Smoke, Risk, and Intergenerational Equity in Flagstaff, Arizona's Wildland-Urban Interface

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Abstract

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This study addresses two questions with a long-term outlook. Both questions address the combined issues of fire hazard and risk reduction and forest health restoration by focusing on smoke production within an intergenerational equity context. First, what are the characteristics of smoke and fuel hazard that might be produced from alternative prescribed fire treatments under several management options available for the wildland-urban interface of Flagstaff, Arizona. The second question addressed is, what general costs and benefits will be passed on to future residents under each management option? Different forest management options will result in different patterns of intergenerational transfers. We discuss the intergenerational concepts of justice and equity in the context of ecological restoration, focusing on the interplay of fire risk, ecological health, and smoke impacts on human health.

A computer simulation approach was used to model potential smoke emissions and concentrations along with changes in fuel hazards. Prescribed fire reduces forest floor fuels, but will result in smoke and its associated health effects. Emissions of particulate matter were highest during initial burns but decreased with repeated prescribed fire. Future smoke emissions can be reduced by burning on a more frequent interval, which keeps fuels from accumulating, and by thinning, which reduces future fuel input to the

forest floor. Thinning also reduces the risk of active crown fire. However, cumulative emissions are higher with more frequent burning. Although areas restored with heavy thinning and frequent burning emitted lower quantities of particulates, results indicated that burning these areas could result in more frequently exceeding air quality standards than either the initial burns. We argue that the no treatment option would transfer the fewest options to the future and therefore is both unjust and unethical to the future as well as the present. Restoration utilizing thinning and burning would benefit both the current and future generations, and transfer the highest amount of natural capital options, but must be balanced against the negative health effects of increased smoke. We suggest that smoke effects may be mitigated by increasing the fire return interval closer to 20 years in heavily thinned stands.

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Table of Contents

List of Tables

List of Figures

Preface

This thesis contains manuscript format chapters. Because each manuscript chapter was written as a separate publishable work, this thesis contains some redundancy. The two manuscripts are collaborative works where the plural pronoun "we" is used. Elsewhere, "I" is used. There are two manuscripts (chapters 2 and 3), a general introduction, literature review and methods (chapter 1), and general conclusions (chapter 4). Each manuscript has its own abstract, introduction and conclusion section, and review of the literature. Given this, the remaining sections in the thesis focus on bringing together the concepts discussed in each manuscript so that as a whole the thesis tells a coherent story.

Chapter 1

Introduction and Literature Review

Introduction

Fire has been officially recognized as a critical natural process, but for over 100 years has often been suppressed. Fire suppression has resulted in severe management problems including hazardous fuel accumulation, uncontrollable wildland fire, increased risk to human life and property, and ecological deterioration of fire dependent ecosystems. Although managers often seek to reduce fuels and risks while attempting to reintroduce fire into the ecosystem, social values often override the importance of restoring fire to the system. We are caught in a reinforcing feedback cycle, where perceived risk of fire leads to suppression, which leads to further increasing risks and hazard, and further suppression (Miller et al. 1996).

The purpose of this thesis is to address the impacts of smoke produced by fuel reduction and restoration projects in the Flagstaff wildland-urban interface. The use of prescribed fire in ecological restoration and fuel reduction treatments will produce smoke. Smoke in the air will directly affect local residents, and depending on the weather patterns at the time of burning may even affect regional residents. The first point of this research study focuses on describing the characteristics of smoke that might be produced from prescribed fire treatments under various management options. The second focus is on the general costs and benefits passed on to future residents under these management options.

This study considers several management options for the interface area, where reduction of the risk of crown fire is a major objective. The study focuses on the amount of smoke expected to be produced when prescribed fire is used in combination with various fuel reduction options, and considers the impacts in the context of intergenerational equity. While the results of this study are specific to management options in the Flagstaff area, the methodology and implication of the results will have general applicability to fuel reduction and restoration projects in the Southwest.

The first manuscript addresses changing smoke emissions and fuel hazards resulting from various management options. We explored the general tradeoffs and interactions between various thinning intensities and frequencies of prescribed burning. We utilized the Forest Vegetation Simulator Fire and Fuels Extension, a growth and yield model with a fire and fuels extension (FVS-FFE) to track changes over a long time period (80 years). The second manuscript addresses the intergenerational equity aspects of the various management options utilizing the information generated in the first manuscript and with the smoke dispersion model SASEM. We redefined the management options as intergenerational transfers of natural capital, and discussed them with a focus on ecosystem health, fire risk, and smoke impacts on current and future generations. We utilized Flagstaff, Arizona's wildland-urban interface as a case demonstration for applying these various management options to a ponderosa pine forest with many of the characteristics of Western forests after years of fire suppression and other land-use changes. While both manuscripts taken together explore the issues involved, the literature review in the second part of this chapter provides additional background information useful in fully appreciating the linkages between the two manuscripts.

Literature Review

Chapter 2 reviews changes in fuel hazard and smoke emissions resulting from various thinning and prescribed burning treatments. Chapter 3 reviews intergenerational transfers of risk and pollution within the conceptual realm of intergenerational equity and justice. This literature review focuses on the connections and overlaps between these concepts. Although focused specifically on Flagstaff, Arizona’s wildland-urban interface, the concepts concern fire adapted ecosystems and what the current generation can do to affect future generations.

