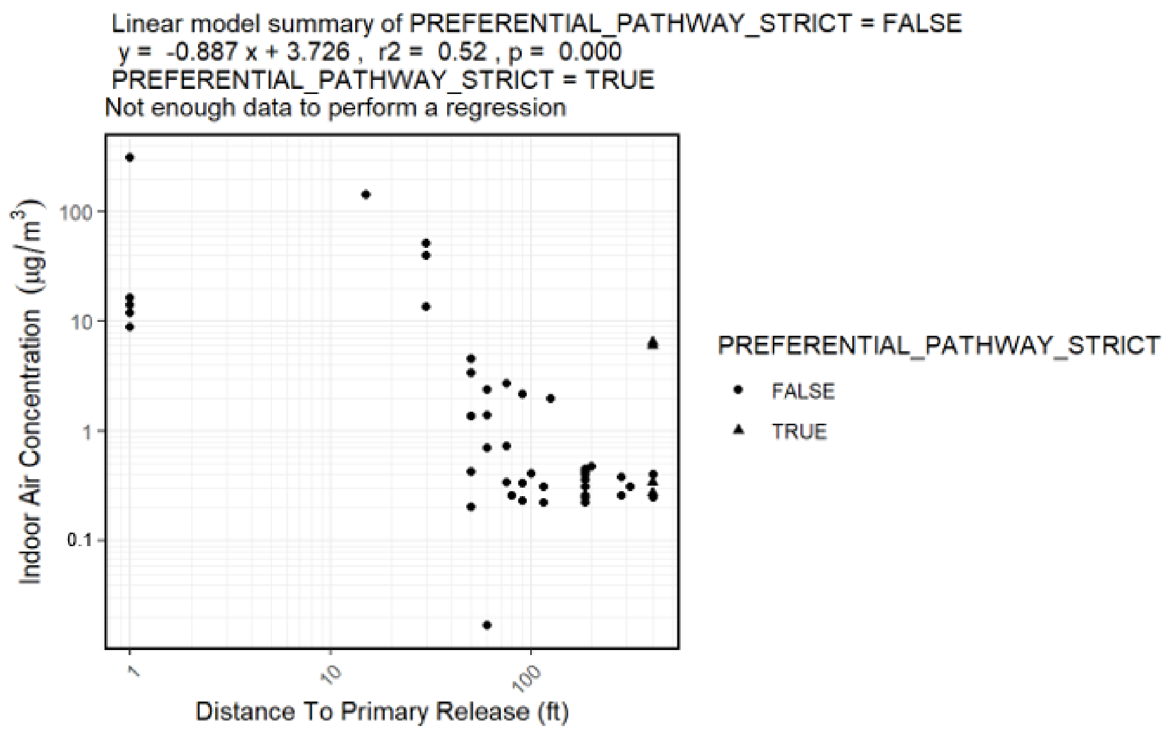
Figure 7-5. PCE Indoor Air Concentration Versus Distance to Primary Release as a Function of Preferential Pathway Status, Semi-log Plots

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Indoor air data screened based on (a) subslab soil gas (1,000X background) and (b) groundwater (5,000X background). In the equation, x represents the distance to primary release and y represents the log of the indoor air concentration.



(a)



(b)

Figure 7-6. PCE Indoor Air Concentration Versus Distance to Primary Release as a Function of Preferential Pathway Status, Log-log Plots

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Indoor air data screened based on (a) subslab soil gas (1,000X background) and (b) groundwater (5,000X background). In the equation, x represents the log of the distance to primary release and y represents the log of the indoor air concentration.

```
Call:
lm(formula = IA_Data ~ MEASURED_MAX_GW_VAPOR_UG_M3 + PREFERENTIAL_PATHWAY_STRICT +
    DISTANCE_TO_PRIMARY_RELEASE, data = SelectedScreensFlatFile_IAAvg)

Residuals:
   Min     1Q Median     3Q    Max
-212.7 -109.5   -8.7   19.5 9486.3

Coefficients:
                               Estimate Std. Error t value Pr(>|t|)
(Intercept)                   6.915e+01  8.507e+01   0.813    0.417
MEASURED_MAX_GW_VAPOR_UG_M3  -6.472e-07  1.547e-05  -0.042    0.967
PREFERENTIAL_PATHWAY_STRICT1 -9.532e+01  5.272e+01  -1.808    0.072 .
DISTANCE_TO_PRIMARY_RELEASE   3.539e-01  6.103e-01   0.580    0.563
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 663.3 on 209 degrees of freedom
Multiple R-squared:  0.01812,    Adjusted R-squared:  0.004028
F-statistic: 1.286 on 3 and 209 DF,  p-value: 0.2803
```


```
Call:
lm(formula = IA_Data ~ MEASURED_MAX_GW_VAPOR_UG_M3 + PREFERENTIAL_PATHWAY_STRICT +
    DISTANCE_TO_PRIMARY_RELEASE, data = SelectedScreensFlatFile_IAAvg)

Residuals:
   Min     1Q Median     3Q    Max
-212.7 -109.5   -8.7   19.5 9486.3

Coefficients:
                               Estimate Std. Error t value Pr(>|t|)
(Intercept)                   6.915e+01  8.507e+01   0.813    0.417
MEASURED_MAX_GW_VAPOR_UG_M3  -6.472e-07  1.547e-05  -0.042    0.967
PREFERENTIAL_PATHWAY_STRICT1 -9.532e+01  5.272e+01  -1.808    0.072 .
DISTANCE_TO_PRIMARY_RELEASE   3.539e-01  6.103e-01   0.580    0.563
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 663.3 on 209 degrees of freedom
Multiple R-squared:  0.01812,    Adjusted R-squared:  0.004028
F-statistic: 1.286 on 3 and 209 DF,  p-value: 0.2803
```


Formula Call – in this case, indoor air is the outcome variable being modeled as a function of groundwater vapor concentration, preferential pathway strict, and distance to primary release

Coefficients of the modeled terms are shown here. The "estimate" is the slope for each term. Pr(>|t|) is the p-value. A low p-value means that a variable is a significant predictor of the outcome variable, i.e., an indication that it is unlikely the relationship between the predictor and outcome variables is observed due to chance. Significance codes (if any) are given to the right of the data. In this case a single "." indicates one of the terms had a p-value better than 0.10 but worse than 0.05.

The multiple r^2 is an indicator of how well the model fits the data; it can be interpreted as the proportion of the variance in the outcome variable that can be explained by the predictor variables (in this case, 0.01812, or less than 2%). The adjusted r^2 corrects for the number of variables considered.

Adapted from: https://feliperego.github.io/blog/2015/10/23/Interpreting-Model-Output-In-R

Figure 7-7. General Linear Model of TCE Indoor Air Concentration as a Function of Groundwater Vapor, Preferential Pathway, and Distance to Primary Release, Using Unscreened Data

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Output table repeated with explanation of how to read it.

```
Call:
lm(formula = IA_Data ~ MEASURED_MAX_GW_VAPOR_UG_M3 + PREFERENTIAL_PATHWAY_STRICT +
    DISTANCE_TO_PRIMARY_RELEASE, data = SelectedScreensFlatFile_IAAvg)

Residuals:
    Min      1Q  Median      3Q     Max
-21.201 -15.014  -2.508   3.817 290.100

Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                  1.325e+01  9.237e+00   1.434   0.1554
MEASURED_MAX_GW_VAPOR_UG_M3 -1.688e-07  1.398e-07  -1.208   0.2306
PREFERENTIAL_PATHWAY_STRICT1  8.745e+00  8.863e+00   0.987   0.3268
DISTANCE_TO_PRIMARY_RELEASE -5.003e-02  2.187e-02  -2.287   0.0248 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 37.04 on 80 degrees of freedom
Multiple R-squared:  0.06537,	Adjusted R-squared:  0.03032
F-statistic: 1.865 on 3 and 80 DF,  p-value: 0.1422
```

Figure 7-8. General Linear Model of PCE Indoor Air Concentration as a Function of Groundwater Vapor, Preferential Pathway, and Distance to Primary Release, Using Unscreened Data
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

```
Call:
lm(formula = IA_Data ~ SS_Data + PREFERENTIAL_PATHWAY_STRICT +
    DISTANCE_TO_PRIMARY_RELEASE, data = SelectedScreensFlatFile_joined)

Residuals:
   Min     1Q Median     3Q    Max
-152.5  -72.6   -4.2    3.2 9552.6

Coefficients:
                               Estimate Std. Error t value Pr(>|t|)
(Intercept)                   6.409e+01  5.315e+01   1.206   0.2289
SS_Data                       8.999e-07  8.431e-06   0.107   0.9151
PREFERENTIAL_PATHWAY_STRICT1 -6.925e+01  3.816e+01  -1.815   0.0707 .
DISTANCE_TO_PRIMARY_RELEASE   1.013e-01  3.716e-01   0.273   0.7853
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 577.4 on 278 degrees of freedom
  (65 observations deleted due to missingness)
Multiple R-squared:  0.01224,	Adjusted R-squared:  0.001579
F-statistic: 1.148 on 3 and 278 DF,  p-value: 0.33
```

Figure 7-9. General Linear Model of TCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Preferential Pathway, and Distance to Primary Release, Using Unscreened Data
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

```
Call:
lm(formula = IA_Data ~ SS_Data + PREFERENTIAL_PATHWAY_STRICT +
    DISTANCE_TO_PRIMARY_RELEASE, data = SelectedScreensFlatFile_joined)

Residuals:
    Min      1Q  Median      3Q     Max
-67.693 -10.945  -5.423   2.299 282.008

Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                  1.201e+01  7.465e+00   1.608   0.1114
SS_Data                      3.859e-06  2.078e-06   1.857   0.0667 .
PREFERENTIAL_PATHWAY_STRICT1  2.794e+00  6.226e+00   0.449   0.6547
DISTANCE_TO_PRIMARY_RELEASE  -3.257e-02  1.892e-02  -1.722   0.0887 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 35.41 on 87 degrees of freedom
  (31 observations deleted due to missingness)
Multiple R-squared:  0.08226,	Adjusted R-squared:  0.05061
F-statistic: 2.599 on 3 and 87 DF,  p-value: 0.0573
```

Figure 7-10. General Linear Model of PCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Preferential Pathway, and Distance to Primary Release, Using Unscreened Data
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

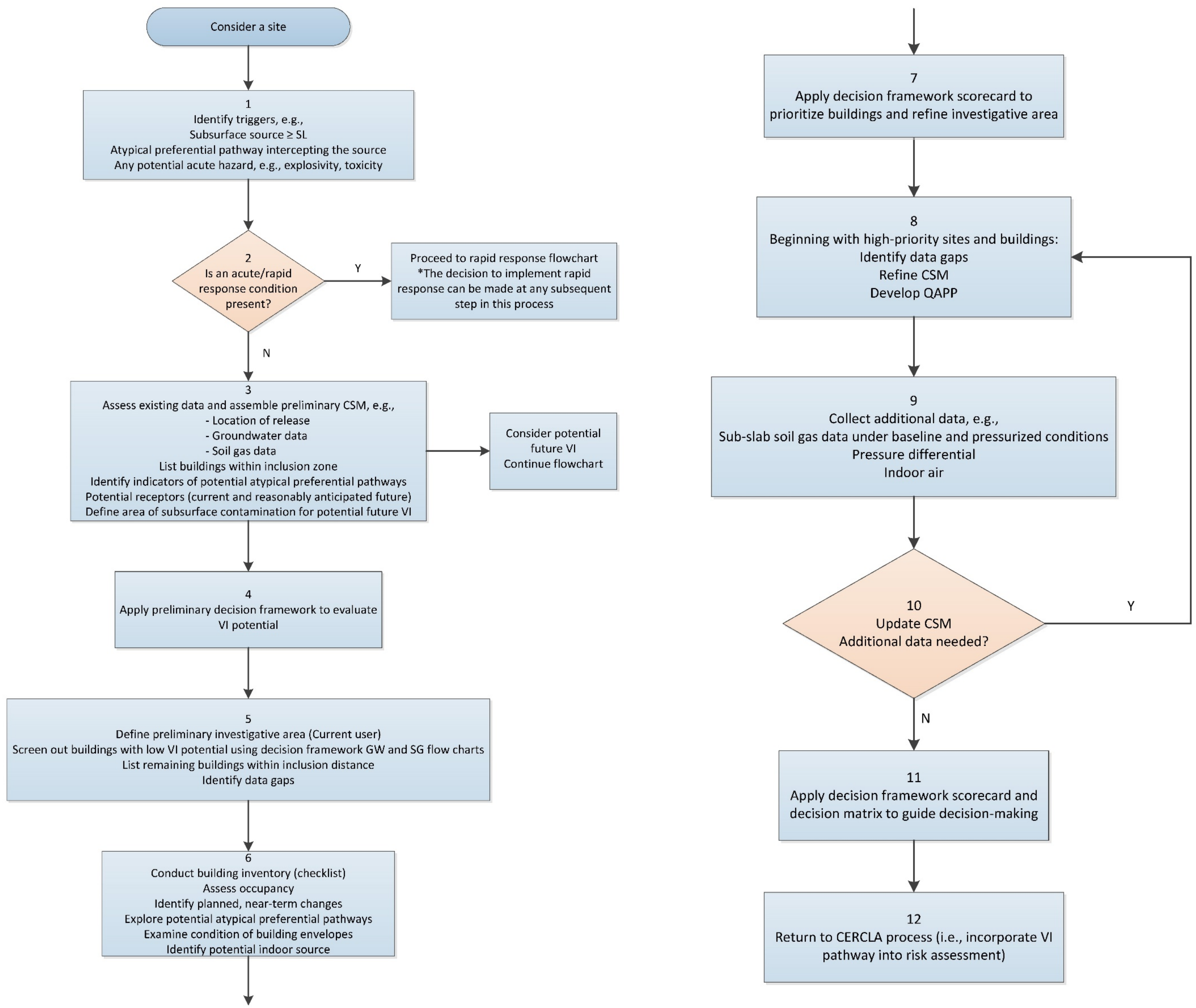
```
Call:
lm(formula = IA_Data ~ MEASURED_MAX_GW_VAPOR_UG_M3 + PREFERENTIAL_PATHWAY_STRICT +
    DISTANCE_TO_PRIMARY_RELEASE, data = SelectedScreensFlatFile_IAAvg)

Residuals:
   Min     1Q Median     3Q    Max
-274.5 -154.3  -18.7   33.4 9424.5

Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                  6.295e+01  1.289e+02   0.488    0.626
MEASURED_MAX_GW_VAPOR_UG_M3  -1.870e-07  2.135e-05  -0.009    0.993
PREFERENTIAL_PATHWAY_STRICT1 -1.102e+02  7.282e+01  -1.514    0.132
DISTANCE_TO_PRIMARY_RELEASE   7.357e-01  1.009e+00   0.729    0.467

Residual standard error: 782.9 on 149 degrees of freedom
Multiple R-squared:  0.02211,	Adjusted R-squared:  0.002418
F-statistic: 1.123 on 3 and 149 DF,  p-value: 0.3418
```

Figure 7-11. General Linear Model of TCE Indoor Air Concentration as a Function of Groundwater Concentration, Preferential Pathway, and Distance to Primary Release, with Data Screened Based on Groundwater 5,000X Background Source Strength Screen
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

