APPENDIX C

EFFECT OF HERBICIDES ON SOIL PRODUCTIVITY AND WATER QUALITY

BY

DANIEL G. NEARY
SOUTHEASTERN FOREST EXPERIMENT STATION
UNIVERSITY OF FLORIDA, GAINESVILLE, FL 32611

AND

JERRY L. MICHAEL
SOUTHERN FOREST EXPERIMENT STATION
AUBURN, AL 36849

INTRODUCTION

The southern yellow pine and hardwood forests of the South constitute some of the most intensively managed forest ecosystems in the world (Stone 1983; Kellison and Gingrich 1982). These forests also occur in a region with one of the fastest growing human populations in the United States. Furthermore, future resource demands in the South will certainly intensify as the population expands and the forest land base shrinks. The whole mix of public and private forest resources including wood, wildlife, recreation, range, and water will need intensive management to meet increased demands. One crucial concern resulting from this intensification of forest management is the potential effect of silvicultural practices on water and soil resources.

Intensive forest vegetation management practices such as short rotations, clearcut harvesting, mechanical site preparation, burning, drainage, and fertilization created concerns in the early 1970's about possible adverse impacts to soil and water resources. Research during the past two decades has demonstrated the range of environmental effects of these practices. If properly prescribed, applied, and guided, these practices can be conducted while conserving valuable soil and water resources. In addition, over the past 5 to 10 years a further intensification of vegetation management has involved increased use of herbicides. These chemicals are now used extensively across the South's managed forests to control weed competition, reduce the use of soil-disturbing mechanical site preparation techniques, and increase tree growth. The driving force behind increased herbicide use has been the need to improve growth on a diminishing forest land base at a lower initial investment cost. In addition, herbicides are being used to minimize the soil displacement and erosion losses that adversely affect site productivity and water quality. Ten years ago, herbicide use was very scattered and mainly in a testing mode. Now it is a widespread practice. Nearly all public and private forestry organizations have operational programs for suitable stands.

The use of herbicides in the South is not new since agriculture has a long history of pesticide applications. However, increased herbicide use in forest management has occurred precisely when states within the region have recognized potential and actual water pollution risks from agricultural pesticides. Thus, the general public and resource managers have questioned the use of herbicides for vegetation management on forests which are sources for much of the South's streamflow and ground water.

The purpose of this paper is to review the effects of herbicides on soil productivity and water quality. This is accomplished by discussion of herbicide characteristics, applications, and environmental interactions as they influence effects on soil productivity and surface and ground water quality. Soil productivity effects are discussed in a general context. In regard to water quality, specific information and research results from Southern studies are used, where possible, for the individual herbicides considered in this EIS.

HERBICIDE USE

Forestry herbicides can affect non-target plants and animals, and surface and ground water quality at several stages in the use cycle. These stages consist of (1) storage, (2) transportation, (3) loading and mixing, (4) application, (5) equipment cleanup, and (6) container disposal. During and after application, herbicide residues usually move onto the landscape in a diffused nonpoint source pattern. It is during this phase that most public concerns for non-target organisms and water quality arise. The other 5 stages of herbicide use usually deal with concentrates which constitute potential point sources of environmental pollution. These stages have historically caused the most environmental problems. A number of publications are available which discuss safe handling of herbicides during all phases of chemical use (Neary and Taylor 1984; Singer 1980; USDA-USEPA 1975).

Most environmental fate and impact studies conducted on forestry herbicides have focused on off-site movement during and after application. It is during this stage of herbicide use that most adverse public reactions and concerns for environmental quality occur. The bulk of this paper will deal precisely with this aspect. However, references will be made to problems with concentrated materials.

ECOSYSTEM FATE

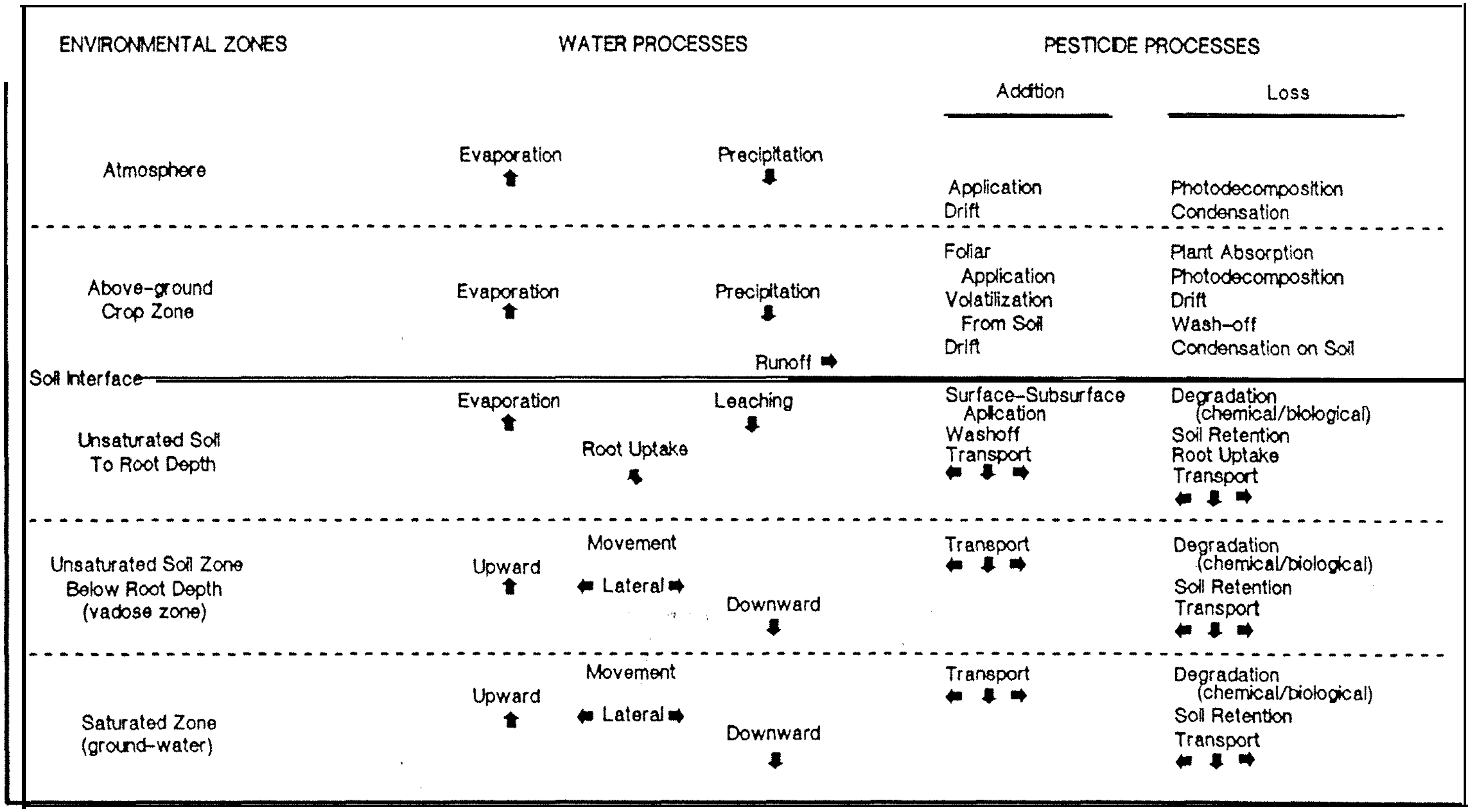
When herbicides are applied to forest ecosystems, a number of processes affect the environmental fate and impact of these chemicals. Understanding these processes is important to determining the environmental impact of herbicide use in vegetation. management programs. To reach such an understanding, we must consider the important zones and processes involved in herbicide application, movement and transformation (figure 1). The key environmental zones are the atmosphere, above-ground vegetation, soil surface, soil rooting zone, unsaturated zone below the rooting depth, and ground water.

