454
457 - 455
455 - 457
45
in: C.T. Youngberg (ed.). 1978.
Forest Soil and Land Use
Proceedings of the fifth North American Forest Soils Conference, Colorado State Univ., Fort Collins, CO
August 1978

A COMPARISON OF HARVESTING METHODS AND THEIR IMPACT ON SOILS AND ENVIRONMENT IN THE PACIFIC NORTHWEST

K. Cromack, Jr., F. J. Swanson and C. C. Grier[1]

The productive evergreen coniferous forests of the Pacific Northwest have accumulated large biomass in individual stands. These evergreen forests are adapted to a winter-wet, summer-dry environment enabling photosynthesis and nutrient uptake and storage during the relatively mild winters (Waring & Franklin 1979). Pacific Northwest forests and their associated streams also support important fisheries resources. Possible future constraints in energy supply, coupled with the need to maintain long-term site productivity, necessitate continued improvement in forest management methods (Bengtson 1978; Bormann & Likens 1979).

To evaluate management activities upon forest ecosystems one must include terrestrial and aquatic habitats and the materials transferred by nutrient cycling and erosion processes. Although large living trees are the dominant element of the mature forest ecosystem, recent studies show other parts of the ecosystem also play important roles. Other functional components of Pacific Northwest coniferous forests, such as the substantial leaf biomass and leaf area of mature conifer stands (Waring & Franklin 1979); large accumulations of roots (Santantonio et al. 1977); dominance of mycorrhizae in belowground organic matter inputs (Fogel & Hunt 1979); and relatively deep and fertile soils from which N leaching losses are small (Sollins et al, in press) all contribute to forest productivity.

In forested watersheds the aquatic environment is small streams. Such streams comprise 86% of the total length of river channels in the US (Leopold, Wolman & Miller 1964). The physical character and energy base of these small

[1]Respectively, Assistant Professor, Dept. of Forest Science, Oregon State University, Corvallis, OR 97331; Research Associate, Dept. of Forest Engineering, Oregon State University (now at USDA Forestry Sciences Laboratory, Corvallis, OR 97331); Research Associate Professor, College of Forest Resources, University of Washington, Seattle, WA 98195.

Department of Forest and Wood Sciences, Colorado State Univ.

streams are dominated by adjacent forests which supply energy, minerals and shade, thus regulating the rate of stream production (Meehan, Swanson & Sedell 1977). Much organic and inorganic material is transferred from the forest to the streams by biotic and physical processes. The storage or transfer of these materials also represents nutrient capital. A diagram illustrates the sources and fates of material coming into and passing through a forest ecosystem (Fig. 1). By careful budgets of where materials are stored and how rapidly they are accumulated or lost, long-term responses to various management options may be evaluated.

As in the case of nutrient cycling regimes, soil/sediment movement through ecosystems is viewed as a series of storage sites linked by transfer processes (Fig. 2). Soil is moved down hillslopes into channels and then downstream. This material transfer, or erosion, is accomplished by a complex set of interacting processes (Dietrich & Dunne 1978; Swanson et al. in press). Soil and sediment are stored at a variety of sites on hillslopes, in channels, and at the interface between slope and channel. Both the capacity of storage sites and rates of transfer processes on slopes and in small streams are regulated by live and dead vegetation. Root systems, for example, anchor the soil mass and reduce potential for shallow, rapid soil mass movements (debris avalanches). Logs in streams temporarily trap sediment and dissipate energy of stream water, thereby reducing its sediment transport capability. To assess management impacts on soil loss and sedimentation one must understand this soil/sediment routing system and identify major processes and storage sites on land and in streams.

Leaching and erosion losses affect one another in both terrestrial and aquatic systems. For example, erosion affects the stability of substrates and in turn the leaching of nutrients in both terrestrial and aquatic environments. Likewise, organic matter in both living and dead forms regulates the erosion rate. In the western US, where coniferous forests dominate, the harvesting of these forests has a particularly large impact upon the aquatic environment.

HARVEST EFFECTS

Current silvicultural and harvesting techniques in the Pacific Northwest attempt to minimize cost in adapting to rugged and unstable terrain. A typical harvest operation requires: roads and landing; felling, bucking and hauling of logs; site preparation; and planting or reseeding of the site. Until the time of final harvest the stand may be entered many times to protect it from fire, insects or disease. To increase growth, fertilization, thinning and brush control are often practical. Although management practices are quite varied we will attempt to generalize the kind and extent of impact upon erosion and leaching.

Effects of Harvesting Upon Subsequent Vegetation

Cutting a forest has a variety of impacts on vegetation. Logging in effect is a perturbation that initiates secondary ecological succession. The vegetation response to perturbation depends upon the type of logging, environmental conditions, local patterns of plant succession and the success of

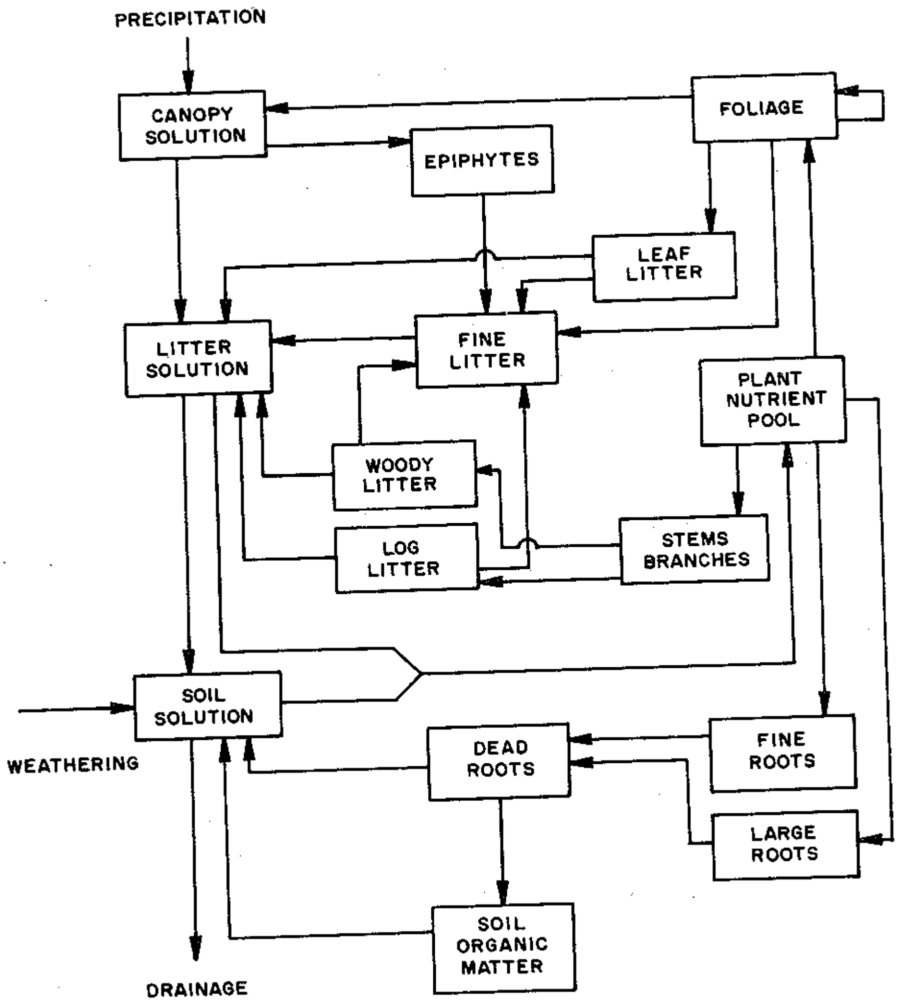

Figure 1. Diagram of a coniferous forest ecosystem showing functional components and nutrient transfers (after Sollins et al., in press).

