Ground Water Monitoring & Remediation

Ground Water Chlorinated Ethenes in Tree Trunks: Case Studies, Influence of Recharge, and Potential Degradation Mechanism

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Abstract

Trichloroethene (TCE) was detected in cores of trees growing above TCE-contaminated ground at three sites: the Carswell Golf Course in Texas, Air Force Plant PJKS in Colorado, and Naval Weapons Station Charleston in South Carolina. This was true even when the depth to water was 7.9 m or when the contaminated aquifer was confined beneath ~3 m of clay. Additional ground water contaminants detected in the tree cores were *cis*–1,2-dichloroethene at two sites and tetrachloroethene at one site. Thus, tree coring can be a rapid and effective means of locating shallow subsurface chlorinated ethenes and possibly identifying zones of active TCE dechlorination. Tree cores collected over time were useful in identifying the onset of ground water contamination. Several factors affecting chlorinated ethene concentrations in tree cores were identified in this investigation. The factors include ground water chlorinated ethene concentrations and depth to ground water contamination. In addition, differing TCE concentrations around the trunk of some trees appear to be related to the roots deriving water from differing areas. Opportunistic uptake of infiltrating rainfall can dilute prerain TCE concentrations in the trunk. TCE concentrations in core headspace may differ among some tree species. In some trees, infestation of bacteria in decaying heartwood may provide a TCE dechlorination mechanism within the trunk.

Introduction

Ground water constituents in tree trunks have been examined for a variety of applications. Inorganic constituents in tree cores have been examined as an aid to investigating solvent dechlorination (Yanosky et al. 2001) and as a tool for examining the history of ground water contamination (Vroblesky and Yanosky 1990; Yanosky and Vroblesky 1992, 1995; Vroblesky et al. 1992). A variety of volatile organic compounds (VOCs) has been found in cores of trees when roots are exposed to contaminated ground water (Newman et al. 1997; Burken and Schnoor 1998; Nietch et al. 1999; Vroblesky et al. 1999; Landmeyer et al. 2000; Ma and Burken 2002). Chlorinated ethenes in tree trunks have been used to delineate ground water contamination plumes in South Carolina (Vroblesky et al. 1999; Vroblesky et al. 2001), Maryland (Burken 2001), Missouri (Schumacher 2001), and Utah (Lewis et al. 2001).

The focus of this paper is the application of tree coring to indicate the presence of ground water chlorinated ethenes. Because tree cores can be collected and analyzed rapidly and inexpensively, the approach has potential for plume delineation and as a reconnaissance tool for directing well placement. This paper presents case studies applying tree coring to examine ground water chlorinated ethene concentrations and discusses some of the factors influencing chlorinated ethene concentrations in tree trunks. VOC sorption onto woody biomass (Ma and Burken 2002) and diffusive loss through the trunk (Vroblesky et al. 1999; Burken 2001; Ma and Burken 2003) have been discussed elsewhere and are not discussed here.

This investigation was a cooperative effort between the U.S. Geological Survey (USGS), the U.S. Air Force, the Southern Division Naval Facilities Engineering Command, and the U.S. Department of Agriculture Forest Service. The investigation involved collection and analysis of tree cores from three different sites containing chlorinated ethene contamination in the ground water. A total of 100 trees were examined between 1998 and 2002. In addition, data were collected on temporal variations in tree-trunk VOC chemistry in eastern cottonwood (*Populus deltoides* Bartr.) in response to irrigation, as an analog to natural rainfall, to investigate the potential for a dilution effect from rainfall. Analysis of tree cores in this study involved placing a tree core in a glass vial and sealing it with a Teflon®-lined rubber

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stopper. Volatile contaminants in the cores equilibrated with the headspace in the vial, which then was sampled by syringe and analyzed by gas chromatography.

Study Area Descriptions

Data for this investigation were collected from three different environments: a subhumid setting at the Carswell Golf Course near Air Force Plant 4, Texas; a semiarid setting at Air Force Plant PJKS, Colorado; and a semitropical setting at the Naval Weapons Station (NWS) Charleston, North Charleston, South Carolina.

Chlorinated ethenes are present in the ground water at the three study sites. Climate information and general aquifer characteristics are given in Table 1. A summary of the trees cored at each site is shown in Table 2. Tree cores from the Carswell Golf Course are designated by the prefix TX. Tree cores from PJKS are designated by the prefix PJ, and tree cores from NWS Charleston are designated by the prefix SC.

Carswell Golf Course

The Carswell Golf Course is adjacent to the Naval Air Station Fort Worth Joint Reserve Base and Air Force Plant 4, Fort Worth, Texas (Figure 1). The shallow ground water at the site is contaminated with trichloroethene (TCE) (< 2 to > 1000 µg/L) and *cis*–1.2-dichloroethene (*c*DCE) (< 2 to > 400 µg/L) from military operations at the adjacent Air Force Plant 4. TCE was a primary solvent used in cleaning metal parts before plating and painting aircraft at Air Force Plant 4. Ground water and surface water flow and contaminant transport is approximately eastward. Most trees at the site are widely spaced around the golf course and they consist of a variety of species (Figure 1).

PJKS

PJKS is located in the foothills of the Colorado Front Range, northwest of Waterton, Colorado, and ~32 km south-southwest of Denver. Activities related to cleaning and testing parts at the site have resulted in ground water contamination by chlorinated aliphatic hydrocarbons, predominantly TCE. TCE concentrations in ground water ranged from < 10 to > 1000 µg/L. The distribution and concentrations of TCE contamination in the alluvial aquifer for September 1994 to April 1995 are shown in Figure 2a; that period marked the time of the most extensive ground water sampling (Parsons Engineering Science Inc. 1999). The tree core TCE concentrations shown in Figures 2a and 2b and ground water TCE concentrations in Figure 2b are from samples collected in 1999. Diameters of trees cored at PJKS predominantly ranged from 20 to 30 cm.

Trees at the site are primarily eastern cottonwood along the East Fork Brush Creek and predominantly Gambel oak along the DI–1 Tributary. An investigation by Vose et al. (2003) showed that the mean daily sapflow in trees used in this investigation at the time that the cores were collected was ~24 kg water/tree/d. East Fork Brush Creek flows west

Table 1
Summary of Study Area Climate and Hydrogeology

Site Name	Climate	Subsurface Lithology	Aquifer Hydraulic Conductivity	Depth Below Land Surface to Ground Water
Carswell Golf Course, Fort Worth, Texas	Subhumid: precipitation is 80 cm/yr, of which ~6 cm/yr recharges ground water[a]	Terrace alluvial deposits forming an unconfined aquifer ~0.3 to 1.5 m thick and underlain by a poorly permeable shaley limestone[a]	1 to ~30 m/d with a geometric mean of ~6 m/d[a]	0.7 m near stream to ~7.9 m in upland areas in July and August 1998[b]
Air Force Plant PJKS, Waterton, Colora	Semiarid: precipitation is 44.2 cm/yr, mostly as snowfall[c]	Unconsolidated silty clays, sands with some cobbles and boulders, < 1 to > 12.2 m thick, forming an unconfined aquifer in valley fill alluvium between outcropping bedrock[c,d]	0.1 to 4 m/d with geometric mean of 1 m/d[e]	At or near land surface beneath trees in parts of East Fork Brush Creek to ~1 m in upland areas
Naval Weapons Station Charleston, North Charleston, South Carolina	Semitropical: precipitation is 129 cm/yr[f]	Unconsolidated sand, ~1 to 6 m thick, forming a locally confined aquifer beneath clay extending from land surface to a depth of ~3 m in most parts of the site[g]	Geometric mean of 0.36 m/d[h]	~3 m to the top of the confined aquifer[g]

[a]Eberts et al. 2003
[b]Hydrogeologic Inc. 1998
[c]Engineering Science Inc. 1993
[d]Bryant et al. 1973
[e]Stone and Webster Inc. 2001
[f]National Oceanic and Atmospheric Administration 1999
[g]Vroblesky et al. 2003
[h]Tetra Tech NUS Inc. 2000

Table 2
Summary of Trees Cored

Site Name	Tree Coring Dates	Number of Trees/Species Investigated	Tree Species Investigated/Number of Trees
Carswell Golf Course, Fort Worth, Texas	1998–2000	29/10	Eastern cottonwood (*Populus deltoids* Bartr.) (12) Oak (*Quercus sp.*) (6) Cedar (*Juniperus virginiana* L.) (3) Willow (*Salix sp.*) (2) Hackberry (*Celtis occidentalis L.*) (1) Pecan (*Carya illinoensis* [Wangenh.] K. Kock) (1) Pine [*Pinus* sp.] (1) American elm [*Ulmus Americana* L.] (1) Unidentified species of elm [*Ulmus* sp.] (1) Unidentified species thought to be a member of the *Sapotaceae* family (1)
Air Force Plant PJKS, Waterton, Colorado	May and July 1999	14/4	Eastern cottonwood (*Populus deltoids* Bartr.) (10) Gambel oak (*Quercus gambelii* Nutt) (1) Narrow-leaf cottonwood (*Populus angustifolia* James) (2) Willow (*Salix* sp.) (1)
Naval Weapons Station Charleston, North Charleston, South Carolina	2000–2002	57/3	Loblolly pine (*Pinus taeda* L.) (57) Oak (*Quercus* sp.) (2) Southern magnolia (*Magnolia grandiflora*) (1)

to east and is in an erosional channel that is ~2 to 3 m deep in places.

