FATE AND TRANSPORT OF FORESTRY HERBICIDES IN THE SOUTH: RESEARCH KNOWLEDGE AND NEEDS [1]

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Abstract. A review of the fate and environmental risks associated with the use of hexazinone, imazapyr, sulfometuron methyl, and triclopyr in pine silviculture in the South is presented. Herbicides used in forestry can contaminate surface waters to varying degrees depending on the application rate, method of application, product formulation, and site specific characteristics, but streamside management zones (SMZ) greatly reduce stream contamination. Highest concentrations measured in streams occurred in short duration pulses during the first two or three storm events following application. Stream contamination usually declined rapidly thereafter. The highest concentrations of herbicides observed in streams are usually lower than concentrations determined to be safe by the Environmental Protection Agency's Office of Drinking Water for domestic drinking water. Persistence of herbicides on treated sites is affected by many factors. Half-life in vegetation is ususally < 40 days and from 7-180 days in soil. Environmental Impact Statements and Risk Assessments completed for the southen United States concluded that: (1) no member of the public, including sensitive individuals, should be affected by typical exposures to herbicides or associated chemicals used for vegetation management in the South; (2) the risk of dying or from cancer is greater after drinking 40 diet sodas with saccharin, consuming a total of 2.7 kg (6 lb) of peanut butter, drinking 750 L (200 gal) of water from Miami or New Orleans, or smoking two cigarettes than it is from exposure to herbicides used in the South, even for workers; and (3) care needs to be taken with herbicides concerning threatened and endangered species. More research is needed for new herbicides because: (1) analytical problems are greater for new herbicides which are used at very low rates and biodegrade rapidly; (2) new herbicides should be screened for toxicity against threatened and endangered plant species; and (3) research should define the role of SMZs in reducing stream contamination so that SMZ size can be prescribed on a site specific basis.

Introduction

There are many issues surrounding use of herbicides in forestry and most of these seem to have arisen from an association with agricultural food crop uses. The distinction between intensive forest management use of herbicides and agricultural is significant, but seldom presented. While agricul-

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tural uses involve multiple applications annually of pesticides on most units of land in use, intensive forest management practices seldom utilize herbicide applications more than twice (site preparation treatment and a release treatment) within a 30- to 80-year rotation cycle (Michael et al., 1990). In the South, herbaceous weed control in the year of planting often precludes the need of a second application for release, resulting in a single application over a 30- to 80-year cycle (Nelson et al., 1985; Michael 1985). Use of herbicides in intensive forest management, then, means that even if every forest site is intensively managed, the risk to the public and the environment is less than one-thirtieth that in food crops. However, the decreased frequency of occurence of concerns does not render them irrelevant.

A National Forest Environmental Impact Statement (EIS) (USDA Forest Service 1989a) provides some insight into the concerns of citizens when management of public forest land is considered. Nearly 900 respondents in 28 states volunteered comments on issues concerning management of this resource. Similar information is not available for industrial lands, but it is instructive to consider the issues brought forth in the EIS. Respondents' comments were categorized according to several broad issues. As may be expected, a major issue dealt with whether National Forest land should be managed regardless of the tools used. Concerns under this broad issue are: (1) too much emphasis on timber production; (2) impacts of forest maragement on wildlife and plant diversity; (3) impacts on visual and cultural (artifacts) resources; and (4) concern over the impacts of changes in forest management practices on management costs and on employment at the local level. Issues that dealt specifically with herbicides were: (1) risks to humans and the environment from aerial application; (2) human health and safety; (3) impacts on plant communities, especially threatened, endangered, and sensitive species; and (4) impacts on soil productivity and water quality. These issues are worthy of consideration regardless of the frequency of occurence. Research has addressed issues 1, 2, and 4 through monitoring studies and risk assessment. This paper presents a brief summary of current research data relative to these topics.

Environmental Pate

Herbicide persistence and contamination of the various environmental matrices related to human health and safety, soil productivity, and water quality have been the subject of monitoring studies in the South.* Except for the phenoxy herbicides, the most often used herbicides have been around for approximately 10-15 years. Phenoxy herbicides have been the subject of very intensive study for several decades and are not covered in this paper. Persistence, described in terms of half-life, determines the length of time over which exposure and therefore direct adverse impacts can occur.

