HERBICIDES—PROTECTING LONG-TERM SUSTAINABILITY AND WATER QUALITY IN FOREST ECOSYSTEMS

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ABSTRACT

World-wide, sediment is the major water quality problem. The use of herbicides for controlling competing vegetation during stand establishment can be beneficial to forest ecosystem sustainability and water quality by minimising off-site soil loss, reducing on-site soil and organic matter displacement, and preventing deterioration of soil physical properties. Sediment losses from sites where competing vegetation is controlled by mechanical methods can be 1 to 2 orders of magnitude greater than natural losses from undisturbed watersheds. On a watershed basis, vegetation management techniques in general increase annual erosion by <7%. Herbicides do not increase natural erosion rates. Organic matter and nutrients that are critical to long-term site productivity can be removed off-site by mechanical vegetation-management techniques and fire, or redistributed on-site in a manner that reduces availability to the next stand.

For several decades, research has been conducted on the fate of forestry-use herbicides in various watersheds throughout the southern and western United States, Canada, and Australia. This research has evaluated chemicals such as 2,4-D, glyphosate, hexazinone, imazapyr, metsulfuron methyl, picloram, sulfometuron methyl, tebuthiuron, and triclopyr. Losses in streamflow, and leaching to groundwater have been evaluated. Field study data indicate that residue concentrations tend to be low, except where direct applications are made to ephemeral channels or streams, and do not persist for extended periods of time. Regional environmental impact statements in the United States demonstrate that forestry herbicide presence in surface and groundwater is not a significant risk to water quality or human health. They also clearly indicate that herbicides can greatly reduce water quality deterioration that is produced by erosion and sedimentation.

Keywords: herbicides; sediment; water quality; environment; site productivity; forestry; vegetation control.

INTRODUCTION

A critical component of inter-rotation forest management is the manipulation of successional vegetation to ensure adequate survival and growth of the next forest crop.

Techniques such as manual removal, mechanical control, prescribed fire, and herbicide application have been used to reduce competition from undesired vegetation. Herbicides have been incorporated into vegetation management programmes on intensively managed forests more frequently in the past two decades (USDA Forest Service 1989a, b, 1990).

In many countries with intensive forestry programmes, considerable controversy has developed concerning the environmental impacts of herbicides. Human health risks of commonly used forestry herbicides and other vegetation management techniques have been addressed by several intensive environmental impact analyses (USDA Forest Service 1989a, b, 1990). On- and off-site impacts on water quality continue to be the subject of much debate and scientific analysis (Norris 1981; Neary *et al.* 1993). Other important parameters of water quality such as sediments and nutrients have been mostly ignored in the continuing focus on herbicide residues. Indeed, the major water quality problem in areas with intensive forest management is sediment, not herbicides (Marion & Ursic 1993; Neary & Hornbeck 1994).

Another issue relating to forest harvesting, vegetation management, and the choice of techniques for manipulating forest vegetation to enhance productivity, is long-term sustainability (Dyck & Skinner 1990; Powers *et al.* 1990). Kimmins (1994) and Neary *et al.* (1990) identified some of the key processes affecting long-term site productivity. These include adequate root system development, sufficient soil moisture availability to maintain nutrient flux to tree root systems, suitable supplies of plant macro- and micro-nutrients in the rhizosphere, fully functioning microbiological processes, and adequate hydrological functioning. Some vegetation management techniques can adversely affect site organic matter reserves, nutrient pools, and soil physical properties. Improperly used vegetation management techniques can effectively displace up to five times the amounts of nutrients removed in whole-tree harvesting (Ballard 1978; Morris *et al.* 1983). This situation occurs when organic matter and topsoil are concentrated into small portions of inter-rotation stands treated to control unwanted vegetation.

Several hypotheses can be formulated about the role of herbicides in forestry. They are considered by some sectors of international environmental interest groups to be agents of environmental degradation. Arguments can be made that they produce neither positive benefit nor adverse impact. Another hypothesis is that the proper use of herbicides actually has a positive role in protecting environmental quality. Herbicide usage during inter-rotation vegetation management of forest stands can do this by maintaining the commercial sustainability of forest ecosystems and protecting water quality. The objective of this paper is to synthesise scientific information on both forest ecosystem sustainability and water quality, focusing on the role of herbicides in keeping soil resources on-site without degrading water quality.

METHODS AND MATERIALS

This paper is a synthesis of many publications dealing with herbicide residue fate, erosion and sedimentation, vegetation management, soil physical conditions, and nutrient distributions in forest ecosystems. Standard hydrological, soil physics and chemistry, erosion, vegetation management, and herbicide residue methodologies were used in the conduct of the research reviewed in this paper. A detailed discussion of the specific methods and materials can be found in the references cited in this synthesis.

RESULTS AND DISCUSSION

Sustainability

The concept of sustainability used in this paper only addresses whether a site can supply sufficient water and nutrients to support successive rotations of commercial forest stands. Forest ecosystem sustainability is a much broader concept that encompasses the entirety of the fauna and flora and associated ecological process occurring within forests. A narrow definition of sustainability was selected because of the forum at which this paper was presented.

Trees require adequate supplies of nutrients and water to grow, and roots need a well-structured soil to develop large enough systems to support that growth (Neary *et al.* 1990). So, the keys to long-term sustainability are organic matter, nutrient supply, soil hydrologic function, and soil physical conditions (Powers *et al.* 1990). Detrimental changes in the status of any of these site characteristics can cause a decline in forest productivity.

