120: Land Use and Land Cover Effects on Runoff Processes: Fire

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Fire dramatically alters hydrologic processes in many regions of the world. Individual fires reduce vegetation and change soil characteristics, sometimes producing dramatic runoff events in the years shortly after a fire. The greatest determinant of the effect of fire on runoff generation is the severity of the fire, which relates to the frequency of fires and other climatic and vegetation characteristics. Severe fires can produce hydrophobic soils or increase risk of soil surface sealing, reducing infiltration rates. Measurements of the spatial pattern of water repellent soils are useful for estimating potential runoff from postfire storms. The most severe events occur during convective storms, so the spatial extent of individual postfire floods is generally limited in extent. Recovery of water repellent soils is relatively rapid, with significant reductions occurring within a few years. Longer-term changes to hydrology are related to the reduced evapotranspiration caused by loss of vegetation biomass. In forests, changes to annual water balances may last decades.

INTRODUCTION

In some parts of the world, fire is an important natural disturbance to landscapes. Its very nature can cause substantial changes in hydrological processes in an area, as it consumes vegetation biomass and sometimes affects the soil characteristics directly. One of the most spectacular hydrologic results of fire is the combination of water repellent soils followed by thunderstorms, which can create locally severe flooding and erosion (e.g. Klock and Helvey, 1976; DeBano, 1981; Swanson 1981; Moody and Martin, 2001; Istanbulluoglu *et al.*, 2002; Miller *et al.*, 2003). Effects of fire on vegetation, soil, and hydrologic processes can be extraordinarily variable, ranging from nearly no noticeable effect to extreme flood events with results such as those shown in Figure 1. The degree of effect depends on the severity of the fire, or how hot and long it burned, and the spatial extent and patchiness of high severity fire. While there are clear deterministic influences on fire behavior, such as fuel amount and condition, air temperature, humidity, and wind, it can be treated stochastically, and in this sense, fire can be thought of as a weather phenomenon itself. Like other hydrologically relevant weather parameters, fire can be considered both from the perspective of regime, with return frequency and severity metrics, and as an event. Fire regime is essentially the climatic context of fire, and just as it would be somewhat nonsensical to discuss flooding processes without mentioning the aridity of the landscape, so it is that fire regime is an important concept for fire effects. This article first discusses fire regimes and their relationship to hydrology and expectation for fire events, followed by a discussion of the hydrologic responses that might be expected from a given fire event.

FIRE REGIMES AND HYDROLOGY

Metrics for fire regimes relate to the frequency with which fire visits an area and what it tends to do to dominant vegetation in the area. The effects of fire can range from minor damage to the dominant vegetation to stand replacement, where all vegetation in the area is consumed (Hessburg and Agee, 2003). Where there is a strong tendency for one type of outcome versus the other, the severity can be classified as "nonlethal" or as "stand replacing." Where the nature of effects tends to change from fire to fire, the severity is classified as "mixed," and a spatially patchy vegetation structure can result. Within

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Figure 1 Mouth of Wren Creek in the Boise National Forest, Idaho. The watershed burned in 1994, and a severe thunderstorm passed over the basin in the summer of 1995, initiating a hyperconcentrated flow event in this and neighboring streams. A color version of this image is available at http://www.mrw.interscience.wiley.com/ehs

a given vegetation community type (e.g. shrub steppe, or forest), severity tends to go hand in hand with frequency. Very frequent regimes, with mean fire intervals less than 25 years, tend to have little fuel to consume with each event, and frequent kills of small trees do not allow for creation of complex vegetation canopies that can act as ladders from ground fuels to the dominant vegetation species. Conversely, very infrequent regimes allow time for buildup of significant fuels and complex canopies, and crown fires are more common in areas where fires occur less frequently.