Herbicides and their breakdown products are transported within ecosystems mainly through the water cycle. Precipitation, evaporation, runoff, leaching, and root uptake are the major water pathways. Within the unsaturated and saturated soil zones and geologic strata, movement can be lateral, upward, or downward. These processes, as they operate in forested watersheds, are discussed,in great detail by Hewlett (1982), Anderson and others (1976), and Crossley and Swank (1987). Runoff, leaching, root uptake, and movement in soil and ground water are the primary hydrologic processes governing herbicide movement. Precipitation and evaporation are the principal driving forces in the water cycle.

A variety of processes occur within the environmental zones which affect the gain or loss of herbicide residues within the system (figure 1). The importance of these processes on' any given site is determined by individual herbicide characteristics, climatic factors, soil-water properties, and indigenous organisms. These processes have been analyzed and discussed in considerable detail (Hance 1980; Grover 1988). The purpose of the discussion here is to give the reader an overview of these key environmental fate processes.

HERBICIDE CHARACTERISTICS

The important characteristics which distinguish herbicides and their potential effects on the environment are listed in table 1. Formulation, solubility, and vapor pressure are the key physical characteristics of herbicides which affect environmental fate. The other. characteristics listed in this table involve interactions with the environment and are discussed later.



ENVIRONMENTAL ZONES	WATER PROCESSES	PESTICIDE PROCESSES	
		Addition	Loss
Atmosphere	Evaporation ↑ Precipitation ↓	Application Drift	Photodecomposition Condensation
Above-ground Crop Zone	Evaporation ↑ Precipitation ↓ Runoff →	Foliar Application Volatilization From Soil Drift	Plant Absorption Photodecomposition Drift Wash-off Condensation on Soil
Soil Interface			
Unsaturated Soil To Root Depth	Evaporation ↑ Root Uptake ↖ Leaching ↓	Surface-Subsurface Aplication Washoff Transport ← ↓ →	Degradation (chemical/biological) Soil Retention Root Uptake Transport ← ↓ →
Unsaturated Soil Zone Below Root Depth (vadose zone)	Upward ↑ Movement ← Lateral → Downward ↓	Transport ← ↓ →	Degradation (chemical/biological) Soil Retention Transport ← ↓ →
Saturated Zone (ground-water)	Upward ↑ Movement ← Lateral → Downward ↓	Transport ← ↓ →	Degradation (chemical/biological) Soil Retention Transport ← ↓ →

Figure 1. Processes affecting water movement and pesticide transport in various environmental zones.

Table 1.-Important environmental characteristics of the silvicultural herbicides in Region 8

Name	Solubility 25 C	Half-Life[1]	Photo-Degradation	Microbial Degradation	Hydro-lysis	Volatil.	Adsorp. Coeff.	LD50[6]	LD50[7]
	ppm	days						mg/kg	mg/kg
2,4-D	3,000,000[2]	28	Minor	Yes	Yes	Yes (F)[8]	0.5[9]	375	168 (F)
2,4-DP	710	10	Minor	Yes	No	Yes (F)	0.5	532	1
Dicamba	4,500	25	No	Yes	No	No	0.1	757	135
Fosamine	1,790,000	< 10	No	Yes	No	No	20.0	24,400	670
Glyphosate	12,000	61	Minor	Yes	No	Low	16.5	4,320	> 1,000
Hexazinone	33,000	30	Yes	Yes	No	Low	0.2	1,690	370
Imazapyr	15,000	30	Yes	Yes	No	No	0.3	> 5,000	100
LFO[10]	—[3]	6	No	Yes	No	Yes	0.8	> 28,000[11] 7,380	> 1
Picloram	430,000[4]	63	Yes	Yes	Yes	No	0.6	8,200	21
Sulfometuron	3005	10	No	Yes	Yes	No	0.7	> 5,000	12
Tebuthiuron	2,500	392	No	Yes	No	Low	2.4	644	112
Triclopyr	430	46	Rapid	Yes	No	Low	1.5	630	148

1 Average half-life
2 Amine salt formulation
3 Light Fuel Oil is not water soluble
4 Water solubility for potassium salt
5 Solubility at pH 7; 10 ppm at pH 5
6 LD50, technical grade, for rats; for formulation
7 LC50 for bluegill sunfish, 96 hrs, see appendix A, tables 6-8 to 6-19
8 Formulated product
9 See appendix A, chapter 4
10 Light fuel oil
11 First figure kerosene and the second diesel

The formulation of a herbicide consists of the active ingredient and inert carrier materials. Chemical manufacturers mix these materials into their trade formulation to provide easy application and efficient weed control. Variations in formulations can be due to changes in either the active ingredient or the inert materials. The whole range of formulations have been discussed in detail (Sassman and others 1984). The inert carrier materials are "inert" only with regard to their herbicidal properties. They range from clay to petroleum solvents. Like all chemicals, their effects on plants and animals can vary. Formulations are important since changes by individual chemical manufacturers can affect the other two physical characteristics, solubility and vapor pressure. The most commonly used forestry herbicide formulations are liquid concentratesi wettable powders, granules, pellets, emulsifiable concentrates, and soluble powders (Neary 1985b). The type of formulation for a particular herbicide also affects the application system and the potential for off-site movement.