In most intensively managed forests, some form of site preparation is practised to improve microsite condition, control competing vegetation, or reduce logging slash to facilitate planting (Crutchfield & Martin 1982). However, it may produce adverse effects on site characteristics which control productivity. Intense fires can consume much of the residual organic matter in slash, litter, and the mineral soil, volatilising nitrogen and leaving nutrient-rich ash susceptible to water or wind transport off-site (DeBano & Conrad 1978; Neary *et al.* 1978). Soils left bare by hot fires increase surface run-off and often develop water-repellent horizons, thereby making sites erosion-prone and drier (DeBano 1981). Mechanical site preparation can redistribute organic matter, effectively removing from seedlings many times more nutrients than whole-tree harvesting (Neary *et al.* 1984; Balneaves *et al.* 1991). Soils are often left bare and susceptible to surface run-off and erosion. Additional machinery passes can increase bulk density in susceptible, mainly fine-textured soils, significantly reducing both rooting volume and available moisture-holding capacity. Herbicides do not produce the adverse effects associated with severe fire and mechanical site preparation, and therefore work to minimise impacts on site productivity and forest sustainability (Neary *et al.* 1990). Herbicide applications to control competing vegetation do not disturb the nutrient-rich litter layer, do not create additional amounts of bare soil, and do not adversely affect watershed condition. Among other things, soils on recently harvested sites treated with herbicides have better moisture contents due to the reduction of surface run-off and the transpiration component of evapotranspiration. These soils are better able to supply the nutrients needed for early growth of the succeeding forest crop (Carter *et al.* 1984; Neary *et al.* 1990; Smethurst *et al.* 1993).

Direct evidence of declines in forest stand sustainability due to inter-rotation site preparation and vegetation managment is scarce because intensive inter-rotation forestry/ management is relatively recent and there is a lack of good long-term databases (Powers *et al.* 1990). Productivity declines of 20% to 30% due to mechanical site preparation (Ballard 1978; Swindel *et al.* 1986; Powers *et al.* 1988; Fox *et al.* 1989; Dyck & Skinner 1990) and fire (Keeves 1966; Squire *et al.* 1985) have been documented. Increases in the productivity of pine stands after herbicide use in the south-eastern United States have been noted by Michael (1980), Knowe *et al.* (1985), Neary *et al.* (1990), Bramlett *et al.* (1991), and Lauer *et al.* (1993). Balneaves *et al.* (1991) reported similar results from New Zealand. A few aspects of the sustainability question relative to organic matter, soil physical conditions, and nutrient supply will be discussed here. Two other papers (Powers *et al.* 1995; Powers &Ferrell 1996) cover these topics in more detail.

Organic matter and nutrient supply

Powers *et al.* (1990) discussed the importance of organic matter to forest productivity through its function of supplying nutrients, augmenting cation exchange capacity, improving soil structure, and chelating metal cations. After harvesting, the main losses of organic matter result from decomposition, erosion, oxidation in fires, residue displacement by mechanical site preparation, or a reduction in new organic matter recruitment (litterfall, fine root turnover, etc.). Since organic matter in the forest floor and surface horizons of the mineral soil is the major nutrient reservoir in forest ecosystems, especially for nitrogen and boron (McColl & Powers 1984), additional losses during vegetation management are a concern.

Fire can have a major effect on organic matter, depending on its intensity and duration. Organic matter oxidation in fires not only affects nutrient pools, but can also affect soil moisture that is critical for ion flux to plant roots, nitrogen fixation, and mycorrhizal development (Jurgensen *et al.* 1990; Neary *et al.* 1990).

The main effect of mechanical site preparation relative to organic matter is displacement in windrows or slash piles, or erosional losses. The impact of site preparation on nitrogen balances in Coastal Plain and Piedmont sites of the south-eastern United States is illustrated in Table 1. Organic matter displacement in windrows can have a major effect on nitrogen balances. Ballard (1978) reported a 16% reduction in the volume of a second-rotation *Pinus radiata* D.Don stand on the central volcanic plateau of New Zealand after piling of logging slash and topsoil into windrows. Balneaves *et al.* (1991) documented that root raking, piling of slash, and burning in the Nelson district of New Zealand removed greater quantities of nitrogen and some macronutrients from portions of *P. radiata* sites than harvesting of saw- and chip-log material.

TABLE 1–Effects of stem harvest, vegetation management, and fertiliser in the south-eastern United States on nitrogen balances (Mg/ha) after 15 years (from Neary *et al.* 1984, 1990)*.

Site preparation	Coastal Plain Flatwoods	Piedmont Wet Flats	Piedmont Uplands
Chop, Herbicide	+0.123	+0.147	+0.106
Chop, Burn	+0.063	+0.083	+0.045
Windrow (careful)	–0.222	–0.058	–0.264
Windrow (careless)	–0.449	–0.674	–0.354

* Assumes application of 0.200 Mg N/ha (50% ecosystem recovery), atmospheric inputs (0.005 Mg/ha/year), and fixation (0.001 Mg/ha/year); nutrients displaced by windrowing considered unavailable.

In combination with residual slash chopping, herbicides have the least impact on nitrogen pools after 15 years (Table 1). Although herbicides do not directly affect organic matter status, they can result in some nutrient losses via leaching and run-off by reducing the amount of successional vegetation available to take up nutrients released through mineralisation processes. This effect is visible in increased nitrate-nitrogen losses sometimes measured after herbicide applications for vegetation management after harvesting. This topic is discussed in more detail in the section on water quality.

Soil physical conditions

Vegetation management techniques can alter the physical characteristics of soils and in turn affect both hydrologic function and site productivity. Fires can leave soils bare of forest floor material and therefore subject to raindrop impact, run-off, and erosion. In some soils and vegetation types, hydrophobic layers develop, causing excessive run-off and erosion (DeBano 1981). Mechanical site preparation can have variable effects on soil physical conditions (i.e., increasing porosity and infiltration rates in some locations and decreasing them elsewhere through compaction) depending on soil textures and moisture, preparation techniques, the type of equipment, and the skills of operators. Vegetation control by mechanical methods usually leaves larger areas of bare soil than harvesting, thus increasing the amount of run-off and erosion. Compaction associated with vehicle traffic on clay or silt-textured soils, during either harvesting or site preparation, reduces soil macroporosity. The result is reduced rooting volumes and moisture storage capacity. Both affect the ability of plants to obtain water and nutrients necessary to sustain productivity, thus reducing growth in the subsequent rotation. However, on sites with extremely coarse-textured soils the opposite effect can occur. Herbicides do not increase the amount of bare soil, and except for some compaction from ground application equipment, do not adversely affect soil physical properties.