Fire regimes have a profound influence on vegetation characteristics, so knowledge of the relationship between plant species and the kinds of fire regimes that they tend to occur with can provide some information about the nature of fires one might expect. Frequency and severity of disturbance can be important in the determination of species (Franklin and Dyrness, 1973), which in turn can affect the probability, severity, and continuity of successive fires. Fire-adapted plant species have strategies to either avoid impacts from flames or to quickly capitalize on freshly burned sites. Trees with thick bark (e.g. Ponderosa Pine, *Pinus ponderosa*) are common in locations with frequent low severity burns, where the bark protects the cambium from the effects of a quickly moving ground fire, and the height of the tree keeps the crown from catching fire. Trees with serrotinous cones (e.g. lodgpole pine, *Pinus contorta*, or Jack pine, *Pinus banksiana*) are more common in locations with rare but severe fires that cover large areas, as the serrotinous cones release seeds into a nutrient rich environment with little competition from more distant seed sources. Invasive fire-adapted grass species (e.g. Cheatgrass, *Bromus tectorum*) can set up a frequent fire regime that prevents regeneration of deeper-rooted native shrub species (Young and Evan, 1985; Billings, 1994).

One of the effects of fire on runoff generation processes may occur where shifts in fire regime force changes in plant communities that affect soil properties and the hydrologic cycle. Fire regime is a function not only of vegetation assemblages but also of the climate. Fire both drives and is driven by vegetation changes in response to climate change. A variety of stratigraphic evidence has shown that substantial variations in precipitation and temperature can occur on long timescales, producing periods of shifting fire regimes and vegetation within an area (Meyer and Pierce, 2003; Whitlock *et al.*, 2003).

Within arid forests and rangelands, physiological adaptations to seasonal aridity are obviously important in determining relative success and spatial distribution of species within the landscape. The ecohydrological optimality principles (*see* **Chapter 12, Co-evolution of Climate, Soil and Vegetation, Volume 1**; **Chapter 101, Ecosystem Processes, Volume 3**; and **Chapter 103, Terrestrial Ecosystems, Volume 3**) that apply well to more humid landscapes (Eagleson, 2002) could potentially represent arid and semiarid landscapes better if fire disturbance, essentially a hydroclimatology phenomenon itself, was included in the conceptualization.

HYDROLOGY AFTER FIRE EVENTS

The effects of an individual fire event on hydrologic processes are tied primarily to the loss of vegetation, loss of organic matter at the soil surface, and the chemico-physical changes to shallow soil horizons that lead to water repellency. The degree of effect is greatly affected by the characteristics of the fire and the fuels it is burning through. Rate and duration of energy releases are key characteristics, and are affected by fuel size and moisture distributions, the amount of fuel available to the fire, volatility of the fuels, and weather (temperature, humidity, wind speed) at the time of burning (Albini *et al.*, 1996). The patchiness of the resulting burn is also important to runoff generation and is tied to continuity and availability of fuels. Effects on soil organic matter and water repellency are less common and depend on soil and vegetation characteristics. One of the primary differences between purposefully set "prescribed" fires and wildfire is that the decision about when to set the fire allows for some degree of control of many of the important factors, including weather, fuel moisture, and soil moisture, which allows for some control on the degree of disturbance to the soil.

Water Repellency

One of the most commonly cited effects of fire on runoff generation processes is the formation of a water repellent layer in the soil, sometimes termed *hydrophobicity* (e.g. DeBano, 1981, 2000). Water repellency is a condition where soil not only loses its usual capillary draw on water, but actually resists entry of water into the soil (*see* **Chapter 68, Water Movement in Hydrophobic Soils, Volume 2**). This condition increases the amount of infiltration excess overland flow (*see* **Chapter 111, Rainfall Excess Overland Flow, Volume 3**). Water repellency occurs naturally in some soils, but seems to be increased in severity, strength, degree, persistence, and continuity by fire (DeBano, 2000). Typically, water repellency occurs in locations with severe heating of the soil surface.