Southwestern Forests

Forests in many parts of the Southwest have undergone significant structural and functional changes since European settlement (1870-1890). The pre-European landscape was predominantly characterized by uneven-aged clumps of trees surrounded by herbaceous and woody understory plants (Cooper 1960, Cooper 1961, Covington and Moore 1994, Fulé et al. 1997, Moore et al. 1999). High-frequency, low-intensity surface fires characterized the fire regime and perpetuated the landscape. Fulé et al. (1997) determined reference conditions for Camp Navajo, about 16 km west of Flagstaff; the mean fire regime between 1637-1883 was 3.7 years for all fires and 6.5 years for widespread fires. The range of variability for all Southwest forests is 2-20 year fire return intervals (Swetnam and Baisan 1996, Moore et al. 1999). Euro-Americans introduced industrial logging and grazing to the region, followed by fire suppression starting in the 1880's. The resulting landscape now consists predominantly of dense, closed canopy forest with few old trees, many small trees, high fuel loads on the forest floor, and low understory production and biodiversity. Many individuals among academia, resource professionals, and the general public agree that active intervention is required to conserve and restore natural (historic) forest structures (native plants, animals, old growth trees) and ecosystem processes (frequent fire regime, nutrient cycling) (Covington et al. 1997a). One area where these issues are being actively addressed is the wildland-urban interface.

The Wildland-Urban Interface (WUI) exists as a continuum where urban areas mix with the forest (Feary and Neuenschwander 1998). Flagstaff, AZ, is located in the largest contiguous ponderosa pine (*Pinus ponderosa*) forest in the world. The city was founded in 1881, and has experienced rapid growth in recent years; the population was estimated to have reached 55,173 by 2002 (www.epodunk.com). Most of the growth involves expansion of suburban developments into previous forested areas and meadows. The majority of Flagstaff's "urban" area lies in the WUI, and is at risk of destruction due to wildfire. The Grand Canyon Forest Partnership, a group of individuals and organizations concerned with the long-term viability and health of the southern Colorado Plateau, developed a boundary that included the area generally within ½ to 1 mile of major developments or city lands (Grand Canyon Forest Partnership 2000a). This zone generally contains the area where most human caused fires begin, gives fire fighters a good area to hold approaching fires, and the distance fire brands can be carried. About 600 wildfires per year occur in the Flagstaff area, and about half of the approximately

76,000 acres in the WUI are classified at high or moderate risk for catastrophic wildfire (Grand Canyon Forest Partnership 2000a).

Several techniques are under study to determine methods of addressing the concerns of fire risk and reference conditions, primarily focused around the ecological restoration concept. The ecological restoration approach emulates reference conditions based on the historic, indigenous ecosystem (Society for Ecological Restoration 1993). The ecological restoration goals in ponderosa pine forests are to recreate forest structure that characterized reference conditions so that ecosystem processes, especially frequent, low-intensity fires, can resume (Covington and Moore 1994, Covington et al. 1997a, Fulé et al. 1997, Mast et al. 1999, Moore et al. 1999). Burn-only experiments began in Fort Valley and Long Valley Experimental Forests in 1975 and focused on reintroducing low intensity surface fire at 1-10 year intervals (Sackett and Haase 1998). Burn-only methods can temporarily reduce fuel loads and release nutrients, but do not effectively thin small trees, and can result in significant old growth tree mortality when the heavy duff loads accumulated around the base burn. Fine fuels reaccumulate rapidly in dense stands. Thus pre-settlement ecological structure (size, number, distribution of trees) is not restored (Harringon and Sackett 1990, Sackett 1980, Sackett and Haase 1998). Thin-only treatments in Taylor Woods have illustrated that positive responses occur with increased thinning intensity, such as increased photosynthesis rates and reduced tree moisture stress (Feeney et al. 1998). However, this approach is limited because high levels of hazardous fuels remain if slash and other forest floor fuels are not removed. Without fire, nutrient recycling is slow in the arid Southwest and the mechanism to prevent future dense overstory conditions is absent.

A combination of thinning and prescribed fire can be used to both alter the forest structure and mimic historic fire regimes. Thin and burn methods have been tested using various spatial patterns in the Grand Canyon National Park (Covington et al. 1997b) and Fort Valley (Covington et al. 1997a, Fulé et al. 1997, Fulé et al. 2000, Harrington and Sackett 1990). The patterns differ in the number of leave trees retained in excess of reference (presettlement) conditions. Research has shown that combining structural restoration and fire alters fire behavior from common crown fires to behavior where surface fires occur but crown fires are uncommon. This treatment produces an increase in herbaceous productivity, and improves multiple resource values (Covington and Moore 1994, Covington et al. 1997a, Covington et al. 1997b, Fulé et al. 1997, Fulé et al. 2000, Moore et al. 1999).