Half-life

The most often used term in describing herbicide persistence is half-life. Generally herbicide disappearance from a site approximates a logarithmic decay curve similar to that of a first-order chemical reaction. Transformation of dissipation data permits graphic representation:

$$\mathrm{Log}_{10} \text{ Tissue Concentration vs. Time.}$$

Simple linear regression of transformed data yields an equation of the form:

$$\text{Log } Y = aX + b,$$

from which the half-life is calculated as the time at which half of the regression maximum concentration (X = Time = 0) has dissappeared. The slope (a) or rate of dissipation is very dependent on the maximum concentration observed in the field and on the timing, rate, and duration of the first precipitation event following application. For volatile chemicals, the rate of dissipation also depends on the temperature and wind conditions immediately following application. While recognizing the weakness of the "half-life" term, we will use it for lack of a better one.

Cycling

One of the main reasons for the weakness of the half-life term is "cycling." Herbicides may move or cycle from one matrix to another and back via physical and biological routes. The movement of sulfometuron methyl from plant tissue to litter resulting in a maximum observed litter concentration 3 days after treatment, and from litter into soil resulting in a maximum observed soil concentration 7 days after treatment, has been noted following very small precipitation events (Fig. 1) (Michael and Neary 1987). Similar transfers have been observed for hexazinone (Michael and Neary 1990).

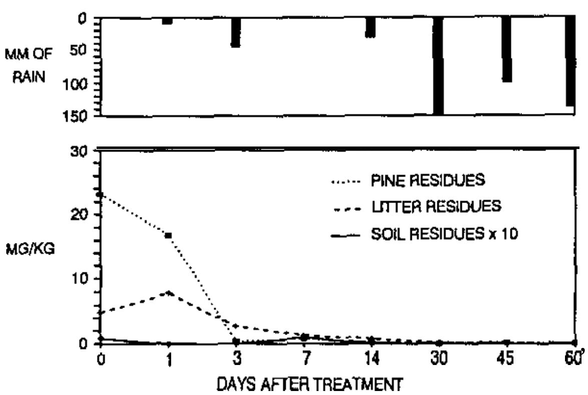

Figure 1. The transfer of sulfometuron from vegetation to litter, and then to soil.

Plants

Herbicide persistence in plants may vary considerably depending on the species, applied rate, and environmental conditions (Table 1). Values reported here are those observed under actual field conditions. Typically, the highest observed concentrations are in the low parts per million range, even for vegetation treated with rates in < **300** g/ha range. Cycling of herbicide from plants to litter to soil and back again to the vegetation has been demonstrated for some herbicides. Sulfometuron methyl cycling is demonstrated in Figure 1. Uptake from soil occurred, following precipitation, within 3 days after treatment, and resulted in observable increases in tissue concentrations by 7 days after treatment.

Soil

Cycling also affects soil concentrations. It can affect the shape of the dissipation curve by causing higher concentrations several days after treatment than observed on the day of treatment (Fig. 1). In addition to

Table 1. **Herbicide** persistence in plants under field conditions.

Herbicide	Applied rate	Half-life	Plant species
	(kg ha^{-1})	(days)	(number)
Hexazinone	1.7	4-15[a]	5
Imazapyr	2.2	12-40[b]	(composited)
Sulfometuron methyl	0.4	1-12[c]	9
Triclopyr	4.5	< 7[d]	(grasses)

[a] Michael and Neary 1990.
[b] Michael 1986.
[c] Michael and Neary 1987.
[d] Bush et al.. 1988.

attenuating the dissipation curve, cycling causes a worse fit (decreased R^2). Half-lives of herbicides under field conditions are highly variable and may be more affected by initial application rates and occurrence of precipitation than by biological activity, but they do indicate trends in persistence (Table 2). Thus laboratory studies of biological activity under controlled conditions must also be considered in determining the environmental fate of herbicides.

Table 2. Eerbicide persistence in forest soils following application for vegetation management.

Herbicide	Applied rate	Half-life
	(kg ha^{-1})	(days)
Hexazinone	1.7-2.9	21-180[a,b,c]
Imazapyr	2.2	19-34[d]
Sulfometuron methyl	0.4	7-26[e]
Triclopyr	4.5	10-46[f]

[a] J.L. Michael, unpublished data.
[b] Bouchard et al., 1985.
[c] Michael and Neary 1990.
[d] Michael 1986.
[e] Michael and Neary 1987.
[f] Bush et al., 1988.

Water

Movement of herbicides through the various site matrices (water, soil, and vegetation) is governed by the relative presence or absence of water. Because all forest herbicides are water soluble to some extent, either by nature or by virtue of the way they are formulated, the water cycle governs their disappearance. This is true whether it is by the more obvious routes of evaporation, runoff, and leaching, or by the less obvious routes of plant uptake, metabolism, hydrolysis, and in some cases even photolysis.