Postfire water repellency is hypothesized to occur by translocation of waxes and other organic compounds with hydrophobic properties from upper layers of the soil and organic matter into lower layers by vaporization where temperatures are high at the surface and condensation on soil particles lower in the soil profile where temperatures are cooler (DeBano *et al.*, 1976). As one might expect, sufficient temperature and duration of heating are necessary for the formation of water repellent layers, and there is some indication that vegetation type affects the formation of water repellent soils (Doerr *et al.*, 2000). The effectiveness of the hypothesized coating process is dependent on the amount of material to be coated, and there is some effect of soil specific surface, generally as measured by grain size. Coarse soils tend to be more susceptible to water repellency than fine grained (DeBano, 1981).

Water repellency is sensitive to soil moisture, and the soil does not impede water movement once wetted (Imeson *et al.*, 1992; Doerr *et al.*, 2000). The requirement for low soil moistures tends to make water repellency a dry season phenomenon, with little effect on runoff generation during snowmelt. Typically, the concern is intense precipitation events during the summer months leading to brief, severe flash flood events. Once the wettable surface layers are wetted, water repellent soils can yield substantial runoff as an infiltration excess process. Over the course of a storm, the infiltration capacity of the soil tends to increase, at least during early times; this is in direct contrast to normally wettable soils that see a decrease in infiltration capacity during a storm (Imeson *et al.*, 1992). After being wetted, soils can become water repellent again if dried.

There are three timescales fundamental to the degree of water repellency, the time for wetting during a storm event (minutes to hours), the variations due to annual wetting and drying, and a longer-term decay of water repellency. While there are a number of examinations of the shortest timescale (e.g. Imeson *et al.*, 1992), and a fairly well known wetting and drying relationship, the longer-term persistence of fire-induced water repellency is not well understood. A water repellent layer may break down due to microbial activity, dissolution during wetting and drying, or physical disturbances like freeze thaw, bioturbation, and soil creep. Severe erosion events (often in the form of rilling) induced by water repellency are a key process for removal of water repellent layers and result in a spatial organization of water repellent and nonrepellent soils, where the upslope interrill patches are repellent but the rills are nonrepellent. There are few published observations of the persistence of water repellency. Dyrness (1976) observed water repellency in a burned area six years after the fire. Personal observations have shown extensive water repellency still existing seven years after severe fire under a subalpine fir stand, and spotty repellency 25 years after a prescribed fire in a coastal Douglas-fir stand. I have also seen extensive water repellency under a subalpine fir stand that had no fire in the last 200 years, but there is no certainty that the repellency originated with a fire in this stand. The erosion mechanism, mentioned above, seems to be the fastest mechanism for removing large areas of water repellent soils. A clearer picture of processes and timescales for recovery from fire-induced water repellency is needed to better understand long-term risks of flooding posed by fires (Doerr and Moody, 2004).

While substantial study has gone into research on water repellency at point and plot scales, an understanding of how it contributes to runoff generation even in small catchments is largely unexplored (Shakesby *et al.*, 2000; Doerr and Moody, 2004). Most of the research on water repellency has focused on methods for measuring the "strength" of the water repellency (Letey *et al.*, 2000). Such measures include water contact angles, head needed to penetrate, or water drop penetration times. At scales of one to a few meters, the tendency of water repellent soils to form preferential flow paths or fingers of wetting has been noted (Imeson *et al.*, 1992; Ritsema and Dekker, 2000). Conceptually, this idealization can apply at larger scales as well, where topology and runoff–runon relationships must be considered (Shakesby *et al.*, 2000; Doerr and Moody, 2004). This conceptualization would argue that if we were interested in the potential for runoff production from a watershed during intense storm events, we would want to measure the fractional area that is water repellent. This approach has seen some success in estimating location of gully initiation sites (Istanbulluoglu *et al.*, 2002).

