FIRE AND GEOMORPHIC PROCESSES

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ABSTRACT

Fire, geomorphic processes, and landforms interact to determine natural patterns of ecosystems over landscapes. Fire alters vegetation and soil properties which change soil and sediment movement through watersheds. Landforms affect fire behavior and form firebreaks which determine burn boundaries. Geomorphic consequences of fire in a landscape-ecosystem type are determined by (a) characteristics of the fire regime,,mainly frequency and intensity; and (b) geomorphic sensitivity or erodibility of the landscape.

KEYWORDS: fire, erosion, watershed management, sedimentation

INTRODUCTION

Fire, geomorphic processes, and landforms interact in a variety of ways that are important determinants of patterns of natural ecosystems over landscapes. Many relationships between fire and geomorphic factors are mediated by vegetation, soil properties, and hydrology. Fire alters vegetation and soil properties; these changes alter the hydrologic regime of a site with the collective effect of changing the movement of soil and sediment through watersheds. Landforms and the long-term operation of processes that shape them influence soil distribution, microclimate, and other factors that control distribution of plant communities on a landscape. By their temporal and spatial patterns of fuel loading, plant communities influence the fire regime of a site.

Types and intensities of these fire-geomorphic factor interactions vary with the time scale at which a landscape-ecosystem unit is viewed. On the short-term scale of landscape-ecosystem response to a single fire, fire affects geomorphic processes through alteration of vegetation, soil, and hydrology. These interactions are most important in fire-prone ecosystems in steep terrain where vegetation regulates physical processes. In the much longer time frame of landscape development the sense of this relationship is reversed. Landforms, especially in areas of high relief, may strongly influence fire behavior and pattern by effects of topography and fire breaks. Vegetation-landscape patterns viewed at any point in time reflect both short- and long-term relations among fire, vegetation, soil, hydrology, and geomorphic factors.

The type of broad perspective studies necessary to evaluate interactions between fire and geomorphic factors in an ecosystem context are rare. The few studies of erosional consequences of fire have been narrow in scope, lacking ecosystem perspective and failing to examine long-term implications of short-term observations. In an effort to expand on these narrow views, Wright (1974) examined geomorphic systems and ecosystems over the time scales of landscape development and plant community change by succession and migration. Reviewing examples from the Appalachian Mountains (Goodlett 1954, Hack and Goodlett 1960) and the Boundary Waters Canoe Area, northern Minnesota (Ohmann and Ream 1971, Heinselman 1973), Wright (1974) saw weak interaction between fire and geomorphic factors. Forests in the steep Appalachian Mountain site experience very infrequent fires but are sensitive to disturbance by erosion and windthrow events. Fire is a controlling factor in vegetation patterning in the northern Minnesota example, but low relief and resistant bedrock result in low erosion potential even after fire.

These two areas do not dramatically express interactions between fire and geomorphic factors, but they do highlight the variables that control these interactions: fire regime, geomorphic sensitivity to vegetation disturbance, and topography. Youthful landscapes with steeper terrain and greater relief have greater sensitivity to fire disturbance. They exhibit more vegetation zonation in response to topography, more active contemporary geomorphic processes that may be subject to vegetation control and acceleration by fire, and greater effect of topography on fire behavior. In these landscapes we can identify such relationships; perhaps when they are better understood we can observe these relationships where they are more subtle.

This paper reviews research on effects of fire on geomorphic processes and sediment yield from watersheds and effects of landforms on fire behavior and pattern. Conceptual approaches with limited examples are presented for analyzing effects of fire on sediment yield over several fire rotations and for contrasting the geomorphic significance of fire in diverse landscape-ecosystem types. However, we begin with a general discussion of soil and sediment routing through watersheds to set a basis for evaluating fire effects on geomorphic systems.

SOIL-SEDIMENT ROUTING

In order to evaluate fire effects on geomorphic processes in an ecosystem, it is necessary to understand the roles of vegetation in regulating soil-sediment routing through watersheds (Dietrich and Dunne 1978, Swanson and others in press). Soil is moved down hillslopes by a variety of mass movement and surface erosion processes. Once in the channel, this material, now termed sediment, is moved downstream by another set of transfer processes. A given particle of material moves through a watershed in a series of steps by different processes, and it may be moved by several processes simultaneously.

During its transit through a watershed, material is temporarily stored in various types of storage sites (Dietrich and Dunne 1978). Down logs in forest ecosystems, for example, trap material moved downslope by surface erosion processes and downstream by channel processes of particulate matter transfer. Sediment is also stored in alluvial fans, flood plains, and in-channel sediment deposits. Residence time of material in storage sites ranges from days to thousands of years (Dietrich and Dunne 1978).

Vegetation affects the rate of each transfer process and the capacity and turnover time of storage sites. Root .networks bind soil, thereby reducing mass movement potential from slopes and stabilizing flood-plain deposits; organic litter protects soil from surface erosion; blowdown of trees causes soil movement, but the down logs form storage sites. These and other factors result in complex response of soil-sediment routing systems to ecosystem disturbance. Since each geomorphic process is regulated by a different set of vegetation factors, each process will recover to predisturbance rates over different time periods, determined in part by the pace of vegetation recovery.

As a result of these vegetation-geomorphic process interactions, destruction of living and dead fuels by fire may alter all components of the soil-sediment routing system of a watershed. On the other hand, just as fire can selectively affect species or vegetation strata, it can also selectively alter components of the soil-sediment routing system. Low-intensity fire, for example, may reduce ground cover, and cause accelerated surface erosion while having no effect on rooting strength and mass movement potential. Although most fire effects research has concentrated on acceletation of individual transfer processes and total sediment yield from drainage basins, fire-induced sediment yield reflects changes in both transfer processes and storage.

SHORT-TERM FIRE EFFECTS

On the time scale of watershed ecosystem response to a single fire, fire works through alteration of vegetation, soil properties, and hydrology to trigger immediate and delayed changes in geomorphic processes on hillslopes and in channels. Many of the complex interactions among fire, vegetation, soil, hydrology, and geomorphic processes are summarized in figure 1. Although this summarization leaves out many details, generalizes where some important exceptions may arise, and covers a broad range of processes that do not all operate in any single environment, it is used as the basis for the following discussion. This discussion concerns mainly wildfire effects on natural vegetation. Effects of slash and prescribed burning are compounded and obscured by impacts of other management activities.