Herbicide formulation can directly affect solubility. An example is 2,4-D; the. dimethylamine salt of 2,4-D is totally water soluble while the butoxyethanol ester of 2,4-D is essentially insoluble in water (WSSA 1986). The solubility of herbicide active ingredients in water is also one index of potential for off-site movement. In general, herbicides with high water solubility have the greatest potential to move by storm runoff into streams and lakes or by deep leaching into an aquifer. Some exceptions occur when herbicides interact strongly with the soil chemical/biological system. All of the herbicides discussed in this EIS are fairly soluble (table 1), and some are very soluble (fosamine, hexazinone, imazapyr, picloram, and tebuthiuron). Glyphosate is an exception to the solubility - transport rule-of-thumb. Although it is readily soluble in water, its potential to move is very low since it is strongly adsorbed onto organic matter in the soil.

Most of the forestry herbicides have low vapor pressures and thus are not prone to volatilization losses (table 1). In addition, many are in stable solid formulations (i.e. pellets, granules, soluble powders, and wettable powders). Herbicides in liquid formulations are mainly non-volatile salts or low-volatile esters.

APPLICATION

Application systems for forestry herbicides are discussed in some detail in the Risk Assessment (appendix A, chapter II) and elsewhere (Cantrell 1985; Miller and Williamson 1987). The environmental effects of herbicides are influenced strongly by application conditions including placement, system, formulation, rate, timing, use pattern, and buffers. Other things being equal, it is mainly the prescription, application, and execution which determine the severity of environmental impacts. There are almost infinite combinations of these factors to consider. Our purpose is to briefly discuss some of the important concepts and comparisons.

PLACEMENT: Herbicides can be placed on the foliage or stems of target plants, on the soil, or directly into stems. Foliar application generally involves a greater hazard because herbicides are spread through the air. They can be moved around by aerial drift, washed off plant leaf surfaces , or physically dislodged. Soil applications may result in a lower hazard of off-site movement, but introduce additional problems of runoff and leaching. Soil-active herbicides usually do not enter the target plants as rapidly as foliar ones. Drift potential is reduced to near zero if solid formulations are used. The least potential hazard comes from direct injection into the target plant since nearly all the herbicide is placed where washoff, runoff, and drift does not occur. However, careless cleanup of equipment may result in water contamination by direct runoff into streams or leaching into wells.

SYSTEMS: various herbicide-application systems are commercially available (Cantrell 1985). The choice of system affects the potential environmental impact and fate of a herbicide. For instance, ground spray systems are not subject to the same drift problems as aerial ones although drift can still occur. Among aerial application methods, helicopters give a greater degree of placement control than fixed-wing aircraft. The type of nozzles selected for spray equipment and the operating pressure of the system directly affect droplet size, distribution pattern and drift potential. A more complete discussion of this topic is found in chapter II, section D of the EIS.

FORMULATIONS: The chemical formulation of a herbicide can also affect environmental fate. For instance, hexazinone is available in a solid as well as a liquid formulation. For aerial application, the solid formulation is much easier to control. Except for short-distance dust movement, drift is not a hazard with aerial application of solid formulations. Also, differences in the chemical , properties of different liquid formulations can affect environmental fate and movement.

RATE: Herbicide application rate strongly affects environmental impact and fate. Rates can vary from 0.1 to 5.0 kg/ha (1 oz/ac to 5 lb/ac) active ingredient, depending on the herbicide and target vegetation. Obviously, with a low rate of herbicide application, residues will dissipate faster, potential exposure of non-target organisms will be lower, and the amount of chemical available for off-site transport into surface water or ground water will be less. Selecting herbicides which will effectively control target weeds at low application rates reduces potential adverse environmental impact.

TIMING: Timing of herbicide applications in relation to climatic conditions and the growing condition of vegetation is important. Often timing is the difference between safe and unsafe use of the same herbicide. This difference can be a matter of seasonal, daily, or hourly timing. Application of a highly soluble herbicide during a dry period with few and low intensity storms presents a far different hazard to water quality than during a rainy season. The same contrast occurs between clear versus rainy or foggy days. Herbicide applications during early morning hours with light winds, or mid-day when winds are gusty, present two different hazard levels.

USE PATTERN: Another important factor determining the environmental impact of herbicides is their use pattern. Generally, forestry use of herbicides *is* of low intensity compared with agricultural use. Forestry herbicides are normally applied once or twice in a 25- to 75-year rotation. Agricultural usage is yearly or even monthly during the growing season. The current level of herbicide use on national forests in Region 8 (appendix A, chapter 1) involves annual applications to only 1 percent of the national forest land base. The two types of special use areas that have herbicide use patterns similar to agriculture are seed orchards and nurseries. They occupy very small land areas and are being handled with separate environmental impact statements.

BUFFERS: The presence and size of buffers has a large effect on the potential impact of herbicides on water quality. Buffers are used as a mitigation measure to reduce or prevent herbicide movement into water. The size of buffer needed is a function of the chemistry of each herbicide , the application system, and the sensitivity of the water resource. Effect of buffer size is discussed in later sections and in the Risk Assessment (appendix A).

DISAPPEARANCE OF HERBICIDE RESIDUES

Once a herbicide is applied to a site, it is subjected to natural processes eventually resulting in its disappearance. The herbicides-initially are retained on-site by being deposited on foliage and litter surfaces, placed directly into vegetation, applied within an inert granule carrier, or adsorbed onto soil surfaces. Their disappearance is a combination of two groups of processes, transport and degradation.

RETENTION PROCESSES: These processes are important in assuring either that the herbicide gets to its target or is kept on the treated site. Foliar penetration is a key process in getting herbicides through the waxy leaf surface and into the target plant. There are many kinds of adjuvants or herbicide formulations which aid this process. Injecting herbicides directly into trees is one obvious way of easily getting herbicides to the target. Herbicides applied in granular formulations are easily placed on-site and then held there until rainfall can disperse the active ingredient. Once herbicides enter the soil, adsorption is an important process. Organic matter content is very important in determining adsorption as it relates directly to the soil's ability to retain chemical residues. The higher the organic matter content of the soil the greater the potential to retain herbicide residues.

TRANSPORT PROCESSES: Herbicide transport processes include drift, foliar and stem washoff (also physical dislodgment), volatilization, plant uptake, leaching, surface runoff, and subsurface flow. Through these processes, herbicides move within a treated area and from target vegetation to water or non-target organisms. All these movement processes are affected by a complex set of chemical, physical, climatic, hydrologic, edaphic, and biologic factors.

Drift is the movement of herbicides in air as suspended droplets or dust. Rainfall can cause foliar and stem washoff after herbicide application, removing herbicide residues from plant surface-s and transporting them to the soil. volatilization occurs while herbicides are still exposed to sunlight and air, and involves chemical movement in the vapor phase in air. Plant uptake removes herbicides from foliage and bark surfaces or from the soil, and temporarily or permanently, depending on the herbicide, removes them from transport. Leaching moves herbicides through litter, soil, and out of the plant rooting zone. Surface runoff rapidly transports residues off-site either in solution or adsorbed to sediment. Subsurface flow of water removes herbicides in solution from the treatment site in slower ground water flow.