Because of the semiarid climate, few trees were present at the site, and those were primarily restricted to the zones immediately adjacent to the creeks. Most trees near East Fork Brush Creek are at or near the bottom of the erosional channel of the creek. It is likely the tree roots were within reach of discharging ground water because the upstream reach of East Fork Brush Creek containing trees PJ5, PJ6, and PJ7, and the downstream reach near trees PJ8, PJ9, and PJ11, historically have been shown to be gaining reaches (Parsons Engineering Science Inc. 1999). The remaining downstream trees appear to be in a reach that is sometimes gaining and sometimes losing (Parsons Engineering Science Inc. 1999).

NWS Charleston

NWS Charleston is ~16 km north of Charleston and ~25.7 km from the Atlantic Ocean. The study area at NWS Charleston is solid waste management unit (SWMU) 12. Chlorinated solvent contamination of the ground water resulted from a leaking underground storage tank and from aboveground runoff of solvents. Primary contaminants in the ground water are tetrachloroethene (PCE), TCE, and 1,1,1-trichloroethane. Ground water contaminants are present in an elongated plume extending from the source area eastward beneath a forest (Figure 3) consisting primarily of loblolly pines (*Pinus taeda* L.) with a limited number of hardwoods. Diameters of the trees used in this investigation ranged from ~20 to 50 cm. An investigation by the U.S. Forest Service showed that evapotranspiration by the pines in this forest is significant during all four seasons, although the hardwood evapotranspiration declines substantially during winter months (Hubbard and Vose 2004).

Unlike the other sites, the contaminated aquifer in the forested area is confined beneath ~3 m of clay, beginning approximately at land surface. The potentiometric surface is relatively flat, with an average hydraulic gradient of 0.0015 to 0.0017.

Methods

Tree Core and Stem Collection and Analysis

Tree cores were collected by using an increment corer. All cores used to examine areal distribution of contamination were collected from a height of ~1.5 m above ground. A mature cottonwood (74.8 cm diameter at ~1.5 m height) at the Carswell Golf Course was cored successively up the trunk to a height of ~11.6 m. During an irrigation experiment, it was cored successively up the trunk to a height of ~3.5 m.

Cores (~38 millimeters mm in length and 5 mm in diameter) were removed immediately from the coring tool and placed in 20 mL glass vials. Teflon-coated septum caps were crimped onto the vials. Typically, the cores contained an average of ~0.5 g of water, as determined by comparison of wet and dry weights.

Tree cores and stem cuttings were collected from trees at the Carswell Golf Course in July 2001 and November 2002. Scissors were used to clip a section of stem about the same length (~38 mm) and diameter (5 mm) as the tree cores. The stem section was placed into a vial and sealed. Stems were analyzed in the same way as the trunk cores for comparison purposes.

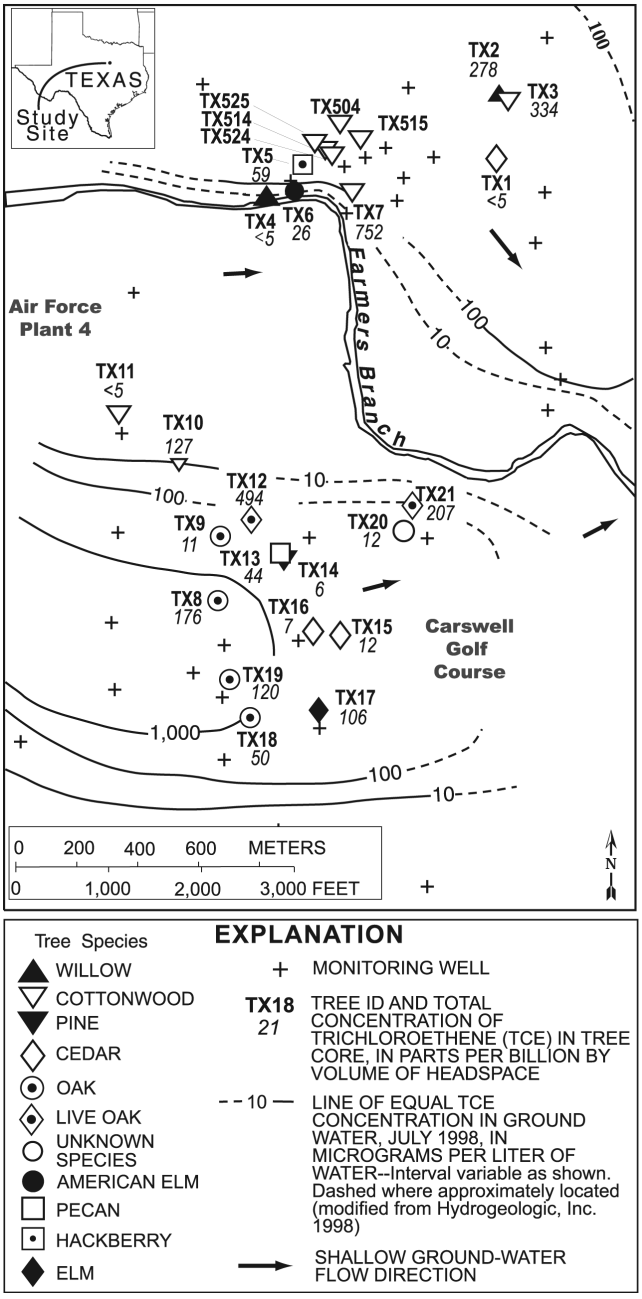

Figure 1. Locations of wells and trees, and concentrations of TCE in ground water (July 1998) and tree cores (September 1998) at the Carswell Golf Course.

Tree cores also were taken from the inner and outer xylem of a narrow-leaf cottonwood tree (27 cm diameter at 1.5 m height) at PJKS. The outer core represented the outer 6 cm of trunk, including the bark. The inner core represented the wood 6 to 12 cm from the outer bark. To minimize the potential for the core barrel to cross contaminate between the inner and outer cores, the cores were collected separately. The outer core was collected first. The core barrel was cleaned with distilled water and dried, the core hole was widened with a drill, and then the inner core was collected.

Duplicate samples were collected from selected trees at each of the study areas. The duplicate samples consisted of two cores, collected ~25 mm from each other. Average concentration differences between duplicate samples was 10% for TCE and 9% for *c*DCE. Selected trees near the leading edge of the ground water contamination plume at NWS Charleston were cored on several dates to observe changes in TCE concentration. One tree (SC1, diameter of 36.5 cm) at NWS Charleston and one at the Carswell Golf Course (TX 7, diameter of 74.8 cm) were cored at four different locations around the trunk.

Background cores were collected from trees in offsite areas with no known history of chlorinated ethene contamination. The background trees were the same species as the trees in the contaminated areas with some exceptions. At the Carswell Golf Course, background samples of hackberry, pecan, and an unidentified member of the *Sapotaceae* family were not collected. At PJKS, a background Gambel oak was not collected. Ambient air samples collected from 1.5 m above land surface adjacent to the trunks of several sampled trees in the contaminated areas contained no TCE at 10 ppb.

Two approaches were used to allow the tree core volatile compounds to equilibrate with the headspace within the vial. In early tests at the Carswell Golf Course, the vials were

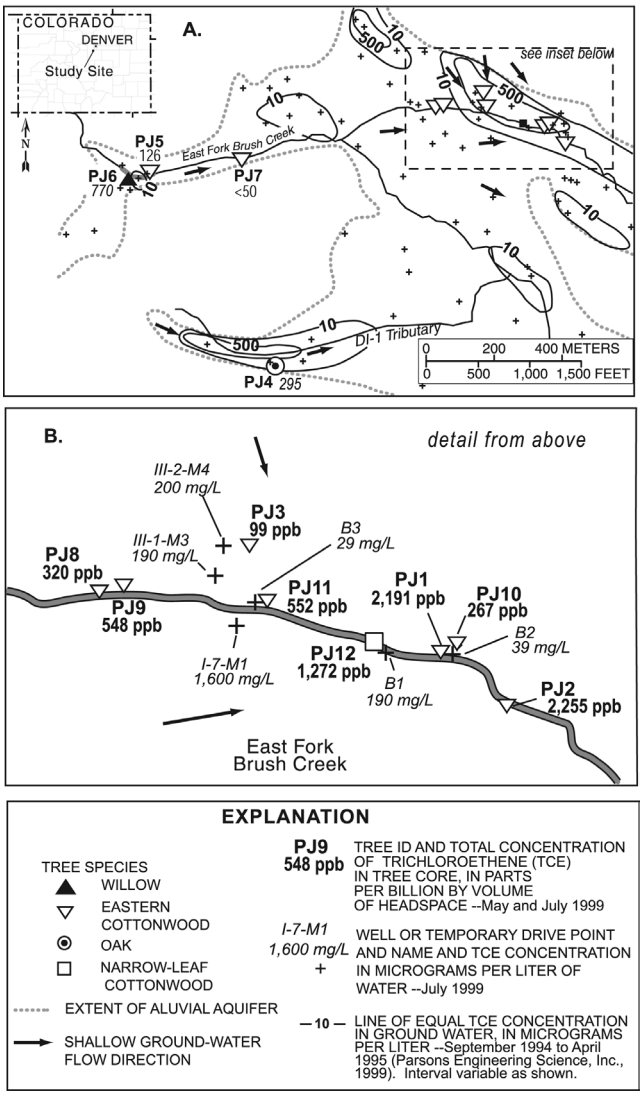

Figure 2. TCE concentrations in ground water (1994–1995), and locations and TCE concentrations in wells and tree cores (May and July 1999), PJKS.

