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Measuring the Removal of Trichloroethylene from Phytoremediation Sites at Travis and Fairchild Air Force Bases

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MEASURING THE REMOVAL OF TRICHLOROETHYLENE FROM PHYTOREMEDIATION SITES AT TRAVIS AND FAIRCHILD AIR FORCE BASES

by

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ABSTRACT

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by

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Past use of trichloroethylene (TCE) as a degreasing solvent for aircraft maintenance has resulted in widespread groundwater contamination at Air Force Bases around the world. Travis AFB in California and Fairchild AFB in Washington are evaluating phytoremediation as a treatment option, since trees have been reported to take up dissolved TCE from shallow groundwater and volatilize it to the atmosphere while enhancing the volatilization of TCE from surrounding soil. Previous studies generally focused on the identification of removal mechanisms. The emphasis of this research was to quantify total TCE removal from phytoremediation demonstration plots at Travis and Fairchild AFBs.

Tree cores, collected using an increment borer and analyzed using headspace GC/MS, were used to determine the relative TCE concentrations within the plume beneath the trees and to estimate the mass of TCE in each tree. To estimate the volatilization of TCE from leaves, a small section of tree branch was placed inside a flow-through glass chamber. Continuous air flow through the chamber maintained normal transpiration and temperature. Air exiting the chamber was sampled for TCE using Tenax® tubes. Humidity probes placed at the chamber entry and exit were used to estimate transpiration. Volatilization of TCE from tree trunk and soil surfaces was measured by enclosing a section of trunk or ground surface within a small stainless steel chamber. Fans in the chamber mixed the air that was recirculated through Tenax® tubes to continuously remove TCE. After a measured time interval, the Tenax® tubes were analyzed for TCE by thermal desorption GC/MS.

By using a Thiessen polygon method, the removal of TCE was estimated to be 839 g/yr at Travis and 18 g/yr at Fairchild with the majority from leaf and soil volatilization. Soil surface volatilization of TCE was greater inside the planted areas than outside the planted areas, indicating that the trees enhance this removal by this mechanism. Based on these estimates phytoremediation removed 5 and 50% of the mass of TCE in the groundwater at Fairchild and Travis Air Force sites, respectively.

(113 pages)

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

The widespread use of trichloroethylene (TCE) in chemical processing and as a degreasing solvent has caused it to become a common contaminant in groundwater. Since TCE has often been used in aircraft maintenance operations, many Air Force bases around the United States and the world have TCE groundwater contamination; however, the focus of this thesis is confined to two specific Air Force bases. TCE does not readily degrade under aerobic conditions and when introduced into the environment can form a dense, non-aqueous phase liquid (DNAPL) that is very difficult and costly to remediate. The Air Force Center for Engineering and the Environment (AFCEE) has invested a great deal of research into developing and investigating alternative remediation mechanisms to replace or enhance the expensive and somewhat inefficient techniques that have historically been used for TCE contaminated site remediation, such as pump and treat systems, barrier walls, and trenches (Mitretek Systems, 1999).

One technology that the Air Force has evaluated within the last decade is phytoremediation. Phytoremediation is defined as the use of trees to clean up or control the spread of groundwater contaminants. This method has gained considerable attention because of its apparent effectiveness and relatively inexpensive capital and maintenance costs. As many as six bases around the country have on-going phytoremediation demonstration sites where feasibility studies are underway including Travis Air Force Base in California and Fairchild Air Force Base in Washington, which are the subjects of this research (Parsons, 2005a). These sites were considered to be great candidates for phytoremediation since they are located in climates with hot, dry summers that make the trees more likely to depend on groundwater to meet their metabolic needs since surface water supplies are limited.

Studies have shown that trees not only take up volatile organic compounds (VOCs) such as TCE from shallow groundwater (Burken and Schnoor, 1998), but they can also volatilize it through the trunk (Ma and Burken, 2003) and leaves (Burken and Schnoor, 1998; Newman et al., 1999) while potentially enhancing volatilization through the nearby soil (Smith, Tisdale, and Cho, 1996; Marr et al., 2006; Andersen et al., 2008). Metabolism within trees is another potential mechanism that could contribute to the removal of TCE, but limited field data suggests it is small (10 to 20 %) relative to the amount removed by volatilization (Doucette et al., 2003; Burken et al., 2005). The ability of trees to act as a sorptive reservoir for TCE is another potential mass removal process that has not been adequately evaluated but will be assessed in this study. The term “sorption” will be used to encompass the material adsorbed and absorbed by the tree as well as the material contained within the transpiration stream since tree core samples operationally include mass of TCE from these sources.

Despite numerous field studies, few have attempted to predict the total amount of TCE that is or could be removed from a specific site using phytoremediation although Wang et al. (2004) tried to quantitate the removal of carbon tetrachloride from a site through leaf, trunk, and soil volatilization, using different methodologies. Studies such as this, although site specific, are valuable to the Air Force and others with similar projects because they provide a means of estimating the effectiveness of such a system and remediation timeframes at a site using phytoremediation technology.

There are several important limitations associated with this project that affect the accuracy of the estimations presented. The budget allowed for only three sampling trips to each site where a small percentage of the trees were sampled. More frequent trips with many trees sampled would be more appropriate. The groundwater data were collected by Parsons from 13 existing wells at Travis and three existing wells at Fairchild during various years. At Travis, there were inconsistencies with the specific wells that were sampled each year, so only 2004 and 2009 data were used since all the wells in or near the site were sampled at these times. At Fairchild, the problem was the small number of wells that are being used to make calculations for the entire site. The most recent soil data are from 2001 and are considered to have questionable accuracy. Without accurate soil data, it is difficult to verify what percentage of the TCE may be sorbed to the soil.

Objectives

The main purpose of this research is to quantify TCE removal from the groundwater at Travis and Fairchild Air Force Base sites through leaf, trunk, and soil surface volatilization as well as through sorption within the trees. The amount of TCE removed by metabolism was not evaluated due to budget constraints and previous data suggesting it was small relative to volatilization. The concentration of TCE in tree core samples was used to help select representative trees for the leaf and trunk volatilization flux samples and to estimate the amount of TCE contained within the trees for evaluation as a potential reservoir for TCE. Another objective is a prediction of the amount of time required to remediate each site. Specific objectives were to:

1. Measure the amount of TCE volatilized from the tree leaves using a flow-through chamber system and scale these measurements to whole trees over the entire site using a modified Penman-Monteith approach in conjunction with the Thiesson Polygon method.
2. Measure the amount of TCE volatilized from the trunk and soil surface using recirculating chamber systems that are scaled to the entire site using the Thiesson Polygon method.
3. Collect and analyze core samples from trees across the site and, assuming constant concentration throughout the tree, determine the average amount of TCE contained within the trees. Scale to the entire site using the Thiesson Polygon Method.
4. Calculate the total TCE removal per year for each phytoremediation site and compare with the amount of TCE in the groundwater within the site to determine the approximate time for complete removal of TCE.

Site Descriptions

Travis Air Force Base (AFB) is located in Solano County, California, 5 km east of the city of Fairfield. Although there are several areas on base with reported groundwater contamination, a phytoremediation demonstration site was implemented as an attempt to remediate only one of them. For this site, the source of contamination was Building 755, shown in Figure 1.1, located on base in the northern section of the West/Annexes/Base Wide Operable Unit (WABOU). Building 755 had been used first as a rocket engine testing site and then as the Battery and Electric Shop where battery acids and chlorinated solvents were regularly discharged until 1978 (Parsons, 2010a). Since then, the source area of contamination has been removed, along with Building 755, and a bioreactor has been installed at that site (Figure 1.1).

Remediation of the groundwater down gradient from Building 755 began in 1998 with the planting of 100 red ironbark eucalyptus trees (*eucalyptus sideroxylon rosea*) to the southeast of the building. In 2000, another 380 trees were planted for a total of 480 trees over a 2.24-acre plot. As of October 2009, only 388 trees remained alive.

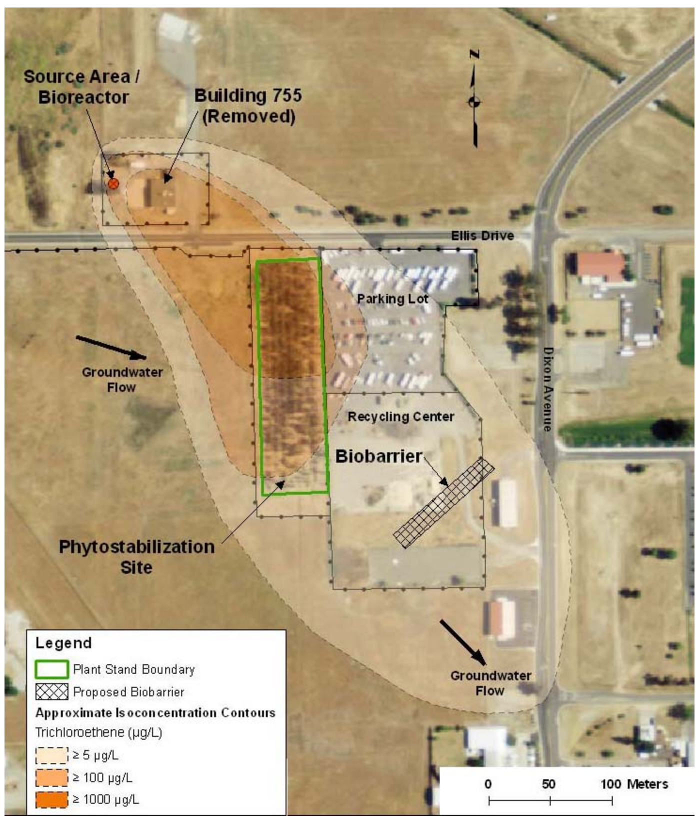

Figure 1.1. Travis AFB site location and plume map (Parsons, 2010a).

The bioreactor, installed in 2008, is 400 ft^2 in area and extends 20 ft below the ground surface. The bottom of the reactor is filled with 3,000 pounds of iron pyrite. A 50/50 mix of gravel and tree mulch that has been sprayed with three gallons of vegetable oil per cubic yard of mix fill the rest of the bioreactor to within two feet of the ground surface. A groundwater infiltration system was installed on top of the mulch, followed by a geotextile layer and clean soil backfill. To date, an average decrease in TCE concentration of 94% has been reported for the monitoring well network around the bioreactor (CH2MHill, 2010a). A biobarrier, also shown in Figure 1.1, was installed mid 2010. It consists of a row of 13 wells, aligned perpendicular to groundwater flow, which has been injected with emulsified vegetable oil (EVO). The natural hydraulic gradient is being used to carry water to and through the biobarrier (CH2MHill, 2010b). Analysis of monitoring well samples around the biobarrier has not yet been conducted.

Climate data from the nearby city of Vacaville indicate a moderate climate with average maximum temperatures in January and July of 13°C and 35°C, respectively, and average minimum temperatures in January and July of 3°C and 13°C, respectively. The highest average monthly rainfall occurs in the winter (December – February), followed by the spring (March – May) with 124 mm and 46 mm accumulated, respectively. The fall months of September through November follow closely with 36 mm of average monthly rainfall, while the summer months of June through August only get 2 mm of average monthly rainfall. These conditions allow for a 289-day growing season (Parsons, 2010a).

Fairchild Air Force Base is located in Spokane County, Washington, 14 km west of the city of Spokane. Like Travis Air Force Base, there are many areas on base with groundwater contamination. A phytoremediation demonstration site was implemented for an area where the sources of contamination are separate groundwater plumes from Sites PS-10 and PS-3. Figure 1.2 shows the site location and plume with groundwater flow direction. In 2001, 1134 trees consisting of three different types of hybrid poplar clones, 184-411(*Populus trichocarpa x Populus deltoides*), OP-367 (*Populus trichocarpa x Populus nigra*), and Eridano (*Populus deltoides x maximowiczii*), were planted over an area of approximately 1 acre near the previously existing intersection of Patriot and Wainwright Boulevards near Building M286 in Site SS-39. As of September 2009, only 273 trees remained alive.

Climate data from the Spokane Airport (Western Regional Climate Center) reports an average annual maximum temperature of 14°C and a minimum of 3°C. Winter (December-February) months are the coldest, followed by fall (September – November),

Figure 1.2. Fairchild AFB site location and plume map (adapted from Parsons, 2010b).

spring (March – May), and then summer (June – August) with average temperatures of 0°C, 9°C, 13°C, and 19°C, respectively. Rainfall follows a similar pattern with winter being the wettest, followed by fall, spring, and then summer with average total rainfall of 49 mm, 35 mm, 30 mm, and 20 mm, respectively. Fairchild AFB also receives an average total snowfall of 1062 mm. These conditions result in a 153-day growing season (Parsons, 2003).

CHAPTER 2

LITERATURE REVIEW

Characteristics of TCE

TCE is a chlorinated hydrocarbon commonly used as a degreasing agent for metals and as an extraction solvent for greases, waxes, and tars. It is used in the manufacturing process of other chemicals and is found in consumer products such as paint removers, adhesives, and rug cleaners (USEPA, 2000). Because of its widespread use, TCE contamination in groundwater is a common problem and can be particularly troublesome for those communities that depend on groundwater for their drinking water. Last estimated by the EPA in 2000, between 9 and 34% of drinking water supply sources in the U.S. are contaminated with TCE. Other sources of exposure for the general public include using products that contain TCE, evaporation from disposal sites, and industrial exposure to factory workers and people living in areas around factories where TCE is being used (USEPA, 2000). Health effects from both acute and chronic exposure have been reported and include: damaged central nervous, immune and endocrine systems; lung, kidney and liver damage; high incidences of miscarriages; congenital heart disease in children; and various types of cancers (USEPA, 2000). Because of the serious health risks associated with TCE, the federal government has put the maximum contaminant level (MCL) for drinking water at 5 parts per billion (ppb). The state MCLs in California and Washington are the same as the federal standard, however, some states have more stringent regulations. Table 2.1 provides a list of the chemical and physical properties of TCE. Burken and Schnoor (1999) correlated volatilization of VOCs from poplar trees

Table 2.1. Chemical and physical properties of TCE

Parameter	**Value**	**Reference**
Chemical Formula	C_2HCl_3	USEPA (2000)
Molecular weight	131.4 g/mol	USEPA (2000)
Odor threshold	28 ppm	USEPA (2000)
Vapor Pressure @ 25°C	74 mm Hg	USEPA (2000)
Henry's Law Constant @ 25°C	0.011 atm-m^3/mol	U. S. Dept. of Health and Human Services (1997)
Water Solubility 25°C	1.366 g/L	U. S. Dept. of Health and Human Services (1997)
Density @ 20°C	1.465 g/mL	U. S. Dept. of Health and Human Services (1997)
Log K_{ow}	2.42	USEPA (2000)
Boiling Point	86.7°C	U. S. Dept. of Health and Human Services (1997)
Half-life in air	7 days	USEPA (2000)
Federal Max. Contaminant Level (MCL) in Drinking Water	5 µg/L	USEPA (2000)
OSHA Permissible Exposure Limit (PEL) Time Weighted Average (TWA)	100 ppm	ATSDR (2007)
NIOSH 10 hr TWA	25 ppm	ATSDR (2007)

with vapor pressure, where a larger vapor pressure (> 0.01 atm) corresponds to more volatilization. The octanol-water partitioning coefficient (log K_{ow}) is related to the lipophilicity (the preferential partitioning into fats, oils, lipids, and non-polar solvents over water) of a compound and indicates potential for partitioning into soil organic matter. It is inversely related to the water solubility of the compound.

Uptake of Organic Contaminants by Trees

The transpiration stream concentration factor (TSCF) has been used to describe how readily organic chemicals are taken up and translocated by plants. The TSCF is equal to the concentration of the compound in the transpiration stream divided by the concentration in the bulk solution (Russell and Shorrocks, 1959). The amount of TCE taken up by trees in the field can be estimated by multiplying the TSCF by the volume of water transpired and the concentration in the bulk solution. Doucette et al. (2003) reported that laboratory measured TSCF values for TCE range between 0.02 and 0.75. As previously mentioned, once TCE has been taken up by the trees, it will then follow one of several fate pathways including: transformation within the plant, sorption (mainly to the lignin), volatilization from the leaves, and/or the trunk. Each of these volatilization mechanisms will be explained in further detail in the following sections. Other reported transformation processes associated with trees include: the microbial degradation of TCE in the rhizosphere (Burken et al., 2005; Chappell, 1997) and within the tree (Chappell, 1997; Gordon et al., 1998). As previously mentioned, transformation of TCE was not evaluated in this project.

Several factors affect the uptake of contaminants by trees including water source (ground or surface water), transpiration rate, and lipophilicy of contaminant (log K_{ow}) (Doucette et al., 2003). Briggs, Bromilow, and Evans (1982) reported an optimal lipophilicity for plant uptake, based on log K_{ow} to be between 1.5 and 2.0. Burken and Schnoor (1998) used a similar approach and found the optimum log K_{ow} for uptake to be at 2.5, which is very similar to the log K_{ow} for TCE reported as 2.42 (Table 2.1). However, more recent studies have presented an empirical relationship between TSCF and log K_{ow} that indicates that compounds that are nonionizable, polar, and more water soluble are most likely to be taken up by plants than those compound that are not (Dettenmaier, Doucette, and Bugbee, 2009). Using either approach, TCE is expected to be taken up by trees.

Tree Cores

The passive uptake of TCE by trees along with the water used for transpiration has been used to map and monitor groundwater contaminant plumes by relating the concentration of TCE in tree core samples to that in the groundwater below the trees (Sorek et al., 2008; Larsen et al., 2008). Generally, higher groundwater concentrations result in higher tree core concentrations, but this is not always the case (Lewis, 2001; Vroblesky et al., 2004; Larsen et al., 2008; Sorek et al., 2008). The relationship between tree core and groundwater concentrations can vary for many reasons including: tree species (Vroblesky, Nietch, and Morris, 1999; Vroblesky et al., 2004; Larsen et al., 2008; Sorek et al., 2008), height along trunk (Vroblesky, Nietch, and Morris, 1999; Lewis, 2001; Vroblesky et al., 2004; Baduru, Trapp, and Burken, 2008; Doucette et al., 2003, 2007), side of the tree from which the core was taken and extent of the root system (Vroblesky, Nietch, and Morris, 1999; Lewis, 2001; Sorek et al., 2008; Ma and Burken, 2003; Larsen et al., 2008), depth to groundwater and age of the tree (Vroblesky et al., 2004; Ma and Burken, 2003; Sorek et al., 2008), and water source (Vroblesky et al., 2004; Sorek et al., 2008).

Due to the extensive variability of the tree core-groundwater relationship, Sorek et al. (2008) and Larsen et al. (2008) suggest using tree cores only as a tool to determine the relative distribution of a contaminant in the groundwater and to identify the best locations for groundwater wells. Sorek et al. (2008) also reported that VOCs such as TCE do not accumulate in trees over an extended period of time, making trees relatively better indicators of recent contamination. However, Lewis (2001) reported relatively stable concentrations of TCE within tree core samples collected over the entire year.

Despite generally consistent and reliable results, it is possible to get a false positive hit for contamination as well as false negatives. False positives can occur, as with any sampling, from contaminated sampling equipment, analytical contamination, etc. Factors that contribute to false negatives include low transpiration rates caused by limited deep root growth in the ground water, or poor tree health (Sorek et al., 2008). The contaminant can also be broken down in the tree or rhizosphere or volatilized and diffused outward from the trunk, changing the steady-state tree core to groundwater concentration ratio.

Leaf Volatilization

The volatilization of TCE from tree leaves along with transpired water has been reported as a potential fate pathway. Many studies including those by Burken and Schnoor (1998) and Newman et al. (1999) have indicated that TCE is taken up into the plant and can be transpired from the leaves or metabolized and dechlorinated within the plant tissue. Newman et al. (1999) attempted to measure the TCE transpired from a single leaf inside a Teflon bag but did not observe significant volatilization of TCE. However, it is unclear if the flow rate of air through the bag was high enough to prevent humidity from approaching 100% which would cause the leaf to stop transpiring. In an attempt to maintain more natural transpiration rates, Doucette et al. (2003) used a different approach for measuring TCE from leaf flux. A small section of branch was placed inside a glass chamber instead of a single leaf. Flow through the chamber was also significantly larger, 3 to 6 liters per minute, to prevent a buildup of humidity within the chamber. It was reported that between 2 and 53 mg of TCE would be removed by each tree every year for their site at Hill Air Force Base (Hill AFB) in Utah, which could account for significant removal over the lifetime of the trees.

More recent research by Utah State University at other Air Force bases has added to the limited pool of data for TCE volatilization from leaves. Rogers (2006) conducted studies at Hill AFB located in Northern Utah and Vandenberg Air Force Base in California. A glass chamber method adapted from Doucette et al. (2003) was used to measure TCE volatilized from the leaves in conjunction with water transpired. Five trees were sampled at Hill AFB resulting in a range of transpiration stream concentration (TSC) values from 13 to 23 μg/L and TCE removal from the leaves ranging from 0.03 to 0.97 g/tree/year with an average of 152 L/day transpired. The TSC is the ratio of the mass of TCE collected to the mass of water collected and is used to determine the mass of TCE fluxed during transpiration (Doucette et al., 2003). At Vandenberg AFB, of the 19 trees that were sampled, only two contained measurable levels of TCE. However, the average transpiration rate for these trees at 55 L/day was much lower than at Hill AFB. In addition to the lower transpiration rates, the TCE groundwater concentrations at Vandenberg AFB (maximum concentration of 4,600 μg/L) were about half the concentrations at Hill AFB (10,000 μg/L). Both factors suggest that TCE would be less likely to be taken up by the trees at the Vandenberg AFB site.

Winters (2008) sampled poplar, willow, and Russian olive trees at Hill Air Force Base in much the same way as Rogers (2006). Transpiration at this site was between 15 and 160 L/day resulting in a range of TSC values between 2.4 and 46 μg/L. It was reported that phytovolatilization could be a significant fate at that site with TCE removal from the leaves resulting in between 0.05 to 1 g/tree/year, similar to Rogers (2006).