Soil displacement

Large amounts of the forest floor and nutrient-rich surface soil horizons can be displaced during mechanical site-preparation. Although this material is not removed off-site, displacement into windrows or slash piles can result in net nutrient losses to 80% or 90% of the stand, equivalent to 2 to 5 times that of whole-tree harvesting (Ballard 1978; Morris *et al.* 1983; Tew *et al.* 1986). In a study of soil and organic matter displacement after blading and windrowing, Morris *et al.* (1983) found that 180 Mg soil and organic matter/ha were displaced into the windrows. From 24% (nitrogen) to 64% (phosphorus) of the nutrient reserves remaining on-site were concentrated on to about 5% of the harvested stand's area (Table 2). This type of nutrient displacement (loss) is of particular concern for intensive plantation-forestry sustainability on nutrient-poor soils. Similar results have been measured elsewhere in the southern United States and New Zealand. Early effects on the productivity of the next tree rotation may not be apparent due to compensating mechanisms such as the control of herbaceous weeds, use of new genetic material, improved soil porosity, reduced transpiration. However, distinct declines of 20% to 30% in the productivity of succeeding stands have been documented after intensive mechanical site-preparation involving windrowing (Ballard 1978; Swindel *et al.* 1986; Tew *et al.* 1986; Fox *et al.* 1989; Dyck & Skinner 1990).

TABLE 2–Effects of harvests and windrowing on nutrient pools (Mg/ha) in a 40-year-old slash pine forest (from Neary *et al.* 1984, 1990)

Component	N	P	K	Ca	Mg
Ecosystem total *	1.550	0.028	0.080	0.303	0.104
Above-ground tree harvest	0.110	0.010	0.036	0.118	0.027
Stem-only harvest	0.066	0.006	0.022	0.090	0.020
Windrow	0.373	0.018	0.027	0.163	0.041

* Above 20 cm soil depth.

Water Quality

Sediment

Sedimentation, or the erosion and transport of rocks, mineral soil, and organic debris to streams, has long been the most obvious and important concern in forestry regarding water quality (Neary & Hornbeck 1994). Sediment yields from major river systems range from 0.2 Mg/ha/year (Wairau; New Zealand) to 1.2 Mg/ha/year (Columbia; United States), to 140.0 Mg/ha/year (Huang Ho; China), and reflect the climate, hydrology, geology, soils, vegetation, physiographic regions, and land-use history of each basin. Natural rates of sediment yield from smaller, forested watersheds are normally low (<0.100 Mg/ha/year) but can vary tremendously (up to five orders of magnitude—O'Loughlin & Ziemer 1982). Water quality in streams emanating from forested watersheds is very important since these streams are typically used for water supplies throughout the world. In addition, these streams are important as habitat and refugia for aquatic biota.

Except during catastrophic mass wasting events, floods, or where bedrock is naturally highly erosive (e.g., Eel River, California; Snake River, Idaho; Waipaoa River, New Zealand), sediment is usually not an important problem in undisturbed forest ecosystems. Debris avalanches can cause major sediment problems in harvested forests of the Pacific Rim and other steeplands. These episodic, spectacular events can account for much of the sediment transported off harvested stands, and seriously affect forest resources and values such as water quality, fish habitat, engineering structures, buildings, recreation areas, reservoir capacity, downstream farmland, etc. The loss of soil strength on steep slopes due to tree root decay 4 to 8 years after cutting is usually the mechanism predisposing slopes to avalanching (Ziemer 1981). Depending on soil type, geology, climate, and slope, forest harvesting can increase both the erosion rate (factor of four) and frequency of debris avalanches, but not necessarily the average size (Swanson *et al.* 1981). Road construction aggravates all debris avalanche hazard factors (erosion rate 120 times that of undisturbed steepland forests).

However, vegetation management after harvesting generally does not appear to aggravate debris avalanching or other mass failures except on highly erosive soils or unstable geologic formations. In these instances, spot spraying of herbicides rather than broadcast application can reduce mass wasting hazards. Another technique used to reduce erosion after forest harvesting on highly erosive steeplands is to oversow with grasses or herbaceous species that can quickly colonise a site and stabilise the soils.

Sediment yields from disturbed and undisturbed forest watersheds have been measured and documented in numerous studies throughout the world (Neary & Hornbeck 1994). It is clearly evident that disturbances which create large areas of bare soil, aggravated by high rainfall, unstable geologic formations, erosive soils, and steep terrain, produce the most sediment yield. Except for some unusual situations with highly erosive, fine-textured soils (Marion & Ursic 1993), erosion losses from harvest-disturbed forested lands usually do not approach those of agriculture (5 to 13 Mg/ha/year—Larsen *et al.* 1983). They also do not persist from the same landscape units, as do sediment losses from agricultural land uses, if normal forest regeneration or re-establishment occurs.

The main impact on water quality from inter-rotation vegetation management is increased sedimentation (Neary & Hornbeck 1994). Next to roads and logging skid trails, the major source of sediment comes from any ground-disturbing activity. Off-site movement of sediment from mechanical, burning, and herbicide site preparation techniques reported in the literature ranges from 97 to 0.17 Mg/ha/year. Natural rates of sediment loss from undisturbed forest watersheds are usually <0.1 Mg/ha/year but in some locations can range up to 0.5 Mg/ha/year. Sediment yields during site preparation are affected by geology, soil, slopes, vegetation and litter cover, and climate. They typically are at a maximum during the first year after site preparation, and decline as vegetation recovers on the treated area (up to 4 years). The highest losses have been documented in China (Lal 1984). Under intensive high-yield forest management in the United States, the highest documented losses (14.25 Mg/ha/year) have occurred on silt-textured soils in the upper coastal plain of Mississippi after cutting and bedding. On clay-textured soils in the Piedmont of North Carolina, sediment losses of 0.97 Mg/ha/year have been reported after mechanical site-preparation (blading and windrowing) to control competing vegetation. In New Zealand, maximum sediment yields after clearfelling and site preparation were estimated to be 3.43 Mg/ha/year with skidder logging and burning with a 20-m riparian buffer, but were much less (0.61 Mg/ha/year) with cable logging and burning with no buffer strip (O'Loughlin *et al.* 1980).

Sediment and vegetation management—Southern United States

In the southern United States, natural erosion rates from forested watersheds are usually low at <0.11 Mg/ha/year) but can range up to 0.22 Mg/ha/year (Maxwell & Neary 1991). However, the disturbances that accompany forest harvesting and site preparation, especially road construction, can cause sediment yields to increase. In some physiographic regions with highly erosive soils, sediment yields after cutting and site preparation for vegetation management have increased temporarily by as much as 278-fold up to the 9 to 14 Mg/ha range (Riekerk *et al.* 1989) (Tables 3 and 4).