Smoke

The use of prescribed fire is one way to meet management objectives, such as reducing fuel hazards and catastrophic wildfire risk. Fire produces smoke, which restricts its use as a management tool. However, mechanical or chemical treatments cannot fully imitate the effects of fire on fire-adapted ecosystems (USDA 1993). When prescribed fire is considered for fuel management, it is necessary to consider the production and effects of smoke. Smoke from fires (wild or prescribed) can degrade ambient air quality, affect respiratory health, impair visibility, and worsen regional haze (Pyne et al. 1996). Water vapor and CO_2 comprise over 90% of the combustion products from forest fires; however smoke also contains carbon monoxide (CO), particulate matter (PM), and hydrocarbons such as aldehydes and benzene (USDA 1978, Reinhardt and Ottmar 1997). Carbon monoxide, the most abundantly produced pollutant, rapidly disperses with distance (USDA 1978). Particulate matter is a major human health concern. Particulates from wildland fires are a mix of soot, tars, and volatile organic substances; they serve as sorbtion surfaces for harmful gasses. Generally, 70% of wood smoke particulates are <2.5 microns in diameter (PM2.5), 20% between 2.5 and 10 microns (PM10), and 10% are greater than 10 microns (Morgan 1989). Visibility can be impaired by PM10 (less than 10 microns in diameter), and PM2.5 (less than 2.5 microns) can be inhaled deep into human lungs (Pyne et al. 1996). In recognition of the negative effects of particulates, the US Environmental Protection Agency (EPA) enacted new 24 hour and annual standards for both PM10 and PM2.5 in 1997. The PM2.5 standards are 65 ug/m3 and 15.0 ug/m3 for a 24-hour average and annual arithmetic mean, and the PM10 are 150 ug/m3 and 50 ug/m3 (24-hour and annual) (US EPA 1997).

The emission rate of smoke production for an area can be estimated from fuel load, fuel consumption, fuel moisture, and an emission factor, the mass of pollutant emitted per mass of fuel consumed (CH2MHILL 1999). The ratio of carbon released as CO_2 to total carbon combusted (combustion efficiency) is never 100%. The remainder is released as other various chemicals. According to Pyne et al. (1996), PM emissions can range over a factor of 10, depending on fire and fuel conditions that affect combustion efficiency. Smoldering combustion is the least efficient, releasing the highest amounts of PM and

CO. Higher intensity fires with longer flame lengths produce larger particles than low intensity and smoldering combustion fires. Emission rates for particulates depend on fire type, intensity, and phase (USDA 1978). Heading fires tend to produce about 3 times more PM than backing fires. Emission factors for particles vary inversely with combustion efficiency (Pyne 1996, USDA 1978).

Fuel loading and weather directly affect fire behavior and smoke emissions. Fuel loads vary with ecosystem type and previous management activity (Reinhardt and Ottmar 1997). Prescribed fire in natural fuels, prescribed fire in activity fuels (fuels resulting from silvicultural practices), and wildfire show different smoke characteristics. Smoldering burns from duff and large woody fuels often contribute the most smoke to a fire (NWCG 1985). Much of the Flagstaff WUI currently possesses ample fuel to support high intensity fire behavior in hot, dry weather, including torching through live fuel ladders and crown fire (Grand Canyon Forest Partnership 2000a). Wildfires tend to burn when fuels are very dry, while burning conditions can be chosen for prescribed fires to lower their intensity.

Intergenerational Justice and Equity

Issues of ecosystem management and sustainability bring up questions about the current generation's obligations to the future. Our ability to affect the way future generations will live imposes a responsibility that involves issues of justice and equity, not just questions of economic efficiency (Norton and Toman 1997). Intergenerational ethics is concerned with how present actions affect future persons and what the present generation owes to the future. Within intergenerational ethics, the concepts of justice and equity are important and can sometimes overlap. Within the concept of intergenerational justice, we are primarily concerned with distributive justice. Distributive justice is concerned with the proper distribution of resources in society over time, while the field of equity focuses on decision-making and the fairness of a given distribution (Church 1999, Young 1992).

Justice is a culturally defined concept which places boundaries on interpersonal actions. The concepts of justice imply standards of judgment defined by culture and society. By labeling something as unjust, a claim is made that is expected to bind the judgments and actions of others. It indicates that others of good conscience ought to condemn the action. A central concern of justice is how our actions affect others and what obligations we have to them (Auerbach 1995). Matters of justice are usually discussed with regards to the current generation (Church 1999). That we have an obligation to act justly towards those unable to defend themselves, such as the mentally handicapped, is not often disputed. Because future generations depend on us and can do us no harm, they also fall under this obligation. Intergenerational justice may be defined as "what we owe to remote (not alive at the same time) … generations as a matter of justice" (Auerbach 1995). Two core issues of intergenerational justice are how our actions affect remote generations and what we owe remote generations. The principles stated in the Rio Declaration on Environment and Development, ratified at the United Nations Conference on Environment and Development, June 1992, acknowledge that future generations have rights (Folke et al. 1994). One argument, that future people exist only as potential persons, and future generations cannot possess rights because only identifiable individuals can possess them, is addressed by Brown Weiss (1994). These rights are redefined as being held by each generation as a class. Therefore, even if we chose to define future generations as strangers (whose welfare we have no obligation to promote), we still have an obligation not to cause harm (Aerback 1995).

Gower (1995) pointed out that when addressing distribution two questions that must be addressed are (1) how the benefits of programs intended to prevent or repair damage to the environment will be distributed among those affected and (2) how the costs of introducing and delivering these programs will be distributed among those who pay. The way these are answered illustrates how justice is defined in that society.