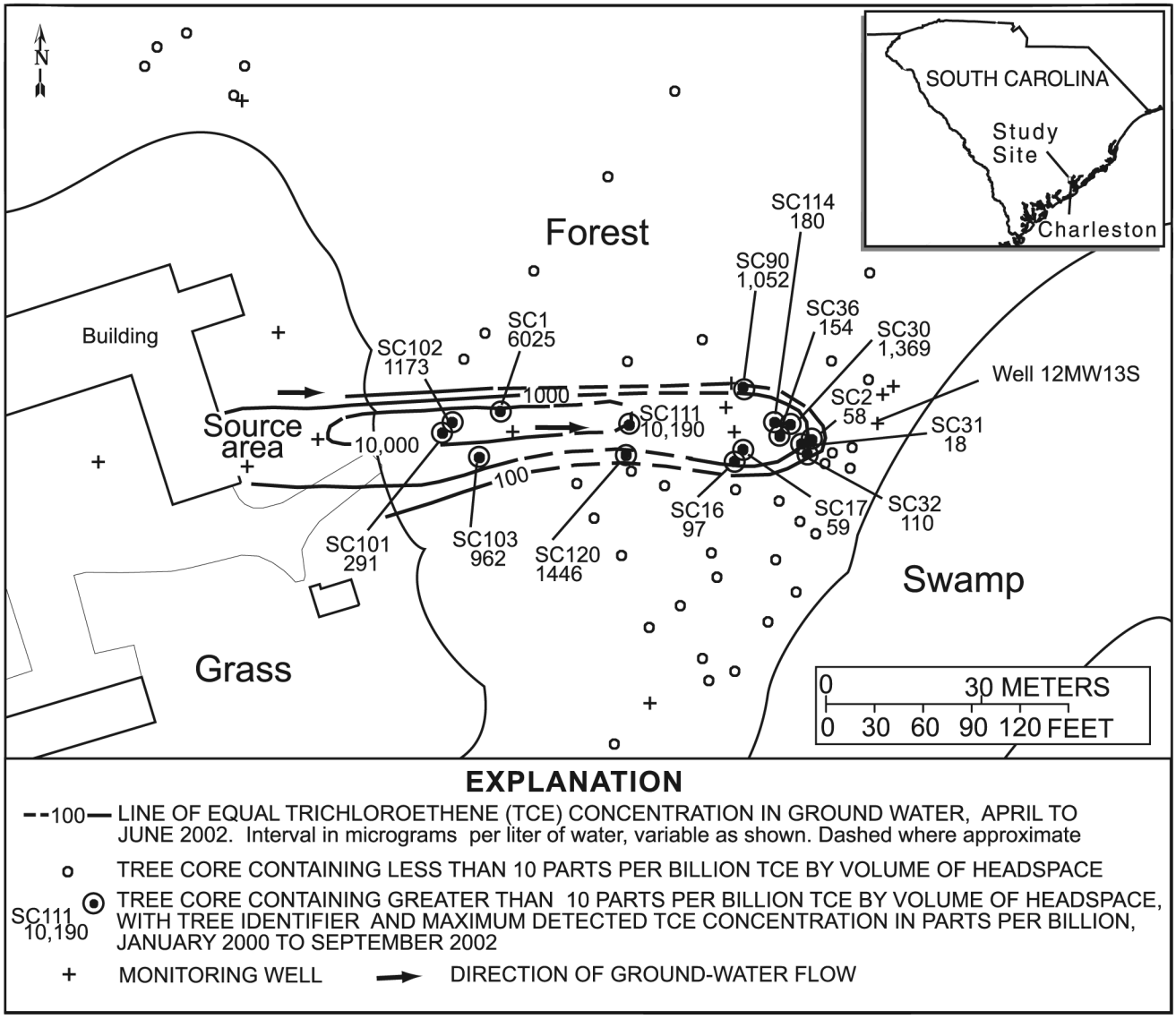

Figure 3. Locations of wells and trees, and concentrations of TCE in ground water and tree cores, SWMU 12, NWS Charleston.

heated at 40°C for 12 h and then cooled to room temperature (25°C) prior to collecting a headspace sample (Vroblesky et al. 1999). A laboratory test for this investigation showed that increasing the temperature increased the headspace concentration of VOCs, but allowing the vials to cool after heating produced headspace VOC concentrations similar to the VOC concentrations obtained by allowing the vials simply to equilibrate at room temperature overnight without heating. The approach of allowing the unheated sealed headspace vials with tree cores to equilibrate 24 to 48 h at room temperature was then used to investigate petroleum hydrocarbons in tree cores (Landmeyer et al. 2000) and for the cores from PJKS and NWS Charleston in this investigation.

A sample of the headspace in the vials was collected by piercing the septated vial cap with a gas-tight syringe and withdrawing 100 µL of vapor. Gas samples were analyzed by photoionization detection on a Photovac 10S Plus gas chromatograph (Waltham, Massachusetts). Collecting the same length and diameter core at all sites minimized potential concentration variations due to differences in mass of core. Although 1,1,1-trichloroethane is a major ground water contaminant at NWS Charleston, its presence in tree cores was not examined during this investigation because photoionization detectors are relatively insensitive to that compound.

Chemical analysis of the water was done by commercial laboratories by using U.S. Environmental Protection Agency Method 8260B (U.S. Environmental Protection Agency 1999). In addition, selected tree cores from the Carswell Golf Course and NWS Charleston were analyzed by gas chromatography/mass spectroscopy (GC/MS) to confirm the presence of TCE. Core preparation for the GC/MS scan is described in Landmeyer et al. (2000). For purposes of this investigation, tree core VOC concentrations are reported as ppb by volume of vial headspace. VOC concentrations in ground water are reported as µg/L of water.

Ground Water Sampling

The distribution of ground water contamination at PJKS and at the Carswell Golf Course primarily was determined during previous investigations. Confirmation ground water samples for this investigation were collected at PJKS at three wells adjacent to East Fork Brush Creek (I–7-M1, III–1-M3, and III–2-M4) and three temporary wells adjacent to selected

trees at the bottom of the East Fork Brush Creek erosional ditch (B1, B2, and B3). A surface water sample from the East Fork Brush Creek at PJKS also was collected. Data used to map the TCE ground water plume distribution at NWS Charleston were taken from monitoring wells sampled in February 2002 and from temporary drive points sampled in April 2002 not shown in Figure 3 (Vroblesky et al. 2003). In addition, data collected from well 12MW11S in August 2001 were used to delineate the northeastern edge of the plume at NWS Charleston because 2002 data were not available and because five quarterly sampling events prior to August 2001 showed low TCE concentrations at that well (ranging from 2.6 to 38 µg/L).

Water samples were collected from wells at PJKS after purging three casing volumes of water. Water samples from wells at NWS Charleston were collected by low-flow methodology (Barcelona et al. 1994; Shanklin et al. 1995).

Investigation of Recharge Influence

The influence of recharge on tree-trunk TCE concentrations was investigated by irrigating a mature cottonwood at the Carswell Golf Course. The tested tree, TX7, was ~ 22 years old (Godsey et al 2003) with a diameter of ~74.8 cm at ~1.5 m height. The irrigation was used to simulate a rainfall event of ~50 mm. Sapflow was estimated using the approach of Zang et al. (1997) by the U.S. Department of Agriculture Forest Service Coweeta Hydrologic Laboratory using thermal dissipation probes before, during, and after the irrigation period as part of a related study (Clinton et al. in press). Six probes were installed on the tested tree at each investigated height up the trunk evenly spaced around the trunk, and measurements were averaged to account for variation in sapwood permeability. Probes were insulated with Styrofoam™, and the entire stem section was covered with aluminum foil to eliminate direct heating of the stem. Sapflow velocity (cm/s) was converted to sapflow rate (kg/h) after determining sapwood area from increment cores taken at the end of the measurement period near the locations of the sapflow probes. At a daily timestep, sapflow is a general approximation of transpiration (Phillips et al. 1997).

Cores were collected and analyzed for TCE from successive heights along the trunk of the mature eastern cottonwood on September 24, 1998, ~2 y prior to the irrigation experiment. Cores again were collected and analyzed for TCE from successive heights along the same tree in July 2000 prior to and following irrigation of the tree. Ground water TCE concentrations from wells within 3 m of the tree were ~55 to 150 µg/L prior to irrigation.

Results and Discussion

Carswell Golf Course

Most trees sampled at the Carswell Golf Course in areas of contaminated ground water contained TCE and *c*DCE (Figure 1). GC/MS analysis of a core from tree TX514 confirmed the presence of TCE. TCE and *c*DCE were not found in cores from background trees.

Two trees of different species (willow and eastern cottonwood) growing directly adjacent to each other (trees TX2 and TX3, respectively) had similar TCE concentrations, with the willow being only slightly lower (Table 3). Similar concentrations were obtained from the same trees when they were resampled ~2 y later. Both the willow and eastern cottonwood have a semidiffuse porous ring structure, suggesting that the two species manage water and TCE uptake in a similar manner.

Although the willow and eastern cottonwood trees appear to recover consistently similar concentrations of TCE from the ground water in this study, previous investigations showed that different species sometimes differ in the TCE concentrations in trunk (Vroblesky et al. 1999) and in the degree of contaminant degradation in the rhizosphere (Shann and Boyle 1994). Moreover, plant utilization of water is influenced by species (Smith et al. 1991; Busch et al. 1992; Thorburn and Walker 1994; Kolb et al. 1997). Therefore, it is useful to examine areal TCE concentration differences within individual species.

TCE concentrations among the oaks showed a general correspondence to ground water TCE concentrations (Figure 1). For example, among the oak trees (trees TX8, TX9, TX18, and TX19), other than live oaks, the highest concentrations (120 and 176 ppb at trees TX19 and TX8, respectively) were found where TCE in ground water exceeded 1000 µg/L during July 1998 (Hydrogeologic Inc. 1998). In areas of lesser ground water TCE concentrations (Hydrogeologic Inc. 1998), the TCE concentrations in oak trees, other than live oaks, were lower (11 and 50 ppb in trees TX9 and TX18, respectively). The depth to water in July and August 1998 near tree TX19 was ~7 m (Hydrogeologic Inc. 1998).