DEGRADATION PROCESSES: Processes that break down herbicide chemical structures include photodecomposition, microbial and plant metabolism, thermal degradation, and hydrolysis. These processes, along with those that transport herbicides, determine the degree to which a herbicide persists in the environment. Herbicide persistence is advantageous for controlling target vegetation, but can be a disadvantage because of movement off-site or toxicity to subsequently planted trees.

Some herbicides readily photodegrade, some do not, and some do so only in water. There are many micro-organisms in the soil that can utilize herbicides as energy sources and break down these chemicals into simpler structures. In addition, plants can alter herbicide structures while the herbicides are affecting the plant's physiology. Herbicides are also degraded into simpler compounds by physical-chemical processes like hydrolysis.

SOIL PRODUCTIVITY

ISSUE: One concern about herbicide use in southern forests is their long-term effect on soil productivity. Does introduction of synthetic chemicals into the forest vegetation and soil system produce adverse, advantageous, or neutral changes? This question can be answered, in part, by examining tree growth responses, erosion effects, and soil micro-organism impacts.

TREE GROWTH

Many studies clearly demonstrate that tree growth responds positively to herbicide applications in the South (Bacon and Zedaker 1987; Knowe and others 1985; Nelson and others 1981; Swindel and others In Press). Application mistakes can cause tree mortality, but the vast majority of experience is with successful treatment results. Elimination of competing plants early in a stand's rotation can have significant impact on short-term and long-term productivity (Glover 1985; Michael 1980, 1985; Swindel and others In Press). Plant nutrients are in short supply in many soil types of the South due to past land use abuses or pedogenic factors. The body of information available now indicates that herbicide use can significantly increase forest productivity (Neary and others In Press).

EROSION

Excessive erosion is currently degrading the productivity of many agricultural soils in the South (Larsen and others 1983). Many forest stands in this region were established on sites that were eroded and impoverished by abusive agricultural practices. Our present forests stabilized eroding soils and have been rebuilding productivity over the past 50 - 80 years.

Erosion and soil dislocations within sites have been identified as potential negative impacts on future forest productivity in the South (Neary and others 1984). The litter and surface soil horizons are crucial for the maintenance of site productivity. The bulk of the nutrients that promote good tree growth are found in these surface layers. Any activities which remove or redistribute these horizons can be potentially damaging to forest productivity. Mechanical site preparation (Beasley 1979; Douglass and Goodwin 1980) and burning (Douglass and Van Lear 1980) have been traditionally practiced to remove obstructions, eliminate competition, and prepare sites for planting. However, intensive mechanical site preparation has been identified as a major factor adversely affecting site productivity.

Herbicide use for site preparation, even in steeper terrain, causes very little erosion and maintains good hydrologic conditions. Herbicides do not disturb the soil and usually leave a good litter layer which mitigates raindrop impact, promotes infiltration, and greatly reduces erosion. Examining erosion from a variety of site preparation techniques and locations in the South, it is evident that herbicide use results in sediment yields more similar to undisturbed watersheds than mechanically prepared ones (table 2).

Table 2.--Sediment yields from forest watersheds in the South during the first year after site preparation

		Sediment Loss		
Reference	Treatment	Mass	8 of Control	Physio-graphic Province[1]
		kg/ha		
Neary and others 1986	Control	67	---	P
	Herbicide	170	254	
Douglass and Van Lear 1983	Control	39	---	P
	Burned	44	113	
Douglass and Goodwin 1980	Control	35	---	P
	Kg,Disk,Grass	720	2,057	
	Kg	3,501	10,000	
	Kg,Disk	9,730	28,700	
Beasley 1979	Control	620	---	UCP
	chop	12,540	2,023	
	Shear	12,800	2,065	
	Bed	14,250	2,298	
Beasley and others 1986	Control	1472	---	UCP
	Shear, Wind.	1,005	684	
	Herbicide	205	139	
Riekerk, 1982; and Neary and others 1982	Control	3	---	LCP
	Burn, Bed	7	233	
	Windrow & Bed	36	1,200	

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[1] P = Piedmont; UCP = Upper Coastal Plain: and LCP = Lower Coastal Plain

[2] Second year data used due to very high stormflow

Evidence on erosion clearly points to the benefits of herbicide use in southern forestry. This is true first from the viewpoint of reducing adverse site productivity by maintaining scarce nutrients. It is also true regarding water quality impacts. Sediment is the biggest water quality problem in the region (Larsen and others 19831 and herbicides show a very positive effect (Neary and others 1986).

SOIL ORGANISMS

Does herbicide use adversely affect soil flora and fauna? Certainly the removal of a live vegetation canopy has significant effects on the thermal and moisture regimes of the forest floor and soil horizons. But the resulting changes in soil organisms are due more to physical than chemical effects (Mayack and others 1982).

The micro- and macro-organisms found in the forest floor and soil horizons play very important roles in the functioning of forest ecosystems. They are important in processes such as organic matter decomposition, nutrient mineralization, nitrogen transformations, respiration, soil structure and porosity formation, etc. Overviews of herbicide effects on soil organisms are provided by Eijasackers and van de Bund (1980), Greaves and Malkoney (1980), Greaves and others (1976), and Martin (1963). Although stimulatory as well as inhibitory responses have been observed in micro-organisms, much remains to be learned about the complex interactions between soil organisms and herbicides. Effects are very much dependent on the herbicide, application rate, and soil environment factors. Where adverse effects have been observed, herbicide concentrations exceeded those measured under actual operational conditions (Fletcher and Friedman 1986). There is, however, a general consensus that herbicide usage at normal forestry rates does not reduce the activity of micro-organisms.

CONCLUSIONS: There is no evidence that the herbicides currently used in forest management in the South produce any adverse effects on site and soil productivity. There is substantial evidence that herbicide usage as a .silvicultural tool can increase site productivity.

WATKR QUALITY

The occurrence and significance of herbicide residues in surface waters result from a complex set of factors. Occurrence depends on the type and location of surface water, mixing and dilution of streamflow, herbicide properties such as solubility and degradation potential, method and timing of application, timing and amount of rainfall, site characteristics, and soil properties. The biological significance of a residue concentration depends upon water usage, toxicity levels, and exposure. The legal significance depends upon water quality standards.

OCCURRENCE

The concentrations of herbicides in surface waters depend largely on the type of water and location in relation to the application area. Streams generally have the most variable concentrations, and surface flow from first-order drainages contains the highest residue concentrations. Streams receiving herbicide residues in flow from ephemeral channels generally have concentrations one to two orders of magnitude higher than those receiving only subsurface flow. Wetlands close to treatment areas may contain higher residue levels because of their small size and lack of flushing. Herbicide concentrations in lakes depend on residue inputs, lake size, and recharge by ground water or streamflow.

