EFFECTS OF PRESCRIBED FIRE ON WATERSHED RESOURCES: A CONCEPTUAL MODEL

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The occurrence of fire in southeastern Arizona ecosystems has been documented since the middle of the nineteenth century. Bahre (1985) concluded that wildfires occurred frequently in all major vegetation communities in southeastern Arizona, including desert shrub, between 1859 and 1890, and that lower frequencies after that period played an important role in the "brush invasion" that started in southeastern Arizona in the 1890s. Wildfire frequency decreased substantially in grasslands after 1882, probably because of overgrazing and the early efforts of Anglo settlers to suppress fire. The suppression of fire and subsequent invasion of brush was reported to be contemporaneous also with increased erosion in the southwestern United States (Leopold 1924).

Several authors have prepared comprehensive reviews on prescribed burning in Arizona ponderosa pine forests (Biswell et al. 1973; Wright 1978) and in mixed conifer, ponderosa pine, pinyon-juniper, and chaparral (Arnold 1963; Zwolinski and Ehrenreich 1967). Despite information on the use of prescribed fire in ecosystem management presented by earlier investigators (Cooper 1961; Kallender 1969; Lindemuth 1960; Weaver 1951) and in more recent studies (Covington and Moore 1992; Swetman 1990), the implementation of prescribed burning programs has been slow in many areas. As a result, critical fire hazard conditions have continued to develop as fuel loading has increased over the years of fire exclusion. For this reason, it is important to revisit the information available on prescribed fire and to place this knowledge in a current perspective, particularly with regard to the impact of different fire severities on soil and water resources.

Substantial scientific information on fire history, vegetation responses, fire behavior, nutrient cycling, and fire prescriptions has been published for a range of southwestern conditions and vegetation types. Some of this information was compiled and published in an earlier proceedings for a symposium on fire ecology and the control and use of fire in wild land management (Wagle 1969). A more recent, and comprehensive, synthesis of fire effects information is contained in the *Proceedings of a Symposium on Effects of Fire Management of Southwestern Natural Resources* (Krammes 1990). The symposium was held in Tucson, AZ in 1988. Discussion of the effects of fire on watershed and soil was included at this symposium. Although there is a large body of published information on the effects of fire on watershed and soil, much of this literature reports the effects of wildfires. Consequently, little quantitative information is available on the effects of prescribed fires on runoff/infiltration, sedimentation, and nutrient losses by runoff and erosion (Robichaud and Waldrop 1994; Robichaud et al. 1993). This is particularly true for watersheds in the southwestern United States.

There are several pragmatic reasons for the abundance of information on wildfire effects. First, the cost of wildfire assessment and associated data collection is usually included as part of emergency funding associated with wildfire suppression and rehabilitation—for example, the cost of monitoring during emergency rehabilitation treatments following fire. Funding at this level is not usually available for prescribed burning and fuels reduction programs. Changes resulting from wildfires are often much easier to document and validate than the more subtle changes produced by lower intensity prescribed fires. As a result, much of the published literature emphasizes severe wildfires that have significant effects on the watershed and associated

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soil and water resources. However, there are isolated reports throughout the literature that report on watershed responses associated with less severe prescribed fires.

Even in the case of wildfires, effects will depend on factors such as postfire precipitation patterns and management activities, and thus prediction of effects becomes a complex process. For example, it has been extremely difficult to quantitatively establish the relationship between the establishment of ryegrass cover and the reduction in erosion immediately following fire because of geographic and annual climatic variability (Barro and Conard 1987).

It is the objective of this paper to develop a simple conceptual model relating fire severity to watershed responses. It can be used as an initial framework for portraying information on watershed and soil responses that have been reported for vegetation and climatic conditions in the southwestern United States.

The Conceptual Model

It is important when discussing fire effects on soil and water to clearly differentiate between fire intensity and fire severity. Fire intensity is a term understood by fire behavior specialists to be the rate of energy release per unit of ground surface area and is proportional to flame height and rate of spread (Chandler et al. 1983). Because fire intensity measurements are difficult to relate to specific soil and water responses (Hungerford 1989), fire severity has been used to describe the amount of vegetation and soil changes associated with a particular fire (Wells et al. 1979). The relationship between fire intensity and fire severity for different vegetation types remains largely unsolved, although substantial progress is being made in developing quantitative models to describe changes in thermal conductivity in soils (Campbell et al. 1994) and soil temperature and water content beneath surface fires (Campbell et al. 1995). These relationships are then being used to develop models that describe fire-driven heat and moisture transport in soils (Albini, in preparation). However, because these quantitative models have not been fully implemented, the resource responses discussed in this paper will refer primarily to different levels of fire severity.