Justice may be approached as mutual advantage or as impartiality (Barry 1989). Justice as a mutual advantage is a hypothetical contract between two parties, an agreement to move from some status quo to a new agreement prospectively beneficial to both. For justice to count as a good reason to do something, it must be in the interest of the agent, so it is based on self-interest. This position requires voluntary cooperation, and results in a more even distribution of benefits than if parties do not cooperate. Justice as impartiality is not based on self-interest, but rather on the idea of an impartial observer. One way to gain an impartial perspective is to determine which outcome would be favored if the position occupied is not known. The motive can be either a direct moral concern for others, or a concern for the opinion of others. Because mutual cooperation between past and future generations is not possible, mutual advantage is ruled out as a possibility, and intergenerational justice must be based on impartiality (Church 1999). There is a problem, however, with the accurate prediction of future needs (Gower 1995). Because future generations are unlikely to conceptualize or value justice as we do, we can only attempt to act justly towards toward them. Thus decisions made with a moral concern for future generations will be made with respect to the standards of the current generations (Auerbach 1995, Church 1999). We know that our policies will affect future generations, and they will have similarities and needs even if they do not have a similar concept of justice. If we have a shared concept of harm (likely on a base level of physical well-being), and we can make certain predictions about future circumstances, we ought to consider the justice implications of our policies on future generations (Gower 1995). Therefore, it is important to find standards to gauge the quality of the world we both inherited and the one we will pass on, because we do not know how future generations will value our contributions.

Auerbach (1995) argued that “we ought to act toward future generations in such a way that future generations are most likely to honor the commitments and build upon the moral traditions of their ancestors.” This recognizes the intergenerational nature of civilization and is especially meaningful for those concerned with the judgment of history. If we establish a tradition of acting justly towards future generations, it is likely that the next generation will continue these socially condoned traditions and also act justly towards the future. A moral obligation to act justly will not be created unless concern for the future is transformed into action.

Equity refers to the consequences of alternative policies and how they affect the fair or just distribution of resources, rights and wealth between people and over time (Young 1992). Relative rather than minimum standards are the focus of equity. On a societal level, because rules have consequences for welfare, they must be justifiable in terms of ethical procedure. There is no general agreement as to how one can determine whether or not a proposal is equitable. Of the various approaches to address intergenerational equity questions, I will briefly discuss the three most well developed and frequently utilized approaches of neo-classical economics, Rawls, and Brown Weiss.

Economics is the science of scarcity, and the neo-classical economics approach to future generations is to discount future values to the present. The discount rate is the rate used to convert a stream of benefits or costs into its present value; how we value future benefits today. It is comparable to the interest rate; how much present investments will produce over time. The two may be the same, but the discount rate can be manipulated to produce a desired outcome (Norgaard and Howarth 1991). Critics of this approach stress the need for reflecting social, rather than individual values and for including intrinsic values on long-term sustainability (Cairns 1995). Young (1992) pointed out that valuing ecological services is difficult for several reasons: consumers are not always the best judges of ecological service values, they often do not understand their value, and most economic studies assume values should be constrained by wealth, not moral or equity concerns.

Is discounting an appropriate approach for intergenerational equity? Brennan (1999) suggested that the question is both a question of obligation and of description. The question of obligation is an ethical question and refers to whether we have a duty to sacrifice for future generations, and if so, how much. The question of description refers to what would be best to do, if we do sacrifice. Brennan (1999) argued that we should sacrifice for future generations only if the average well being increases by more than we lose on average today, ensuring future gains exceed our losses. People have a pure-time preference, so more than a dollar’s worth of future benefits are required to give up that amount today. As long as resource scarcity makes tradeoffs inevitable, consideration of policies to benefit future generations should not ignore economic opportunity cost. However, ultimately policy decisions will come from the political field, which involves ethical reflection and judgment (Brennan 1999).

Norgaard and Howarth (1991) demonstrated that indiscriminate use of discounting does not reflect a moral concern for future generations because how a society cares about the future (in terms of asset transfer) and the valuation of environmental services are interdependent. How rights and assets are distributed across generations determines whether an efficient resource allocation will sustain human welfare across generations. Environmental valuation with sufficient (not easily defined) caring about the future results in sustainability, while valuation with too little asset transfer will not lead to sustainability.

To decide equity questions, Rawls (1971) proposed using the original position under a veil of ignorance where people collectively decide on societal rules without knowing what position they will occupy in society, or what generation they will be part of (Young

1992). From this exercise, the principle of maxi-min was developed, where the emphasis is on raising the welfare of the worst off person, or, in this case, the worst off generation (Church 1999, Schrader-Frechette 1996). Maxi-min tends to favor a conservative position regarding environmental damage and acceptability of technological risk because it focuses on potentially catastrophic consequences and probabilistic uncertainty (Schrader-Frechette 1996). With maxi-min, it is rational to choose the action that avoids the worst possible consequence of all options. Maxi-min tries to maximize the minimum outcome by avoiding policy with the worst possible consequences or that harms the worst-off persons. Maxi-min would lead to giving the interests of the least advantaged the highest priority and avoids using a utility function, designed for risk taking, in the area of morals, where it does not belong. However, this approach is biased toward the values of the present generation because it involves estimating the welfare, values, and preferences of future generations. It may also entail the current generation making a large sacrifice to increase the welfare of future generations. This is very unlikely to occur in reality (Young 1992, Church 1999).

Brown Weiss (1990, 1994) argued that future preference and value assumptions should not be made. Each generation is part of a natural system with special responsibilities as well as rights. Each generation receives from its ancestors a natural and cultural legacy in trust, which it has a right to benefit from as well as an obligation to conserve for future generations. Many of our actions place burdens on future generations by depleting resources and degrading environmental quality. Brown Weiss developed three principles to guide intergenerational equity decisions: conservation of options, conservation of equality, and conservation of access. Conservation of options is based on the idea that each generation ought to conserve the diversity of the natural and cultural resource base so it does not overly restrict future options for solving problems and satisfying values, and each generation is entitled to diversity comparable to that of previous generations. To conserve equality, each generation should pass on the planet in no worse condition than it was received. To conserve access, each generation should provide its members with equitable access rights to the resource base and conserve this access for future generations.