Trunk Volatilization

Vroblesky, Nietch, and Morris (1999) noticed a statistically significant decrease in concentration with height up a tree trunk and suggested that trunk volatilization may be responsible. Other explanations include degradation and sorption within trunk. This claim was examined by Ma and Burken (2003) who also suspected that diffusion from the trunk to be another potential fate of TCE after it is taken up by the tree. Diffusion is related to flux through Fick's First Law, which states that flux is equal to the diffusion coefficient multiplied by the concentration gradient over a distance, with the diffusion coefficient being dependent on the medium through which the contaminant is moving. Since diffusion appears to take place in tree trunks (Ma and Burken, 2002), it is reasonable to suggest that a flux of TCE from the trunk would also occur, however few direct measurements of flux from tree trunks have been reported to date. Winters (2008) sampled trunk flux using a tedlar bag recirculating system sealed to the trunk of a tree. Results ranged from 0.02 – 1.32 pg/cm^2/min translating into an average flux rate of 4.1 mg/tree/year and a high of 62 mg/tree/year. Overall results at the site indicated that volatilization of TCE through the tree trunk was much smaller than volatilization from the tree leaves or surface of the soil located around the trees.

As with the tree core samples previously mentioned, a decrease in trunk volatilization has been measured with height up the trunk (Ma and Burken, 2004; James et al., 2009). Some suggest that this decrease is related to the transpiration rate since the concentration of TCE in the transpiration stream decreased in all cases (Ma and Burken, 2003). Other researchers have not see a decrease in flux with height (Baduru, Trapp, and Burken, 2008; Wang et al., 2004).

Wang et al. (2004) used a glass chamber attached to the trunk to measure trunk flux of carbon tetrachloride (CT) and reported a max trunk flux that accounted for only 7% of the average CT removed, therefore deeming it an insignificant removal path. The differences in the chemical and physical properties of the contaminants and trees sampled, as well as the sampling method, may have much to do with the differences in results between the various studies.

Diffusion from tree trunks also depends on physical and chemical properties of the contaminant. Highly volatile compounds are potentially removed more easily than compounds with lower vapor pressures through volatilization; this could result in larger loss of mass through the trunk (Ma and Burken, 2003; Baduru, Trapp, and Burken, 2008). Effective diffusivity is inversely related to the square root of the molecular weight of the contaminant as demonstrated by Fick's Law, where the diffusion coefficient decreased with increasing molecular weight. In other words, larger compounds do not as readily diffuse through the trunk.

Not only has TCE efflux been seen to decrease with height, but it is also reported to decrease with radial distance from the center of the trunk. Concentration of TCE decreases with outward radial distance, which provides evidence that diffusion is in fact taking place (Ma and Burken, 2003). However, Gopalakrishnan, Burken and Werth (2009) concluded that the diffusion coefficients in the bark are between 2 and 10 times smaller than in the wood, and TCE is preferentially stored in the bark rather than in the wood. This was supported by core samples containing 42-60% of the total measured TCE in the bark, indicating that the bark is a barrier to volatilization into the atmosphere (Gopalakrishnan, Burken, and Werth, 2009). Volatilization from large, tall trees has been found to be slower than from smaller trees and the small branches of trees due to the decreases in TCE efflux with height and radial distance (Baduru, Trapp, and Burken, 2008; Trapp, 2007).

Soil Volatilization

Volatilization of contaminant from the soil surface is another potential pathway for removal of VOCs from field sites with contaminated groundwater; however, there are many factors that contribute to the level of volatilization that will occur. Some of these factors include: changes in atmospheric conditions, depth to groundwater, concentration of contamination in the groundwater, soil moisture, porosity of the soil, and the presence of trees (Marr et al., 2006; Choi, Tillman, and Smith, 2002).

Although diffusion is considered the dominant transport mechanism through soil, a difference of 1 to 4 orders of magnitude has been measured between total and diffusive volatilization fluxes of TCE, which indicates that another mechanism is present (Smith, Tisdale, and Cho, 1996). That mechanism is thought to be advection, which is driven by atmospheric temperature and pressure changes (Smith, Tisdale, and Cho, 1996; Marr et al., 2006). A decrease in atmospheric pressure would increase the advection of TCE upward to the soil surface. The response of subsurface air to atmospheric pressure changes is known as barometric pumping (Auer et al., 1996).

Since changes in atmospheric pressure are generally small, the increased volatilization of VOCs from the soil surrounding the trees may be due to another phenomenon known as Hydraulic lift. The occurrence of hydraulic lift in plants is driven by the transpirational demand of the plants during the day that depletes soil water. At night, water rapidly flows from the deeper roots as a function of soil water potential into the upper layers of soil (Richards and Caldwell, 1987). This water rehydrates the plants and is able to be stored in the upper soil layers to support transpiration and provide a buffer for several days of drought. Volatile organic compounds contained in this water may then more readily volatilize through the soil surface

Characteristics of the groundwater have an enormous effect on contaminant volatilization flux from the soil surface. Water table elevation has a direct effect on flux in that the closer the groundwater is to the soil surface the larger the fluxes (Auer et al., 1996; Marr et al., 2006; Andersen et al., 2008). Similarly, vapor concentrations in the soil increase with depth of groundwater (Smith, Tisdale, and Cho, 1996). Also, as would be expected, soil over areas of high groundwater concentrations results in larger volatilization fluxes of the contaminant than areas of lower groundwater concentrations (Marr et al., 2006).

The presence of trees over areas of groundwater contamination has also been shown to enhance the flux of VOCs from the soil by affecting several soil characteristics. One particular case showed that a phytoremediation planting over a contaminated area increased volatilization through the soil by a factor of four (Marr et al., 2006). Trees pull water from the soil thereby decreasing the soil moisture content surrounding them and increasing the flux from the soil (Smith, Tisdale, and Cho, 1996; Choi, Tillman, and

Smith, 2002; Marr et al., 2006; Andersen et al., 2008). After a rainfall event, trees will preferentially use that easily accessible water over soil water or groundwater. With air then replacing the water-filled pore spaces in the soil, diffusion of TCE to the ground surface is more rapid since diffusion coefficients in air are higher than those in water. The decrease in rainfall infiltration does not allow the rain to reduce the soil concentrations by dilution (Marr et al., 2006; Andersen et al., 2008). The root systems themselves can also enhance volatilization by creating “preferential pathways” through which the VOC vapors can easily navigate to the soil surface (Marr et al., 2006).

CHAPTER 3

FIELD SAMPLING AND SAMPLE ANALYSIS METHODS

Three separate trips were taken to each base for sampling. In each case, the first trip consisted of taking tree core samples from approximately 20 trees and sampling soil surface flux at three locations within the planted area and six locations outside the planted area. The tree core samples were used to assess the relative distribution of TCE in the trees and to determine the most appropriate trees to sample leaf and trunk flux on the next trip. The last two trips focused on six trees from which tree cores and leaf and trunk flux samples were taken. Soil surface flux samples were also taken during the last two trips, but were measured from within the planted area only. Descriptions of the processes by which tree cores and leaf, trunk, and soil flux samples were collected and analyzed follow.

Method Detection Limits

Method Detection Limits (MDLs) are the minimum concentration of a substance that can be measured and reported with 95% confidence that the analyte concentration is greater than zero. In this project, MDLs were calculated by multiplying the standard deviation of a minimum of seven replicate spiked samples (tree cores or Tenax® tubes) by the appropriate student's t value following the general approach outlined in the USEPA guidance document for method development and validation (USEPA, 1992). For the tree core analysis, sample specific MDLs were dependent on the sample size (average sample size is 1.37 grams) but were generally 0.1 µg TCE/kg fresh plant tissue, as shown

Table 3.1. Method detection limits

	MDL	
Tree Core	0.1	µg/kg
Leaf Flux	0.05 - 0.30	µg/m^2-hr
TSC	0.31 - 4.03	µg/L
Trunk Flux	0.003	µg/m^2-hr
Soil Flux	0.002	µg/m^2-hr

in Table 3.1. For transpiration stream concentrations, MDLs were dependent on the amount of transpired water collected in addition to the amount of TCE captured on the Tenax® sorbent tube. Using the range of volumes of transpired water collected and the minimum mass of TCE that can be reliably detected (39 pg), the range of sample specific MDLs for TSC was calculated. For volatilization flux measurements, the MDLs were dependent on the leaf, trunk, or soil surface area covered by the flux chambers, split ratio, and time interval of sample collection in addition to the amount of analyte captured on the Tenax® sorbent tube. Based on typical values used during the field sampling, the MDLs, presented in Table 3.1, were determined for leaf, trunk and soil flux measurements. Measurements detected above the MDLs are considered useable with respect to evaluating the significance of phytoremediation.

Tree Cores

Tree cores were collected using an increment borer with a 5.15 mm diameter core (Ben Meadows Company, Janesville, WI). The borer was hand drilled into the tree trunk to produce a core approximately 10 cm long. The core was pulled out, broken into several pieces, and placed into a pre-weighed, 20 milliliter (mL) headspace vial with a screw thread cap (MicroLiter Analytical Supplies, Suwanee, GA) containing 10 mL of a matrix modifier solution (MMS). The MMS is a saturated solution of sodium chloride that is acidified to pH 2 using phosphoric acid. It was prepared and used according to the USEPA in SW-846, Method 5021 (USEPA, 1992). After sample collection was complete, all samples were shipped overnight to the Utah Water Research Laboratory (UWRL) where they were re-weighed and analyzed using a gas chromatograph/mass spectrometer (GC/MS). The difference in initial and final weights of each vial was assumed to be the mass of the tree core. Quality control measures included trip blanks and spikes sent on each sampling trip as well as laboratory blanks and control samples.

A Hewlett-Packard® 7890A gas chromatograph (GC)/5973C mass spectrometer (MS) equipped with a CTC PAL autosampler configured for headspace sampling was used to determine the concentrations of TCE in the plant tissue samples. Headspace vials containing the tree core samples and MMS were heated to 60˚C with gentle agitation for 10 minutes. A 1 mL sample of the headspace gas was then injected into the GC at a rate of 200 microliters per second (µL/second) in a pulsed splitless mode, 20 pounds per square inch (psi) for 20 seconds, and then split at a 15:1 ratio for 1 minute. The concentrations of TCE in the plant tissue samples were determined indirectly from the concentrations of TCE in the headspace. External standards (minimum of five different concentrations), made by spiking known amounts of a commercial standard into the MMS, were used to define the relationship between the headspace and MMS concentrations. The standards were made directly in headspace vials just prior to calibration. The GC/MS was operated in Selected Ion Monitoring (SIM) mode monitoring three ion channels per analyte. Field tree core data from Travis and Fairchild are found in Table A-1 and B-1, respectively.

Leaf Flux

To measure the flux of TCE from the leaves, an apparatus adapted from Doucette et al. (2003) was used. A small section of a tree branch was placed inside a glass chamber and sealed around the stem with a closed cell foam stopper as shown in Figure 3. Electrical tape around the foam provided an even tighter seal and helped hold the foam to the glass chamber. Stainless steel fittings and Teflon tubing connect all parts of the system so as to minimize adsorption of the TCE. A compressed gas mixture containing 21 percent (%) oxygen, 78% nitrogen, and 0.04% carbon dioxide (Praxair Certified Standard) was used to purge the chambers of TCE and water vapor. This simulated air mixture, containing 400 parts per million (ppm) carbon dioxide, was used to maintain natural stomatal response and avoid potential TCE contamination commonly found in compressed breathing air.

Air flow through the chamber was maintained between 6 and 8 L/min to prevent a buildup of humidity and condensation inside the chamber. With such a high flow rate, it was necessary to subsample the chamber effluent. As shown in Figure 3.1, the sample was pulled through Tenax® tubes at a flow rate of between 100 and 200 mL/min where the TCE was collected, by a sampling pump (SKC Inc., Eighty Four, PA). The Tenax® tubes were connected in series to capture the TCE on the front tube and any breakthrough on the back tube. A mass flow meter (Model GFS-010343, Aalborg, Orangeburg, NY) was used to regulate the flow through the tubes. Samples were collected for between 30 and 40 minutes at a time. Where possible, a gas cylinder blank sample was

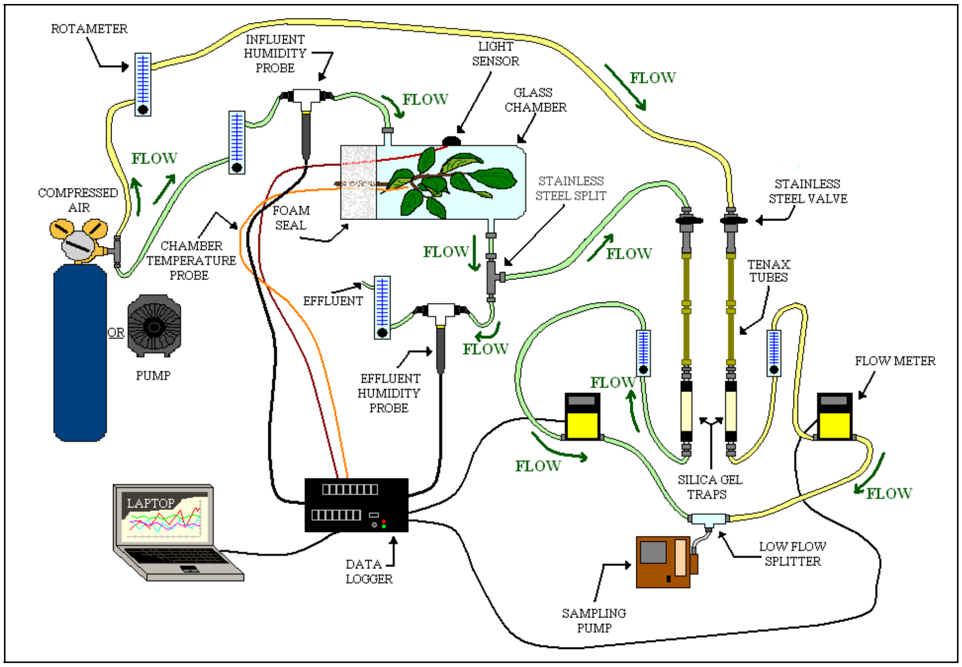

Figure 3.1. Leaf volatilization sampling schematic (adapted from Doucette et al., 2003).

run in parallel to measure background concentrations specific to each sampling time. This was not possible when the number of available Tenax® tubes was very limited.

Humidity and temperature were measured directly before and after the glass chamber using Campbell Scientific, Inc. Model CS-215 probes. The difference in humidity was used to calculate the amount of water transpired from the leaves. The relative humidity probes and mass flow meters were connected to a datalogger (Model CR200, Campbell Scientific, Inc., Logan, UT) where measurements of relative humidity, temperature, and flow rate were recorded every 60 seconds for both the sample and the cylinder blank.

After each sampling, the portion of the branch within the chamber was cut and preserved in a plastic bag so that the leaf area could be measured. The cuttings were sent back to the UWRL with the leaf volatilization samples by overnight air delivery. To measure the leaf area for each tree cutting, the leaves were carefully taken off the branch and fed through a LICOR Instruments, Model 6000 leaf area meter at the Crop Physiology Laboratory.

The Tenax® sorbent tubes were analyzed using thermal desorption GC/MS. These samples were introduced into a Hewlett-Packard® 6890/5793 GC/MS equipped with a J&W DB-624 capillary column (30 meter x 0.25 mm inside diameter [ID] x 1.4 µm film thickness) using a Perkin Elmer Turbomatrix ATD thermal desorber equipped with cryo-focusing and moisture control-system.

The secondary desorption trap was connected directly to the analytical column via the transfer line, and the GC injection port was bypassed. The MS was operated in SIM mode with three ion channels monitored per compound. TCE was quantified using a five-point external standard curve. Each run included the initial calibration samples, method blank, calibration check and calibration verification samples. Standards were prepared by loading known amounts of TCE dissolved in methanol onto clean Tenax traps with a microsyringe. Field leaf volatilization data from Travis and Fairchild are found in Table A-2 and B-2, respectively.

Trunk Flux

Volatilization of TCE through the tree trunks was measured using a stainless steel chamber constructed from an 8.5 x 5 inch loaf pan with foam gasket shown in Figure 3.2. The chamber was strapped to the tree with the open side against the trunk and pulled tight to form a seal. The area of trunk sampled beneath the pan was 0.025 m^2. Slotted, stainless steel tubing running through the inside of the chamber allowed the air underneath to be pulled through Tenax® tubes using a portable sampling pump (SKC Inc., Eighty Four, PA) at approximately 100 mL/min. Two small DC fans (Model 273-240, RadioShack) inside the chamber helped circulate the air underneath. Tenax® tubes were placed back to back, as with the leaf flux setup, to capture the TCE on the front tube and any breakthrough on the back tube. Sampling time for the trunk flux measurements was approximately 30 minutes. Once sampling was complete, all Tenax® tubes were carefully packaged and shipped overnight to the UWRL for analysis using a thermal desorber and GC/MS in the same manner as the leaf flux samples. Field trunk volatilization data from Travis and Fairchild are found in Table A-3 and B-3, respectively.

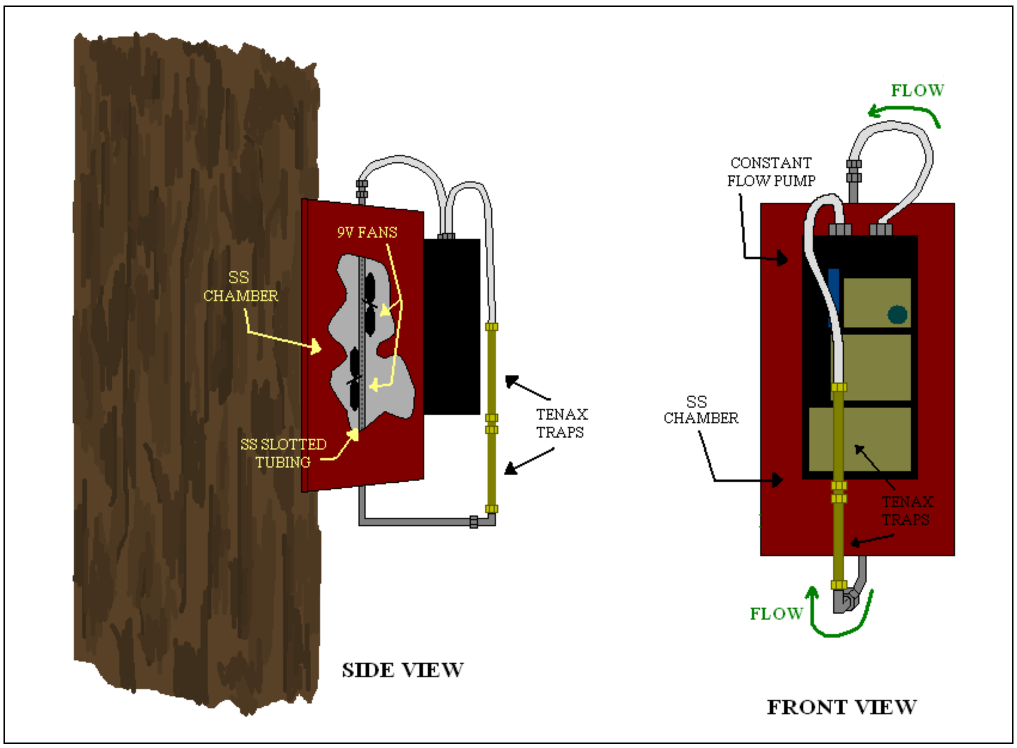

Figure 3.2. Trunk flux sampling schematic.

Soil Surface Flux

The design for soil flux measurement equipment was modeled after the vertical flux chamber used by Tillman and Smith (2004), which proved to have little impact on natural fluxes from the soil. Figure 3.3 shows the design used in the present experiment of flux of TCE through the soil surface, which was measured using a 1.5 quart stainless steel mixing bowl with an 8 inch diameter. The bowl was placed, open side down, on the ground, and clean playground sand was put around the edges to minimize exchange with the atmosphere. Smith, Tisdale, and Cho (1996) reported that disturbing the shallow soil was not a significant source of error. The area of soil surface sampled beneath the chamber was 0.035 m^2. Slotted, stainless steel tubing running through the inside of the chamber allowed the air underneath to be pulled through Tenax® tubes using a portable sampling pump (SKC Inc, Eighty Four, PA) at approximately 100 mL/min. Since Tillman and Smith (2004) reported inadequate mixing which increased the headspace concentration, two small fans (Model 273-240, RadioShack) inside the chamber were used to help circulate the air underneath. Tenax® tubes were placed back to back, as with the leaf and trunk flux setups, to capture the TCE on the front tube and any breakthrough on the back tube. Sampling time for the trunk flux measurements was approximately 30 minutes. Once sampling was complete, all Tenax® tubes were carefully packaged and shipped overnight to the UWRL for analysis using a thermal desorber and GC/ MS in the same manner as the leaf and trunk flux samples. Field soil surface volatilization data from Travis and Fairchild are found in Table A-4 and B-4, respectively.

