Variability in Evaluating Environmental Impacts of Treated Wood

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ABSTRACT

Preservative treated wood contains components that may be toxic to non-target organisms if released into the environment in sufficient quantities. Numerous studies have been conducted to determine the rate of preservative release from treated wood and/or the extent of their subsequent accumulation in the environment. These studies have produced a wide range of results with a corresponding range of interpretations and recommendations. This paper reviews research on wood preservative leaching and environmental accumulation and discusses sources of the variability in research findings. Factors such as wood properties, pressure treatment techniques, construction practices, exposure conditions, and site conditions are discussed.

Keywords: Wood preservatives, treated wood, leaching, variability, environmental accumulation

INTRODUCTION

Concerns about the safety and environmental impact of preservatives used to protect wood from biodegradation have increased in recent years, as has research to quantify preservative leaching and environmental accumulation. Early studies of preservative leaching tended to focus on the ability of a preservative to provide long-term protection. Preservative permanence in the wood is critical to efficacy, and leaching studies remain an integral part of research to evaluate potential new preservative systems. These types of leaching trials emphasize comparative evaluations of preservative formulations, and they typically use methods that accelerate leaching. More recently, emphasis has shifted to conducting studies that evaluate the environmental impact of wood preservatives. These later studies place greater emphasis on quantifying in-service leaching rates and measurement of environmental concentrations of leached preservative. Researchers who are relatively unfamiliar with preservative formulations, treatment practices, and wood properties often conduct these environmental impact evaluations. Not surprisingly, studies conducted by researchers with varying fields of expertise and a range of research objectives have produced results that are often conflicting and may be difficult to compare and interpret. This paper discusses some approaches used to evaluate preservative leaching and/or environmental accumulation, and the influence of various aspects of these methods on research results. Evaluations of preservative leaching and environmental accumulation can be grouped into two general types: those in which study conditions are controlled and those that are more observa-

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tional in nature. Controlled studies are often laboratory studies and observational studies typically utilize existing in-service structures, although there is overlap between these groups.

CONSIDERATIONS IN LABORATORY STUDIES

In controlled studies, researchers must consider methods involving selection of test specimens and treatment with preservative, exposure of samples to a source of leaching, and determination of preservative loss.

Selection of Test Specimens

The size and dimensions of test specimens have a great effect on the percentage of preservative leached from the wood. Smaller specimens have a larger portion of their surface area exposed for leaching and allow more rapid water penetration. The effect of grain orientation is also exaggerated in smaller samples. The rate of movement of liquids along the grain of the wood is several orders of magnitude greater than that across the grain, and samples with a high proportion of exposed end-grain will exhibit exaggerated rates of preservative leaching [1,2]. The standard leaching method used by the American Wood Preservers' Association (AWPA) purposefully employs small blocks with a high proportion of exposed end-grain to accelerate leaching (AWPA Standard E11 [3]). Although a valuable comparative method, this method and others using small specimens should not be used to predict the amount of leaching that will occur from product-sized material in service. It may not be practical, however, to conduct a laboratory leaching study using full-length lumber, poles, or piles. To avoid the problem of end-grain effect, specimens may be cut from product-size material and end-sealed with a waterproof sealer prior to leaching.

Wood species can also greatly affect the rate of preservative loss from treated specimens. Permeability varies greatly among wood species, and those species that are more permeable tend to leach at a higher rate because of more rapid movement of water through the wood [4,5]. One study of the leaching characteristics of small specimens cut from the surfaces of commercially treated poles found that rates of preservative leaching from red pine were approximately double those from lodgepole pine, Douglas-fir, and western redcedar [6]. A subsequent study found that hardwoods such as maple, red oak, and beech have a greater percentage of extractable arsenic than does red pine [7,8] (Fig. 1). Other studies also indicate that preservative components may be more leachable from hardwoods than from softwoods [9–11]. Wood species may also affect the distribution of preservative within the wood and, as discussed below, the chemical reactions that occur to fix water-based preservatives within the wood. Because of these species effects, it is important to use a species that is typical for the application under evaluation or to at least identify