Pearce et al. (1989) argued that achieving intergenerational equity requires earlier generations to leave succeeding generations all forms of wealth, including "a stock of knowledge and understanding, a stock of technology, a stock of man-made capital and a stock of environmental assets no less than that inherited by the current generation." A stock of knowledge and understanding is highly resistant to entropy, and can even result in negative entropy. This can be used to generate corrective behavior to offset environmental and ecological damage, but humans are not always capable of applying knowledge rationally to improve their well being. Stocks of man-made capital and improved technology are not all environmentally benevolent or consistent with sustainability. Cumberland (1991) argued that effective transfer mechanisms must be centered not only upon monetary and fiscal measures, but upon real resources relevant to ecological sustainability. Environmental capital in the form of intact and fully functioning natural resource systems and large-scale ecologies may be the scarcest resources of the next century. Young (1992) argued that each generation should maintain its inherited resource base and leave the next generation with a per capita stock no less than it inherited. If a generation acts to increase future population, it must also increase the resource stock so the expected per capita stock of conditionally renewable resources, resource diversity, and assimilative capacity stays the same. Church (1999) argued that a conservation of options approach is appropriate to address forest management; the most equitable forest condition to pass on to the future is one that is the most balanced among different structural classes. The least equitable condition to pass on would consist of mostly one class. These condition classes can be thought of in terms of an ecosystems' evolutionary environment and can be defined with the help of the historic range of variability for the ecosystem in question (Moore et al. 1999). Restoration can be used to restore a balanced condition.

Sustainability and Natural Capital

Sustainability is an ambiguous concept with many published definitions. The Brundtland Commission described sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). This definition is vague enough to be accepted by economists and ecologists alike, but offers little in the way of guidance for achieving sustainability. Viederman (1992) defined a sustainable society as one that "ensures the health and vitality of human life and culture and of nature's capital, for present and future generations. Such a society acts to stop the activities that serve to destroy human life and nature's capital, and to encourage those activities that serve to conserve what exists, restore what has been damaged, and prevent future harm." This definition alludes to intergenerational equity and specifies maintenance of natural capital as prerequisites for sustainability.

Ecosystem services, the activities of the ecosystem that benefit humans, are conditionally renewable resources and their management involves sustaining them over time (Costanza et al. 1997). There is a large segment of society that believes technology can repair or compensate for any problems that may arise from our mismanagement of nature. However, the ecological resources that may become scarce are not those we have a long experience successfully managing, let alone technical innovation to mitigate constraints (Norton and Toman 1997). Moreover, most resource managers believe that ecosystems can provide services at less cost and with more reliability than technology.

Because the natural "capital" of many ecosystems has been depleted by past management, such as fire exclusion, the ecological surplus (interest) has suffered to the point that we are living off the principle. Once damaged, ecological restoration is an option for returning some of their services. Cairns (1995) defines restoration as "the return of an ecosystem to a close approximation of its condition prior to disturbance". The central idea of restoration is that ecosystems function best under the conditions in which they adapted over evolutionary time, and if these conditions are returned at satisfactory spatial and temporal scales this will result in the preservation and continued evolution of the system's biodiversity (Swanson et al. 1994). For Southwest ponderosa pine forests, these evolutionary conditions included open, park-like forests, productive herbaceous understory, and frequent low-intensity fires (Fulé et al. 1997, Moore et al.

1999). Current conditions represent a large departure from the historic range of variability for these factors. The introduction of widespread livestock grazing, selective logging, and active fire suppression, while appearing at the time to be wise uses of the ponderosa pine-bunchgrass community surrounding Flagstaff, were in hindsight disinvestments that served to depreciate natural capital. We need to rebuild the ecological capital by reinvesting in the system so it will once more be able to provide long-term goods and service by-products.

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Chapter 2

Projected Smoke Emissions and Fuel Changes Associated with Restoration in Flagstaff, Arizona's Wildland-Urban Interface

Abstract

A variety of management options, many involving prescribed fire, have been proposed as methods for restoring ecosystem health and lowering the risk of catastrophic wildfire in the Wildland-Urban Interface areas in the Southwestern US. However, smoke from fires can degrade air quality, affect respiratory health, and decrease visibility. This study models expected smoke production by varying the return interval of prescribed fire on four different thinning intensities. Much higher emissions were produced during preliminary burns, but decreased rapidly with repeated burning. Stand history prior to thinning had little effect on emissions. Smoke emissions decrease in quantity over time in response to repeated burning. Increased thinning results in lower future emissions. Total emissions produced over time were highest with more frequent burning, but less during any one burn. Potential smoke emissions from crown fire followed the same pattern. Although the 20-year burning intervals result in approximately twice the smoke emitted per acre compared with a 5-year interval, the 5-year interval results in burning each acre 4 times as often.