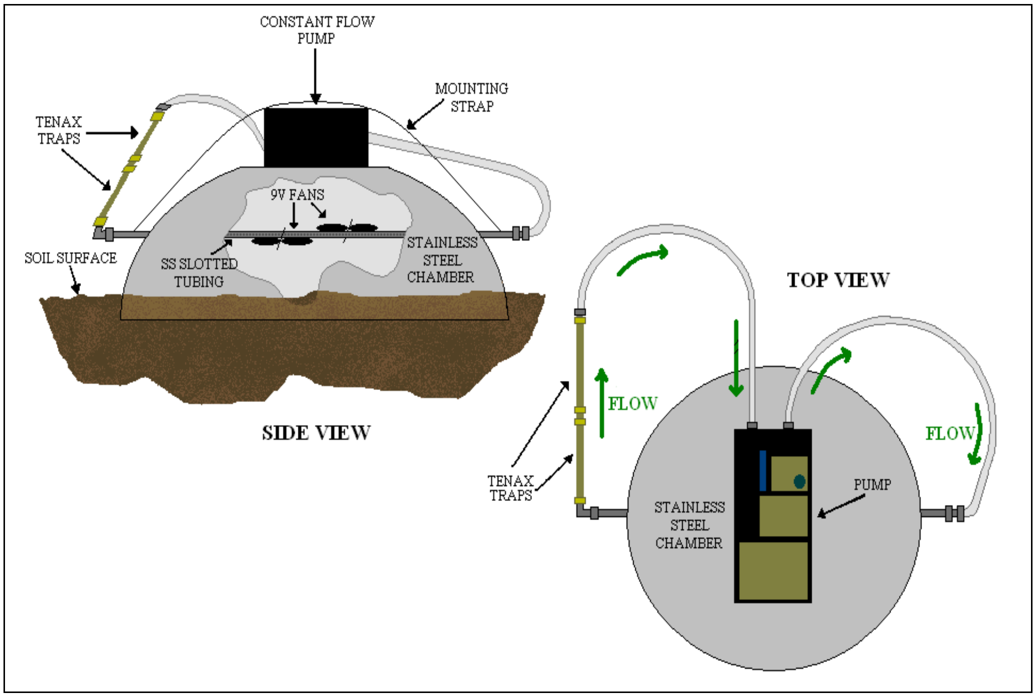

Figure 3.3. Soil surface flux sampling schematic.

<u>Thiessen Polygon Method</u>

Thiessen polygons, known by a wide variety of names such as Dirichlet Tessellations, Voronoi Diagrams, and Wigner-Seitz unit cells, have been used for centuries and applied to areas such as epidemiology, condensed matter physics, and meteorology. In the early 1900's, Alfred Thiessen used this method to interpret data from rain gauges within a watershed, and it was renamed the Thiessen polygon method when used for this application.

The Thiessen polygon method can be used to determine the best estimate of a measurement over an area given several data points across that area. Straight lines are drawn between sampling points and perpendicular bisectors are used to create the polygons. Figure 3.4 shows an example of the Thiessen polygon method using the

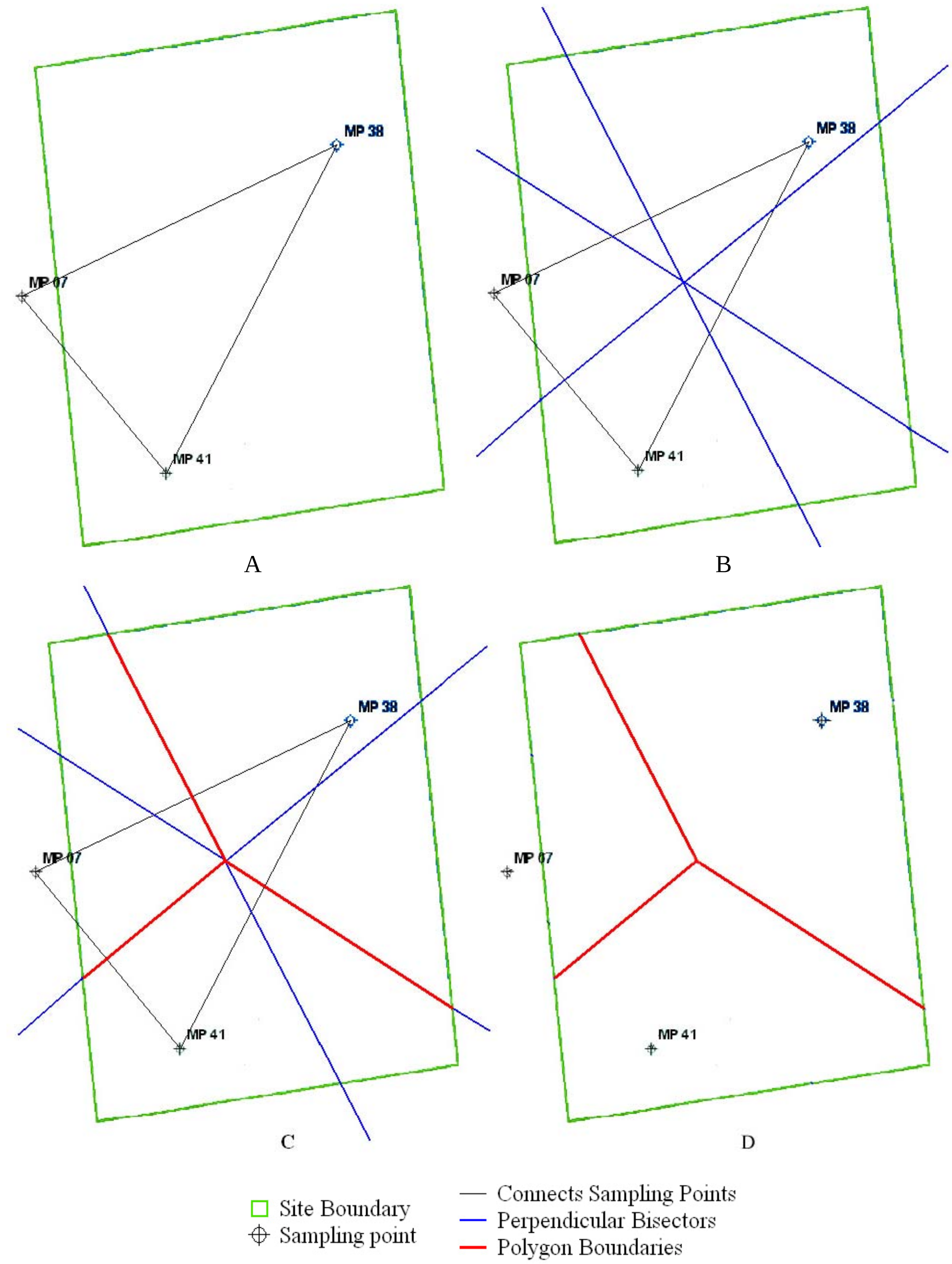

Figure 3.4. Thiessen polygon method. A) Connect sampling points with straight lines. B) Draw perpendicular bisectors through lines created in previous step. C) Cut off lines where they intersect each other and the site boundaries to form polygons. D) Final sketch of polygons at the site.

groundwater monitoring wells at Fairchild AFB. This method was used extensively to provide estimates of TCE removal over each site based on a small number of samples. The sample flux within each polygon is considered to be representative of the entire area of the polygon. By calculating a mass for each polygon and summing all polygons, it is possible to estimate the total mass removed at each site. Since the number of sample locations at each site was large enough to make the manual creation of polygons complicated, a computer program (Gorder and Holbert, 2010) was used to create the polygons and to calculate the area of each polygon. For each site, the sum of the areas of each of the smaller polygons created for each sampling set was equal to the total area at each site as shown in the calculation tables in Appendix C and D.

CHAPTER 4

RESULTS AND DATA ANALYSIS

Tree Cores

At both Travis and Fairchild Air Force Bases, cores were collected from 20 trees during the initial visit to the sites. These cores were used to delineate relative groundwater concentrations of the TCE plume beneath the phytoremediation sites so that areas of higher concentration could be focused on during subsequent sampling events. These core concentrations were also later used to calculate the mass of TCE that is sorbed within the trees across each site. The locations with the highest concentrations, indicated by the oranges and reds, in Figures 4.1 and 4.2 can be compared to the locations of further investigation on subsequent sampling trips as shown in the following sections.

The ranges of tree core concentrations, shown in Table 4.1 varied widely among sampling trips and also between sites. At Travis, six trees were sampled on all three trips. Plotting core concentrations over time shows a generally decreasing trend for most trees (Figure 4.3). This may be the result of the eucalyptus trees response to the increasing temperatures observed during the three sampling periods. One mechanism that trees can use to survive high heat, low water conditions is to close their stomata and reduce transpiration (Whitehead and Beadle, 2004). The decrease in groundwater use decreases the amount of TCE taken into the tree. If the TCE within the tree continues to be removed through volatilization and metabolism, the concentration within the tree would decrease.

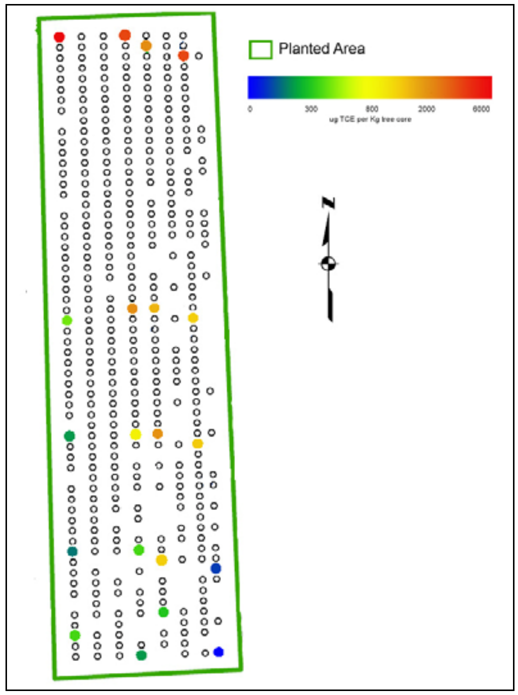

Figure 4.1. Initial core sampling locations at Travis AFB and relative core concentrations.

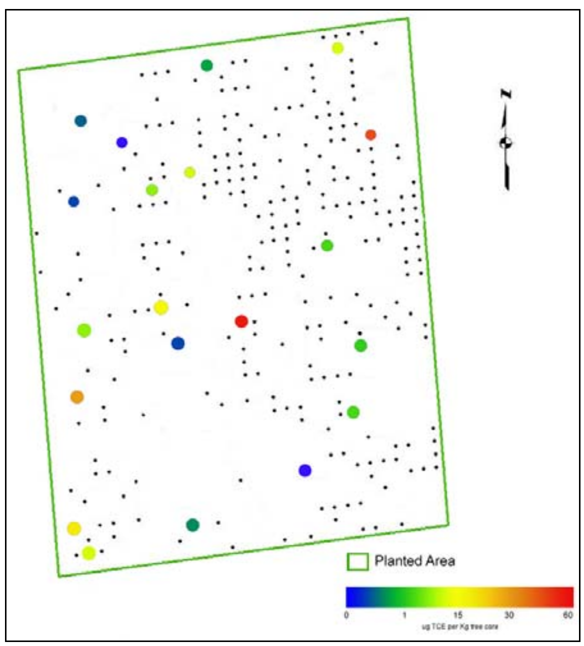

Figure 4.2. Initial core sampling locations at Fairchild AFB and relative core concentrations.

At Fairchild, only four trees were sampled on all three trips and the trend is less obvious (Figure 4.4). Two of the trees peaked in concentration in July. Since it is warmest during the summer months, unless under stressed conditions, the trees will take up more groundwater to stay alive, because it is available. As previously mentioned, the more contaminated water the trees are taking up typically results in higher core concentrations relative to losses.

The trees at each site are utilizing different mechanisms to survive the hot summer conditions since they are living in different climates. At Travis, average high temperatures are at least 70 °F April through October, while at Fairchild those temperatures are reached between June and September, three months less than Travis. Fairchild also receives more average monthly precipitation than Travis. For any given month during the summer, the trees at Fairchild are not likely to be heat stressed since they are getting more water from precipitation and have potentially not been exposed to high temperatures for as long as the trees at Travis based on average high temperatures since "summer" begins later. Table 4.1 shows the daytime high temperatures for each

Table 4.1. Ranges of tree core concentrations at Travis and Fairchild AFBs

Travis			**Fairchild**		
Number of Samples	**TCE Range (µg TCE/kg Fresh Wt)**	**Daytime High Temperature (°F)**	**Number of Samples**	**TCE Range (µg TCE/kg Fresh Wt)**	**Daytime High Temperature (°F)**
Trip 1: June 2			Trip 1: June 9		
25	2 - 6026	79	25	0.05 - 56	69
Trip 2: June 23-24			Trip 2: July 15		
18	0.56 - 3515	96, 86	19	4.5 - 142	85
Trip 3: October 6-7			Trip 3: September 8-10		
27	72.5 - 3438	76, 81	23	0.07 - 201	69, 76, 78

trip. Trip 1 is the only one close enough to compare directly between sites, and Travis was already 10 °F warmer than Fairchild in early June.

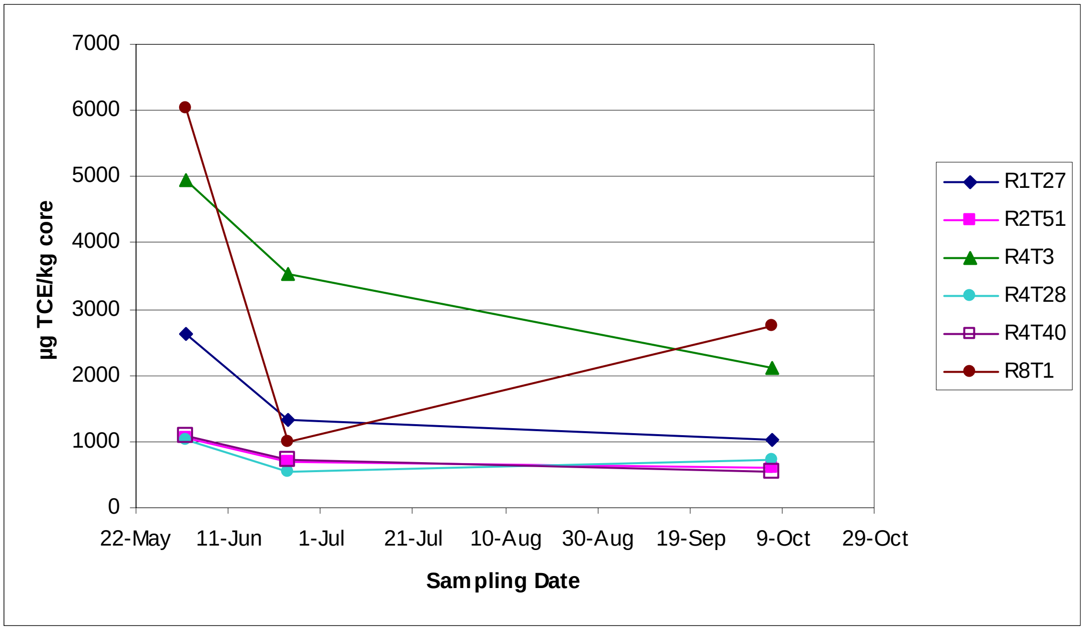

Figure 4.3. Core concentrations at Travis AFB over time.

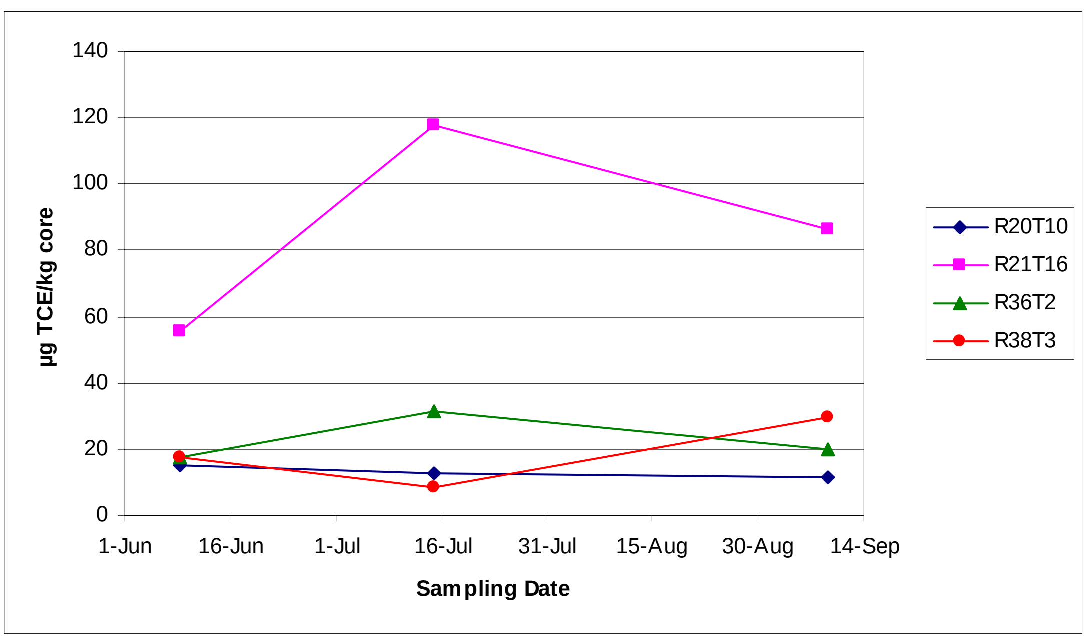

Figure 4.4. Core Concentrations at Fairchild AFB over time.

Decreasing contaminant concentrations within tree cores as sampling height increases has led some researchers to suggest that volatilization from the trunk is a significant mechanism in TCE loss from trees. While not a main focus of the sampling effort, at each site, multiple trees were cored at a minimum of two heights along the trunk to evaluate this trend. Looking at the most recent sampling events at each site (Trip 3), concentration was plotted against height to determine if there is TCE loss as it moves up the trunk. Trip 3 was used because there were the most instances of duplicate measurements at multiple heights for both sites. At Travis, five trees were cored at multiple heights with three of the five trees showing a decrease in concentration with height (Figure 4.5). At Fairchild only three trees were cored at multiple heights on the third trip and in only one of the three trees concentration decreased with height (Figure 4.6). If there is no significant change in concentration with height, the trees are thought to be at a steady state condition. This means that the amount of TCE that is taken up is the same amount that is leaving the tree by various mechanisms. It would be less likely to see measureable leaf volatilization at sites where trees are not at steady state. However, if groundwater concentrations are low, trees could still be at steady state but leaf volatilization may be too low to measure.

To summarize, due to different climactic conditions, the trees at each site use different strategies to survive the hot summer months. Since temperatures begin to rise as early as April at Travis, the trees may be stressed by June and continue to experience heat stress as the summer progresses. In response, the trees close their stomata and reduce transpiration to survive the drought conditions. At Fairchild, high temperatures are not typically experienced until June, and more precipitation falls during the summer months,

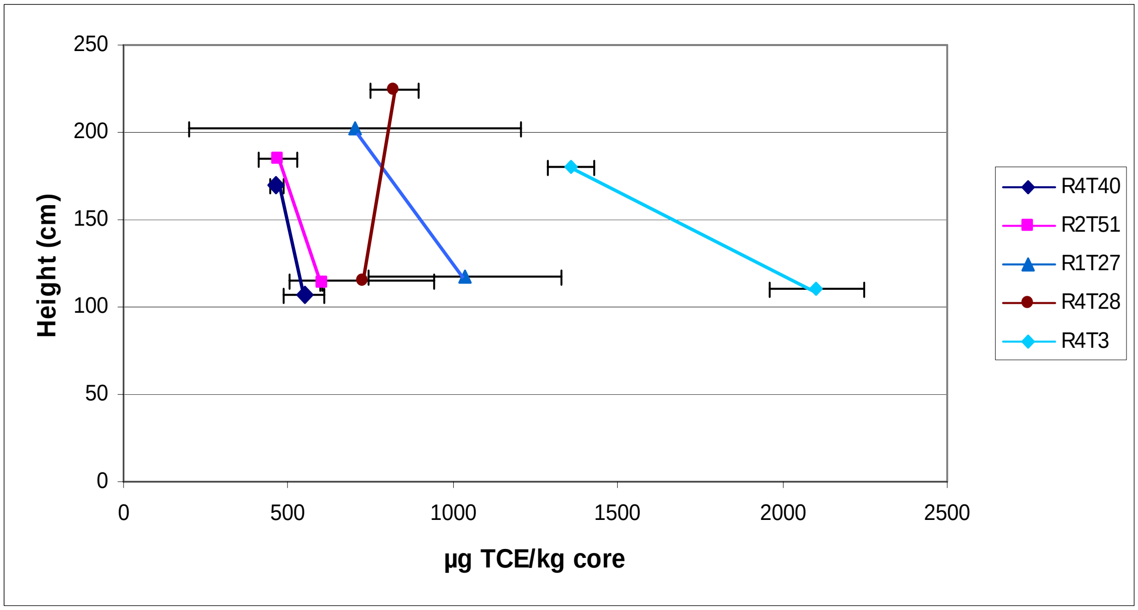

Figure 4.5. Travis tree core concentrations with height along trunk (error bars represent the 95% confidence interval).

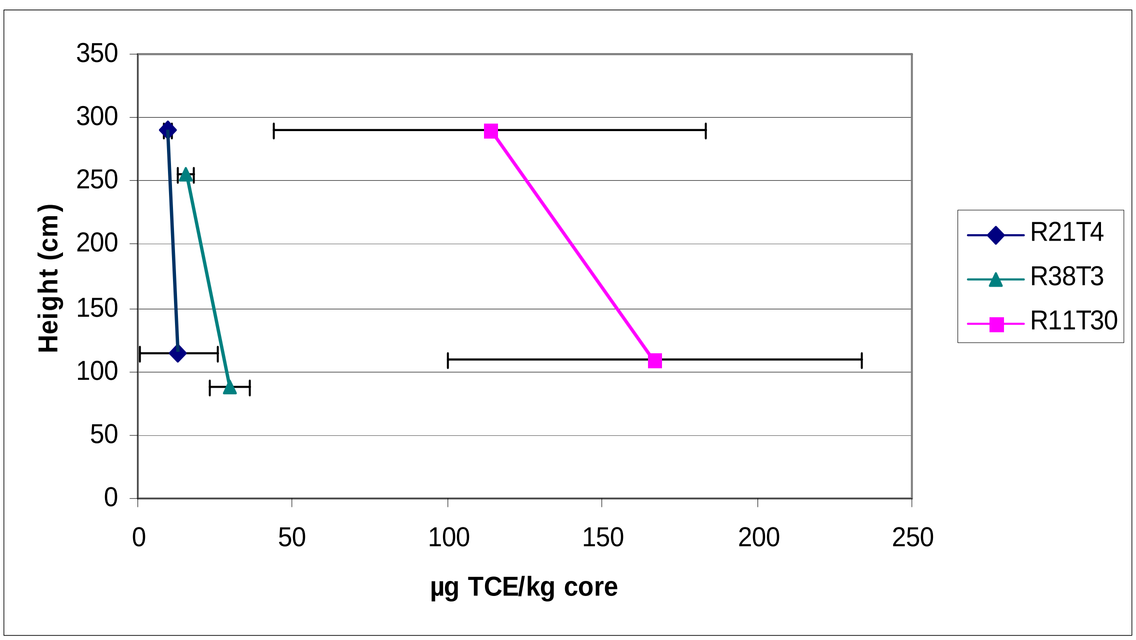

Figure 4.6. Fairchild tree core concentrations with height along trunk (error bars represent the 95% confidence interval).

so the potential for heat stress is reduced compared to Travis. Since the trees at Fairchild do not typically experience drought conditions, they continue to take up water and transpire.