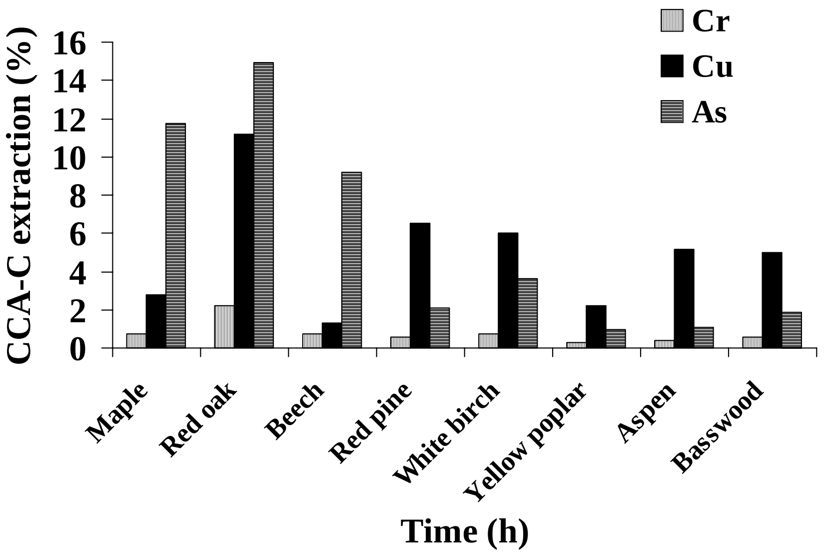

Figure 1 Relative leaching of CCA components from different species (AWPA E11 leaching test) [8].

and report the wood species.

Leaching of preservatives may also be affected by the presence and amount of heartwood in a sample. In most wood species, the inner heartwood portion of a tree is much less permeable than the outer sapwood portion. Accordingly, heartwood portions of test specimens may contain much less preservative than does the sapwood and may also be more resistant to penetration of the leaching medium. These effects might be expected to result in lower leaching rates from heartwood, but this generalization may be confounded by differences in preservative fixation in heartwood or by the presence of a higher concentration of preservative at the heartwood surface. Because the presence of heartwood in specimens complicates interpretation of leaching results, heartwood should either be avoided or quantified and reported. Heartwood represents a major proportion of the wood produced from some wood species, such as Douglas-fir, but a much smaller proportion of wood produced from Southern Pine species.

In some studies, a researcher may have the objective of characterizing rates of leaching from a particular species/preservative combination. In the design of such studies, the researcher must be aware that even within the sapwood or heartwood of a single tree species there can be variability in wood properties, including rate of preservative leaching. Not surprisingly, wood properties typically vary much more between trees and boards than within a single board. Consequently, it is desirable to obtain specimens from as many different boards as possible. For example, if 10 replicates are to be used in a leaching evaluation, it is usually more appropriate to cut a single specimen from each of 10 boards than to cut 10 replicate specimens from a single board. Obtaining boards from a range of geographic locations can achieve an even greater sense of variability, as well as broaden the inference space. As mentioned previously, specimens cut from longer boards may be end-sealed to prevent exaggerated leaching rates attributable to exposed end-grain.

Preservative Treatment and Fixation of Test Specimens

Obtaining preservative treated specimens is a problematic step for many researchers. Many laboratories do not have ready access to stock solutions of commercial wood preservatives or the equipment needed to conduct pressure treatments. In these cases researchers typically purchase commercially treated products for leaching trials. A disadvantage of this approach is that the researcher has no knowledge of the treatment process, treating solution concentration, and fixation conditions. Ideally, the treated products will be purchased from several retailers over a period of time to make the sample more representative. In some cases, researchers have purchased commercially produced lumber and then cut specimens to smaller width or thickness than that of the original board. Because penetration of a preservative is often not uniform throughout the thickness of a board, specimens cut in this manner may have one or more faces that have a different (usually lower) preservative concentration than that of the original board face.