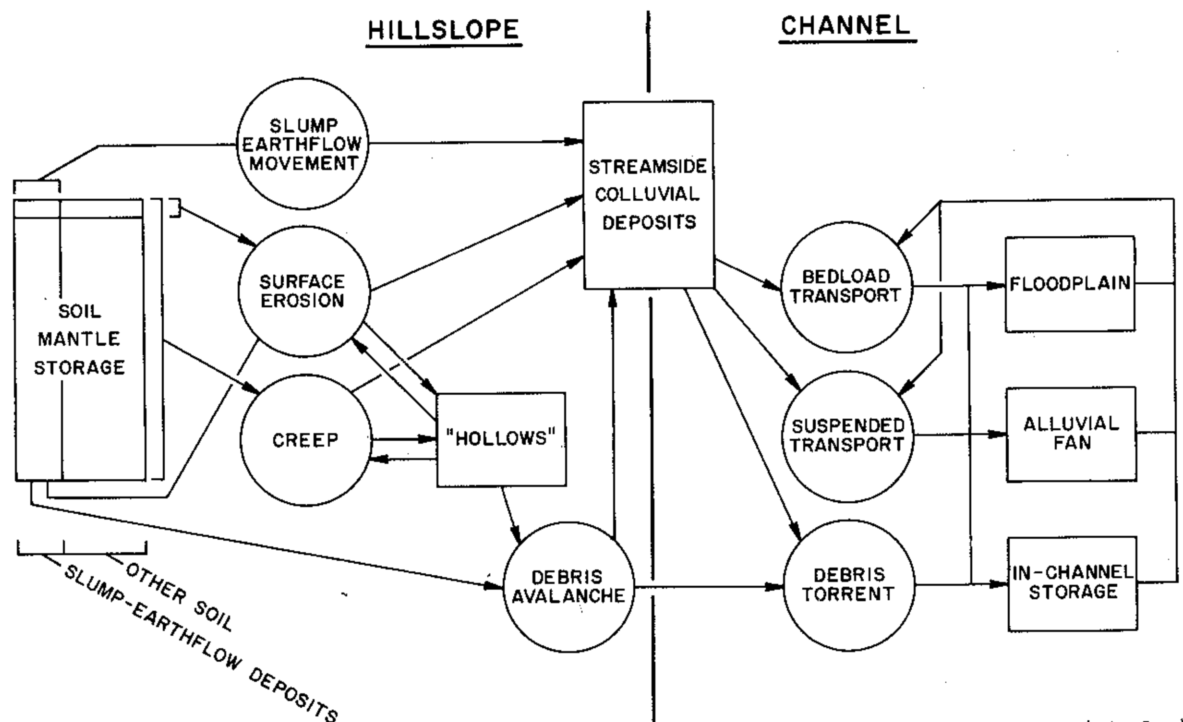

Figure 2. Flow chart showing soil and sediment storage sites (boxes) and transfer processes (circles). Debris avalanches are shallow, rapid soil mass movements from slopes. Slump-earthflow is slow, deep-seated soil movement on a discrete failure surface. Creep is subtle soil mantle deformation without development of discrete failure surface. Surface erosion includes sheetwash, rill, dry period and freeze-thaw related processes. Debris torrents are rapid movements of debris down channels. "Hollows" occur at headward tips of channels (Dietrich & Dunne 1978). In-channel storage occurs in gravel bars and is associated with organic debris accumulations. See Dietrich and Dunne (1978) and Swanson et al. (in press) for additional discussion and definitions.

regenerating efforts. Changes in the vegetation immediately following harvest are an important factor to be considered in stand regeneration. Release of brushy species by logging can result in competition for young conifers.

Methods of shrub treatment will influence brush development. When a site is left unburned, species already present will dominate. For example, if salal (*Gaultheria shallon*) or vine maple (*Acer circinatum*) were present in the understory prior to harvest, they will be following harvest.

Slash burning, on the other hand, favors new species absent from the original understory. Species that reproduce by windborne seed, and germination from buried seed appear to be favored by slash burning (Ahlgren & Ahlgren 1960).

Three stages in secondary succession should be recognized (Ahlgren & Ahlgren 1960; Franklin & Dyrness 1973): 1) herbaceous stage, 2) shrub stage; and 3) young forest stage. Other stages are absent in managed forests.

On sites that are broadcast burned, succession generally proceeds through all three stages, but on unburned sites, the herbaceous stage is not always present. In areas where logging exposes mineral soil, patterns of secondary succession resemble those on burned sites (Dyrness 1973).

The herbaceous stage occupies the site for the first few years and consists mainly of invading herbaceous species such as *Senecio sylvaticus* and fireweed (*Epilobium angustifolium*). Annuals such as *Senecio* are among the first to invade a logged site. These are replaced later by perennials such as fireweed and bracken fern (*Pteridium aquilinum*) that dominate the site for two or three years. Species invading recently disturbed sites tend to be "generalists" having rather wide ecological tolerances (Franklin & Dyrness 1973). Eventually shrubs become established and replace the herbs.

The shrub stage of succession is dominated by species such as salal, vine maple or snowbrush (*Ceanothus velutinus*). In contrast to the wider ranging generalists in the herbaceous stage, the shrub species are more closely adapted to soils and climate of the site. Thus on drier sites grow species such as salal and hazel (*Corylus cornuta var. californica*). On moderately moist sites, salal may still be found with *Rhododendron macrophyllum*, Oregon grape (*Berberis nervosa*), vine maple, and snowbrush. Snowbrush is a common shrub on burned sites in the Oregon Cascades. Seeds of this species lie dormant in the soil until a fire triggers germination. Consequently, snowbrush is common on clearcut areas but usually is absent from established forests. In western Washington, salal, vine maple and Oregon grape are the primary shrub species occupying more moist harvested sites. On wetter sites the most common species are red alder (*Alnus rubra*), salmonberry (*Rubus spectabilis*) and swordfern (*Polystichum munitum*).

The time required for a forest to develop varies. The third stage of succession, development of a seral forest stand, is dependent on factors such as the type of disturbance, means of establishment (e.g. planting, natural seeding, advanced regeneration) and environmental conditions. Probably the most common occurrence, especially with the advent of large scale tree planting, is the development of a pure, even-aged stand of Douglas-fir. These stands eventually become dense enough to eliminate almost all of the competing understory and, barring disturbance, remain this way until harvest. In wetter, cooler areas of the Northwest, such as the Oregon and Washington coasts or the northern Cascades of Washington, dense, young stands of western hemlock become established following the brush stage (Franklin & Dyrness 1973). This frequently occurs in spite of initial planting with Douglas-fir seedlings.

Red alder is among the first trees to re-establish on many of the moist and wetter sites. Pure stands of red alder are common in the Oregon and Washington coastal mountains and in many parts of the Puget Sound region. Formerly a common species only in riparian habitats, red alder has substantially expanded its area of occupancy - mainly as a result of earlier logging and fires. During normal succession, alder gradually is replaced by Douglas-fir or western hemlock. As alder can dominate a site for up to 90 years (Franklin & Dyrness 1973), foresters apply herbicides or harvest the alder to speed conversion to the more valuable conifers.

Effect of Harvesting on Nutrient Losses

Nutrient and erosion losses from undisturbed forest ecosystems are relatively small for elements such as N, P, and K (Sollins et al. in press). For elements such as Ca, Mg and Na, stream export from deep weathering is considerably greater (Fredriksen 1972; Sollins et al. in press). They are, however, accelerated following major disturbances such as logging, fire or major storms (Cole & Gessel 1965; Fredriksen 1971). In the Pacific Northwest, when watersheds have been gauged and sediment trapped, net losses of various elements are known (Fredriksen 1971, 1972 & Fredriksen[2]). Although accelerated nutrient losses of N, P, K, Ca and Mg do occur following logging (Cole & Gessel 1965; Fredriksen 1971), more concern exists for loss of N since it generally is a limiting element in Pacific Northwest forests.

Nutrient cycling studies in a variety of Pacific Northwest forests report N inputs in precipitation ranging from 1.1-4.1 kg/ha/yr; organic N in dust may add an additional 0.06-1.3 kg/ha/yr (Fredriksen[2]). In marked contrast, N in precipitation is as high as 21 kg/ha/yr in northeastern forests at Hubbard Brook (Bormann, Likens & Melillo 1977), reflecting urban and industrial pollution N inputs to the atmosphere. At the Coweeta Hydrologic Laboratory in North Carolina, Swank and Douglas (1977) reported precipitation contained N totalling 4.5-7.2 kg/ha/yr.

Under relatively undisturbed conditions, N precipitation and dryfall inputs generally exceed system losses so that net accumulation of N may be occurring (Fredriksen[2]). Such short-term nutrient accumulation must be balanced, however, against episodic losses of soil and litter during major erosion events (Fredriksen 1970), wildfire, harvesting and slash burning.

---

[2]R. L. Fredriksen. 1975. Nitrogen, phosphorus, and particulate matter budgets of five coniferous forest ecosystems in the western Cascades Range, Oregon. Ph.D. thesis. Oregon State University, Corvallis, Oregon.

Soil disturbance and compaction, and fire-induced hydrophobic behavior of surface soil are two of the most important in situ alterations of forest soils. Compaction and disturbance occur during roading and harvest activities. Froehlich (1973a, 1974, 1976,1978) provides excellent summaries of research on these topics for the Pacific Northwest. The portion of a management unit compacted or otherwise disturbed varies greatly with the types of road and harvest systems employed (Table 1). Of course, terrain, equipment capabilities, definitions of ground surface conditions and other factors vary somewhat from study to study, but several general relations between the degree of soil disturbance and logging systems do emerge.

In general, the most complex, expensive yarding systems are designed to operate in the steepest terrain and to have the least impact in terms of soil compaction and disturbance. Clearcutting by tractor yarding generally occurs on slopes less than 50%. In tractor yarded units, values of percent of area compacted and deeply disturbed range from about 20 to 40% (Table 1 and other studies). Dyrness (1965, 1967a, 1972) reports 36% of a tractor yarded clearcut as deeply disturbed or compacted, while skyline and balloon yarded units had only 8 and 4%, of the total area in these two disturbance classes. Results of other studies also show less soil disturbance by yarding systems capable of greater suspension of logs.