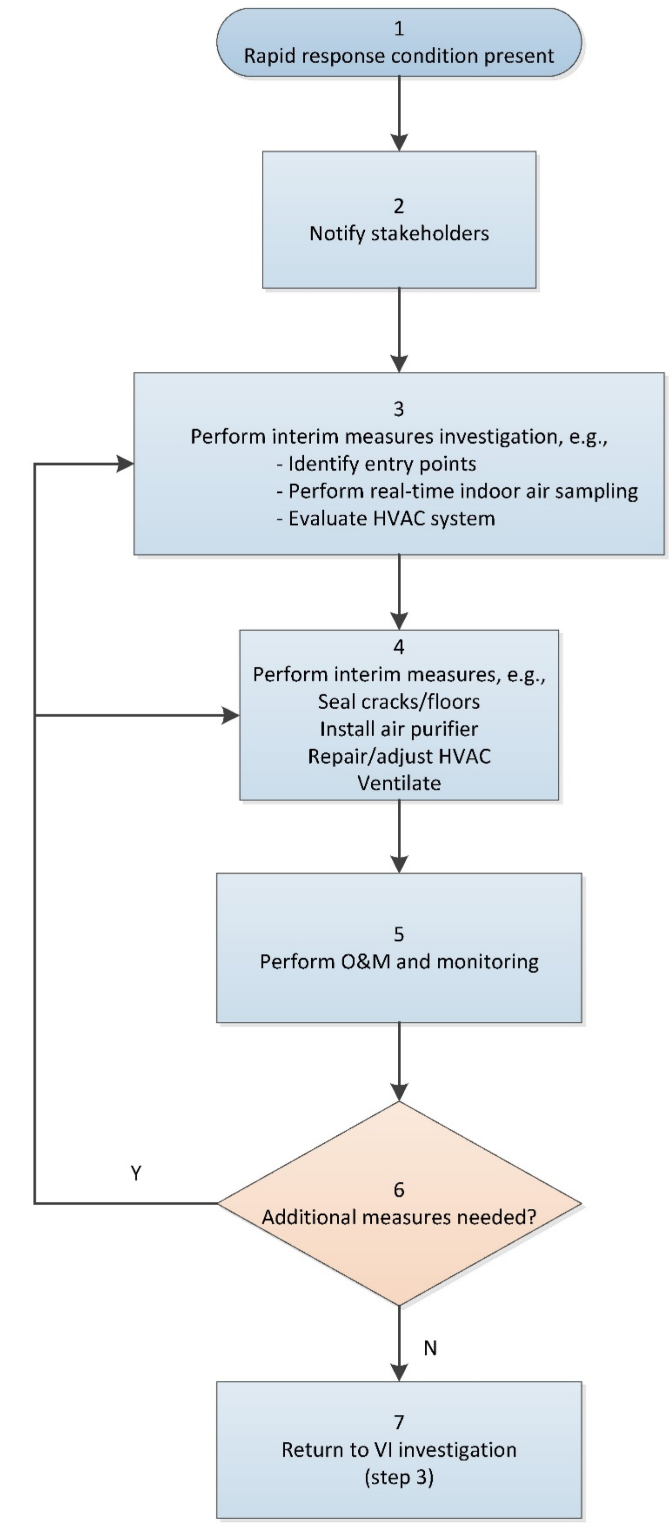
```
[1] "Indoor concentration as a function of Sub-Slab Soil Gas Concentration and Preferential Pathway"
[1] "TCE"
[1] "SS1000XBGRD"

Call:
lm(formula = IA_Data ~ SS_Data + PREFERENTIAL_PATHWAY_STRICT +
    DISTANCE_TO_PRIMARY_RELEASE, data = SelectedScreensFlatFile_joined)

Residuals:
    Min      1Q  Median      3Q     Max
-46.512 -21.637 -16.561  -1.035 184.299

Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                  3.702e+01  7.529e+00   4.917 4.17e-06 ***
SS_Data                      2.301e-06  6.661e-07   3.455 0.000858 ***
PREFERENTIAL_PATHWAY_STRICT1 -1.130e+01  4.777e+00  -2.366 0.020222 *
DISTANCE_TO_PRIMARY_RELEASE  -1.768e-01  8.610e-02  -2.054 0.043033 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 45.15 on 86 degrees of freedom
  (26 observations deleted due to missingness)
Multiple R-squared:  0.2251, Adjusted R-squared:  0.1981
F-statistic: 8.329 on 3 and 86 DF,  p-value: 6.339e-05
```

Figure 7-12. General Linear Model of TCE Indoor Air Concentration as a Function of Subslab Soil Gas Concentration, Preferential Pathway, and Distance to Primary Release, with Data Screened Based on Subslab Soil Gas 1,000X Background Source Strength Screen

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings



Vapor Intrusion Investigation Lifecycle



Vapor Intrusion Investigation Rapid Response Flowchart

Figure 8-1. Quantitative Decision Framework Vapor Intrusion Investigation Flowcharts
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

BUILDING 1 SCORECARD

Step 1: Enter Building/Zone Name:
Building 1

Step 2: Indicate which type of data is available
A. Only groundwater

Step 3: Fill out appropriate scorecard
Choose the VI Prioritization Point Value for each parameter (rows 17-55)

Step 4: Fill out uncertainty score
2 (see row 57)

FINAL SCORE: 29

Color meaning:
Yellow cells = Enter data based on site information
Blue cells = Data updated automatically
Grey cells = Not applicable for site

A. Only groundwater data available - Fill out this spreadsheet

Parameter	Range Observed	VI Prioritization Point Value	Interpretation
Average Subslab Soil Gas (SSSG) Concentration N/A			
Average Groundwater Vapor Concentration **(GWVC)** (Deep soil gas concentration) (Calculated Using Interpolated Groundwater Concentration Beneath Sample Zone and Henry's Law or Results of Near Slab Soil Gas Sampling >15 ft below ground surface)	**GWVC** < [1,000 x IA VISL]	0	Data analysis shows that concentrations above a minimum value in groundwater (inflection point) are needed to observe any corresponding increase in indoor air concentrations if groundwater is the source. Indoor air concentrations, however, do not rise with a 1:1 slope proportional to groundwater concentrations in this and other studies; thus, the point score increases more slowly than the groundwater concentration. An empirical fit to data shows indoor air concentration increasing 2x for every 40x increase in groundwater concentration. When a strong vadose zone source is present, subslab concentrations may be substantially higher than would be expected based on groundwater results; normally some groundwater impact would also be observed.
	[1,000 x IA VISL (chemical specific)] < **GWVC** < [40,000 x IA VISL (chemical specific)] (or no information available)	3	
	[40,000 x IA VISL] < **GWVC** < [1,500,000 x IA VISL]	6	
	GWVC > [1,500,000 x IA VISL]	12	
	Assigned score for given parameter	6	
Potential for vadose zone source near building?	Known or strongly suspected release of solvents within 200 ft of the building and fine soil type	6	Documented history of chlorinated solvent release at the building suggests that potential vadose zone sources close to the foundation may remain. One can assume that there is some likelihood of a release based on documented long-term, large volume use of chlorinated solvents in the building. Without a documented release, patterns of data in soil gas or groundwater suggesting a release point near the building would generally suggest a vadose zone source. While the absence of detectable chlorinated solvents in bulk soil samples is not sufficient to rule out the presence of a vapor intrusion source, the detection of chlorinated solvents in bulk soil would be a line of evidence pointing toward a vadose zone source. Cases where use of solvents was likely in small volume, or incidental, such as barracks, classroom buildings, or office/HQ facilities would generally be categorized as "No known or strongly suspected release". Data analysis shows that fine soils tend to limit the potential for natural attenuation through volatilization, leaching etc.
	Known or strongly suspected release of solvents within 200 ft of the building and coarse soil type (or insufficient information)	3	
	No known or strongly suspected releases of solvents within 200 ft of the building	0	
	Assigned score for given parameter	3	
Presence of atypical preferential pathway? (elevator shaft, tunnel, open soil visible beneath pit or wall etc.)	yes	4	The database analysis indicates that there is not a clear and consistent relationship between the presence of strict atypical preferential pathways and subslab concentrations in the dataset. There is insufficient evidence to conclude that strict atypical preferential pathways as a class systematically increase indoor air concentrations. Still, this does not eliminate the possibility that in some instances, strict atypical preferential pathways would contribute to higher indoor air concentrations, as was shown in other studies, including McHugh, T. and L. Beckley "Sewers and Utility Tunnels as Preferential Pathways for Volatile Organic Compound Migration Into Buildings: Risk Factors and Investigation Protocol," ESTCP Project ER-201505, November 2018.
	insufficient information	2	
	known to be absent	0	
	Assigned score for given parameter	2	
Distance to Primary release point or high concentration source zone (from closest point within sample zone)	**Distance** < 10 ft	12	Data analysis shows an association between proximity to the primary release and higher subslab and indoor air concentrations.
	10 ft < **Distance** < 30 ft	9	
	30 ft < **Distance** < 100 ft	6	
	100 ft < **Distance** < 200 ft	2	
	Distance >200 ft	0	
	Assigned score for given parameter	8	
Depth to impacted groundwater and soil type	<4.9 feet (1.5 meters) and Coarse soil	4	In the multivariate analysis of the database, the effect of depth is clearest when the coarse soil cases are analyzed separately; and in those cases, shallow depths are associated with higher indoor air concentrations. Thus the QDF limits the points contribution for shallow groundwater to coarse soils only. Fine soils are given a score of +4 regardless of depth to groundwater if the building being assessed is close to the point of suspected release. Other studies also suggest that when an intact fine soil layer is present between a groundwater-only source and the building, this layer has a protective effect. Several residential studies suggest that the depth to groundwater is significant but only provides a moderate influence except at very shallow values. In the EPA database study (2012) at the 25, 50th and 75th percentiles, the <1.5m AF (normalized indoor air concentration) is 4.6 to 9 times higher for <1.5m depth than for 1.5m-3m; the 1.5m-3m depth group is about 2 times higher than the 3-5m group; the difference at >5m is not consistent.
	4.9 to 9.8 feet (1.5 to 3 meters) and Coarse soil [or no information available on depth to groundwater]	2	
	9.8 to 16.4 feet (3.0 to 5.0 meters) and Coarse soil	1	
	>16.4 feet (5 meters) and Coarse soil	0	
	Any depth and fine soil with potential release within 200'	4	
	Groundwater >4.9 ft (1.5 Meters) with fine soil and no potential for a release within 200'	0	
	Assigned score for given parameter	4	
Presence or absence of a centralized, properly designed engineered HVAC system.	Absent	4	Engineered HVAC systems were empirically shown to be associated with lower TCE indoor air concentrations. Such systems provide a designed minimum amount of fresh air ventilation and may also provide positive pressurization of indoor air vs. subslab soil gas in many areas.
	Present	0	
	Assigned score for given parameter	0	
Year of building's original construction	1939-1959	4	Empirical evidence suggests that 1939-1959 DoD buildings are associated with strong subslab soil gas sources. In many cases, those buildings also have favorable attenuation factors, which may limit the effect of the strong subslab sources.
	All other dates	0	
	Assigned score for given parameter	4	

Step 4: Fill out uncertainty score
Uncertainty Rating for each unknown parameter above +1
Input value between 0 and 7 --> 2

Uncertainty Score	Uncertainty Description
0	low
1-2	moderate
2-4	high
>4	very high

B. Groundwater and subslab data available - Fill out this spreadsheet

Parameter	Range Observed	VI Prioritization Point Value	Interpretation
Average Subslab Soil Gas (SSSG) Concentration	**SSSG** < [300 x Indoor Air (IA) VISL (chemical specific)]	0	Data analysis shows that concentrations above a minimum value in subslab soil gas (inflection point) are needed to observe any corresponding increase in indoor air concentrations. Revised data analysis continues to show a strong correlation between subslab concentration and indoor air concentration. In this and other studies, however, indoor air concentration does not increase proportionally to subslab concentration thus, the point score increases more slowly than subslab concentration. An empirical fit to data shows indoor air concentration increasing 2x for every 4.3x increase in subslab concentration. The subslab concentration was found to be a notably better predictor of indoor air concentration than the groundwater concentration and, thus, is more heavily weighted.
	[300 x IA VISL] < **SSSG** < [1,500 x IA VISL]	1	
	[1,500 x IA VISL] < **SSSG** < [5,000 x IA VISL] (or no information available)	2	
	[5,000 x IA VISL] < **SSSG** < 25,000 x IA VISL]	4	
	[25,000 x IA VISL] < SSSG < 100,000 x IA VISL]	8	
	SSSG > [100,000 x IA VISL]	16	
	Assigned score for given parameter	2	
Average Groundwater Vapor Concentration **(GWVC)** (Deep soil gas concentration) (Calculated Using Interpolated Groundwater Concentration Beneath Sample Zone and Henry's Law or Results of Near Slab Soil Gas Sampling >15 ft below ground surface)	**GWVC** < [1,000 x IA VISL]	0	Data analysis shows that concentrations above a minimum value in groundwater (inflection point) are needed to observe any corresponding increase in indoor air concentrations if groundwater is the source. Indoor air concentrations, however, do not rise with a 1:1 slope proportional to groundwater concentrations in this and other studies; thus, the point score increases more slowly than the groundwater concentration. An empirical fit to data shows indoor air concentration increasing 2x for every 40x increase in groundwater concentration. When a strong vadose zone source is present, subslab concentrations may be substantially higher than would be expected based on groundwater results; normally some groundwater impact would also be observed.
	[1,000 x IA VISL (chemical specific)] < **GWVC** < [40,000 x IA VISL (chemical specific)] (or no information available)	1	
	[40,000 x IA VISL] < **GWVC** < [1,500,000 x IA VISL]	2	
	GWVC > [1,500,000 x IA VISL]	4	
	Assigned score for given parameter	2	
Potential for vadose zone source near building?	Known or strongly suspected release of solvents within 200 ft of the building and fine soil type	8	Documented history of chlorinated solvent release at the building suggests that potential vadose zone sources close to the foundation may remain. One can assume that there is some likelihood of a release based on documented long-term, large volume use of chlorinated solvents in the building. Without a documented release, patterns of data in soil gas or groundwater suggesting a release point near the building would generally suggest a vadose zone source. While the absence of detectable chlorinated solvents in bulk soil samples is not sufficient to rule out the presence of a vapor intrusion source, the detection of chlorinated solvents in bulk soil would be a line of evidence pointing toward a vadose zone source. Cases where use of solvents was likely in small volume, or incidental, such as barracks, classroom buildings, or office/HQ facilities would generally be categorized as "No known or strongly suspected release". Data analysis shows that fine soils tend to limit the potential for natural attenuation through volatilization, leaching etc.
	Known or strongly suspected release of solvents within 200 ft of the building and coarse soil type (or insufficient information)	4	
	No known or strongly suspected releases of solvents within 200 ft of the building	0	
	Assigned score for given parameter	4	
Presence of atypical preferential pathway? (elevator shaft, tunnel, open soil visible beneath pit or wall etc.)	yes	4	The database analysis indicates that there is not a clear and consistent relationship between the presence of strict atypical preferential pathways and subslab concentrations in the dataset. There is insufficient evidence to conclude that strict atypical preferential pathways as a class systematically increase indoor air concentrations. Still, this does not eliminate the possibility that in some instances, strict atypical preferential pathways would contribute to higher indoor air concentrations, as was shown in other studies, including McHugh, T. and L. Beckley "Sewers and Utility Tunnels as Preferential Pathways for Volatile Organic Compound Migration Into Buildings: Risk Factors and Investigation Protocol," ESTCP Project ER-201505, November 2018.
	insufficient information	2	
	known to be absent	0	
	Assigned score for given parameter	2	
Distance to Primary release point or high concentration source zone (from closest point within sample zone)	**Distance** < 10 ft	8	Data analysis shows an association between proximity to the primary release and higher subslab and indoor air concentrations.
	10 ft < **Distance** < 30 ft	6	
	30 ft < **Distance** < 100 ft	4	
	100 ft < **Distance** < 200 ft	2	
	Distance >200 ft	0	
	Assigned score for given parameter	6	
Depth to impacted groundwater N/A			
Presence or absence of a centralized, properly designed engineered HVAC system.	Absent	3	Engineered HVAC systems were empirically shown to be associated with lower TCE indoor air concentrations. Such systems provide a designed minimum amount of fresh air ventilation and may also provide positive pressurization of indoor air vs. subslab soil gas in many areas.
	Present	0	
	Assigned score for given parameter	3	
Year of building's original construction	1939-1959	3	Empirical evidence suggests that 1939-1959 DoD buildings are associated with strong subslab soil gas sources. In many cases, those buildings also have favorable attenuation factors, which may limit the effect of the strong subslab sources.
	All other dates	0	
	Assigned score for given parameter	0	

