Cumulative Watershed Effects of Fuel Management in the Western United States

CHAPTER 8.

Effects of Fuel Management Practices on Water Quality

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Introduction

Fuel management practices in the Rocky Mountain region may include prescribed fire, timber harvesting (patch cuts, thinning, high-grading, or selective logging), mechanical treatments (mulching, chipping or chunking), chemical treatments, or grazing to reduce undesirable species (Chapter 4). The application of any of these treatments has the potential to affect water quality. Understanding the effects of land use practices on hydrologic processes is of primary importance when assessing water quality effects. Unlike agriculture where there are often many activities each year, fuel managements practices occur once every year to once over several decades. Fuel management activities should be implemented with best management practices (BMPs) to minimize or prevent water quality changes or nonpoint source pollution.

Fire

Research has largely focused on the effects of wildfire on water quality. Few address prescribed or controlled fires as smaller watershed level effects are expected. In general, wildfires are more intense (EPA 2005) and more extensive in area than prescribed fires, resulting in potentially greater effects on watershed processes. Watershed effects from fire depend on several variables, including fire size, fire severity, soils, watershed slope, vegetation, vegetation regrowth, precipitation, physical location on the watershed, and proportion of watershed burned.

Temperature

Soil heating may occur following the removal of cover (vegetation, litter and duff, and organic material) by fire (Wells and others 1979). The magnitude of heat pulse into the soil depends on fuel loading, fuel moisture content, fuel distribution, rate of combustion, soil texture, and soil moisture content (Chapter 9). The movement of heat into the soil is not only dependent upon the maximum temperature reached, but the length of time and the heat source that is present. Because fuel is not evenly distributed, a mosaic of heating occurs. The highest soil temperatures are associated with areas of greatest fuel consumption and longest duration of burning. In forested areas, high subsurface soil temperatures usually occur beneath fuel accumulations, with the highest temperatures most likely found in association with consumption of large piles of harvest residue or windrow or very thick duff layers.

Rangelands have lighter fuel loadings, resulting in fires of shorter duration and less subsurface heating. The greatest subsurface heating likely occurs where thick, dry litter layers are consumed beneath shrubs and isolated trees. The soil heat pulse, including both amount and duration, is instrumental in eventual effects of fire on plants (DeBano and others 1998). Excessive soil heating can kill plants and decrease vegetative cover and influence stream temperature from loss of riparian cover to soil water heating.

Exposure of small streams to direct solar radiation is the dominant process responsible for stream temperature increases (Tiedemann and others 1978). Other mechanisms include increased air temperature, channel widening, soil water temperature increases, and streamflow modification (Ice 1999). Streams with smaller surface areas may be more susceptible to heating, but usually return to expected temperature within 500 ft (150 m) downstream (Andrus and Froehlich 1991). Maintaining shade in riparian zones can be used to avoid most temperature increases in small streams. As stream width increases, more of the water surface is exposed to sunlight, consequently reducing the influence of riparian canopy on stream temperature.

The ability of a forest fire to change the temperature of any particular watercourse or water body depends on the amount of water subject to heating. More precisely, it depends on the affected unit's surface-area-to-volume ratio. In essence, this means that temperatures rise faster in smaller and shallower water bodies than in larger and deeper ones. All else equal, the magnitude of any temperature change depends on both the amount of heat directed at the water surface per unit time and the duration of heating. As fire burns in surrounding vegetation and woody debris, it can raise the temperature of water in forest streams (Amaranthus and others 1989; Cushing and Olson 1963; Feller 1981; Hall and Lantz 1969; Helvey 1972; Levno and Rothacher 1969; Spencer and Hauer 1991; Swift and Messer 1971).

The best management practices for prescribed fire are to schedule burning when the soil moisture conditions will minimize heat conductivity into the soils. Streamside management zones or buffers along stream channels can provide shade for stream temperatures and provide filter strips for sediment and nutrients as described later. Streamside buffers are often difficult to exclude from a prescribed burn, but the soil and vegetation are usually moist and do not burn.