Proportion of selectively cut areas disturbed and compacted by tractor and skyline methods are remarkably similar to areas affected by these systems in clearcuts (Table 1 and other studies). This results from the need for access to all areas of a harvest unit regardless of whether it is being thinned or clearcut.

Exposure of bare mineral soil by yarding or site preparation activities often is desirable to aid establishment of species such as Douglas-fir, but soil compaction may significantly reduce site productivity. The persistence and long-term impact of compaction depends on severity of initial treatment, the ability of various species to cope with compacted soils, and rates of processes tending to decompact the soil. Youngberg (1959) reports a 43% reduction in seedling height growth on primary skid trails relative to uncompacted clearcut areas. The greatest reported impact of compaction on growth of Douglas-fir is in unpublished Bureau of Land Management data (Froehlich 1973a) which indicate a 57% reduction in height growth of 8-year-old trees relative to uncompacted sites in clearcuts. On a 55-year-old railroad yarded clearcut Power (1974) estimates a 40% reduction of yield from compacted areas.

Rate of recovery of compacted areas in the Pacific Northwest has received very little study, but is known to vary greatly with soil type and effectiveness of decompacting processes such as freeze-thaw action (Froehlich 1973a). In much of the Douglas-fir region processes of soil decompaction operate slowly or infrequently, so in many areas compacted conditions may persist for years.

Development of hydrophobic soil conditions in the Pacific Northwest has been observed following wildfire (Dyrness 1976) and slash burning (J. Maxwell, personal communication). Dyrness (1976) observed overland flow and erosion due to decreased infiltration rates from volcanic ash soils after a wildfire

Scott[4] has shown that snowbrush can increase growth of Douglas-fir seedlings relative to seedlings growing without shade during the first seven to nine years. Red alder is more competitive with Douglas-fir on moist sites. Increasing environmental concern with herbicides is catalyzing research on alternative methods of utilizing the N fixing capacity of red alder and other species by underplanting in already established stands of Douglas-fir. Berg and Doerksen (1975) estimate naturally invading red alder to add from 220 to 848 kg/ha of N to a heavily thinned Douglas-fir stand during a 17 year period. Basal area of the 80-year-old Douglas-fir dominated stand has increased 55% post thinning, not including biomass added by the red alder. In the thinning regime evaluated by Berg & Doerksen (1975), gradual closure of the Douglas-fir canopy is eliminating the alder following the positive benefits of its N accretion.

Longer-term input of N into forests by N fixation also is being studied in older coniferous forests. Nitrogen fixation in decaying coniferous logs occurs at low levels with highest rates in wood with advanced decay (Larsen et al. 1978). Assuming approximately 215 mT/ha of down logs in old-growth Douglas-fir forests as reported by Grier and Logan (1977) and assuming rates reported by Larsen et al. (1978) we estimate 5 kg/ha/yr of N fixation in logs in the western Cascades of Oregon. Trees rooting into rotting logs may utilize this N source. An additional 5 kg/ha/yr of N may be fixed by old-growth canopy-inhabiting lichens (W. C. Denison, pers. commun.). Nitrogen inputs by these long-term processes thus may be several times precipitation and dryfall N inputs and may be important in maintaining productivity of older coniferous forests.

Effects of Fertilization

Fertilization of watersheds has resulted in small but significant increases of inorganic N in streams from both direct fertilizer application into streams and as a result of percolation through the soil mantle (Fredriksen et al. 1975). Cole and Gessel (1965) observed a slight increase in organic N at nearly 1 m depth in the soil mantle following application of 220 kg/ha of urea on one plot and 220 kg/ha of ammonium sulfate on another plot. The maximum loss reported was with ammonium sulfate fertilization, which doubled the total N solution loss. A favorable benefit:cost ratio makes it likely that N fertilization will be widely used in the Pacific Northwest for at least the next decade (Miller & Fight 1979; Bengtson 1979).

Effects on Soil Integrity and Erosion

The sequence of harvest activities affects the physical integrity of soil in two general ways: 1) by in situ alteration of soil physical properties and 2) by acceleration of soil erosion. Each step in the harvest sequence may have distinctive effects on soil physical properties that differ in type, magnitude and duration of impact.

---

[4]W. Scott. 1970. Effect of snowbrush on the establishment and growth of Douglas-fir seedlings. MS thesis. Oregon State University, Corvallis, Oregon.

Losses of N capital from harvesting alone or from harvesting and slash burning removed from 20-132 times as much N as did annual stream runoff in a western hemlock forest in British Columbia (Kimmins & Feller 1976). Grier[3] reported a loss of greater than 95% of N capital in slash by volatilization in fire; on the Entiat Experimental Forest in Washington, 855 kg/ha of N was lost by volatilization from litter and soil. Kimmins and Feller (1976) reported 581 kg/ha of N lost in slash burning and from 92-124 kg/ha of N removed by logging.

Clearcutting alone and clearcutting followed by burning generally result in modest increases in solution losses of N draining below rooting zones or from first-order streams draining small watersheds (Cole & Gessel 1965; Fredriksen 1971; Kimmins & Feller 1976). In one instance, McColl (1978) actually observed a significant decrease in NO_3 following clearcutting. Partial cutting or shelterwood cutting resulted in only a modest increase in N loss in stream runoff (Fredriksen et al. 1975).

In summary, solution losses of N from Pacific Northwest forests which have been harvested generally are small relative to the very large N losses, particularly NO_3^- nitrogen, reported in the eastern US (Bormann et al. 1977). Timber harvesting can accelerate N losses as a result of increased soil removal (Fredriksen 1971). Catastrophic losses of soil from forests can occur both as a result of major storms (Fredriksen 1970) and as a consequence of harvesting or harvesting-related activities such as road building. Soil loss results in a decline of both nutrients and soil productivity until new soil is formed. Consequently, improvements in harvesting techniques which minimize soil loss are desirable.

Nutrient Restitution Following Harvesting

Nitrogen removed from Pacific Northwest forests by harvesting or slash burning can be replaced by N fixation and precipitation or by fertilization. Although fertilizers are widely used in the Northwest and produce a positive growth response, their rapidly rising costs have led to increased consideration of biological N fixation to restore N capital of harvested sites (Bengtson 1979).

Estimates of the quantity of N fixed by trees such as red alder and by shrubs such as snowbrush in Northwestern forests range from 32-325 kg/ha/yr (McNabb, Geist and Youngberg 1977; Newton et al. 1968). The low value reported by McNabb, Geist & Youngberg (1977) is from a snowbrush stand in eastern Oregon where severe moisture stress limits N fixation. Even in that case, N fixation over a 10 year period could result in a stand accretion of 320 kg/ha of N. On a more favorable site in eastern Oregon, Youngberg & Wollum (1976) reported N accretion of 715 kg/ha in a decade.

---

[3] C.C. Grier. 1972. Effects of fire on the movement and distribution of elements within a forest ecosystem. Ph.D. thesis. University of Washington, Seattle, Washington.

TABLE 1. SUMMARY OF PACIFIC NORTHWEST STUDIES OF SOIL DISTURBANCE AND COMPACTION BY VARIOUS YARDING SYSTEMS. DATA ARE IN PERCENT OF HARVEST UNIT AREA IN SOIL DISTURBANCE CLASS. SYMBOLS ABOVE COLUMNS DENOTE SOURCE OF DATA. HIGH-LEAD DATA FROM SOURCES * AND ++ ARE AVERAGES OF SAMPLES FROM 3 AND 11 UNITS RESPECTIVELY. TRACTOR DATA FROM ++ AN AVERAGE OF TWO UNITS

Soil Disturbance Class	Yarding System (data source)										
	Tractor-skidder				High Lead		Skyline			Balloon	Heli-copter
	*	**	+	++	*	++	**	+	Δ	ΔΔ	++
Clearcuts											
Undisturbed	36	58			57		73		64	78	
Slightly disturbed	26	14	12	11	22	18	9	8	24	16	2
Deeply disturbed	9	29	16	58	10	11	24	3	5	3	3
Compacted	27	31			9		27		3	2	
Non-soil Area	2				2				.4	2	
Selective Cuts											
Undisturbed		43					70				
Slightly disturbed		24					16				
Deeply disturbed		35					13				
Heavy compaction		31					14				

* Dyrness 1965
** F. M. McCorison, pers. commun.
\+ Wooldridge 1960
++ Bockheim et al. 1975
Δ Dyrness 1967a
ΔΔ Dyrness 1972

through a predominantly *Pinus contorta* forest. Conditions of increased water repellency of soil at depths up to 23 cm lasted for five years. Effects of slash fires on soil wettability and related accelerated erosion have not been researched in the western coniferous forest. Many forest soils in the region are coarse-textured and occur on steep slopes, conditions which form soils with high infiltration rates even after fire, and prone to surface erosion by dry ravel rather than by sheet and rill erosion. Increases in peak flows from clearcut and burned watersheds in western Oregon have been interpreted in terms of road density and soil compaction rather than hydrophobic soils (Harr 1976). Therefore, development of hydrophobic soils by slash fires has not been considered a significant problem in the Pacific Northwest.