Fire Effects During Burning

Records of geomorphic processes immediately during fire are based almost entirely on personal communications and popular accounts of major fires. Intense drying of soil, combustion of organic matter that binds soil aggregates, loss of litter cover, and strong convective winds produced by the fire's heat all contribute to debris movement down steep slopes during hot fires. In steep terrain, rolling rocks and logs released by burning of roots and other supportive organic matter endanger firefighters and trigger downslope movement of other material. Strong winds in very intense fires have caused extensive blowdown (Holbrook 1943, Cohen and Miller 1978, Felt 1978), leading to formation of large areas of pit and mound microtopography. This phenomenon also greatly increases concentration of large woody debris on slopes and in stream channels which affect movement of soil and sediment.

Rock materials exposed at the ground surface as outcrops or cobbles and boulders may shatter and spa11 in response to direct differential thermal effects and vaporization of interstitial water. These processes of rock degradation reduce the particle size and persistence of boulder fields and accelerate soil forming processes (Blackwelder 1927, Birkeland 1974).

Recent research on fire alteration of soil properties focuses on formation of hydrophobic soil properties, especially in chaparral vegetation (DeBano and others 1977). This work involves monitoring the thermal regime of the upper portion of the soil profile during burning. Steep thermal gradients occur in the upper few centimeters to decimeters of soil beneath fire. Vaporization and transfer of water across the gradient are instrumental in movement of other compounds. Under these conditions an efficient distillation process leads to coating of soil particles below the surface with nonwettable organic compounds.

Delayed Fire Effects

In contrast to the poor documentation and quantification of immediate fire effects on geomorphic processes, effects of fire on hydrology and geomorphology following burning have been studied in some detail. Most fire-initiated changes in hydrology and geomorphic processes take place over periods of up to decades following

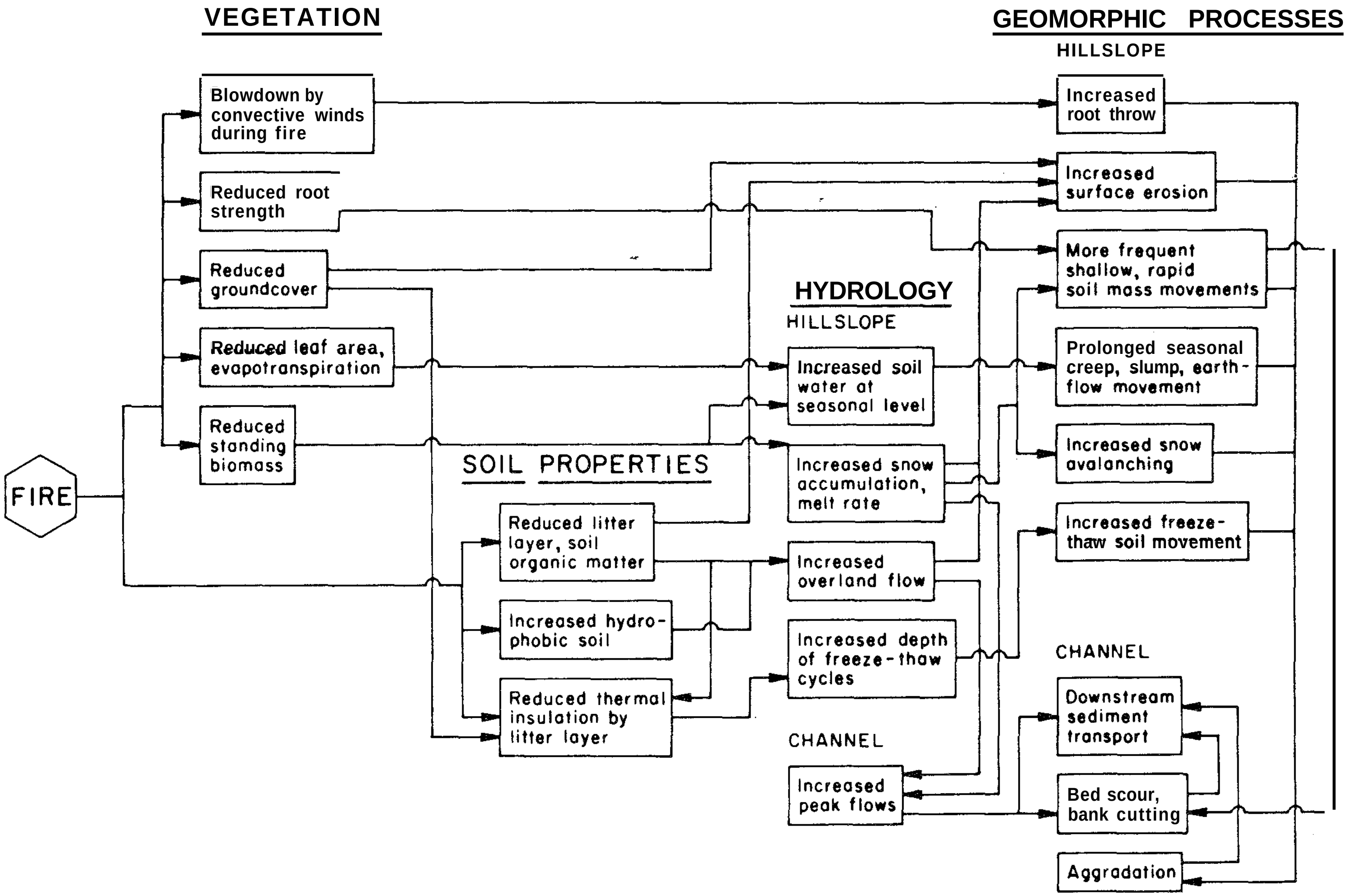

Figure 1.--Effects of fire on vegetation, soil properties, hydrology, and geomorphic processes.

a fire. Fire may have delayed effects on vegetation, as in the case of fire damage to trees which opens the way for attack by insects and decomposer organisms that eventually lead to mortality. As more years elapse before storms and other events trigger change in geomorphic processes, the geomorphic consequences of a fire decrease in response to revegetation. Thus the impact of a fire depends on the timing of major storms. Fire-initiated changes in geomorphic processes may be obvious during the early postfire years, but it is difficult to specify and quantify fire influence in later successional stages.