Introduction

Forests in many parts of the Southwest have undergone significant structural and functional changes since European settlement (1870-1890). The introduction of grazing, logging, and fire suppression resulted in a landscape with a high catastrophic wildfire risk (Cooper 1960, Cooper 1961, Covington and Moore 1994, Covington et al. 1994, Fulé et al. 1997, Moore et al. 1999). The Wildland-Urban Interface (WUI) exists as a continuum where urban areas mix with the forest (Feary and Neuenschwander 1998). Flagstaff, AZ is located in the largest contiguous ponderosa pine (*Pinus ponderosa*) forest in the world. Flagstaff, founded in 1881, has experienced rapid growth in recent years. The population in was 52,894 in 2000, and was estimated to have reached 55,173 by 2002 (www.epodunk.com). Most of the growth involves expansion of suburban developments into previous forested areas and meadows. The majority of Flagstaff's "urban" area lies in the WUI, and is at risk of destruction due to wildfire. About 600 wildfires per year occur in the Flagstaff area, and about half of the 180,000 acres in the WUI are classified at high or moderate risk for catastrophic wildfire (Grand Canyon Forest Partnership 2000).

Techniques are under study to determine methods for addressing these concerns, primarily focused around the ecological restoration concept. The ecological restoration goals in ponderosa pine forests are to recreate forest structure that characterized reference conditions so that ecosystem processes, especially frequent, low-intensity fires, can resume (Moore et al. 1999). Structural restoration combined with prescribed fire produces an increase in herbaceous productivity and old growth tree responses (Covington et al. 1997, Fulé et al. 2001, Kolb et al. 2001). The use of prescribed fire also meets management objectives, such as reducing fuel hazards and decreasing catastrophic wildfire risk. Mechanical or chemical treatments probably cannot fully imitate the effects of fire on fire-adapted ecosystems (USDA 1993). However, the use of fire produces smoke, which constrains its use as a management tool. When prescribed fire is considered for fuel management, it is necessary to consider the production and effects of smoke.

Smoke from wildland fires and other sources, such as fuelwood burning, can degrade ambient air quality, affect respiratory health, impair visibility, and worsen regional haze (Pyne et al. 1996). Exposure to smoke reduces lung function, increases the severity of existing lung disease, irritates eyes, and triggers headaches, while long-term exposure may lead to emphysema, chronic bronchitis, and various cancers (Washington State Department of Ecology 1997). Smoke has a complex chemistry that varies with time and space within and between burn episodes. Water vapor and CO2 comprise over 90% of the combustion products from forest fires, but smoke contains varying amounts of carbon monoxide (CO), particulate matter (PM), and hydrocarbons (Pyne et al. 1996, Reinhardt and Ottmar 1997, USDA 1978). Carbon monoxide is the most abundantly produced pollutant, but it rapidly disperses with distance (USDA 1978). Aldehydes, such as formaldehyde and acrolein, are irritants and some are suspected carcinogens (Dost 1991). Polycyclic aromatic hydrocarbons, such as benzo(a)pyrene, are often mutagenic and carcinogenic (Koenig et al. 1988, Morgan 1989).

Particulate matter (PM) found in smoke is a major public health concern. It forms primarily by agglomeration of condensed hydrocarbons and tar as well as mechanical entrapment of vegetation fragments and ash. These particles also serve as sorbtion surfaces for harmful compounds. The size distribution of particles varies with fire type and distance from source, but generally, 70% of wood smoke particulates are <2.5 microns in diameter (PM2.5), 20% between 2.5 and 10 microns (PM10), and 10% are greater than 10 microns (Morgan 1989). PM10 is < 10microns and includes PM 2.5. PM10 can penetrate the respiratory tract, and PM2.5 is small enough to reach the alveolar region of the lungs and also has the maximum effect on visibility. Prescribed fire smoke constituents are regulated through the Clean Air Act, as well as other state and local regulations, with a focus on particulates. Recently, the US EPA initiated 24-hour PM2.5 standards of 65 ug/m3 and lowered existing PM10 standards to 150 ug/m3 (US EPA 1997).

We examined a range of management options designed to reduce fire risk and restore ponderosa pine forests in Flagstaff's WUI. We addressed the following research questions:

- What amounts of smoke (PM10 and PM2.5) would be produced under three return intervals for prescribed fire following four different levels of thinning intensity?
- What effect would these management options have on fuel hazards?

Methods

Study Area

The Fort Valley Experimental Treatments are located in and adjacent to the Fort Valley Experimental Forest, approximately 9.5 miles northwest of Flagstaff, AZ. The elevation is approximately 7200-7400 ft. and the climate cool and subhumid with an early summer drought (USDA 1998). About half of the average 22 in. of precipitation occurs as snow, and the mean annual temperature is 45.5 F. Soils are weathered from basaltic parent material, with bedrock at approximately 10 in. The vegetation consists of scattered presettlement ponderosa pine (*Pinus ponderosa*) characterized by larger size and yellowed bark ("yellow pines"), with dense thickets of smaller, dark-barked trees ("blackjacks") (Dieterich 1980). The understory consists of perennial grasses, mainly Arizona fescue (*Festuca arizonica*), mountain muhly (*Muhlenbergia montana*), and squirreltail (*Sitanion hystrix*), and scattered forbs and shrubs. The Fort Valley Experimental Forest has not experienced fire for around 120 years.

Experimental Blocks and Treatments

We utilized stand data from three thinning treatments and unthinned controls being tested in Fort Valley study area (Fulé et al. 2001, USDA 1998). The treatments varied in terms of residual tree densities, which are based on different numbers of trees selected to replace dead presettlement trees. Evidence of presettlement trees included stumps, snags, and logs of presettlement age. Where such evidence was found, several of the largest trees within 30 ft. were retained. The search radius was expanded to 60 ft. if needed to locate appropriate trees. All living presettlement trees were retained. The **heavy thin** (full restoration) treatment retained 1.5-3 postsettlement replacement trees for each evidence of a dead presettlement replacement tree. The number of replacement trees was determined by size of selected replacements. If available replacement trees were greater than 16 in. diameter an average of 1.5 replacements were selected, otherwise three trees were selected. This produced a tree density nearest to presettlement levels (Table 2.1). The **medium thin** and **light thin** prescriptions represented higher tree densities, with 2-4 replacements and 3-6 replacements, respectively. The **no thin** treatment retained dense stands of small trees with interspersed yellow pines.