Sediment

Watershed responses to prescribed fire may include changes in runoff characteristics, sediment yield, and water chemistry. Under pre-fire conditions, grasses, brush, and the forest canopy intercept precipitation and release it as throughfall, supporting infiltration. Infiltration reduces direct overland flow from precipitation. Runoff is generated through the variable source area concept where infiltration exceeds the saturation potential of soils. As the erosive potential of overland flow is minimized, nutrients and sediments are retained on site. In the absence of vegetative cover, runoff becomes flashier as more streamflow is generated by overland flow, resulting in sharper, higher peak flows and often lower baseflows. With less infiltration, vegetative uptake and retention of water, total water yields from burned watersheds are higher. Once runoff begins, loose soils and ash are quickly removed from steeper slopes. Fire-associated debris is swiftly delivered directly to streams in large quantities. The first storm of the year may produce a 'rolling black' that is a storm event high in suspended sediment and ash. Suspended concentrations over 40,000 mg/L were measured in the first storm event after the 2000 Bobcat fire in Colorado (Kunze and Stednick 2005).

Organic compounds in litter, probably aliphatic hydrocarbons, are volatilized during combustion, migrate into the soil profile, and condense on soil particles, forming a water repellant layer (DeBano and others 1998). The phenomenon is more evident in dry, coarse textured (sandy) soils. It also appears that high temperatures, above 550 °F, destroy the compounds responsible for water repellency. These data suggest fires that heat soils to an intermediate range of temperature (400 to 500 °F) are more likely to cause the formation of a non-wettable layer than fires that heat only the soil surface or those that cause deep penetration of high temperatures. In addition, certain plant communities, such as those containing chaparral species, are more likely to be affected. It is important to recognize that hydrophobicity occurs naturally (DeBano 1981) and may develop under prescribed fire conditions (Huffman and others 2001); however, the effect is not long-lived. Repeated measurements of hydrophobicity after fire suggested the phenomenon lasted up to 22 months in forest soils of the Colorado Front Range, but is usually gone after less than 1 year (Huffman and others 2001).

Suspended sediment is the major nonpoint-source pollution problem in forests, most often associated with forest roads (MacDonald and Stednick 2003). Sediment and turbidity are the most significant water quality responses associated with fire (Beschta 1990). Erosion resulting from prescribed burning is generally less than that resulting from roads, skid trails, and site preparation techniques that cause soil disturbance, which are often a necessary component of prescribed burn projects (EPA 2005).

A controlled burn is usually designed to modify a vegetation type (Chapter 3), while uncontrolled wildfires are less selective in modifying vegetation type or age class. Erosion rates following fires may increase from decreased vegetative cover and/or modified soil properties, including decreased infiltration, hydrophobicity and movement of ash or debris and increased rill erosion from hillslopes directly to the stream channel. Soil erosion may cause decreases in soil nutrients, but unless soil erosion rates are excessive, more nutrients are usually “lost” through the consumption of vegetative fuel. Actual soil erosion and nutrient loss varies by site as a function of vegetation type and recovery, soil type, fire severity, topography, slope position in relation to surface waters, and climate. Significant climate modification has been linked to large area fires. For example, the Bobcat Fire was severe and subsequent storms that occurred had low recurrence intervals, resulting in higher frequency peakflows and higher soil erosion rates (Kunze and Stednick 2005).

Burned areas are sometimes seeded to rapidly establish plants or are given physical treatments to quickly stabilize the soil (Moench and Fusaro 2004). Following severe wildfire, the Forest Service and other land managers may implement Burn Area Emergency Rehabilitation (BAER) treatments to reduce the risk of high runoff and sediment flows. The effectiveness of the most widely used BAER practice, contour-felled log barriers, has not been systematically studied (Robichaud and others 2000). The second most used BAER practice, postfire broadcast seeding with grasses, has been studied and the majority of studies found that this treatment did not significantly reduce erosion during the critical first 2 years after fire (Robichaud and others 2000). Research on the effectiveness of other watershed restoration treatments is ongoing.

Reseeding with grasses is not a reliable technique for erosion control after severe wildfire. Additionally, when an area is seeded with nonnative grass species, native plant species may be effectively excluded leading to questions about long-term stability. Firelines, particularly those that are created by bulldozers, are potential areas of increased soil erosion and establishment of non-native plants. Firelines may be difficult to stabilize with vegetation because much of the nutrient-rich surface soil is cast aside. Hence, they are likely to be slow to revegetate with perennial vegetation. Application of native seed and fertilizer is an effective way to protect firelines (Klock and others 1975; Tiedemann and others 1979).

Nutrients

There are regional differences in the effects of fire on water quality. Of the few studies available for the southeastern United States, results have shown either no effect or small increases in stream nutrients following fires (Richter and others 1982). This contrasts with regions in the western United States where fires have a notably larger effect on water quality (Gresswell 1999; Neary and others 2005; Spencer and others 2003; Stednick 2000). Dissolved nutrients in streamflow are derived primarily from weathering, decomposition of plant material, and anthropogenic sources. Vegetative communities accumulate and cycle large quantities of nutrients (Tiedemann and others 1979). Fire can disrupt this cycle and cause nutrient leaching, volatilization, and transformation.