EFFECTS ON VEGETATION

Alteration of vegetation by fire has several effects on hydrology and geomorphic processes (fig. 1). Fire reduces ground cover of living and dead organic matter and directly causes or initiates mortality and decay of vegetation. Loss of protective organic litter exposes mineral soil, generally increasing its susceptibility to the full spectrum of surface erosion processes. Since a mat of organic matter is also an effective thermal insulator, its removal affects soil temperature regime which is especially important in permafrost terrain. In forest ecosystems, mortality and decay of trees and shrubs leads to reduced rooting strength and increased mass movement potential in steep terrain. Burning of vegetation reduces interception of precipitation and evapotranspiration with resulting increases in soil moisture. The density and distribution of aboveground organic matter also affect snow hydrology, including spatial patterns of accumulation and melt rate.

EFFECTS ON SOIL PROPERTIES

Ahlgren and Ahlgren (1960), Brown and Davis (1973), and others extensively review many effects of fire on soil properties. This review concentrates on soil wettability (hydrophobic tendencies) and thermal effects on frozen ground, because of their important influences on site hydrology which in turn affects geomorphic processes. Combustion of soil organic matter also influences soil properties and geomorphic processes by reducing aggregate stability and thereby increasing susceptibility of soil to surface erosion.

Water repellent soils have been observed in a great variety of ecosystems in dry, unburned soil and soils burned by wildfire and slash fire (DeBano 1969, DeByle 1973, Dyrness 1976, Megahan and Molitor 1975, Campbell and others 1977, and others). Most severe hydrophobic soil conditions are thought to develop in response to fire through litter or slash over dry soils where steep thermal gradients can develop in the soil. Most tests for soil wettability are applied to individual soil particles or aggregates, and hydrologic effects of repellent soils at a broader level are generally unknown. Similarly, the geomorphic consequences of water repellent soil particles are unknown. Increased rill, sheet, and mass movement erosion are commonly observed following intense fire, but the relative importance of repellency, loss of organic matter cover, and other factors in accelerating individual erosion processes have not been determined.

Removal of ground-covering organic matter also affects soil temperature regime, which is particularly significant in soils that experience seasonal freeze-thaw cycles. Hydrologic and geomorphic effects of fire in such systems occur largely in response to alteration of seasonal freeze-thaw cycles (Viereck 1973a, 1973b). Loss of the surface layer of insulating organicmatter can result in increased depth and duration of seasonal thawing for a period of at least 15 years following fire (Viereck 1973a). Heat from the fire itself generally has no immediate effect on depth to frozen soil (Brown 1965). Thickening of the active layer may lead to local subsidence, formation of thermokarst, and accelerated solifluction activity in tundra and taiga ecosystems (Viereck 1973a, D. N. Swanston, personnal communication). In some vegetation types, vigorous recovery of vegetation over several years results in shrinking of the active layer to a thickness less than prefire conditions (Kryuchkov 1968, in Viereck 1973a).

EFFECTS ON HYDROLOGY

Nonpermafrost terrain also experiences a variety of complex hydrologic responses to fire-induced vegetation and soil changes. In terms of altered ground-water regime, hot ground fire can reduce water storage capacity of surface organic matter (Dyrness and others 1957). Reduced interception and evapotranspiration may result in decreased summer drawdown of soil-water by vegetation (Klock and Helvey 1976a), although in some cases, such as heath vegetation, water loss can be increased when the soil surface is exposed (C. H. Gimingham, Univ. of Aberdeen, personal communication). Effects of reduced interception and evapotranspiration may be offset in part by increased overland flow in response to reduced infiltration due to loss of litter layer, development of hydrophobic soil, compaction by raindrop impact, plugging of pores by fine soil material, and in some instances, actual fusing of soil surface (Dyrness and others 1957; Ahlgren and Ahlgren 1960; Brown 1972; Helvey 1972, 1973; Rice 1973; Anderson and others 1976; Campbell and others 1977; and others). In general, these factors lead to increases in both soil-water storage and runoff from burned sites.

Contrasts in snow hydrology of burned and unburned ecosystems have received very little study, particularly in terms of fire-induced changes in ground-water regime. Snow accumulation and melt in open (clearcuts, natural treeless areas) and forested areas have been the subject of extensive research, but a stand of blackened snags presents a very different environment than either forest or treeless areas. Speculation on snow hydrology of burned areas is complicated by the great contrasts between cold-dry and warm-wet snow types and between snowpack and multiple accumulation-melt seasonal regimes. Work on warm snowpacks by Smith (1974) and others does suggest, however, that formation of melt zones around blackened snags and rapid condensation melting may cause greater melt water input to the soil in burned areas than in forests and snag-free open areas. Forests may have greater loss by evaporation, and snowpacks in open areas may contain continuous, relatively impermeable horizons which carry melt water directly to streams.

These fire-related effects on surface and subsurface hydrology of hillslopes, of course, have direct impact on streamflow. Increased total annual and peak streamflow have been observed from a variety of temperate to semiarid ecosystems involving both snow and rain systems (Rich 1962, Storey and others 1964, Brown 1972, Anderson and others 1976, Helvey and others 1976, Campbell and others 1977, and others). In general, fire-induced changes in streamflow reflect complex interactions among many soil and vegetation factors. Baseflow conditions are most closely related to evapotranspiration and soil-water storage capacity, while peak flows are more controlled by infiltration rate and, possibly, snow hydrology.

EFFECTS ON GEOMORPHIC PROCESSES

Accelerated erosion from burned sites may occur by a variety of surface erosion processes, including dry period ravel, sliding, and surface creep (Anderson and others 1959; Krammes 1960, 1965; Franklin and Rothacher 1962); rill and sheetwash erosion (Sartz 1953, Brown 1972, Rice 1973, Megahan and Molitor 1975, Griffin 1978, Wells and White 1978); wind (Blaisdell 1953, Hinds 1976, Murai and Iwasaki 1976); and cycles of needle-ice formation and melt (Franklin and Rothacher 1962, Wells and White 1978). The relative importance of each of these processes and degree of acceleration due to fire is determined by interactions among soil, topography, vegetation, and climate. Coarser textured soils on steep slopes, for example, are prone to dry-period surface erosion, whereas fine-textured soils are most susceptible to erosion by wind and overland flow processes.