When the researcher treats specimens, care should be taken to prepare or obtain a preservative solution that is nearly identical to the commercial formulation. Leaching of active ingredients can be sensitive to proportions and types of solvents used. For example, leaching of copper from copper amine preservatives can be increased if an excess of amine is used in preparation of the treatment solution. In addition, some types of preservatives may be or may have been produced in multiple formulations. Before chromated copper arsenate Type C (CCA-C) became the industry standard, wood was also treated with CCA-A and CCA-B. Past studies indicate that arsenic release from wood treated with CCA-B was greater than that from wood treated with CCA-A or CCA-C [12]. The treatment process used should ensure adequate penetration of the specimens without development of surface deposits. With some preservative systems, extended soaking periods that allow evaporation of solvents may produce a precipitate surface residue on the wood.

The fixation conditions that specimens are exposed to after treatment can also affect the outcome of a leaching study. In general terms, fixation refers to the series of chemical reactions that render water-based preservatives difficult to leach during service. Although the fixation reactions of preservatives differ, they all depend on solution concentration, time, temperature, and rate of drying.

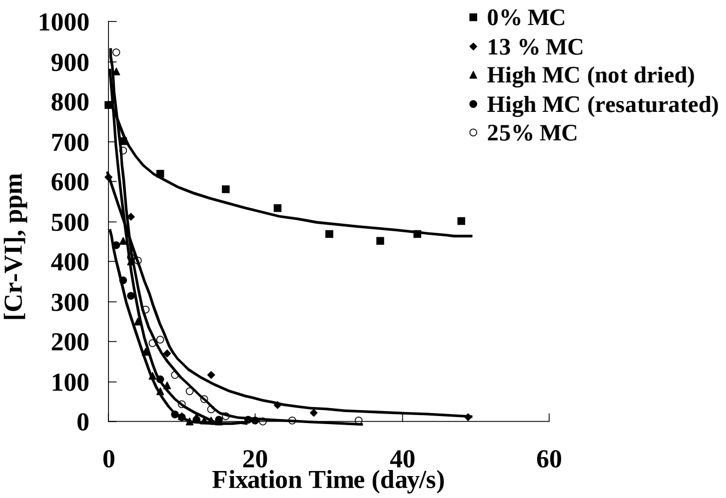

Figure 2 Effect of wood moisture content on chromium fixation.

Complete fixation of CCA depends on the wood species; it requires 10 to 20 days at room temperature for pine species [7]. Test specimens exposed to leaching within a few days after treatment may exhibit abnormally high leaching rates of chromium, copper, and arsenic. The fixation reactions also require moisture [7,13], and rapidly drying specimens after treatment may lead to inadequate fixation even after a lengthy fixation period (Fig. 2). This is particularly a concern for small specimens such as the 19-mm cubes specified by the AWPA leaching standard [3]. For CCA, the rate of fixation and subsequent leaching of CCA components are dependent on wood species. In general, species in which fixation occurs very rapidly also tend to have a higher rate of arsenic leaching [7,8]. Differences in the chemical composition of the wood, and especially the amount and type of lignin, can affect the rate of fixation and subsequent preservative leachability [14]. Again, it is important to identify wood species when reporting leaching results. The solution strength or retention of preservative in the wood can also affect the rate of fixation. For CCA, arsenic fixation is more rapid at higher solution concentrations, while fixation of chromium and copper is slowed. Higher retentions have also been reported to slow fixation of copper in amine copper based preservative systems [15].

Controlled Leaching Exposures

Most controlled leaching trials of preservative treated wood expose samples to leaching via immersion. Immersion is perhaps the simplest type of leaching mechanism to control and replicate, and it provides a severe leaching environment. However, the immersion conditions can affect the results obtained. In some situations, the leached preservative in the water may reach concentrations that inhibit further leaching [16]. This problem can be addressed by either frequently changing the leaching water, as specified in AWPA Standard E11 [3], or by constructing a flow-through leaching apparatus that circulates fresh leaching water [16]. In the latter case, care must be taken to accurately control or measure the flow rate so that the dilution factor can be calculated.