Many studies have looked at the change in tree core concentration with an increase in height along the trunk and have seen a wide range of results: increase in concentration, decrease, or no change as height increases. In this study, some trees showed a decrease in concentration, while in others there was no statistically significant change. If there is no change in concentration, the trees are potentially at a steady state and TCE is likely to volatilize through the leaves in measureable quantities where the groundwater concentrations are high enough.

TCE Contained Within Trees

To calculate the amount of TCE contained within the trees, the Thiessen polygon method was used to create 20 polygons corresponding to the first sampling event at each site. The first sampling trip was used for this calculation since the largest number of trees was sampled (20). In addition, the sampled trees were spread out across the entire site, theoretically yielding the most representative results. Figure C-1 shows these 20 polygons at Travis AFB, and Figure D-1 shows them for Fairchild AFB. The following equations were then used to calculate the TCE contained within the trees at each site. Since the species of tree at each site is different, eucalyptus at Travis and hybrid poplar at Fairchild, different empirical equations, typically used in the forestry industry to predict wood yield, were found to calculate the dry mass of each type of tree.

At Travis, dry mass was calculated by:

$$M_{dry} = 1.22 * D^2 * (H \text{ x } 10^{-4}) \qquad (1)$$

where M_{dry} is the dry mass in kilograms (kg), D is the average diameter of trees within the polygon in millimeters (mm), and H is the average height of trees within the polygon in meters (m) (Senelwa and Sims, 1997).

The dry mass at Fairchild was calculated by:

$$M_{dry} = 0.05 * D - 0.35 \qquad \text{when } D < 4 \text{ cm} \qquad (2)$$

$$M_{dry} = 2.6 * D - 9.64 \qquad \text{when } D > 4 \text{ cm} \qquad (3)$$

where M_{dry} is the dry mass (kg) and D is the average diameter of trees within the polygon in centimeters (cm) (Felix et al., 2008). For both sites, fresh weight was calculated by:

$$M_{fresh} = \frac{M_{dry}}{1 - \%\ \text{moisture}} \qquad (4)$$

where M_{fresh} is the fresh mass (kg) and % moisture is assumed to be 0.55 (Donaldson et al., 1988; Tharakan et al., 2003) for both species of tree using an average of measurements from multiple trees within the eucalyptus and poplar families. The amount of TCE contained by each polygon was calculated by:

$$M_{sorbed} = N * M_{fresh} * 10^6 \ \mu g/g * C_{TCE} \qquad (5)$$

where M_{sorbed} is the mass of TCE sorbed by the trees in each polygon in grams (g), N is the number of trees in the polygon, M_{fresh} is the fresh mass of each tree (kg), and C_{TCE} is the concentration of TCE found in the tree cores of the trees sampled within the polygon in micrograms per kilogram (μg/kg). The mass of TCE contained within the trees in each polygon was added together to yield the total mass contained within the trees at each site.

By using these calculations, it was determined that the TCE contained within the trees Travis accounts was 45 g. The data associated with this calculation are found in

Table C-1. A significantly smaller mass of TCE, 0.1 g, was contained in the trees at Fairchild. Data associated with the Fairchild sorption calculation are found in Table D-1. At both sites, the TCE contained within the trees is considered removed from the site since it will eventually be volatilized or metabolized.

Leaf Volatilization

Since only a small branch on a tree is measured for TCE volatilization, it was necessary to scale that branch to the whole tree stand. This was done by multiplying the average TSC value in micrograms per liter (μg/L) by the annual water use of the tree stand (L). The annual water used and transpired by the tree stand was calculated by a modified Penman-Monteith approach:

$$ET_c = ET_r * K_c \quad (6)$$

$$Q_t = ET_c * A \quad (7)$$

where ET_c is the crop evapotranspiration (mm), ET_r is the reference evapotranspiration (mm), K_c is the crop coefficient (dimensionless), Q_t is the total evapotranspiration of the stand of trees (L/year), and A is the area of the tree stand (m^2) (Allen et al., 1998). The Penman-Monteith equation is a combination of energy balance and mass transfer. It is used to compute the evaporation of water from an open water surface. The parameters used in this calculation include solar radiation, temperature, humidity, wind speed. It has been further developed for application to crops by including factors for aerodynamic and surface resistance (Allen et al., 1998). It is possible and appropriate to use these equations as opposed to others that include a leaf area index (LAI) since it is assumed that the canopies at both sites are closed and most of the solar radiation is intercepted (Parsons, 2010a).

Each site has its own reference evapotranspiration, determined by local meteorological data. The ET_r for Travis is very straightforward and found using a map provided by the California Irrigation Management Information System (CIMIS). The ET_r for Fairchild was calculated using the average of the AgriMet database's three closest stations to the base (CHAW, RTHI, and SBMW) (AgriMet, 2010a). The crop coefficient accounts for differences in crop canopy and aerodynamic resistance as well as physical and physiological differences between crops and the reference crop. K_c changes throughout the growing season and throughout the stages of life. It is often larger in areas of high rain or irrigation and under windy conditions (Allen et al.,1998). The crop coefficients were determined for the type of tree at each site, eucalyptus at Travis and hybrid poplar at Fairchild. At Travis a K_c of 0.6 was found to be relevant (Haver, 2009) while at Fairchild the average of the poplar crop curve for three year or older trees, shown in Figure 4.7, yielded a K_c of 0.8 (AgriMet, 2010b). This information and subsequent calculations are located in Table 4.2.

Leaf volatilization is scaled from the small branch to the whole site using a modified Penman-Monteith approach that uses a reference crop evapotranspiration and crop coefficient to calculate evapotranspiration for the whole site. The crop coefficient is important because it accounts for differences between the reference crop and the trees at each site as well as the characteristics of the canopy and potential stresses inflicted by climate or site conditions. Using these parameters, as well as the area of each site, the

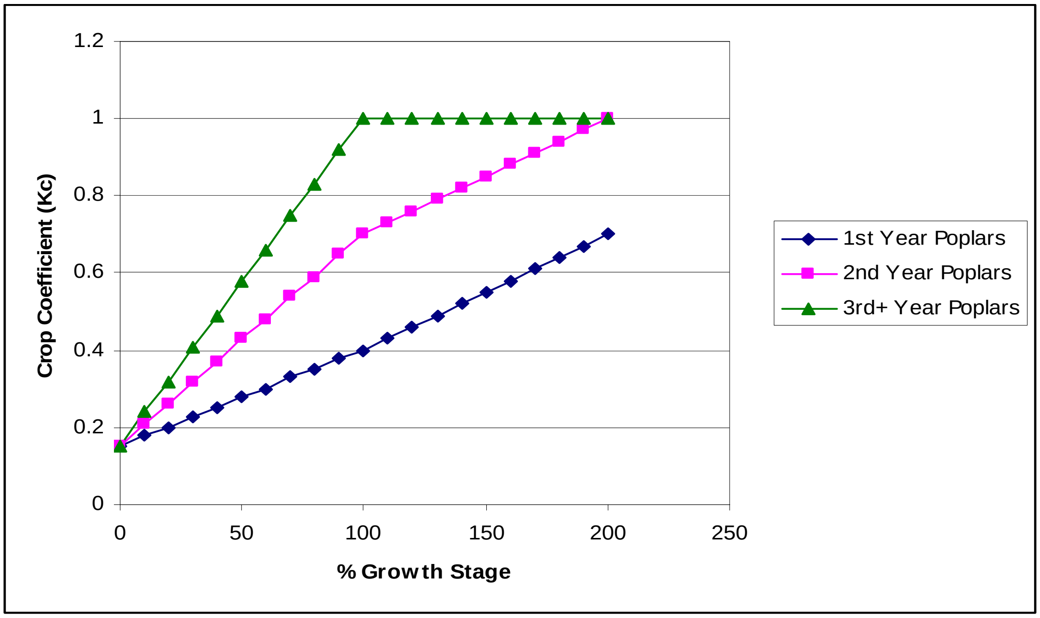

Figure 4.7. Poplar crop curve for various aged trees (Agrimet, 2010b).

Table 4.2. Travis and Fairchild transpiration data and calculations

	ET_r (mm)	Kc	ET_c (mm)	Area (m^2)	Q_t (L/yr/stand)
Travis AFB	1254.8	0.6	753	9065	6800000
Fairchild AFB	1146.2	0.8	917	4047	3700000

total evapotranspiration rate at Travis was calculated to be nearly twice the rate at Fairchild.

Removal by Leaf Volatilization

After the volatilization measurements were scaled appropriately, they were used to calculate the mass of TCE that is being removed through this pathway. Polygons were created at each site using the trees that were sampled for leaf volatilization. At Travis, seven polygons (Figure C-2) were created whereas at Fairchild eight polygons were created (Figure C-3). These polygons were used to provide an estimate of TCE loss through the leaves. The mass of TCE removed by trees in each polygon was calculated by:

$$M_{leaf} = TSC * Q_t * F * (10^{-6}\ g/\mu g) \quad (8)$$

where M_{leaf} is the mass of TCE removed through the leaves (g), TSC is the average transpiration stream concentration (µg/L), Q_t is the total evapotranspiration (L/year/stand), and F is the fraction of the total area represented by the polygon. The mass removed from each polygon was summed to determine the total removal of TCE from the groundwater by volatilization through the leaves.

Using the yearly evapotranspiration from Table 4.2, the TSCs, and polygon information from Table C-3, the removal of TCE attributed to the leaves at Travis AFB is 300 g/yr. If we assume that the trees were under water stress and were no longer transpiring, the TCE that is already in the leaves will have continued to volatilize. With the same mass of TCE being collected with little to no transpiration water, it is possible to obtain artificially high TSC values resulting in an inflated removal rate. The removal at Fairchild AFB, calculated using Tables 4.2 and D-4 is 11 g/yr.

The TSC from each of the sampled trees can also be used to calculate the tree TSCF by dividing it by the concentration of TCE in the groundwater. To do this, groundwater monitoring well polygons were created and overlaid with the leaf volatilization sampling locations. The TSC for each tree within a polygon was divided by the groundwater concentration measured in that well to get the TSCF for each tree. The average TSCF for the trees at Travis is 0.04 with a 95% confidence interval of ± 0.03. At Fairchild the average TSCF is 0.03 with a 95% confidence interval of ± 0.02.

Statistically, the TSCFs for these sites are no different from each other. Calculations are found in Table C-7 and D-7 for Travis and Fairchild, respectively.

Trunk Volatilization

Flux measurements were taken from trees whose diameters were large enough for the sampling apparatus to be securely attached to the trunk. The minimum diameter trunk that was sampled was 40 cm. Only a few measurements of trunk flux were taken at varying heights along the trunk in total. Since no replicate samples were taken, it is unclear whether or not there is any change in flux as height increases.

Measurements of tree height, diameter, and circumference were taken of trees throughout each site as indicated by Table 4.3. The table shows that the size of the trees at each site is not statistically different from the other. These measurements were broken down further to obtain more appropriate averages corresponding to individual polygons.

Table 4..3. Tree measurements at Travis and Fairchild Air Force Bases (reported as average value ± standard deviation)

	Trees Measured	**Average Height (m)**	**Average Diameter (cm)**	**Average Circumference (cm)**
Travis	51	10 ± 4	14 ± 7	43 ± 21
Fairchild	43	9 ± 5	11 ± 7	34 ± 2

Removal by Trunk Volatilization

The removal of TCE through volatilization from the tree trunks was determined by Thiessen polygons created using the trees in which trunk volatilization was measured at each site and average tree sizes from each polygon. At Travis, the seven trunk flux polygons are identical to the leaf flux polygons shown in Figure C-2. At Fairchild, five entirely new polygons were created, shown in Figure D-2. The following calculation provided the mass of TCE removed through trunk volatilization.

$$M_{trunk} = TF * \frac{24\,hr}{day} * \frac{days}{growing\,season} * 10^{-6}\,g/\mu g * N * SA \qquad (9)$$

where M_{trunk} is the mass of TCE removed through the trunk (g), TF is the flux of TCE measured in the field (μg/m^2/hr), N is the number of trees in the polygon, and SA is the average surface area of trees within the polygon. The mass removed from each polygon was summed to determine the total removal of TCE from the groundwater by volatilization through the trunks.

Removal of TCE at Travis through volatilization from the tree trunks accounts for 4.55 g/yr using the information in Table C-2. The polygon information in Table D-2 shows 0.67 g/yr removed from the tree trunks at Fairchild AFB.

Volatilization from Soil Surface

Soil volatilization flux samples were taken during each of the three trips to both sites. During the first trip to each site, nine measurements were taken consisting of three within the tree stand and six outside the tree stand, shown in Figures 4.8 and 4.9. These measurements are later compared. Subsequent trips focused sampling within the planted areas. At Travis, the third trip paired soil flux locations with leaf and trunk flux locations. Although similar pairing was planned for Fairchild, there was a limited number of sampling tubes available, so only three locations were sampled. Samples from Trip 3 were used to calculate removal of TCE from each site through soil flux.

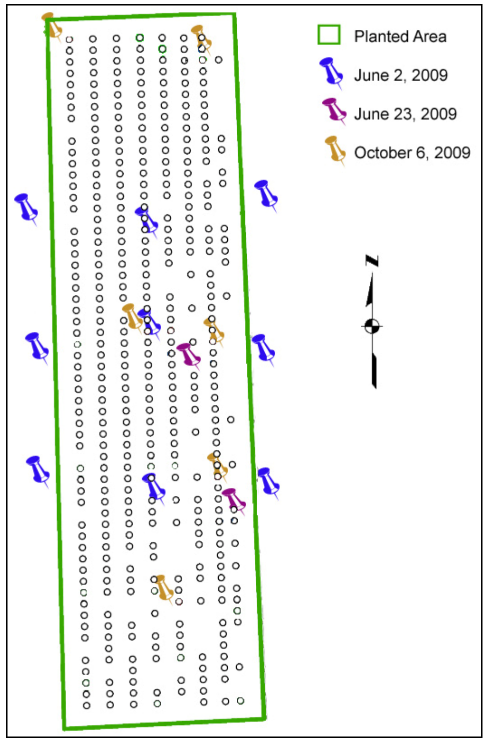

Figure 4.8: Soil Flux Sampling Locations at Travis AFB.

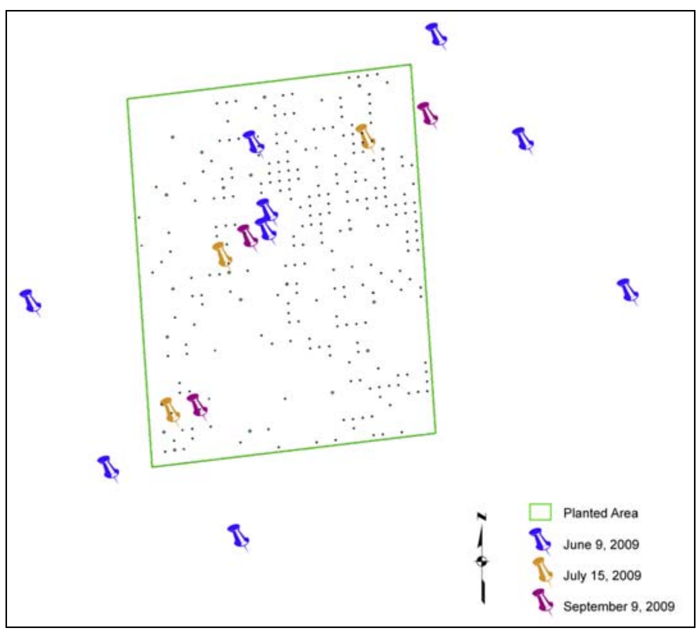

Figure 4.9. Soil Flux Sampling Locations at Fairchild AFB.

Removal by Soil Surface Volatilization

For soil volatilization flux calculations, three separate sets of polygons were created for each site. The first set divides the sites by sampling locations measured on Trip 3 within the tree stand. At Travis, this set consists of six polygons (Figure C-3), and at Fairchild there are three (D-4). These polygons were used to appropriately scale TCE removal from the soil surface within the planted areas of each site, since they were better spatially distributed over each site. The mass of TCE removed was calculated by:

$$M_{soil} = SF * \frac{24\,hr}{day} * \frac{days}{growing\,season} * 10^{-6}\,g/\mu g * \left(A - A_T * N\right) \qquad (10)$$

where M_{soil} is the mass of TCE removed through the soil (g), SF is the flux of TCE measured in the field ($\mu g/m^2/hr$), A is the area of the polygon, A_T is the average cross sectional area of the trees within the polygon, and N is the number of trees in the polygon. The mass removed from each polygon was summed to determine the total removal of TCE from the groundwater by volatilization through the soil. The area that the trees take up at each site was accounted for in the calculation using the average cross sectional area of the trees within each soil flux polygon; however, it did not make a significant difference in the total mass removed each year. Growing season was used instead of an entire year since the ground is assumed to be frozen during the rest of the year, not allowing TCE to volatilize through to the ground surface. These polygons and calculations showed that 470 g/yr is being removed at Travis (Table C-4), while 7 g/yr is being removed at Fairchild (Table D-4).

For comparison, two additional sets of polygons were created using samples from Trip 1 located within the planted area and outside the planted area at each site to determine if the presence of trees enhances the soil volatilization. Polygons for outside the planted area and inside the planted area at Travis are shown in Figures C-4 and C-5, respectively, while polygons for Fairchild are in Figures D-5 and D-6, respectively. The calculations shown in Tables C-5 and C-6 indicate that significantly less volatilization is taking place outside the planted areas at Travis with only 5 g/yr removed in the unplanted area and 126 g/yr removed in the planted area. Tables D-5 and D-6 show that slightly less volatilization is occurring inside the planted area at Fairchild with 0.7 g/yr removed as opposed to 1 g/yr removed from an unplanted site with an equal area.

CHAPTER 5

DISCUSSION

Groundwater concentrations at Travis AFB are much higher than at Fairchild AFB. In 2009, groundwater concentrations at Travis ranged from 1.4 to 9196 µg/L, corresponding to an approximate mass of 6.7 kg of TCE beneath the site, while at Fairchild the range was 9 to 190 µg /L, which corresponds to an approximate mass of 0.9 kg of TCE beneath the site. Mass of TCE in the groundwater beneath each site was calculated by creating polygons based on the groundwater monitoring well locations. The area of each polygon was multiplied by the porosity of the site, the aquifer thickness, and the concentration measured at the well. Appropriate conversions were made and the mass of each polygon was summed to get the mass for the entire site. The differences in concentration and mass of TCE at each site have a direct effect on the fluxes and total removal. Phytoremediation sites with higher concentrations of contaminated groundwater are expected to have relatively higher concentrations in the trees and larger mass removed than sites with lower groundwater concentrations.

The distribution of TCE throughout the phytoremediation site at Travis, based on mapping from core concentrations, match closely to the groundwater concentration contours shown in Figure 5.1. This observation shows a direct correlation between tree cores and groundwater concentration. Relatively speaking, the higher the groundwater concentration, the more TCE will be in the trees. A similar comparison was not done for Fairchild since a detailed map of the plume was not available. Concentrations in the

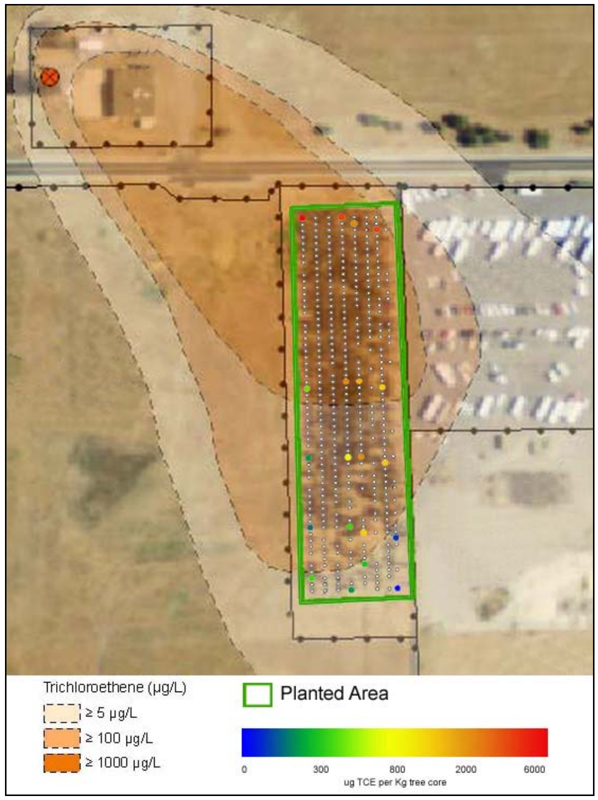

Figure 5.1. Correlation between tree core and groundwater data at Travis.

cores and groundwater monitoring wells at Fairchild are somewhat correlated, but there are so few wells that a clear picture cannot be derived.