Increased occurrence of shallow, rapid soil mass movement (of debris flow, debris slide, debris avalanche, debris torrent and rapid mudflow types) has also been observed following wildfire (Scott 1971, Rice 1973, Cleveland 1973, Helvey 1973, Klock and Helvey 1976b, Jackson 1977, Scott and Williams 1978). These events are initiated either on hillslopes or in stream channels (Klock and Helvey 1976b). Hillslope events occur in response to rapid rise in ground water level, which may be influenced by fire effects on soil and hydrology, and to reduced rooting strength. The timing of mass movement occurrences following disturbance of vegetation has been explained in terms of root strength variation during the period of root system development by incoming vegetation and decay of dead residual roots of plants killed by clearcutting (Nakano 1971, Swanston 1970, Burroughs and Thomas 1977, and others) and wildfire (Rice 1973). Rapid mass movement events are also initiated in narrow, steep channels when high streamflow entrains large volumes of colluvium along the channel (Anderson and others 1959, Krammes 1965, Scott 1971, Rice 1973, Scott and Williams 1978). Fire affects this process by contributing to increased peak streamflow and by accelerating hillslope erosion processes that supply colluvium to channels between storm events.

Sediment storage in channels also undergoes change in response to fire effects on bedload transport and large organic debris in streams. Increased peak flows may scour and enlarge channels on or close to burn sites (Rich 1962, Griffin 1978). These eroded materials may then be deposited further downstream, aggrading the channel (Rich 1962). Sediment movement and storage in forested streams is also altered when fire increases debris loading, hence channel storage capacity, by causing convective winds that blow trees into channels or triggering downslope log movement. Fire may also decrease debris loading by burning debris in channels and by increasing the potential for channel-flushing mass movement events. Organic debris loading in streams flowing through coniferous forests in the Pacific Northwest may also decrease over about a century following wildfire as residual material from the prefire stand decomposes and is washed away and while the postfire stand develops to the point where it begins to contribute large debris to streams (Swanson and Lienkaemper 1978).

Fire impacts on large, deep-seated (depth to failure surface >2 m) mass movement features such as slumps, earthflows, and zones of deep soil creep are virtually unknown. The greatest potential effects of fire or other types of devegetation involve reduced evapotranspiration and increased soil moisture which could prolong wet season or storm-event related periods of movement (Swanston and Swanson 1976). Effects of rooting strength are trivial in the case of large, deep-seated mass movement features.

The burning of forests on steep slopes at higher elevation may also result in increased snow avalanche activity (Munger 1911, Winterbottom 1974). This occurs in response to reduced effect of vegetation in anchoring snow to slopes and altered snow accumulation and melt patterns in avalanche initiation areas. As a result, unburned forest in the downslope runout area may be battered by snow avalanches. Geomorphic effects of snow avalanches include transport of soil, rock, and organic matter, and uprooting of trees. Repeated snow avalanching and deposition of snow at the end of runout areas suppress revegetation and stabilization of the entire avalanche track area.

The net result of these numerous observed and hypothetical fire effects on individual erosion processes commonly is increased yield of suspended and bedload sediment (reviewed in Wells and others 1978, Rich 1962, Storey and others 1964, Rice 1973, Klock and Helvey 1976b, Campbell and others 1977, Scott and Williams 1978). Increased sediment yield has been reported for watersheds as large as the Trask (370 km^2) and Wilson Rivers (410 km^2) after the multiple, holocaustic Tillamook fires in northwest Oregon (Anderson 1954). In the case of such large fires and long time periods, however, fire effects on sedimentation are confounded by the impact of salvage loading operations and associated roads.

FIRE EFFECTS OVER SEVERAL ROTATIONS

Analysis of Individual Landscape-Ecosystem Types

The overall effect of fire on denudation and sediment yield is best assessed on the intermediate time scale of several fire rotations where both frequency and magnitude of fire-induced periods of accelerated erosion may be examined. Using methods analogous to hydrograph separation, hypothetical patterns of sediment yield are split into components of accelerated sediment yield due to fire and "baseflow" sediment yield rate typical of conditions of well-established vegetation (figure 2). The following examples are from the few areas for which fire regime and related sediment yield data are available.

Perhaps the greatest impact of fire on geomorphic processes occurs in steep land chaparral of southern California where geologically rapid rates of mountain uplift, periods of intense rain, and frequent, intensive wildfire contribute to rapid erosion. Impacts of these factors on rapidly expanding residential development have resulted in extensive study of fire and erosion in this landscape-ecosystem type. Analysis of sediment data from flood-control basins indicates that sediment yield in the first year following fire may be more than 30 times the rate 10 or more years following a fire and that recovery to this "baseflow" rate takes place over 8 to 10 years (Storey and others 1964, Scott and Williams 1978). Fire frequency in chaparral is quite variable, but a frequency of 20 to 30 years is common for many widespread, low elevation southern California chaparral communities (Kilgore 1979).

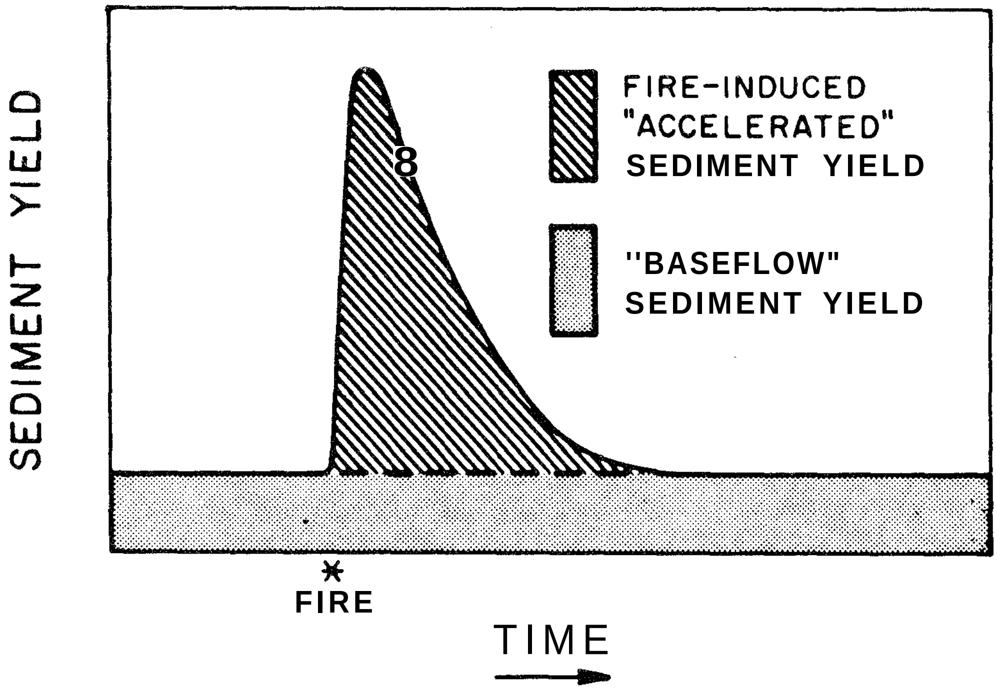

Figure 2.--Hypothetical variation in sediment yield during the period of watershed response to fire. Sediment yield is separated into fire-induced accelerated yield and "baseflow" yield components.