A comprehensive analysis of sediment production from forests of the southern United States was conducted by Marion & Ursic (1993). They examined data sets from 37

TABLE 3–Effect of forest harvesting and vegetation management on sediment yield, United States.

Location	Treatment	Sediment yield (Mg/ha)	Reference
Hubbard Brook	Uncut	0.042	Hornbeck *et al.* (1987)
New Hampshire, USA	Clearcut	3.650	
Moonshine Creek	Uncut	0.067	Neary *et al.* (1986)
Georgia, USA	Herbicide, cut	0.170	
Clemson Forest	Uncut	0.020	Van Lear *et al.* (1985)
S. Carolina, USA	Cut/burn	0.151	
Piedmont	Uncut	0.035	Douglass & Godwin (1980)
N. Carolina, USA	Cut/blade	9.730	
Gulf Coast	Uncut	0.620	Beasley (1979)
Mississippi, USA	Cut/bed	14.250	
Bradford Forest	Uncut	0.003	Riekerk (1983)
Florida, USA	Cut/windrow	0.036	
Ouachita Mountains	Uncut	0.071	Beasley *et al.* (1986)
Arkansas, USA	Cut/herbicide	0.251	

TABLE 4—Effect of forest harvesting and site preparation on sediment yield, Europe, South America, Asia, Australia, New Zealand.

Location	Treatment	Sediment yield (Mg/ha/year)	Reference
Wales	Undisturbed	0.037	Francis & Taylor (1989)
United Kingdom	Drainage	0.090	
Oxapampa	Uncut	0.121	Plamondon *et al.* (1991)
Peru	Cut/pasture	0.542	
Hong Kong	Uncut	2.000	Lal (1984)
China	Partial cut	67.000	
	Clearcut	97.000	
Koolau	Uncut	0.536	Doty *et al.* (1981)
Hawaii, USA	Cut/Ag.	2.090	
Tawhai Forest	Uncut	0.429	O'Loughlin *et al.* (1980)
New Zealand	Cut, burn*	0.611	
	Cut, burn†	3.432	

* Cable logged and burned, no riparian buffer
† Skidder logged and burned, 20-m riparian buffer.

watersheds ranging in area from 1 to 2266 ha and representing 189 years of records (Table 5). Sediment data were transformed to concentrations (g/m^3) to eliminate variations caused by high rainfall variability in the region (1000 to 2000 mm). Natural background rates of individual watershed average annual sediment concentrations ranged from 18 to 106 g/m^3 (potential range of 0.18 to 2.12 Mg/ha/year), and for undisturbed watersheds as a group averaged 62 g/m^3. Marion & Ursic (1993) concluded that post-harvest vegetation control with herbicides did not elevate sediment losses above natural rates of erosion (Table 6). Burning created a sediment loss problem only in Coastal Uplands. The main source of sediment from vegetation control techniques in the region originated from soil-disturbing mechanical methods on previously eroded soils or steep terain. This was particularly true in the Piedmont and Coastal Uplands where average annual sediment concentrations from mechanical site-preparation were 17- to 43-fold greater than natural background concentrations.

TABLE 5—Summary of average annual sediment concentrations (g/m^3) in streamflow from 37 watersheds throughout the southern United States (adapted from Marion & Ursic 1993).

Location	Natural	Harvest	Site preparation	
			Burning or herbicides	Mechanical
Interior highlands	16	22	53	97
Piedmont	37	212	35	1617
Coastal - Uplands	98	109	1357	1725
Coastal - Lowlands	11	<10	<10	18

As part of a regional vegetation management environmental impact analysis, 27 representative watersheds in different National Forests of the southern United States, covering all physiographic regions, were evaluated to determine the effect of vegetation management on sediment yields (Maxwell & Neary 1991). Within each physiographic

TABLE 6–Cumulative 10-year sediment yields (Mg) from typical watersheds in the Coastal Plain and Piedmont, southern United States (from USDA Forest Service 1989a).

Source	Brushy 2	Payne	Cottonwood	Hager	Red Prong	Buck	Nine Mile	Two Barrel	Indian 2	Patterson
Natural	12 987	1 432	1 542	944	2 558	736	399	417	9 907	1 161
USFS										
Roads	96	34	13	33	79	15	8	6	4 264	396
Harvest	244	19	209	28	38	4	4	4	266	32
Veg. mgt	375	24	9	68	58	9	7	8	494	59
Private										
Roads	385	11	15	83	22	5	1	2	2 012	131
Forest	3 175	46	25	88	442	6	3	2	8 169	343
Crops	1 333	0	71	47	0	53	0	0	25 354	1 065
Pasture	611	0	659	139	128	17	0	0	7 676	161
Total increase	6 219	134	1 001	486	767	109	23	22	48 223	2 187
Percentage increase	48	9	65	51	30	15	6	5	487	188
Veg. mgt percentage increase	3	2	1	7	2	1	2	2	5	5

region, watersheds representing a range of areas (1781 to 22 096 ha), land types (10 in the Coastal Plain and Piedmont alone), and ownerships (United States Federal Government, State, and private, ranging from 56% to 99% Federal) were analysed. Modelling of sediment yields over a 10-year period indicated that the cumulative effect of all land management activities (forestry, agriculture, grazing, road maintenance, etc.) within the studied watersheds would be an elevation of natural sediment yields (0.022 to 0.134 Mg/ha/year) by 5% to 487% (Table 6). In forest watersheds with mixed land uses, agriculture usually results in the greatest increase in sediment yield (487%). Forest harvesting has the potential to increase sediment production 1–13% above natural rates.

Current low-intensity, post-harvest vegetation management operations required on United States National Forest lands (moderate fire, light mechanical, herbicides, or combination treatments) can increase sediment loss by another <1% to 7% (Maxwell & Neary 1991). Use of high-impact mechanical vegetation control methods could increase sediment loss on portions of watershed units by one or two orders of magnitude (Table 7). By comparison, roads (usually the largest and most constant source of sediment) on both National Forest and private lands, account for sediment yield increases from 2% to 156% of the natural erosion rate. So, Maxwell & Neary (1991) concluded that the impact of vegetation management techniques on erosion and sedimentation of water resources is herbicides<fire<mechanical. They also concluded that sediment losses during inter-rotation vegetation management could be sharply reduced by using herbicides and moderate burning instead of mechanical methods and heavy burning.