Figure 8-2. Quantitative Decision Framework Vapor Intrusion Potential Scorecard
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

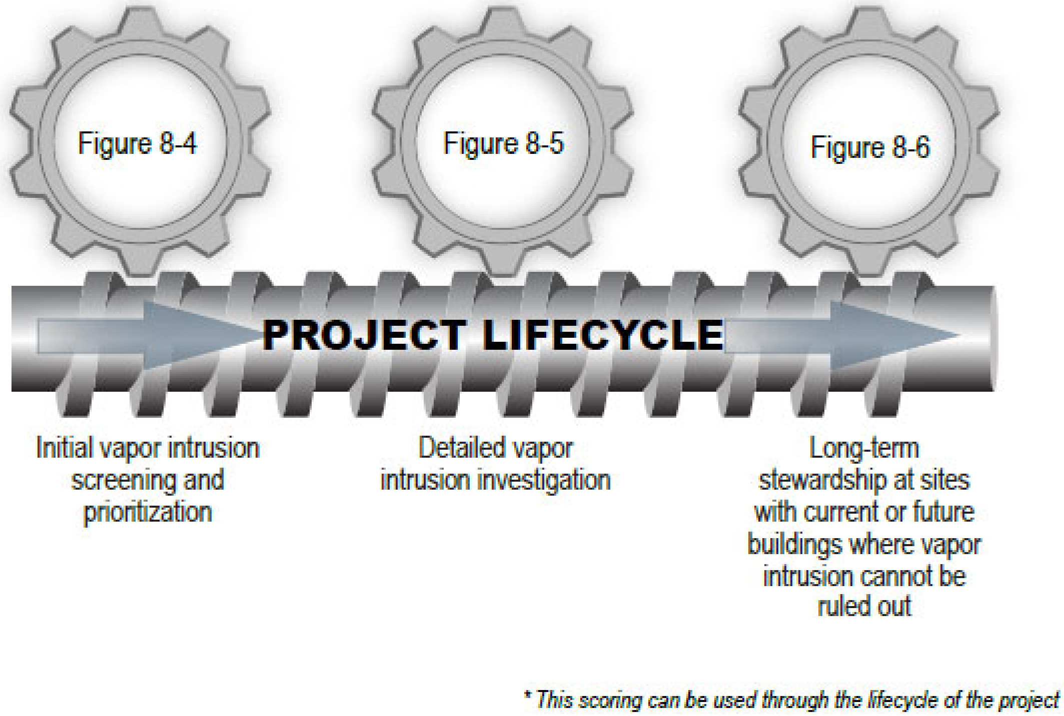


Figure 8-3. Key to Scorecard Interpretation During Project Lifecycle
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

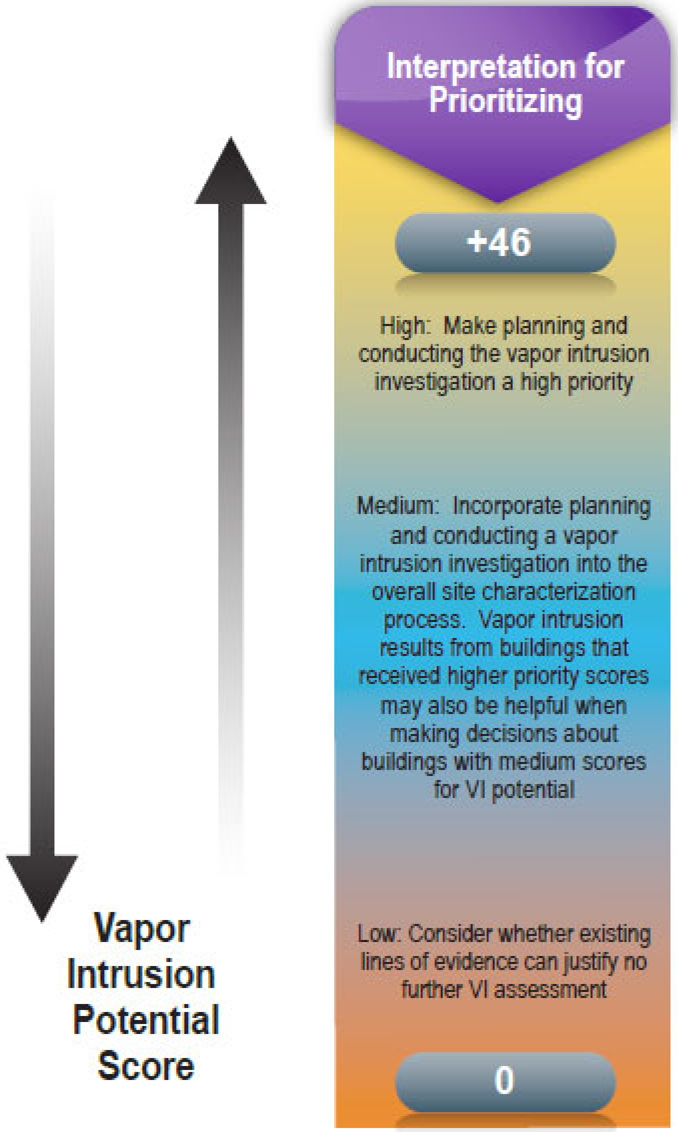


Figure 8-4. Interpretation of Vapor Intrusion Potential Score for Prioritizing Initial Investigation Efforts
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

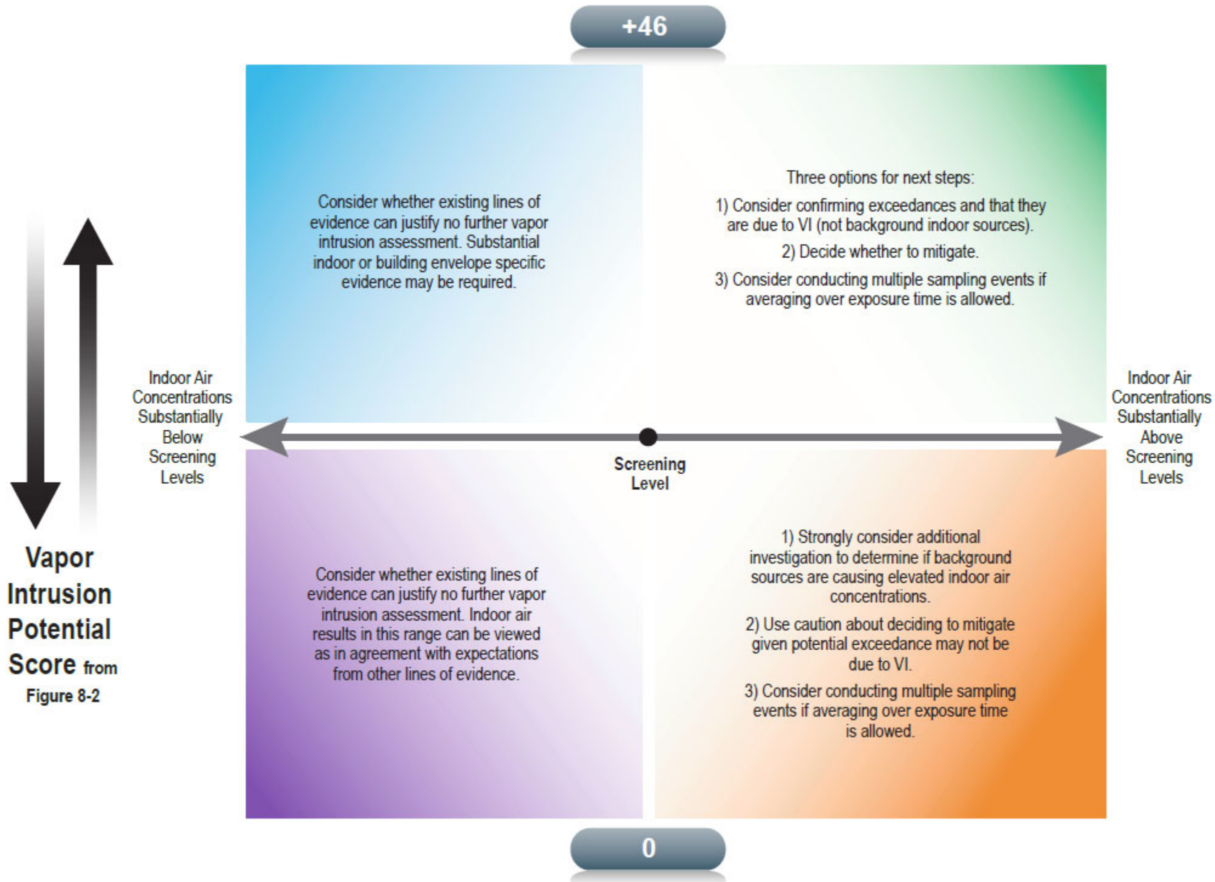


Figure 8-5. Interpretation of Vapor Intrusion Potential Scores at Sites with Indoor Air Data

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

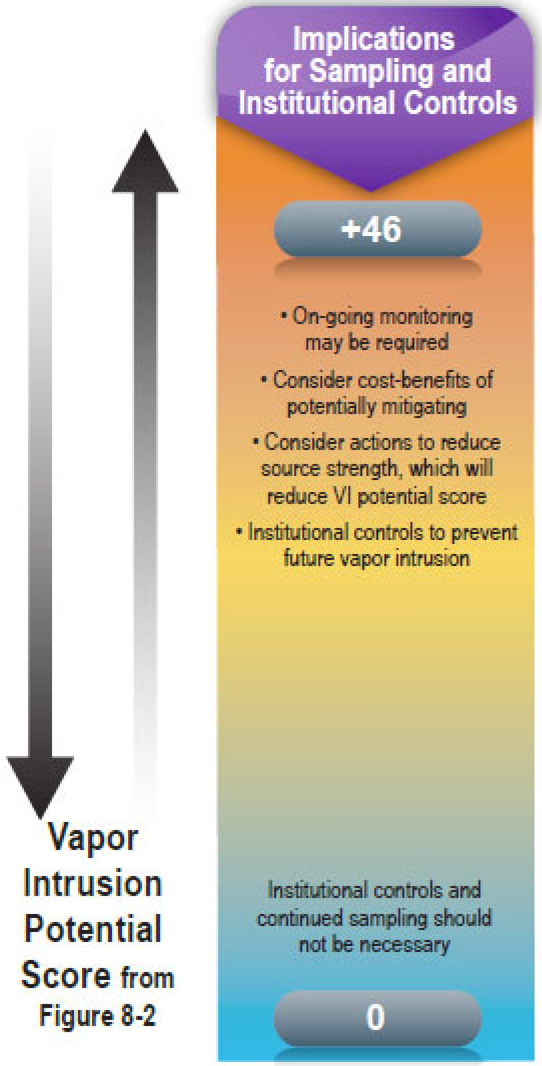


Figure 8-6. Interpretation of Vapor Intrusion Potential Score to Design Appropriate Long-Term Stewardship
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

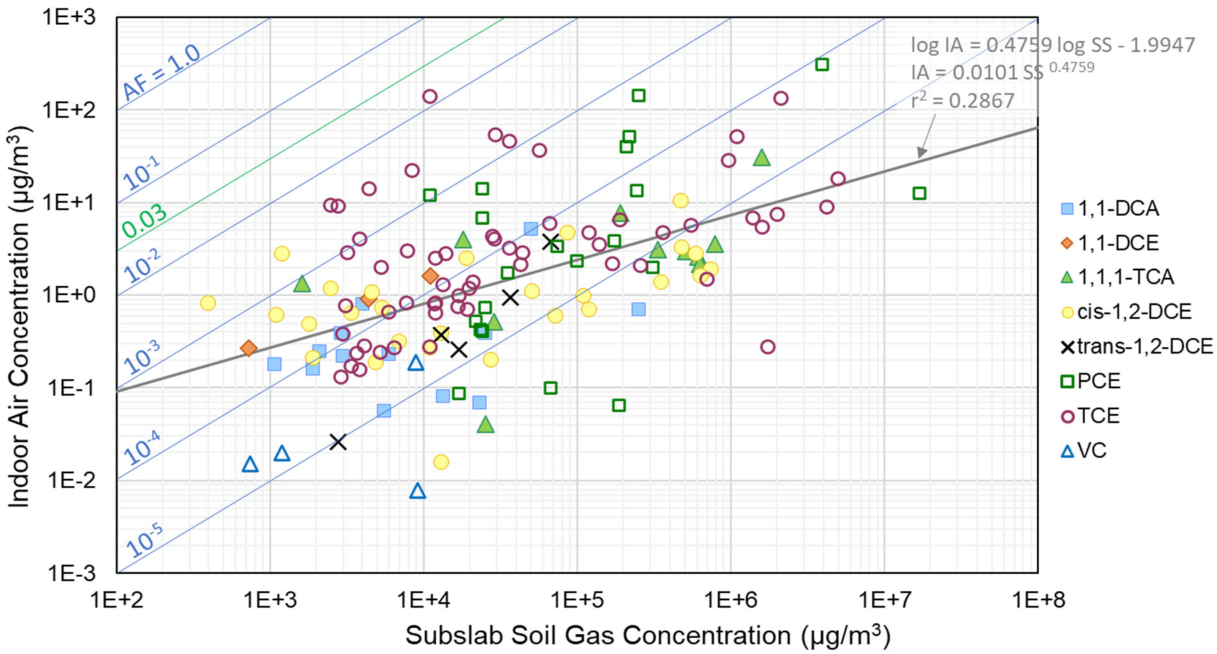


Figure 8-7. Paired Subslab Soil Gas-Indoor Air Concentration Plots for All VOCs in the Analysis with Linear Best Fit in Log-log Space
Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each data pair represents the average indoor air and subslab soil gas concentrations for a building sample zone for a given sampling event. The pairs on the plots passed either the 1,000X background source strength screen for VOCs with background values (TCE, PCE, 1,1,1-TCA, 1,1-DCE, and VC) or the 1,000 µg/m^3 source strength screen for VOCs without background values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE). Pairs with an indoor air concentration below detection limit are not shown. The blue oblique lines represent subslab soil gas-to-indoor air AF lines ranging from 10^{-5} to 1.0. The green line represents the USEPA default AF of 0.03. There were no pairs meeting the various filtering criteria for 1,2-DCA.