The TCE concentrations in cores from live oaks also showed a general correspondence to the ground water TCE concentrations. A tree core from live oak TX12, which was near a site where 877 µg/L of TCE was found in ground water, contained 494 ppb of TCE, while less TCE (207 ppb) was measured in live oak TX21, growing where only 459 µg/L of TCE was found in ground water (Figure 1). However, the high concentrations of TCE and *c*DCE in a core from live oak TX12 relative to the concentrations in nearby tree TX9, a different oak species, implies that there may be a difference in contaminant uptake between live oaks and other oaks (Table 3). The depth to ground water during July to August 1998 near trees TX9, TX12, and TX21 was ~5.6 m (Hydrogeologic Inc. 1998).

Two cedar trees, TX15 and TX16, were examined in the same part of the study area and contained 11 and 7 ppb of TCE and 18 and 26 ppb of *c*DCE, respectively (Figure 1, Table 3). The cedar trees grew in an area where ~515 µg/L of TCE and only 66 µg/L of *c*DCE were measured in the ground water (Costello 1999). The depth to ground water near these trees during July to August 1998 was ~7.9 m (Hydrogeologic Inc. 1998). Thus, tree core TCE and *c*DCE concentrations were useful indicators of subsurface contamination even when the depth to water was 7.9 m.

The remaining trees were predominantly widely dispersed or single species. These trees were all in areas where contaminated ground water was found and all except a cedar tree (TX1) contained TCE and *c*DCE (Table 3). By comparison, no TCE or *c*DCE was found in a background eastern cottonwood (TX22) from Fort Worth, Texas, or in background

Table 3

Detected Concentrations of *c*DCE and TCE in Tree Cores from 1.4 to 1.5 m Above Land Surface (September 1998 to July 2000) and Probable Range of TCE Concentration in Ground Water Near the Cored Trees (1998), Carswell Golf Course, Fort Worth, Texas

Tree Cores						Probable Range of TCE Concentration in Nearby Ground Water[a] (µg/L)
Tree Number (Figure 1)	Type of Tree	Collection Date	*c*DCE (ppb)	TCE (ppb)	*c*DCE/TCE Ratio	
TX1	Cedar	9/23/1998	< 5	< 5	—	100–1000
TX2	Willow	9/23/1998	< 10	278	<0.04	100–1000
TX2	Willow	7/20/2000	---	255	—	100–1000
TX3	Eastern cottonwood	9/23/1998	66	334	0.2	100–1000
TX3	Eastern cottonwood	7/20/2000	57	340	0.2	100–1000
TX4	Willow	9/23/1998	324	< 5	> 64	< 10
TX5	Hackberry	9/23/1998	9.1	59	0.2	100–1000
TX6	American elm	9/23/1998	458	26	17.6	10–100
TX7	Eastern cottonwood: northern side	7/17/2000	2339	1392	1.7	55–150*
TX7	Eastern cottonwood: eastern side	7/17/2000	1074	995	1.1	55–150*
TX7	Eastern cottonwood: southern side	7/17/2000	1682	788	2.1	55–150*
TX7	Eastern cottonwood: western side	7/17/2000	1295	724	1.8	55–150*
TX8	Oak	9/23/1998	12	176	0.1	>1000
TX9	Oak	9/23/1998	5	11	0.5	100–1,000
TX10	Eastern cottonwood	9/23/1998	256 [253]	101 [127]	2.5 [2]	10–100
TX11	Eastern cottonwood	9/23/1998	464	< 5	> 92	< 10
TX12	Live oak	9/23/1998	174	494	0.4	100–1000
TX13	Pecan	9/23/1998	32	44	0.7	100–1000
TX14	Pine	9/23/1998	19	6	3.2	100–1000
TX15	Cedar	9/23/1998	18 [14]	11 [12]	1.6 [1.2]	100–1000
TX16	Cedar	9/23/1998	26	7	3.7	100–1000
TX17	Elm	9/23/1998	12	106	0.1	100–1000
TX18	White oak	9/23/1998	10	50	0.2	100 - 1,000
TX19	White oak	9/23/1998	8	120	0.1	>1000
TX20	Unknown species	9/23/1998	< 5	12	< 0.4	100–1000
TX21	Live oak	9/23/1998	60	207	0.3	100–1000
TX22‡	Offsite Eastern cottonwood	9/23/1998	< 5	< 5	—	< 1 0

[ ] Concentration in duplicate sample
— Not applicable
‡Not shown in Figure 1
[a]Hydrogeologic Inc. 1998
*USGS analysis July 2000

pines and live oaks from South Carolina, elms and cedars from West Virginia, and elm and several oak varieties from Georgia.

In most parts of the site, ground water *c*DCE concentrations were less than ground water TCE concentrations. However, ground water near tree TX11 (Figure 1) contained 439 µg/L of *c*DCE and no detectable TCE (Costello 1999). In agreement with this, a core from tree TX11 contained a substantial amount of *c*DCE and no TCE (Table 3). A potential explanation for the high *c*DCE relative to TCE in ground water near tree TX11 is that the aquifer near tree TX11 is an area of reductive dechlorination of TCE to *c*DCE. Therefore, relatively high *c*DCE/TCE ratio in the core from tree TX11 may reflect subsurface dechlorination. This is in agreement with previous work at this site that showed a general relation between TCE/*c*DCE ratios in ground water and stem tissue in a mature cottonwood relative to immature cottonwoods at this site (Eberts et al. 2003). In addition, Eberts et al. (2003) note that, north of Farmer's Branch, where the depth to ground water is ~3 m or less, delivery of dissolved organic carbon to the aquifer is sufficient to initiate reductive declorination of TCE. Consistent with this, the *c*DCE/TCE ratios in cores from trees TX4 and TX6 growing north of Farmer's Branch where the shallow ground water was ~1 m deep were higher than in all other trees except the previously mentioned tree TX11. As further support, tree cores from tree TX7 showed higher *c*DCE than TCE concentrations (Table 3). Previous investigations have shown that the rhizosphere of

tree TX7 contains a mature anaerobic microbial population capable of dechlorinating TCE (Godsey et al. 2003) and that reductive dechlorination of TCE to *c*DCE is taking place in the ground water near the tree (Lee et al. 2000). The data suggest that large amounts of *c*DCE relative to TCE in some tree cores at this site reflect subsurface dechlorination of TCE.

TCE concentrations found in tree cores were higher than concentrations found in small stems branching from the trunk in almost all cases (Table 4). The difference may be an artifact of sampling. The stems were cut sections with intact bark and were about the same size as the tree cores. Therefore, a possible explanation for the difference in concentrations is that the bark covering on the stems may have limited the gas exchange from the core to the headspace in the vials. In any case, it appears that headspace analysis of stem cuttings sometimes can be used to locate TCE in ground water; however, in this study, headspace analysis of tree cores typically provided a stronger TCE signature than analysis of stems and, thus, may afford a more reliable method of detecting TCE in ground water.

In summary, data from the Carswell Golf Course show that the presence of TCE and *c*DCE in tree cores can be used as indicators of subsurface contamination. The data imply that within an individual tree species, higher ground water TCE concentrations can produce higher tree core TCE concentrations. The amount of TCE taken up into trees appears to be similar for some species, such as eastern cottonwood and willow, and may differ among other species, such as between live oak and some other oaks. Relatively high *c*DCE/TCE ratios in the trees may reflect subsurface dechlorination activity.

PJKS

TCE was detected in all cores from trees growing in areas of known ground water TCE contamination at PJKS. The only cores that did not contain TCE were from tree PJ7, growing on-site, but in an area thought not to contain shallow TCE contamination (Figure 2) and from trees PJ13 and PJ14 (Table 5), growing off-site in a presumably uncontaminated background area that is not shown in Figure 2. Thus, despite the relative sparseness of vegetation, tree coring was useful in locating ground water TCE contamination near creeks.

Table 4
TCE Concentrations in Tree Cores and Stem Cuttings, Eastern Cottonwood, Carswell Golf Course, Fort Worth, Texas, July 2001 and January 2002

Tree Number (Figure 1)	Collection Date	TCE (ppb)	
		Tree Core	Stem Cutting
TX504	7/18/2001	561	60
TX504	1/23/2002	108	85
TX506*	1/23/2002	456	< 10
TX508*	1/23/2002	527	< 10
TX514	1/23/2002	140	< 10
TX515	1/23/2002	312	< 10
TXT524	7/18/2001	15	21
TX525	7/18/2001	137	13
TX525 trunk A	1/23/2002	58	< 10
TX525 trunk B	1/23/2002	221	< 10

*Tree not in the mapped area of Figure 1

The trees containing the highest TCE concentrations (trees PJ1, PJ2, and PJ12) (Figure 2, Table 5) all grew near each other and immediately adjacent to East Fork Brush Creek. These data imply that the ground water beneath them contained higher TCE concentrations or was more accessible to uptake than ground water beneath other trees that were studied.

Data from eastern cottonwood trees PJ1 and PJ10 imply that the depth to contaminated ground water is a potential influence on tree core TCE concentrations. The trees were about the same diameter and were within 3 m of each other, but the tree at the higher elevation contained less TCE. A temporary boring showed the presence of 39 µg/L of TCE in the ground water near the trees at a depth of < 1 m (Figure 2b). However, tree PJ1, which contained 2191 ppb TCE, was at the bottom of the East Fork Brush Creek erosional ditch, and tree PJ10, which contained only 267 ppb, was ~1 m up the side of the ditch embankment. A potential explanation for the difference is that the roots of tree PJ1 were in more intimate contact with the ground water contamination than the roots of tree PJ10.