Figure 3A depicts variation in sediment yield from steep, chaparral watersheds assuming a 30-fold increase in sediment yield in the first year following fire, recovery to "baseflow" sediment yield over 10 years, and fire frequency of 25 years. This curve of hypothetical variation in sediment yield is smoothed to remove irregularity due to year-to-year variation in peak flows. Based on integrating the area under this curve and separating fire-induced from "baseflow" sediment yield (fig. 2), fire-accelerated sediment yield totals over 70 percent of total long-term yield from these steep, chaparral watersheds. Rice (1973) has estimated that almost 70 percent of long-term sediment yield from such watersheds occurs in the first year after fire, suggesting an even greater overall fire effect. Results of computer simulation modeling by Bonnicksen (1977) suggest that debris production from a watershed can be ameliorated by managing the frequency of burning and portion of a watershed burned.

The *Pseudotsuga menziesii* - *Tsuga heterophylla* forests of western Oregon present another example where accelerated erosion following wildfire is an important, though less dramatic and more poorly documented, contributor to overall sediment yield from small, steep watersheds. Fire regime and related erosion have not been carefully studied in these landscape-ecosystem types, but estimates can be based on reconnaissance studies of fire history and analysis of erosional consequences of clearcutting. These ecosystems experience long return interval, crown fires (Martin and others 1976) at frequencies of 50 to more than 400 years. A 200 year return period may be typical of central western Cascade Mountain forests, although the actual fire regime may involve a longer rotation except for moderate probability of reburn several decades after a fire (Swanson unpubl. data). Following clearcutting and slash burning, erosion by debris avalanches, a dominant erosion process in this steep land, may be increased by about 200 percent over rates measured in forested areas (Swanson and Dyrness 1975). Assuming that other erosion processes are also accelerated, intense wildfire in these steep, unstable terrains may cause a fivefold increase in sediment yield, and recovery to the baseflow" rate may occur over 20 to 30 years. These estimates of fire frequency and magnitude and duration of accelerated sediment yield are shown as a curve of hypothetical variation in sediment yield in figure 3. Integrating the area under this curve, in the same manner as in the chaparral example, accelerated sediment yield due to fire is about 25 percent of overall sediment yield.

Effect of fire on erosion and sediment yield can also be estimated from studies of varve thickness and charcoal deposition in lakes serving as natural sediment traps. Swain (1973) analyzed the sediment record in a small northeastern Minnesota lake in a mixed conifer-hardwood ecosystem in glaciated terrain of moderate to steep relief. He observed an increase in varve thickness by about 35 percent for approximately 15 years following fire and a fire return period of about 60 years. Under these conditions fire-accelerated erosion contributed a maximum of 8 percent of total long-term sediment yield.

In a *Pinus strobus* - P. *resinosa* - hardwood ecosystem and similar landscape in southern Ontario, Cwynar (1978) measured increased varve thickness of about 25 percent for approximately 15 years following fire and an 80-year fire recurrence interval. Based on these estimates, fire-accelerated erosion accounts for up to 6 percent of long-term sediment yield.

Estimates of fire effects on sediment yield using lake sediment records involve uncertainties of not knowing how fire, erosion, and lake sedimentation are coupled and what portions of the basin were burned by individual recorded fires. A more important source of error in these two cases is the predominance of algal gyttya forming the sedimentary record. Much of this material may result from in-lake primary production, and, therefore, does not indicate change in allocthonous inputs.