The concentrations of inorganic ions often increase in streams after a fire (DeBano and others 1998). Studies indicate that changes in chemistry and flow conditions after forest fires are temporary, usually lasting less than 5 years (Chorover and others 1994; Covington and Wallace 1992; Fredriksen 1971; Hauer and Spencer 1998; Ice and others 2004). Early reestablishment of vegetative ground cover after a wildfire is an important factor controlling the recovery.

Water from forested watersheds is typically lower in nutrients than water draining from other land uses. Forest management activities, such as forest cutting and harvesting, may increase annual water yields (Bosch and Hewlett 1982; Stednick 1996) and disrupt the natural cycling of nutrients (Stednick 2000). Several chemical constituents are likely to increase after forest and rangeland burning. The primary constituents of concern are nitrate (NO_3^-), phosphate (PO_4^{3-}), calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+). Nitrate is a mobile ion and easily leached from burned areas. Stream nitrate responses to prescribed fire are generally lower than for wildfire (Stednick 2000). Conversely, phosphorus binds readily to sediment and is thus predominately transported with soil erosion. The bulk of phosphorus transport is as total phosphorus, and orthophosphate concentrations are low (Stednick and others 1982). Changes in concentrations of sulfate, pH, total dissolved solids, chloride, iron, and other constituents have been measured. If organic compounds leach into surface waters, water color, taste, and smell may be affected.

Nitrate-nitrogen (NO_3-N) concentrations are usually quite low (0.002 to 1.0 mg/L) in streams draining undisturbed forest watersheds (Binkley and Brown 1993a,b). Concentrations are low because nitrogen is rapidly used by ecosystem biota, and nitrate formation (nitrification) is relatively slow in forest soils. Slow rates of organic matter decomposition, acid soil conditions common in forest environments, and bacterial allelopathy all decrease rates of nitrification. Organic matter and anaerobic conditions in saturated riparian soils allow for denitrification, the reduction of nitrate to nitrogen gas, which may be lost to the atmosphere.

Often, fires will create soil environmental conditions that are favorable for increased microbial activity (Ballard 2000). These include near neutral pH, increased soil moisture (because there are no interception or evapotranspirational losses), a food or carbon source, and soil temperatures. The increased microbial activity often results in a short-term increase in nitrogen availability. Depending on the monitoring frequency and site specifics, an ammonium pulse may be seen, but usually a pulse of nitrate is measured. The short increase in nitrogen availability helps new or existing vegetation become established. Increased nitrogen mineralization rates persisted for 1 year in range grassland and up to 2 years in a shrub community (Hobbs and Schimel 1984).

If vegetation is quickly reestablished, nutrient exports are short-lived and usually do not represent a threat to water quality or site productivity. There are a couple of possible exceptions. Nitrogen deposition can accumulate in forest soils over time, especially in areas with air quality concerns (Riggan and others 1985; Silsbee and Larson 1982). If timber harvesting occurs in these areas, mobilization of accumulated soil nitrogen may result in higher nitrate concentrations and outputs in the streamwater. Values for nitrate generally increased after fire but not to a level of concern, except in nitrogen-saturated areas. Nitrogen-saturated areas are where the atmospheric inputs of nitrogen compounds from precipitation and dryfall exceed the plant uptake requirement, and thus, excess nitrogen moves through the system. The most striking response of nitrate concentration in streamflow after wildfire was observed east of Los Angeles in southern California (Riggan and others 1994).

Immediately after a fire, stream pH may be affected by direct ash deposition as oxides form from the volatilization of metallic cations. In the first year after fire, increased soil pH may also contribute to increased streamwater pH (Wells and others 1979). In most studies, pH values were little changed by fire and fire-associated events (Landsberg and Tiedemann 2000). Transient pH values up to 9.5 were measured 8 months after the Entiat fires in eastern Washington (Tiedemann 1973, 1981).

Measures that reduce on-site soil erosion and stream vegetative buffers, such as riparian areas, will minimize effects of fire on water quality.

Timber Harvesting

Timber harvest, whether marketable or not, is often used as a tool in fuel management (Chapter 4). The effects of timber harvesting on water quantity and quality are well known. Most water quality studies are conducted at small watershed levels in order to decipher treatment effects from variability in water quality data. The effects of timber harvesting as a thinning, selective cut, or other partial canopy removal treatment, will have less of an effect than complete canopy removal. Less site disturbance will result in less erosion potential and remaining vegetation will quickly utilize increased available nutrients and water from evapotranspiration savings.