Another example of the probable influence of depth to water on tree core TCE concentrations is eastern cottonwood tree PJ3. A core from the tree contained only 99 ppb of TCE despite the presence of 200 µg/L of TCE in nearby ground water at well III–2-M4 (Figure 2b). The depth to the ground water at tree PJ3 was ~8 m. In contrast, eastern cottonwoods PJ1 and PJ11 (containing 2191 ppb and 552 ppb, respectively) were growing at the bottom of the creek erosional channel where the ground water contained only 29 to 39 µg/L TCE and was < 1 m deep. Despite the lower TCE concentrations in ground water at trees PJ1 and PJ11 relative to tree PJ3, the TCE concentrations in trees PJ1 and PJ11 were higher than in tree PJ3 (Figure 2b). The probable explanation is that the roots of trees PJ1 and PJ11 were in more intimate contact with the contaminated ground water than the roots of tree PJ3, as evidenced by the differences in depth to ground water.

In summary, the data from PJKS show that tree core analysis can be used to locate TCE-contaminated ground water even in a semiarid area where vegetation is sparse. The data also imply that TCE concentrations in tree cores are influenced by the depth to the TCE-contaminated ground water, with higher concentrations found in trees growing closer to the contaminated ground water.

NWS Charleston

Of the 49 trees (some of which are not in the mapped area of Figure 3) cored at SWMU 12, all those containing TCE were growing above the ground water TCE plume, even though the contaminated aquifer was confined below ~3 m of clay (Figure 3). The highest concentrations of TCE in the trees generally were associated with the highest concentrations of TCE in the ground water (Figure 3).

Table 5
Detected Concentrations of TCE in Tree Cores and Water Chemistry at Air Force Plant PJKS, Waterton, Colorado, 1999

Tree Cores			
Tree Number (Figure 2)	**Type of Tree**	**Date Collected**	**TCE (ppb)**
PJ1	Eastern cottonwood	5/25/1999	2191
PJ2	Eastern cottonwood	5/25/1999	2255
PJ3	Eastern cottonwood	5/25/1999	99
PJ4	Gambel oak	5/25/1999	295
PJ5	Eastern cottonwood	5/25/1999	126
PJ6	Willow	5/25/1999	770
PJ7	Eastern cottonwood	5/25/1999	< 50
PJ8	Eastern cottonwood	5/25/1999	320
PJ9	Eastern cottonwood	5/25/1999	548
PJ10	Eastern cottonwood	7/20/1999	267
PJ11	Eastern cottonwood	7/20/1999	552
PJ12	Narrow-leaf cottonwood	7/20/1999	1272
PJ13*	Offsite eastern cottonwood	7/22/1999	< 50
PJ14*	Offsite narrow-leaf cottonwood	10/26/1999	< 50
Water Samples			
Sample Location (Figure 2)	**Type of Sample**	**Date**	**TCE µg/L**
I-7-M1	Well	7/22/1999	1600
III-1-M3	Well	7/22/1999	190
III-2M-4	Well	7/22/1999	200
SWB-1	Surface water	7/22/1999	< 5
B1	Temporary drive point	7/21/1999	190
B2	Temporary drive point	7/20/1999	39
B3	Temporary drive point	7/20/1999	29

*Not shown in Figure 2

Trees SC101 and SC111, growing along the axis of the most contaminated part of the ground water plume, also contained PCE (38 and 72 ppb, respectively, in February 2000). These trees are located in the part of the aquifer beneath the forest that contains the highest ground water PCE concentrations (740 µg/L in December 1999 and 360 µg/L in March 2000 at well 12MW05S). Thus, headspace analysis of tree cores is useful for tracking PCE concentrations as well as TCE in shallow ground water.

Examination of the tree core TCE concentrations collected from different sides of the trunk at tree SC1 showed variations around the tree. The northeastern and northwestern sides of the tree contained similar concentrations (1925 and 1975 ppb, respectively) and were substantially lower than the concentrations from the southeastern and southwestern sides (6025 and 5087 ppb, respectively) (Table 6). Tree SC1 is located north of the ground water TCE plume axis (Figure 3). Because most trees have root systems that extend beyond the spread of the crown (Kozlowski and Pallardy 1997), it is reasonable to expect that roots on opposite sides of the tree may sample water having substantially different TCE concentrations. Thus, the lower TCE concentrations along the northeastern and northwestern parts of the trunk probably reflect lower aquifer TCE concentrations along the edge of the plume, rather than in the more central part of the plume as shown in samples from the southeastern and southwestern parts of the tree.

In addition, it appears that some of the trees at the leading edge of the plume began to take up TCE in increasing amounts as the plume advanced through the aquifer. Tree SC30 contained only 127 ppb of TCE when first sampled in February 2000. Within 1 y, the concentration increased to > 1000 ppb of TCE (Figure 4). TCE began appearing in tree SC2, 8.2 m downgradient from tree SC30, in May 2001 (Figure 4). By comparison, the TCE concentration in ground water at downgradient well 12MW13S ranged between 3.9 and 5.2 µg/L during four quarterly sampling measurements from December 4, 2001, and September 10, 2002. During the sampling in January 2003, the TCE concentration in well 12MW13 rose to 22 µg/L, possibly indicating advancement of the ground water plume. A reasonable explanation for these data is that the changes in tree core TCE concentration represent advancement of the TCE ground water plume. Thus, tree coring potentially can provide useful information on the downgradient progress of chlorinated ethene plumes. Prudence should be exercised, however, to avoid excess coring of individual trees in an effort to minimize stress to the tree.

Although areas of relatively high and low TCE concentrations in the tree cores generally coincide with areas of relatively high and low ground water TCE concentrations, the variety of factors influencing solute and water uptake in trees sometimes complicates direct correlation between tree and ground water TCE concentrations. In some cases, the TCE concentration in the trees can be relatively high when the ground water concentrations, as determined by well sampling, are relatively low. Tree SC90 contained 939 ppb of TCE in January 2001, while the ground water at adjacent well 12MW11S contained only 16 µ/L in February 2001. It is unlikely that the ground water was significantly diluted

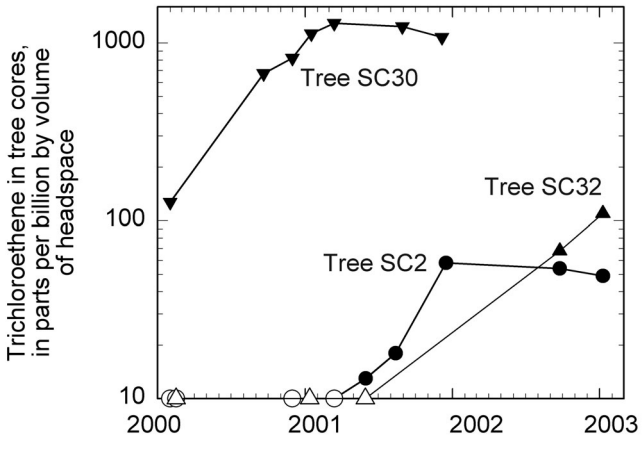

Figure 4. Changes in the TCE concentration of tree cores over time at the leading edge of the ground water contamination plume, NWS Charleston, SWMU 12, 2000–2002. Open triangles indicate no detections of TCE at a detection limit of 10 ppb by volume of headspace.

Table 6
Detected TCE Concentrations in Tree Cores, SWMU12, Naval Weapons Station, Charleston, South Carolina, February 2000 to September 2002

Tree Number	Side of Tree	Collection Date	TCE (ppb)
SC1	NE	2/1/2000	1925
SC1	NW	2/1/2000	1975
SC1	SE	2/1/2000	6025
SC1	SW	2/1/2000	5087
SC1	W	11/30/2000	6484 [7313]
SC1	W	9/20/2002	8535 [9015][7774]
SC2	W	5/31/2001	13
SC2	W	8/31/2001	18
SC2	W	12/6/2001	58
SC2	NW	9/24/2002	54
SC2	W	9/24/2002	54
SC16	NW	1/23/2002	97
SC17	W	2/1/2000	59
SC30	W	2/16/2000	127
SC30	W	9/20/2000	674
SC30	W	11/30/2000	822
SC30	W	1/12/2001	1369
SC30	W	1/16/2001	1128
SC30	W	3/14/2001	1292
SC30	W	5/16/2001	1528 [1371]
SC30	W	8/31/2001	1237
SC31	NW	2/16/2000	18
SC32	NW	9/24/2002	68
SC32	NW	1/9/2003	110
SC36	NW	2/16/2000	51
SC36	NW	4/10/2000	154
SC90	W	1/16/2001	939
SC90	W	8/30/2001	773
SC90	NW	1/23/2002	1052
SC101	SW	2/1/2000	31
SC101	NW	9/24/2002	291
SC102	SW	2/1/2000	1173
SC103	NW	9/24/2002	962
SC111	W	2/1/2000	3756
SC111	NW	1/23/2002	10190
SC114	W	2/1/2000	114
SC114	NW	2/16/2000	70
SC114	NW	4/10/2000	180
SC120	NW	1/23/2002	1446

NE, northeastern side;
NW, northwestern side
SE, southeastern side
SW, southwestern side
W, western side
[ ], duplicate sample concentrations

between the two sampling events because only ~8.9 mm of rain fell during that time period, and the ground water TCE concentration at well 12MW11S had increased by ~12 µg/L since the previous sampling event in November 2000. The tree and well are on the edge of the contaminant plume (Figure 3). The well derives water from only a small part of the aquifer compared to the root system of tree SC90. Thus, well 12MW11S samples probably contained only slightly contaminated water from the edge of the plume, whereas tree SC90 probably took up water that included some of the much higher TCE concentrations within the plume, resulting in a relatively large TCE concentration in the tree cores.