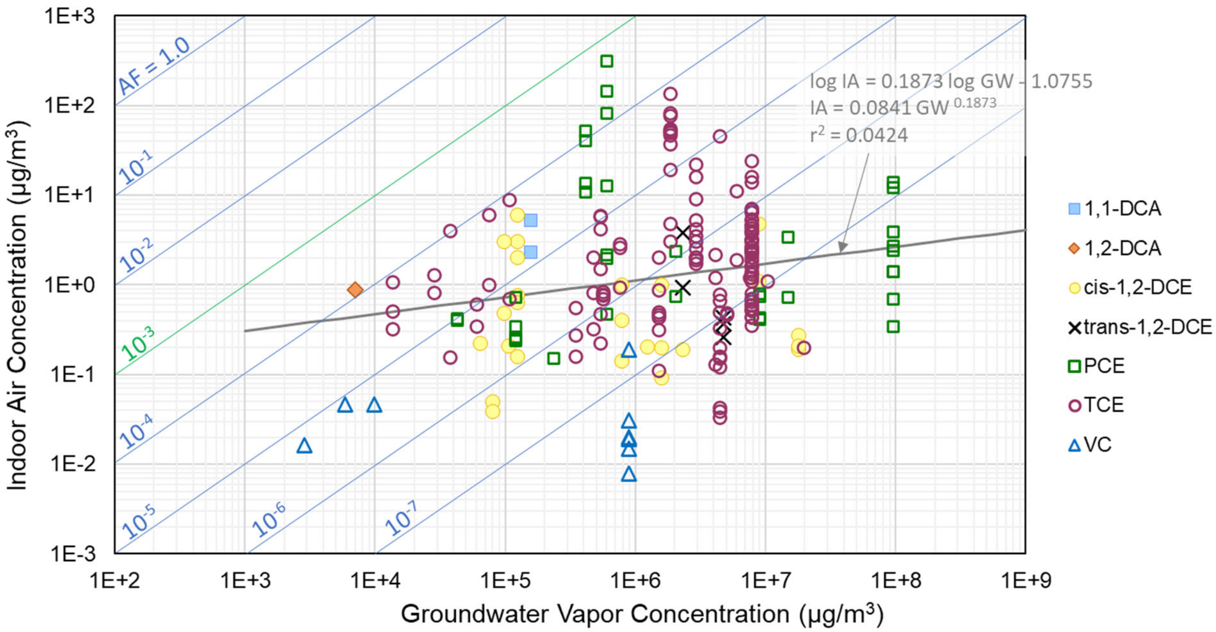


Figure 8-8. Paired Groundwater-Indoor Air Concentration Plots for all VOCs in the Analysis with Linear Best Fit in Log-log Space

Reanalysis of Department of Defense Vapor Intrusion Database of Commercial and Industrial Buildings

Each data pair represents the groundwater vapor and average indoor air concentrations for a building sample zone for a given sampling event. The pairs on the plots passed either the 5,000X background source strength screen for VOCs with background values (TCE, PCE, 1,2-DCA, and VC) or the 10,000 µg/m^3 source strength screen for VOCs without background values (1,1-DCA, cis-1,2-DCE, and trans-1,2-DCE). Pairs with an indoor air concentration below detection limit are not shown. The blue oblique lines represent groundwater-to-indoor air AF lines ranging from 10^{-7} to 1.0. The green line represents the USEPA default AF of 10^{-3}. There were no pairs meeting the various filtering criteria for 1,1,1-TCA and 1,1-DCE.

Appendix A
Clausen Correspondence

From:	Lutes, Christopher/RAL
To:	Hallberg, Keri/CLT; Lund, Loren/DEN
Cc:	Levy, Laurent
Subject:	CRREL building coding
Date:	Friday, November 15, 2019 10:29:56 AM

Laurent and I met with Jay Clausen by phone on 11/1/19 and went through each of the buildings at CRREL in the NESDI database (and talked secondarily about the range of dates in that dataset). We addressed three primary groups of questions:

- Whether they had identified atypical preferential pathways, when those were present and whether they significantly influenced indoor concentrations

- Whether they had identified indoor sources, and when those sources might have been present.

- When mitigation systems or SVE remediation were present (datasets after those operational dates were supposed to be excluded from the QDF dataset).

Jay said that overall TCE on campus was phased out by around 1987, but as discussed below there are still some buildings with indoor sources after that.

<u>CRREL01 Child Development Center</u>

No evidence of preferential pathway or indoor source, HAPSITE survey was done.

<u>CRREL03 Main Laboratory Building</u>

- Sewer gas sampling in 2010 had results similar to adjacent soil gas localities which suggests not a big discharge to the sewer. On the North side of the building there are some utility lines where stainless steel pipes had completely rusted away leaving just a hole, some of which go through the source zone.

- There were several rounds of smoke testing and sealing of toilet seals, pipes and the like. These did not appear to significantly change the indoor concentrations as indicated by the HAPSITE. So the atypical preferential pathway existed – but do these qualify for atypical preferential pathway "strict".

- In the center of the building are ten cold boxes, which were chilled with a glycol/ammonia mixture, at one time there was some TCE in the mixture, they were at one point flushed to try to eliminate the TCE and then ripped out more recently. There is potentially some contribution from those lines in historical samples, to me that counts as an indoor source.

- The cold boxes also had insulation that when ripped out was found to be "soaked" with fluids including TCE. That didn't seem like a major source until they started ripping into it, when it showed considerable emissions, but still I think that is evidence that an indoor source existed until recently.

- Air cleaner use was phased in the building between 2012 and 2014 and remain in the buildings until now, although they aren't always operated – sounds like they are individually controlled. (there appear to be data in the database from this time or later that should be excluded)

- A subslab system came on line in 2015 and eliminated most detects in the basement as indicated by HAPSITE sampling. That suggests that the basement was experiencing at least some "real VI"

- Recent rebound tests where the SVE and SSD were turned off showed that concentrations had dropped 2 to 3 orders of magnitude

- Finally as Jay briefed more recently there is the persistent roofing related source to the second floor on one end of the building. Jay believes since it is localized it is more likely a "reservoir source" of historic preferential pathway VI then a true building materials source.

- In summary I believe that between the indoor sources (like the cold boxes and refrigerant lines) and the mitigation/remediation systems I think all of the data from the main building should be dropped from the analysis.

<u>CRREL04 Lab Addition Sub-basement</u>

- This is connected to the main building through doorways on all floors. I think we should lump it in with the main building and drop it for the same reasons.

<u>CRREL05 Logistics Management Facility:</u>

- A HAPSITE search was done in 2010. There were initially some TCE detects in the building, but an indoor source was never found.

- This building is downgradient of AOC 9 so it has a credible VI source

- No obvious preferential entry points

<u>CRREL06 Directorate of Public Works</u>

- No indoor source was found with a HAPSITE search

- No preferential pathways

- On the edge of the AOC9 plume so probably a low level VI source

CRREL07 Remote Sensing Facility

- No indoor source
- No identified preferential pathways
- Groundwater plume passes beneath the building so credible VI source

Chris Lutes

Principal Technologist

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VI Preferential Pathways: Rule or Exception

- Dr. Jay Clausen, ERDC-CRREL
- 22 October 2019

CRREL COLD REGIONS RESEARCH AND ENGINEERING LABORATORY

Acknowledgements

- Laurie Haines-Eklund (U.S. Army Environmental Command)
- Terry Harwood (USACE ERDC-CRREL)
- Darrell, Maoore, Dan Groher (USACE NAE)
- Dave Becker (USACE EMCX)
- Jack Besse, Scott Calkin, Rod Rustad, Jeffrey Picket, Glen Gordon, Wolfgang Calicchio (Wood Plc)

CRREL COLD REGIONS RESEARCH AND ENGINEERING LABORATORY

Building Specifics

- Government laboratory building built in 1954, multiple additions
  - Two stories with basement and subbasement
  - Foundation slab on prepared excavation
  - Building footprint 16,000 ft^2 - total all floors 52,000 ft^2
  - No HVAC system in main laboratory
    - Cooling water utilized
  - Air distribution in laboratory addition

CRREL COLD REGIONS RESEARCH AND ENGINEERING LABORATORY

Building Occupancy

- Government laboratory facility
  - Over 50 office and laboratories per floor
  - Over 150 people in the building
  - Rooms occupied during sampling events
- Sampling Indoor Source Investigation
  - Carbon Air Purifier's installed in offices in 2012 - 2014
  - Deployment of Summa canisters biannually
  - Daily HAPSITE™ use, 30+ rooms/day
  - Sleuthing of sources with HAPSITE™
- Action Plan developed to respond to elevated readings
- Site Action Level of 8.8 µg/m^3 established

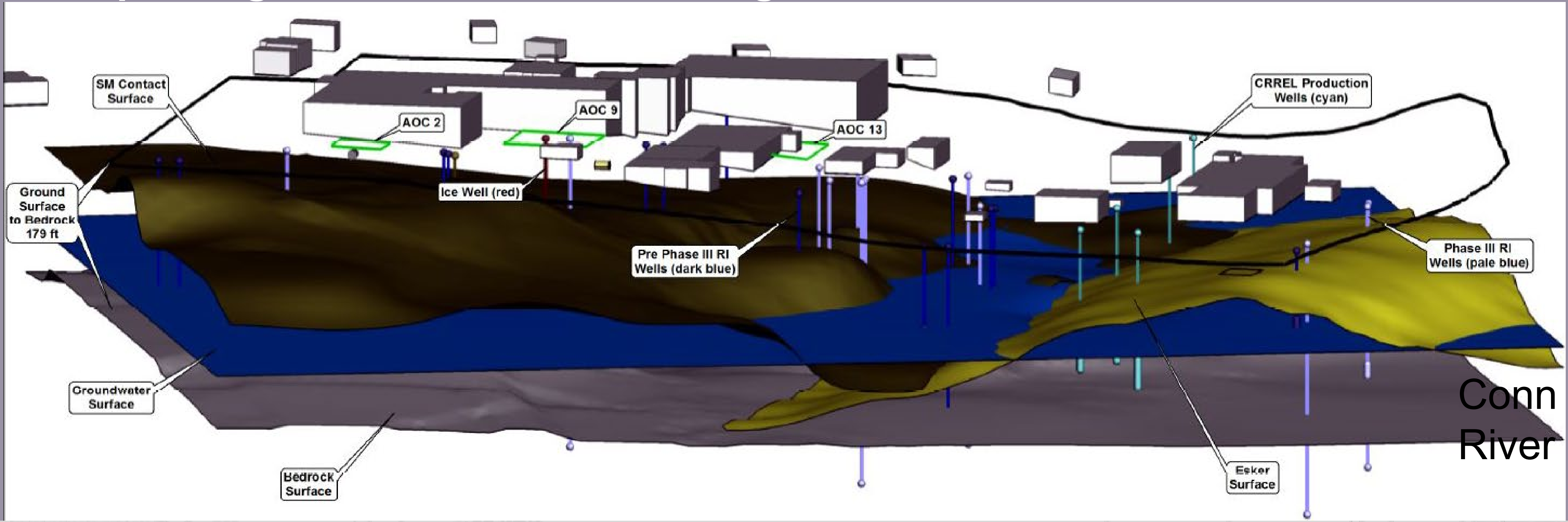
Contaminant Site Specifics

- Release conditions
  - Catastrophic and repetitive slow release from TCE leaks
  - Limited DNAPL observed initially in shallow soil
  - Subsurface vapor plume feeds VI and groundwater plume
  - Releases within 100 ft north of building and 300 ft west of building and adjacent
- Pre-remedial contaminant distribution
  - Subsurface soil gas TCE concentrations near main laboratory in excess of 10,000,000 ug/m^3
  - Sub-slab TCE concentrations up to 5,900,000 µg/m^3
  - Indoor air sub-basement TCE concentrations, 25 to 91 µg/m^3
  - Indoor air basement TCE concentrations, 15 to 241 µg/m^3
  - Indoor air 1st floor TCE concentrations, 0.86 to 4.7 µg/m^3
  - Indoor air 2nd floor TCE concentrations, 2.5 to 11 µg/m^3

CRREL COLD REGIONS RESEARCH AND ENGINEERING LABORATORY

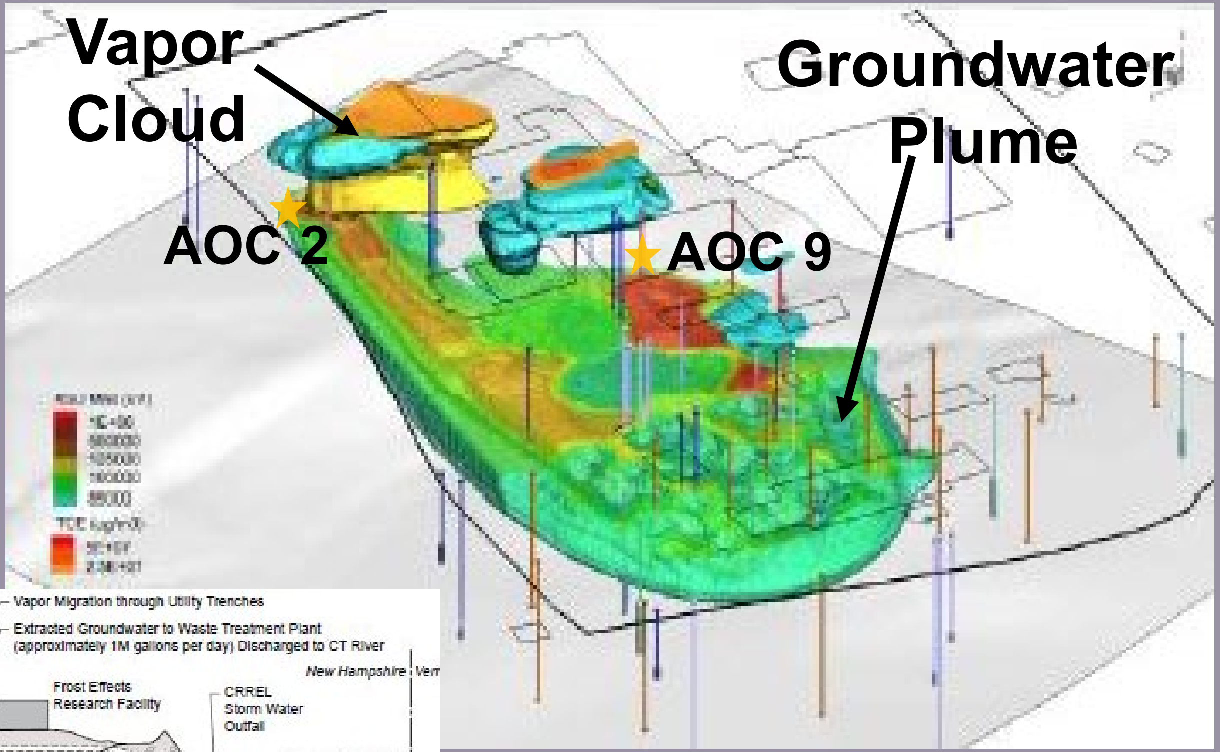
Site Location

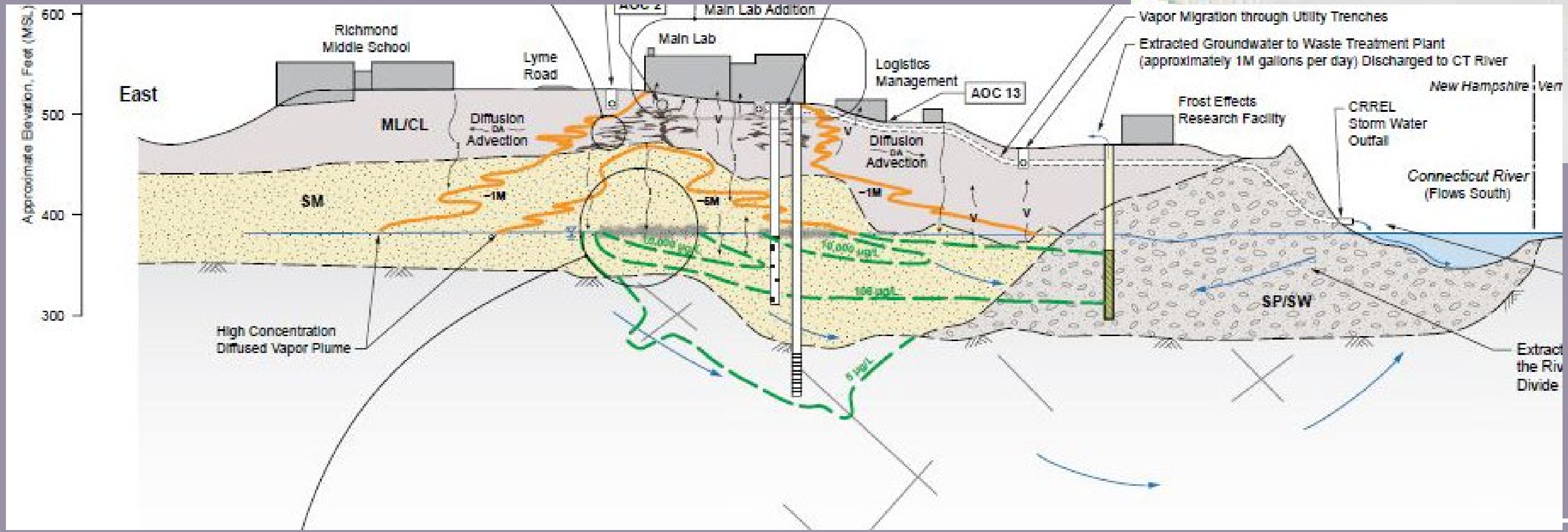
- Hanover, NH, Climate zone 4b
- Fine sands coarsening downward to bedrock
- Esker located downgradient by river
- Depth to groundwater ~ 150 ft, flat gradient