These treatments were tested on three experimental blocks in and adjacent to the Fort Valley Experimental Forest. Treatments were randomly assigned. Larson et al. (1999) characterized three types of ponderosa pine stands at Fort Valley: yellow pine, blackjack pine, and mixed yellow and blackjack. Experimental block 1 corresponded to the yellow pine type, containing 30+ yellow pines/acre; trees characterized by yellow bark, large size, and an age greater than 150 years. These stands also contained a large number of small trees, giving them a bimodal diameter distribution. The blackjack type (block 3), contained younger and smaller trees with black bark. Block 3 was located outside the Experimental Forest and differed from the others in past management practices. It has been more heavily harvested for large trees and thinned from below, removing both large and small trees from the site and leaving it dominated by mid-sized trees. Block 2 typified a mixed yellow and blackjack stand with large numbers of small trees as well as a small number (<12 trees/acre) of yellow pines. The yellow pine and mixed units (blocks 1 and 3) contained more large trees than the blackjack stand, but trees in the smallest size class remained numerically dominant.

Blocks were thinned between November 1998 and September 1999. Blocks 1 and 2 were thinned with a mechanical feller and limbed at the tree, resulting in broadcast fuels. Block

3 was whole tree harvested and the resulting slash piles were burned in February 2000. All blocks were broadcast burned in 2000 and 2001.

Sampling Methods

Twenty 0.1 acre plots were established in each of the 12 units and permanently marked with iron stakes (Fulé et al. 2001). Slope and aspect were recorded. Live and dead overstory trees over breast height (4.5 ft.) were measured and species, condition class, and dbh were recorded. Stumps and downed trees were also recorded. Tree heights and average crown base height per plot were measured. Trees below breast height were tallied by condition class and by three height classes (0-15.7 in., 15.8-31.5 in., and 31.6-54 in.) on a nested 0.025 acre subplot. Forest floor material and dead woody biomass were measured on a 50 ft. planar transect in a random direction from each plot center. Woody debris biomass was calculated using methods described in Brown (1974) and Sackett (1980). Plots were originally measured from August through November 1998, and were remeasured in October 1999 to obtain the post thinning, pre-burn fuel loading. Prior to thinning, fuel loads ranged from 5.5 to 26.6 tons/acre. Preburn, post thin fuel loads were similar in all units before treatment ranging from 21.5 to 27.7 tons/acre. Total surface fuels were representative of similar forests in the Southwest (Sackett 1979, Sackett and Haase 1998).

Simulations

We utilized the Central Rockies Variant of the Forest Vegetation Simulator Fire and Fuels Extension (FVS-FFE) to compare the effects of 16 combinations of thinning treatments and prescribed burning (Table 2.2) on PM10 and PM2.5 emissions and surface fuels. FVS is an individual tree, distance independent growth and yield model that is widely accepted for planning purposes and supported by the USDA Forest Service (Dixon 2001, Wykoff et al. 1982). The Central Rockies Variant of FVS was originally developed in 1990, based on the growth equations of the GENGYM model (Edminster et al. 1991, Dixon 2001). Sites near the present study area were measured to develop growth and yield equations for the Central Rockies Variant (Edminster et al. 1991).

The Fire and Fuels Extension (FFE) to FVS simulates fire effects, fuel loading, and snag dynamics (Beukema et al. 1998). The FFE integrates FVS with elements from existing fire behavior and effects models. Snags are tracked from the time they are created to their removal through user-specified management or falling. Snags experience gradual crown and height loss and decay, which move material into the fuels component. The fuels submodel tracks litter, duff, and woody surface fuels as well as live and dead crown fuels. Woody surface fuel is tracked in 6 size classes and 4 decay rate classes, based on species and diameter of wood when added to the pool. Input comes from snags, live tree crowns, and management slash. The model contains default fuel levels based on stand cover and age, but we chose to use measured fuel loads for each plot to increase accuracy. Removal occurs through decay, management, or fire. With decay, 1/10 of the material moves into the duff pool annually, while the remainder is lost to the atmosphere. Movement between size classes is not modeled. The submodel also tracks live herbaceous and shrub fuels to a limited extent. These fuels are important to smoke calculations, but are not dynamically simulated by FFE. Instead, it represents them as habitat-type specific constant values.

The fire submodel is only active if the user has specifically requested it and can simulate fires only if the user defines the times and parameters. The FFE does not simulate fire spread or probability of fire. FVS provides information about the trees in the stand, and the fuel submodel provides information about fuel loading. The burn model then calculates the predicted or simulated effects of the fire on fuels, live trees, and snags, and also fuel consumption and smoke emissions. Fire intensity does not *directly* affect fuel consumption in FFE, although in reality it has a significant effect on the proportion of large and small particles. The model calculates smoke production as PM2.5 and PM10 using a series of emission factors applied to the amount of fuel consumed. Fuel consumption is determined by: size, moisture content, and type (natural, piled).