Using previous year's groundwater data for Travis (Parsons, 2010a) and Fairchild (Parsons, 2003, 2005b, 2010b), a clear reduction in the mass of TCE in the plume beneath the planted area is observed at both sites as shown in Figure 5.2. Since there is no evidence of TCE in the form of a DNAPL at either site, all of the TCE in the phytoremediation area is assumed to be in the dissolved phase. The difference in groundwater mass, as calculated by Parsons using the Thiessen Polygon Method and the groundwater monitoring wells onsite, over the 5-year period between 2004 and 2009 indicates that 1.68 kg is being removed each year at Travis. This calculation assumes that the removal rate of TCE from the groundwater is linear. In actuality, the rates of removal should decrease over time as the concentrations of TCE in the groundwater decline. Nevertheless, this rate is approximately twice the rate that was calculated in 2009 (0.84 kg/yr) as the sum of all phytoremediation loss rates. Since the larger number is an average of five years, it is possible that the mass of TCE removed in 2009 was on the lower end of that range. Another possibility for the discrepancy is that there is another major mechanism at work at this site that was not accounted for in this study, such as reductive dechlorination from the upstream bioreactor or metabolism within the trees. Groundwater sampling data over an 8-year period was available for Fairchild as shown in Figure 5.2. The slope of the best-fit line gives the average mass removed per year, 376.5 g. This is well above the mass calculated mass removed at Fairchild in 2009 by the phytoremediation sampling (18 g/yr). Using only the groundwater samples collected between 2004 and 2009 provides an average estimated removal of 15 g/yr, which is much closer to the removal by phytoremediation observed in 2009. More sampling will be necessary to tell if the sampling and calculations consistently fit the groundwater data over the next few years.

At Travis, there is evidence that reductive dechlorination is taking place with the decrease in TCE mass and increase in the mass of total dichloroethylene (DCE) and vinyl chloride (VC), shown in Figure 5.3. These products are likely moving on-site from the biobarrier up gradient where microorganisms are degrading TCE near the source area. No reductive dechlorination products were found in the groundwater samples taken in 2004 or 2009 at Fairchild.

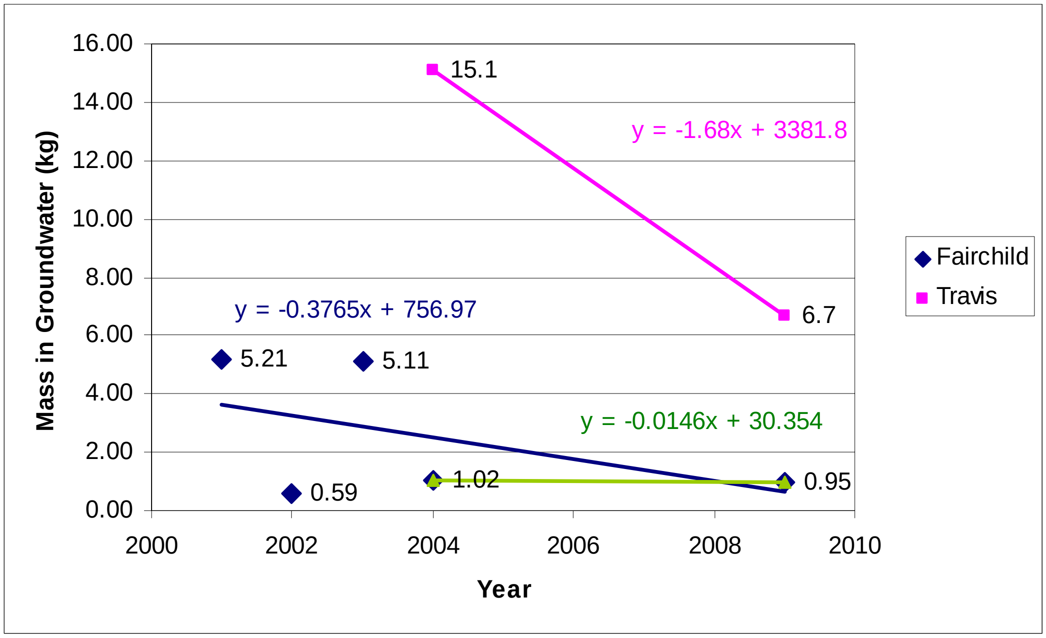

Figure 5.2. TCE mass reduction over time at Travis and Fairchild.

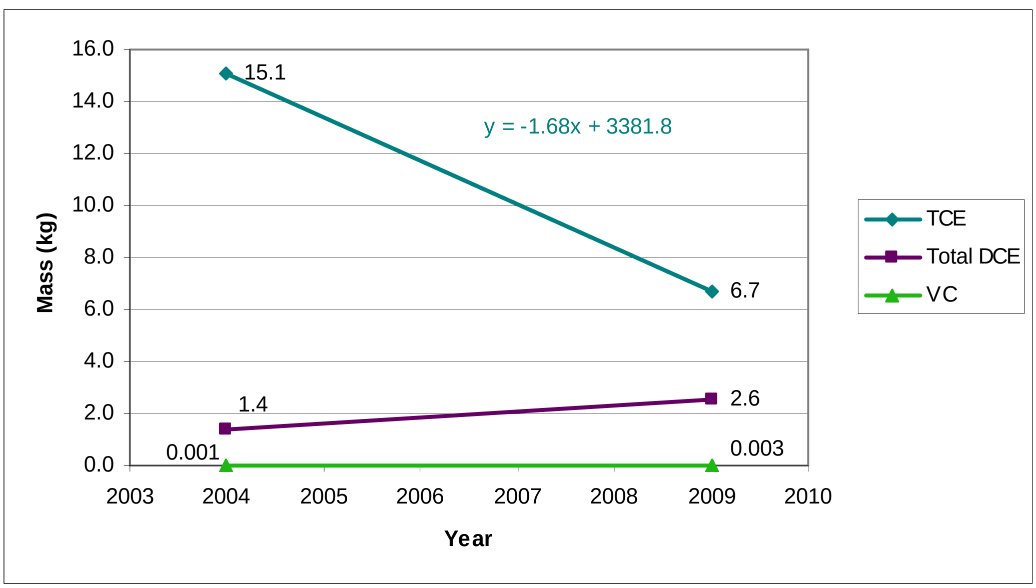

Figure 5.3. Change in mass of TCE and its dechlorination products below the planted area within the plume at Travis AFB over time.

By using the Thiessen Polygon software, a calculation of the center of mass of the plume can be made. Knowing how the centroid moves over the years provides an estimate of the stability of the plume. Figure 5.4 shows the location of the center of mass at Travis AFB in 2004 and 2009. Despite having only two years of data, it appears that the centroid is moving in the opposite direction of groundwater flow. This, coupled with the decrease in mass over the same time period, indicates that attenuation within the plume has increased. More data is necessary to conclusively determine the state of the plume. The mass of TCE in the groundwater at Fairchild is also decreasing over time; however the center of mass, shown in Figure 5.5, is clearly moving in the direction of groundwater flow indicating a shrinking plume that is undergoing some attenuation. It also provides evidence that the source of contamination has been cut off or removed.

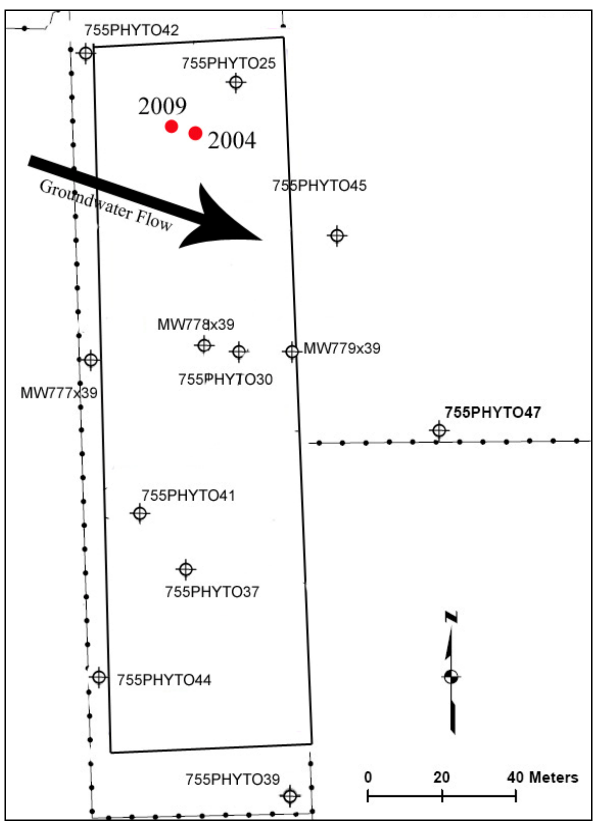

Figure 5.4. Location of the center of mass over time of the TCE groundwater plume at Travis AFB.

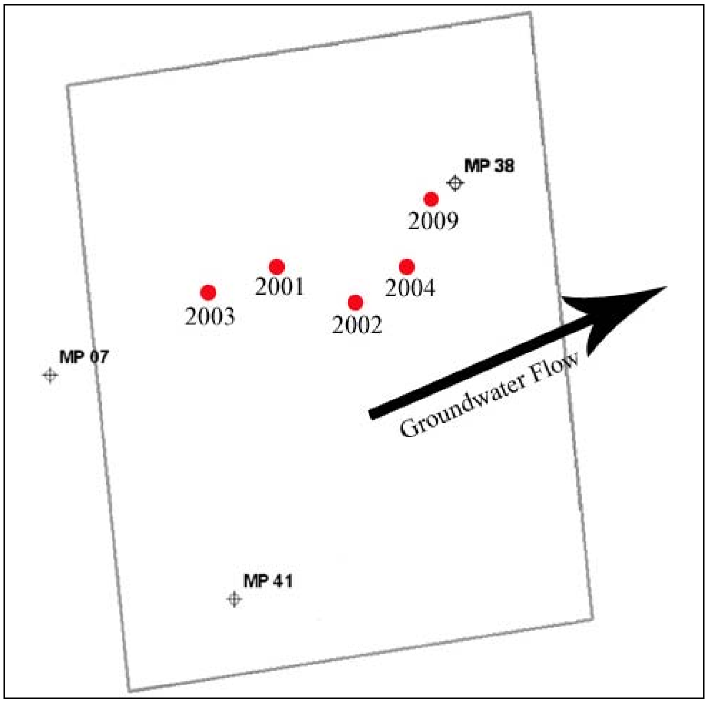

Figure 5.5. Location of the center of mass over time of the TCE groundwater plume at Fairchild AFB.

A summary of the mass removed by the mechanisms within the phytoremediation site at each base is provided in Table 5.1. It shows that leaf and soil volatilization are the most import removal mechanisms, and trunk volatilization and sorption are least important at these sites.

Table 5.1. Summary of annual TCE mass removal at Travis and Fairchild AFBs

Removal Mechanism	**Travis (Eucalyptus) (g/yr)**	**Fairchild (Hybrid Poplar) (g/yr)**
Leaves	300	11
Trunk	5	0.7
Sorption	45	0.1
Soil	470	7
Total	0.8 kg/yr	0.02 kg/yr

Tree Cores and Sorption

A comparison of core concentrations between 2004 and 2009 at Travis and is shown in Figure 5.6 and compiled from data in Parsons (2005a, 2010a). The figure shows a comparison between the 2004 sampling and the nearest tree sampled in 2009. In almost every case, the core concentrations at both sites have dramatically increased. One tree at Fairchild was sampled in both 2004 and 2009; however, unlike Travis, the concentration decreased slightly. Since no replicates were taken, it is unclear if the decrease is statistically significant. Lower concentrations in 2004 would be expected for several possible reasons. Both sites were irrigated during the first few years after planting. At Travis, irrigation water was supplied to the initial trees planted until 2002, while trees in the secondary planting were irrigated until 2003. At Fairchild, the trees were irrigated until 2004. The trees will preferentially take up surface water over groundwater since it is easier to access. Irrigation water that reached the groundwater would dilute the concentrations that the trees would be taking up when groundwater is used. It may also have taken a few years for the trees to acclimate to the climate without regular watering after irrigation was discontinued. Another contributing factor may be the growth rates of young trees compared to older trees. During the first several years of life, plants grow at an exponential rate (Leopold and Kriedemann, 1975), possibly resulting in the new biomass being comparable to the mass of TCE taken up from the water by a phenomenon known as growth dilution. Later in life, the growth rate slows and generally stabilizes until the end of life where it begins to drop off.

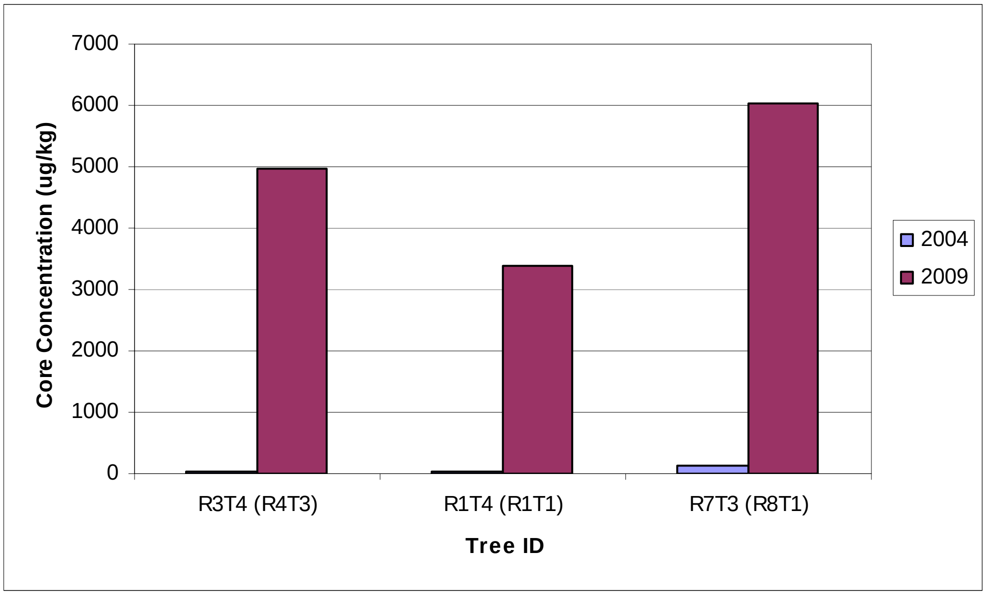

Figure 5.6. Comparison of tree core concentrations between 2004 and 2009 at Travis AFB. (Tree ID in parentheses refers to closest tree sampled in 2009 for comparison.)

Sorption calculations for each site are based on empirical equations from the literature for two different tree species. Despite very different groundwater concentrations feeding each system, the removal results for each site are a fairly low percentage of the overall TCE removed. At Travis, sorption accounts for 45 g/yr or 5.3% of removal, while at Fairchild, it is only 0.1 g/yr or 0.6%. Low removal rates may be due to the sampling and analysis of tree cores. The equilibrium headspace method used for analysis of the tree core samples does not completely account for the TCE that is sorbed to the sample. Evaluation of this method using spiked samples of MMS with and without tree cores should provide an estimate of the percent of TCE that is being recovered and used for sorption calculations.

Leaf Volatilization

Leaf flux is one of the most important removal mechanisms at both sites. At Travis, approximately 300 g/yr or 37.9% of the total TCE removed was through the leaves, while at Fairchild, it accounted for 11 g/yr or 56.1% of the total TCE removed. Although leaf flux was the dominant removal mechanism at Fairchild, the mass removed was very small compared to Travis. On average, trees at Travis transpired 48 L/tree/day while the trees at Fairchild only transpired 37 L/tree/day. The amount of water transpired has a direct effect on the mass removed. There is a large difference between the two sites in both average TSC values and mass removal values with Travis being the larger in both cases. There was not a significant decrease in transpiration in replicate samples that would indicate plant stress as described by Rogers (2006). As previously mentioned, the average TSCF values for both sites were not significantly different from one another. This makes sense since it is a ratio of TSC to groundwater. Although Travis has high groundwater concentrations, the average TSC values are also high and vice versa for Fairchild. Since they TSCFs are essentially the same, it indicates that there is a relationship between groundwater concentration and leaf volatilization for trees of similar age, relying on groundwater of at similar depth.

Trunk Volatilization

Trunk flux was very insignificant at Travis (5g/yr or 0.5% total mass removed) but more significant than sorption at Fairchild (0.7 g or 3.6%). This difference is possibly due to differences in type of tree, including wood and bark. Poplars have a softer wood and thinner, smoother bark than eucalyptus, which could translate into a tighter seal of the sampling apparatus on the poplar trunks. Again, although a larger percentage of the total mass was removed through the trunks at Fairchild, more absolute mass was removed at Travis. This is likely due to the maximum groundwater concentrations being nearly 50 times higher at Travis.

Soil Volatilization

Soil flux proved to be another important and effective removal mechanism for TCE at both sites. At Travis, 470 g/yr or 56.3% of the total TCE removed was through the soil. At Fairchild, 7 g/yr or 39.6% of the total removal was through the soil. These percentages are almost exactly opposite the leaf flux numbers. It is possible that the less dense planting at Travis allows more TCE to penetrate the surface. This may be the preferred pathway over uptake from trees. Another contributing factor is the difference in groundwater concentration between the sites, which has a direct effect on volatilization from the soil. Fairchild has almost two orders of magnitude less TCE concentration at its maximum than Travis. With less of a TCE concentration gradient between the groundwater and the soil surface, the flux is much less.

Limitations

There are several limitations to this study involving the frequency of sampling and limited data available and collected. The trees were cored and soil flux measurements were taken a maximum of three times during the growing season. Leaf and trunk volatilization sampling was done a maximum of twice during the growing season for a given tree. These measurements were averaged over the entire growing season to provide an estimate of TCE removal. Another issue is the number of trees sampled. The original 20 trees cored at each site, used for estimating the TCE contained within the trees, represent only 5-7% of the total trees per site. Of those 20 trees, only the six or seven most likely to produce results were used for trunk and leaf volatilization sampling. At Travis, the same six trees were sampled during Trips 2 and 3, while at Fairchild only four trees were sample during both trips. The small number of trees sampled and the inconsistency in which trees were sampled limits proper comparison between sites and sampling events.

There is also some danger associated with scaling up to the entire site from so few measurements. The most accurate scenario for site estimations would be to sample every single tree, so scaling would not be necessary; however, that is not realistic. A small subset of those trees was sampled and scaled to the entire site. One of the major issues, besides the obviously small quantity of trees sampled, is the matter of their representativeness. The original 20 trees were chosen to be representative, but the subset of those trees was chosen based on the highest tree core concentrations and general proximity to each other. Sampling only the highest concentrations may contribute to an overestimation of TCE removal at each site.

Groundwater data at each site is very limited by both the number of wells and the historical data available. It appears that not all wells at the sites were sampled during the same years at Travis, making it difficult to determine what is happening to the plume. At Fairchild, there are only three monitoring wells in or near the one acre phytoremediation site. These few measurements are being used to estimate the extent of contamination beneath the phytoremediation site, but may not be representative. More wells would provide a better picture and more accurate estimations of groundwater concentrations below the phytoremediation plots. The same is true with Travis, which has only 13 wells in or near the 2.24 acre site.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The trees at Travis and Fairchild Air Force Bases are using the contaminated groundwater beneath the sites for their water needs and are volatilizing TCE to the atmosphere through trunk and leaves, sorbing it to the woody tissue, and enhancing volatilization in surrounding soil (at Travis). From the results, most of the TCE at Travis is removed by volatilization from the soil surface, followed by volatilization from the leaves, then sorption, and finally volatilization through the trunk. Fairchild is similar with the most removal from the leaves, followed by the soil, then the trunk, and lastly sorption. This shows that at these two phytoremediation sites, leaf and soil volatilization are the most import removal mechanisms, and trunk volatilization and sorption are least important.

Considering that the TCE plume beneath the phytostabilization site at Travis currently contains 6.7 kg and TCE is being removed at a rate of 0.8 kg/yr, it will take approximately eight years to remove the TCE at that site, assuming the removal rate is constant. At Fairchild, 0.9 kg of TCE is present beneath the phytostabilization site. At a removal rate of 0.02 kg/yr, it will take approximately 49 years to remove the TCE at that site. This is likely not a reasonable timeframe for removal compared to alternative methods, so additional or alternative remediation techniques may help reduce the timeframe. The scattered data points for groundwater sampling between 2001 and 2009 show a more significant average removal of TCE and indicate that phytoremediation may not be very effective at this site. More data is needed to determine a better estimate of the TCE removal rate in the groundwater.

Recommendations

The more information available about a site, the better the remediation plan and estimates can be. For this reason, it is recommended that more groundwater monitoring wells be placed throughout the phytostabilization sites, especially at Fairchild. Adequate soil data are also needed at both sites to assess the proportion of TCE that is potentially associated with soil particles. Monitoring every year or every few years could more accurately describe what is happening with the plume. This research provides a starting point for determining if the plumes are shrinking or growing and at what rate. This is especially important at Travis, where the groundwater sampling has not been consistent with the wells used in the past.

Considering reports of tree bark acting as a barrier to volatilization and allowing contaminants to build up within it, the concentrations of TCE in the bark should be measured in addition to the tree core concentrations. Miles and Smith (2009) reported various eucalyptus trees having an average bark volume of 15.2% of the tree and poplar trees having a range of average bark volume between 14 and 22%. As previously mentioned, one study found that 42-60% of the total measured TCE in core samples is in the bark (Gopalakrishnan, Burken, and Werth, 2009). By these numbers, the mass of TCE within the bark could account for a significant change in the sorption calculations and indicate that it plays a larger part in TCE removal in trees than is presented here.

Statistical analyses of trunk flux measurements, especially with height along the trunk, were not performed since no replicate samples were taken. It is recommended that replicates be taken to provide a better understanding of trunk volatilization as a loss mechanism for TCE.

More frequent sampling of the trees and soil surface flux could also provide more accurate estimates of the magnitude of these loss mechanisms. Monthly sampling events throughout the growing season would help our understanding of seasonal effects on plant uptake and translocation and build a reliable sampling history that can be extrapolated to obtain a more realistic time frame for complete TCE removal. Monthly sampling may not be realistic, but the more often, the better.