Mixing and dilution are very important in determining amount and duration of herbicide residues in surface waters. Neary and others (1983) measured hexazinone concentrations that averaged 0.442 ppm (mg/L) in stormflow from 2.5 ac (1 ha) ephemeral watersheds, but were less than 0.002 ppm during the same storm downstream at a 250 ac (100 ha) watershed. This resulted in an actual dilution factor of 221 compared to a straight area ratio of 100. Within large watersheds (50,000 ac or about 20,000 ha) entirely under intensive silviculture, dilution factors for forestry herbicide residues could range from 30 to 45,000 times. The former value is a straight area ratio based on herbicide treatment of each unit area of land once in a 30 year rotation. The latter value is based on only one unit area (1 ha or 2.5 ac) of the large watershed being treated with one particular herbicide and application of the field-measured dilution factor (221).

Herbicide properties such as use rate, solubility, adsorption coefficient, and half-life are very significant in determining the amounts of residues which enter into surface waters. Herbicides with a typical use rate of greater than 4.0 kg/ha (greater than 3.6 lb/ac) are more likely to be detected in surface flow than those used at less than 0.40 kg/ha (less than 0.36 lb/ac). Solubility is a general index of potential to move in water, but there are exceptions. Positively charged glyphosate is highly soluble in water but generally does not move off-site to any appreciable extent since it is quickly adsorbed to organic matter in the soil and immobilized. Negatively charged picloram is highly soluble and easily mobile. Although picloram can be adsorbed to the soil it is readily desorbed and mobilized. A herbicide like sulfometuron methyl, with a short half-life of less than 10 days, is less likely to move into surface water than tebuthiuron (half-life of 392 days)(table 1). Herbicides subject to photodegradation are also less likely to be found in surface water.

The method and timing of applications is extremely important. Generally, the risk of water pollution is less with ground applications than aerial ones, and granular formulations are easier to control than liquid formulations. The type of equipment.. used and the timing in relation to climatic and vegetation--variables are also critical.

Rainfall timing, amount, and intensity affect herbicide concentrations in streamflow. These effects are very much a result of the type of hydrologic response (surface runoff versus subsurface flow). Very large storms (greater than 25 year return period) generally do not result in high herbicide concentrations because of dilution by large flow volumes. Likewise, small storms (less than 1 month return period) may not produce sufficient stormflow. It is the intermediate storms that produce the higher concentrations.

Site characteristics like topography, treatment-area size in relation to watershed area, and distance to nearest perennial stream are other factors affecting occurrence of herbicide residues in surface waters. Soil characteristics are also important. Organic matter is the most important factor. Soils high in organic matter have a large potential to retain herbicide residues in an adsorbed condition while soils low in organic matter like sands have a low capacity to hold herbicide residues within the soil profile.

SIGNIFICANCE

If herbicide residues enter surface or ground water, their significance is determined by residue duration, water usage, chemical toxicity, and potential exposure of humans, animals, or plants. For many herbicides there are no water quality standards because of their low toxicity, the infrequency of their occurrence in drinking water supplies, and the *recent* nature of their use in forests. Herbicides such as 2,4-D (0.100 ppm) and picloram (1.050 ppm) have established drinking water quality standards (NRC 1983).

One important issue to consider is the distinction between contamination and pollution. All water is contaminated. That is, no surface or ground water is pure. All water contains varying levels of other elements or compounds. On the other hand, water is normally considered polluted only when concentrations of contaminants exceed a water quality standard and threaten some use of the water. In the case of herbicide residues in water, the scientific contamination/pollution distinction often conflicts with individual perceptions of risk. As analytical instrumentation and techniques improve, herbicide residues are being measured at lower concentrations. Detection of herbicide residues, other compounds, or elements does not imply that pollution has occurred or that a health risk exists. Thus, objective evaluations of the significance of short-duration, low-level concentrations of herbicides in water must be made.

HERBICIDE RESIDUES IN SURFACE WATERS

The remainder of this section will discuss the occurrence of herbicide residues in surface water. Data from the South will be used where they are available. References from other forest ecosystems will be used to augment these data where information on particular chemicals is lacking.

2,4-D: This is one of the phenoxy herbicides that functions as a plant growth regulator. Since its introduction into forestry in the late 1940's, it has become the most widely used and intensively studied forestry herbicide still in use (Norris 1981a). A large variety of formulations are available commercially (Sassman and others 1984). Salt formulations are readily absorbed through the roots of weeds, and ester formulations are most easily absorbed through the foliage.

Toxicological studies indicate that most formulations are mildly toxic to mammals and birds (table 1). 2,4-D does not bioaccumulate to any appreciable extent. It is highly soluble in water and is translocated and metabolized readily within plants. Persistence of 2,4-D in forest soils is rather short (less than 4 weeks) as it is degraded by microbes, translocated into plants, and photodegraded to a limited extent (Norris 1981b). Volatilization is dependent on formulation. Transport losses from soils to water are mediated by organic matter, low surface runoff in most forest soils, and moderately rapid microbiological degradation.

A review of 2,4-D residues in water after forestry applications in the Pacific Northwest indicated that 90 percent of the streamflow samples contained no 2,4-D and the remainder had an average concentration of less than 0.040 ppm (Sassman and others 1984). 2,4-D was applied to all but a narrow (less than 5 m) buffer strip of Watershed 6 (9 ha or 22 ac) at the Coweeta Hydrologic Laboratory in western North Carolina (Douglass and others 1969). Application of 3.4 kg/ha (3.0 lb/ac) in 760 L of water carrier by a ground spray system did not result in any detectable 2,4-D in the stream.

Throughout the South, 2,4-D is used for injection of hardwood stems. This application method is less hazardous than spraying and is the commonest 2,4-D application method in national forests. A recent operational monitoring of 2,4-D injections in Alabama, Georgia, Tennessee, and Kentucky did not detect residues of this herbicide in streamflow from treated watersheds. In most of these applications, minimum buffers of 9.1 m (30 ft) were maintained.

2,4-DP: This herbicide is also a phenoxyacetic acid chemical and very closely related to 2,4-D (Norris 1981a). It is available in a variety of formulations like 2,4-D but is less soluble and degrades faster (table 1). There is virtually no information on the fate of 2,4-DP residues in forest watersheds in the South.

DICAMBA: This herbicide is a benzoic acid derivative used as a pre- and post-emergence treatment on broad leaved weeds and brush resistant to phenoxy compounds. It is available in several formulations including water soluble salt and granular formulations. Dicamba is readily absorbed by leaves and roots and translocated within plants. It is an auxin-like growth regulator for plants but is only slightly toxic to aquatic and terrestrial animals (table 1). Dicamba does not bioaccumulate nor photodegrade, but is readily metabolized by plants and micro-organisms (Smith and Cullimore 1975). It has a moderate half-life in soil (table 1).

