FIRE, LOGGING, AND DEBRIS DISPOSAL EFFECTS ON SOIL AND WATER IN NORTHERN CONIFEROUS FORESTS

Norbert V. DeByle, Principal Plant Ecologist
U.S. Department of Agriculture, Forest Service
Intermountain Forest and Range Experiment Station
Ogden, Utah 84401, U.S.A.[1]

SUMMARY

Many seral northern coniferous forest types are dependent upon periodic wildfire for their perpetuation. Man partially mimics the role of wildfire by clearcut logging of these forests and often by subsequent burning of the logging debris. Mineral soil is exposed and conditions are provided for forest regeneration.

Impacts on the environment sometimes are associated with these sudden disturbances. Most obvious, and best documented, are increased soil erosion, channel cutting, and siltation of streams. Some more subtle impacts are: decreased evapotranspiration and increased streamflow, increased insolation and altered microclimate, induced water repellency of soils by fire, changes in the nutrient cycling processes, and flushes of dissolved materials out of the system and into the aquatic environment. Most subtle and difficult to measure is the possibility of long-term site quality changes.

Particularly during the past decade there has been unprecedented concern about these impacts. This concern has resulted in much research, some of which is summarized and interpreted in this paper. An explanation is given that shows why, under some conditions, clearcutting or fire has severe impacts on the environment and why, under others, the impacts are minimal or not even detectable. The variables of soils, geology, topography, climate, and forest type are considered.

Keywords: wildfire; clearcutting; forest residues; site quality; water quality; nutrient cycling.

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[1] Stationed in Logan, Utah, at the Forestry Sciences Laboratory maintained in cooperation with Utah State University.

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EFFETS DES INCENDIES, DE L'ABATTAGE DES ARBRES ET DE LA DISPOSITION DES DEBRIS SUR LES TERRAINS ET LES EAUX DANS LA FORET DE CONIFERES BOREALE

Norbert V. DeByle
Principal Plant Ecologist
USDA Forest Service
Intermountain Forest and Range Experiment Station
Ogden, Utah 84401, U.S.A.

RESUME

Plusieurs types de forêts de conifères boréales, lesquels types de forêts sont transitionnels, dépendent, pour leur perpétuation, des incendies de forêt périodiques. L'homme mimique le rôle des incendies en abattant des portions de ces forêts et le plus souvent, en brûlant les débris ainsi obtenus. Le sol minéral est, de cette facon, exposé, fournissant les conditions nécessaires pour la régénération de la forêt.

On associe parfois certains effets sur le milieu environnant à ces perturbations soudaines. Les effets les plus manifestes, et ceux sur lesquels on s'est le mieux documenté, sont l'augmentation de l'érosion du terrain, un ravinement dense et l'envasement des cours d'eaux. Quelques effets plus subtils sont: un décroissement de l'évapotranspiration et un accroîssement du débit des cours d'eaux, un accroîssement de l'insolation et altération du micro-climat, une imperméabilité du sol causée par le feu, un changement dans les processus cycliques de nutrition et l'expulsion de matériaux dissous hors du système et dans le milieu aquatique environnant. L'effet le plus subtil et le plus difficile à mesurer est le changement potentiel à long terme de qualité du site.

Particulièrement pendant les dix dernières années, ces effets ont causé une inquiétude sans précédent. Cette inquiétude a résulté en beaucoupe de recherche, dont une partie est résumée et interprétée dans cet article. Il y est donné une explication qui montre pourquoi, dans certaines conditions, l'abattage des arbres ou l'incendie de forêt a des effets graves sur le milieu environnant et pourquoi, dans d'autres conditions, les effets sont minimes et même indétectables. Les variables telles que terrain, géologie, topographie, climat, et type de forêt sont considérées.

FOLGEN VON FEUER, KAHLSCHLAG UND VERBRENNEN VON UEBRIGBLEIBENDEN HOLZRESTEN AUF DIE BOEDEN UND WASSERLAEUFE IN DEN NOERDLICHEN NADELWAELDERN

Norbert V. DeByle
Principal Plant Ecologist
USDA Forest Service
Intermountain Forest and Range Experiment Station
Ogden, Utah 84401, U.S.A.