Effects of forest management activities on soil erosion have been reviewed by Rice et al. (1971), Megahan (1972), Stone (1973), Fredriksen et al. (1975), Swanston and Swanson (1976) and others. Most studies of soil erosion from forest land have been based on sediment yield from small watersheds, although some plot studies (Hauge 1977) and process-level investigations (Dyrness 1967b, Swanson & Dyrness 1975, and others) assess management effects. The magnitude of increases in soil erosion due to management activities is highly variable and depends largely on relationships between the type of harvest sequence used and the susceptibility of the landscape to erosion. A particular activity may have very different impacts under differing soil and slope conditions. Careful practices in difficult, erosion-prone terrain may have soil erosion impacts comparable to poor practices carried out on naturally stable ground.

Several examples from among the experimental watershed studies in western Oregon demonstrate the broad range of watershed responses to harvest activities. In a case of minimal impact of harvest activities, the Fox Creek watersheds in the Bull Run drainage, western Cascade Mts., experienced no detectable increases in suspended sediment export following 25% clearcutting of a small, gently sloping watershed with soils of low erosion potential on a 71 ha drainage (Fredriksen et.al. 1975, and Fredriksen and Harr 1979). In very steep, erosion-prone terrain some increase in sediment yield to streams by conventional harvest systems is essentially unavoidable. Studies on watersheds 1, 2 and 3 at the H. J. Andrews Experimental Forest, western Cascade Range, Oregon, exemplify impacts of practices used in the mid-1960's on such terrain. Skyline logging and broadcast burning of the 96 ha Watershed 1 resulted in an approximately 9-fold increase in suspended sediment export in the first 13 years following burning compared with control watershed 2 (Fredriksen & Harr 1979). After 6% of 100 ha Watershed 3 was roaded and 25% clearcut and broadcast burned in three units, suspended sediment export over an 18 year post-treatment period was about 24 times the yield of the control (Fredriksen & Harr 1979). Of the total 12 year post-treatment yield of coarse material from Watershed 3, 99% was exported by two major storms in WY 1965 which triggered numerous debris avalanches (shallow, rapid soil mass movements on hillslopes) and channel scour events.

The overwhelming importance of the two WY 1965 storms in the long records from the H. J. Andrews watershed studies underscores some of the difficulties of interpreting results from the paired watershed study design. Small watersheds are unique in time and space. They have particular physical characteristics and histories of natural and management-related processes.

Therefore, in assessing management impact there are certain advantages to process-level studies in which key erosion processes are inventoried on broad time and space scales.

In steep terrain, inventories of debris avalanches over areas of 10 km^2 or more and time periods of a decade or more provide a basis for measuring the impact of roads and clearcuts relative to forested areas on soil erosion by debris avalanches. In six studies in steep land of the Pacific Northwest debris avalanche erosion rate in clearcuts was found to be 0 to 10 times the rate in forested areas and the average increase was 2.4 times (Swanston & Swanson 1976, Ketcheson & Froehlich 1978, F. J. Swanson, unpub. data). Five of these studies include estimates of debris avalanche erosion from forest road right-of-way and rates vary from 25 to 340 and average 125 times the forest area rate (Swanston & Swanson 1976, F. J. Swanson, unpub. data). Of course, these surveys primarily assess effects of some earlier logging and roading methods which have been modified or abandoned, so these figures may not reflect the impact of modern practices. Only continued inventories will measure the benefits of new methods in terms of reduced debris avalanche erosion and associated impacts on streams.

These measures of road and clearcut impacts on debris avalanche erosion reinforce the common belief that roads are the predominant source of erosion accelerated by forest practices. However, although roads have a high impact they affect only a small proportion of the landscape, generally less than 6 or 7% (Froehlich 1978). The smaller, but significant impact of clearcutting influences the remaining 93 or 94% of the landscape. Based on these and several other assumptions, Swanson and Dyrness (1975) estimate that accelerated debris avalanche erosion due to clearcutting alone may roughly equal that of roads.

No studies have contrasted the impact of harvest practices other than clearcutting on erosion by debris avalanches or other single erosion processes. The longer-term soil erosion impacts of timber harvest activities in the Pacific Northwest are unknown, because the natural history of erosion in the region has included periods of accelerated erosion following wildfire. As part of the assessment of long-term impacts, the frequency and erosional consequences of premanagement wildfire should be compared with the frequency and erosional consequences of management activities (Swanson et al., in press). Information necessary to make this comparison is lacking.

Effects on Streams

Small streams draining steep forest land are intimately linked with forest and soil erosion conditions on adjacent slopes. Even in streams as large as third-order the forest canopy may be closed over the stream and erosion from steep hillslopes may be deposited directly into streams. Stream side vegetation affects the stream environment in a variety of ways: it shades streams, thereby regulating water temperature and sunlight available for primary production; supplies nutrients in the form of litter for aquatic invertebrates and microorganisms; stabilizes streambank and bed with root systems; supplies large organic debris to the stream which shapes the physical structure of aquatic habitats and regulates sediment storage in the channel system; retards downslope and downstream movement of soil, sediment, particulate organic matter and nutrients dissolved in stream and soil water; and forms a distinctive wildlife habitat (Meehan et al. 1977). Upslope vegetation influences streams by regulating runoff characteristics (Harr 1976) and the rate of sediment supply to streams. Consequently, forest practices that affect riparian vegetation and hillslope vegetation and erosion rates have a broad range of impacts on the aquatic environment.

Here we focus only on the effects of timber harvest activities on organic debris loading in streams because this is a dominant management impact on physical characteristics of the stream environment (Swanson et al. 1976; Swanson and Lienkaemper 1978). Effects of forest practices on stream debris vary greatly with timber type, topography and timber felling and yarding systems (Table 2). In studies of ten cable-yarded units in old-growth Douglas-fir in western Oregon Froehlich (1973b) noted negligible changes in coarse (diam.>10 cm) and fine debris loading for units with free-falling buffer strips, but free-felled units without buffer strips experienced about a two-fold increase in coarse debris loading and a five-fold increase in fine organic debris. Cable assist, directionally-felled units without buffer strips had no increase in coarse material but about a three-fold increase in fines.

In spruce-hemlock forests on Prince of Wales Island, southeast Alaska, Swanson & Lienkaemper (unpub. data) observed coarse and fine debris loadings in three high-lead yarded clearcuts that were about 3 and 7 times the levels measured in three uncut streams.

The visual effects of altered organic debris loading in streams are conspicuous, but efforts to determine effects of these alterations on aquatic organisms, sediment routing and development of riparian vegetation are just beginning. In general guidelines for management of stream debris are based on the quantities and size and spatial distributions of debris observed in natural forested streams.

CASE STUDY - H. J. ANDREWS WATERSHED 10

Site Description and Methods

The discussion to this point has been focused primarily on the general effects of harvest and stand regeneration on Northwestern coniferous forest sites. But, generalizations are useful only in that they describe the types of responses one might expect following a harvest disturbance. Differences among sites in topography, soils, climate and vegetation virtually guarantee the land manager a wide range of responses to a given treatment.

In order to give more specific examples of ecosystem response to clearcutting we describe observations from a small watershed in the central western Cascade Range of Oregon which was intensively studied before and after timber harvest. This study exemplified responses to current harvest and regeneration practices.

Watershed 10 is a small (10.2 ha) watershed adjacent to the H. A. Andrews Experimental Forest near Blue River, Oregon. The forest, stream and erosion processes of this watershed were intensively studied before harvest by scientists associated with the Coniferous Forest Biome, US International Biological

TABLE 2. ORGANIC DEBRIS LOADING DATA FOR FOREST AND CLEARCUT STREAM REACHES (STREAM WIDTH 1 TO 8.5 m) IN WESTERN OREGON AND SOUTHEAST ALASKA. BULK DENSITY OF WOOD IN THE OREGON STREAMS WAS ASSUMED TO BE 0.58 AND FOR ALASKA 0.50 g/cm^3

Location	Sample size	Before logging		After logging	
		Coarse*	Fine	Coarse*	Fine
		kg/m^2			
Western Oregon+					
Old-growth forest	10	39.1	3.0		
Clearcut					
Free-falling	3	24.9	2.6	56.6	11.5
Cable-assist directional falling	4	50.1	3.8	46.0	12.0
Free-falling, buffer strip	3	38.5	2.5	35.8	3.2
Prince of Wales Island, AlaskaΔ					
Old-growth forest	3	5.3	1.0		
Clearcut, free-falling	3			15.6	7.1

* Diameter of coarse debris > 10 cm.