Temperature

Surprisingly, few recent studies have been published on the effects of silvicultural practices on water temperature, and most of these were conducted in the 1970s. These studies include harvesting with and without streamside vegetation buffers (Beschta and others 1987; Binkley and Brown 1993a; Swank and Johnson 1994).

Literature on the effects of timber harvesting on stream temperatures shows daily maximum stream temperature increases from 1.5 to 8 °C in eastern forests and 0.6 to 10 °C in western forests. The range in temperature increases reflects a range in streamside vegetation buffers from no buffer to a 100-m buffer. Changes in minimum nighttime stream temperatures (during the winter or dormant season) range from no change to less than 1 °C in the East and from zero to less than 2 °C in the West (Stednick 2000).

Temperatures in small streams may increase when the streamside vegetation canopy is removed. Providing streamside buffers or management zones can mitigate this effect. Several studies have reported temperature increases with streamside buffers, but the increases are much smaller than those of fully exposed streams. The lack of documentation on buffer characteristics makes extrapolation difficult. Different measurements of stream temperature also make direct comparisons difficult. Attributes needed to estimate the contribution of forest overstory to stream surface shade include stream width, distance from vegetation to stream, stream orientation, height and density of vegetation, crown or canopy measurement, latitude, date, and time (Quigley 1981).

Generally, forest practices that open small stream channels to direct solar radiation increase stream temperatures. Retention of streamside vegetation appears to mitigate potential temperature changes, especially temperature extremes. These principles are well documented by research throughout the country. Streamside canopy removal may also decrease winter stream water temperatures, since radiation losses may be increased. For small streams, temperature returns to expected levels within a short distance downstream of where canopy shade is reestablished (Andrus and Froehlich 1991). In general, removal of streamside vegetation cover has the potential to increase streamwater temperatures during the day in the summer. In certain settings, the vegetation removal may allow for decreased nighttime temperatures, especially in the winter. Temperature changes return to pretreatment levels as the streamside vegetation reestablishes. The maintainence of streamside vegetation as a thermal cover is key to maintaining stream temperatures at existing levels.

Sediment

Fuel management practices that result in soil disturbances may increase soil erosion. Soil erosion is the detachment and movement of soil particles, measured as tons/acre/year (Mg/ha/yr). Suspended sediment is eroded soil material transported in the water column of a stream. It is measured as a concentration such as mg/L or as turbidity, an optical measurement of the water's ability to diffract light expressed as Nephelometric Turbidity Units (NTU) (Stednick 1991).

Site properties that affect erosional processes include vegetative cover, soil texture, soil moisture, and slope (Falletti 1977; Renfro 1975). The sediment load of streams (both suspended and bedload) is determined by characteristics of the drainage basin such as geology, vegetation, precipitation, topography, and land use. Sediment enters the stream system through erosional processes, often as pulse events during storms. To achieve stream stability, an equilibrium must be maintained between sediment entering the stream and sediment transported through the channel, thus resulting in a stream profile that neither aggrades or degrades over time. A land use activity that significantly changes sediment load can upset this balance and result in physical and biological changes to the stream system (State of Idaho 1987).

Undisturbed forest watersheds usually have erosion rates from near 0 to 0.25 tons/acre/year (0.57 Mg/ha/yr) (Binkley and Brown 1993a). Erosion rates have been estimated as less than 0.1 tons/acre/year (0.2 Mg/ha/yr) for three-quarters of eastern and interior western forests (Patric and others 1984). Typical timber harvesting and road construction activities may increase erosion rates to 0.05 to 0.25 tons/acre/year (0.11 to 0.57 Mg/ha/yr). More intensive site preparation treatments, such as slash windrowing, stump shearing, or roller chopping, may increase soil erosion rates by up to 5 tons/acre/year (11.2 Mg/ha/yr). Soil erosion from a single precipitation event from a wildfire burned watershed was 0.42 tons/ac (0.95 Mg/ha) and accounted for 90 percent of the estimated annual erosion (Kunze and Stednick 2005). Erosion from unpaved road and trail surfaces may be higher.

Numerous studies have been done on the effects of different forest management practices on erosion rates or sediment production. In general, increased site disturbance will result in increased soil erosion and subsequent sediment production. The type and magnitude of erosion depend on the amount of soil exposed by management practices, the kind of soil, steepness of the slope, weather conditions, and any treatments after the disturbance (Swank and others 1989).