There are two major routes of herbicide entry into streams. The first is direct application and the second is through stormflow. Less important are interflow (water movement in the saturated and unsaturated portions of the soil profile) and underflow (movement of water under stream beds). Direct application is responsible for the most severe stream contamination (Table 3), and is the easiest

Table 3. Maximum observed concentrations of herbicides in surface water from environmental fate studies in the southern United States.

Herbicide	Applied rate	SMZ[a]	Concentration	Number of studies
	(kg ha^{-1})		(μg L^{-1})	
Hexazinone	1.7-2.9	Yes	ND-37	9[b,c,d]
	0.8-1.7	No	442-2400	2[e,f]
Imazapyr	2.0	Yes	130	1[G]
	2.0	No	680	1[G]
Picloram	0.3-5.0	Yes	ND-21	7[b]
	5.6	No	241	1[h]
Sulfometuron methyl	0.4	Yes	7-44	2[i]
Triclopyr	4.5	Yes	2	1[j]

[a] Streamside Management Zone.
[b] J.L. Michael, unpublished data.
[c] Bouchard et al., 1985.
[d] Michael and Near-y 1990.
[e] Neary et al., 1986.
[f] Miller and Bace 1980.
[g] Michael 1986.
[h] Michael et al., 1989.
[i] Michael and Neary 1987.
[j] Bush et al.. 1988.

to control. It includes direct application to active streams and dry stream channels. Another and less obvious path of direct insertion into streams is throughfall. In this process, vegetation which overhangs streams and stream channels is impacted with herbicide spray. Subsequent drippage or runoff from foliage and stems can fall directly into streams. Additionally, a heavy dew (as often occurs during spring application window) or storm event can result in washoff of herbicide which has not been completely absorbed. This washoff can also fall directly into streams. When throughfall or washoff falls into previously dry stream beds it is in place to be moved into perennial streams by stormflow.

Stormflow is the path by which most post-application stream contamination occurs. Research has shown that approximately 90 percent of all herbicide leaving a site and contaminating a stream reaches that stream during the first two to three storm events following application. The longer the period between application and the first storm event, the less severe is stream contamination. Stormflow is made up of several components but especially important is the contribution of flow over previously dry areas. These include ephemeral stream channels, and overland flow across the landscape surface. When large storm events occur, much water may be deposited in small to large channels which are drainage channels but are usually dry. They can be recognized in the field by scouring of the soil surface (landscape incision) and often by the deposits of litter and sticks left by receding stormflow from earlier events. Overland flow is that flow of water over the surface of soil that has never infiltrated the soil surface. The rate of precipitation required to initiate overland flow is based on the soil type, surface characteristics, (i.e., whether it is covered by litter, vegetation, or is bare and whether it is disturbed or undisturbed), and rainfall intensity. Generally speaking, the infiltration rate of bare clay textured forest soils ranges from 0 to 5 mm of water per hour while that for the same soil covered by vegetation is 5 to 10 mm/hr. When the rate at which rain is falling exceeds the infiltration rate, there will be overland flow. Thus when the rate of rainfall on some of typical Piedmont soils in the South exceeds 5 mm/hr for bare ground and 10 mm/hr for vegetation covered soil, there is a distinct probability of overland flow. On many well-developed and undisturbed forest soils, infiltration rates always exceed maximum rainfall intensities. The distance over which overland flow occurs varies widely, but it must be accepted that when overland flow reaches a drainage channel of any size it will contribute to the overall level of stream contamination.

Maximum observed concentrations of herbicides in water from treated areas varies depending on a number of factors including the application method, the applied rate, and the existence of a streamside management zone (SMZ), or an untreated buffer zone. The U.S. Environmental Protection Agency (EPA) has established a "Safe Drinking Water Level" of 200 µg/L (parts per billion) for hexazinone (U.S. EPA 1989). Use of an SMZ typically maintains even the maximum observed water concentrations well below this level (Table 3). These maximum observed levels are ephemeral, often lasting less than 15 minutes and are well below observed toxic levels for most southern aquatic species. Use of a streamside management zone is the most easily controlled factor in reducing surface water contamination. While SMZs do not have to be large to be effective, little is known about their exact role in mitigating stream contamination. Obviously maintenance of an SMZ greatly reduces the amount of direct stream input, but the attenuating effects on stormflow and baseflow inputs has not been defined.