Soil Surface Sealing

Surface sealing is another frequently suggested mechanism for reductions in infiltration capacity and increases in overland flow (*see* **Chapter 111, Rainfall Excess Overland Flow, Volume 3**) following fire (e.g. Rowe, 1948; Swanson, 1981; Benavides-Solorio and MacDonald, 2001; Meyer and Pierce, 2003). Surface sealing has not received as thorough a treatment for postfire periods as it has in the literature addressing agricultural and severely disturbed soils (e.g. Mohammed and Kohl, 1987; Bosch and Onstad, 1988; Luce, 1997). Surface sealing occurs when raindrop impact and rapid wetting break up soil aggregates, effectively reducing the surface grain size and hydraulic conductivity, and potentially forming a crust. Erosion initiated with the loss of the protective surface organics can also cause relocation of surface fines into macropores, reducing their capacity to move water into deeper layers quickly. Luce (1997) noted reductions in hydraulic conductivity in excess of 70%. The degree of reduction depends on clay content and type, the kinetic energy of the precipitation, and the duration of exposure. Soils with high clay content (nondispersive clays) and high organic matter content tend to have stronger aggregates (Kemper and Koch, 1966). Reduced surface hydraulic conductivity can lead to the initiation of infiltration excess (Horton) overland flow during rainfall events with intensities greater than the hydraulic conductivity. Organic matter reductions are patchy, with organic matter consumption generally related to local burn conditions. If soils in a watershed are susceptible to surface sealing, the hillslope scale runoff generation will depend on the degree of surface sealing, and the proportion of the hillslope and downslope continuity of patches where the organic matter is completely consumed.

Vegetation Loss

The effects of vegetation canopy loss are similar to other land use effects such as forest harvest or rangeland chaining (*see* **Chapter 119, Land Use and Landcover Effects on Runoff Processes: Forest Harvesting and Road Construction, Volume 3**). These effects include reductions in evapotranspiration, reduced interception of liquid and solid precipitation, and increased snowmelt rates during periods of solar dominated melt (e.g. Reifsnyder and Lull, 1965; Harr, 1976; Waring and Schlesinger, 1985 and *see* **Chapter 42, Transpiration, Volume 1**, **Chapter 43, Evaporation of Intercepted Rainfall, Volume 1**, **Chapter 39, Surface Radiation Balance, Volume 1**). Reductions in evapotranspiration and interception generally lead to higher soil moistures (Johnston, 1970; Klock and Helvey, 1976) and greater annual water yields (Megahan, 1983; Troendle and King, 1985; Kuczera, 1987; Watson *et al.*, 1999). The result is greater low flow generation during summer, with springs active higher in watersheds, and more opportunity for production of peak flows (Harr, 1976; Campbell and Morris, 1988). Reduced shading by canopy can substantially increase snowmelt rates leading to increased peak flows in snowmelt-dominated systems (*see* **Chapter 160, Energy Balance and Thermophysical Processes in Snowpacks, Volume 4**). Although we understand that standing dead trees can inhibit turbulent exchange between the snowpack and the atmosphere, the strength of the effect of wildfire on turbulent heat transfers is less well researched. Reductions in organic matter on the soil surface accompanying other vegetation loss primarily yield a reduction in water interception, which can be important during brief precipitation events. While some effect of vegetation loss on runoff generation is expected for almost every fire, the degree of the effects listed is greatly determined by the degree of vegetation loss. A crown fire may remove branches and needles from a tree, where a ground fire may result in patchy mortality and gradual dying of leaves and needles.

Scale of Effects

Although fire creates soil and vegetation conditions that are more conducive to severe hydrologic behavior and rapid runoff forming processes, the more catastrophic postfire runoff events also require substantial precipitation or snowmelt events. There are generally some limitations on the spatial and temporal scales of extreme events (*see* **Chapter 1, On the Fundamentals of Hydrological Sciences, Volume 1**). Although we have seen large fires (e.g. greater than 20 000 ha) in some parts of the world in recent years, it is not uncommon for severe hydrologic events to be confined to a small portion of the fire, even to a small portion of the severely burned areas, suggesting that the characteristic patch scale of intense precipitation and rapid snowmelt events is generally smaller than that of large wildfires (Miller *et al.*, 2003). The fact that these events tend to be limited in their scale is of great consequence to fish, which have evolved migratory life histories and metapopulation strategies to cope with fire related disturbances (Dunham *et al.*, 2003; Rieman *et al.*, 2003).