In contrast, cores from loblolly pine tree SC101 contained lower TCE concentrations than expected. In February 2001, tree SC101 contained only ~31 ppb TCE, while ~1.2 m away, loblolly pine tree SC102 contained 1173 ppb TCE (Figure 3). Both trees were growing above an area most likely containing > 10,000 µg/L of TCE in ground water (Figure 3). Although the trees are different diameters, it is unlikely that tree size is an important factor causing the difference because the smallest diameter tree (SC102, diameter of 25 cm) contained higher concentrations than the larger diameter tree (SC101, diameter of 39 cm). One difference between the two trees is that tree SC101, containing only a low amount of TCE, was growing in a cluster of several trees 0.05 to 0.49 m from each other, whereas tree SC102, with substantially more TCE, was an isolated tree. It is unknown whether root competition can result in decreased uptake of TCE, or if the disparate findings are due to local differences in subsurface hydrogeology or local differences in ground water contaminant concentrations. In any case, despite the overall correlation of relatively high tree core TCE concentrations with relatively high ground water TCE concentrations, environmental influences apparently can affect specific tree core TCE concentrations.

The preceding discussion illustrates that tree diameter (therefore tree age) is not always a reliable indicator of which trees will have the higher concentrations. Logic suggests that cores from trees too young to have roots in a deep enough position to incorporate ground water TCE concentrations will have lower TCE concentrations than older trees with roots in intimate contact with TCE-contaminated ground water. However, once trees have matured enough for their roots to incorporate ground water TCE, the data imply that the age of the tree becomes less influential in determining tree core TCE concentrations.

The data from NWS Charleston also demonstrate that tree coring can be an effective tool to indicate TCE- and PCE-contaminated ground water, even when the contaminated aquifer is confined beneath 3 m of clay. Concentration variations in cores from differing sides of the tree may reflect differences in ground water TCE concentrations on differing sides of the tree.

Influence of Recharge

Differences in TCE concentration with height up the trunk can reflect a variety of causes. A decrease in TCE concentration with height up a tree trunk was observed in a previous investigation and attributed to contaminant loss up the trunk, probably by volatilization loss (Vroblesky et al. 1999). Subsequent laboratory work has presented evidence of volatilization loss through the trunk (Burken 2001; Ma and Burken 2003). Data collected during this investigation, however, showed an increase in concentrations with height up the eastern and southeastern sides of the trunk of tree TX7 at the Carswell Golf Course. The upward increase illustrates an additional influence on tree core TCE concentrations. As will be shown, the vertical differences in TCE concentrations at tree TX7 in September 1998 (Figure 5) appear to be caused

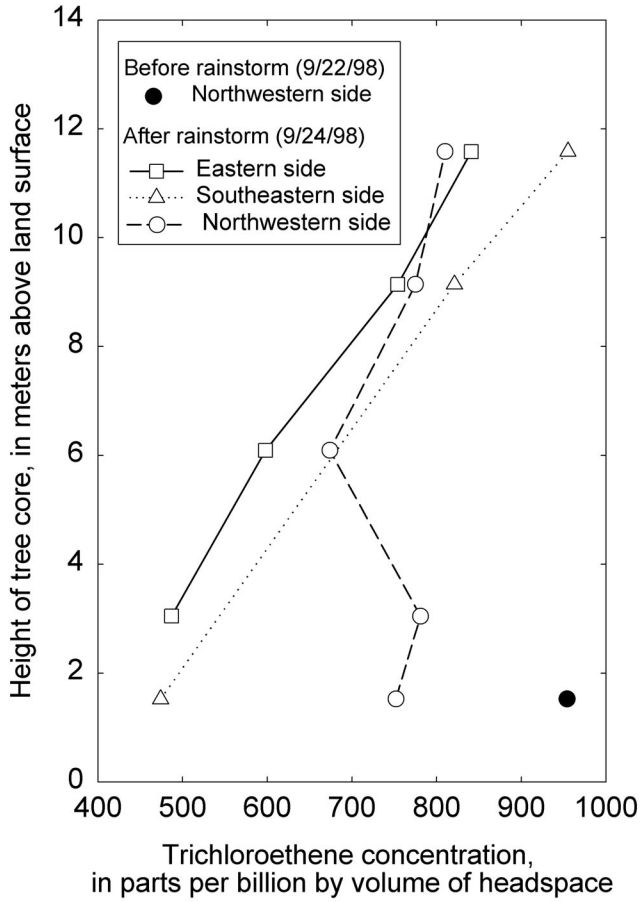

Figure 5. TCE concentrations in headspace analysis of tree cores from various heights up eastern cottonwood tree TX7, Carswell Golf Course, September 1998. The degree of error is ~10%.

primarily by opportunistic uptake of infiltrating rain water diluting the tree core TCE concentrations.

The cores from tree TX7, representing increasing height up the trunk (Figure 5), were collected in September 1998 following a heavy rainstorm. The rainstorm followed a period when the area had been without rain for several weeks. As the rainstorm began, a single increment core was collected from the same tree on the northwestern side at a height of 1.5 m. The core contained 954 ppb of TCE, but when the rain ceased 2 d later, a core collected near the pre-rain core showed a concentration reduction to 752 ppb (Figure 5). The prerain TCE concentration in the trunk (954 ppb) at a height of about 1.5 m, however, was similar to the concentrations in the trunk at a height of ~11.6 m after the rainfall event (955 ppb on the southeastern side, 841 ppb on the eastern side, and 810 ppb on the northwestern side). Thus, one possible explanation for the lower concentration at 1.5 m on the northwestern side of the tree from prestorm to post-storm conditions, and the increasing concentrations with height up the tree trunk following the storm, is that the infiltrated rain water diluted the tree core water, resulting in decreased concentrations at the base of the tree. The concentrations up the tree may represent a time series of water movement, with the lowest part of the trunk representing upward moving diluted infiltrating water.

The higher concentrations in the lower part of the tree on the northwestern side relative to the other sides (Figure 5) may be because the northwestern side is in the direction of the highest contaminant concentrations. The more uniformly distributed concentrations around the tree in higher parts of the trunk is consistent with many trees in which upward moving water can be distributed tangentially around the trunk, particularly in the case of spiral upward transport, which is common in many conifers (Rudinsky and Vitè 1959; Kozlowski and Winget 1963).

The results of an irrigation field test in July 2000 provide additional insight into the concentration differences observed in cores from tree TX7 in September 1998. Ground water TCE concentrations from wells within 3 m of tree TX7 were ~150 to 210 µg/L at the time of the test, with the depth to ground water of ~2.8 m (Hydrogeologic Inc. 1998). In this test, TCE concentrations in cores from three different sides around the trunk were averaged to produce a single representative concentration for a particular height. TCE concentrations at 1.5, 2.29, and 3 m up the trunk of the mature eastern cottonwood showed similar values during the two sampling events prior to irrigation (Figure 6). Following irrigation, a concentration decrease was observed at all of the sampling heights (Figure 6). Clinton et al. (in press) conducted a related study on transpiration and isotopic signatures of tree sap during the irrigation. Their findings showed that sapflow rates increased at all tested heights following irrigation. In addition, their work showed that the stable isotopic signatures of oxygen ($d^{18}O$) and deuterium (dD) of the xylem sap shifted toward heavier values following irrigation, representing an influx of the irrigation water, which was isotopically heavier than the ground water. They found that isotopic values became successively lighter at heights of ground level, 2 m, and 4 m, indicating that the isotopically heavier irrigation water was beginning to migrate up the trunk. These data indicate that irrigation resulted in facultative uptake of TCE-free irrigation water, resulting in a rapid dilution of TCE concentrations as the water moved up the trunk.

This shift in tree source water has been observed by phreatophytic vegetation in other locations as well. For example, in areas where rainfall is unreliable, riparian trees may develop roots primarily in the capillary fringe and phreatic zone rather than throughout the soil profile (Ehleringer and Dawson 1992), thus primarily using ground water. Cottonwoods and willows growing along streams in

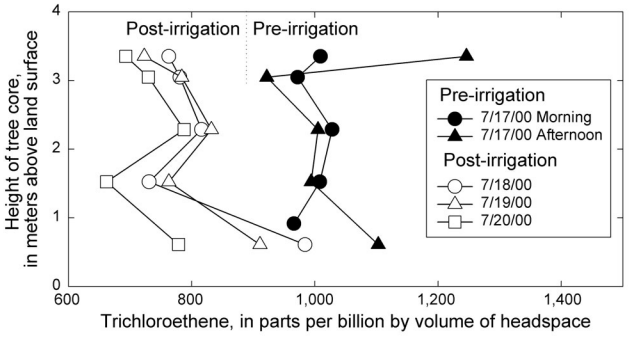

Figure 6. TCE concentrations in headspace analysis of tree cores from eastern cottonwood TX7 before and after artificial irrigation, Carswell Golf Course, July 2000. Concentrations are an average of cores collected from three sides of the tree.