Because of its high solubility and low soil adsorption (table 1), dicamba is a fairly mobile herbicide (Norris and Montgomery 1975). Spray application of 1.12 kg/ha (1.0 lb/ac) to about 25 percent of a watershed in Oregon produced a maximum stream concentration of only 0.037 ppm which was attributed to spray drift. Concentrations of dicamba in streamflow did not persist much beyond 2 days. Other studies have only measured low (less than 0.001 ppm) and infrequent concentrations of dicamba. Micro-organisms in water are very important in dicamba dissipation in surface waters (Scifres and others 1973). As with 2,4-DP there is virtually no information on dicamba movement in forest watersheds of the South. Based on data from the Pacific Northwest, dicamba residues would not be expected to be very high nor persist long because of microbiological activity (Norris 1981b).

FOSAMINE: This herbicide is a selective chemical that is absorbed, translocated, and metabolized within plants. Fosamine does not photodegrade, but degrades rapidly in soil due to microbial activity (table 1). Its short half-life is a function of rapid micro-organism metabolism and strong adsorption in soils. Fosamine does not bioaccumulate because of the ease and speed with which it is metabolized. In water, fosamine is subject to adsorption onto sediments and rapid micro-organism attack. There is virtually nothing in the literature to indicate expected fosamine concentrations in surface waters under operational use conditions, and no data exist for southern forest watersheds.

GLYPHOSATE: This is a broad spectrum herbicide that is very effective on a number of forest weed species. The isopropylamine salt formulation is soluble in water, but glyphosate is strongly adsorbed in the soil (table 1). This herbicide is readily absorbed and translocated within plants but is not metabolized. The major degradation pathway is microbial breakdown in the soil although varying rates result in a longer half-life than some of the other herbicides (table 1). Glyphosate does not photodecompose to any extent and does not volatilize (Rueppel and others 1977). It is low in toxicity to aquatic and terrestrial organisms.

Glyphosate residues up to 5.2 ppm have been measured in runoff from agricultural fields with high transport of sediment. Residues in canals from weed control with glyphosate on ditchbanks were considerably lower (0.010 ppm) (Sacher 1978). Aerial application of glyphosate to a forested watershed resulted in low initial concentrations in streamflow (0.070 ppm). No buffer strips between the perennial stream and the herbicide-treated area were used. A peak concentration of 0.550 ppm occurred 14 days after application with a rapid decline in concentrations because of micro-organism degradation (Newton and-others 1984). No data are available from applications in southern forest watersheds.

HEXAZINONE: Hexazinone is a selective triazine herbicide that controls many annuals and perennials. It is a very effective and widely used forestry herbicide because many conifers can tolerate it at rates that control competition. Granular and liquid formulations are available.

Hexazinone is practically non-toxic to aquatic and terrestrial organisms and established toxicity thresholds are not experienced in the environment (table 1). Since hexazinone is readily soluble in water , it is susceptible to off-site movement by surface runoff and leaching. It is degraded by microbial action and photodecomposition (Rhodes 1980). Hexazinone is not prone to loss by volatilization. Its half-life is generally less than 30 days, but varies between 2 weeks and 6 months, depending on soil and climatic conditions. Some phytotoxic metabolites are produced by microbial degradation but they are generally short-lived.

Hexazinone fate and transport in southern forested watersheds is better documented than any of the other herbicides. Miller and Bace (1980) reported high concentrations (up to 2.400 ppm) from direct fall of hexazinone pellets into a perennial stream. The pellets were accidentally dropped when a helicopter overflew a streamside buffer zone on one pass. Concentrations fell within 24 hours to 0.110 ppm and by 10 days were down to less than 0.010 ppm. In another aerial application in Tennessee, pellets were applied to less than 20% of a large watershed but no streams were overflown (Neary 1983). Consequently, hexazinone was never detected in streamflow during a 7 month period following application.

In a more detailed study in the upper Piedmont of Georgia, four small ephemeral watersheds (1.0 ha or 2.5 ac) were broadcast-treated with hexazinone pellets at a rate of 1.68 kg/ha (1.5 lb/ac) (Neary and others 1983). For the next year surface runoff from 26 storms was collected to determine hexazinone transport in streamflow. Residues peaked in the first storm (0.442 ppm) and declined steadily thereafter. Loss of hexazinone from the treated sites averaged 0.53 percent with two storms accounting for nearly 60 percent of the off-site transport. subsurface movement in baseflow occurred 2 months after the hexazinone pellet application, lasted for less than 2 weeks, and produced a short-term pulse with a peak of 0.024 ppm.

Hexazinone was applied to a 11.5 ha (28 ac) watershed in Arkansas as a liquid spot application with somewhat different results (Bouchard and others 1985). The application rate for this study was slightly higher than in the Georgia study, but the ephemeral channels were not treated. As a result, hexazinone residues were never detected in surface storm runoff. Baseflow from this watershed continued to carry low levels of hexazinone (less than 0.014 ppm) for over a year. Similar concentrations (0.006 to 0.036 ppm) were measured in streamflow in another set of spot treatments in Alabama and Georgia.

IMAZAPYR: This herbicide is new to southern forestry. Imazapyr comes from the imidazolinone family of chemicals and is a very effective, broad-spectrum herbicide. It is practically non-toxic to aquatic and terrestrial organisms (table 1). Imazapyr has a low adsorption coefficient and intermediate half-life of 19-34 days. It is degraded by micro-organisms, photodecomposes, and does not bioaccumulate. Imazapyr is readily absorbed through foliar and root surfaces and easily translocates to meristem tissues.

Application of imazapyr by air to 40 to 121 ha (99 to 299 ac) watersheds in Alabama produced peak streamflow concentrations of 0.130 ppm where a streamside management zone was employed (Michael 1986). However, this concentration lasted less than 4 hours, and daily average peak stream concentrations did not exceed 0.030 ppm. In 180 days of monitoring after treatment only 4 of 184 stream samples contained quantifiable residues of imazapyr.

Imazapyr half-life was determined in treated vegetation and soil in Alabama. The half-life for vegetation under field conditions ranged from 12 to 35 days and in soil from 19 to 34 days.

LIGHT FUEL OIL: There are no data in the literature on the concentrations and movement of light fuel oil in forested watersheds of the South.

PICLORAM: This herbicide belongs to the picolinic acid family of chemicals and functions similarly to the phenoxyacetic acid herbicides in mimicking growth hormones. It is very effective on many resistant woody weeds (NRCC 1974) and is used most frequently as a salt formulation in combination with 2,4-D.