The characteristics of the leaching water can also influence leaching of preservatives. Standardized methods, such as AWPA Standard E11, generally specify the use of deionized or distilled water to minimize these effects. The presence of some types of inorganic ions in water has been reported to increase leaching from CCA treated wood [17–20], while they have been reported to decrease leaching with at least one type of preservative [21]. Water pH can also affect leaching of preservatives. Leaching of CCA is greatly increased when the pH of the leaching water is lowered to below 3, and the wood itself also begins to degrade [1,6,22]. Water pH ranges more typical of those found in the natural world are less likely to have a great effect on leaching [23], although the presence of organic acids may influence leaching at more moderate pH levels. Warner and Solomon [24] reported that adding citric acid to leaching water greatly increased leaching in laboratory tests. Although it is doubtful that high levels of citric acid will be a problem in service, surface waters containing high levels of humic or fulvic acid from peaty organic soils can have the potential for increasing CCA leaching [6,9]. Cooper and Ung [25] compared CCA-C losses from jack pine blocks exposed in garden soil and organic-rich compost and found that leaching was more than doubled by compost exposure.

Water temperature has also been reported to significantly affect leaching from wood treated with a CCA formulation [26]. In that study, copper, chromium, and arsenic leaching were approximately 1.4, 1.6, and 1.5 times greater, respectively, from wood leached at 20°C than from wood leached at 8°C. Brooks [16] also concluded that leaching of copper from CCA treated wood could be substantially increased as water temperatures increased from 8°C to 20°C. A similar temperature effect was noted in a study of release of creosote components from treated wood [27].

The rate of water movement around the test specimens can also influence leaching, although this effect has not been well quantified. Xiao et al. [27] reported that release of creosote was greatest at the highest flow rate tested and that turbulent flow may have greatly increased leaching. Van Eetvelde et al. [26] also reported that leaching of CCA was greater when using stirred leaching water than with static leaching trials. The AWPA standard leaching test specifies the use of a slow stirring speed (e.g., a tip speed of 25 to 50 cm/sec) [3]. However, care must be taken that the method of stirring or agitation used does not mechanically abrade the surface of the wood.

Although an immersion leaching exposure may be relatively simple to simulate, most treated wood in-service is not placed directly in water. Terrestrial applications are more common, and in such cases the treated structure is above ground or water or in soil contact. Because studies have illustrated that soil composition may affect both leaching and subsequent mobility of CCA components [28,29], efforts have been made within the AWPA to develop a standard method of evaluating preservative loss in soil exposures [29]. One challenge in this type of exposure is choosing a representative soil type; the authors recommend using at least three different soil types as well as characterizing and reporting soil properties.

Both immersion and soil contact leaching tests are likely to greatly overestimate the amount of leaching that will occur from treated wood exposed above ground. However, laboratory evaluations of aboveground leaching are rare, in part because it is difficult to simulate natural rainfall. It appears that rate of rainfall, not just volume, can affect the amount of leaching from wood exposed above ground. Studies in outdoor exposures have indicated this effect [4,30], and recent laboratory evaluations [31] have attempted to quantify the effect of rate of rainfall on leaching (Fig. 3). Laboratory evaluations also indicate that exposure to UV light may increase leaching from CCA treated wood exposed above ground [32].

The orientation of the wood product (vertical versus horizontal) can also affect the amount of water that enters the wood to facilitate leaching [1]. Although complex, further research is needed to determine principal factors affecting leaching from wood exposed above ground and to develop laboratory methods to predict leaching in service.

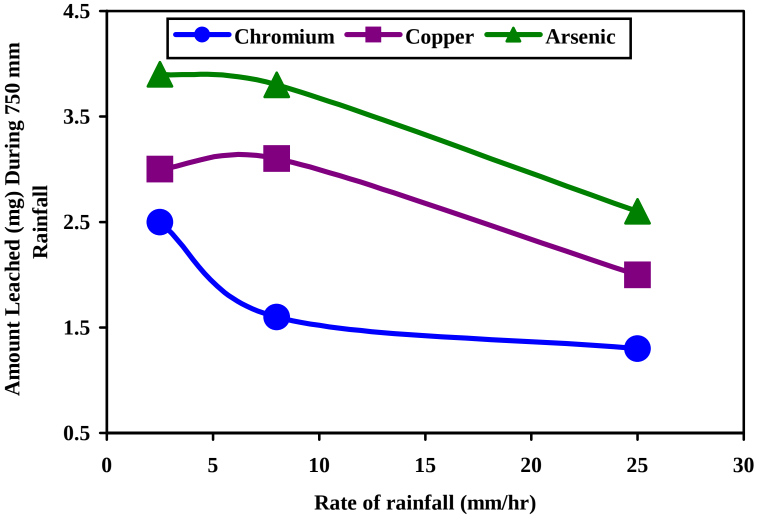

Figure 3 Effect of rate of rainfall on leaching of chromium, copper, and arsenic from CCA treated decking.