TABLE 7–Estimates of sediment loss (Mg/ha/year) by landscape type and vegetation management treatment in intensively managed forests of the southern United States (from Maxwell & Neary 1991).

Landtype	Vegetation management erosion rates—First year only				
	Moderate		Severe		
	Natural erosion	Burn or herbicides	Chop pile	Burn rake/bed	Heavy disk
A. Coastal Plain					
Rolling uplands	0.045	0.040	0.061	0.303	1.211
Upper hills	0.024	0.090	0.134	0.672	2.691
Loess uplands	0.134	0.133	0.296	0.999	3.994
Flatwoods	0.022	0.010	0.015	0.074	0.296
Sand ridges	0.022	0.017	0.025	0.123	0.492
B. Piedmont					
Piedmont	0.044	0.165	0.247	1.237	4.949

Sediment and vegetation management—Western United States

In the forests of the western United States, fire and herbicides have traditionally been used as post-harvesting vegetation management tools because of the frequency of steep and dissected terrain. Mechanical methods such as chopping, and chaining were once used extensively for vegetation management on low-gradient terrain. Results of these practices and of wildfires are summarised in Table 8. These natural disturbances aggravate erosion just about anywhere in the western United States. On some geologically unstable terrain with erosive soils, prescribed fire can dramatically increase sediment yield, but not to the extent

TABLE 8–Estimates of sediment loss (Mg/ha/year) from vegetation management in the western United States.

Location	Treatment	Sediment yield Control	Sediment yield Treated	Reference
1. Vegetation management				
Montana	Clearcut	<0.001	0.168	DeByle & Packer (1972)
Texas	Control burn	<0.001	0.028	Wells *et al.* (1979)
California	Control burn	<0.001	<0.001	Wells (1979)
California	Control burn	0.210	7.340	Debano & Conrad (1976)
Arizona	Herbicide	0.019	0.002	Ingebo & Hibbert (1974)
Arizona	Herbicide	2.565	2.049	Renard *et al.* (1991)
2. Wildfire				
Arizona	Wildfire	2.200	50.500	Hibbert (1985)
California	Wildfire	5.530	55.300	Krammes (1960)
Washington	Wildfire	0.013	2.353	Helvey (1980)

that wildfires do (Debano & Conrad 1976). On the whole, light control burns and herbicides do not accelerate erosion. Fast regrowth of sediment-trapping grasses and herbaceous plants is usually responsible for this phenomenon (Ingebo & Hibbert 1974).

Sediment: In-stream physical effects and nutrients

Unlike organic chemicals and plant nutrients originating from fire or chemical vegetation control techniques, physical sediment added to stream systems does not degrade, and becomes part of normal fluvial sediment transport and storage processes. The residence time of this sediment in fluvial geomorphic systems can range from months to hundreds of years (Heede *et al.* 1988). The residence time of chemicals is much shorter and their persistence in storage sinks is related to the intrinsic rate of degradation of each chemical.

Sediment losses resulting from inter-rotation vegetation management affect both on- and off-site environmental quality. Mechanical site preparation, which produces the largest mass of sediment loss, can result in nitrogen and phosphorus losses 20 to 30 times the normal annual rate of undisturbed forest watersheds (Neary *et al.* 1984). While these losses are low compared to agriculture-related nutrient losses (Larsen *et al.* 1983), they do present a concern for long-term forest management. For example, some forests in the southern United States now under intensive forest management were highly eroded during abusive agriculture in the late nineteenth and early twentieth centuries. Because of loss of nutrient-rich A horizons, these forests remain sensitive to potential productivity decline unless augmented with fertilisers or vegetation control.

Since herbicide applications do not disturb the forest floor and slash material from the previous stand, herbicides work to protect water quality and maintain site productivity by retaining nutrient-rich organic matter and soil surface horizons on-site. Sediments retained on-site do not contribute to additional nutrient loadings or physical deterioration of aquatic ecosystems and water resources.

Herbicide residues

Environmental fate: A large number of herbicides are used for vegetation management in forest ecosystems throughout the world, but a dozen account for the majority of the usage, in both frequency and total amounts applied. These herbicides are 2,4-D, 2,4-DP, dicamba, fosamine, glyphosate, hexazinone, imazapyr, metsulfuron methyl, picloram, sulfometuron methyl, tebuthiuron, and triclopyr. This discussion will focus on those herbicides which are in wide-spread use for inter-rotation vegetation managment in forest stands.

Norris (1981), USDA Forest Service (1989a), Michael & Neary (1993), Neary *et al.* (1993), Rashin & Graber (1993), and Neary & Hornbeck (1994) discussed herbicide fate studies in North American forest ecosystems. They listed numerous studies that examined sampling matrices such as water, soil, and vegetation, and measured peak concentrations in some detail.

Maximum observed concentrations of hexazinone, imazapyr, sulfometuron methyl, picloram, triclopyr, and 2,4-D measured in streamflow in a large number of studies in North America are summarised in Tables 9–13. There are several common features of these data. Firstly, measured peak concentrations were of short duration. Secondly, the highest concentrations (>130 mg/m^3) occurred where buffer strips were not used or streams were accidentally overflown during a herbicide application.

Instantaneous and 24-hour average water quality standards have been recommended by toxicologists or set by either Canadian or the United States regulatory agencies based on human or plant toxicology concerns. A standard process has not been developed for setting water quality standards for herbicides, so some disagreements exist. The most commonly used instantaneous water quality standards in the United States are: glyphosate 700 mg/m^3, hexazinone 200 mg/m^3, imazapyr 10 000 mg/m^3, picloram 500 mg/m^3, triclopyr ester 30 mg/m^3, and 2,4-D ester 70 mg/m^3. Standards for Canada are currently lower, being 190, 280, and 100 mg/m^3 for picloram, glyphosate, and 2,4-D, respectively. Except for those instances where buffer strips were not used or streams were overflown, water quality standards have not been exceeded by forestry chemical vegetation management operations.

Of the newer silvicultural herbicides (<20 years old), hexazinone has the largest database on residues in streamflow or standing water. There are three instances reported in the

TABLE 9–Maximum observed hexazinone residues in streamflow or surface water from treated sites in North America.