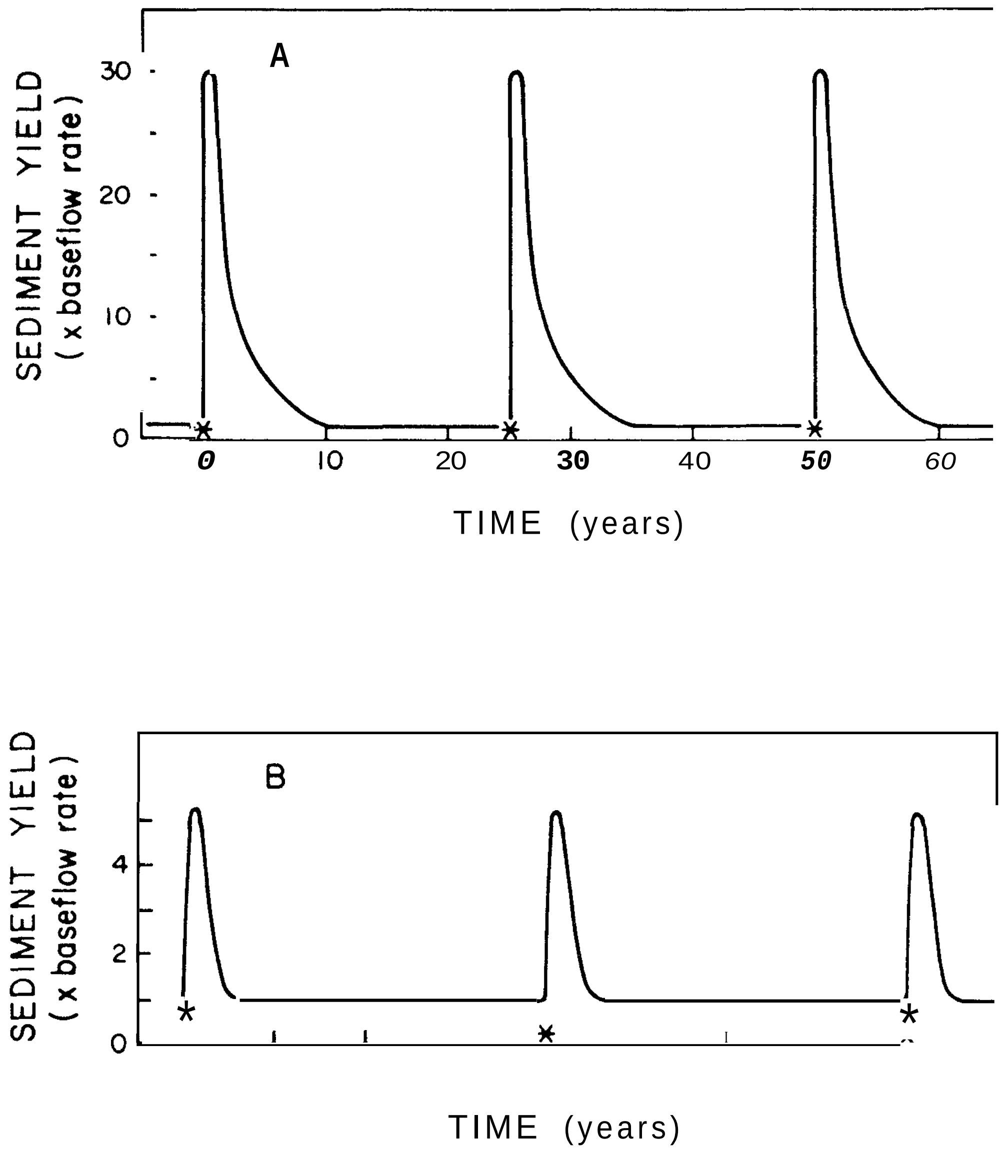

Figure 3.--Hypothetical variation in sediment yield for several fire rotations for a steep-land chaparral system (A) and a <u>Pseudotsuga menziesii</u> western Cascade Mountain system (B). * denotes occurrence of fire. Note different scales.

These analyses follow the simplifying assumption that successive fires are independent events occurring at some average frequency longer than the period of recovery to "baseflow" sediment yield. The geomorphic consequences of repeated reburning and related suppression of revegetation due to nutrient depletion and site physical instability have not been examined. Casual observations at sites of repeated intense fire suggest that in portions of these areas recovery of vegetation and the soil-sediment routing system may take centuries.

The strategy for contrasting disturbance-related sediment yield with the "baseflow" yield outlined for chaparral and *Pseudotsuga menziesii* forests has been proposed as a means of judging impacts of forest management activities relative to the natural fluctuations of the soil-sediment routing system (Swanson and others in press). A key element of this approach is to contrast the frequency, duration, and erosional consequences of natural and man-imposed disturbances of ecosystems. This approach involves a broader time perspective than studies that evaluate management impacts by comparing manipulated experimental areas with undisturbed control areas.

Comparison of Fire Effects in Diverse Landscape-Ecosystem Types

Long-term effectiveness of fire in altering geomorphic processes and sediment yield is best determined on the time scale of several fire rotations. The geomorphic role of fire is determined by (a) fire regime, as defined by Heinselman (1978), and (b) sensitivity of soil-sediment routing systems to disturbance by fire. These two properties are the principal bases for comparing physical consequences of fire in diverse landscape-ecosystem types (fig. 4).

Unfortunately, fire regime and geomorphic and sediment yield consequences of fire are known for very few landscape-ecosystem types. Consequently, figure 4 is proposed as a possible conceptual framework for contrasting fire effects in diverse landscape-ecosystem units. Additional studies of fire regime and associated geomorphology could test and quantify this approach to defining key system property.

Essential elements of fire regime are type (crown or surface), intensity, size, and frequency. Ecosystems with frequent, severe, widespread fires have greatest potential for fire impact on soil-sediment routing. Fire regimes identified by Heinselman (1978) can be roughly ranked by increasing potential impact on geomorphic processes: (Type 0) no (or very little) natural fire; (Type 1) infrequent, light, surface fires; (Type 6) very long interval, crown fire; (Type 2) frequent, light surface fire; (Type 5) long interval, crown fire; (Type 3) infrequent, severe, surface fire; (Type 4) short interval, crown fire. This ranking is somewhat arbitrary, because regimes in many ecosystems involve both crown and surface fire (Heinselman 1978) and the relative geomorphic consequences of these two fire types have not been determined. Geomorphic consequences of a particular fire regime vary with proportions of sprouting plants in burned vegetation, live versus dead fuel consumed, and other ecosystem-specific properties.

To rank ecosystems in terms of fire's potential for impacting geomorphic processes, a more general fire index is used (fig. 4). Fire index increases with increasing fire intensity, frequency, and areal extent.

The sensitivity of a geomorphic system to alteration by fire is largely controlled by hillslope gradient and the effectiveness of vegetation in regulating soil-sediment routing. In landscapes where root strength, ground cover, and other vegetative factors regulate routing, geomorphic processes have high potential for disturbance by fire. This typically occurs in steep, moderately to well-vegetated terrain where surface erosion and mass movement processes are active even under vegetation cover.

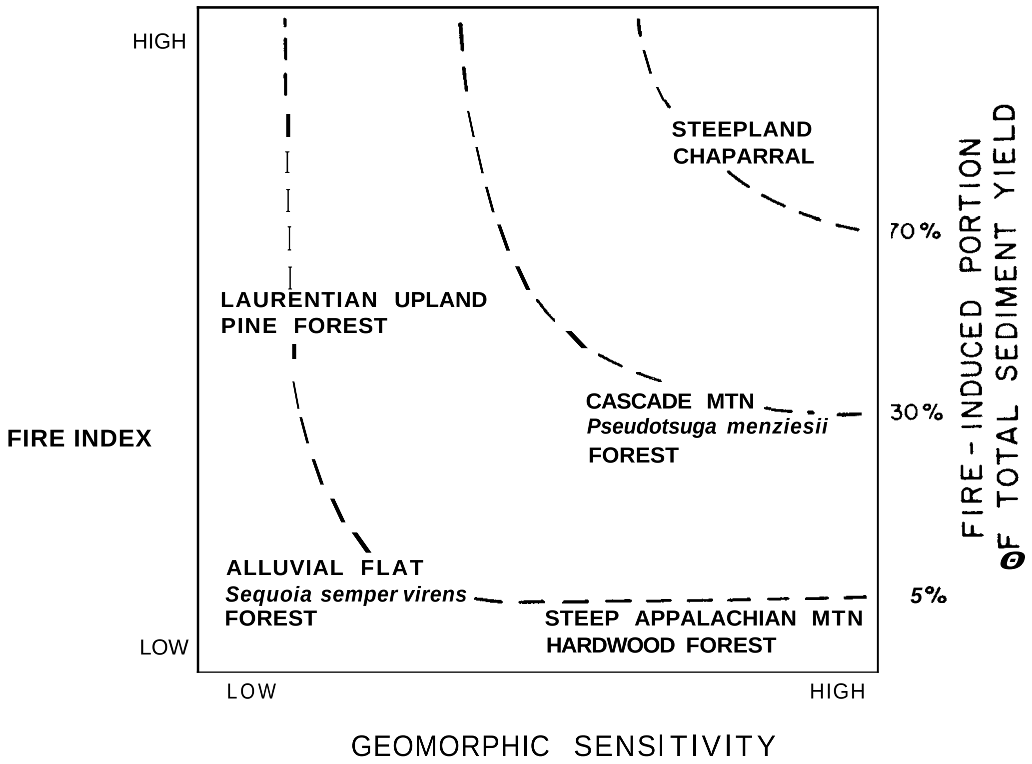

Figure 4.--Hypothetical distribution of selected landscape-ecosystem types with respect to geomorphic sensitivity, fire index (frequency and intensity), and portion of total sediment yield that is fire induced.