ZUSAMMENFASSUNG

Viele Seralarten der nördlichen Nadelwälder erfordern periodisch Waldbrände für ihr Fortbestehen. Der Mensch ahmt teilweise die Rolle von Waldbränden durch Kahlschlag dieser Wälder und oft auch durch nachfolgendes Verbrennen der beim Kahlschlag anfallenden Holzreste nach. Mineralboden wird dadurch blosgelegt und die Voraussetzungen für eine Wiederaufforstung werden geschaffen.

Einwirkungen auf die Umgebung sind manchmal mit diesen plötzlichen Störungen verbunden. Am deutlichsten und in der Vergangenheit am klarsten belegt sind die gesteigerte Auswaschung des Bodens, die Furchenbildung und Versandung der Wasserläufe. Einige heimtückischere Folgen sind die verminderte Ausdünstung und gesteigerter Wasserablauf; gesteigerte Austrocknung durch die Sonne und veränderte klimatische Standortbedingungen; induzierte Wasserabstoßung der Böden, verursacht durch Feuer; Veränderungen in den Nahrungskreislaufsprozessen und Abfluß von aufgelösten Stoffen aus dem System in eine wasserhaltige Umgebung. Am heimtückischsten und schwierig zu messen ist die Möglichkeit von bodenständigen Qualitätsveränderungen auf lange Sicht hinaus.

Besonders während der letzten zehn Jahre sah man eine noch nie dagewesene Besorgnis betreffs dieser Einwirkungen. Diese Besorgnis führte zu umfangreicher Forschungsarbeit; ein Teil davon wurde in der vorliegenden Arbeit zusammengefaßt und erklärt. Eine Auslegung wurde hier wiedergegeben die zeigt, warum unter bestimmten Voraussetzungen der Kahlschlag oder das Feuer starke Einwirkungen auf die Umgebung hat, und warum bei anderen Voraussetzungen die Einwirkungen minimal oder überhaupt nicht feststellbar sind. Die Variablen von Böden, der Geologie, der Topographie, des Klimas und die Art des Waldbestandes sind dabei mit in Betracht gezogen.

FIRE ECOLOGY

The information in this paper applies to many forest types in the circumboreal forests and conifer extensions to the south. Most of the citations come from North America, from the boreal conifer forest, the eastern temperate pine-hardwood forest, and the western temperate conifer forest. Many tree taxa in these forests are "fire types." They have evolved through many centuries to reproduce in abundance and colonize freshly burned areas with even-aged seral stands.

The principal boreal tree taxa are spruces, firs, larches, birches, and aspens (Picea, Abies, Larix, Betula, and Populus spp., respectively). The spruces, birches, and aspens are most widespread; the latter two are typical fire species, and under the right conditions, so is spruce. The principal temperate forest taxa to the immediate south are pines, oaks, beeches, and maples (Pinus, Quercus, Fagus, and Acer spp., respectively). Many pines are fire species; this discussion particularly applies to them. However, many temperate zone hardwoods, notably oaks, also reproduce vegetatively following fire (Spurr and Barnes 1973).

In North America, the forests discovered and utilized by the European settlers were frequently even-aged stands of seral species. They found these to be the most valuable timber producers and, as a result, we have continued to manage much of our forested land to assure a sustained supply of them. These seral species require full sunlight and minimum competition to effectively colonize and dominate a site. Some require exposed mineral soil for seed germination and seedling survival. These conditions historically were provided by periodic wildfires and, in some areas, particularly near the coasts, by periodic high winds which caused extensive blowdown. At times, severe insect or disease outbreaks may open these forests sufficiently to permit regeneration of intolerant seral trees. But wildfire has been by far the most important regenerative agent in the coniferous forests of North America.