Logs are moved (skidded) from the stump to a landing by tractor, cable, aerial systems, or animals. Tractor skidders may be either crawler or wheeled units, both of which are frequently equipped with arches for reducing the extent of contact between log and ground. Site disturbance will vary greatly with the type of skidding or yarding system. Crawler tractors generally cause the greatest amount of site disturbance, followed closely by wheeled skidders. On some sites, use of wheeled skidders can result in more compaction than crawler tractors. One method of decreasing the amount of soil disturbed by crawler tractors or wheeled skidders is through careful layout of skid trails. Location of skid roads away from the stream channel and off steep slopes can greatly decrease the impact of tractor logging. Logging slash placement on used skid trails increases surface roughness and may decrease soil and water runoff. Cable logging systems will result in less site disturbance because yarding trails are established to the yarding tower machinery, which is restricted to road surfaces. Cable systems can be ranked in order of decreasing soil disturbance as follows: single drum jammer, high lead cable, skyline, and balloon (Stone 1973). Helicopters and balloons will likely result in minimum site disturbance, but both are costly and subject to operational constraints.

Unlike many other land uses that disturb soil for long periods, any increase in sediment yields from timber management activities is usually short-lived. Surface soil disturbances provide a sediment supply, but once the finer materials are transported and revegetation occurs, the site is less apt to continue eroding. Sediment yields or measured suspended sediment concentrations decrease over time as a negative exponential (Beschta 1978; Leaf 1974; NCASI 1999). This time factor should be considered when assessing watersheds for effects on water quality (Stednick 1987).

Most timbering operations will involve the use of forest roads for site access and removal of wood products. Roads are recognized as a potential source of erosion and sediment. BMPs related to roads include road location, road design, time of use, road construction and maintenance, and road obliteration. Roads are addressed by Luce and Reiman in Chapter 12.

Streamside vegetation or filter strips have been used to prevent overland flow and soil erosion from reaching surface waters. The filter strip, or equivalent, decreases the velocity of the overland flow by creating surface roughness. The decreased velocity allows sediment to settle out and overland flows to infiltrate into the undisturbed soils. The streamside vegetation filters were originally used to control or limit road-derived sediment from reaching forest streams. The filter had a recommended width of 10 to 100 m and was dependent on hill slope. These filter strips are effective in sediment removal unless an extreme precipitation or overland flow event exceeds the sediment detention/retention capacity. The characteristics that determine filter strip efficiency include width, vegetative and litter cover, surface roughness, and microtopography.

Fuel management by forest thinning is a relatively new practice and few studies have been conducted to assess the influence of these practices on water quantity and quality. A recent study in New Mexico on thinning in pinyon-juniper forests showed that water yield increased more on slash piled plots than scattered plots, when compared to a control. Similarly, sediment yields were higher on the slash piled plots than scattered plots. When slash was scattered, erosion was lower than the control plots (Madrid 2005).

Nutrients

Cutting vegetation disrupts the nutrient cycle and may accelerate dissolved nutrient leaching and loss via streamflow. Exposing sites to direct sunlight may increase the rate of nitrogen mineralization. Phosphorus is commonly associated with eroded soil particles and sediment and may be lost from the site (Swank and others 1989). Usually, there is minimal opportunity for a buildup of these nutrients in the stream system after a timber harvest because of the normally brief period of increased nutrient flux to the stream (Currier 1980). Throughout the United States, studies have found that nutrient losses from silvicultural activities are minimal and water quality (in terms of nutrients) was not affected (Aubertin and Patric 1972; Chamberlain and others 1991; Hornbeck and Federer 1975; Reuss and others 1997; Sopper 1975; Stednick 2000).

Catchment studies have produced a large body of information on streamwater nutrient responses, particularly from clearcutting. Changes in streamwater nutrient concentrations vary substantially among localities, even within a physiographic region. In central and southern Appalachian forests, nitrate-nitrogen (NO_3-N), potassium (K^+), and other constituents increased after harvesting, but the changes were small and did not affect downstream uses (Swank and others 1989). Clearcutting in northern hardwood forests may result in large increases in concentrations of some nutrients (Hornbeck and others 1987). Research on catchments has identified some of the reasons for varied ecosystem response to disturbance (Swank and Johnson 1994).