Location	Rate (kg/ha)	Buffer	Concentration (mg/m^3)	Reference
Quebec, Canada	3.6	Yes	15	Legris (1987)
Quebec, Canada	3.6	Yes	5	Legris (1988)
Quebec, Canada	3.6	No	820	Legris (1988)
Georgia, USA	1.7	No	442	Neary *et al.* (1983)
Georgia, USA	1.6	Yes	6	Michael & Neary (1993)
Georgia, USA	1.6	Yes	9	Michael & Neary (1993)
Tennessee, USA	1.7	No	0	Neary (1983)
Arkansas, USA	2.0	Yes	20	Bouchard *et al.* (1985)
West Virginia, USA	1.4	Yes	9	Lavy *et al.* (1989)
Alabama, USA	2.9	Yes	37	Michael & Neary (1993)
Alabama, USA	2.9	Yes	24	Michael & Neary (1993)
Alabama, USA	2.9	Yes	23	Michael & Neary (1993)
Alabama, USA	2.9	Yes	8	Michael & Neary (1993)
Alabama, USA	0.8	No	2400	Miller & Bace (1980)

literature where the water quality standard (200 mg/m^3) was exceeded during operational use. The two highest concentrations measured, 2400 and 820 mg/m^3 (Table 9), occurred when herbicide pellets were placed directly into a dry channel, and when application aircraft overflew surface water. In the third (442 mg/m^3), hexazinone pellets were distributed uniformly across small watersheds containing many ephemeral, first-order channels. In all other instances, hexazinone residues did not exceed 37 mg/m^3.

Imazapyr and sulfometuron methyl show a similar pattern to hexazinone, with the highest concentration (imazapyr 680 mg/m^3) associated with an aerial application on areas having no buffer strip (Table 10). A concentration of 130 mg imazapyr/m^3, well below the 10 000 mg/m^3 water quality standard, was measured in Alabama, even with a buffer strip in use, because of surface run-off. Sulfometuron methyl, which hydrolyses readily in acidic water, has not been detected above 44 mg/m^3 in streamflow.

Glyphosate has been used frequently in forest ecosystems because of its low mobility. It is readily immobilised by organic matter in the forest floor. Most studies (Table 11) have measured peak glyphosate concentrations in streamflow at or below 10 mg/m^3 (more than an order of magnitude below the 700 mg/m^3 water quality standard). As seen with other herbicide data, the highest glyphosate peak concentration (270 mg/m^3) occurred where a buffer strip was not used as a Best Management Practice.

TABLE 10–Maximum observed imazapyr and sulfometuron methyl residues in streamflow or surface water from treated sites.

Location	Rate (kg/ha)	Buffer	Concentration (mg/m^3)	Reference
1. Imazapyr				
Alabama. USA	2.2	No	680	Michael & Neary (1993)
Alabama, USA	2.2	Yes	130	Michael & Neary (1993)
Washington, USA	0.1	Yes	1	Rashin & Graber (1993)
Washington, USA	0.1	Yes	1	Rashin & Graber (1993)
2. Sulfometuron methyl				
Mississippi, USA	0.4	Yes	23	Michael & Neary (1993)
Mississippi, USA	0.4	Yes	44	Michael & Neary (1993)
Florida, USA	0.4	Yes	5	Neary & Michael (1989)
Florida, USA	0.4	Yes	7	Neary & Michael (1989)

TABLE 11–Maximum observed glyphosate residues in streamflow or surface water from treated sites.

Location	Rate (kg/ha)	Buffer	Concentration (mg/m^3)	Reference
Quebec, Canada	1.5	Yes	5	Legris *et al.* (1985)
Quebec, Canada	1.5	Yes	5	Legris (1987)
Quebec, Canada	1.5	Yes	10	Legris (1988)
Quebec, Canada	1.5	Yes	0	Legris & Couture (1989)
Washington	1.3	Yes	2	Rashin & Graber (1993)
Washington	1.7	Yes	8	Rashin & Graber (1993)
Washington	1.3	Yes	4	Rashin & Graber (1993)
Oregon	1.3	No	270	Newton *et al.* (1984)

Maximum measured concentrations of picloram, triclopyr, and 2,4-D are listed in Tables 12 and 13. The pattern in the data is the same as observed in the other herbicides, namely that high concentrations (80–620 mg/m^3) are associated with a lack of buffer strips. Otherwise, peak concentrations of these three herbicides did not exceed 40 mg/m^3. The only exception is the picloram concentration of 370 mg/m^3 reported by Davis & Ingebo (1973). That study involved a very high application rate (10.4 kg/ha) of a persistent herbicide in a desert environment which has a low herbicide residue degradation rate as a result of the arid climate. Even under these conditions, the human health water quality standard for picloram (500 mg/m^3 in the United States) was not exceeded. Some agricultural crops can be affected by picloram levels <10% of that standard.

Where buffer strips are used or other mitigatory techniques are employed, forestry herbicides generally do not pose a threat to water quality. Peak concentrations are usually low (<100 mg/m^3) and do not persist for long periods of time (<6 months) (Michael & Neary 1993).

TABLE 12–Maximum observed picloram and triclopyr residues in streamflow or surface water from treated sites.

Location	Rate (kg/ha)	Buffer	Concentration (mg/m^3)	Reference
Picloram				
Georgia, USA	0.3	Yes	0	Michael & Neary (1993)
Georgia, USA	0.3	Yes	0	Michael & Neary (1993)
Georgia, USA	0.3	Yes	6	Michael & Neary (1993)
Kentucky, USA	1.3	Yes	21	Michael & Neary (1993)
Kentucky, USA	0.3	Yes	10	Michael & Neary (1993)
Tennessee, USA	0.6	Yes	4	Michael & Neary (1993)
Alabama, USA	5.6	No	442	Michael *et al.* (1989)
N.Carolina, USA	5.0	Yes	10	Neary *et al.* (1985)
Arizona, USA	10.4	Yes	370	Davis & Ingebo (1973)
Arizona, USA	2.8	No	320	Johnsen (1980)
Triclopyr				
Florida, USA	2.0	Yes	2	Neary & Michael (1989)
W. Virginia, USA	11.2	No	80	McKellar *et al.* (1982)
Brit. Columbia, Canada	0.9	No	620	Wan (1987)
Ontario, Canada	3.9	No	350	Thompson *et al.* (199)1

TABLE 13–Maximum observed 2,4-D residues in streamflow or surface water from treated sites.