The northern conifer forest builds up a stockpile of organic matter over a long period of time after stand establishment (Olson 1963). As it does, on the mesic sites particularly, it becomes increasingly predisposed to destruction by wildfire. Barring intervention by man, most sites ultimately will burn. They may be burned frequently by low-intensity fires that consume only fine surface fuels, as in many ponderosa pine (Pinus ponderosa) stands of the mountainous western United States. Or they may burn infrequently, but with such severity that the entire stand is killed. In the latter case, the site becomes recolonized with fire species and the process begins anew (Habeck and Mutch 1973). Thus, we have a natural fire cycle on most mesic sites. The average length of this cycle, up to 400 years, and deviation from the average will vary depending upon site characteristics, climatic conditions, and tree species (Beaufait 1971).

These fires, even though natural, have measurable impacts on the environment. Without extremely intensive management of large forested areas in North America, there is little man can do to prevent these perturbations and their associated impacts.

CLEARCUTTING

Management techniques for the seral fire species usually have been dictated by their regeneration requirements. A mosaic of even-aged stands, each in turn harvested by clearcutting when mature, is the ultimate result of such management. Clearcutting and removal of the merchantable material is often followed by prescribed fire or by mechanical means of debris disposal. Thus, man replaces the natural fire cycle with his cutting cycle.

However, there are marked differences between the natural fire cycle and man's cutting cycle. Some of the important factors with differences that have the potential of influencing the environment and the future forest are:

Factor	Wildfire	Clearcutting and debris disposal
Cycle length	Variable within broad limits.	Set to rotation age.
Area affected	From small patches to thousands of hectares.	Small and set within relatively narrow limits.
Season	When driest, usually late summer.	All seasons, with prescribed burning only when controllable.
Intensity of fire	Intense over long cycles, low intensity at short intervals. May be intense in crowns with low intensity at forest floor.	If used, usually of lower intensity for broadcast debris; or, with piled debris, from extreme in piles to nonexistent between.
Prior soil condition	Dry surface organic horizon, usually over dry mineral soil. Often results in pronounced heating of mineral soil.	Variable water content, depending on season of cutting; burning usually done over a wet soil mantle; Virtually no mineral soil heating, except under burned piles, where it is severe.
Resulting soil surface	Blackened, and frequently burned to bare mineral soil.	Depends upon debris treatment: 1. Disturbed duff and understory due to harvesting; soil covered with limbs, tops, and culls. 2. Same as (1) but blackened after broadcast burning; mineral soil exposed on 5% to 25% of area. 3. Machine piling of debris bares mineral soil on the 75% of area between piles. Surface organic horizon often scraped away or mixed into mineral soil.
Physical disturbance of mineral soil	No direct disturbance.	Logging roads, landings, and skid trails, often followed by dozer piling of debris cause soil disturbance.
Forest stand	Trees remain standing as live, dying, or dead; often a viable seed crop is in canopy.	Boles removed; limbs and tops remain on ground to decay, to be piled and burned, or to burn in place.
Regeneration	Natural, with seral brush or herbaceous species sometimes preceding conifers by many years.	Natural, often later thinned; seeded or planted if natural regeneration is unsatisfactory.

DEBRIS DISPOSAL

After clearcutting most coniferous stands, especially the overmature old growth common in the western United States and Canada, it becomes necessary to dispose of the logging residue. The quantity varies from 500 metric tons per hectare in coastal Douglas fir (Pseudotsuga menziesii) (Jemison and Lowden 1974), to 250 t/ha in interior larch-fir (Beaufait et al. 1975), to 120 t/ha in old-growth lodgepole pine (Pinus contorta) (Foulger and Harris 1973). Disposal should (1) reduce or eliminate the fire hazard, (2) provide a natural seedbed or at least a surface suitable for planting, (3) open the clearcut interior to access, (4) sanitize the site to reduce insect and disease hazards, and (5) improve esthetic qualities.

Disposal may be accomplished by natural decay processes, by burning the debris in place, by piling (usually with bulldozers) and burning, by mechanical means such as roller-crushing or chipping, or by yarding entire trees and unmerchantable material in the harvesting process and later burning what remains at the landings. Through high utilization it is possible to reduce the debris volume to such small amounts that natural decay becomes a feasible method of disposal (Brown 1974). However, in most instances, burning has been relied upon as an expeditious and economical residue disposal technique after harvesting mature and overmature (old-growth) conifer stands in North America.