Conceptual Site Model

- TCE mass primarily in vapor phase
- Secondary source soil
- Pathway from vapor to Groundwater
- Conventional advection/ diffusion





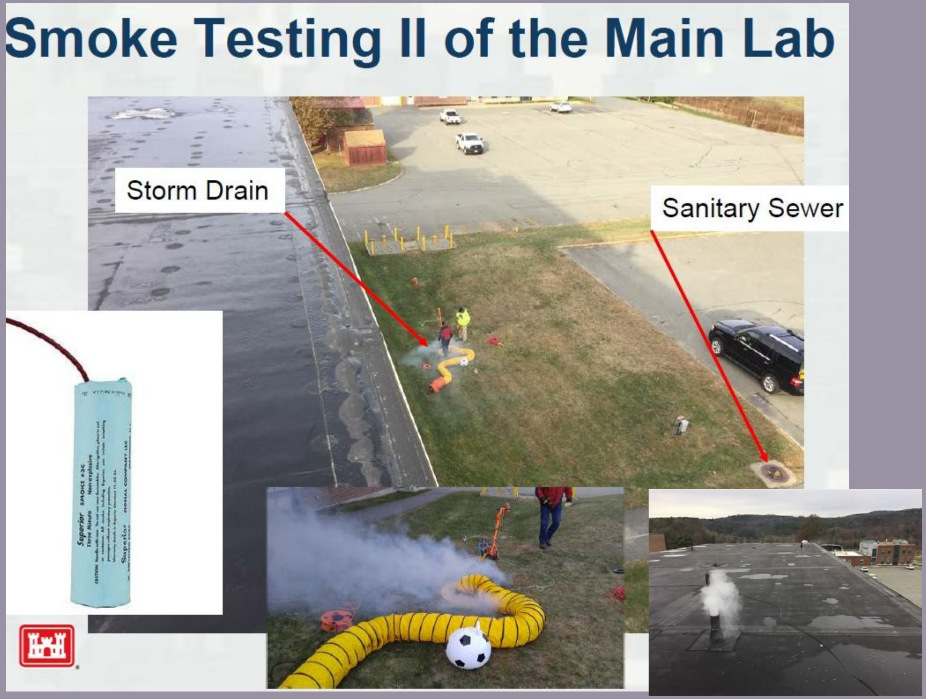
Mitigation Measures

- **1960 - 1987 - TCE released from various leaks and spills at the Cold Regions Research and Engineering Laboratory in Hanover, NH**
- **2010 - Vapor Intrusion (VI) detected in main laboratory**
- **2012 - 2014 - Carbon Air Purifier's installed in offices in**
- **2015 - Sub-slab Depressurization System (SSDS) installed**
- **2015 - 2018 – Soil Vapor Extraction (SVE) Pilot Tests conducted at two locations**
- **2016 - One-way valves installed on roof drain piping**
- **2017 - TCE pumped out of old refrigeration lines in building**
- **2018 - Smoke Test conducted and VI utility leaks fixed**
- **2019 - Refrigeration lines removed**
- **2019 – Carbon Air Purifier's installed in Plenum/Roof Truss Space**

CRREL COLD REGIONS RESEARCH AND ENGINEERING LABORATORY

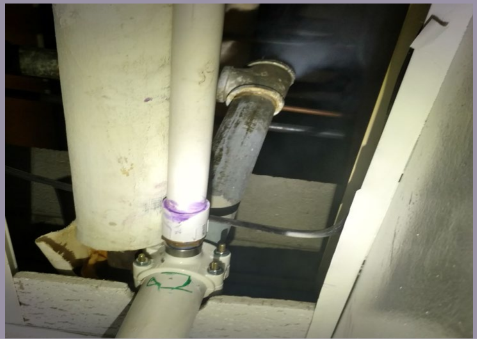
Investigation/Monitoring Information

- Initially full VOC suite analyzed
- Subsequent focus on TCE
  - Summa and HAPSITE™
- Ancillary data collected daily
  - Outside air temperature and pressure
  - Subsurface soil temperature and pressure
  - Building temperature and pressure
- HAPSITE™ Sleuthing



Toilet Seal

Sanitary Sewer Line Above Suspended Ceiling



Open Pipe Beneath Raised Floor

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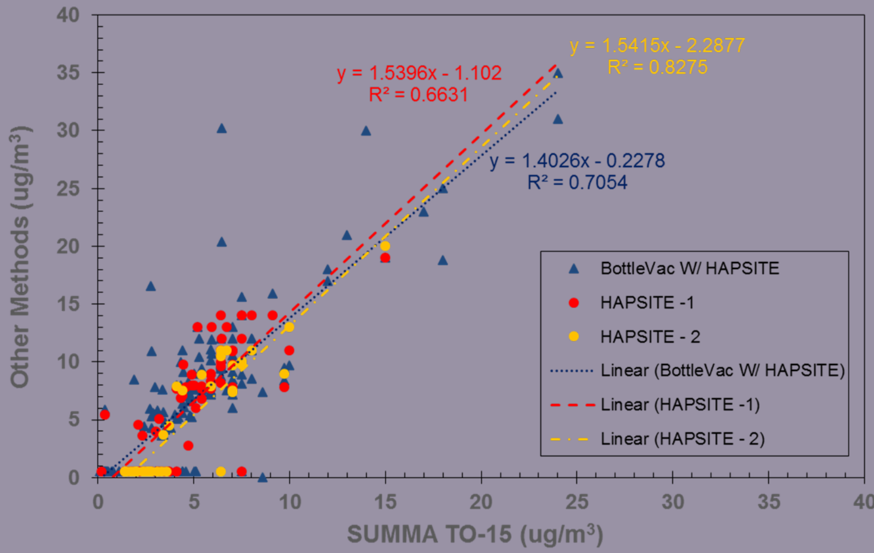
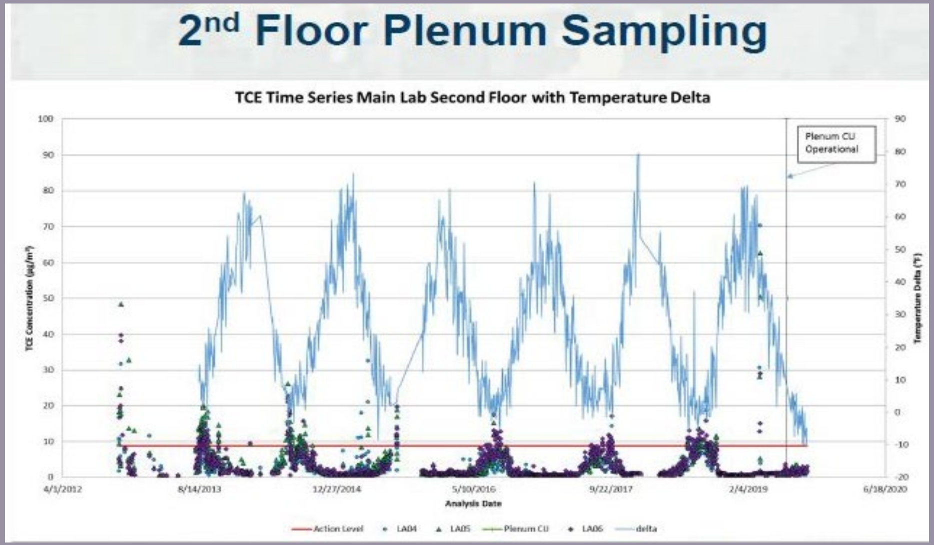
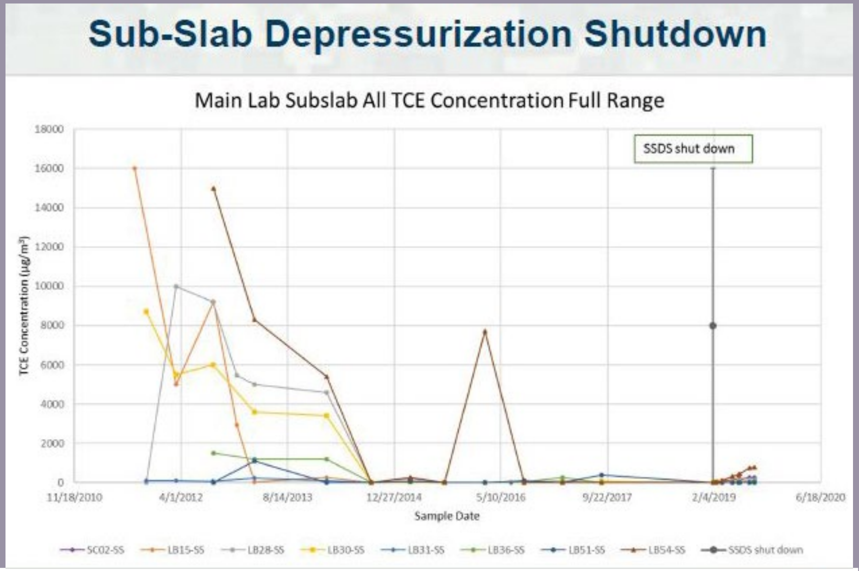
Data Analysis