Diverse landscape-ecosystem types may be subjectively ordered with respect to fire index and geomorphic sensitivity (fig. 4). Greatest fire impact occurs in the geomorphically sensitive chaparral where short return interval, crown fires may trigger more than 70 percent of long-term sediment yield. Fire is geomorphically less significant in Pseudotsuga menziesii forests in unstable Cascade Mountain terrain, largely because of the much longer return interval for fire in this ecosystem. Furthermore, denudation rate of this landscape is only about 5 percent of the rate in the most actively eroding steep, chaparral watersheds in the Transverse Ranges in southern California (Scott and Williams 1978, Swanson, unpubl. data) indicating that the Cascade landscape may be less sensitive to disturbance. These two examples are extreme cases which illustrate geomorphic response to fire that occurs to a more moderate degree in areas of less relief and more stable terrain.

Fire in the boreal and Pinus strobus - P. resinosa forests of the continental interior Laurentian Upland physiographic province (Heinselman 1973, Swain 1973, Cwynar 1978) is substantially more frequent (60- to 100-year frequency) than in western Cascade Pseudotsuga menziesii forests. However, these areas of continental glaciation are topographically subdued, tectonically quiet, and relatively unerodible. Much of the topography has been sculpted by continental glaciation, and nonglacial processes operating over the past 15,000 or so years since glacial retreat have modified the landscape little. Despite moderate frequency, fire has minor geomorphic effect in this landscape-ecosystem, triggering less than 8 percent of long-term sediment yield.

Fire appears to be geomorphically even less significant in the central and northern Appalachian Mountain forests (Wright 1974). Here steep landscapes exhibit moderate to high erosion potential, expressed in part by abundant mass movement activity in response to major storms (Flaccus 1959, Hack and Goodlett 1960, Williams and Guy 1973). Although the natural fire regimes for this area have been obscured by centuries of interference by European man, the wet summer season results in a fire regime of very low frequency and intensity. Consequently, fire plays a very minor role in this landscape-ecosystem type.

In yet other ecosystems fire is virtually nonexistent, limited by low quantities and scattered distribution of fuel in very arid desert ecosystems or by year-round wetness in the cases of tropical forests and coastal *Sequoia sempervirens* and *Picea sitchensis* - *Tsuga heterophylla* forests. These ecosystems occur in landscapes of quite variable erosional sensitivity but, regardless of hydrologic and geomorphic regimes, fire is insignificant, due to climatic factors.

LONG-TERM FIRE-LANDFORM RELATIONS

Relationships between landforms and fire occur as (1) effects of landforms on fire behavior and pattern, and (2) effects of fire on landform development. Long-term interactions among topography, macro- and microclimate, soil, vegetation, and site disturbance factors determine the productivity and community composition of a site, thereby determining local fuel dynamics and fire regime. The distribution of landforms thus has the potential for controlling vegetation patterns on a landscape through its effects on fire.

Aspects of fire behavior such as intensity and rate of spread are regulated in part by topography (Brown and Davis 1973). Faster, more intense burning occurs on steeper slopes due to convective winds and preheating of fuels on the uphill side of a fire front. Steep slopes facing the midday and afternoon sun receive more solar radiation that dries fuels than do flatter slopes or slopes with other aspects. These factors result in faster spreading, more intense fires and higher probability of crowning in forest fires on steeper slopes more oriented to the afternoon sun (Brown 1972). These relations hold only to a certain point, because on slopes over about 40^{o} vegetation and fuels may have a patchy distribution interspersed with exposed bedrock, and these conditions restrict fire spread.

Topography also inflences fire pattern by creating firebreaks. Vegetation types that exhibit low fire-carrying capability form subtle firebreaks determined in part by topography and related soil distribution. Completely forested, but sharp, ridges may act as effective firebreaks where upslope mountain winds prevent a fire from crossing. Open water, talus and boulder fields, snow avalanche and landslide tracks, and other barren or sparsely vegetated landscape features form more conspicuous fire-breaks. Interesting sets of feedback mechanisms can occur where, for example, fire increases the probability of other disturbance events such as snow avalanches which may create and maintain breaks, thereby restricting the spread of subsequent fires.

Major traditional animal trails may also serve as firebreaks in grassland terrain with little other interruption in topography and fuel continuity. Trails are commonly aligned relative to geomorphic features such as streams, waterholes, and wallows (Clayton 1975, 1976; Babcock 1976). Bison tracks have been recognized as distinctive, though subtle, topographic features in the Great Plains (Clayton 1975, 1976), suggesting that these paths were sufficiently wide, compacted, and poorly vegetated to block grass fires. Tracks of large ungulates in grasslands of the Serengeti Plains, East Africa, mark margins of some grass fires (C. Kucera, personal communication).

The effectiveness of rivers, lakes, wetlands, scarps, and other features as fire-breaks depends on several fire-firebreak relationships. A key consideration is break width relative to the ability of fire to jump or spot over it. Rivers with broad, unvegetated channels, particularly braided channels, are more effective breaks than steeper, smaller streams where less canopy opening and local effects of steep topography may result in complete burning through the stream corridor.

Effects of landforms as firebreaks are more pronounced for low- and moderate-intensity fires. Large, high-intensity forest fires may spread erratically, dis-regarding slope and spotting long distance over firebreaks (Brown and Davis 1973). These relationships are exhibited in Tande's (1977) stand origin map for the Jasper townsite area, Canadian Rockies where unvegetated river channels are most effective as breaks for smaller forest fires. During years of widespread burning, possibly by multiple large fires, stand age class boundaries are less commonly defined by water courses.