Broadcast burning perhaps is the best imitator of the natural fire cycle in these forests. It causes little disruption of the mineral soil; it has relatively uniform intensity over the entire area; it consumes some of the organic layer on the mineral soil surface; it blackens the entire area; and coarse debris is left scattered over the clearcut. However, it is difficult to control and can be effectively applied only during a relatively short season each year.

Logging debris can be piled during a much longer season. This is usually done as part of the logging operation. The piles of stumps, cull logs, limbs, and tops can be burned when snow is on the ground or when the forest is wet--when fire control is no problem. The piling operation is costly, but some of the costs are offset by negligible burning costs.

Mechanical methods of crushing the slash, as with large rollers, or reducing it to small particles with chippers are applied at the time of logging or at any time later when saturated soils or deep snowpacks do not prevent these practices. Mechanical disposal is limited to suitable terrain. These methods are being used increasingly in North America as stronger restrictions are placed on the use of fire. However, we must consider that these are energy-intensive means of residue disposal that often may not be economically or morally justified in an energy-deficient world.

EFFECTS

Except through closely controlled research, it is difficult or impossible to separate the effects of forest harvesting from the effects of debris disposal. Fortunately, for practical purposes, these effects need not be considered separately because the combined product, the total harvest impact, is our real concern.

Logging

Logging directly removes some nutrients from the site. In the environment being considered, the nutrients removed in the form of wood and bark through conventional harvesting are a minor part of the available plant nutrients and a very small fraction of the total nutrients on most sites. Stone (1973) summarized this loss to be from 1 to 10 kg/ha/yr for each of the major elements. Solution loss from forested lands into streamflow is often this great or greater. Whole tree utilization and extremely short rotations may increase this loss from two- to fivefold.

Many logging systems set up conditions that result in potential soil and water impacts from other causes. For example, soil is often bared and severely disturbed, thus exposing it to erosional forces (Rice et al. 1972). Dyrness (1967) concluded that increases in erosion rates may be expected following road construction and logging. The nature and severity of this erosion will depend upon the type of harvesting operation, design and location of roads and skid trails, and inherent characteristics of the individual area. Roads and skid trails are usually the primary sources of sediment from logged areas (Packer 1967b); however, their proper design, location, and drainage will markedly alleviate this problem (Packer 1967a).

Stream temperatures are raised by clearcutting vegetation that shades the water (Meehan 1970; Levno and Rothacher 1967; Swift and Messer 1971). Raised water temperatures and increased solar radiation will affect the aquatic environment and are particularly important in streams containing trout or other salmonoid fishes (Gibbons and Salo 1973). Leaving an uncut buffer strip will moderate these changes (Swift and Baker 1973).

Increased streamflow volume following forest removal is well documented and is reviewed by Hibbert (1967). In the 39 studies reviewed, first-year response to complete forest reduction varied from 34 to 450 mm increased streamflow. This increase declines as the forest regrows. Both the amount of increase and the rate of decline are site specific, dependent upon several climatic, edaphic, and biological factors.

Destruction of vegetation by clearcutting temporarily halts the annual cycling of plant nutrients. The chemical nature of the nutrients will be altered and the quantities held in each compartment of the system will change. This often leads to additional nutrient loss by leaching or solution in overland flow (Cole and Gessel 1965; Likens et al. 1970).

A third indirect impact is that of altered microclimate. Insolation at the forest floor is markedly increased by clearcutting. The forest, which absorbed 60% to 90% of solar radiation (Reifsnyder and Lull 1965), is now virtually gone. Also, transpiration is much reduced and soils remain wetter throughout the growing season (Johnston et al. 1969; Johnston 1975). The altered microclimate, both above and below ground, affects the development of vegetation. It can change microbial populations in the litter and in the soil. Decay processes may be accelerated (Stone 1973). The amount and availability of nutrients, particularly nitrogen, will be changed. Some nutrients will be leached if in excess of amounts that can be held in the soil or immediately taken up by new vegetation (Bormann et al. 1974; DeByle 1976; Stone 1973).