Engineering Significance

In this research, volatilization of TCE was measured from leaves and trunks of trees as well as from the soil surface near the trees. Tree core samples were used to estimate the amount of TCE that is being sorbed by the trees at each site. These measurements were scaled to represent the entire phytoremediation demonstration site at two air force bases to estimate the removal of TCE from the groundwater below them.

This type of research and information is important because it quantifies the mass of contaminant removed from a site and highlights some of the important and site-specific factors that contribute to the effectiveness of such an endeavor such as species of tree, depth to groundwater, etc. This information is useful to others using phytoremediation to restore a site because a complete picture of removal pathways is included and can be easily reproduced. From such measurements and calculations, a timeframe for total removal can be estimated to provide a comparison to other techniques.

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APPENDICES

APPENDIX A

TRAVIS DATA

Table A-1. Tree core TCE Concentrations for 2009 at Travis AFB

Tree ID	Vial Number	Sample Date	TCE (µg/kg)	Sample Weight (g)	Sample Height (cm)	Sample Orientation
R2T27	66	06/02/2009	1798.10	1.59	120	North
R4T28	67	06/02/2009	1023.90	1.77	120	North
R1T27	68	06/02/2009	2634.29	1.64	110	North
R8T28	69	06/02/2009	439.63	1.73	120	North
R8T39	70	06/02/2009	214.09	1.79	126	North
R1T39	71	06/02/2009	851.95	1.7	124	North
R2T39	72	06/02/2009	2076.14	1.56	110	North
R4T40	73	06/02/2009	1077.33	2.02	115	North
R5T60	74	06/02/2009	2.17	1.52	102	South
R1T60	75	06/02/2009	196.95	1.78	100	South
R8T58	76	06/02/2009	344.58	1.72	116	Southwest
R2T56	77	06/02/2009	301.80	1.76	110	South
R5T52	78	06/02/2009	113.00	1.95	104	North
R2T51	79	06/02/2009	1044.33	2.05	120	North
R1T50	80	06/02/2009	345.70	2.19	110	South
R8T50	81	06/02/2009	163.00	1.54	120	North
R8T1	83	06/02/2009	6026.07	1.47	106	North
R1T1	84	06/02/2009	5196.94	2.07	116	Southwest
R1T1	85	06/02/2009	3795.27	2.03	116	Southeast
R1T1	86	06/02/2009	1197.31	2.02	116	West
R2T2	87	06/02/2009	2255.15	1.79	124	North
R4T3	88	06/02/2009	4960.66	2.08	109	Northeast
R2T27	89	06/02/2009	1537.04	1.16	260	Southwest
R1T27	90	06/02/2009	1922.33	1.65	270	Northeast
R2T51	201	06/23/2009	620.00	1.59	121	North
R2T51	202	06/23/2009	753.69	1.41	121	North
R2T51	203	06/23/2009	0.56	1.64	260	West
R2T27	204	06/23/2009	1485.88	1.7	110	East
R2T27	205	06/23/2009	3101.21	1.65	110	East
R2T27	206	06/23/2009	1516.59	1.67	220	Northeast
R8T1	207	06/23/2009	1217.78	1.67	100	Southwest
R8T1	208	06/23/2009	792.90	1.97	100	Southwest
R4T3	209	06/24/2009	3515.34	1.76	105	North
R4T3	210	06/24/2009	1514.39	1.53	190	West
R4T28	211	06/24/2009	475.96	1.83	114	North
R4T28	212	06/24/2009	624.60	1.26	114	North
R4T40	214	06/24/2009	736.02	1.86	108	South

Table A-1 (Continued)

Tree ID	Vial Number	Sample Date	TCE (µg/kg)	Sample Weight (g)	Sample Height (cm)	Sample Orientation
R4T40	215	06/24/2009	700.00	1.75	115	Southwest
R1T27	216	06/24/2009	1737.70	1.83	124	West
R1T27	217	06/24/2009	933.73	1.69	120	Southwest
R1T27	218	06/24/2009	937.64	1.78	203	Southwest
R8T1	485	10/6/2009	3437.90	1.79	100	Southwest
R8T1	486	10/6/2009	3197.49	1.83	100	Southwest
R8T1	487	10/6/2009	1639.21	1.79	100	Southwest
R4T3	488	10/6/2009	2032.10	1.83	100	Southwest
R4T3	489	10/6/2009	2177.11	0.62	40	Southwest
R4T3	490	10/6/2009	1320.63	1.9	110	West
R4T3	491	10/6/2009	1394.31	1.69	110	West
R4T28	492	10/7/2009	611.00	1.67	180	West
R4T28	493	10/7/2009	835.58	1.79	180	West
R4T28	494	10/7/2009	141.20	1.83	115	West
R4T28	495	10/7/2009	858.25	1.54	115	West
R4T28	496	10/7/2009	786.10	1.18		West
R4T40	497	10/7/2009	72.57	1.41	224	West
R4T40	498	10/7/2009	517.94	1.71	224	West
R4T40	499	10/7/2009	580.29	1.28		South
R2T51	500	10/7/2009	599.39	1.44	107	Northwest
R2T51	501	10/7/2009	602.24	1.55	107	Northwest
R2T51	502	10/7/2009	439.06	1.56	114	Northwest
R2T51	503	10/7/2009	500.31	1.62	114	Northwest
R1T27	504	10/7/2009	886.41	1.95	185	West
R1T27	505	10/7/2009	1183.83	1.4	185	West
R4T40	506	10/7/2009	475.87	1.6	118	West
R4T40	507	10/7/2009	454.94	1.46	118	West
R1T27	508	10/7/2009	959.78	1.93	170	West
R8T1	512	10/7/2009	2658.74	1.22	180	Southwest
R8T1	513	10/7/2009	3323.14	1.89	180	Southwest
R1T27	514	10/7/2009	445.83	1.53	202	West
N.D.: Non-detect. Sample concentration was below instrument detection limits.						

Table A-2. Leaf TCE volatilization data for 2009 at Travis AFB

Tree ID	**Sample Date**	**Mass TCE (pg)**	**Leaf Area (m^2)**	**Sample Time (hr)**	**Split Ratio**	**Water collected (g)**	**Flux (µg/m^2-hr)**	**TSC (µg/L)**
R1T27	6/24/09	2005.73	0.052	0.5	0.023	0.019	3.35	106.18
R1T27	10/7/09	127.28	0.029	0.717	0.016	0.010	0.38	13.16
R2T27	6/23/09	171.65	0.039	0.5	0.019	0.123	0.47	1.40
R2T51	6/23/09	782.66	0.043	0.5	0.015	0.042	2.51	18.69
R2T51	6/23/09	1474.51	0.043	0.667	0.013	0.058	4.12	25.51
R2T51	10/7/09	858.81	0.061	0.5	0.019	0.035	1.50	24.61
R4T3	6/24/09	3816.92	0.091	0.5	0.018	0.075	4.77	50.70
R4T3	10/7/09	4760.79	0.035	0.5	0.015	0.048	17.79	100.00
R4T3	10/7/09	5316.03	0.035	0.5	0.017	0.047	17.58	112.64
R4T28	6/24/09	4057.62	0.062	0.5	0.017	0.061	7.59	66.30
R4T28	6/24/09	1733.80	0.062	0.5	0.019	0.058	2.93	30.02
R4T28	10/7/09	2278.84	0.0346	0.5	0.021	0.068	6.40	33.49
R4T40	6/24/09	1209.07	0.0414	1.05	0.024	0.128	1.17	9.46
R4T40	10/7/09	858.09	0.0400	0.5	0.010	0.037	4.16	23.51
R8T1	6/23/09	2528.73	0.043	0.567	0.012	0.019	8.63	132.51
R8T1	10/6/09	3474.23	0.019	0.5	0.019	0.032	19.78	109.13
R8T1	10/6/09	3151.91	0.019	0.5	0.020	0.033	16.37	96.73

Table A-3. Trunk TCE volatilization data for 2009 at Travis AFB

Tree ID	Sample Date	Area (m^2)	Height (cm)	Mass TCE (pg)	Sampling Time (hr)	TCE flux (μg/m^2-hr)
R1T27	6/24/09	0.02468	73	3740.35	0.55	0.276
R1T27	10/7/09	0.02468	62	3267.28	0.5	0.265
R2T27	6/23/09	0.02468	102	4323.14	0.483	0.362
R2T27	6/23/09	0.02468	225	6757.69	0.5	0.548
R2T51	6/23/09	0.02468	110	1404.90	0.5	0.114
R2T51	6/23/09	0.02468	110	1268.76	0.517	0.100
R2T51	6/23/09	0.02468	220	130.36	0.5	0.011
R2T51	10/7/09	0.02468	75	3472.47	0.5	0.281
R4T3	6/24/09	0.02468	65	17344.20	0.5	1.429
R4T3	10/6/09	0.02468	34	44696.40	0.567	3.196
R4T28	6/24/09	0.02468	100	2960.42	0.5	0.240
R4T28	10/7/09	0.02468	46	6661.59	0.55	0.491
R4T40	6/24/09	0.02468	107	4131.89	0.55	0.304
R4T40	10/7/09	0.02468	118	2173.40	0.5	0.176
R8T1	6/23/09	0.02468	40	1226.42	0.5	0.099
R8T1	10/6/09	0.02468	42	7787.39	0.5	0.631
R8T1	10/6/09	0.02468	42	10616.12	0.517	0.833
Blank	10/7/09	0.02468		242.98	0.5	0.020

Table A-4. Soil surface flux data for 2009 at Travis AFB

Location	**Sample Date**	**Area (m^2)**	**Mass TCE (pg)**	**Sampling Time (hr)**	**TCE Flux (µg/m^2-day)**
Waypoint 016	6/2/09	0.034636	966.07	0.5	0.056
Waypoint 017	6/2/09	0.034636	1211.00	0.5	0.070
Waypoint 018	6/2/09	0.034636	567.65	0.5	0.033
Waypoint 019	6/2/09	0.034636	95.53	0.5	0.006
Waypoint 020	6/2/09	0.034636	60815.96	0.5	3.512
Waypoint 021	6/2/09	0.034636	53156.50	0.5	3.069
Waypoint 022	6/2/09	0.034636	6796.45	0.5	0.392
Waypoint 023	6/2/09	0.034636	135.44	0.5	0.008
Waypoint024	6/2/09	0.034636	482.00	0.5	0.028
Blank	6/2/09	0.034636	935.29	0.5	0.054
Waypoint 059	6/23/09	0.034636	30148.34	0.5	1.741
Waypoint 059	6/23/09	0.034636	30655.30	0.5	1.770
Waypoint 059	6/23/09	0.034636	82045.22	0.55	4.307
Waypoint 0091	6/23/09	0.034636	70468.89	0.467	4.360
Blank	6/23/09	0.034636	140.15	0.5	0.008
Waypoint 0022, R8T1	10/6/09	0.034636	626579.06	0.5	36.8
Waypoint 0032, R4T3	10/6/09	0.034636	336337.87	0.5	19.42
Waypoint 0042, R4T28	10/7/09	0.034636	110567.26	0.517	6.179
Waypoint 0053, R4T40	10/7/09	0.034636	<MDL	0.5	<MDL
Waypoint 0063, R2T51	10/7/09	0.034636	43991.8	0.517	2.458
Waypoint 0074, R1T27	10/7/09	0.034636	17089.92	0.5	0.987
Blank	10/6/09	0.034636	1283.43	0.5	0.074

APPENDIX B

FAIRCHILD DATA

Table B-1. Tree core TCE concentrations for 2009 at Fairchild AFB

Tree ID	Vial Number	Sample Date	TCE (μg/kg)	Sample Weight (g)	Sample Height (cm)	Sample Orientation
R36T2	153	6/9/2009	17.71	1.52	108	Southeast
R37T11	154	6/9/2009	0.66	0.98	106	East
R34T20	155	6/9/2009	0.05	1.07	66	Southeast
R30T24	156	6/9/2009	3.21	1.51	115	East
R38T3	157	6/9/2009	10.09	1.99	114	East
R38T3	158	6/9/2009	13.46	1.47	114	East
R38T3	159	6/9/2009	13.56	0.75	278	East
R38T3	160	6/9/2009	7.37	1.93	278	South
R26T3	161	6/9/2009	29.64	1.53	120	East
R23T11	162	6/9/2009	0.33	1.60	120	East
R25T25	163	6/9/2009	1.80	1.24	125	East
R21T4	164	6/9/2009	4.99	1.83	116	East
R20R10	165	6/9/2009	15.05	1.79	120	East
R20R10	166	6/9/2009	15.01	1.16	42	East
R22T16	167	6/9/2009	55.48	1.12	118	East
R17T23	168	6/9/2009	2.75	1.78	118	East
R11T4	169	6/9/2009	0.33	1.53	100	East
R11T10	170	6/9/2009	4.69	1.79	116	East
R10T13	171	6/9/2009	9.75	2.01	122	East
R9T27	172	6/9/2009	42.12	1.71	123	East
R5T5	173	6/9/2009	0.43	1.51	123	East
R7T8	174	6/9/2009	0.18	1.47	120	East
R2T15	175	6/9/2009	0.69	2.23	117	East
R2T25	176	6/9/2009	11.11	1.48	110	East
R2T25	177	6/9/2009	N/A	-1.73	110	East
Cottonwood1	178	6/9/2009	29.90	1.72	117	East
Maple1	179	6/9/2009	0.33	1.39	110	East
Maple2	180	6/9/2009	2.88	1.81	123	East
Cottonwood2	181	6/9/2009	42.14	0.16	140	East
Cottonwood2	182	6/9/2009	6.90	1.19	140	East

Table B-1 (Continued)

Tree ID	Vial Number	Sample Date	TCE (µg/kg)	Sample Weight (g)	Sample Height (cm)	Sample Orientation
R11 T30	249	7/15/2009	120.47	1.24	115	West
R11 T30	250	7/15/2009	74.81	1.76	115	West
R11 T30	251	7/15/2009	102.59	1.13	300	West
R11 T30	252	7/15/2009	91.19	1.19	300	West
R17 T 30	253	7/15/2009	45.65	1.81	70	West
R17 T 30	254	7/15/2009	67.10	1.21	128	West
R17 T 30	255	7/15/2009	65.36	1.57	264	West
R21 T16	256	7/15/2009	117.95	1.63	113	Northwest
R21 T16	257	7/15/2009	141.72	0.96	260	Northwest
R19 T10	258	7/15/2009	22.76	1.60	262	Northeast
R19 T10	259	7/15/2009	12.69	1.61	120	Northeast
R38 T3	260	7/15/2009	4.53	1.22	105	Northeast
R38 T3	261	7/15/2009	12.33	1.36	105	Northeast
R38 T3	262	7/15/2009	12.29	1.45	235	Northeast
R38 T3	263	7/15/2009	11.49	1.35	235	Northeast
R36 T2	264	7/15/2009	40.38	0.77	108	West
R36 T2	265	7/15/2009	22.34	1.89	108	West
R36 T2	266	7/15/2009	18.31	1.65	250	West
R36 T2	267	7/15/2009	23.16	1.29	250	West
R11T30	410	9/8/2009	132.63	1.98	110	West
R11T30	411	9/8/2009	200.94	1.66	110	West
R11T30	412	9/8/2009	149.29	1.40	290	Southwest
R11T30	413	9/8/2009	78.03	1.41	290	Southwest
R17T30	414	9/8/2009	105.43	1.26	110	Southwest
R17T30	415	9/8/2009	143.34	0.96	258	Southwest
R21T16	416	9/8/2009	86.18	1.66	116	North
R21T16	417	9/8/2009	0.07	1.21	255	Northwest
R23T15	418	9/8/2009	0.07	1.65	112	Southeast
R23T15	419	9/8/2009	0.08	1.40	260	South
R20T10	420	9/8/2009	11.29	1.95	121	North
R20T10	422	9/8/2009	14.95	0.85	285	North
R21T4	423	9/8/2009	19.62	1.08	115	North
R21T4	424	9/8/2009	6.78	1.44	115	North

Table B-1 (Continued)

Tree ID	**Vial Number**	**Sample Date**	**TCE (μg/kg)**	**Sample Weight (g)**	**Sample Height (cm)**	**Sample Orientation**
R21T4	425	9/8/2009	8.89	1.12	290	Northeast
R21T4	426	9/8/2009	10.48	0.73	290	Northeast
R36T2	427	9/8/2009	19.79	2.13	104	Southeast
R36T2	428	9/8/2009	39.40	1.68	265	East
R38T3	429	9/8/2009	26.39	1.27	88	East
R38T3	430	9/8/2009	33.10	1.46	88	East
R38T3	431	9/8/2009	13.95	1.68	256	East
R38T3	432	9/8/2009	16.71	1.54	256	East
R38T2	433	9/8/2009	11.81	1.62	106	East
Control 1	434	9/8/2009	0.02	1.10	104	East
Control 1	435	9/8/2009	0.02	0.98	104	East
Control 2	436	9/8/2009	N.D.	1.18	106	Northeast
Control 2	437	9/8/2009	N.D.	1.13	106	Northeast
N.D.: Non-detect. Sample concentration was below instrument detection limits.						

Table B-2. Leaf TCE volatilization data for 2009 at Fairchild AFB

Tree ID	**Sample Date**	**Mass TCE (pg)**	**Leaf Area (m^2)**	**Sample Time (hr)**	**Split Ratio**	**Water collected (g)**	**TCE Flux (μg/m^2-hr)**	**TSC (μg/L)**
R11T30	7/15/09	51.75	0.037	0.5	0.017	0.056	0.17	0.92
R11T30	7/15/09	66.72	0.037	0.5	0.014	0.068	0.22	0.99
R11T30	9/9/09	232.58	0.045	0.5	0.022	0.028	0.47	8.37
R17T30	7/15/09	129.78	0.061	0.5	0.014	0.072	0.30	1.81
R17T30	9/9/09	242.93	0.042	0.5	0.021	0.042	0.56	5.77
R20T10	7/15/09	<MDL	0.031	0.5	0.017	0.048	<MDL	<MDL
R20T10	9/9/09	<MDL	0.030	0.5	0.016	0.015	<MDL	<MDL
R21T4	9/9/09	<MDL	0.052	0.5	0.019	0.061	<MDL	<MDL
R22T16	7/15/09	406.10	0.021	0.517	0.017	0.035	2.19	11.46
R23T15	9/9/09	<MDL	0.047	0.5	0.015	0.035	<MDL	<MDL
R23T15	9/9/09	43.44	0.047	0.5	0.018	0.049	0.10	0.88
R36T2	7/15/09	73.85	0.015	0.5	0.018	0.0396	0.56	1.86
R36T2	7/15/09	<MDL	0.015	0.5	0.017	0.0371	<MDL	<MDL
R36T2	9/9/09	179.03	0.024	0.5	0.018	0.0329	0.85	5.44
R38T3	7/15/09	83.70	0.038	0.517	0.018	0.0638	0.24	1.31
R38T3	7/15/09	<MDL	0.042	0.5	0.022	0.0708	<MDL	<MDL
R38T3	9/9/09	270.18	0.063	0.5	0.019	0.0698	0.46	3.87
Control 1	9/10/09	<MDL	0.042	0.5	0.023	0.1048	<MDL	<MDL

Table B-3. Trunk TCE volatilization data for 2009 at Fairchild AFB

Tree ID	**Sample Date**	**Area (m^2)**	**Height (cm)**	**Mass TCE (pg)**	**Sampling Time (hr)**	**TCE flux (μg/m^2-hr)**
R11T30	7/15/09	0.02468	120	6676.38	0.5	0.54
R11T30	7/15/09	0.02468	300	761.66	0.5	0.062
R11T30	9/9/09	0.02468	64	<MDL	0.5	<MDL
R17T30	7/15/09	0.02468	70	5142.99	0.5	0.417
R17T30	9/9/09	0.02468	47	733.75	0.5	0.060
R21T4	9/9/09	0.02468	50	3403.27	0.567	0.243
R36T2	7/15/09	0.02468	23	1099.93	0.5	0.089
R36T2	7/15/09	0.02468	23	1028.14	0.5	0.083
R36T2	9/9/09	0.02468	75	57.65	0.5	0.005
R38T3	7/15/09	0.02468	100	1118.25	0.5	0.091
R38T3	7/15/09	0.02468	230	915.13	0.5	0.074
R38T3	9/9/09	0.02468	78	47.92	0.5	0.004
Control 1	9/10/09	0.02468	130	31.57	0.5	<MDL

Table B-4. Soil surface flux data for 2009 at Fairchild AFB

Location	**Sample Date**	**Area (m^2)**	**Mass TCE (pg)**	**Sampling Time (hr)**	**TCE Flux (μg/m^2-day)**
Waypoint 025	6/9/09	0.034636	132.67	0.5	0.008
Waypoint 026	6/9/09	0.034636	337.74	0.5	0.020
Waypoint 027	6/9/09	0.034636	3797.88	0.5	0.219
Waypoint 028	6/9/09	0.034636	869.73	0.5	0.050
Waypoint 029	6/9/09	0.034636	1240.89	0.5	0.072
Waypoint 030	6/9/09	0.034636	729.97	0.5	0.042
Waypoint 031	6/9/09	0.034636	173.51	0.5	0.010
Waypoint 032	6/9/09	0.034636	248.77	0.5	0.014
Waypoint 033	6/9/09	0.034636	1763.00	0.5	0.102
Blank	6/9/09	0.034636	133.77	0.5	0.008
Blank	6/9/09	0.034636	100.75	0.5	0.006
Waypoint 007	7/16/09	0.034636	217.34	0.5	0.013
Waypoint 007	7/16/09	0.034636	219.03	0.5	0.013
Waypoint 007	7/16/09	0.034636	262.52	0.5	0.015
Waypoint 009	7/16/09	0.034636	539.87	0.5	0.031
Waypoint 009	7/16/09	0.034636	309.33	0.5	0.018
Waypoint 009	7/16/09	0.034636	99.56	0.5	0.006
Waypoint 012	7/16/09	0.034636	5063.85	0.5	0.292
Waypoint 012	7/16/09	0.034636	774.92	0.5	0.045
Waypoint 012	7/16/09	0.034636	2810.06	0.5	0.162
Waypoint 004	9/8/09	0.034636	29823.87	0.5	1.722
Waypoint 004	9/9/09	0.034636	8792.50	0.5	0.508
Waypoint 008	9/8/09	0.034636	10418.48	0.5	0.602
Waypoint 008	9/9/09	0.034636	78.62	0.5	0.005
Waypoint 013	9/8/09	0.034636	44.96	0.5	0.003
Waypoint 013	9/9/09	0.034636	<MDL	0.5	<MDL
Control 1	9/10/09	0.034636	64.65	0.5	0.004