The conceptual model described below portrays fire severity as a continuum ranging from minor resource responses under a cool-burning prescribed fire to major responses that could be expected to occur during stand-replacing wildfires in forests. The fire response continuum in the southwestern United States is large (Baker 1990). In Figure 1, prescribed fire conditions are depicted on the left side of the fire response continuum and represent lower temperature–higher humidity burning conditions where fuel loading is minimal and fuel moisture is high. These conditions produce lower fire intensities, and thereby expose the soil and water resources to lower fire severities. Prescribed fire usually has minor hydrologic impacts on watersheds because the surface vegetation, litter, and forest floor are only partially burned (Baker 1990). Other resources (soils, wildlife, vegetation) are also changed very little by a prescribed fire. On the other end of the fire response continuum (right side of Figure 1), fire behavior more nearly represents that present during wildfires, where the temperatures, wind speeds, and fuel loadings are high, and the humidities and fuel moisture are low. In contrast to prescribed burning, wildfires can have a major effect on basic hydrologic processes, leading to increased sensitivity of the site to eroding forces and to reduced land stability (Baker 1990). Large changes also occur in the other resources (denuded landscapes, large losses of plant nutrients, and so on).

The differences in impacts between prescribed burning and wildfires depend partly on the vegetation type being burned. For example, in ponderosa pine forests there can be large differences; during a cool prescribed fire, only the litter and smaller diameter surface fuels are ignited as compared to near total canopy consumption during intense wildfire. In contrast, fires burning in chaparral are mainly carried by the shrub canopies. Therefore, it is more difficult to control the behavior and intensity of the fire so that only minimum impacts to the soil and vegetation occur. In order to obtain less severe fires in chaparral, fires are ignited during marginal burning conditions, or by using special heat-generating ignition techniques (e.g., helitorch). Also, low-severity fires in chaparral often result in mosaics of burned and unburned patches because the slight differences in slope and aspect make total ignition and coverage impractical.