Determining Preservative Leaching in Laboratory Exposures

Regardless of the leaching exposure, one must somehow quantify the amount of preservative that has been lost from the wood. This is usually accomplished by either assaying the wood before and after leaching, or by analyzing the leaching water and calculating the rate of leaching and cumulative amount leached. Although analysis of the treated wood before and after leaching is a convenient way to assess leaching, this approach may not provide meaningful data unless substantial leaching has occurred. With well-fixed preservative systems, only a small percentage of preservative is typically lost during a laboratory leaching trial, and error in measurement of preservative content in the wood can easily obscure or over- or underestimate leaching. Lower levels of leaching can be detected by analysis of leaching water, although care must be taken in calculating the dilution factor, and complex error structures may arise if repeated measurements are made over time. Analysis of leaching water also allows a researcher to evaluate changes in the rate of leaching over the course of the exposure period.

FIELD STUDIES OF IN-SERVICE STRUCTURES

There has been a recent increase in evaluations of preservative release from in-service structures. These are generally observational (not controlled) studies. Evaluations of in-service structures provide valuable information on leaching and environmental accumulation in actual applications. The disadvantage of these types of studies is that they are specific to the conditions at that specific site and are difficult to relate to other exposures. The original treatment may be unknown, and there may be little historical data to indicate whether the site was previously exposed to contamination from construction debris or other non-leaching sources. In-service leaching results are affected by a range of site-specific conditions in addition to the treatment, fixation, and species effects discussed in the previous text. These include the age of the structure, type of exposure, climate, and construction and maintenance practices.

Age of Structure

In general, the greatest rate of leaching from treated wood occurs upon initial exposure to the leaching medium. An initial wave of readily available and unfixed or poorly fixed components moves out of the wood; it is followed by a rapid decline to a more stable leaching rate [1,18,28,30,33,35] (Fig. 4). This time-dependent leaching pattern is a function of the size of the treated product, the amount and type of surface area exposed, and the extent to which the preservative components are fixed. It also appears to depend on the severity of leaching exposure, with a steeper gradient occurring under more severe leaching condition such as water immersion, and a flatter gradient occurring for wood exposed above ground. However, regardless of specific conditions, it is likely that rate of leaching occurring during the first year of exposure will be greater than that during subsequent years. Extrapolating early rates of leaching to longer time periods may overestimate long-term leaching.

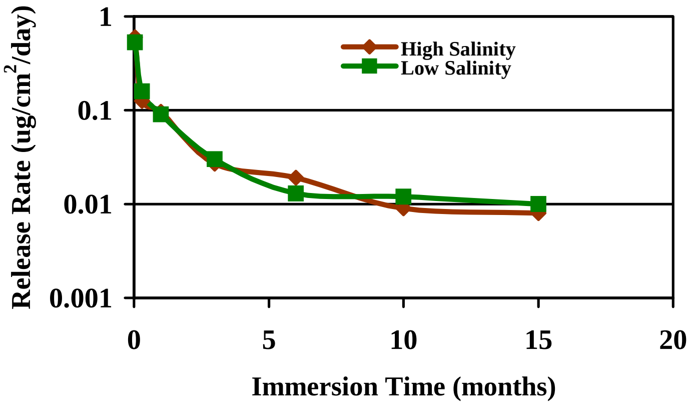

Figure 4 Change in rate of arsenic release from CCA treated 2 by 4 specimens immersed in seawater.