Location	Rate (kg/ha)	Buffer	Concentration (mg/m^3)	Reference
Washington, USA	2.1	Yes	2	Rashin & Graber (1993)
Oregon, USA	2.2	No	132	Norris (1967)
Oregon, USA	4.6	Yes	22	Norris *et al.* (1982)
Oregon, USA	6.7	Yes	10	Norris *et al.* (1982)
Pacific NW, USA*	V†	Y/N	40	USDA Forest Service (1984)

* 133 separate sprayings—117 with no detected residues, 13 with 2,4-D < 5 mg/m^3, and 2 with 2,4-D of 5–10 mg/m^3.

† Various rates were used.

Buffer strips: Zones of undisturbed vegetation alongside riparian areas and other surface waters, are frequently employed as "Best Management Practices" to reduce the impact of herbicides on aquatic ecosystems. The efficacy of buffer strips in mitigating pesticide transport into wetlands or riparian zones is quite varied due to the many factors which can affect pesticide transport (Comerford *et al.* 1992). Except for the work of Rashin & Graber (1993), none of the environmental fate studies summarised in Tables 10–13 was designed to investigate the effects and functions of differing buffer strip sizes. Where buffer strips were used, other criteria determined the buffer strip size or orientation.

Herbicide chemistry, application rate, distribution method, buffer size, and weather conditions are very important in determining how well buffer strips work (Comerford *et al.* 1992). In all studies listed in Tables 10–13 where resulting streamflow concentrations were high (>130 mg/m^3), no buffer strips were used or the buffer was violated during herbicide application. Generally speaking, buffer strips of 15 m or larger are effective in minimising pesticide residue contamination of streamflow (Neary *et al.* 1993). The use of buffer strips can keep herbicide residue concentrations within water quality standards. They are not absolute and one as large as 140 m did not keep residues out of a perennial stream in North Carolina (Neary *et al.* 1985). However, the measured peak concentration was 50 times lower than the water quality standard.

Groundwater: Herbicide contamination of groundwater has become a priority environmental issue in the past few years because of growing incidents of agricultural herbicide residues being detected in well samples. In most rural areas, residences are dependent upon groundwater for a water supply. Also, significant areas of North America utilise groundwater for major municipal water sources. A major contamination of an aquifer system would not be easily reversed because of long residence times of water in aquifer systems. Thus it is important to address the issue of potential groundwater pollution from operational use of forestry herbicides.

In general terms, forestry use of herbicides poses a low pollution risk to groundwater because of its use pattern. For instance, herbicide use in forestry is only 10% of agricultural usage and likely to occur only once or twice in rotations of 25 to 75 years. Application rates are generally low (<2 kg/ha) and animal toxicities are low. Some of the silvicultural herbicides can affect non-target plants at low concentrations (<20 mg/m^3) and could affect the quality of water for irrigation purposes. Within large watersheds where extensive groundwater recharge occurs, intensive use of silvilcultural herbicides would affect <5% of the area in any one year. The greatest potential hazard to groundwater comes from stored concentrates, not operational application of diluted mixtures.

Regional, confined, groundwater aquifers are not likely to be affected by silvicultural herbicides (Neary 1985). Surface, unconfined aquifers in the immediate vicinity of herbicide application zones have the most potential for contamination. It is these aquifers which are directly exposed to leaching of residues from the root zone. Several examples are given.

In Georgia, United States, hexazinone was applied at a rate of 1.68 kg/ha to four small (<1 ha) first-order watersheds (Neary *et al.* 1983). Hexazinone concentrations in groundwater entering perennial stream channels as baseflow were very low (<24 mg/m^3), and did not persist for more than 30 days. Bouchard *et al.* (1985) reported a very different situation with hexazinone applied to an 11.5-ha watershed in Arkansas at 2.0 kg/ha. Hexazinone residues

(14 mg/m^3) were consistently measured in groundwater entering perennial stream channels for over a year after application. In South Carolina, application of hexazinone at 2.8 kg/ha did not produce any groundwater contamination in sandy soils where the water table ranged from 2 to 14 m below surface (Bush *et al.* 1990). On a Florida site with similar soils and a lower application rate (1.7 kg/ha), hexazinone was detected in groundwater (17 to 35 mg/m^3), but not until a year later.

Sulfometuron methyl was applied at a rate of 0.4 kg/ha to 4-ha watersheds in Florida (Neary & Michael 1989). Residues of this herbicide did not penetrate to shallow groundwater (<1 m deep). A structurally similar herbicide, metsulfuron methyl, applied to a similar site in Florida also did not leach into shallow (<1 m) groundwater (Michael & Neary 1991).

Triclopyr was applied to small watersheds (4 ha) in Florida in both the amine (2.0 kg/ha) and ester (1.6 kg/ha) formulations by ground sprayer. Monitoring of both streamflow and surface groundwater (<1 m deep) for 5 months following application did not detect any residues of triclopyr (Bush *et al.* 1988). Application of picloram (5.0 kg/ha) to steep watersheds of the Appalachian Mountains produced ephemeral groundwater contamination (Neary *et al.* 1985). A 140-m buffer strip between the application area and a first-order perennial stream reduced picloram concentrations in baseflow down to sporadic peaks of <10 mg/m^3 during a 17-month monitoring period. Intensive sampling of a spring immediately below the picloram-treated area measured only trace concentrations.

The only known groundwater contamination incidents of any importance (contamination of bedrock aquifers, persistence >6 months, concentrations in excess of the water quality standard, etc.) in the southern United States, where significant amounts of forestry herbicides are used, involved (1) use of extremely high rates, or (2) spills of concentrates. Because of the high concentrations in these instances, herbicide residues were detected in groundwater 4 to 5 years after the contamination. These situations are definitely not typical of operational use of forestry herbicides. Proper handling precautions during herbicide transport, storage, mixing-loading, and clean-up are extremely important for preventing groundwater contamination.