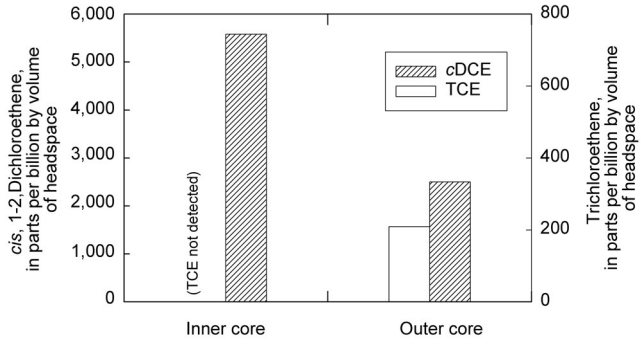

Figure 7. TCE and *c*DCE concentrations in cores from tree PJ12 in the outer core (0 to 6 cm from the outer bark) and the inner core (6 to 12 cm from the outer bark), narrow-leaf cottonwood, PJKS, October, 1999.

western Arizona used ground water throughout the growing season regardless of the depth to ground water (Busch et al. 1992). Plants with roots distributed in multiple soil zones may use various combinations of ground water, rainfall infiltrate, and stream water, sometimes responding opportunistically to rainfall events (Mensforth et al. 1994; Thorburn and Walker 1994; Dawson and Pate 1996; Jolly and Walker 1996). Trees near a perennial stream in California used shallow soil water early in the growing season and then primarily used ground water in the latter part of the season when the soil dried (Smith et al. 1991). Mature box elders used only ground water in spite of the apparent availability of perennial stream water or shallow soil water in northern Utah (Dawson and Ehleringer 1991), but box elders did use soil water from precipitation at ephemeral and perennial stream reaches in Arizona (Kolb et al. 1997). In areas where plants typically obtain part of their water from precipitation infiltration, TCE concentrations in tree tissue have been found to be 10 to 100 times less than in areas of lower rainfall, suggesting that plants in areas of lower rainfall uptake a higher fraction of contaminated ground water (Doucette et al. 2003).

The rate at which water moves upward in tree trunks is variable, but can be rapid. Maximum rates of sapflow have been observed to vary between 1 and 2 m/h in conifers, 1 to 6 m/h in diffuse-porous trees, and 4 to 44 m/h in ring-porous trees (Zimmerman and Brown 1971). Thus, recharge can be a major factor influencing TCE concentrations in tree trunks over time periods of less than a day, and TCE concentrations in cores collected following rainfall may be less than the concentrations in cores collected during a drier period.

Potential Degradation Mechanism

Analysis of tree cores from tree PJ12 at PJKS showed variations in the TCE and *c*DCE concentrations in the inner and outer xylem, implying the presence of a potential degradation mechanism (Figure 7). TCE was found in the outer 6 cm of core, but was not detected in the inner core (6 to 12 cm from the outer bark). Conversely, *c*DCE was substantially more concentrated in the inner core than in the outer core. It is noteworthy that after the outer core was collected and the core barrel was being advanced to collect the inner core, the tree began spitting water and gas through the core barrel. Rapid degassing through the core barrel has been observed in outwardly healthy trees growing in poorly drained soils (Carter 1945), but does not appear to represent normal healthy growth patterns (Abell and Hursh 1931; Zeikus and Ward 1974). Rather, it appears to indicate an infestation of methanogenic and other bacteria in the tree heartwood (Stankewich et al. 1971; Zeikus and Ward 1974). Methane was present in the cores from tree PJ12, suggesting that methanogenic conditions driven by microbial infestation were present in the inner part of tree PJ12. Methanogenic conditions are associated with efficient dehalogenation of TCE to *c*DCE (Parsons et al. 1984; Parsons et al. 1985; Kloepfer et al. 1985; Wilson et al. 1986). Thus, the tree core TCE and *c*DCE distribution between the inner and outer cores of tree PJ12 are consistent with microbial dehalogenation of TCE within the apparent methanogenic inner trunk. The spitting of water and gas from the tree core hole also was observed in the background tree (PJ14), implying that the effect may not be unusual for this species.

Summary

Comparisons were made between the distribution of chlorinated ethenes in ground water and the presence of chlorinated ethenes in tree cores as determined by headspace analysis. Measurements were made in a subhumid setting at the Carswell Golf Course, a semiarid setting at PJKS, and a semitropical setting at NWS Charleston. At all three sites, TCE was found in headspace analysis of cores from trees growing above TCE-contaminated ground water. Chlorinated ethenes were not found in headspace analysis of cores from trees in uncontaminated areas. Thus, tree coring appears to be an effective tool for locating shallow subsurface chlorinated ethene concentrations in a variety of environments. Relatively high tree core *c*DCE concentrations and tree core *c*DCE/TCE ratios may indicate dechlorination activity.

The tree coring approach was useful in detecting ground water TCE in an area of the Carswell Golf Course, where depth to ground water ranged from 0.7 to 7.9 m, and at PJKS, despite the relative sparseness of vegetation. The method was also useful for mapping subsurface TCE at NWS Charleston, even though the contaminated aquifer was confined beneath 3 m of clay. A variety of species demonstrated the ability to take up TCE contamination from the ground water, although the amount of TCE uptake may differ between some species. In some cases, tree coring offers an advantage over well sampling at the reconnaissance level because of the simplicity and low cost of sample collection, and because wells sample a smaller volume of the water than trees.

In addition, it appears that some of the trees at the leading edge of the plume at SWMU 12 began to take up TCE in increasing amounts over time as ground water concentrations increased in a nearby well. A probable explanation is that the increased TCE concentration over time in the trees represents advancement of the TCE ground water plume. Thus, tree core analysis may provide useful information on the downgradient progress of chlorinated ethene plumes. Care should be taken, however, to avoid excess coring of individual trees in an effort to minimize stress to the tree.

Although relatively high and low TCE concentrations in tree cores generally are found in areas of correspondingly high and low ground water TCE concentrations, a variety of factors influencing solute and water uptake in trees complicates a direct correlation between tree and ground water TCE concentrations. Extensive lateral root systems have the potential to interact with a larger area of the aquifer than does a well, and thus trees can incorporate water and solutes from areas more distant from the well. Thus, there is a potential that differing TCE concentrations in source water around the tree can produce differing TCE concentrations in tree cores from various sides of the trunk. The vertical distance between the tree and the ground water contamination also appears to be a potential factor influencing concentration differences, as implied by the higher TCE concentrations at PJKS found in trees that were closer to the contaminated aquifer.

An additional factor influencing tree core TCE concentrations is uptake of recharge water into the transpiration stream. An experiment measuring transpiration and tree core TCE concentrations before and after irrigating a tree found that TCE concentrations decreased and maximum transpiration values increased. These data suggest that the uptake of irrigation water resulted in a rapid dilution of TCE concentrations in the trunk. Thus, TCE concentrations in tree cores collected after a rainfall may be less than before the rainfall.

Infestation of methanogenic and other bacteria in decaying heartwood may provide a TCE dechlorination mechanism within the trunk. TCE was detected in the outer core, but was not detected in the apparently methanogenic inner core, whereas *c*DCE was substantially more concentrated in the inner than outer core. This finding is consistent with microbial dehalogenation of TCE to *c*DCE in the core of the tree.

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References

Abell, C.A., and C.R. Hursh. 1931. Positive gas and water pressure in oaks. *Science* 73, 449.

Barcelona, M., H.A. Wehrmann, and M.D. Varljen. 1994. Reproducible well purging procedures and VOC stabilization criteria for ground water sampling. *Ground Water* 32, 12–22.

Bryant, B., R.D. Miller, and G.R. Scott. 1973. Geologic map of the Indian Hills Quadrangle, Jefferson County, Colorado. U.S. Geological Survey Quadrangle Map GQ–1073.

Burken, J.G. 2001. Uptake and volatilization of chlorinated solvents by poplars at field scale. In *Phytoremediation, Wetlands, and Sediments*, ed. A. Leeson, E.A. Foote, M.K. Banks, and V.S. Magar, 113–120. Columbus, Ohio: Battelle Press.

Burken, J.G., and J.L. Schnoor. 1998. Predictive relationships for the uptake of organic contaminants by hybrid poplar trees. *Environmental Science & Technology* 32, no. 21: 3379–3385.

Busch, D.E., N.L. Ingraham, and S.D. Smith. 1992. Water uptake in woody riparian phreatophytes of the southwestern United States—A stable isotope study. *Ecological Applications* 2, 450–459.

Carter, J.C. 1945. Wetwood of elms. *Bulletin of the Illinois Natural History Survey* 23, 407–448.

Clinton, B.D., J.M. Vose, D.A. Vroblesky, and G.J. Harvey. In press. Determination of the relative uptake of ground versus surface water uptake by *Populus deltoids* trees during phytoremediation. *International Journal of Phytoremediation*.

Costello, J. 1999. Written communication with Don A. Vroblesky on June 4 via e-mail.

Dawson, T.E., and J.R. Ehleringer. 1991. Streamside trees that do not use stream water. *Nature* 350, 335–337.

Dawson, T.E., and J.S. Pate. 1996. Seasonal water uptake and movement in root systems of phreatophytic plants of dimorphic root morphology—A stable isotope investigation. *Oecologia* 107, 13–20.

Doucette, W.J., B.G. Bugbee, S.C. Smith, C.J. Pajak, and J.S. Ginn. 2003. Uptake, metabolism, and phytovolatilization of trichloroethylene by indigenous vegetation: Impact of precipitation. In *Phytoremediation: Transformation and Control of Contaminants*, ed. S.C. McCutcheon and J.L. Schnoor, Chapter 18, 561–588. New York: Wiley.

Eberts, H., S.A. Jones, and S.W. Beckman. 2003. Multiple-process assessment for a chlorinated solvent plume. In *Phytoremediation: Transformation and Control of Contaminants*, ed. S.C. McCutcheon and J.L. Schnoor, Chapter 19, 589–633. New York: Wiley.

Ehleringer, J.R., and T.E. Dawson. 1992. Water uptake by plants—Perspectives from stable isotope composition. *Plant, Cell, and Environment* 15, 1073–1082.

Engineering Science Inc. 1993. Supplemental remedial investigation/feasibility study, Air Force Plant PJKS, Colorado. Consultant's report to U.S. Air Force Aeronautical Systems Center Installation Restoration Program.

Godsey, E.M., E. Warren, and V.V. Paganelli. 2003. The role of microbial reductive dechlorination of TCE at a phytoremediation site. *International Journal of Phytoremediation* 5, no. 1: 78–87.