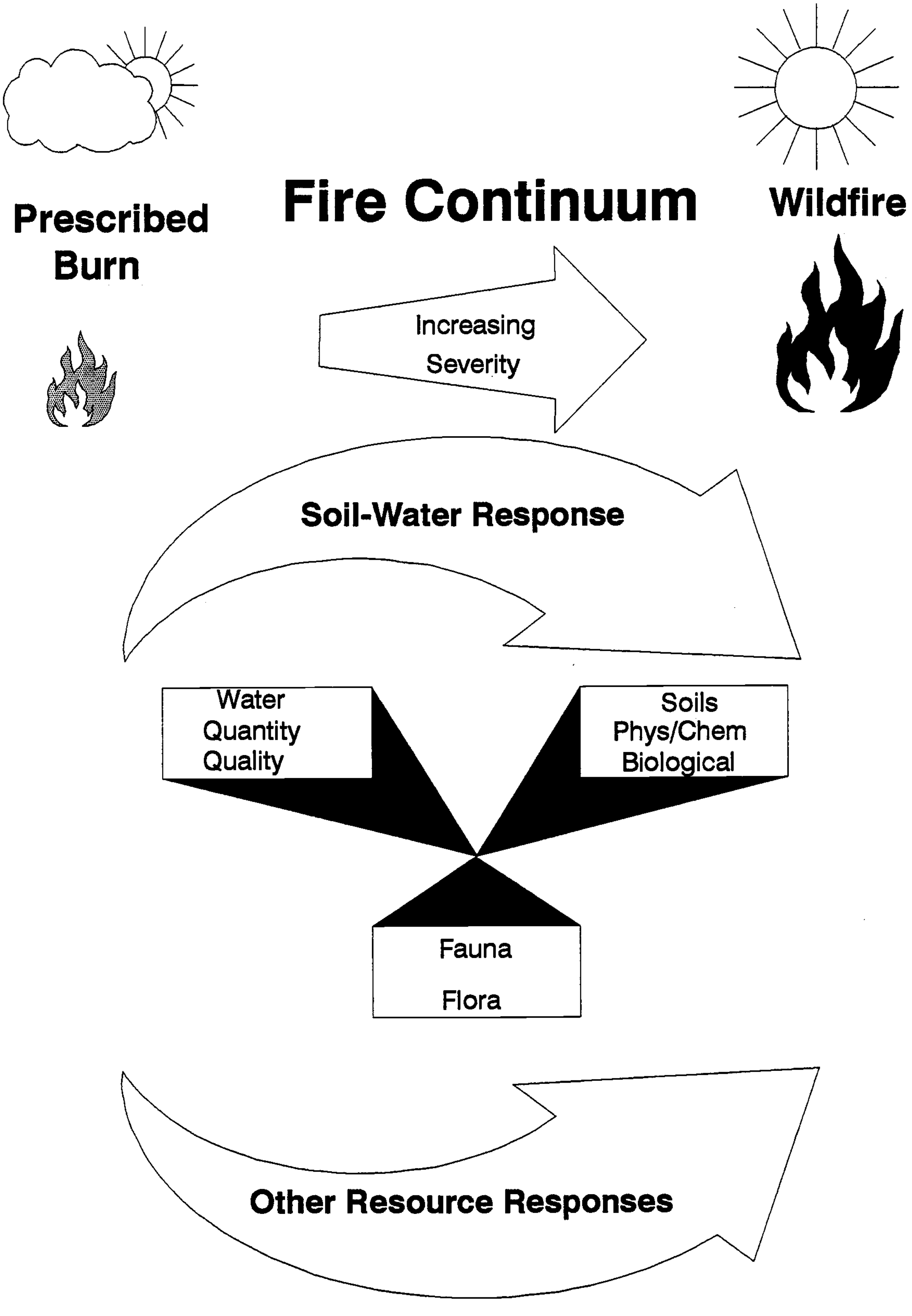

Figure 1. Conceptual model relating immediate resource responses to a fire severity continuum extending from cool-burning prescribed fires to severe wildfires.

Data for Model Development

Before the conceptual model described above can be developed, the response functions for the different resources to a range of fire severities (extending from low to high severity fires) need to be defined. Another important factor affecting the postfire hydrologic scenario is the postfire precipitation pattern. The hydrologic response model is visualized as being a three-dimensional surface with a particular hydrologic response (peak flow, sedimentation rate, etc.) as being a function of both fire severity and a time variable reflecting climatic events following a fire. The immediate soil and watershed response would be most closely related to fire severity (e.g. how much litter and plant cover had been destroyed by the fire, amount of nitrogen volatilized, etc.), and would probably be a nonlinear function, as the one that describes infiltration into a wettable dry soil. An additional time function, reflecting precipitation events, would be necessary to define the longer term hydrologic responses to a particular fire severity. The dimension of time is essential for the model because of the possibility of variable precipitation events that could follow a fire. For example, a low-intensity prescribed fire can produce substantial runoff and soil loss as sediment if the fire is immediately followed by high-intensity rainstorm events. Conversely, severely burned watersheds can produce little runoff and erosion if a fire is followed by a relatively mild year with gentle rains and warm temperatures that allow a protective vegetation cover to develop. The time function that reflects precipitation events will be stochastic in nature and will have to be constructed within a probability framework so that best estimates of outcomes can be determined. Information for the two-dimensional part of this model has been developed by Ffolliott et al. (1988), and with some modification could be used as a starting point for developing the time dimension following fire.

The first iteration of the above model is being prepared to describe soil and watershed responses. All available information on hydrologic responses for Arizona and the southwestern United States is currently being consolidated in order to define and quantify hydrologic responses to both wildfires and, more importantly, cooler burning prescribed fires. Unfortunately a very meager data base is available on the hydrologic responses of watersheds to lower fire severities. The best hydrologic response data available in the literature are for ponderosa pine forests (Campbell et al. 1977; Gottfried and DeBano 1990; Rich 1962; Sims et al. 1981; Zwolinski 1971) and Arizona chaparral (Davis 1989; Glendening and Pase 1961; Heede 1990; Hibbert et al. 1974; Pase and Ingebo 1965; Pase and Lindemuth 1971). Soil response data is likewise most readily available for ponderosa pine (Covington and Sackett 1984, 1990; Wagle and Eakle 1979) and Arizona chaparral (DeBano 1989, 1990; Weinhold and Klemmedson 1992). Much less information exists for watershed and soil responses to fire in mixed conifer, pinyon–juniper, and desert grasslands, although there is pertinent information in nearby areas in the western United States that are applicable to Arizona and the southwestern United States.

Concluding Statement

Prescribed fire continues to be an important tool for managing southwestern ecosystems. The use of fire, however, must be carefully planned and implemented in order to gain the desired response without damaging the watershed resources. It is important when planning fires to clearly differentiate between prescribed burning and wildfires and to burn under cooler conditions. A conceptual model has been developed to illustrate more clearly the differences in impacts between prescribed burning and wildfires on different watershed resources. Although there is much information on the fire impacts on watershed resources, most of it has been collected after wildfires. Scant information is available on the soil and water resource responses to lower severity prescribed fires. Any model describing hydrologic responses must also include a time dimension that represents the sequence of postfire precipitation events.

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