Type of Exposure

The type of exposure or application also greatly influences in-service leaching. Regardless of whether the treated wood is exposed to precipitation, freshwater, seawater, sediments, or soil, the movement and composition of water is the key to the leaching of preservative components from the wood. Structures that are only intermittently exposed to precipitation will have much lower leaching rates than those continually immersed in water, especially in water containing solubilizing organic or inorganic components. Cooper [1] proposed a hierarchy of leaching exposures based on application and site conditions (Table 1). Within each of these types of exposures is a range of conditions that may potentially affect leaching. These include temperature and composition of soil and water. Because most treated wood is exposed above ground, climate plays an important role in leaching. Amount and rate of rainfall affect leaching [35], and it is likely that temperature and the presence or absence of freezing temperatures do as well. Although these conditions cannot be controlled, they should be noted and factored into the interpretation of leaching results.

Construction and Maintenance Practices

Construction and maintenance practices for a structure can also affect the rate of preservative leaching or the amount of preservative detected in the environment. If treated wood sawdust or shavings generated during construction are allowed to enter soil or water below a treated structure, they make a disproportionately large contribution to environmental contamination. As shown in Figure 5, leaching of CCA from construction debris immersed in water is vastly greater than that from solid wood. Environmental samples removed from areas where construction debris was deposited are likely to have much higher elevations of preservative components than might be expected from leaching alone. This effect may be responsible for some of the higher soil arsenic levels reported in recent studies of soil adjacent to CCA-treated decks [36,37], while other studies reported much lower concentrations [35,38]. Although associated with the treated structure, environmental contamination caused by construction debris is attributable to construction practices and is not an inherent characteristic of the treated wood [39]. Cleaning and maintenance practices such as aggressive scrubbing, power-washing, or sanding can also remove particles of treated wood and deposit them in soil or water beneath a treated structure. In addition, some ingredients used in deck cleaners have been shown to react with and potentially increase the solubility of preservative components [40].

Application of Finishes

While construction debris and cleaning activities may increase environmental releases from a treated structure, application of finishes appears to have the opposite effect. One report indicated that a clear water-repellent finish greatly decreased CCA release from fencing [41]. Even after 2 years, arsenic concentration in rainwater collected off the finished specimens was approximately five times lower than that from the unfinished specimens. An observational study of the concentrations of arsenic, copper, and chromium in soil under residential decks noted that levels appeared to be lower under a deck that had been painted, although the design of that study did not allow a controlled comparison [36]. A laboratory study has also indicated that latex paint, oil-based paint, and semi-transparent penetrating stains are all effective in decreasing leaching from horizontal surfaces [42]. Again, although construction and maintenance activities generally cannot be controlled in an in-service leach-

Table 1 Hierarchy of Severity of Leaching Exposures in Order of Increasing Severity [1]

Exposure condition	Typical or example application
Partially protected from rainfall	Covered patios, gazebos, siding, substructure of decks and bridges
Occasional or partial exposure to rainfall	Fence boards
Complete exposure to rainfall	Shakes and shingles, decking, railings, stairs, steps
Exposure to soil	Fence posts, poles, land piles, retaining walls, treated wood foundations
Exposure to fresh surface water	Cribs, lock gates, fresh water piles
Exposure to seawater, acidified water, or warm water	Marine piles, piers, cribs, cooling towers, acid lakes
Exposure to metal complexing compounds	Silos, bog water (hypothesized), wood stave pipes and tanks, citric acid

ing evaluation, they should be considered in the interpretation of leaching results.

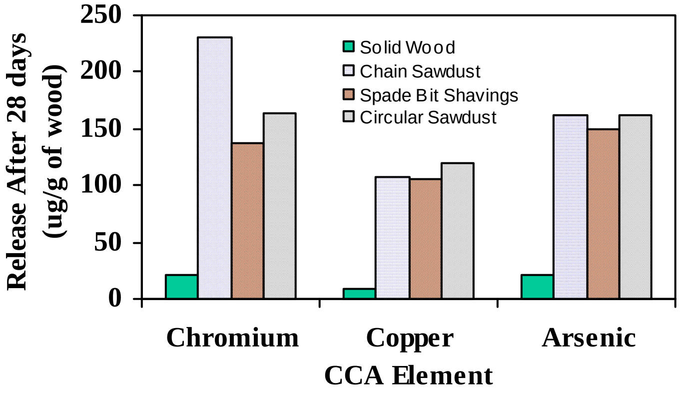

Figure 5 Comparison of amount of preservative released from solid wood or construction debris.