In general, nutrient mobility from disturbed forests follows the order: nitrogen > potassium > calcium and magnesium > phosphorus (Stednick 2000). Thus, forest harvesting or other disturbances, such as fire, generally produce larger differences in nitrogen concentrations in streamwater than in other constituents. Possible exceptions are the loss of calcium and potassium documented in the northeast United States when precipitation inputs had greater acidity from fossil fuel combustion (Federer and others 1989). Phosphorus is often associated with sediments and increased sediment inputs to the stream may increase phosphorus concentrations.

If vegetation is reestablished quickly, nutrient exports are short-lived and do not represent a threat to water quality or site productivity. Minimization of site disturbance areas will reduce potential soil erosion and allow for quick vegetation establishment. Use of streamside vegetation zones or buffers are effective in removing sediment from upslope overland flows and nutrients from surface and subsurface flows.

Fertilization

As noted earlier, there are some instances where site restoration or revegetation may require fertilization. The most common fertilizer used in wildland management is nitrogen, usually in the form of urea. Urea fertilizer is highly soluble in water and readily moves into the forest floor and soil with any appreciable amount of precipitation. Under normal conditions, urea is rapidly hydrolyzed (4 to 7 days) to the ammonium ion (NH_4). When moisture is limited, urea may be slowly hydrolyzed on the forest floor. Fertilizer is usually applied in the spring or fall to take advantage of seasonal low intensity and short duration precipitation events (Stednick 2000). If the fertilizer stays dry, the soil surface pH favors formation of ammonia (NH_3), which is lost by volatilization. These losses may be significant, and ammonia absorption by surface water is minimal (USDA Forest Service 1980).

The reported effects of forest fertilization on water quality, particularly nutrient concentrations in streams are variable (reviews by Binkley and Brown 1993b; Binkley and others 1999; Fredriksen and others 1975). Nutrient retention by forest soils is excellent and nutrient concentrations in surface waters after forest fertilization are usually low. Fertilizers may enter surface water by several routes. Direct application of chemicals to exposed surface water is the most significant. Identification of surface water bodies prior to the application essentially eliminates this entry mode.

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Nitrate concentrations, if measured in surface waters, usually peak 2 to 4 days after fertilizer application (USDA Forest Service 1980). The magnitude of the peak concentration may depend on the presence and width of streamside buffers and the density of smaller tributaries to the streams. Peak nitrate-nitrogen concentrations usually decrease rapidly, but may remain above pretreatment levels for 6 to 8 weeks. Winter storms may also result in peak nitrate-nitrogen concentrations, but these peaks usually decrease over successive storms and concentrations decrease quickly between storms (Stednick 2000).

Careful delineation of application areas will avoid direct stream inputs of fertilizer. Fertilizer application should be timed to avoid high precipitation periods as fertilizer might be moved directly to surface waters. When fertilizer is properly applied at a rate and time when vegetation can benefit, fertilizers do not adversely affect surface waters. Streamside vegetation is an effective nutrient removal system and any increase in nutrient concentrations in surface waters from fertilizer applications is usually short-lived.

Mechanical Treatments

When vegetation is too thin for prescribed fire, logging is not economical, or fire is not acceptable, mechanical treatments can be effective in fuel management (Chapter 4). Properly used, mechanical treatments reduce fire hazards, increase plant diversity, control noxious weeds, and improve the quality and quantity of vegetation for wildlife and livestock (Zachman 2003). Treatment increases ground cover, which often results in increased infiltration rates and decreased surface runoff and soil erosion.

Roller chopping is a mechanical treatment that is frequently applied to mountain shrub types and pinyon-juniper stands with stem diameters up to 20 cm. The method is effective for knocking down brush and trees and chopping up the slash. Roller chopping can be done when the soil is firm and dry enough to support the heavy equipment.

Low-pressure tires or tracked vehicles can be used on soils that may be subject to compaction.

A cylindrical roller or drum, equipped with several full-length blades, is towed behind a crawler-type tractor or "cat." The roller chopper may be pulled straight or at a diagonal to increase the chopping action. Two roller choppers are sometimes towed in tandem and at slightly contrasting angles. The cat will usually have its blade positioned low to the ground to push over trees and brush. The heavy weight of the roller chopper crushes the trees and brush, while the blades chop them and help roughen the ground surface (Zachman 2003). The increase of litter and the increased soil surface roughness will increase infiltration and decrease soil erosion.

The use of a Hydro-axe is a mechanical treatment that is frequently applied to mountain shrub types and pinyon-juniper stands. This method is effective for knocking down brush and trees and chopping up the slash. A Hydro-axe, also known as a Hydro-mower, is an articulated tractor with a mower-mulcher mounted on the front of the machine. The Hydro-axe has rubber flotation-type tires that cause little disturbance to the surface of the ground. The machine can move around trees to treat selected areas (Zachman 2003).