- Distribution Maps
- XY Plots
- Regression Time Analysis
- Correlation Analysis



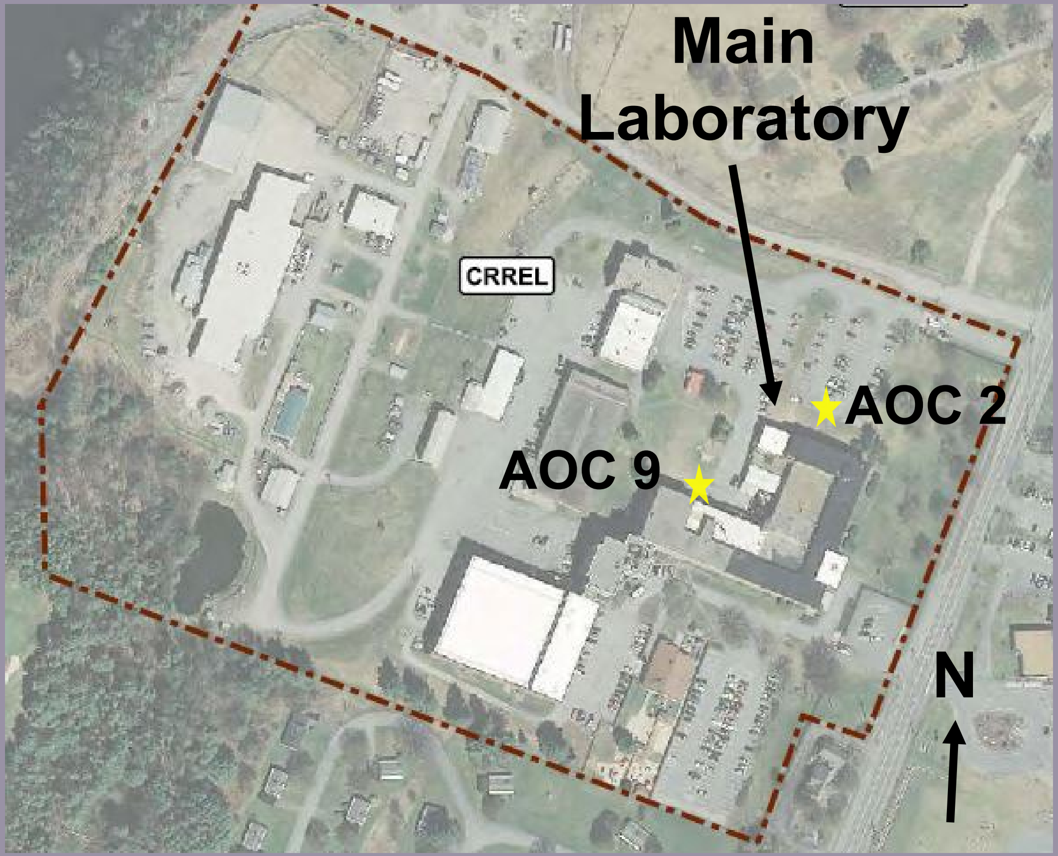


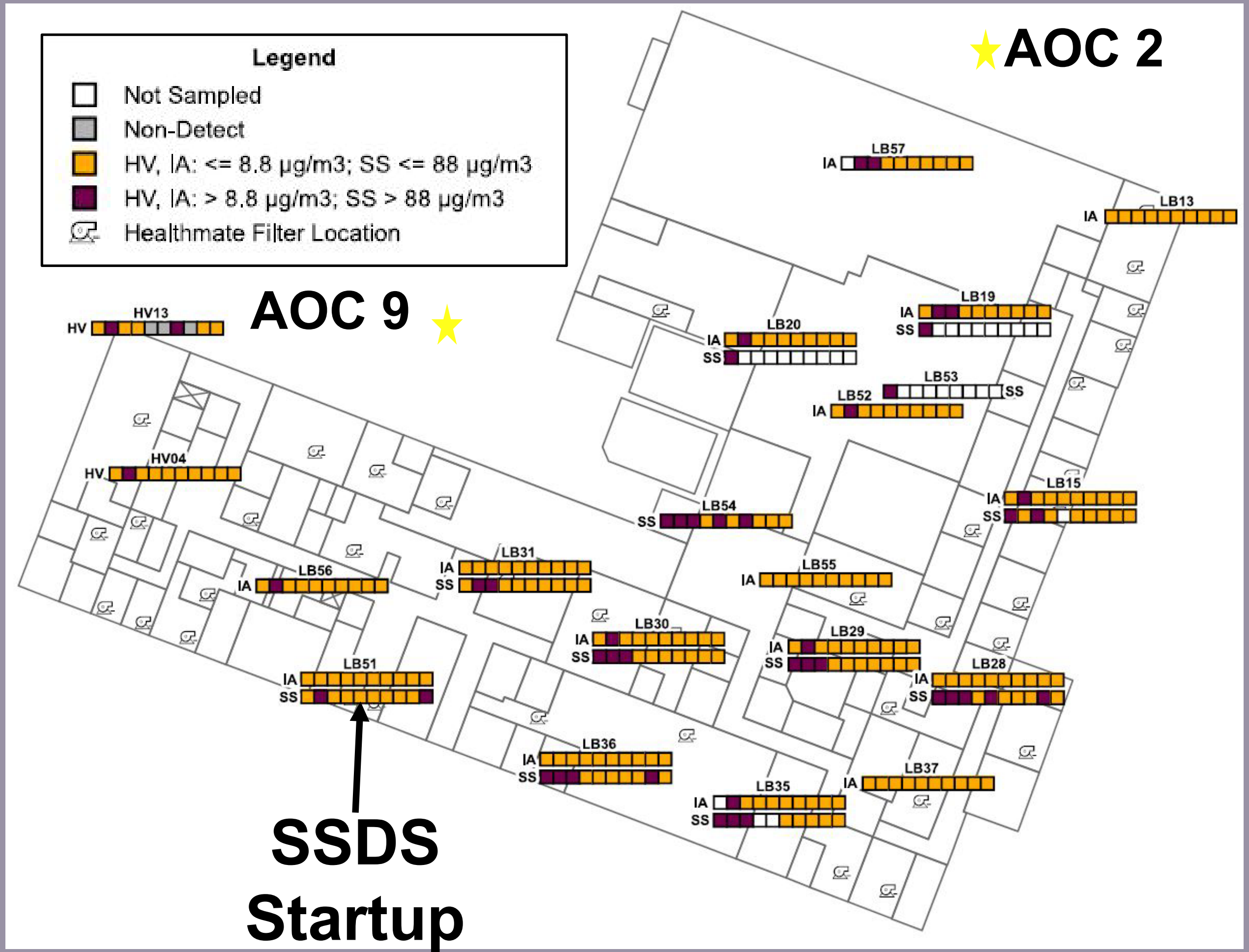


CRREL COLD REGIONS RESEARCH AND ENGINEERING LABORATORY

TCE Building Spatial Distribution

Basement TCE Levels





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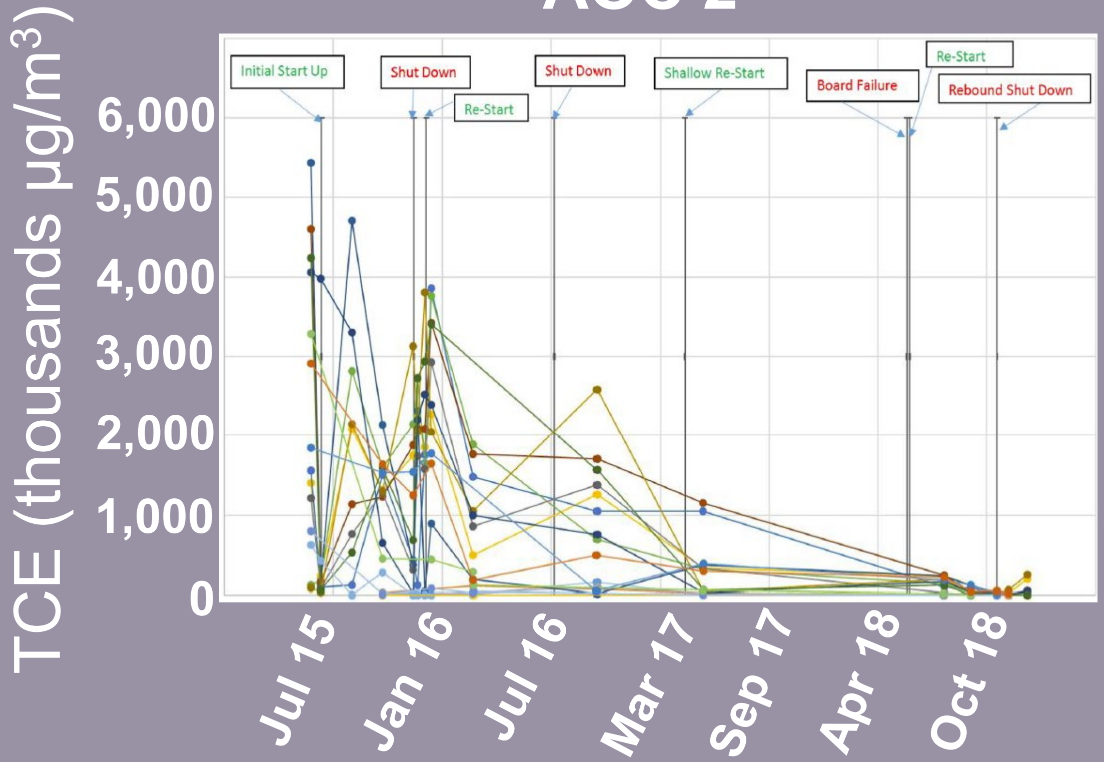
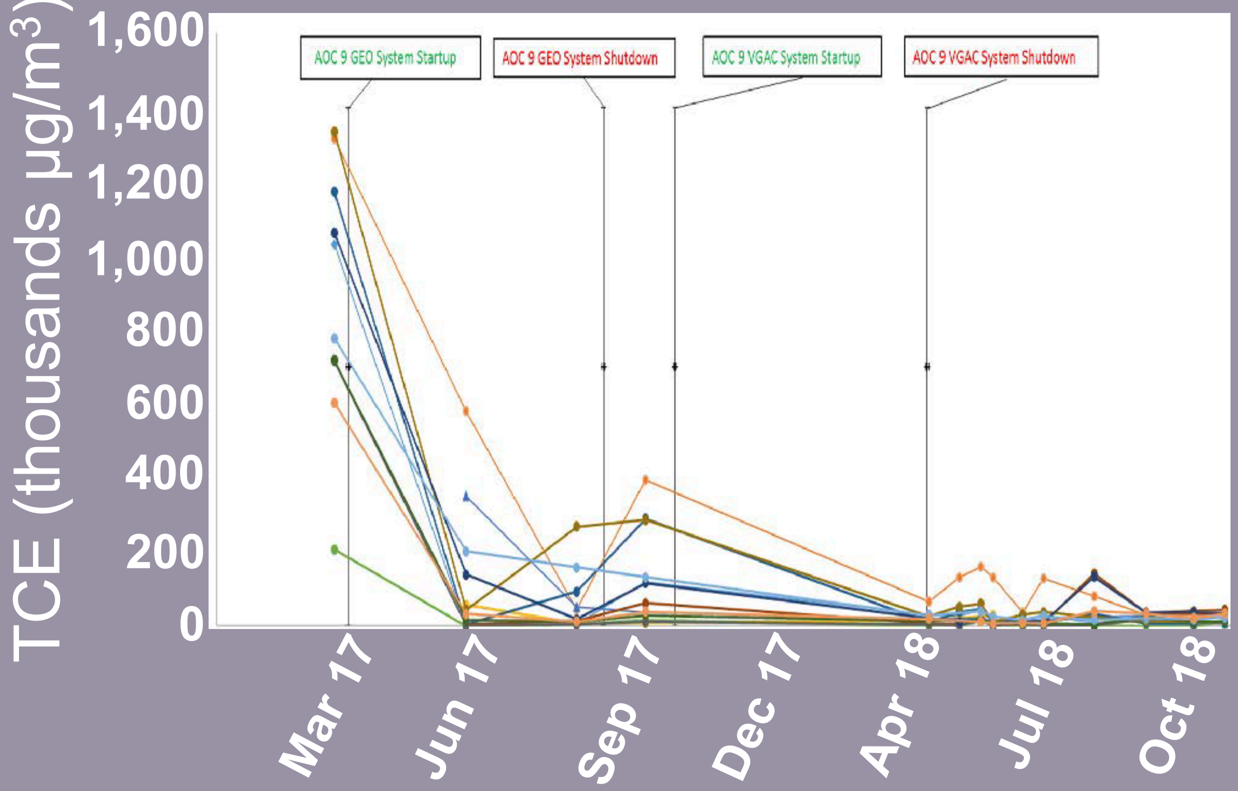
SVE Soil Gas Level Variability

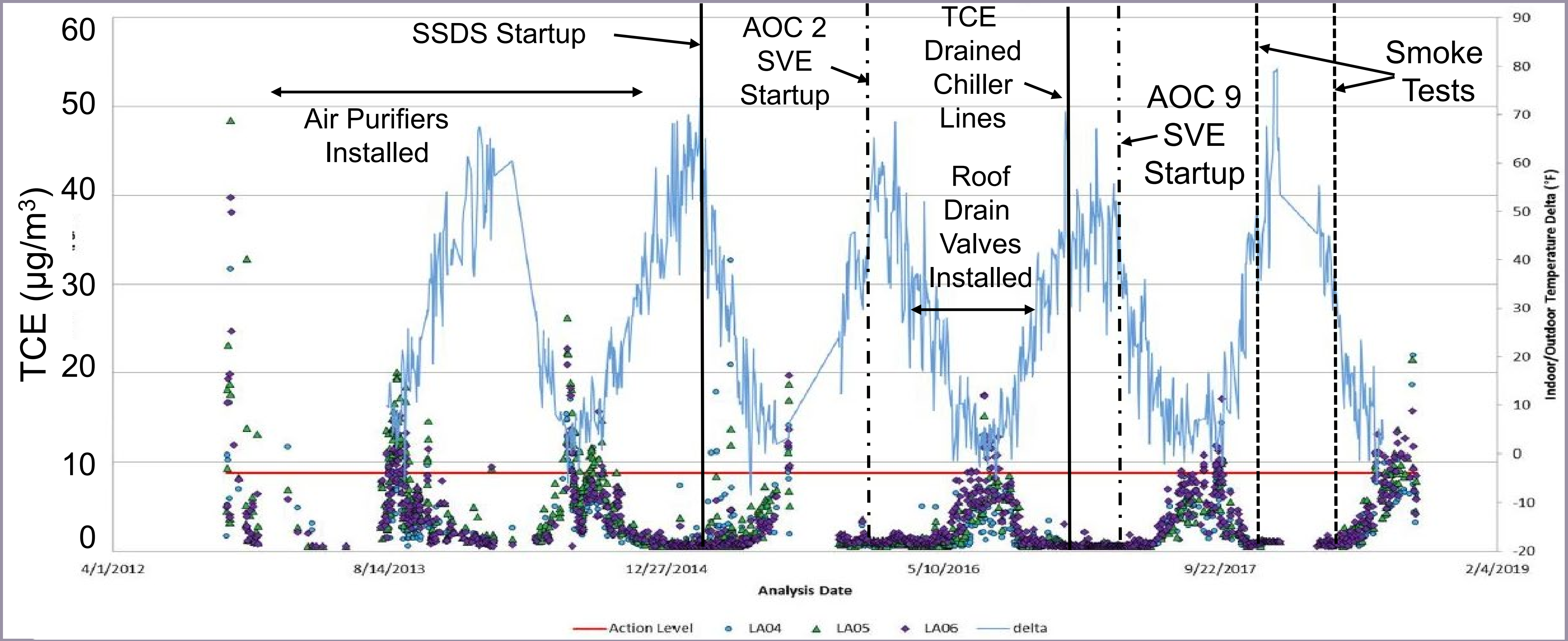
AOC 2



AOC 9



TCE Seasonal Variability (2nd Floor Main Laboratory)



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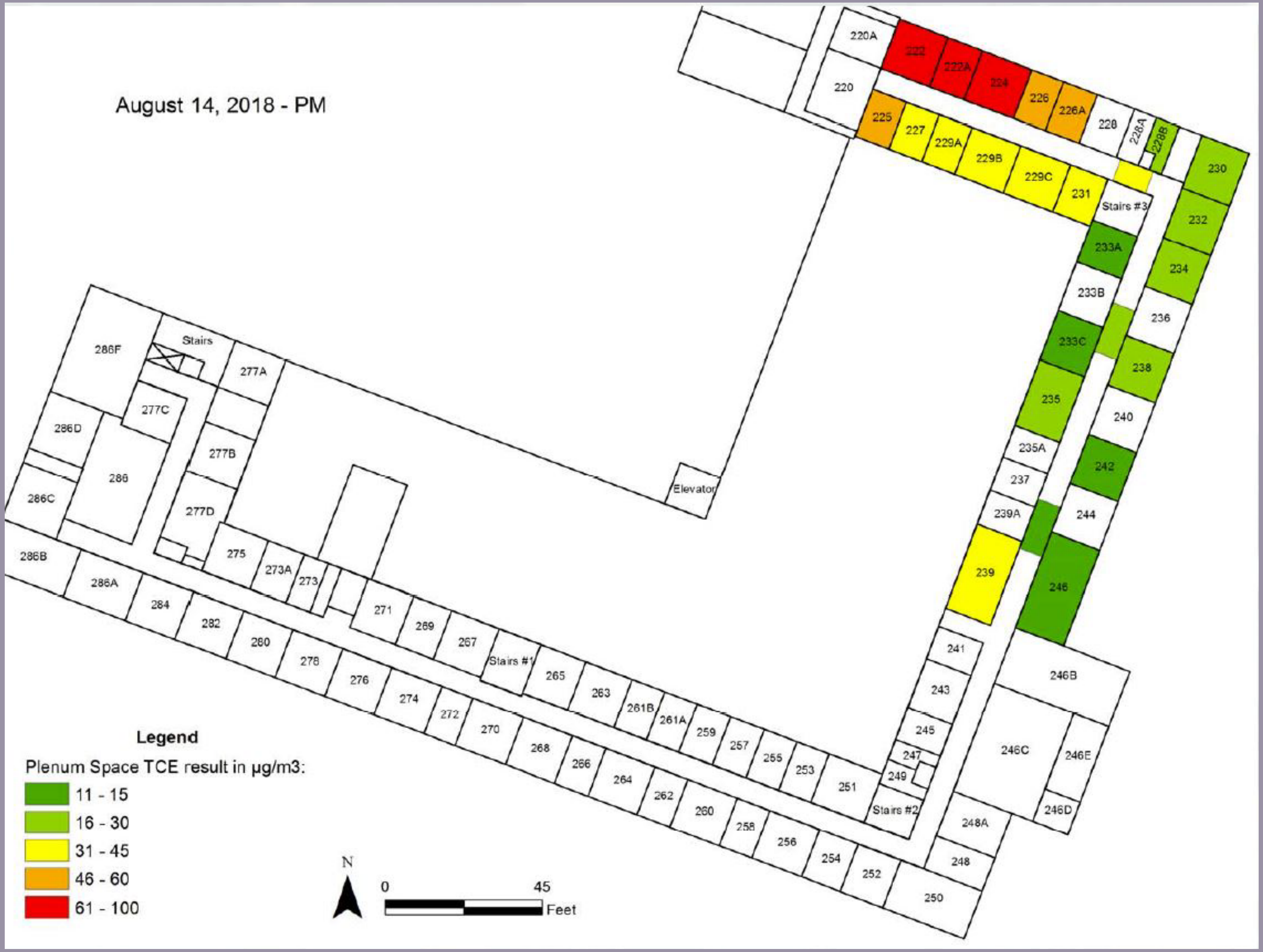
TCE Distribution in Plenum