Picloram and its salts are relatively nontoxic to most non-target organisms including micro-organisms, fish, and birds (table 1). Since picloram is formulated as a potassium or isopropanolamine salt, it has a high water solubility. That combined-with a relatively low adsorption coefficient makes water contamination a concern with the use of piclotam. This is particularly-the case since many vegetable crops are sensitive to picloram at concentrations as low as 0.010 ppm (Baur and others 1972).

Losses of picloram due to volatilization are low and photodegradation occurs only in direct sunlight. Picloram is only slowly degraded by micro-organisms which is why it has one of the longer half-lives (table 1). Half-life of picloram is climate and soil dependent and can be as short as 30 days in humid-warm climates and as long as 180 days in cold-dry ones (NRCC 1974).

Picloram concentrations in streamflow have been studied extensively in a number of ecosystems (NRCC 1974). Applications to rangelands in Texas have produced peak concentrations of up to 2.170 ppm. usually this involves surface runoff shortly after application with no buffer strip.

Picloram was manually broadcast at a rate of 5.0 kg/ha (4.5 lb/ac) to 17% of a 30 ha (74 ac) watershed in the Appalachian Mountains (Neary and others 1985). Residues of the herbicide were measured in soil solution on the treatment site at concentrations up to 0.350 ppm. A 100 m (328 ft) buffer strip between the application area and a first-order perennial stream reduced picloram concentrations down to sporadic peaks of less than 0.010 ppm during 17 months of monitoring.

Picloram pellets were also applied to an Upper Coastal Plain site in Alabama. On that watershed, picloram was applied at a slightly higher rate by air (Michael and others 1987). Buffer strips for perennial streams were established but demarcation difficulties resulted in some of the stream areas being overflown. Streamflow at site of the overflight contained a maximum of 0.241 ppm. Picloram concentrations downstream were diluted down to a maximum of 0.077 ppm but persisted for over 475 days in the 0.020 to 0.030 ppm range.

SULFOMETURON METHYL: This herbicide belongs to the substituted-urea class of chemicals. It is very low in toxicity to aquatic and terrestrial organisms. Sulfometuron methyl is readily absorbed and translocated by roots and foliage. Its solubility in the soil is pH dependent, decreasing as acidity rises. Hydrolysis and microbial metabolism are the major degradation pathways which produce a short half-life (Anderson and Dulka 1985). Sulfometuron methyl is available in two formulations, and applied at very low rates (approximately 0.2 kg/ha or 4 oz/ac).

Sulfometuron methyl is a fairly new herbicide. Its environmental fate has been studied at two sites in the South (Michael and Neary 1987). The herbicide was applied as water-dispersible granules and pellets to large (450 ha) watersheds in Mississippi, and small (4 ha) watersheds in Florida. A 15-m (49 ft) streamside, buffer strip was used in the Mississippi study and a 5-m (16 ft) one in Florida. At both sites, residues of this herbicide in streamflow were intermittent and did not persist beyond 7 days (Florida) to 63 days (Mississippi). The long persistence in Mississippi was attributed to low soil temperatures at the time of application which slowed hydrolysis and microbial degradation. Most movement of sulfometuron methyl occurred during the first two storms and the herbicide was not detectable beyond 150 m downstream. The peak concentrations were very low at 0.007 ppm (Florida) and 0.044 ppm (Mississippi).

TEBUTHIURON: Tebuthiuron is another herbicide belonging to the substituted-urea group. Unlike sulfometuron methyl, it has a very long half-life (table 1) and is more strongly adsorbed in the soil. Tebuthiuron accumulates in plants where it is subject to metabolic breakdown. It leaches slowly in the soil due to its lower solubility and its adsorption tendency. In water, tebuthiuron does not hydrolyze, and photodegradation losses are negligible.

The movement of tebuthiuron in surface water has been studied mainly on grasslands of the southwest. Its transport and appearance in streamflow is a function of sediment movement since the herbicide is strongly adsorbed onto soil surfaces. A study of tebuthiuron movement (Sassman and Jacobs 1986) reported a peak streamflow concentration of 0.180 ppm from a 2.2 kg/ha (2.0 lb/ac) application, but residues were still detectable at low levels (0.007 ppm) 2 years later. Bovey and others (1978) simulated rainfall on small plots and produced a runoff concentration of 2.230 ppm after application of the same rate of tebuthiuron. However, after 3 months concentrations were down to 0.040 ppm and were not detectable after 13 months. Emmerich and others (1984) reported low amounts of tebuthiuron loss (less than 0.5 percent) from rangelands in Arizona. There are no data available on tebuthiuron movement elsewhere in forested watersheds.

TRICLOPYR: This herbicide is a picolinic acid compound available in amine salt or ester formulations. It is readily absorbed by roots and foliage and translocates easily to meristems. Triclopyr is metabolized by bacteria and photodegrades rapidly. Its half life is less than 10 hours in water but it is more persistent in soils (table 1). It is moderately soluble and not strongly adsorbed in the soil, but studies indicate that it should not be a leaching problem under normal use (Lee and others 1986). Triclopyr, like most of the other forestry herbicides, is low in toxicity to wildlife and fish.

In a West Virginia study, triclopyr applied at a rate of 11.2 kg/ha (10 lb/ac) to small watersheds resulted in peak streamflow concentrations of only 0.080 ppm (McKellar and others 1982). Triclopyr was applied to small watersheds (4 ha or 10 ac) in Florida in both the amine (2.0 kg/ha or 1.8 lb/ac) and ester (1.6 kg/ha or 1.4 lb/ac) formulations. Buffers of 5 m were left next to ephemeral stream channels. Monitoring of streamflow for 5 months following application did not detect any residues of triclopyr (Neary and others 1987).

HERBICIDE RESIDUES IN GROUND WATER

Contamination of ground water has become a national priority environmental issue in the past few years because of growing incidents of herbicide residues being detected in wells. In most of the South, rural residences depend on ground water for a water supply. Also, significant areas of the Coastal Plain utilize ground water for major municipal water sources. For the region as a whole, 98 to 100 percent of the rural population relies on ground water while 14 to 89 percent of the urban population does (Canter and others 1987). Thus it is important to address the issue of potential ground water pollution from operational use of forestry herbicides.

In general, forestry herbicides pose a low pollution risk to ground water because of their use pattern. Herbicide use in forestry is only 10 percent of agricultural usage and likely to occur only once or twice in rotations of 30 to 100 years. Application rates are generally low (less than 2 kg/ha) and animal toxicities are low. Some of the silvicultural herbicides can affect non-target plants at low concentrations (less than 0.020 ppm) and could affect water quality for irrigation. Within large watersheds where extensive ground water recharge occurs, intensive use of silvilcultural herbicides would occur in a dispersed pattern on less than 5% of the area in any one year. Thus the potential for dilution of herbicide residues is enormous.