The vegetation/soil litter following this treatment is much finer than that resulting from other mechanical treatments. The Hydro-axe allows the operator to be precise in the areas and vegetation treated. The mulch creates a protective vegetal layer for the rubber tire tractor to travel over, thus reducing surface disturbance. Large safety zones are required when using the machine since materials of varying size are frequently thrown from the machine

Depending on the fuel load, other site conditions, and the effectiveness of the chipper or mulcher, woody material is reduced to an organic layer of various thicknesses. Some of these organic horizons have been observed to be up to 30 cm in depth. Any increase in the organic horizon will reduce overland flow potential and hence erosion, but the deep layer may decrease soil temperatures and decrease vegetation establishment (USDA Forest Service 1979). To avoid the potential decrease in soil temperatures and to allow organic matter to decompose over a longer time period, some land mangers are using "chunking." Chunking is the mechanical breakdown of woody materials to larger sizes rather than the less than 3 cm on a side. Some operations produce woody debris from 15 to 30 cm on a side.

Mechanical treatments are new as a fuel management practice, and few studies are completed that determine their effect on water resources. Nonetheless, best professional judgment would suggest that if soil disturbance is minimized by limiting the number of tractor passes, avoiding steep slopes (greater than 35 percent), and scattering the woody material, overland flow and soil erosion will not be a problem. Vegetative cover reduction will temporarily increase on-site water quantity, which can be utilized by the remaining vegetation. If sufficient watershed area is treated, channels with intermittent flows may become perennial.

Grazing

Grazing animals can be used to remove vegetation. The management objective may be to remove understory vegetation or reduce noxious weeds. The effects of the grazing practices on water quality would be expected to be minimal if best management practices are followed. Most grazing lands are in ponderosa pine or pinyon-juniper type communities.

The ponderosa pine range is the most extensive forested range in the western United States. It occupies the low elevations of the mountains and foothills in many areas, but mixes with other tree species at moderate elevations. This type of community is associated with an understory of bunchgrasses and shrubs. As the tree density increases, there is generally a curvilinear decrease in understory production. This range commonly serves as spring, summer, and fall range for cattle. Both rest-rotation and deferred-rotation grazing systems, under proper stocking rates, benefit these forested ranges in terms of maintaining vegetative cover and precipitation infiltration (Leininger and Stednick 2002).

The pinyon-juniper range is located between the ponderosa pine forest and desert shrub or grassland. The pinyon-juniper range generally occurs on rocky, poorly developed soils, and in many locations it alternates with big sagebrush, which occupies deeper soils. Cattle and sheep frequently graze this range in spring before moving to higher-elevation summer ranges and again in fall as they return to their wintering areas.

Fire suppression and overgrazing by livestock have allowed woodlands to expand both upslope and downslope over the past 100+ years (Gruell 1999). Prescribed burns and mechanical removal of pinyon and juniper trees by chaining—large tractors pulling anchor chains or cables over the land—are frequently used to reduce this invasion. Desirable grasses are also commonly seeded into recently treated areas to increase forage for livestock and wildlife.

The most important deleterious effect of improper range management on water quality is soil erosion and the subsequent suspended sediment production. Vegetative cover and soil properties determine the infiltration rates of precipitation water and the amount of streamflow that occurs on grazed lands. Vegetative cover is the dominant factor in controlling runoff and water erosion from agricultural lands and rangelands. Livestock grazing may alter the natural infiltration-runoff relationships by reducing vegetative cover, reducing and scattering litter, and compacting the soil through trampling. The magnitude of these changes is determined by topography, climate, vegetation, stocking rate, and animal species.

This reduction in vegetative cover may in turn increase the occurrence of overland flow and contribute to the desertification of marginal rangelands. Water yield due to overland flow may be increased by decreased infiltration rates and capacities due to soil compaction. As use of an area increases, so does the probability of soil compaction. Animal bedding grounds, stock trails, watering locations, and salt licks are areas of potential soil compaction. Soil texture, moisture, and the amount of organic matter influence the degree of compaction. Soil compaction may also reduce plant growth or range productivity through changes in soil aeration and soil moisture.

Animal activity along stream channels or other open waters may change the chemical and bacterial quality of water. Specifically, animal feces may contaminate waters with bacteria or act as sources of nitrate and phosphate. Studies of two adjacent pastures along Trout Creek in central Colorado indicated only minor chemical effects of cattle grazing on water quality. The bacterial contamination of the water by fecal matter, however, increased significantly. After the cattle were removed, bacterial counts quickly dropped to background levels (Johnson and others 1978).