August 14, 2018 - pm



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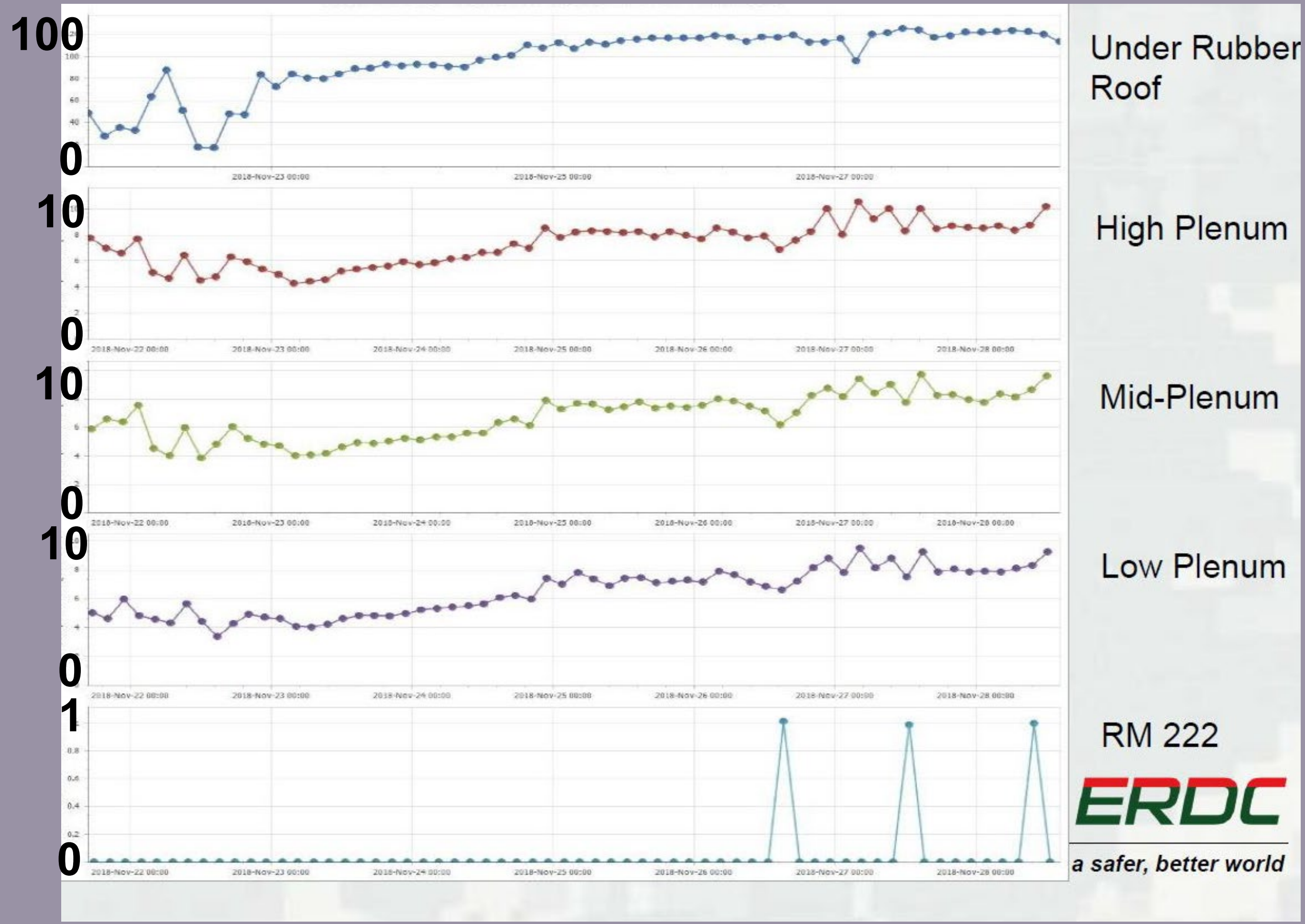
Plenum TCE Levels

TCE (µg/m³)



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Current Status

- No rebound of TCE observed at SVE pilot-test locations
- SSDS influent TCE levels below 880 ug/m^3 regulatory guideline
- SSDS TCE vapor concentrations generally below 100,000 ug/m^3
- Periodic TCE fluctuations above action levels in second floor north wing offices in late Summer, mitigated since carbon purifiers installed in plenum/truss space
- Air in roofing material space contaminated

Conclusions

- Vapor emanations along utility lines (roof drains, sewer lines, refrigeration lines), elevator shaft, from volatile back diffusion from building materials (concrete, insulation, roofing) and other sources contributed to indoor TCE
- Periodic SUMA canister sampling is insufficient for assessing VI
- Extrapolation of VI pathways from residential studies to industrial sites is inappropriate and misleading
- Term VI should be broadened to not only include emanations through sub-slab but emanations from volatile back diffusion of building materials and subsurface preferential pathways (utility lines)

Appendix B
Database Modifications Pseudocode

Database Modifications/Pseudocode Changes

1. Database

1.1 Location \\snowbird\proj\USNAVFAC\458093NESDI\NESDI_Database\Reanalysis_2_GSI\

1.2 Frontend: NESDI_VITool_v2.1.accdb

1.3 Backend: NESDI_VITool_be.accdb

1.4 Reference database: The database was updated from the version stored in \\snowbird\proj\USNAVFAC\458093NESDI\NESDI_Database\, which is more recent than the database files stored in \\Tarheel\Proj\EBL\NESDI\Reanalysis_2_GSI\Database as Delivered to Navy\ The database stored in snowbird contains the data table updates through June 2019.

2. Table Updates

2.1 Revised tables:

2.1.1 SAMPLE_ZONE_DATA. Added SAMPLING_ROUND field. This field is populated with the year and month value of the first sample collection date for the sampling round, in the format 'YYYYMM'.

2.2 New tables:

2.2.1 VERSION. Version information table created in June 2018.

2.2.2 CHANGELOG. Change log table created in June 2018

2.2.3 D_SOURCE_STRENGTH_SCREEN_TYPES. Lookup table that describes source strength screen types.

2.2.3.1 Background value for indoor air screening:

SOURCE_STRENGTH_SCREEN_TYPE	SOURCE_STRENGTH_SCREEN_TYPE_NAME
BGRD	Selected background value for the purpose of this study and for indoor air screening

2.2.3.2 Source strength database screen for subslab soil gas data:

SOURCE_STRENGTH_SCREEN_TYPE	SOURCE_STRENGTH_SCREEN_TYPE_NAME
SS10XBGRD	10X selected background value
SS50XBGRD	50X selected background value
SS100XBGRD	100X selected background value
SS500XBGRD	500X selected background value
SS1000XBGRD	1000X selected background value
SS100CV	Fixed common value of 100 µg/m3
SS500CV	Fixed common value of 500 µg/m3
SS1000CV	Fixed common value of 1,000 µg/m3

2.2.3.3 Source strength database screen for subslab soil gas data:

SOURCE_STRENGTH_SCREEN_TYPE	SOURCE_STRENGTH_SCREEN_TYPE_NAME
GW100XBGRD	100X selected background value
GW500XBGRD	500X selected background value
GW1000XBGRD	1000X selected background value
GW5000XBGRD	5000X selected background value
GW1000CV	Fixed common value of 1,000 µg/m3
GW10000CV	Fixed common value of 10,000 µg/m3
GW100000CV	Fixed common value of 100,000 µg/m3

2.2.4 D_BACKGROUND_REFERENCE_VALUES_EXTENDED. A major modification was made on the table D_BACKGROUND_REFERENCE_VALUES to allow storage of the multiple database screens identified in 2.1.3

2.2.4.1 The following fields were removed: BASE_90th, Multiple_90th, INDOOR_BG, SUBSLAB_BG, and GROUNDWATER_BG.

2.2.4.2 The following fields were added:

SOURCE_STRENGTH_SCREEN_TYPE

BACKGROUND_REFERENCE: This contains the following possible values:

INDOOR_BG, SUBSLAB_BG, or GROUNDWATER_BG

BACKGROUND_VALUE: This is the source screen value for a given source strength screen type, analyte, and background reference.

2.2.5 SAMPLE_ZONE_DATA_NESDI_FLAGS_EXTENDED. An extended version of NESDI flags table SAMPLE_ZONE_DATA_NESDI_FLAGS, modified to accommodate the requirements of the source strength screening criteria and the flag for subslab literature background by sample zone ID level and by building ID level. The following fields were added:

2.2.5.1 SOURCE_STRENGTH_SCREEN_TYPE

2.2.5.2 FLAG_SUBSLAB_LITERATURE_BACKGROUND2: This flag is equivalent to FLAG_SUBSLAB_LITERATURE_BACKGROUND, but applied at the building level.

2.2.6 SAMPLE_ZONE_ANALYSIS_EXCLUSION_LIST. List of SAMPLE_ZONE_IDs marked for exclusion in the analysis.

3. Query Updates (Business Requirements)

1. Perform analyses where different multipliers for the source strength screen (i.e. 10x, 50x, 100x the national background value for sub-slab) are explored and select the best screening multiplier for further analysis of the database. This analysis should support an attenuation factor distribution that is not significantly influenced by indoor sources.
2. Analyze and assess the effect of a common source strength screen across all compounds (i.e. 100 µg/m3, 500 µg/m3 and 1000 µg/m3)
3. Recalculate attenuation factors using only the maximum subslab concentration and maximum indoor concentration for a particular sampling round in a particular sampling zone and particular compound. Implement the source strength screen selected above on these maximum values.
4. Recalculate zone average attenuation factors after applying source strength screen only at the source zone level.
5. Recalculate attenuation factors at the building level (averaging across all sample zones in the building).

The database queries that generate the flat file were modified to implement the following database-level tasks:

3.1 The extended NESDI flags table SAMPLE_ZONE_DATA_NESDI_FLAGS_EXTENDED was updated by evaluating the following fields using the selected background value for the purpose of this study and for indoor air screening, source strength database screen for subslab soil gas data, and source strength database screen for groundwater data:

3.1.1 FLAG_INDOOR_LITERATURE_BACKGROUND. This field is flagged with ‘Yes’ for the data record of an indoor air sample if the sample zone result value is less than or equal to (<=) the

selected background value for the purpose of this study and for indoor air screening, otherwise 'No'.

3.1.2 FLAG_SUBSLAB_LITERATURE_BACKGROUND. This field is flagged with 'Yes' for the data record of an indoor air sample if the average subslab results at the sample zone level for a particular sampling round where samples are collected within 30 days is less than (<) the selected subslab literature background value, otherwise 'No'. If a particular subslab port in the sample zone is non-detect then it is averaged at the reporting limit.

3.1.3 FLAG_SUBSLAB_LITERATURE_BACKGROUND2. This new field is flagged with 'Yes' for the data record of an indoor air sample if the maximum subslab results at the building level is less than (<) the selected subslab literature background value, otherwise 'No'.

3.1.4 FLAG__MEASURED_GROUNDWATER_LITERATURE_BACKGROUND. This field is flagged with 'Yes' for the data record of an indoor air sample if the sample zone measured maximum groundwater vapor source concentration is less than the selected groundwater literature background value, otherwise 'No'.

3.1.5 FLAG__INTERPOLATED_GROUNDWATER_LITERATURE_BACKGROUND. This field is flagged with 'Yes' for the data record of an indoor air sample if the sample zone interpolated maximum groundwater vapor source concentration is less than the selected groundwater literature background value, otherwise 'No'.

3.2 The following NESDI flags did not change and the values were brought over from the original table.

3.2.1 FLAG_SUBSLAB_ND

3.2.2 FLAG_GROUNDWATER_INTERPOLATED_MAX_ND

3.2.3 FLAG_GROUNDWATER_MEASURED_MAX_ND

3.2.4 FLAG_BACKGROUND_REPORTED_INDOOR_SOURCE

3.2.5 FLAG_BACKGROUND_REPORTED_RATIO

3.2.6 FLAG_BACKGROUND_SITE_AMBIENT

3.2.6.1 FLAG_OTHER. Other results flagged for reasons identified in notes.

3.3 The flat file export summary was modified by

3.3.1 including the following new fields:

3.3.2 SOURCE_STRENGTH_SCREEN_TYPE. Source strength screening criteria

3.3.3 SUBSLAB_LIT_BACKGROUND_BASIS. This field either has SAMPLE_ZONE_ID or BUILDING_ID as basis for determining the subslab results less than the criteria literature indoor air background.
RunDate. The date and time the flat file was generated.

3.3.4 The table ZoneSourceType_Lutes was excluded in the flat file output criteria. The Classification field from this table was subsequently dropped from the output.

3.3.5 Sample zones from the exclusion list were excluded in the output.

3.3.6 Two binary Excel files for analysis are generated:

3.3.6.1 FlatFile_dbReanalysis2_SAMPZONE_mmddyy.xlsb – Output of all source strength screening criteria where the subslab literature background is determined by SAMPLE_ZONE_ID.

3.3.6.2 FlatFile_dbReanalysis2_BUILDING_mmddyy.xlsb – Output of all source strength screening criteria where the subslab literature background is determined by BUILDING_ID.

Appendix C
Selection of Background Values

APPENDIX C

Background Volatile Organic Compound Values in Indoor Air

Review and Selection for Deriving Source Strength Screens and Filtering Data in the DoD Vapor Intrusion Database of Commercial and Industrial Buildings

Background VOC values in indoor air were selected for deriving source strength screens used for filtering data in the Department of Defense (DoD) vapor intrusion (VI) database of commercial and industrial buildings (DOD VI Industrial Database). These values were selected using several background indoor air studies in both residential and commercial (or other nonresidential) settings (**Table C.1**). No other North American nonresidential building studies beyond those discussed in this appendix were readily available in a suitable format at the time this review was conducted.