Regional, confined ground water aquifers are not likely to be affected by forestry herbicides (Neary 1985a). Unconfined surface aquifers in the immediate vicinity of herbicide application zones have the highest risk of contamination. These aquifers are directly exposed to leaching of residues from the root zone. Discussion will focus on these surface aquifers.

SOURCES: In the operational use of silvicultural herbicides there are two types of sources of herbicide contaminants in ground water. These are point sources which occur as a result of spills in the transportation, storage, mixing, and loading phases of herbicide use. Point source pollution is a hazard with the use of any chemical not just forestry herbicides, and accounts for some of the worst cases of localized ground water pollution. During and after the application of herbicides in forest ecosystems, movement of residues into ground water could occur on a landscape scale. This type of pollution is non-point in nature and will be the focus of this discussion.

The data base on ground water contamination from forestry herbicide use in the South is very limited. Few studies have focused on the non-point source aspect of forestry herbicide fate and transport. Also, because of the infrequent use, and low application rate of forestry herbicides, few aquifer contamination problems have arisen from operational application of forestry herbicides. Some information for typical operational conditions is available for hexazinone, picloram, sulfometuron methyl, triclopyr, and 2,4-D. All of these data are from unconfined surface aquifers within 1 to 6 m (3 to 20 ft) of the soil surface.

HEXAZINONE: In a study in the Georgia Piedmont, this herbicide was applied in a pellet formulation at a rate of 1.68 kg/ha (1.5 lb/ac) to four small (lha) first-order watersheds (Neary and others 19831. Subsurface movement of hexazinone in baseflow was detected 3 to 4 months after application of the herbicide during dry weather. concentrations of ground water entering perennial stream channels were very low (less than 0.024 ppm), and were short in duration (less than 30 days). The peak hexazinone concentration was 25 times lower than one suggested water quality standard for hexazinone (0.600 ppm; Leitch and Flinn 1983), and 20 percent of a published Health Guidance Level for agricultural chemicals in ground water (0.125 ppm; NACA 1985). These hexazinone concentrations were never high enough to adversely impact even the most sensitive aquatic species much less higher organisms (Mayack and others 1982).

In an Arkansas study, hexazinone was applied as a liquid formulation in a spot treatment (2.0 kg/ha) to an 11.5 ha watershed (Bouchard and others 1985). Hexazinone residues were measured consistently in ground water entering perennial stream channels as baseflow for over a year after the application. But concentrations never exceeded 0.014 ppm and were below a suggested water quality standard by a factor of 42.

PICLORAM: Use of this herbicide at low rates (less than 1.0 kg/ha) with 2,4-D for injection has not produced any significant ground water contamination. Monitoring of a number of watersheds in Georgia, Tennessee, and Alabama did not detect picloram residues in baseflow originating from shallow ground water. Application of 5.0 kg/ha (4.5 lb/ac) of picloram as a pelleted formulation for site preparation was monitored in the Appalachian Mountains (Neary and others 1985). Picloram residues were detected in baseflow which fed a spring system of a first-order watershed for only 18 days and were less than 0.001 ppm. Infrequent and short duration pulses of picloram (less than 0.010 ppm) occurred over a 17-month period in a 10 ha (25 ac) first-order perennial stream. Peak concentrations were 1 percent of the suggested drinking water standard, 'but close to levels which might affect sensitive agricultural crops. In-channel dilutions between the treated watershed and any potential irrigation intakes were of such a large magnitude to preclude deterioration in irrigation water quality.

SULFOMETURON METHYL: A study of sulfometuron methyl impact on shallow ground water was recently completed in the Coastal Plain of north Florida (Michael and Neary 1987). Application of 0.42 kg/ha (0.37 lb/ac) active ingredient by ground spray and granule spreading systems to two flatwoods watersheds did not affect ground water quality. Samples were collected from 14 wells for a year. Water in this highly sensitive ground water system (less than 1 m below the ground surface) never contained detected herbicide residues. The rate of sulfometuron methyl application was relatively low compared to other forestry herbicides, but high for this particular chemical.

TRICLOPYR: Another study of herbicide residue fate and movement into shallow ground water was conducted in the Coastal Plain flatwoods. Triclopyr was applied to small watersheds (4 ha - 10 ac) in both the amine (2.0 kg/ha or 1.8 lb/ac) and ester (1.6 kg/ha or 1.4 lb/ac) formulations. Monitoring of 14 surface ground water wells for 5 months following application did not detect any residues of triclopyr (Neary and others 1987).

OTHER HERBICIDES: Ground water data on the other herbicides analyzed in this environmental impact statement are not available for typical forestry situations. Additional research is planned to fill these data gaps. The topic of ground water contamination by pesticides has become a national priority research issue. Most problems have resulted from repeated applications of agricultural pesticides. Based on the limited forestry data, which include a very soluble chemical applied at a high rate (picloram), normal use of the'other herbicides should not pose a ground water contamination problem much less a pollution one.

SUMMARY AND CONCLUSIONS

This paper has examined the patterns and types of herbicides used on national forests in the South. These forest ecosystems often overlie major ground water recharge zones and contain streams often used for domestic water supplies. We have discussed the limited herbicide fate and movement data from typical forestry uses to indicate some of the potential impacts on water quality. The following conclusions can be made regarding the impacts of silvicultural herbicides on the quality of surface waters and ground water:

1. The majority of herbicide use in intensive forestry will involve low-toxicity chemicals applied infrequently (once or twice in 30- to 100-year rotations) over extensive land areas.

2. Current herbicide application technology exists to minimize herbicide residue movement into sensitive surface waters. Short-duration-residue concentrations of 0.5 to 1.0 ppm might occur during stormflow. On-site degradation processes and in-stream dilution and degradation result in quick dissipation of herbicide residues. Short-term water quality effects are minimal, and long-term water quality is not adversely affected. Long-term water quality can be improved by herbicide use since stream sedimentation is reduced.

3. Site productivity in southern forests can be increased significantly by herbicide use. There is no documentation or indication of adverse biological effects from use of the silvicultural chemicals, examined in this environmental impact statement.

4. At currently registered herbicide application rates, some short duration, low level (less than 0.024 ppm) pulses of herbicide residues could enter unconfined surface aquifers. Detectable residues would not persist for a long time and would not be likely to exceed water quality standards. Contamination of regional ground water aquifers is not likely with even intensive operational use of silvicultural herbicides.

5. The greatest hazards to surface and ground water quality arise from a possible accident or mishandling of concentrates during transportation, storage, mixing and loading, equipment cleaning, and container disposal phases of the herbicide use cycle.

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