Quantifying Leaching for In-service Exposures

For in-service evaluations, leaching is generally evaluated by either assaying the treated wood or by collecting and analyzing environmental samples adjacent to the treated wood. Determining preservative loss by assaying wood after exposure requires knowledge of original preservative retention in the wood. Often original retention is assumed based on the specified target or standard retention for treated wood used in that application. This assumption can be problematic, as preservative retention in a treated product can be substantially higher or lower than the target retention. This is particularly true for some oil-type treatments where retention is controlled by adjusting the treatment process, and not by adjusting the treatment solution concentration. Even with water-based preservatives, retention can vary greatly between material in a single charge and even more greatly between treating plants. Figure 6 shows the distribution of CCA retention in CCA treated 2 by 6 Southern Pine lumber purchased from several retailers over the course of 1 year. All the boards were treated to a target retention of 6.4 kg/m^3. It is evident that retention varies greatly between boards, and that leaching would be either overestimated or underestimated for most boards based on an assumed original retention of 6.4 kg/m^3. Variability in retention can be even greater in more difficult to treat wood species.

Another technique used to quantify leaching in-service is comparison of the aboveground or above-water retention to the below-ground or below-water retention, with the assumption that leaching is minimal for samples exposed above ground [10,44,45]. This method can provide an indication of significant losses in the lower portions of treated wood. However, it is vulnerable to underestimation of leaching because some leaching does occur from above ground and the preservative may redistribute within the wood during service [45–47].

Because of challenges associated with assaying the treated wood to quantify leaching from in-service structures, researchers may instead collect environmental samples adjacent to a treated structure. This approach has the advantage of providing information on environmental accumulation of leached preservatives, but it gives limited information on the amount of preservative released from the wood. Environmental sampling also introduces a range of sources of variability into a leaching study. In addition to leaching rate, environmental concentrations of preservative components will be a function of background concentrations, sampling location, and soil or water characteristics.

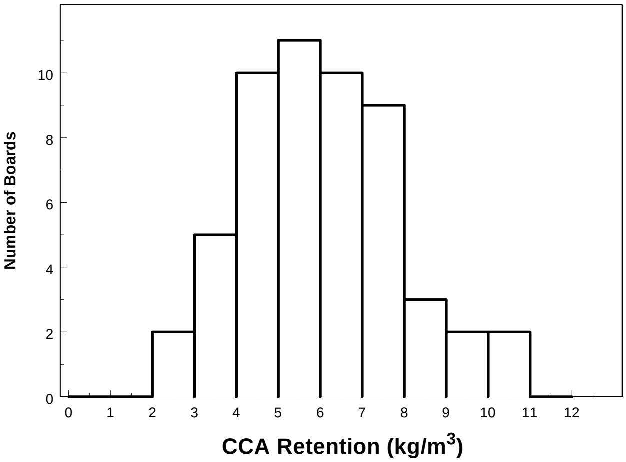

Figure 6 Range of CCA retentions measured in 2 by 6 Southern Pine lumber treated to target retention of 6.4 kg/m^3.

Determining background or preconstruction environmental concentrations of preservative components is a key, but sometimes difficult, step in evaluating environmental accumulation. Many wood preservative components, including copper, chromium, and arsenic, have been widely used for other applications in the past, and soil and sediments may contain unpredictable concentrations of these components. This problem has generally been addressed by removing environmental samples at varying distances from the treated structure [36–38] and considering those at an extended distance from the structure as representing the background concentration. While generally a valid approach, there is the concern that human activities probably are, or have been, greater in close proximity to the treated structure, and thus the risk of other sources of contamination is greater in that area than may be in a nearby but less used area.