Risk Assessment

The U.S. Forest Service has intensively analyzed the environmental impacts of herbicide use for vegetation management on National Forest System lands in the South. The result of this analysis has been publication of EISs for the geographical areas where herbicide use is proposed (USDA Forest Service 1989a, 1989b, 1990). One component of the EIS is a Risk Assessment which deals specifically with human health and safety.

There are three major components to a Risk Assessment. The first is a Hazard Analysis. In the Hazard Analysis, published data and publicly available summaries of proprietary data were reviewed concerning the hazardous properties of individual herbicides. The review considered acute, subchronic and chronic toxicity effects for all major routes of exposure. It also determined threshold toxicity values for LD_{50}s, systemic and reproductive no-observable-effect-levels, carcinogenicty, and mutagenicity for each herbicide.

The second component, Exposure Analysis , estimated single and multiple exposures for workers and members of the public likely to be exposed. Three exposure scenarios were developed. The "typical" scenario considered exposures likely to occur during application, the "maximum" scenario estimated the maximum exposure likely to occur in the absence of an accident, and the "accident" scenario estimated direct exposure from concentrated herbicide, spray mix, and spills.

The third component, Risk Analysis, combines the hazard analysis, the exposure analysis for various scenarios, and the probability that exposure could occur to predict health effects on indivivuals. This last step also considers common risks from alternative vegetation control measures. Where valid human studies existed, a tenfold safety factor was applied if there was no indication of carcinogenicity. If no human studies were available, but long-tern animal studies existed, a safety factor of 100 was built into the analysis. In cases where there were no long term animal studies and toxicological data were limited, a safety factor of 1000 was built into the risk analysis.

The Risk Analysis (USDA Forest Service 1989a) concluded that no member of the public, including sensitive individuals, should be affected by typical exposures to herbicides or associated chemicals used for vegetation management in the South. Workers were found to be, at greatest risk, but even workers are subject to less than one in a million chance of adverse health effects except for the accident scenario in which workers did not wash spilled herbicide off their bodies. Even in this extreme case, lifetime cancer risks were less than one in a million for all of the 14 chemicals considered except 2,4-D. By comparison, the probability of death or cancer for all individuals is one in a million over a lifetime from: (1) drinking 40 diet sodas with saccharin; (2) consuming a total of 2.7 kg (6 lb) of peanut butter; (3) drinking 750 L (ZOO gal) of water from Miami or New Orleans; or (4) smoking two cigarettes (USDA Forest Service 1989a).

Research Needs

While we know much more now about the fate of herbicides in southern forest ecosystems and public and worker risk than we did 15 years ago, there is still much to be learned. New chemicals are continually being developed that are effective at lower and lower rates. The newest herbicides belong to a class of compounds known as acetolactate synthase (ALS) inhibitors (Moberg and Cross 1990). Acetolactate synthase inhibitors include the sulfonyl ureas, triazolopyrimidines, and imdiazolinones. These compounds inhibit the synthesis of branched-chain amino acids (valine, leucine, and isoleucine) considered to be essential to mammals, but which mammals cannot synthesize. Because mammals lack the ability to synthesize branched-chain amino acids, the mode of action of these herbicides is inherently selective for plants. Many of these new compounds are very short-lived in the forest environment, i.e., sulfometuron methyl has a hydrolytic half-life of about 20 days at pH 5. New compounds may or may not behave similarly to existing herbicides and research will be needed to determine their persistence and potential for adverse site effects.

The new chemicals--along with most existing forestry herbicides--are water soluble and so their movement into water should be guarded against. More research is needed to provide a sound basis for mitigation techniques in water quality protection. In addition there is a trend toward development of herbicides effective at extremely low application rates. This means they are phytotoxic at extremely low concentrations, possibly below our current detection levels. Detection limits currently are around 1 µg/L (ppb) for herbicides in very clean samples like stream water and around 20 to 50 µg/L for other samples like soil and plant tissue. Phytotoxicity of the newest herbicides may occur below 1 µg/L for some aquatic plant species. Environmental fate studies are complicated by this level of activity because accidental significant cross-contamination of samples is much easier and because the chemical analysis becomes much more difficult. In order for impacts on aquatic ecosystem form and function to be assessed, new and more sensitive analytical techniques must be developed. Methods using the enzyme-linked immunosorbent assay (ELISA) afford quantitation at extremely low levels of contamination and provide a new approach to this most difficult of analytical problems.