+ From Froehlich (1973b).

Δ From Swanson & Lienkaemper (unpub. data).

Program. Research on the forest was focused on its growth, nutrition and water use; stream research was concentrated on sources and utilization of energy and nutrients by stream biota. Of particular concern to both terrestrial and aquatic researchers was the interaction between forest and stream.

Watershed 10 was clearcut in 1975. After clearcutting, both terrestrial and aquatic research continued (first by the CFB and subsequently through a series of grants also funded by the National Science Foundation). The primary objective of post-clearcut research has been to examine the processes involved in re-establishing nutrient cycles with emphasis on vegetation regrowth; soil erosion; and stream biology and chemistry.

Watershed 10 is typical of the steep, deeply incised drainages in this part of the Oregon Cascades. Elevations range from 430 m at the outlet to about 670 m on the upper ridgelines. Average slope of the stream channel is 24°, side slopes range between 25° and 50°.

The climate is typical for the western Cascades. Annual precipitation averages 230 cm of which about 75% falls between October and March, mostly as rain. Mean annual temperature is 8.5°C; mean January and July temperatures are about 0.5°C and 18°C respectively.

Soils generally are deep and well drained. They are classed as typic distrochrepts (Soil Survey Staff 1960) and have an A_1 horizon about 20 cm deep over 50-80 cm of a B1-B2-B3 sequence. Soils are primarily gravelly clay loams with gravel content (>2 mm) ranging from 15-50% of soil volume. The soils are moderately acid; pH averages about 6.0.

Forest floors were classed as duff-mulls (Hoover & Lunt 1952). The average forest floor consisted of an L and F layer about 4-5 cm thick. No H layer was present. Numerous fallen logs were present on the soil surface.

Before logging the watershed was dominated by a 450-year-old site class II-III (Dilworth 1974) Douglas-fir forest. Forest environments within the watershed ranged from relatively hot and dry to cool and moist (Grier & Logan 1977). These environmental differences were reflected mainly in the composition of understory vegetation. In drier habitats the understory was dominated by rhododendron, salal and beargrass (*Xerophyllum tenax*). In the more mesic habitats, the understory was dominated by rhododendron, salal and/or Oregon grape. Understory vegetation in cool-moist environments was mainly swordfern and a variety of herbs such as twinflower (*Linnaea borealis*). A well developed understory tree stratum was present in all environments.

Table 3 shows the distribution of organic matter and N in various components of vegetation on Watershed 10 prior to and one year after harvest. Accumulations of living biomass and N contained in this biomass were large, especially in comparison with younger Douglas-fir stands (Cole et al. 1967, Turner[5]). Accumulations of organic matter and nutrients in detritus on the

[5] J. Turner. 1975. Nutrient cycling in a Douglas-fir ecosystem with respect to age and nutrient status. Ph.D. thesis. University of Washington, Seattle, Washington.

TABLE 3. DISTRIBUTION OF ORGANIC MATTER AND NITROGEN IN VARIOUS COMPONENTS OF A 450-YEAR-OLD DOUGLAS-FIR FOREST ON WS 10, H. J. ANDREWS EXPERIMENTAL FOREST BEFORE AND ONE YEAR AFTER CLEARCUTTING

Component	450-year-old Forest		One Year Clearcut	
	Organic Matter*	N**	Organic Matter	N
	kg/ha			
Trees				
Foliage	12,400	128	0	0
Woody	699,000	391	0	0
Understory				
Foliage	1,470	15	359+	4+
Woody	5,310	3	850+	1+
Roots	152,000++	198++	146,000++	205++
Total Vegetation	870,180	735	147,209	210
Detritus				
Forest Floor	51,200	256	30,870ΔΔ	171ΔΔ
Logs, snags, stumps	215,000	215	103,000ΔΔ	51ΔΔ
Soil	133,000Δ	3,724Δ	156,077ΔΔ	3,902ΔΔ
System Total	1,269,380	4,930	437,156	4,334

* From Grier & Logan (1977)

** C. C. Grier, unpub. data; methods outlined by Grier (1977)

\+ From Gholz, Hawk & Campbell (1977)

++ From Santantonio, Hermann & Overton (1977); with no decomposition of large roots during the first year and 25% annual decomposition for fine roots (Sollins, Cromack, Fogel & Li, in press).

Δ From Sollins et al. (in press)

ΔΔ K. Cromack, Jr., unpub. data

soil surface were also large compared with younger forests (Harris et al. 1973; Cole et al. 1967). Forest floor material and standing and fallen dead trees amounted to 21% of the total soil organic matter accumulation, and 9.5% of N accumulation.

Soil organic matter constituted only 10.5% of the total organic accumulations in the ecosystem prior to clearcutting. In contrast, the major N reserve was the soil, which contained 75.5% of the total system N.

Leaf biomass and leaf area (all sides of all leaves) on the watershed were comparable with values reported for other mature Douglas-fir stands (Grier & Running 1977; Gholz et al. 1976). In contrast with many younger forests, 12% of leaf biomass and about 15% of total leaf area were in the understory of this old-growth forest.

Aboveground net primary production on the watershed averaged 7970 kg/ha/yr while belowground net production was about 2900 kg/ha/yr. Net production was entirely detritus; living biomass declined at the rate of about 8400 kg/ha/yr during the study. This is in distinct contrast with younger stands in which 70-85% of net production accumulates annually as woody biomass (Grier & Logan 1977).

In spite of low production, decreasing biomass and the large amounts of decomposing detritus, the ecosystem was basically conservative of nutrients. Inputs of N in precipitation and dust averaged 2.0 kg/ha/yr; N-fixation by canopy-inhabiting lichens added an additional 2.7 kg/ha/yr (Sollins et al. in press).

Overall, the old-growth forest of Watershed 10 had several unique attributes and several characteristics similar to those of younger forests. Unique aspects were the large accumulations of biomass and detritus and a production economy dominated by detritus. The old-growth forest was similar to younger ones in conserving essential nutrients.

Harvest and Site Preparation

During the summer of 1975, Watershed 10 was clearcut. No roads were constructed on the watershed itself but two landings were built on the ridgeline. Trees were felled upslope and then yarded using a skyline cable system. Cull logs and a large proportion of the fallen logs from earlier mortality also were yarded to the landing and sorted. Unusable material was piled near the landings for later burning; merchantable material was placed on trucks.

Slash remaining after "clean yarding" the watershed was not burned. The following spring the cutover area was planted with 2-0 bareroot Douglas-fir seedlings on a 2.4 x 2.4 m spacing.

Harvest - Removal of Vegetation, Debris and Nutrients

Yarding of material from the watershed resulted in the removal of 815 mT/ha of organic matter, or 64.2% of the total organic matter in the system (Table 3). However, only 574 kg/ha of N were removed by harvesting, or about 12% of the total N in the system. Residual aboveground live biomass on the watershed one year after logging totaled only 0.16% of prelogging vegetation biomass. Roots constituted the largest single organic matter pool following logging. Soil organic matter was assumed to increase by approximately 23,077 kg/ha or 17% due to stirring of soil and mixing in of forest floor by logging.

During the first year after logging, uptake of N by residual vegetation is estimated to have been approximately 4 kg/ha, assuming essentially complete new foliage. Immobilization or even temporary uptake of N may have occurred in woody residues, both above and belowground. Sollins, Cromack, Fogel and Li (in press), found decomposing fine roots of Douglas-fir to increase 19% in total N mass during first-year decomposition, indicating that rapid fine root decay may be a temporary "sink" for soil N. Coarse roots take much longer to decompose, hence, would be a long-term input to soil organic matter (S. Cline, personal commun.).

Loss of N dissolved in stream runoff totaled 0.8 kg/ha the first year post-clearcutting (P. Sollins, personal commun.). Export of particulate organic N totaled 2.0 kg/ha during the first year post-clearcutting (Swanson, personal commun.).

Erosion activity in Watershed 10 has been monitored since cutting in order to assess the effect of deforestation and ecosystem recovery on each erosion process and total sediment yield. With only three years of post-cutting data available, it is premature to assess management impacts in detail. However, preliminary evaluation of bedload export for WY 1976 through WY 1978 does yield interesting insights and hypotheses.

Four storms during WY 1976 washed 17 T of particulate into the sediment basin at the base of the watershed. The first two storms produced peak flows that typically occur several times a year, yet they exported 6.1 T of bedload which is nearly 7 times annual export for old-growth forest conditions (Swanson et al. in press). About two-thirds of this material was organic matter, mostly needles and twigs input to the stream during logging operations. The third storm was larger and it exported 7.0 T of bedload of which 31% was organic matter. The fourth storm produced a still larger peak flow but this event exported only 3.5 T of bedload material including only 17% organic matter. Apparently by this time, much of the readily transported organic material had been flushed downstream to the sediment basin or it was deposited in more stable debris accumulations within the channel. Total bedload export during the first year following clearcutting was 19 times greater than the estimated average annual value for the forested condition (Swanson et al., in press).