Fresh logging debris on the soil surface has immediate direct effects. It shades the soil, thus partially protecting it from the increased insolation. This retards evaporation and keeps the microclimate at the soil surface cooler and more stable than a bare site. The debris begins losing soluble components with the first soaking rain and continues to do so throughout the decomposition process. Some elements, such as potassium and sodium, are readily leached from the fine material without microbial action. Others, such as calcium, require some breakdown of the organic structure before being transferred back to the soil. Some organic compounds, phenols for example (Hart and DeByle 1975), are also leached from debris and either passed downward through the soil or lost in surface runoff waters. For the first few years after clearcutting, while the site is sparsely colonized with new vegetation, these processes result in net chemical additions to the soil that are greater than those that would occur through annual additions from the mature standing forest.

The same type of additions occur below ground, too. Roots of the severed vegetation decay and their elements are returned to the soil. At first this process is rapid, as fine roots decay; later it slows as the larger, less uniformly distributed roots of the cut trees decay.

Debris Disposal

Each method of debris disposal has its own set of potential impacts on soil and water. Generally, all methods accelerate the return of chemical elements to the forest floor.

Microbial action alone takes years to reduce conifer slash sufficiently so little or no fire hazard exists. Burning, in effect, compresses this decomposition period into minutes (Bollen 1974) and thus has the potential of causing the greatest immediate impact. The debris is rapidly decomposed; most minerals are transformed into readily soluble ash; and the organics are largely volatilized and lost to the atmosphere. Much nitrogen (DeBell and Ralston 1970) and some sulfur and phosphorus are lost through volatilization. The surface is blackened; shading from the debris is greatly reduced; and soil surface insolation is maximized. Some or all of the surface organic horizon of the soil is consumed, and mineral soil is bared. If the mineral soil is heated, it may become water repellent (DeBano and Rice 1973). In his summary of erodibility of forest watersheds, Dyrness (1967) concluded that severe burning may alter soil characteristics sufficiently to affect erodibility, but that light to moderate fires have very little direct effect on physical soil properties. However, the removal of protective vegetation and litter by fire is an important indirect cause of erosion

After clearcutting and broadcast burning there may be a surge of nutrients lost in runoff during the first posttreatment year (Fredriksen 1971; DeByle and Packer 1972). Fredriksen (1971) found cation content of streamflow increased up to threefold during this surge. Nutrient losses rapidly returned to preharvest levels during subsequent years.

Piling and burning debris compounds the impact on the site. All the effects of burning are now concentrated and intensified on 20% to 30% of the logged area. All the plant nutrients in the debris are likewise concentrated. Often the underlying soil is literally baked. The effects on revegetation are readily demonstrable (Vogl and Ryder 1969). The impacts between piles vary from negligible if the piling is done by hand to extreme if it is carelessly done with bulldozers. In the extreme, the stumps are torn out, surface soils are much disturbed and mixed, litter and mineral soil are pushed into the piles, and bare mineral soil remains. This may provide an excellent seedbed, or be easy to plant, but the bare soil is exposed to erosional forces until it is revegetated.

Mechanical means of disposal are used where burning is unnecessary or not permitted. Rollers and choppers break up the slash, reduce its depth, and place it more directly in contact with the soil surface. Chipping can accomplish this, too, especially on small areas, such as road rights-of-way.

Mechanical disposal produces a layer of fine slash or chips that mulches the soil surface. This finely divided debris decomposes more rapidly than it would in its original state (Bollen 1974), thus producing a flush of minerals and organic compounds to the mineral soil below (Hart and DeByle 1975). This debris mulch also alters the soil microclimate through shading and insulation. The surface mineral soils, especially at the beginning of the growing season, remain cooler and wetter than elsewhere. The heavily mulched site is not a good seedbed for most tree species, but it is protected from erosional forces.

INTEGRATION--DISCUSSION

Many of the northern coniferous forest sites have developed over thousands of years with fire periodically disturbing the system. The vegetation, soils, fauna, drainage systems, and topography developed and evolved with these disturbances. Management of these forests in North America began only yesterday in this time frame. In comparison to Europe, management of the North American forests is of low intensity--techniques usually are extensively applied.