APPENDIX C

TRAVIS POLYGON AND REMOVAL RESULTS

Table C-1. Tree core sampling polygon information and TCE removal calculations at Travis AFB

Polygon ID	Area (m^2)	Fraction Total Area	Number of Trees	Core Conc. (µg/kg)	Average Height (m)	Average Diameter (cm)	Dry Weight (kg)	Fresh Weight (kg)	TCE Sorbed (g)
R8T58	387.76	0.04	12	345	7.01	10	8.55	19.01	0.08
R8T50	471.7	0.05	17	163	7.01	9.15	7.16	15.91	0.04
R8T28	820.34	0.08	31	440	11.81	13.58	26.55	59.01	0.8
R8T39	527.21	0.05	20	214	10.06	13.95	23.88	53.07	0.23
R8T1	598.16	0.07	27	6026	11.2	14.73	29.63	65.85	10.71
R1T60	247.68	0.03	7	197	5.38	12.1	9.62	21.37	0.03
[a]R1T50	402.84	0.04	11	0.46	7.7	13.18	16.3	36.22	0
R1T39	436.93	0.04	22	852	15.04	19.23	67.86	150.8	2.83
R1T27	819.69	0.08	42	2278	11.84	15.7	35.59	79.1	7.57
R1T1	204.15	0.03	10	4496	9.14	16.8	31.49	69.97	3.15
[b]R2T56	325.96	0.03	13	302	6.58	14.14	16.06	35.69	0.14
R2T51	249.33	0.03	8	1044	8.38	17.2	30.25	67.23	0.56
[c]R2T39	326.35	0.03	11	2076	11.07	15.6	32.88	73.07	1.67
R2T27	627.71	0.06	28	1668	9.6	14.35	24.12	53.6	2.5
R2T2	520.83	0.06	28	2255	12.19	17.33	44.69	99.31	6.27
R4T40	420.62	0.05	21	1077	7.11	11.97	12.43	27.61	0.62
R4T28	500.31	0.07	21	1024	8.76	13.6	19.77	43.94	0.94
R4T3	745.47	0.09	38	4961	8.89	11.98	15.55	34.56	6.52
R5T60	182.49	0.03	7	2	7.32	7.5	5.02	11.16	0
R5T52	262.47	0.04	14	113	5.03	11.3	7.83	17.41	0.03
Totals:	9,078.00	1	388						44.69

[a]Average height and diameter of polygons R8T50 & R2T51. [b]Average height and diameter of polygons R1T60 & R2T51. [c]Average height and diameter of polygons R1T39 & R4T40

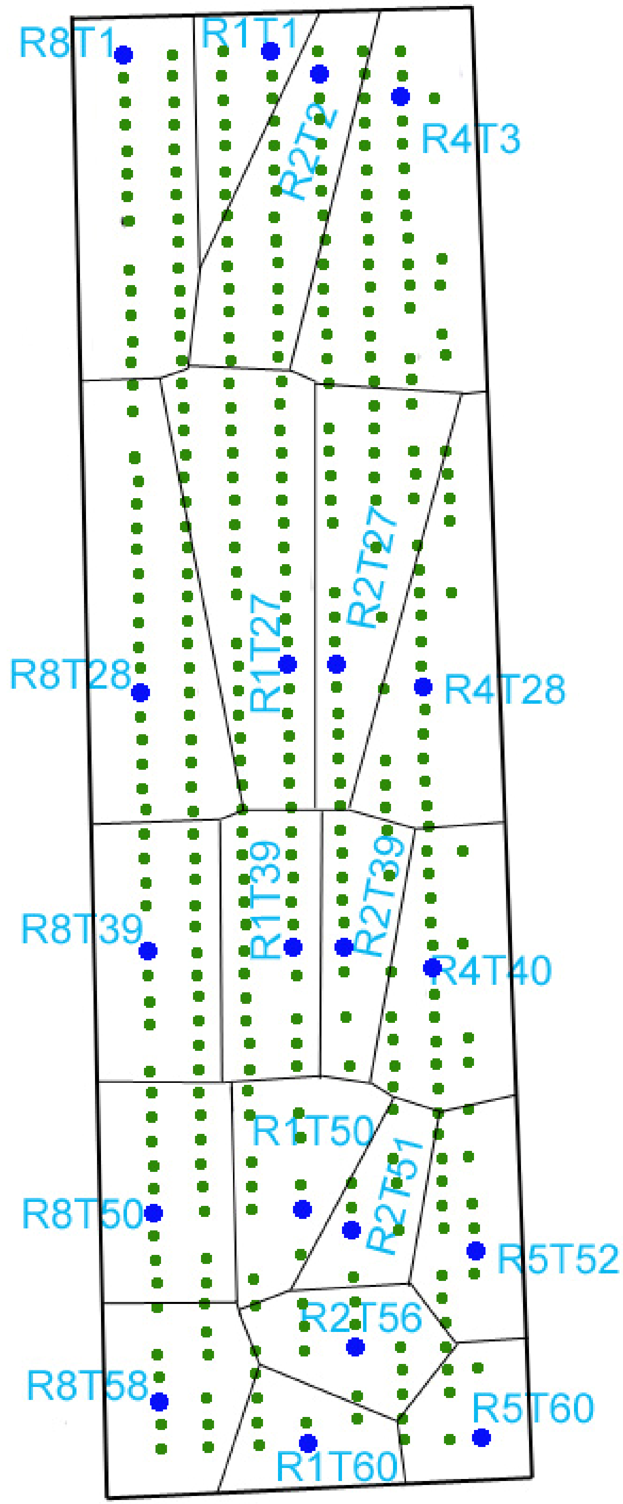

Figure C-1. Initial tree core sampling polygons at Travis AFB.

Table C-2. Trunk sampling polygon information and TCE removal calculations at Travis AFB

Polygon ID	Number of Trees	Trunk Flux (µg/m²/hr)	Average Height (m)	Average Circumference (cm)	Average Surface Area (m²)	TCE Removal (g/yr)
R8T1	42	0.52	10.92	44.92	4.91	0.74
R1T27	84	0.27	11.81	44.92	5.31	0.84
R2T51	94	0.13	6.12	32.00	1.96	0.16
R2T27	32	0.46	12.27	60.48	7.42	0.75
R4T40	56	0.24	10.52	47.20	4.96	0.46
R4T28	17	0.36	8.76	42.73	3.74	0.16
R4T3	63	0.72	10.10	45.18	4.56	1.43
Totals:	388					4.55

Table C-3. Leaf sampling polygon information and TCE removal calculations at Travis AFB

Polygon ID	Area (m²)	TSC (µg/L)	TCE Removal (g/yr)
R8T1	856.98	112.80	72.67
R1T27	1909.22	59.67	85.64
R2T51	2667.61	22.94	46.00
R2T27	641.41	1.40	0.68
R4T40	1274.23	16.48	15.79
R4T28	514.12	43.27	16.72
R4T3	1214.44	87.78	80.14
Totals:	9078		317.64

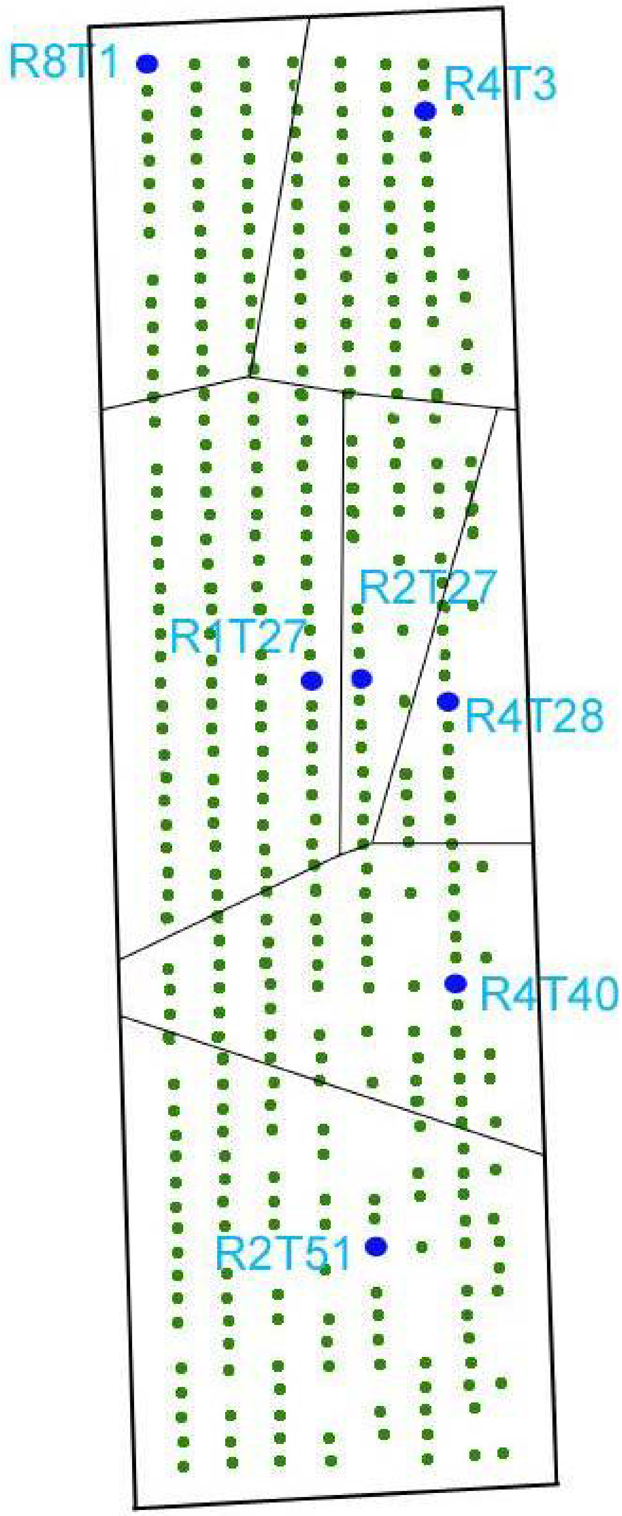

Figure C-2. Trunk and leaf volatilization sampling polygons at Travis AFB.

Table C-4. Trip 3 soil flux sampling polygon information and TCE removal calculations for the phytostabilization site at Travis AFB

Polygon ID	**Area (m^2)**	**Soil Flux ($\mu g/m^2$-hr)**	**Average X-section Area (m^2)**	**Number of Trees**	**TCE Removal (g/yr)**
R8T1	856.98	36.18	0.018	37	214.89
R1T27	2,329.22	0.99	0.020	105	15.93
R2T51	2,667.61	2.46	0.010	93	45.47
R4T40	1,274.86	<MDL	0.018	58	0.00
R4T28	725.87	6.18	0.010	28	31.09
R4T3	1,223.48	19.42	0.015	67	164.68
Totals:	9,078.00				472.06

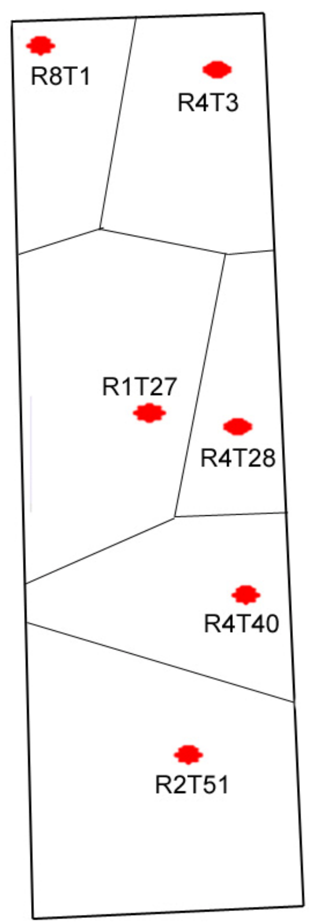

Figure C-3. Trip 3 soil volatilization sampling polygons within phytostabilization site at Travis AFB.

Table C-5. Trip 1 soil flux sampling polygon information and removal calculations outside planted area at Travis AFB

Waypoint	**Area (m^2)**	**Soil Flux (μg/m^2-hr)**	**TCE Removal (g/yr)**
WP24	1,833.58	0.0278	0.35
WP22	942.08	0.3924	2.56
WP23	1,946.51	0.0078	0.11
WP16	878.67	0.0558	0.34
WP17	1,611.54	0.0699	0.78
WP18	1,865.62	0.0328	0.42
Totals:	9,078.00		4.57

Table C-6. Trip 1 soil flux sampling polygon information and removal calculations inside planted area at Travis AFB

Waypoint	**Area m^2**	**Flux (μg/m^2-hr)**	**Removal (g/yr)**
WP019	3,425.95	0	0
WP020	1,743.30	3.512	42.4653
WP021	3,908.75	3.069	83.204
Totals:	9,078.00		125.67

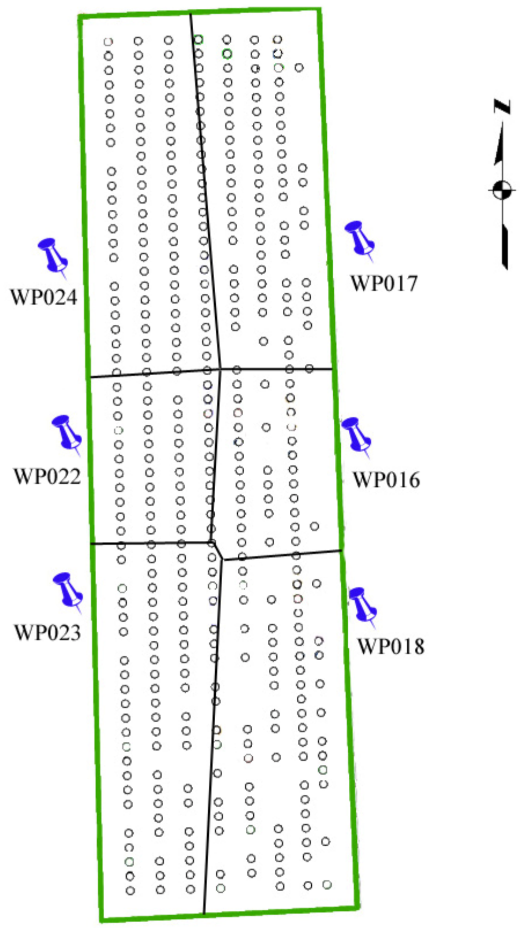

Figure C-4. Trip 1 soil volatilization sampling polygons for samples outside the planted area at Travis AFB .

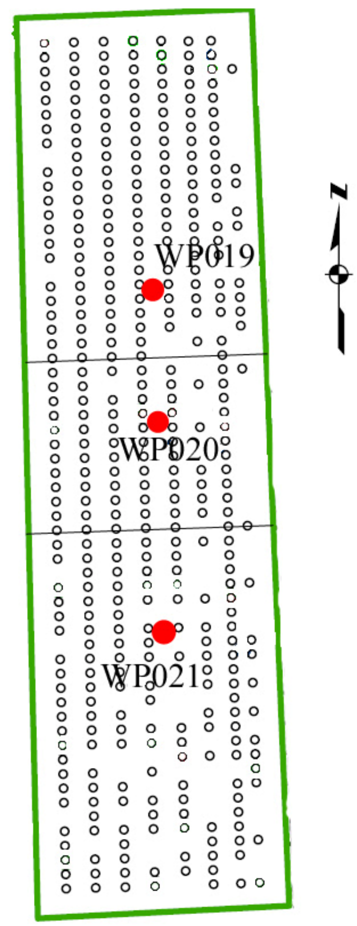

Figure C-5. Trip 1 soil volatilization sampling polygons for samples inside the planted area at Travis AFB.

Table C-7. Groundwater sampling polygon information and TSCF values at Travis AFB

Well ID	**Groundwater Concentration (μg/L)**	**Average GW Conc. (μg/L)**	**Tree**	**TSC (μg/L)**	**TSCF**
755PHYTO42	146	2614	R8T1 R4T3	112.79 87.78	0.04 0.03
755PHYTO25	5082				
755PHYTO39	1.4	2457.85	R4T40 R2T51	16.48 22.94	0.01 0.01
755PHYTO37	443				
755PHYTO44	9196				
755PHYTO41	191				
755PHYTO30	658	792	R4T28	43.27	0.05
MW779x39	1530				
755PHYTO45	188				
MW778x39	9	559.5	R1T27 R2T27	59.67 1.40	0.11 0.003
MW777x39	1110				
				Average	0.04
				95% CI	0.03

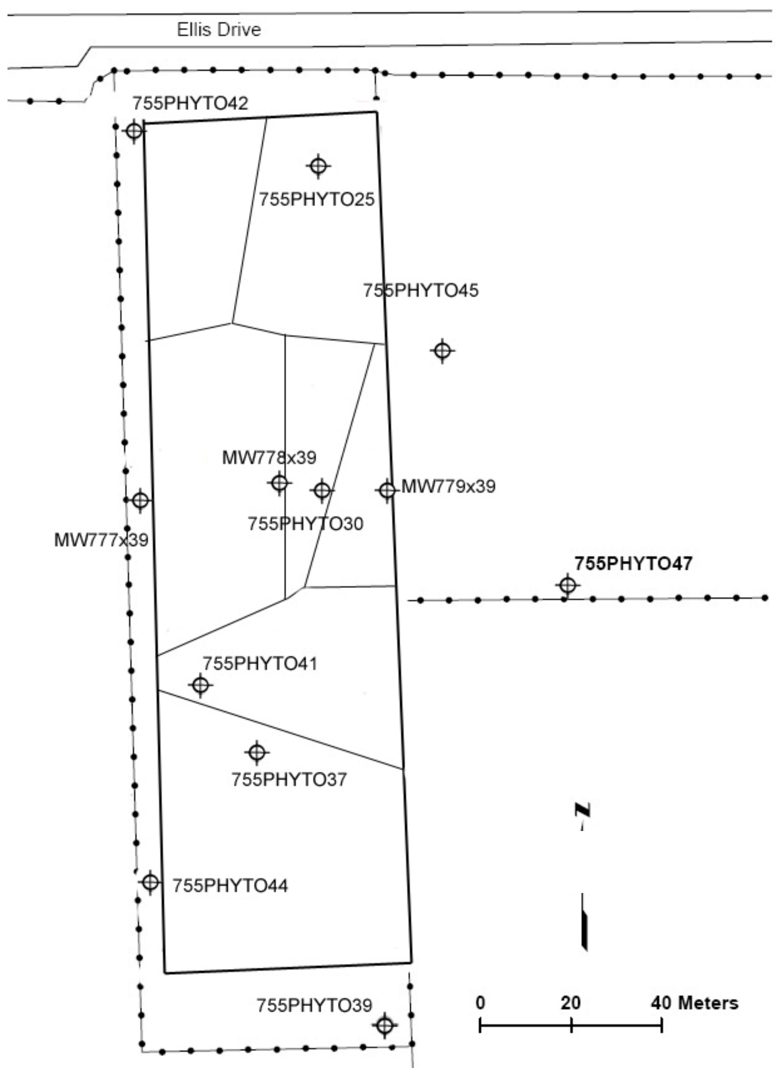

Figure C-6. Monitoring well locations within tree polygons at Travis AFB.