Water Year 1977 was the driest in the 86 year history of precipitation records in central western Oregon, and there was no significant bedload discharge from the watershed. During WY 1978 several major events caused deposition of 8.9 T of material in the basin.

These results follow two general patterns: 1) a decline in total export through the sequence of major storms and 2) a decrease during a season in the proportion of organic matter in major export pulses. Water Year 1976 experienced about twice the total export as WY 1978, although the later period included the two highest flows since clearcutting occurred.

The impact of logging practices on particulate matter export can be considered in terms of two factors: 1) availability of material to be moved and 2) occurrence and magnitude of storm flow events necessary to move it. Timber harvest activities may affect both sediment availability and watershed hydrology. In several of the experimental watershed studies in western Oregon, forest practices, in particular construction of an extensive road system, have resulted in increased peak flows for some types of events (Harr 1976). However, for Watershed 10 following clearcutting Harr & McCorison (1979) have noted decreased peak flows for events involving snowmelt and no detectable changes in peak flow for rainfall only events. Therefore, changes in sediment export following clearcutting primarily reflect changes in storage and availability of materal for export rather than altered watershed hydrology.

Based on study of organic debris storage in the channel and channel geometry, export from Watershed 10 apparently will come from three sources, each associated with a specific time frame: 1) material input to the channel during the logging operation itself which was mainly fine, green organic matter (material larger than about 5 cm diameter, 50 cm length was hand cleaned from the channel) and some mineral soil; 2) material which had entered the channel by natural processes before logging and had been in temporary storage behind obstructions (logs and root wads) in the channel, but was released from storage when the obstructions were yarded out of the channel; and 3) material input to the channel by hillslope erosion processes following logging. There may be a general phasing of export of these three sources of material with source 1 mainly contributing material to watershed export in the first one to three years following cutting; source 2 gaining importance in the latter part of this period; and post-logging hillslope erosion (source 3) becoming the dominant source several years after cutting. This routing of material through a watershed is an important element of ecosystem response to disturbance and it is relevant to interpretation of sediment yield data from experimental watersheds. For example, sediment yield is commonly interpreted in terms of hillslope erosion where in many cases initial post-disturbance pulses of sediment primarily reflect changes in channel storage. These interpretations must be based on a whole-system level understanding of soil and sediment routing as depicted in Fig. 2.

Harvest Disturbance and Compaction of Soil

Following yarding of Watershed 10, soil disturbance and compaction were inventoried using a continuous line transect sampling method (Harr & McCorison 1979). In Watershed 10 following logging 70% of the area was uncompacted, 10% slightly compacted, and 20% deeply compacted, based on evidence of more than 3 passes of equipment or logs. Undisturbed areas covered 50% of the watershed, 16% was lightly disturbed, and 34% deeply disturbed. These figures indicate a much greater degree of soil compaction and disturbance than that reported from previous studies of skyline yarding for clearcuts and thinning operations (Table 1). Both heavily compacted and deeply disturbed soils on Watershed 10 were about 7 times more extensive than in the skyline clearcut studied by Dyrness (1967a). The definition of terms in these two studies was essentially the same, so these marked differences must derive from real contrasts in conditions or differences in field interpretation.

The topography and landing location in Watershed 10 did not permit full suspension of logs over all areas of the watershed. Topography and landing location resulted in many logs being dragged across the southeast slope, exposing mineral soil and in some instances uprooting stumps. Logs on the northwest side were yarded away from the slope, so ground disturbance was minimal.

Effects on Streams

We determined changes in organic debris loading in and adjacent to the stream on Watershed 10. Before logging coarse (diameter > 10 cm) debris in a 3 m wide band along the stream was 8.8 m^3/100 m of channel length in the main branch and 18.5 m^3/100 m in tributary channels (Froehlich et al. 1972). After logging the main branch contained 17.2 m^3/100 m and the tributaries had 25.3 m^3/100 m (H. A. Froehlich, personal commun.).

Coarse debris loading in the stream corridor increased by about 30 to 95%, in spite of efforts to keep debris from entering the channel by directional felling with hydraulic jacks. Side slopes of up to 70% and the heavy down hill lean of numerous, massive old-growth trees contributed to increased debris loading in the stream area. In contrast, the terrestrial standing crop of down logs was reduced to 22% of the pre-logging level (Table 3).

Most of the recorded increase in debris loading is material on the stream bank rather than in the active channel. The annually active streambed experienced a reduction of coarse debris loading. About half of the large debris pieces which trapped sediment in the main channel before logging were removed for utilization or fire hazard reduction. Hand cleaning of the channel involved placing slash in piles along the stream bank. These practices resulted in heavy slash concentrations (> 30 cm deep) bordering 50% of the stream perimeter. The deeper slash accumulations along the channel margins are trapping sediment transported downslope by surface erosion processes. These slash deposits, composed primarily of piles of limbs, also affect development of riparian vegetation by forming sites unsuitable for establishment of many important riparian species, such as red alder, which commonly establish on bare mineral soil or deposits of sediment. The long-term effects of these conditions on sediment routing, riparian vegetation development and aquatic organisms are being followed as part of the study on response of the Watershed 10 ecosystem to clearcutting.

Summary of Harvest Effects on Watershed 10

The major removal of N from the watershed was the export of logs. Watershed output of N by stream transport of soluble and particulate transport has been very modest, totalling 2.8 kg/ha during the first year. All losses of N from harvesting, solution and erosion were 577 kg/ha, which represented 11.6% of the total system N capital.

Sediment losses increased 19 times over the pre-cutting annual average for the forested condition (Swanson et al. in press). Increased erosion resulted from both removal of pre-logging debris dams and increased sediment deposition within the channel.

Harvest effects on soils in Watershed 10 resulted in 20% severe compaction, less than half that of typical tractor-skidder logging. Heavy soil compaction was about four times more extensive on Watershed 10 than in the skyline clearcut studied by Dyrness (1967a); the topography and landing location in Watershed 10 did not permit full suspension of logs over all areas of the watershed.

Debris loading along the streambanks increased 130 to 195% over pre-logging conditions, while coarse debris loading of the stream decreased. The deeper slash deposits bordering 50% of the stream margin are trapping sediment transported downslope by surface erosion processes, while inhibiting establishment of riparian vegetation such as red alder.

ALTERNATIVES TO CURRENT PRACTICES

Future Management Considerations for Nitrogen Cycling

Typical harvest and slash burn practices in Pacific Northwest forests remove less than 20% of the total system N capital. Provided soil compaction and erosion are minimized by use of logging methods appropriate to the terrain, maintenance of sustained productivity of forested lands depends upon restitution of essential nutrients in sufficient quantities. Nitrogen capital can be restored either by fertilizer or by N fixation; however, increased energy costs and priority use of fertilizers for food production (Bengtson 1978, 1979), may encourage renewed silvicultural interest in N fixation. Future questions which need research include how to manage the various kinds of N fixers available in the Pacific Northwest, including red alder, snowbrush and both native and introduced legumes, to best realize the potential benefits of such species. If the goal of forest management is maintenance of sustained site productivity, then different time allowances for managing secondary succession, including N fixation, may be necessary for different site qualities. Integrated studies of conifer seedling survival in the context of both nutrient availability and potential competition are needed if proper evaluation of the benefits: cost of N fixation are to be adequately assessed. Modern methods for studying plant-water relations and C allocation should be utilized in assessing the reality of competition by N fixing species with conifers. Furthermore, animal damage studies should consider the possible protective benefits of brush species such as snowbrush, which usually are considered strictly as competing species. The potential silvicultural benefits of brush in protecting sites from excess erosion while desirable conifer stands are being re-established should also be considered (Youngberg 1966).

Management of Soils

Management strategies designed to minimize soil losses benefit both forest and aquatic resources by maintaining water quality and productivity of tree-growing sites and reducing disturbance of the stream environment. Forest land managers in the Pacific Northwest are currently experimenting with methods to decrease erosion accelerated by roads and timber harvest activities. Improved road placement, design, construction methods, and maintenance have been a big part of this effort. Common techniques involve keeping roads high on ridges, minimizing construction of fills by "end-hauling" and "fully benching", and maintaining road drainage systems, particularly during large storms.

Improvements in yarding system capabilities, such as longspan skyline, reduce road mileage and the amount of soil damage due to the logging system itself. In the very steep, debris avalanche-prone lands in portions of the Oregon Coast Range, forest land managers are experimenting with felling, yarding and slash disposal systems designed to reduce the occurrence of soil mass movements from the heads of small streams. Where wind throw potential of residual trees is judged to be low, small stands of trees are left in these critical headwall areas. Other headwalls are cut with directional felling techniques, but they are not broadcast burned in order to maintain the soil binding root systems of residual brushy vegetation.