Orientation of breaks with respect to the direction of fire-driving winds is also important in determining the effectiveness of breaks in controlling fire spread (Daubenmire 1936). Elongate breaks will have greatest influence on limiting fire spread where fire burns across the "grain" of topography.

Landforms may affect vegetation pattern on a landscape by contributing to develop-ment of plant communities with contrasting fire frequencies or intensities. Vegetation in the lee of breaks may be characterized by older communities with a higher proportion of fire-sensitive species than in less protected sites (Daubenmire 1936, Wells 1965, Grimm, unpubl. cited in Wright, 1979). Firebreaks define boundaries between some major vegetation types, such as the prairie-forest border in Minnesota (Daubenmire 1936, Grimm unpubl. cited in Wright 1979). Based on examples from coniferous forests of the Transverse Ranges, southern California, Minnich (1977) argues that slope steep-ness and smoothness affect conifer mortality and, thereby, distribution of plant communities. Mapping of fire history in coniferous forests of Mt. Rainier National Park (M. A. Hemstrom, personal communication) and the central Oregon Cascade Range (F. J. Swanson and P. M. Morrison, unpubl. data) reveals an apparent pattern of more frequent fire on upslope areas than along streams. In some areas fires clearly left buffer strips of trees along streams.

Effects of fire on long-term landform development are unknown. Clearly, in some landscape-ecosystem types such as steep-land chaparral, fire has an important influence on rate of erosion and, therefore, rate of landscape development. It is unclear, however, whether altered fire regime and attendant changes in vegetation would affect the type of landforms developed as well as the rate. Key difficulties in identifying the role of fire in landform development are that fire regime is not an isolated variable. Vegetation, soils, microclimate, animal populations and other factors are all interdependent.

On the time scale of broad landform changes all these factors undergo significant natural variation. But on this scale of decades to centuries records are commonly insufficient to determine cause-effect relationships among these variables and to isolate fire effects on gross landform change.

Interpretation of widespread arroyo cutting in the American Southwest between about 1850 and 1920 exemplifies problems in analyzing complex fire-flora-fauna-climate-land use-landform interactions (Cooke and Reeves 1976). Humphrey (1958) and Harris (1966) suggest that reduced fire frequency as a result of suppression by Anglo-Americans allowed encroachment of woody plants into grasslands. Attendant changes in hydrology and soil erosion have been suggested causes of arroyo cutting. However, Hastings and Turner (1965) conclude that fire and fire effects are relatively unimportant in several vegetation zones where arroyo cutting is prominent. In an analysis of 13 factors contributing to arroyo incision Cooke and Reeves (1976) rank altered fire regime as "probably irrelevant."

In certain favorable circumstances, effects of fire on gross landscape morphology may be less equivocal. For example, such effects might be demonstrable where major valley asymmetry is produced by more rapid erosion from south aspect tributaries which deposit sediment in the main stem, forcing it southward to undercut and steepen northern aspect tributary watersheds (Dohrenwend 1978). If more frequent, intense fire in the south aspect watersheds contributes greatly to higher, long-term sediment yield there, fire is instrumental in shaping gross valley asymmetry. Reduced fire frequency due to suppression or climate change on the scale of millenia might result in a more symmetrical valley cross-profile.

RESEARCH NEEDS

Few, if any, research projects have squarely addressed the problem of identifying and quantifying fire-geomorphic factor relations on both short-term and long-term bases. A summarization of work to date involves compiling information from diverse sources, even for a single area or ecosystem, because there have been no thoroughly integrated studies of fire-vegetation-hydrology-geomorphic process interactions. Such a broad perspective study is underway in southern California Mediterranean ecosystems (Mooney and Conrad 1977).

The key ingredients in such a study are analysis of (a) fire frequency and intensity; (b) patterns of soil and sediment routing through watersheds, including interactions among transfer processes, storage sites, and vegetation; (and c) relations between fire and soil and sediment routing. This information would provide a basis for contrasting the role of fire in different ecosystems and for predicting hydrologic and geomorphic consequences of different fire regimes which would be useful in assessing alternative management practices.

SUMMARY

Interactions among fire, hydrology, and geomorphology vary with the time scale on which a landscape-ecosystem unit is considered. On the short time frame of immediate effects of a single fire on hydrology and geomorphology, fire operates principally through alteration of vegetation and soil properties to alter hydrologic and geomorphic processes. The effects are generally increased soil water and overland flow which result in accelerated erosion by a variety of surface and mass movement processes.

The contribution of fire-induced accelerated erosion to overall sediment yield can be assessed on the intermediate time scale of several fire rotatbons. At this scale both frequency and magnitude of fire impact may be taken into account. Highly erosive landscapes with frequent, intense fire may have more than 70 percent of their long-term sediment yield exported during the period of accelerated erosion during and immediately following a fire. Most landscape-ecosystem types experience much lower fire impact on soil-sediment routing and sediment yield.

The magnitude of geomorphic effects of fire in an ecosystem depends on (a) the frequency and intensity of fire and (b) the sensitivity of geomorphic systems to disturbance by fire. Geomorphic sensitivity is controlled by hillslope and channel steepness and the effectiveness of vegetation in regulating physical processes in the system. These two properties--fire regime and geomorphic sensitivity--may be used to characterize and contrast geomorphic consequences of fire in diverse landscape-ecosystem types. Frequent, intense fire in highly erosive landscapes, such as steep-land chaparral in southern California, is an extremely important component of some geomorphic systems. Fire is progressively less significant in systems in which fire is less frequent and/or less intense and where erosion potential is lower.

Fire-landform interactions involve topographic effects on fire behavior and pattern and fire effects on landform development. Landforms and associated soil distribution affect vegetation patterning, and vegetation of low fire-carrying capacity forms subtle firebreaks. A variety of hydrologic and geomorphic features function as firebreaks. Long-term fire effects on landform development are uncertain. Fire clearly affects rate of landscape development in fire-prone geomorphically sensitive systems, but whether fire controls the type of landforms developed is unknown.

Clear delineation of fire's effect on physical processes in ecosystems requires analysis of (a) fire frequency and intensity; (b) patterns of soil and sediment routing through watersheds, including interactions among storage sites, transfer processes, and vegetation; and (c) effects of fire on this routing system. Research thoroughly integrating these subjects would increase understanding of ecosystem functioning and provide a basis of evaluating consequences of alternative fire management schemes.

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