APPENDIX D

FAIRCHILD POLYGON AND REMOVAL RESULTS

Table D-1. Tree core sampling polygon information and TCE removal calculations at Fairchild AFB

Tree ID	Area (m^2)	Fraction Total Area	Number of Trees	Core TCE (μg/kg)	Average Diameter (cm)	Dry Weight (kg)	Fresh Weight (kg)	Sorbed (g)
R5T5	170.29	0.04	1	0.43	3.35	1.33	2.94	0.00
R7T8	106.91	0.03	6	0.18	15.00	29.36	65.24	0.00
R11T14	169.97	0.04	5	0.33	3.40	1.35	3.00	0.00
[a]R11T10	117.67	0.03	10	4.69	10.83	18.51	41.14	0.00
R10T13	223.01	0.06	26	9.75	16.00	31.96	71.02	0.02
R2T15	195.72	0.05	15	0.69	7.00	8.56	19.02	0.00
R2T25	180.98	0.05	15	11.11	16.17	32.39	71.99	0.01
R9T27	262.24	0.07	32	42.12	13.42	25.25	56.12	0.08
R17T23	328.75	0.08	41	2.75	12.80	23.64	52.53	0.01
R25T25	247.41	0.06	18	1.80	7.43	9.69	21.53	0.00
R22T16	237.20	0.06	17	55.48	10.58	17.86	39.68	0.04
[b]R23T11	187.96	0.05	4	0.33	10.64	18.04	40.08	0.00
R20T10	147.25	0.04	8	15.03	11.00	18.96	42.13	0.01
R21T4	158.18	0.04	9	4.99	10.50	17.66	39.24	0.00
[c]R26T3	190.88	0.05	8	29.64	11.50	20.26	45.02	0.01
R30T24	277.78	0.07	23	3.21	9.90	16.10	35.78	0.00
R34T20	341.83	0.09	16	0.05	7.50	9.86	21.91	0.00
[d]R37T11	271.03	0.07	6	0.66	10.00	16.36	36.36	0.00
R36T2	116.10	0.03	7	17.71	13.00	24.16	53.69	0.01
R38T3	68.83	0.02	6	11.12	10.50	17.66	39.24	0.00
Totals:	4,000.00		273					0.11

[a]Average diameter of polygons R10T13, R20T10, R11T14, R7T8. [b]Average diameter of polygons R21T4, R20T10, R22T16. [c]Average diameter of polygons R21T4, R36T2. [d]Average diameter of polygons R38T3, R36T2, R34T20

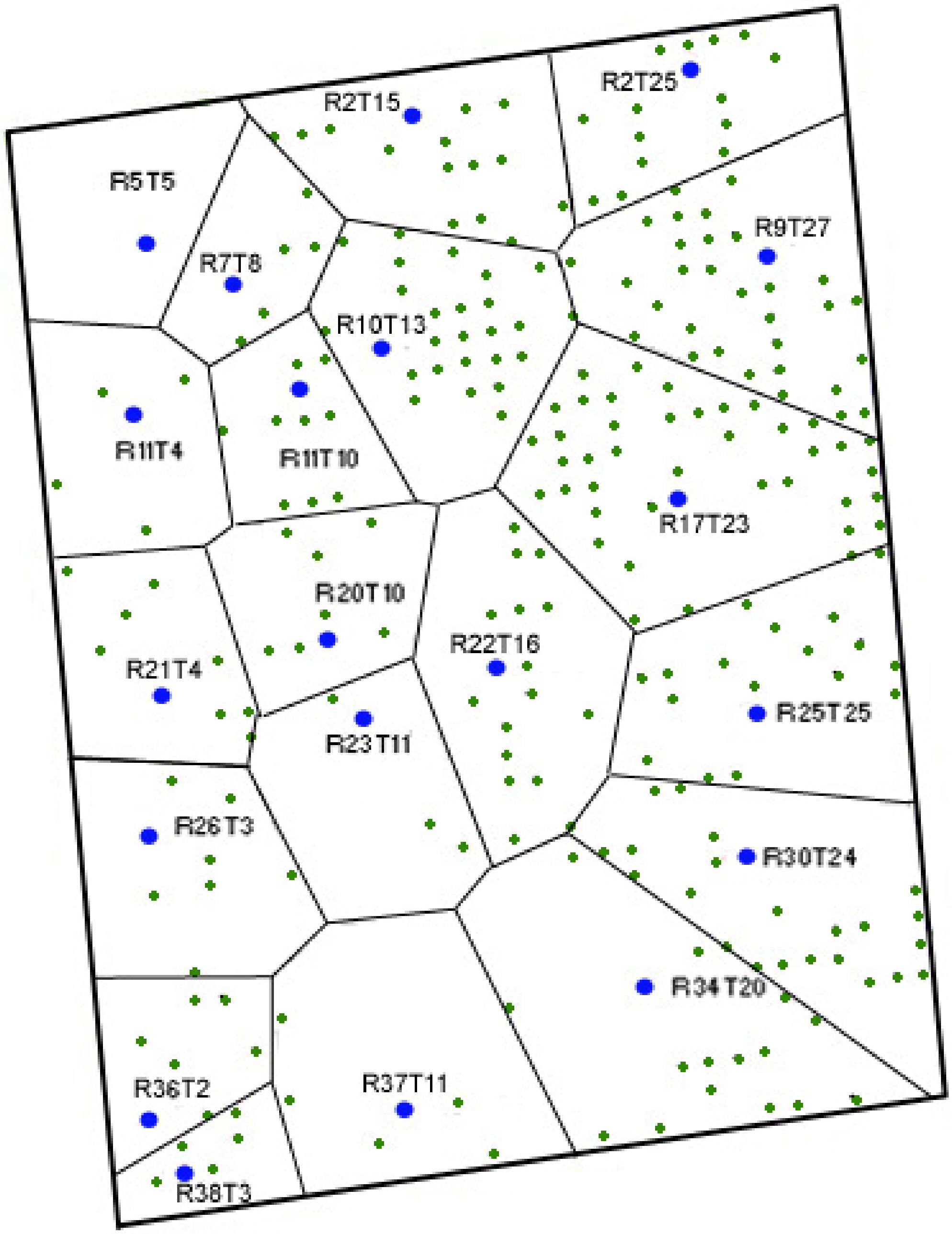

Figure D-1. Initial tree core sampling polygons at Fairchild AFB.

Table D-2. Trunk sampling polygon information and TCE removal calculations at Fairchild AFB

Tree ID	Number of Trees	Trunk Flux μg/(m^2-hr)	Average Height (m)	Average Circumference (cm)	Average Surface Area (m^2)	TCE Removal (g/year)
R11T30	84	0.20	11.86	43.23	5.13	0.32
R17T30	90	0.24	8.34	28.05	2.34	0.18
R21T4	68	0.24	7.95	32.99	2.62	0.16
R36T2	9	0.06	8.38	21.21	1.78	0.00
R38T3	22	0.02	8.84	37.70	3.33	0.01
Totals:	273					0.67

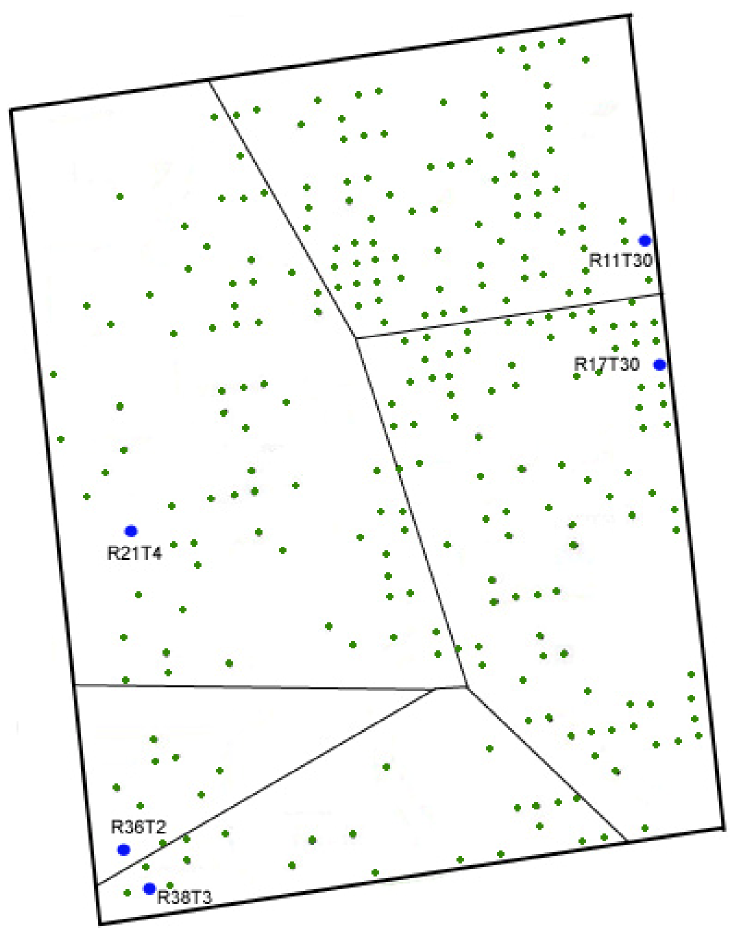

Figure D-2. Trunk volatilization sampling polygons at Fairchild AFB.

Table D-3. Leaf sampling polygon information and TCE removal calculations at Fairchild AFB

Tree ID	Area (m^2)	Fraction Total Area	TSC (μg/L)	TCE Removal (g/year)
R11T30	658.43	0.16	3.43	2.09
R17T30	412.72	0.10	3.79	1.45
R22T16	509.73	0.13	11.46	5.42
R20T10	750.45	0.19	0.00	0.00
R21T4	501.40	0.13	0.00	0.00
R23T15	687.58	0.17	0.44	0.28
R36T2	230.75	0.06	2.44	0.52
R38T3	248.92	0.06	2.59	0.60
Totals:	4000.00			10.36

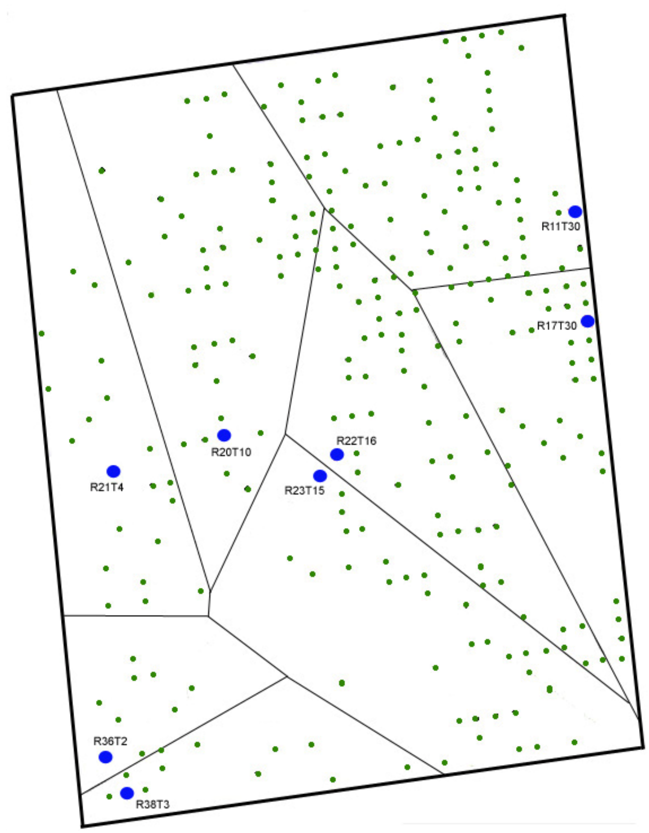

Figure D-3. Leaf volatilization sampling polygons at Fairchild AFB.

Table D-4: Trip 3 soil flux sampling polygon information and TCE removal calculations for the phytostabilization site at Fairchild AFB

Well	Area (m^2)	Soil Flux ($\mu g/m^2$-hr)	Avg. Tree X-section Area (m^2)	Number Of Trees	TCE Removal (g/year)
WP013	684.14	0.00	0.009	32	0.003
WP008	2,102.70	0.30	0.007	118	2.34
WP004	1,213.15	1.11	0.012	123	4.96
Totals:	4,000.00				7.30

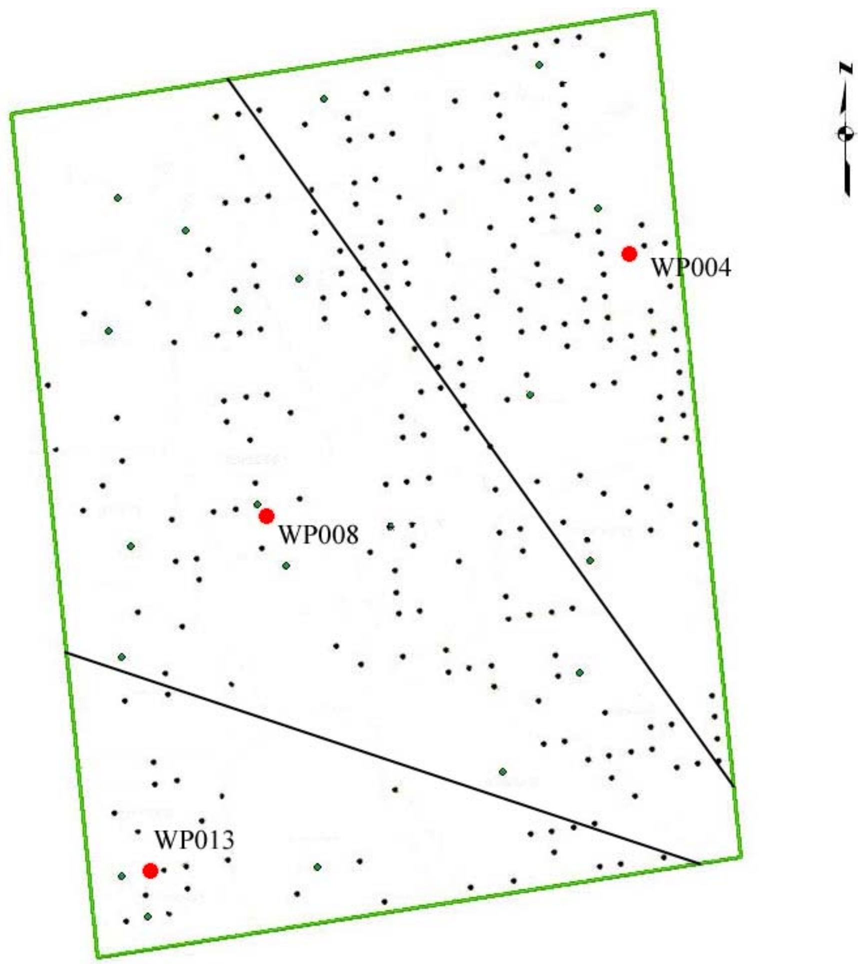

Figure D-4. Trip 3 soil volatilization sampling polygons within phytostabilization site at Fairchild AFB.

Table D-5. Trip 1 soil flux sampling polygon information and removal calculations outside the planted area at Fairchild AFB

Waypoint	Area (m^2)	Soil Flux ($\mu g/m^2$-hr)	Removal (g/yr)
WP25	1,062.11	0.01	0.03
WP26	456.95	0.02	0.03
WP27	741.56	0.22	0.60
WP33	1,095.24	0.10	0.41
WP32	580.71	0.01	0.03
WP31	63.43	0.01	0.002
Totals:	4,000.00		1.10

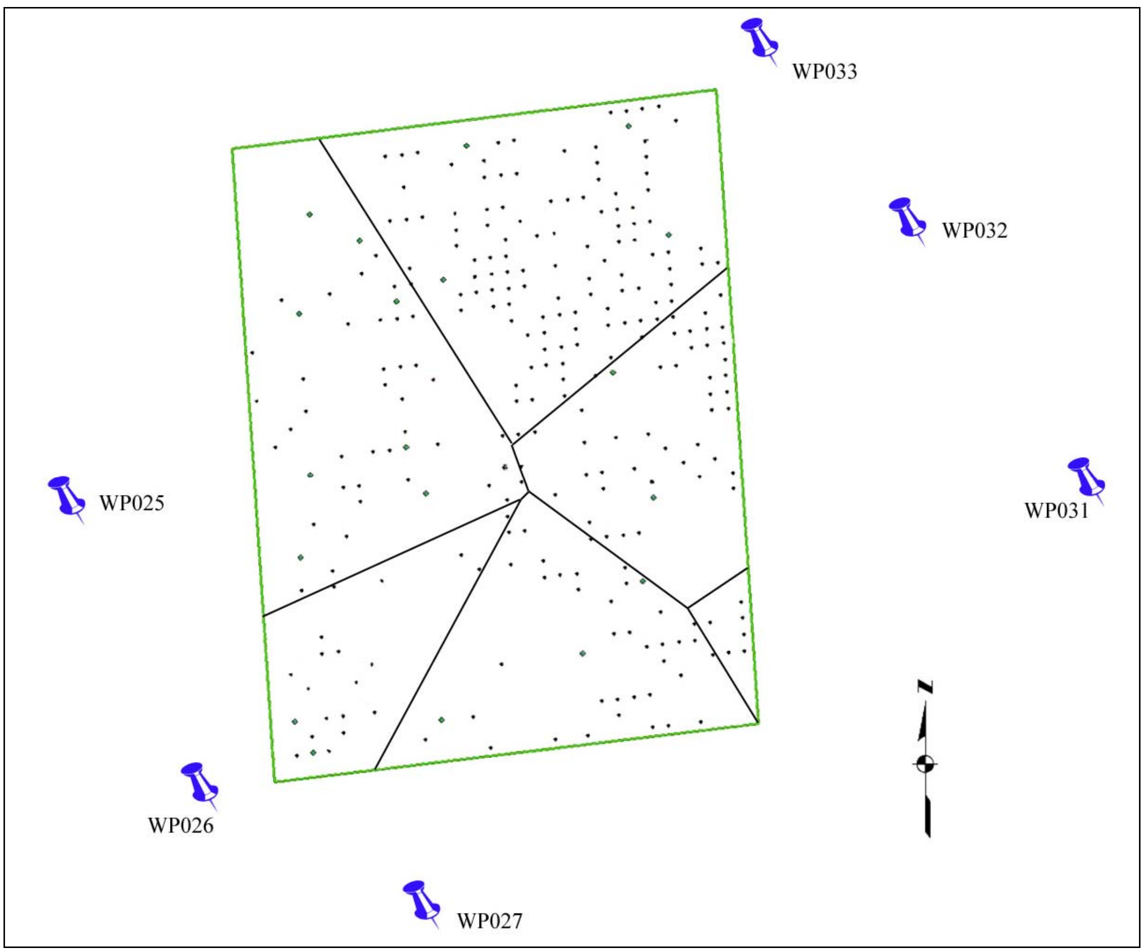

Figure D-5. Trip 1 soil volatilization sampling polygons for samples outside the planted area at Fairchild AFB.

Table D-6. Trip 1 soil flux sampling polygon information and removal calculations inside the planted area at Fairchild AFB

Waypoint	Area (m^2)	Flux ($\mu g/m^2$-hr)	Removal (g/yr)
WP028	1,220.94	0.05022	0.22515
WP029	496.93	0.07165	0.13074
WP030	2,282.13	0.04215	0.35322
Totals:	4,000.00		0.71

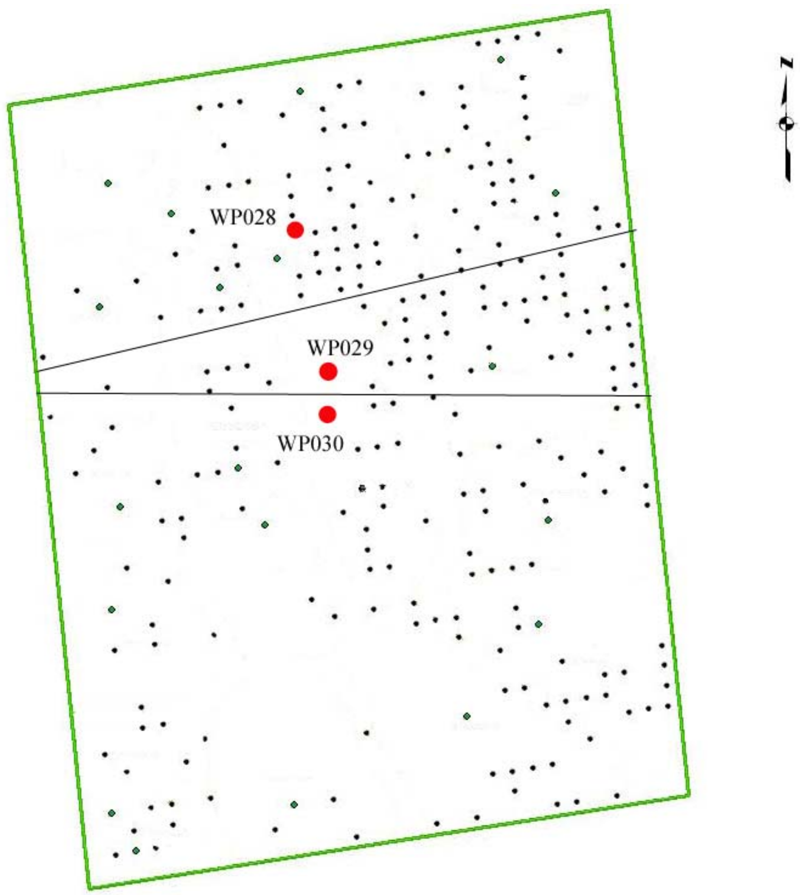

Figure D-6. Soil volatilization sampling polygons for samples inside phytostabilization site Trip 1 at Fairchild AFB.

Table D-7. Groundwater sampling polygon information and TSCF values at Fairchild AFB

Well ID	Groundwater Concentration (µg/L)	Tree	TSC (µg/L)	TSCF
MP 07	67	R21T4 R20T10	0.00 0.00	0.00 0.00
MP 38	150	R11T30 R22T16 R17T30	3.43 11.46 3.79	0.02 0.08 0.03
MP 41	51	R23T15 R36T2 R38T3	0.44 2.44 2.59	0.01 0.05 0.05
			Average	0.03
			95% CI	0.02

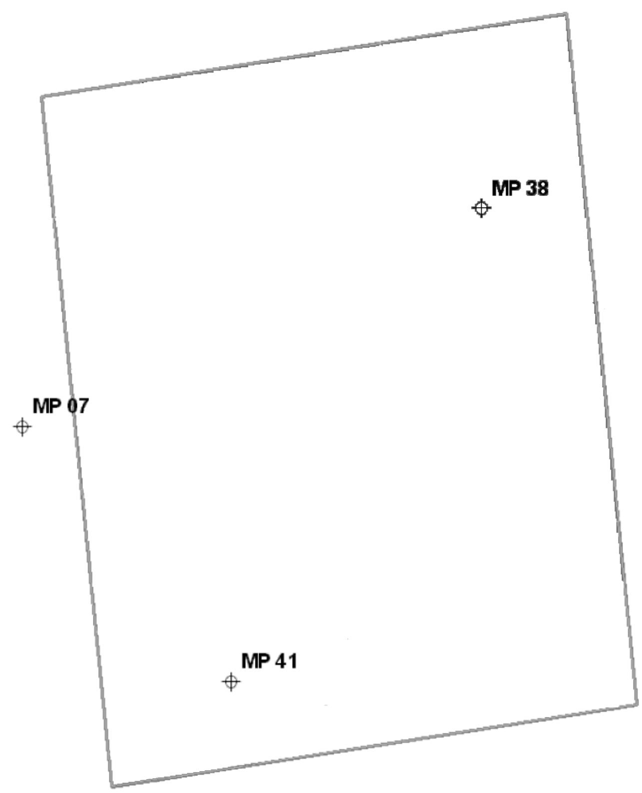

Figure D-7. Monitoring well locations at Fairchild AFB.