On the basis of these studies, background values were selected as follows:

- Trichloroethene (TCE), tetrachloroethene (PCE), and 1,1,1-trichloroethane (1,1,1-TCA) – The previous quantitative data analysis (Venable et al., 2015) used the 90th percentile concentrations of United States Environmental Protection Agency (USEPA)'s Building Assessment and Survey Evaluation (BASE) study indoor air distribution (NYSDOH, 2006, Appendix C, Section C.2, Table C2; USEPA, 2017, 2020).[1] The BASE study database was derived using sampling data obtained in 1994-1998 from 100 randomly selected public and commercial office buildings in the United States. Because these data are approximately 10 or more years older than the sampling data in the DOD VI Industrial Database (2008-2017), it was decided that that the reference background concentrations should be lowered to account for the reduction in TCE, PCE, and 1,1,1-TCA background concentrations observed over time in both residential and nonresidential settings, as supported by recent data (MTDEQ, 2012, Table 4.0.1; Rago et al., 2014; Rago, 2015; **Table C.1**), as well as time series of both background indoor air concentrations (USEPA, 2011, Figures 1 and 2) and ambient (outdoor) air concentrations (USEPA, 2019, Exhibit 9). To account for this reduction, background values equal to half of the 90th percentile BASE concentrations were used for TCE, PCE, and 1,1,1-TCA, corresponding to 2.1, 8.0, and 10.3 micrograms per cubic meter (μg/m^3), respectively. For PCE and TCE, these values are greater than the 90th and 95th percentile values derived by Rago's larger commercial and school building study (Rago, 2015; **Table C.1**) and are consistent with those obtained in another recent study (Loh et al., 2006 Figure 1, Table S1), where the geometric means of TCE and PCE concentrations in indoor air from retail stores ranged from 0.03 to 1.10 μg/m^3 and from 0.47 to 2.96 μg/m^3, respectively (no percentile concentrations were provided).
- 1,1-dichloroethane (1,1-DCA), 1,1-dichloroethene (1,1-DCE), cis-1,2-dichloroethene (cis-1,2-DCE), vinyl chloride (VC) – The BASE study 90th percentiles for these four compounds were below detectable levels (**Table C.1**). Because 1990s-era reporting limits were relatively elevated, the median of 90th percentile concentration from the USEPA residential study compilation was used as a substitute (USEPA, 2011, Table ES-1; USEPA, 2012, Table 5; **Table C.1**). Accordingly, background values remain below reporting limits for 1,1-DCA and cis-1,2-DCE but yield detectable levels for 1,1-DCE and VC (0.8 and 0.01 μg/m^3, respectively) (**Table C.1**).
- 1,2-DCA – The BASE study 90th percentile background concentration for this compound was below reporting limit (**Table C.1**) and the 90th percentile concentrations from the USEPA residential study compilation did not

[1] The use of the 90th percentile values is consistent with the approach in the USEPA VI database study (USEPA, 2012, Table 5), which used a median of the 90th percentile background concentration in North American residences (USEPA, 2011, Table ES-1).

exceed 0.4 µg/m^3 with a median of 0.1 µg/m^3 (USEPA, 2011, Table ES-1; USEPA, 2012, Table 5; **Table C.1**). More recent sampling data, however, indicate an increase in indoor air concentrations for this compound (MTDEQ, 2012, Table 4.0.1; Rago, 2015; **Table C.1**), which reflects the presence of 1,2-DCA in plastic products observed in recent years (e.g., Doucette et al., 2010; Simms et al., 2019). As a result, a background value of 0.34 µg/m^3 was used, which is the 95th percentile concentration of the Rago study (Rago, 2015; **Table C.1**).

- trans-1,2-Dichloroethene (trans-1,2-DCE) – Neither residential nor nonresidential studies reported background levels above reporting limits for this VOC; however, there is some evidence to suggest trans-1,2-DCE can be found in indoor air at background concentrations due to its usage as a solvent and specialty cleaner (e.g., ICF Consulting, 2004, Section 4.2.3; Axiall, 2016). Although no background value was set for the purpose of this project, fixed source strength screens are able to filter out potential background contributions related to this VOC.

The use of background data from residential building studies is not ideal, but provide useful information when background nonresidential data are not available, because of the following:

- Many products for cleaning, pest control, and general maintenance or repairs are purchased from the same sources for both residential and commercial uses. Cosmetics, cooking, building materials, furniture, and human exhalation are all examples of VOC sources that are present to varying extents in many residential and commercial environments; however, air exchange rates and building volumes are often different for residential and commercial (or other nonresidential) structures.
- Other than office buildings or schools (and other institutional buildings), it can be difficult to find industrial/commercial buildings with no possibility of previous industrial use of VOCs that are geographically separated from other industrial users of VOCs, and thus are certain to be representative of "background" conditions.

Note that the choice made to use the residential background data when the BASE study had 90th percentile concentrations below reporting limit have limited impact, because there were only two VOCs for which it was needed: VC and 1,1-DCE. These two compounds are not featured extensively in the original DoD VI database evaluation (Venable et al., 2015), although they are discussed in places. In each case, the residential 90th percentile result was less than the BASE study reporting limit.

References

Axiall. 2016. *Product Stewardship Summary: VersaTRANS Solvent*. Edition 2. October. Accessed September 21, 2020. https://www.westlake.com/sites/default/files/VersaTRANS%20Summary%20Ed1.pdf.

Doucette, W.J., A.J. Hall, and K.A. Gorder. 2010. "Emissions of 1,2-Dichloroethane from Holiday Decorations as a Source of Indoor Air Contamination." *Ground Water Monitoring & Remediation*. Vol. 30, No. 1. pp. 65-71. Accessed November 1, 2019. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1013.1487&rep=rep1&type=pdf.

ICF Consulting. 2004. *The U.S. Solvent Cleaning Industry and the Transition to Non Ozone Depleting Substances*. Prepared for the U.S. Environmental Protection Agency. September. Accessed September 21, 2020. https://www.epa.gov/sites/production/files/2014-11/documents/epasolventmarketreport.pdf.

Loh, M.M., E.A. Houseman, G.M. Gray, J.I. Levy, J.D. Spengler, and D.H. Bennett. 2006. "Measured Concentrations of VOCs in Several Non-residential Microenvironments in the United States." *Environmental Science & Technology*. Vol. 40, No. 22. pp. 6903-6911. Accessed November 1, 2019. https://pubs.acs.org/doi/abs/10.1021/es060197g.

Massachusetts Department of Environmental Protection (MassDEP). 2008. *Residential Typical Indoor Air Concentrations*. October. Accessed October 31, 2019. https://www.mass.gov/files/documents/2016/08/xi/iatu.pdf.

Montana Department of Environmental Quality (MTDEQ). 2012. *Typical Indoor Air Concentrations of Volatile Organic Compounds in Non-Smoking Montana Residences Not Impacted by Vapor Intrusion*. August. Accessed October 31, 2019. https://deq.mt.gov/Portals/112/Land/StateSuperfund/Documents/VI_guide/CompleteIndoorVOCReport.pdf.

New Jersey Department of Environmental Protection (NJDEP). 2016. *Background Levels of Volatile Organic Chemicals in Homes: A Review of Recent Literature*. August. Accessed October 29, 2019. https://www.nj.gov/dep/srp/guidance/vaporintrusion/vig_background_levels_of_vos.pdf.

New York State Department of Health (NYSDOH). 2006. *Guidance for Evaluating Soil Vapor Intrusion in the State of New York.* Center for Environmental Health, Bureau of Environmental Exposure Investigation. Final. October. Accessed October 29, 2019. https://www.health.ny.gov/environmental/investigations/soil_gas/svi_guidance/.

Rago, R.J., J.P. Kullman, and A. Rezendes. 2014. "Background Indoor Air Levels of Volatile Organic Compounds (VOCs) and Air-Phase Petroleum Hydrocarbons (APH) in Office Buildings, Commercial Buildings, and Schools." *In Proceedings Ninth International Conference on Remediation of Chlorinated and Recalcitrant Compounds*. Monterey, CA. May 19-22. Accessed October 31, 2019. https://www.battelle.org/conference-proceedings/conference-proceedings.

Rago, R.J. 2015. "Background Indoor Air Levels of Volatile Organic Compounds and Air Phase Petroleum Hydrocarbons in Office Buildings and Schools." Presented at the Environmental Business Council of New England, Inc. (EBC) Site Remediation & Redevelopment Program "Vapor Intrusion – What's in the Air These Days," Woburn, MA. June 26. Accessed October 31, 2019. https://www.haleyaldrich.com/Portals/0/Downloads/vapor-intrusion-ebcne-june-2015.pdf.

Simms, J., C. Lutes, and L. Lund. 2019. "Distinguishing Indoor Source Effects from Preferential Pathway and Conventional Vapor Intrusion." Presented at the 29th Annual International Conference on Soil, Water, Energy, and Air, Association for Environmental Health and Sciences (AEHS), San Diego, CA, March 18-21.

United States Environmental Protection Agency (USEPA). 2011. *Background Indoor Air Concentrations of Volatile Organic Compounds in North American Residences (1990-2005): A Compilation of Statistics for Assessing Vapor Intrusion*. Office of Solid Waste and Emergency Response (OSWER), EPA 530-R-10-001. June. Accessed February 18, 2019. https://www.epa.gov/sites/production/files/2015-09/documents/oswer-vapor-intrusion-background-report-062411.pdf.

USEPA. 2012. *EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings*. Office of Solid Waste and Emergency Response (OSWER), EPA 530-R-10-002. March 16. Accessed September 19, 2019. https://www.epa.gov/sites/production/files/2015-09/documents/oswer_2010_database_report_03-16-2012_final_witherratum_508.pdf.

USEPA. 2017. *Overview of the Building Assessment Survey and Evaluation Study*. Office of Radiation and Indoor Air, Indoor Environments Division. February 22. Accessed September 17, 2020. https://www.epa.gov/indoor-air-quality-iaq/overview-building-assessment-survey-and-evaluation-study

USEPA. 2019. *Ambient Concentrations of Selected Air Toxics*. September 12. Accessed September 17, 2020. https://cfpub.epa.gov/roe/indicator.cfm?i=90.

USEPA. 2020. *Summarized Data of the Building Assessment Survey and Evaluation Study.* Office of Radiation and Indoor Air, Indoor Environments Division. July 16. Accessed September 17, 2020. https://www.epa.gov/indoor-air-quality-iaq/summarized-data-building-assessment-survey-and-evaluation-study.

Venable, P., T. Chaudhry, D. Caldwell, I. Rivera-Duarte, C. Lutes, L. Lund, and K. Hallberg. 2015. *A Quantitative Decision Framework for Assessing Navy Vapor Intrusion Sites*. Naval Facilities Engineering Command (NAVFAC) Engineering and Expeditionary Warfare Center (EXWC), TR-NAVFAC-EXWC-EV-1603. June. Accessed September 19, 2019. https://clu-in.org/download/issues/vi/TR-NAVFAC-EXWC-EV-1603.pdf.

Table C.1 Review of Indoor Air Background Concentration Information Found in the Literature

Analyte[a]	BASE study indoor air distribution (NYSDOH, 2006, Appendix C, Section C.2, Table C2)[b]		BASE study indoor air distribution (USEPA, 2017, 2020)[c]	Concentrations from multiple residential studies (USEPA, 2011, Table ES-1)[d]		Residential concentrations used in USEPA VI database (USEPA, 2012, Table 5)	Residential concentrations from New Jersey review (NJDEP, 2016, Table G-2)[e]	Residential concentrations from Massachusetts review (MassDEP, 2008, Table 1)[f]	Residential concentrations from Montana study (MTDEQ, 2012, Table 4.0.1)[g]		Office and school building study (Rago et al., 2014)[h]	Office and school building study (Rago, 2015)[i]		Selected background value for the purpose of this study and for indoor air screening	Rationale for Selected Value
	90th percentile	95th percentile	95th percentile	Range of 90th percentiles	Range of 95th percentiles	Median of 90th percentiles	Range of 90th percentiles	90th percentile	90th percentile	95th percentile	95th percentile	90th percentile	95th percentile		
1,1,1-Trichloroethane	20.6	33.0	21	<RL-68	3.4-28	3.1	<RL-5.5	3.0	<1.0	<1.7	0.30	N/A	N/A	10.3	Historical background values from the BASE study (which is based on data from the mid-1990s) have likely decreased over the past 25 years, as supported by more recent (but limited) data (MTDEQ, 2012; Rago, 2014). The selected value is half the 90th percentile BASE concentration and corresponds to about three times the median 90th concentration from the USEPA residential study (USEPA, 2012, Table 5).
1,1-Dichloroethane	<0.7	<0.8	<LOQ	<RL	<RL	<RL	<RL-43.21	ND	<0.98	<1.3	N/A	N/A	N/A	<RL	Below RL in most studies.
cis-1,2-Dichloroethene	<1.9	<2.0	N/A	<RL	<RL-1.2	<RL	<RL	ND	<0.98	<1.3	N/A	N/A	N/A	<RL	Below RL in most studies.
trans-1,2-Dichloroethene	N/A	N/A	N/A	<RL	<RL	<RL	<RL	ND	<0.98	<1.3	N/A	N/A	N/A	<RL	Below RL in all studies.
Tetrachloroethene	15.9	25.4	18	<RL-7	4.1-9.5	3.8	<RL-4.5	4.1	2.3	2.8	8.2	1.8	1.8	8.0	Historical background values from the BASE study (which is based on data from the mid-1990s) have likely decreased over the past 25 years, as supported by more recent (but limited) data (MTDEQ, 2012; Rago, 2015). The selected value is half the 90th percentile BASE concentration and corresponds to about twice the median 90th concentration from the USEPA residential study (USEPA, 2012, Table 5).
Trichloroethene	4.2	6.5	2.6	<RL-2.1	0.56-3.3	0.5	<RL-0.9	0.8	0.58	1.3	24.6	0.53	0.53	2.1	Historical background values from the BASE study (which is based on data from the mid-1990s) have likely decreased over the past 25 years, as supported by more recent (but limited) data (MTDEQ, 2012; Rago, 2015). The selected value is half the 90th percentile BASE concentration and corresponds to about two and half times the median 90th concentration from the USEPA residential study (USEPA, 2012, Table 5).
Vinyl Chloride	<1.9	<2.2	<LOQ	<RL-0.04	<RL-0.09	0.01	<RL-0.03	ND	<0.049	<0.064	N/A	N/A	N/A	0.01	Historical background values from the BASE study (which is based on data from the mid-1990s) are below RL, but residential studies show detections at the 90th percentile. The selected value is based on the median 90th concentration from the USEPA residential study (USEPA, 2012, Table 5).
1,1-Dichloroethene	<1.4	<1.6	<LOQ	<RL-0.8	0.7	0.8	<RL-0.83	ND	<0.98	<1.3	N/A	N/A	N/A	0.8	Historical background values from the BASE study (which is based on data from the mid-1990s) are below RL, but residential studies show detections at the 90th percentile. The selected value is based on the median 90th concentration from the USEPA residential study (USEPA, 2012, Table 5).
1,2-Dichloroethane	<0.9	<1.0	<LOQ	<RL-0.4	<RL-0.2	0.1	<RL-0.15	ND	0.82	1.2	N/A	N/A	0.34	0.34	Historical background values from the BASE study (which is based on data from the mid-1990s) are below RL, but more recent (but limited) data show detections at the 90th or 95th percentile (MTDEQ, 2012; Rago, 2015). The selected value is based on the 95th percentile concentration from the Rago study (Rago, 2015).

[a] All values reported in micrograms per cubic meter ($\mu g/m^3$)
[b] 100 public and commercial office buildings in the US, sampled in 1994-1996, generally three VOC samples per building
[c] 100 private/commercial, government, and academic buildings, sampled in 1994-1998, three locations per building sampled for VOCs
[d] Review of 15 studies of North-American residences sampled in 1990-2005, total 2898 samples documented in USEPA VOC background study compilation report (USEPA, 2011, Table 1, Appendix C)
[e] Review of 10 residential studies for homes sampled in 1990-2006, similar to USEPA compilation study (USEPA, 2011)
[f] Review of 8 US residential studies, similar to USEPA and NJDEP compilation studies (USEPA, 2011; NJDEP, 2016)
[g] 50 non-smoking residences in both urban and rural parts of Montana, one sample per residence collected in March 2012
[h] 10 offices and 10 schools in Massachusetts, some multiple floors, sampled winter 2013, total 37 samples
[i] 59 office building samples (professional, academic, municipal) and 25 school building samples (K-8, middle and high school, university), 20 collected in winter 2003 (Massachusetts) and 64 in 2014-2015 (multi-state)
< = less than
BASE = Building Assessment and Survey Evaluation
LOQ = limit of quantitation
N/A = not available
ND = not detected
RL = reporting limit
US = United States
USEPA = United States Environmental Protection Agency
VI = vapor intrusion
VOC = volatile organic compound