In spite of expanded use of these methods, clear assessment of their benefits has not been conducted. Inventory of erosion under forested conditions and following various roading and logging practices should be carried out to determine which erosion processes are dominant and what are the erosional and economic benefits of innovative harvest and roading systems employed to minimize erosion. Such inventory systems are being developed by several National Forests in the Pacific Northwest and Rocky Mountains. In these areas of steep terrain, inventories of debris avalanches, based on studies of aerial photographs and updated by field surveys following major, debris avalanche-triggering storms, provide a basis for estimating erosion from different types of roads and harvest systems.

On a broader scale, forest land managers should plan soils management on the scale of large drainage basins, since management activities affect soil and sediment routing on this scale. At present, these effects are randomly distributed and efforts to minimize these impacts are based on localized, site specific decisions. Perhaps in the future we will have the capability and inclination to manage soil and sediment routing on a broader scale. In this view, watersheds could be considered a mosaic of roaded, forested and regenerating sites each with a characteristic susceptibility to erosion determined by natural and man-induced factors. Management of such a landscape would have the objective of distributing zones of high erosion potential geographically and over time, in order to minimize concentration of land in highly erodable conditions near sensitive stream reaches.

Future Management Considerations for Streams

Over the past decade federal and state legislation have encouraged the protection of small streams which make up such a large proportion of the total length of river systems. In steep forest land small streams are particularly sensitive to changes in vegetation and soil conditions on adjacent hillslopes. Therefore, management of streams involves not only consideration of in-stream factors, but also variation in long-term vegetation and soil erosion conditions on hillslopes.

A key element of small streams in the forest environment is woody organic debris. Management activities may greatly increase or decrease total organic debris loading and alter the size distribution of in-stream organic debris. Currently suggested guidelines for stream debris management in the Pacific Northwest are to leave the natural pieces of debris which had entered the channel before logging, to introduce no new organic material during logging operations, and to plan for future large debris inputs to streams (Swanson & Lienkaemper 1978). In very steep terrain, however, these goals are difficult to accomplish, as the Watershed 10 example demonstrates.

Stream protection may be provided by buffer strips of vegetation along streams. Although buffer strips usually are justified on the basis of minimizing stream water temperature increases, streamside vegetation has a great variety of effects on the aquatic ecosystem (Meehan et al. 1977). Shading by streamside vegetation reduces sunlight available to drive in-stream primary productivity. Riparian vegetation provides coarse and fine litter for the stream that serves as a primary source of nutrients for aquatic invertebrates and shapes the physical structure of the stream ecosystem. This vegetation also stabilizes banks and retards downstream and downslope movement of soil and sediment. Consequently, in judging the value of buffer strips their full range of functions for the stream ecosystem should be considered. Some of these functions may continue to be carried out even if a buffer strip experiences blow down.

Recognition of the role of streamside vegetation as the source of large organic debris for streams raises some questions concerning long-term implications of forest practices (Swanson & Lienkaemper 1978). Good silvicultural practices are designed to minimize production of unutilized woody debris by frequent thinning and harvesting. Unless streamside vegetation is specifically managed with one goal being production of large woody debris for the stream, levels of debris loading in streams will gradually decline as natural debris and slash from the first logging entry is decomposed and transported downstream. Reduced debris loading will result in altered aquatic habitat, reduced in-stream sediment storage associated with large organic debris, and increased rate of sediment movement through stream systems. The biological and physical consequences of these broad scale changes in stream systems are unknown.

ACKNOWLEDGEMENTS

We thank R. L. Fredriksen, G. Lienkaemper and F. M. McCorison, for permission to use unpublished data. P. Sollins reviewed the manuscript. CFB grants GB-20963, GB-36810X1, and NSF grant DEB-77-06075 supported our work.

LITERATURE CITED

Ahlgren, I. F. and C. E. Ahlgren. 1960. Ecological effects of forest fires. Bot. Rev. 26:483-533.

Bengston, G. W. 1978. Strategies for maintaining forest productivity: a researcher's perspective. p. 123-159. In: Proc. of a Symposium on Principles of Maintaining Productivity on Prepared Sites. USDA For. Serv., So. For. Exp. Stn., New Orleans, LA.

Bengston, G. W. 1979. Forest fertilization in the United States: Progress and outlook. J. of Forestry 77:222-227.

Berg, A. and A. Doerksen. 1975. Natural fertilization of a heavily thinned Douglas-fir stand by understory red alder. Res. Note No. 56. Forest. Res. Lab. Oregon State Univ., Corvallis, OR. 3 p.

Bockheim, J. G., T. M. Ballard and R. P. Willington. 1975. Soil disturbance associated with timber harvesting in southwestern British Columbia. Can. J. For. Res. 5:285-290.

Bormann, F. H., G. E. Likens and J. M. Melillo. 1977. Nitrogen budget for an aggrading northern hardwood forest ecosystem. Science 196:981-983.

Bormann, F. H. and G. H. Likens. 1979. Pattern and Process in a Forested Ecosystem. Springer-Verlag, New York, NY. 244 p.

Cole, D. W. and S. P. Gessel. 1965. Movement of elements through a forest soil as influenced by tree removal and fertilizer additions. p. 95-104. In: C. T. Youngberg (ed.). Forest-soil relationships in North America. Oregon State Univ. Press. Corvallis, OR.

Cole, D. W., S. P. Gessel and S. F. Dice. 1967. Distribution and cycling of N, P, K and Ca in a second-growth Douglas-fir ecosystem. p. 197-232. In: Symposium on primary productivity and mineral cycling in natural ecosystems. Amer. Assoc. Adv. Sci. 13th Ann. Meeting, New York, Univ. Maine Press, Orono, ME.

Dietrich, W. E. and T. Dunne. 1978. Sediment budget for a small catchment in mountainous terrain. Zeit. für Geomorphol. Suppl. Bd. 29:191-206.

Dilworth, J. R. 1974. Log scaling and timber cruising. Oregon State University Book Stores, Inc. Corvallis, OR.

Dyrness, C. T. 1965. Soil surface disturbance following tractor and high-lead logging in the Oregon Cascades. J. For. 63:272-275.

Dyrness, C. T. 1967a. Surface soil conditions following skyline logging. USDA For. Serv. Res. Note PNW-55. 8 p.

Dyrness, C. T. 1967b. Mass movements on the H. J. Andrews Experimental Forest. USDA For. Serv. Res. Paper PNW-42. 12 p.

Dyrness, C. T. 1972. Soil surface conditions following balloon logging. USDA For. Serv. Res. Note PNW-182. 7 p.

Dyrness, C. T. 1973. Early stages of plant succession following logging and burning in the western Cascades of Oregon. Ecology 54:57-69.

Dyrness, C. T. 1976. Effect of wildfire on soil wettability in the high Cascades of Oregon. USDA For. Serv. Res. Paper. PNW-202. 18 p.

Fogel, R. and G. Hunt. 1979. Fungal and arboreal biomass in a western Oregon Douglas-fir ecosystem: Distribution patterns and turnover. Canad. J. For. Res. 9:245-256.

Franklin, J. F. and C. T. Dyrness. 1973. Natural vegetation of Oregon and Washington. USDA For. Serv. Tech. Rep. PNW-8. 417 p.

Fredriksen, R. L. 1970. Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds. USDA For. Serv. Res. Paper PNW-104. 15 p.

Fredriksen, R. L. 1971. Comparative chemical water quality--natural and disturbed streams following logging and slash burning. p. 125-137. In: J. T. Krygier and J. D. Hall (eds.) Forest land uses and stream environment.

Fredriksen, R. L. 1972. Nutrient budget of a Douglas-fir forest on an experimental watershed in western Oregon. p. 115-131. In: J. F. Franklin, L. J. Dempster and R. H. Waring (eds.). Proc. of a Symposium on Research on Coniferous Forest Ecosystems. Pac. Northwest For. and Range Exp. Sta., Portland, OR.

Fredriksen, R. L., D. G. Moore and L. A. Norris. 1975. The impact of timber harvest, fertilization and herbicide treatment on streamwater quality in western Oregon and Washington. p. 283-313. In: B. Bernier and C. H. Winget (eds.). Forest soils and forest land management. Les Presses de l'Universite Laval. Quebec, Canada.

Fredriksen, R. L. and R. D. Harr. 1979. Soil, vegetation and watershed management. p. 231-260. In: P. E. Heilman, H. W. Anderson and D. M. Baumgartner (eds.). Forest Soils of the Douglas-fir region. Wash. State Univ. Exten. Serv., Pullman, WA.

Froelich, H. A., D. McGreer and J. R. Sedell. 1972. Natural debris within the stream environment. US Intern. Biol. Prog. Conif. For. Biome Internal Rep. 96. 10 p.

Froehlich, H. A. 1973a. The impact of even-age forest management on physical properties of soils. p. 199-220. In: R. K. Hermann and D. P. Lavender (eds.). Even-age management. Proc. of Symp. Oregon State University. Corvallis, OR.