The removal of plant cover by grazing may increase the impact of raindrops, decrease the amount of organic matter in the soil, increase surface crusting (puddling), decrease infiltration rates, and increase erosion. Increased overland flow, reduced soil moisture, and increased erosion translate into greater concentrations of suspended sediment. Other water quality concerns, such as increased bacterial and nutrient concentrations, do not appear to be a problem with grazing systems, except perhaps in riparian zones. The impact of livestock grazing on watersheds has recently become a resource management issue of national proportions. Research project data have often been evaluated emotionally or according to the political advantages offered rather than by scientific and objective thinking. Recent interest in federal grazing practices, particularly grazing allotments, may bring a reevaluation of the environmental and economic implications of grazing systems on watershed resources (Leininger and Stednick 2002).

Changes in the chemical quality of water due to grazing activities are generally not significant or long-lasting unless animals and their waste products are concentrated in one area. Grazing under best management practices does not adversely affect water quality (Leininger and Stednick 2002).

Best management practices for grazing include vegetation monitoring. Most water quality related problems result from loss of vegetative cover. Other practices include off-channel water sources, salting, and pasture or allotment rotation.

Pesticides

Vegetation management usually refers to the treatment of competing vegetation to allow the release of the desired species, for example, spraying of hardwoods to release conifer regeneration or growth. Vegetation control or removal by herbicides can be considered a fuel management practice when the target vegetation represents a contribution to the site fuel load. Similarly, removal of noxious species by herbicides may improve the existing vegetation used by grazing. Noxious weeds control is often accomplished with herbicides. Noxious weeds are usually nonnative species that, lacking natural controls, spread quickly and take over or reduce habitat for native species. Vegetation management often includes the protection of desired vegetation from pathogens, competing vegetation, insects, and animals (Michael 2000). Pesticides provide management with an effective and often inexpensive method to achieve these goals. The Federal Insecticide, Fungicide, and Rodenticide Act as amended (PL92-516) provides for the registration of pesticides in the United States. An integral part of protecting public health and environmental values is the requirement that pesticides must be applied according to directions approved by the U.S. Environmental Protection Agency and on the label of every registered pesticide. The USDA Forest Service requires training of personnel who recommend and use pesticides, applicator certification, and safety plans to assure the safety of personnel and the protection of environmental values (Michael 2000).

In most situations, herbicide applications are infrequent and often may be a one-time treatment. Monitoring for chemicals in water bodies depends on the type of pesticide, rate of application, area soils, and precipitation events following the application. Water quality monitoring for chemicals after pesticide application using best management practices shows that little to no chemicals are detected in water bodies. Studies of the effects of forest herbicide use (applied under regulatory guidelines) on streamwater element concentrations revealed that no levels were high enough to warrant concern (Binkley and Brown 1993b; Michael 2000). In general, when pesticides were detected in surface waters after their application, concentrations were well below the threshold of concern.

Today's more commonly used pesticides rapidly degrade in the natural environment, often a half-life of days. Degradation of pesticides includes biological, hydrolytic, and phtolytic processes that occur in the soil and water. Probably the most important process is the breakdown of organic chemicals by soil microorganisms. Most pesticides have a high affinity for clay and organic matter and may be removed from the soil water as they are bound to soil particles. Once bound, pesticides are often difficult to desorb (MacKay 1992; Michael 2000).

When pesticides are applied to wildlands near surface waters, a buffer zone is usually left between the application area and the water resources. The width of the buffer varies with site conditions, site sensitivity, and state or local regulations. Little research has been done on the buffer width necessary on forested landscapes; more work has been done on agricultural lands.

Hand application of pesticides is easily controlled and site personnel can be advised to avoid streams or other sensitive areas. Pesticide analysis is expensive and any monitoring program can use surrogate assessments. Spray cards can be used to assess pesticide coverage and drift. Often the pesticide carrier (diesel) can be looked for in water quality samples to determine if overspray or drift resulted in pesticides entering surface waters.

Conclusions

A variety of fuel management practices are available to decrease fuel load or improve forest heath condition. These treatments have the potential to affect water quality, but the implementation of best management practices (BMPs) will minimize or eliminate potential water quality effects. There is a relationship between the amount of area disturbed and the amount of potential erosion, thus the amount of disturbed area should be minimized. Streamside management zones or streamside buffers are effective in capturing overland flows, removing sediment and nutrients, and aiding in maintaining stream temperature.

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