Surface Area

The surface area of a structure contributing to soil levels in a particular area is an important consideration in environmental sampling. In complicated structures such as decks it may be difficult to determine the surface area of the structure that is contributing to soil accumulations in any specific sampling location. Other structures, such as utility poles, have a large aboveground surface that drains into a small volume of soil at the base of the pole, and it is not surprising that relatively high levels of preservative components have been detected in soil adjacent to poles [48].

Number and Location of Samples

For a field study, the specific parameters and/or hypotheses of interest relevant to the inference population(s), such as a 95% confidence interval for the median amount of copper within 152 mm of a structure, need to be identified before the study starts. Then, the best sampling strategy and analysis methodologies to address these information needs can be selected. Selection and number of sampling locations for removal of environmental samples can also influence levels of preservative components detected. Common preservative components such as copper, chromium, and arsenic are reactive with soil constituents [12] and are not freely mobile in soil. Thus, environmental concentrations tend to be concentrated in areas immediately adjacent to treated wood or where water drips off treated wood into soil. Even when soil samples are removed from directly under the drip line of a deck, environmental concentrations of leached preservative components can vary greatly [35]. Because of this wide variation, a statistically designed sampling plan is needed to characterize preservative concentration in the environment adjacent to treated wood. Practical general advice on environmental studies can be found in van Belle [49], while more specific statistical methodology is given in Gilbert [50], Gibbons and Coleman [51], and Manly [52].

Environmental sampling typically yields many samples with relatively low levels of preservative components and a few samples with much higher levels [35–37]. Because of this skewness, traditional normality-based statistical methods directly applied to samples from an underlying skewed distribution may be overly sensitive to the “outlying” observations and lack power in comparing parts of the distribution where there is less information. Lognormal distributions are commonly assumed in environmental sampling; Ott [53] discusses in detail the physical and stochastic reasons why lognormal populations naturally arise in environmental settings. Gibbons and Coleman [51] provide statistical methods for testing distributional assumptions as well as for testing for outliers. If the lognormal distribution can be assumed, the normality-based methods can be applied to log transformed data, and the results reverse transformed to the original scale, to estimate various population parameters as well as confidence limits. For example, the sample geometric mean provides a simple estimate of the median, which can be a better estimator than the sample median of the median preservative concentration within that area. However, for small sample sizes with high skewness, this estimator has higher levels of associated positive bias [50]. Parametric approaches can offer more sophisticated modeling approaches than do nonparametric procedures, but depending on the particular questions that are to be answered in a particular study, nonparametric methods may also be appropriate [49].

Besides potential sampling, temporal, and spatial variability, analytical uncertainty is another consideration, as discussed by Gibbons and Coleman [51]. Care needs to be taken that analytical uncertainty is not used to characterize other types of variability. Also common to field studies are values that are censored below the quantitation limit(s) of a measurement device, necessitating appropriate statistical analysis methods to accommodate the censored data. Although there is agreement about using an appropriate statistical procedure, the particular choice depends on several things, including the objectives, degree of censoring, and ease of use [51].

Site Characteristics

Independent of leaching rates, site characteristics strongly influence environmental accumulation of leached preservative components. Leached preservative components are reactive with naturally occurring ligands in soil, sediments, and water, which limits their mobility. Movement in soil is generally limited but is greater in soils with high permeability and low organic content [23,54–60]. Mass flow with a water front is probably most responsible for moving metals appreciable distances in soil, especially in permeable, porous soils [60]. It is apparent that preservatives leached into water have the potential for greater migration compared with that of preservatives leached into soil, with much of the mobility occurring in the form of suspended sediment [35,61]. These environmental factors interact with leaching rates to create a pattern of environmental accumulation specific to a particular site.

SUMMARY

Evaluation of the leaching and environmental accumulation of preservatives from treated wood is a complex process, and many factors can influence the results of such studies. In laboratory studies, the effects of specimen dimensions, wood species, treatment practices, fixation, and leaching exposure must be considered. Evaluation of in-service structures introduces additional variability, with factors such as age of the structure, type of exposure, construction and maintenance practices, and site characteristics. There is no perfect study design to account for all of these factors, and in many cases they are out of the control of the researcher. However, the researcher should be aware of these factors and the relative importance of these sources of variability to a particular study should be considered when interpreting and reporting the study results.

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