Froehlich, H. A. 1973b. Natural and man-caused slash in headwater streams. Loggers' Handbook. Pacific Logging Congress. 33:1-8.

Froehlich, H. A. 1974. Soil compaction: implication for young-growth management. p. 49-64. In: A. B. Berg (ed.). Managing young forests in the Douglas-fir region. Proc. of Symp. Oregon State University. Corvallis, OR.

Froehlich, H. A. 1976. The influence of different thinning systems on damage to soil and trees. p. 333-344. In: Proceedings XVI IUFRO World Congr. Div. IV. Norweg. IUFRO Congr. Committee c/o Norweg. For. Res. Inst. Ås-NLH, Norway.

Froehlich, H. A. 1978. The physical effects of timber harvesting on forest soils. Proc. 1977 Nat. Conv. Soc. Am. For. Albuquerque, NM. p. 229-237.

Gholz, H. L., F. K. Fitz and R. H. Waring. 1976. Leaf area difference associated with old-growth forest communities in the western Oregon Cascades. Can. J. For. Res. 6:49-57.

Gholz, H. L., G. M. Hawk and A. Campbell. 1977. Secondary succession studies in the Douglas-fir region: component biomass and leaf area development after clearcutting on a small western Oregon watershed. Bull. Ecol. Soc. Am. 58:61.

Grier, C. C. 1977. Biomass, productivity and N-P cycles in hemlock-spruce stands of the central Oregon coast. p. 71-81. In: R. J. Zasoski and W. A. Atkinson (eds.). Western hemlock management. Inst. For. Products contrib. No. 34. Coll. For. Res. Univ. of Wash. Seattle, WA.

Grier, C. C. and M. S. Logan. 1977. Old-growth *Pseudotsuga menziesii* communities of a western Oregon watershed: biomass distribution and production budgets. Ecol. Monogr. 47:373-400.

Grier, C. C. and S. W. Running. 1977. Leaf area of mature northwestern coniferous forests: relation to site water balance. Ecology 58:893-899.

Harr, R. D. 1976. Forest practices and streamflow in western Oregon. USDA For. Serv. Gen. Tech. Rep. PNW-49. 18 p.

Harr, R. D. and F. M. McCorison. 1979. Initial effects of clearcut logging on size and timing of peak flows in a small watershed in western Oregon. Water Resources Res. 15:90-94.

Harris, W. F., R. A. Goldstein and G. S. Henderson. 1973. Analysis of forest biomass pools, annual primary production and turnover of biomass for a mixed deciduous forest watershed. p. 41-64. In: H. E. Young (ed.). IUFRO biomass studies. Univ. Maine Press. Orono, ME.

Hauge, C. J. 1977. Timber harvesting and soil erosion. Interim report. Ca. State Dept. For. 55 p.

Hoover, M. D. and A. H. Lunt. 1952. A key for the classification of forest humus types. Soil Sci. Soc. Am. Proc. 16:368-370.

Ketcheson, G. L. and H. A. Froehlich. 1978. Hydrologic factors and environmental impacts of mass soil movements in the Oregon coast range. Water Resources Res. Inst. Pub. No. 56. 94 p.

Kimmins, J. P. and M. C. Feller. 1976. Effect of clearcutting and broadcast slash burning on nutrient budgets, streamwater chemistry and productivity in western Canada. p. 186-200. In: Proceedings XVI IUFRO World Congr. Div. I Forest Environment and Silviculture. Norweg. IUFRO Cong. Committee. c/o Norweg. For. Res. Inst. Ås-NLH, Norway.

Larsen, M. J., M. F. Jurgensen and A. E. Harvey. 1978. N_2 fixation associated with wood and wood decay fungi in western Montana. Canad. J. For. Res. 8:341-345.

Leopold, L. B., M. G. Wolman and J. P. Miller. 1964. Fluvial processes in geomorphology. Freeman. San Francisco, CA. 522 p.

McColl, J. G. 1978. Ionic composition of forest soil solutions and effects of clearcutting. Soil Sci. Soc. Am. J. 42:358-363.

McNabb, D. H., J. M. Geist and C. T. Youngberg. 1977. Nitrogen fixation by *Ceanothus velutinus* in northeastern Oregon. p. 127-128. In: Agronomy Abstracts.

Meehan, W. R., F. J. Swanson and J. R. Sedell. 1977. Influences of riparian vegetation on aquatic ecosystems with particular reference to salmonid fishes and their food supply. p. 137-145. In: R. R. Johnson and D. A. Jones (eds.). Importance, preservation and management of riparian habitat: a symposium. USDA For. Serv. Gen. Tech. Rep. RM-43.

Megahan, W. F. 1972. Logging, erosion, sedimentation--are they dirty words? J. For. 70:403-407.

Miller, R. E. and R. D. Fight. 1979. Fertilizing Douglas-fir forests. USDA Forest Serv. Gen. Tech. Rpt. PNW-83. 20 p.

Newton, M., B. A. El-Hassan and J. Zavitkovski. 1968. Role of red alder in western Oregon forest succession. p. 73-84. In: J. M. Trappe, J. F. Franklin, R. F. Tarrant and G. H. Hansen (eds.). Biology of alder. Pac. Northwest For. and Range Exp. Stn., Portland, OR.

Power, W. E. 1974. Effects and observations of soil compaction in the Salem District. USDI Bureau Land Mgmt. Tech. Note T/N-256. 12 p.

Rice, R. M., J. S. Rothacher and W. F. Megahan. 1971. Erosional consequences of timber harvesting: an appraisal. p. 321-329. In: R. S. Pierce, C. W. Martin, C. C. Reeves, G. E. Likens and F. H. Bormann (eds.). Proc. Nat. Symp. on Watersheds in Transition. Am. Water Res. Assoc., Fort Collins, CO.

Santantonio, D., R. K. Hermann and W. S. Overton. 1977. Root biomass studies in forest ecosystems. Pedobiologia 17:1-31.

Soil Survey Staff. 1960. Soil classification--a comprehensive system--7th approximation. USDA, Wash., D.C. 265 p.

Sollins, P., K. Cromack, Jr., R. Fogel and C. Y. Li. Role of low molecular weight organic acids in the inorganic nutrition of fungi and higher plants. In: D. Wicklow and G. Carroll (eds.). Fungal ecology, Marcel Dekker, New York (in press).

Sollins, P., C. C. Grier, F. M. McCorison, K. Cromack, Jr., R. Fogel and R. L. Fredriksen. The internal element cycles of an old-growth Douglas-fir stand in western Oregon. Ecol. Monogr. (in press).

Stone, E. L. 1973. The impacts of timber harvest on soils and water. p. 427-467. In: Report of the President's advisory panel on timber and the environment. US Govt. Printing Office.

Swank, W. T. and J. E. Douglas. 1977. Nutrient budgets for undisturbed and manipulated hardwood forest ecosystems in the mountains of North Carolina. p. 343-364. In: D. L. Correll (ed.). Watershed research in eastern North America. Chesapeake Bay Center for Environmental Studies. Smithsonian Inst. Edgewater, MD.

Swanson, F. J. and C. T. Dyrness. 1975. Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade range, Oregon. Geology 3:393-396.

Swanson, F. J., G. W. Lienkaemper and J. R. Sedell. 1976. History, physical effects and management implications of large organic debris in western Oregon streams. USDA For. Serv. Gen. Tech. Rep. PNW-56. 15 p.

Swanson, F. J. and G. W. Lienkaemper. 1978. Physical consequences of large organic debris in Pacific Northwest streams. USDA For. Serv. Gen. Tech. Rep. PNW-69. 12 p.

Swanson, F. J., R. L. Fredriksen and F. M. McCorison. Material transfer in a western Oregon forested watershed. Int. Biol. Prog. Coniferous Forest Biome Synthesis Volume. (in press).

Swanston, D. N. and F. J. Swanson. 1976. Timber harvesting, mass erosion and steepland forest geomorphology in the Pacific Northwest. p. 199-221. In: D. R. Coates (ed.). Geomorphology and engineering. Dowden, Hutchison and Ross, Inc. Stroudsburg, PA. 360 p.

Waring, R. H. and J. F. Franklin. 1979. Evergreen coniferous forests of the Pacific Northwest. Science 204:1380-1386.

Wooldridge, D. D. 1960. Watershed disturbance from tractor and skyline crane logging. J. For. 58:369-372.

Youngberg, C. T. 1959. The influence of soil conditions following tractor logging on the growth of planted Douglas-fir seedlings. Soil. Sci. Soc. Am. Proc. 23:76-78.

Youngberg, C. T. 1966. The silvicultural benefits of brush. Soc. Amer. For. Proc. p. 55-59.

Youngberg, C. T. and A. G. Wollum, II. 1976. Nitrogen accretion in developing *Ceanothus velutinus* stands. Soil Sci. Soc. Am. J. 40:109-112.