Water quality—Nutrients

Any disturbance to a forest ecosystem (fire, insects, windthrow, harvesting) can alter the equilibrium in biogeochemical cycling, and ultimately produce changes in surface and groundwater quality. Nitrogen is the element most sensitive to biogeochemical changes since it can be volatilised by fire and mineralised by decomposition into highly mobile forms (nitrate-nitrogen; NO_3-N). Vitousek & Mellilo (1979) examined the patterns and processes of nitrate-nitrogen losses from disturbed forest ecosystems throughout the world. The only instances where nitrate-nitrogen levels exceeded the 10 mg/m^3 water quality standard involved additions of herbicides or use of other techniques to inhibit the regrowth of vegetation.

A representative range of nitrate-nitrogen peak concentrations in streamflow is given in Tables 14–16. As indicated by Vitousek & Mellilo (1979), all the studies listed in these tables with streamflow concentrations >5.3 mg/m^3 involved herbicides. In the studies where peak concentrations exceeded the water quality standard, either repeated applications were used or rates of application were high. Most operational applications of forestry herbicides

TABLE 14—Effect of vegetation management on maximum nitrate-nitrogen concentrations in streamflow (eastern United States).

Location	Forest type	Treatment	Maximum NO_3-N (mg/ℓ)	Reference
Hubbard Brook New Hampshire, USA	Northern hardwoods	Cut	6.1	Hornbeck *et al.* (1987)
Hubbard Brook New Hampshire, USA	Northern hardwoods	Cut herbicide	17.8*	Pierce *et al.* (1970)
Fernow Forest W. Virginia, USA	Mixed hardwoods	Cut	1.4	Aubertin & Patric (1974)
Coweeta Lab N. Carolina, USA	Convert to grass	Cut herbicide	0.7	Swank (1988)
Coweeta Lab N. Carolina, USA	Mixed hardwoods	Cut	0.2	Swank (1988)
Moonshine Creek Georgia, USA	Hardwoods	Herbicide	5.3	Neary *et al.* (1986)

* Treated in consecutive years with bromacil to stop regrowth

TABLE 15—Effect of vegetation management on maximum nitrate-nitrogen concentrations in streamflow (western United States).

Location	Forest type	Treatment	Maximum NO_3-N (mg/ℓ)	Reference
Andrews Forest Oregon, USA	Douglas-fir	Cut burn	0.6	Fredricksen *et al.* (1975)
Alsea Basin Oregon, USA	Douglas-fir	Cut	2.1	Brown *et al.* (1973)
Three Bar Arizona, USA	Chaparral grass	Herbicide	15.3	Davis (1984)
Three Bar Arizona, USA	Chaparral grass	Herbicide burn	18.4	Davis (1987)

involve relatively low rates and are not likely to be repeated in successive years, Total mass losses of nutrients from watersheds in streamflow are not usually large relative to other processes (Neary & Hornbeck 1994). Therefore, the impact of additional nitrogen losses from herbicide use is minimal.

CONCLUSIONS

In several decades of research on the fate and environmental effects of herbicides on forest watersheds, sufficient progress has been made to support several regional environmental impact statements (USDA Forest Service 1989a, b, 1990). Additional research will be necessary in the next decade to examine the environmental fate of new pesticides as well as determine indirect effects and cumulative effects of forestry herbicide use.

Numerous research and monitoring studies have documented low concentrations and short persistence of forestry herbicides in surface waters. In the southern United States,

TABLE 16–Effect of vegetation management on maximum nitrate-nitrogen concentrations in streamflow (Canada, Europe, New Zealand)

Location	Forest type	Treatment	Maximum NO_3-N (mg/ℓ)	Reference
Narrows Mtn N.B., Canada	Hardwoods & conifers	Cut	1.6	Krause (1982)
Haney B.C., Canada	Western hemlock	Cut burn	0.5	Feller & Kimmons (1984)
Okanagan B.C., Canada	Spruce-fir	Cut	0.4	Hetherington (1976)
Totenasen Norway	Spruce, alder	Cut herbicide	9.1	Ogner (1993)
Tawhai Forest New Zealand	Beech-podocarp	Cut	0.2	Neary *et al.* (1978)
Tawhai Forest New Zealand	Beech-podocarp	Cut burn	0.4*	Neary *et al.* (1978)

* Post-burn

applications of hexazinone, imazapyr, metsulfuron methyl, picloram, sulfometuron methyl, and triclopyr at rates of 0.3 to 5.6 kg/ha produced peak stream concentrations <130 mg/m^3 when buffer strips were maintained (Michael & Neary 1993; Neary *et al.* 1993). Aerial applications to entire watersheds in both the United States and Canada have resulted in peak streamflow concentrations in the 442–680 mg/m^3 range where buffer strips were not used or maintained. Higher concentrations (up to 2400 mg/m^3) have been reported in short sections of streams after accidental overflights. These types of peak streamflow concentrations do not persist and rapidly attenuate. Although water quality standards do not exist for all forestry herbicides or the standards are under debate, monitoring experience clearly indicates that the rates and use patterns of these chemicals do not pose any problem for surface water quality. For instance, the suggested water quality standard for hexazinone has only been exceeded for a short time where ephemeral or perennial channels were treated. Where forestry herbicides have been detected in streamflow, the residues usually dissipate within a few months, and persist mainly in low concentrations (<44 mg/m^3).

Forestry herbicides have been detected in shallow, surficial groundwater (unconfined aquifer of soil, colluvium, or saprolite) only from broadcast applications and then only in about half the studies that monitored for them. In none of these situations were the herbicide residue concentrations of any toxicological significance. No cases exist of a bedrock aquifer being contaminated on localised or landscape scales by operational use of forestry herbicides. Transport and storage of concentrated herbicide products are the only activities with any risk for localised contamination of major aquifers.

From both the water quality and sustainability perspectives, herbicides have a real advantage for stand establishment and inter-rotation vegetation management. By keeping soil on site and not in streams, long-term forest sustainability is protected and water quality is not adversely affected. Considerable research and monitoring studies have shown that operational use of forestry herbicides for inter-rotation vegetation management does not create a significant risk to water quality as far as herbicide residues are concerned.

However, when the scientific evidence of risks and benefits is carefully analysed, herbicides actually have a positive role in protecting environmental quality. They do this by maintaining the sustainability of forest ecosystems and protecting water quality.

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