Hubbard, R.M., and J.M. Vose. 2004. Written communication with Clifton Casey on January 11 via letter report.

Hydrogeologic Inc. 1998. TCE plume investigation, NAS Ft. Worth, JRB Texas, July/August 1998. Consultants map for Air Force Center for Environmental Excellence, Brooks AFB, Texas.

Jolly, I.D., and G.R. Walker. 1996. Is the field water use of *Eucalyptus largiflorens* F. Muell affected by short-term flooding? *Australian Journal of Ecology* 21, 173–183.

Kloepfer, R.D., D.M. Easley, B.B. Haas Jr., T.G. Deihl, D.E. Jackson, and C.J. Wurrey. 1985. Anaerobic degradation of trichloroethylene in soil. *Environmental Science & Technology* 19, no. 3: 277–280.

Kolb, T.E., S.C. Hart, and R. Amundson. 1997. Boxelder water source and physiology at perennial and ephemeral stream sites in Arizona. *Tree Physiology* 17, 151–160.

Kozlowski, T.T., and C.H. Winget. 1963. Patterns of water movement in forest trees. *Botanical Gazette* 124, 301–311.

Kozlowski, T.T., and S.G. Pallardy. 1997. *Physiology of Woody Plants*, 2nd edition. San Diego, California: Academic Press.

Landmeyer, J.E., P.M. Bradley, and D.A. Vroblesky. 2000. MTBE in trees transpiring gasoline-contaminated ground water. In *Proceedings of the Second International Conference on Remediation of Chlorinated and Recalcitrant Compounds*, May 22–25, Monterey, California. Columbus, Ohio: Battelle Press.

Lee, R.W., S.A. Jones, E.L. Kuniansky, B.S. Lollar, and G.F. Slate. 2000. Phreatophyte influence on reductive dechlorination in a shallow fluvial aquifer contaminated with trichloroethene (TCE). *International Journal of Phytoremediation* 2, no. 3: 193–211.

Lewis, K., W. Doucette, B. Bugbe, and J. Ginn. 2001. Relationship between trichlorethylene concentrations in tree cores and ground water for plume delineation. In *Proceedings of the Society of Toxicology and Environmental Chemistry 22nd Annual Meeting Abstract Book*, November 11–15, Baltimore, Maryland. Pensacola, Florida: Society of Toxicology and Environmental Chemistry.

Ma, X., and J.G. Burken. 2002. VOCs fate and partitioning in vegetation: Use of tree cores in groundwater analysis. *Environmental Science & Technology* 34, 4663–4668.

Ma, X., and J.G. Burken. 2003. TCE diffusion to the atmosphere in phytoremediation applications. *Environmental Science & Technology* 37, 2534–2539.

Mensforth, L.J., P.J. Thoraburn, S.D. Tyerman, and G.R. Walker. 1994. Sources of water used by riparian *Eucalyptus camaldulensis* overlying highly saline groundwater. *Oecologia* 100, 21–28.

National Oceanic and Atmospheric Administration. 1999. *Climatological Data Annual Summary, South Carolina* 102, no. 13: 21.

Newman, L.A., S.E. Strand, N. Choe, J. Duffy, G. Ekuan, M. Ruszaj, B.B. Shurtleff, J. Wilmoth, P. Heilman, and M.P. Gordon. 1997. Uptake and biotransformation of trichloroethylene by hybrid poplars. *Environmental Science & Technology* 31, no. 4: 1062–1067.

Nietch, C.T., J.T. Morris, and D.A. Vroblesky. 1999. Biophysical mechanisms of trichloroethene uptake and loss in baldcypress growing in shallow contaminated ground water. *Environmental Science & Technology* 33, 2899–2904.

Parsons Engineering Science Inc. 1999. Installation restoration program supplemental remedial investigation report for Air Force Plant PJKS, Colorado, v. IV. Prepared for U.S. Air Force Aeronautical Systems Center Wright-Patterson Air Force Base, Ohio, March.

Parsons, F., P.R. Wood, and J. DeMarco. 1984. Transformation of tetrachloroethene and trichloroethene in microcosms and ground water. *Journal of the American Water Works Association* 72, no. 2: 56–59.

Parsons, F., G.B. Lage, and R. Rice. 1985. Biotransformation of chlorinated organic solvents in static microcosms. *Environmental Toxicology and Chemistry* 4, 739–742.

Phillips, N., A. Nagchaudhuri, R. Oren, and G. Katul. 1997. Time constant for water transport in loblolly pine trees estimated from time series of evaporative demand and stem sapflow. *Trees* 11, 412–419.

Rudinsky, J.A., and J.P. Vitè. 1959. Certain ecological and phylogenetic aspects of the pattern of water conduction in conifers. *Forest Science* 5, 259–266.

Schumacher, J. 2001. Detection of ground-water contamination through analysis of tree-ring tissue. Presented at *The Annual Meeting of the U.S. Geological Survey Department of Defense Environmental Conservation Program*, May 1–4, Charleston, South Carolina.

Shanklin, D.E., W.C. Sidle, and M.E. Ferguson. 1995. Micropurge low-flow sampling of uranium-contaminated ground water at the Fernald Environmental Management Project. *Ground Water Monitoring & Remediation* 15, no. 3: 168–176.

Shann, J.R., and J.J. Boyle. 1994. Influence of plant species on in situ rhizosphere degradation. In *Bioremediation Through Rhizosphere Technology*, ed. T.A. Anderson and J.R. Coates, 71–81. Washington D.C.: American Chemical Society.

Smith, S.D., A.B. Wellington, J.A. Nachlinger, and C.A. Fox. 1991. Functional responses of riparian vegetation to streamflow diversions in the eastern Sierra Nevada. *Ecological Applications* 1, 89–97.

Stankewich, J.P., B.J. Cosenza, and A.L. Shigo. 1971. *Clostridium quercicolum* sp. n., isolated from discolored tissues in living oak trees. *Antonie van Leeuwenhoek Journal of Microbiology and Serology*, 37, 299–302.

Stone and Webster Inc. 2001. OU–5 East Fork Brush Creek geotechnical investigation (final report), July 17. Consultant's report prepared for the U.S. Army Corps of Engineers.

Tetra Tech NUS Inc. 2000. RCRA facilities investigation report for SWMU 12, Naval Weapons Station Charleston, Charleston, South Carolina. Consultant's report to Southern Division Naval Facilities Engineering Command, North Charleston, South Carolina, March.

Thorburn, P.J., and G.R. Walker. 1994. Variations in stream water uptake by *Eucalyptus camaldulensis* with differing access to stream water. *Oecologia* 100, 293–301.

U.S. Environmental Protection Agency. 1999. SW–846 methods, http://search.epa.gov/epaoswer/hazwaste/test/tx8xxx.htm#8XXX (accessed December 21, 1999).

Vose, J.M., G.J. Harvey, K.J. Elliott, and B.D. Clinton. 2003. Measuring and modeling tree and stand level transpiration. In *Phytoremediation: Transformation and Control of Contaminants*, ed. S.C. McCutcheon and J.L. Schnoor, 263–282. New York: Wiley.

Vroblesky, D.A., and T.M. Yanosky. 1990. Use of tree-ring chemistry to document historical ground water contamination events. *Ground Water* 28, no. 5: 677–684.

Vroblesky, D.A., T.M. Yanosky, and F.R. Siegel. 1992. Increased concentrations of potassium in heartwood of trees in response to ground-water contamination. *Environmental Geology and Water Science* 19, no. 2: 71–74.

Vroblesky, D.A., C.T. Nietch, and J.T. Morris. 1999. Chlorinated ethenes from ground water in tree trunks. *Environmental Science & Technology* 33, 510–515.

Vroblesky, D.A., C.C. Casey, G. Harvey, J.T. Morris, and J.M. Vose. 2001. TCE and DCE in tree trunks in diverse environments, in situ and on-site bioremediation. Presented at *The Sixth International In Situ and On-Site Bioremediation Symposium*, June 4-7, San Diego, California.

Vroblesky, D.A., C.C. Casey, M.D. Petkewich, M.A. Lowery, and R.P. Gorman. 2003. Interim progress report on ground-water contamination at solid waste management unit 12, Naval Weapons Station Charleston, North Charleston, South Carolina, 2000–2003. U.S. Geological Survey Administrative Report.

Wilson, B.H., G.B. Smith, and J.F. Rees. 1986. Biotransformations of selected alkylbenzenes and halogenated aliphatic hydrocarbons in methanogenic aquifer material—A microcosm study. *Environmental Science & Technology* 20, no. 10: 997–1002.

Yanosky, T.M., and D.A.Vroblesky. 1992. Relation of nickel concentrations in tree rings to ground-water contamination. *Water Resources Research* 28, no. 8: 2077–2083.

Yanosky, T.M., and D.A.Vroblesky. 1995. Element analysis of tree rings in ground-water contamination studies. In *Tree Rings as Indicators of Ecosystem Health*, ed. T.E. Lewis, 177–208. Boca Raton, Florida: CRC Press.

Yanosky, T.M., B.P. Hansen, and M.R. Schening. 2001. Use of tree rings to investigate the onset of contamination of a shallow aquifer by chlorinated hydrocarbons. *Journal of Contaminant Hydrology* 50, 159–173.

Zang, H., L.P. Simmonds, J.L. Morison, and D. Payne. 1997. Estimation of transpiration by single trees—Comparison of sapflow measurements with a combination equation. *Agricultural and Forest Meteorology* 87, 155–169.

Zeikus, J.G., and J.C. Ward. 1974. Methane formation in living trees—A microbial origin. *Science* 184, 1181–1183.

Zimmerman, M.H., and C.L. Brown. 1971. *Trees—Structure and Function*. Berlin and New York: Springer-Verlag.

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