Threatened and endangered (T&E) species are assumed to be adversely affected by forestry herbicides, but that is not necessarily correct. There are many plant species resistant to herbicides and it may be that some T&E species are also resistant. A screening program could identify T&E species which have been focal points in forest management, particularly those located in the coastal plain pine growing regions. Identification of herbicide resistance in these species could save herbicides as forest management tools for some areas previously slated for exclusion.

Streamside management zones have been mentioned several times as a way of reducing contamination of streams with herbicides. There is proof that they work, but not much is known about site-specific design of SMZs. Research needs to define the conditions and parameters under which SMZs are effective.

Challenges to Management

A statement often heard is, "We never do that." During one study, the pilot was instructed to shut-off application over streams carrying water and to side dress those buffers. After the application one of the land managers came up and said, "Why did you do that?" the answer was simply, "The label says so." Logan Norris, Oregon State University, and former Project Leader with the Pacific Northwest Forest and Range Experiment Station, said it well when he said, "If you don't want it in the water, don't put it there." It is not clear what size SMZ is optimal, but any SMZ helps keep herbicides out of surface waters. *The challenge to forest management is to so instill in their employees caution when it comes to herbicide application that when they go to a site and tell the applicators to keep it out of the water, everyone will respond, "We always do that." In the years ahead, forestry will always have to justify its professional position on the use of pesticides, but with sound management practices, based on research results, there will be a future.*

Literature Cited

Bouchard, D.C.; Lavy, J.L.; Lawson, E.R. 1985. Mobility and persistence of hexazinone in a forested watershed. J. Env. Qual. 14:229-233.

Bush, P.B.; Near-y, D.G.; Taylor, J.W. 1988. Effect of triclopyr amine and ester formulations on groundwater and surface runoff water quality in the coastal plain. Proc. South. Weed Sci. Soc. 41:226-232.

Michael, J.L. 1985. Growth of loblolly pine treated with hexazinone, sulfometuron methyl, and metsulfuron methyl for herbaceous weed control. South. J. Appl. For. 9:20-26.

Michael, J.L. 1986. Fate of Arsenal in forest watersheds after aerial application for forest weed control. USDA Forest Service, Southern Forest Experiment Station Final Report No. FS-SO-4105-1.20 (Problem 1).

Michael, J.L.; Neary, D.G. 1990. Hexazinone cycling in a coastal plain sandhills forest ecosystem. Agronomy Abst. 82:337.

Michael, J.L. ; Neat-y, D.G. 1987. Movement of sulfometuron methyl in forest watersheds after aerial application of Oust (R) for herbaceous weed control. USDA Forest Service, Southern Forest Experiment Station Final Rep. FS-SO-4105-1.19 (Problem 1).

Michael, Jerry L.; Neary, Daniel G.; Gjerstad, Dean H.; D'Anieri, Peter. 1990. Use, fate, and risk assessment of forestry herbicides in the southern United States. pp. 300-311, In: Proceedings of XIXth IUFRO World Congress; August 5-11; Montreal, Canada; Canadian International Union of Forestry Research Organizations: Vol. 2.

Miller, J.H.; Bace, A.C. 1980. Streamwater contamination after aerial application of pelletized herbicide. USDA Forest Service Res. Note SO-255. 4 p.

Moberg, William K.; Cross, Barrington. 1990. Herbicides inhibiting branched-amino acid biosynthesis. Pestic. Sci. 29:241-246.

Neary, D.G.; Bush, P.B.; Grant, M.A. 1986. Water quality of ephemeral forest streams after site preparation with the herbicide hexazinone. For. Ecol. and Manage. 14:23-40.

Nelson, L.R.; Zutter, B.R.; Gjerstad, D.H. 1985. Planted longleaf pine seedlings respond to herbaceous weed control using herbicides. South. J. Appl. For. 9:236-240.

U.S. Environmental Protection Agency, Office of Drinking Water. 1989. Health Advisory Summary: Hexazinone. January 1989. U.S. Government Printing Office, Washington, D.C. 2 p.

USDA Forest Service. 1989a. Final Environmental Impact Statement: Vegetation Management in the Piedmont and Coastal Plain. USDA Forest Service Southern Region Management Bulletin R8-MB-23, Atlanta, GA. 1248 p.

USDA Forest Service. 1989b. Final Environmental Impact Statement: Vegetation Management in the Appalachian Mountains. USDA Forest Service Southern Region Management Bulletin R8-MB-38, Atlanta, GA. 1638 p.

USDA Forest Service. 1990. Final Environmental Impact Statement: Vegetation Management in the Ozark/Ouachita Mountains. USDA Forest Service Southern Region Management Bulletin R8-MB-23, Atlanta, GA 842 p.