With prevailing management practices, it would seem wise if we altered the natural conditions least while utilizing these forests. The seral conifer species we find most valuable are more easily grown when clearcutting is practiced and when fire is retained as a silvicultural tool. Wise and careful use of fire and clearcutting, in view of the long-term history of these forests, should result in the fewest man-induced impacts. This premise holds until we prove that man can truly improve upon nature while meeting his array of needs from these forests. The entire ecosystem must be considered when implementing any such improvements.

Some coniferous forest sites have burned very infrequently or not at all. They do not fit the previous argument. They and the trees that occupy them (cedar [Thuja], hemlock [Tsuga], and some spruces) have evolved without periodic fire disturbance. Use of prescribed fire on these sites is more likely to cause marked impacts on the ecosystem. Similarly, clearcutting may be a foreign agent on such sites, unless the natural system has been periodically disturbed by extensive blowdowns, or catastrophic disease or insect outbreaks.

The more closely man follows nature in his management of the forest, the least will be his long-term impact on the system. Intense wildfire or clearcutting do not always have the environmentally catastrophic results that some people claim. As scientists and resource managers, we must take an objective view of these forest perturbations.

The effects of fire, clearcutting, and debris disposal are too frequently simplified by overlooking the varying controls on these effects from the array of soils, geological types, topography, and climate possible throughout the range of even a single tree species. Some systems have little buffering capacity and readily react to these impacts by losing nutrients to the water system. An example is Hubbard Brook, where shallow, acid soils overlie impervious bedrock (Likens et al. 1970). Perhaps most forests growing on shallow, very sandy soils in a warm and humid climate would react similarly. When these forests are cut or burned, the litter and soil organic matter readily decompose. The released nutrients are then easily flushed from the sand with the annual surplus of precipitation.

In contrast, deep soils with a high clay content are much better able to retain the nutrients released by cutting or burning the forest. Their organic matter content may be reduced, pH raised, and available nutrient content increased; but they are less likely to lose nutrients into ground water or streamflow (DeByle and Packer 1972; DeByle 1976). In a sense, they have a high buffering capacity.

Precipitation received in moderate amounts throughout the growing season, with a small surplus to be flushed through the soil annually, is least likely to remove a significant quantity of soluble nutrients. In contrast, where a large surplus of precipitation exists, there is greater potential for nutrient outflow. This is true on the west coasts of Oregon, Washington, and British Columbia, and is exemplified by research results from the sandy soils on the Cedar River watershed near Seattle (Cole 1966; Cole et al. 1967).

The following tabulation is a summary of this discussion. The conditions that result in the most stable sites are contrasted with the conditions that result in the least stable with respect to their ability to absorb the impacts of fire, logging, and debris disposal without a significant loss of soil or nutrients and possible site quality changes.

Most stable sites	Least stable sites
Level terrain.	Steep, long slopes.
Deep soils.	Shallow soils over impervious bedrock.
Well-drained soils.	Saturated soils, high ground water table.
Soils with high clay content.	Sands and gravels.
Little or no surplus precipitation.	Large precipitation surplus.
Favorable growing season for rapid revegetation of site.	Short, cold, dry, or otherwise unfavorable growing season.
Seral forest type on site.	Climax forest type on site.
Site has history of periodic destructive wildfires blowdown, or other catastrophic tree removal.	A site with no history of fire, blowdown, or catastrophic forest destruction.
Present vegetation regenerates readily after fire or blowdown.	Catastrophic destruction of forest removes propagules; new species must invade site.

CONCLUSIONS

In recent years much concern has been expressed about the environmental effects of forest fire and clearcutting. Particular interest and effort has been directed at the effects on soils and on water quality. Past research has shown effects that range from virtually undetectable to those that could drastically alter site or water quality. The range in results is due to several interacting factors of climate, soils, geology, topography, vegetation type, fire intensity, and site history. Care should be used in applying research results; all factors must be recognized and understood.

More research is needed to achieve full understanding of these controlling factors as they affect the impacts upon the environment after forest perturbation. We also need to integrate our present knowledge into a working model that allows the forest manager to make a reasonable prediction of impacts from fire, clearcutting, blowdown, or other drastic forest disturbances.

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