Flash flood events and related hyperconcentrated flows are partially constrained in scale by the size of the thunderstorm causing the event. Infiltration excess runoff generation processes require that a threshold precipitation intensity be exceeded in order for runoff to occur, and intense precipitation from thunderstorms cover a limited extent. Consequently, it is not uncommon to have only a few small patches within a burned area, typically less than 20 square kilometers each, affected by severe runoff processes (Moody and Martin, 2001; Miller *et al.*, 2003). This dependence on area is not a new concept, as evidenced by a long and prolific literature on the subject of spatial scaling for design precipitation events (e.g. Rodriguez-Iturbe and Mejia, 1974; Rodriguez-Iturbe, 1986; Sivapalan and Blöschl, 1998; Seed *et al.*, 1999 as a small sample). In most engineering applications, the areal reduction factor (ARF) approach has been used. The ARF relates a decrease in storm intensity to the size of the basin. To examine the change in probability of an event of particular intensity and duration as a function of the area under consideration, storm-centered ARFs are needed. Statistics for both storm-centered and basin-centered ARFs can be developed from radar precipitation images of a series of storms. The size of individual basins affected by hyperconcentrated flows is effectively governed by tributary junctions with larger stream channels, with major deposition occurring when what constitutes a major event to a tributary is insignificant to the receiving channel.

Debris flows related to rapid snowmelt characteristically have larger patch dimensions (Miller *et al.*, 2003). Rapid snowmelt generally occurs in concert with large synoptic scale precipitation events covering patches a few hundred kilometers in extent, and in practicality, rapid snowmelt is constrained in scale by elevation. Rapid snowmelt is driven by the high winds during these events and occurs only where air temperatures over a snowpack are above freezing, in one major storm, the elevation range was less than 500 m (Miller *et al.*, 2003). The severe landslide events related to it are further constrained by the land slope, and the final extent of related debris flows is constrained by channel slope, which generally restricts them to headwater basins.

Less dramatic changes to subsurface flow runoff generation processes caused by loss of vegetation or changes in vegetation density are probably effectively constrained by elevation as well. Most measurements of changes in annual water yield only show differences in humid climates. In the interior west of the United States, changes have been seen in mixed conifer and subalpine vegetation types, with little to no change occurring in montane systems at lower elevations (e.g. compare Troendle and King, 1985 to Megahan, 1983).

SUMMARY

Fire is fundamentally intertwined with hydrology. Its occurrence is controlled by seasonal and longer timescale hydroclimatology, and it greatly affects hydrologic processes through its controls on vegetation and soil conditions.

Fire regime presents some expectation for the nature of fire events that might occur in an area. Specifically, some idea of the degree to which vegetation will be removed, the degree to which the soil might be altered, and the patchiness of those effects are tied to the fire regime. Fire regimes also control the type and density of vegetation present in an area.

After a fire, the potentially most destructive runoff generation process is infiltration excess runoff generation, which is influenced by the fractional area with water repellent soils and by the degree to which surface sealing occurs. Observations of these quantities in burned areas are largely missing. In addition, we can expect a greater amount of subsurface flow contribution to streams because of reduced interception and evapotranspiration. The magnitude of these effects is largely controlled by the severity and heterogeneity of the burn, with large homogeneous severe burns having the greatest potential for severe runoff events.

Although postfire runoff generation processes can be spectacular in their magnitude and results, they seem to be generally limited in the areal extent of their effect. This characteristic is critical to the evolved ecology of aquatic ecosystems in response to natural disturbances.

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