We ran each of the 20 plots per block individually for 80 years, simulating prescribed fire beginning at year 0 using three different burn intervals; 5, 10, and 20 years. The shorter intervals are within the historic range of variability for many Northern Arizona ponderosa pine forests (2-8 years) (Moore et al. 1999). The 20 year interval was included to look at a longer interval that may serve the management goal of reducing fire hazard, and is still within the 2-20 year range of variability for all Southwestern ponderosa pine forests (Swetnam and Baisan 1996). We also simulated the stands with fire exclusion. The FVS default simulation cycle is 10 years. To incorporate the 5-year burn cycle, we altered the cycle length to 5 years. Altering the time interval between projections introduces bias into the predicted stand attributes (Wykoff et al. 1982). For consistency, we used 5-year cycles for all FVS-FFE runs. We ran each plot as an individual stand and then summarized the output for each management option. Based on a review of several prescribed burn plans for Fort Valley, we used the following parameters: throttle-back burn, 3 ft. flame length, and 0 percent crowning. Flamelengths in this range are still controllable by direct attack at the head and flanks using hand tools, and throttle-back burns further reduce flamelength by 30% by confining the burn to thin strips (Pyne et al. 1996).

Sensitivity Analysis

The model parameters for FVS have been the subject of extensive testing (Wykoff et al. 1982). The FFE, however, is relatively new. We ran a sensitivity analysis on three factors that were under direct user control, two affecting the fuels submodel and one affecting the fire submodel. We altered (1) the decay rate for all fuel and decay classes, (2) the proportion of decayed material that enters the duff pool from each fuel category, and (3) the flamelength of the prescribed burn to analyze the effects of slight changes in the burn conditions. We chose these factors because they should have a considerable effect on smoke emissions through control of fire intensity and fuel loading. Although flamelength does not directly affect fuel consumption in the FFE, it does affect mortality and snag dynamics, which in turn affect the fuel submodel. Using the default values and stand input parameters as the base, we analyzed the sensitivity by separately varying each factor by +/- 10%. The sensitivity of FVS-FFE to each factor was measured by computing the percent change in PM10 emissions for the thinning treatments with the largest difference between PM10 emissions, the no-thin and heavy-thin treatments. These treatments were run using 20-year burn intervals, as this would allow the largest differences in fuel loads to accumulate.

Analysis

Statistical analysis was conducted using SAS-JMP 4.0 (Sall and Lehman 1996). We analyzed fuel loading and smoke emissions in terms of PM10 and PM2.5 by comparing differences between blocks, treatments, and burning intervals using ANOVA. Alpha level was 0.05. Following a statistically significant ANOVA result, treatment means were compared with a post-hoc Tukey's procedure. We compared differences within the same treatment/burn interval between the first burn (year 2000), the next subsequent burn (5, 10 or 20 years later) and at year 2080 using a paired t-test to detect significant differences between time periods. Because fuel hazards generally increased between burns, we analyzed pre-burn fuel loads to compare fuel hazards. Only significant ($p>0.05$) changes are presented below.

Results

Fuel Loading

Since we kept fire characteristics constant, fuel loading was the variable primarily responsible for differences in smoke production. All fuels were reduced with burning, followed by a subsequent rise (Figures 2.1a-e). The magnitude of fuel accumulation between burns was determined by the intensity of thinning and the amount of time between burns. There was a clear difference between unburned and burned simulations, and the unthinned and the three thinning treatments, showing that thinning reduced future available fuel. Burning on a 5-year interval did not allow much fuel build-up on any unit, even the unthinned stands, while a 20-year interval allowed time for a larger fuel buildup.

Without thinning or burning, total surface fuels experienced an initial decrease, then an increase to 57% above the initial fuel load. By year 80, fuels in the 0-3 in. range increased steadily to 27% above year 0. Fuels in the 3+ category showed an initial sharp decrease (possibly an artifact of the model), then an increase to 51% above year 0. Litter and duff increased gradually and continually over time. Thinned, unburned stands exhibited reductions in total fuels over the first 20 years, indicating decomposition outpaced accumulation, followed by an increase through year 80, indicating the reductions were short term in nature. Fuels in the 0-3 in. range also exhibited an initial, gradual reduction, followed by an increase proportional to the thinning intensity. Heavier thinning resulted in a smaller increase. Fuels in the 3+ category showed the same pattern and possible program artifact as the unthinned treatment, but remained below pre-thin levels. Litter gradually decreased, but by year 80 began to increase. Duff showed a slight increase.

Burning at year 0 resulted in an average of 82% reductions in total surface fuels for all thinning treatments. Burning at any of the three burn intervals resulted in a significant reduction in total fuel loads compared to preburn loads. Total surface fuels showed consistent reductions with burning, with less fuel remaining with increased burning frequency and thinning intensity. Fuels in the 0-3 in. range decreased with the first burn between 73 and 35%, followed by a gradual increases for both 10 and 20-year burning intervals. Subsequent 0-3 in. fuels remained low for 5-year burn intervals. The same pattern is seen with 3+ in fuels, with a much greater initial reduction. Significant differences between treatments did not appear for 3+ in. fuels until year 20. Litter loads showed reductions of 83-97% with the first burn, and a continuous reduction for 5-year burns, a leveling off for 10-year burns, and a gradual increase for 20-year burns. The first burn reduced duff by 77% and continued burning at any of the three intervals continued to reduce duff loading.

Smoke Emissions

The initial differences between blocks in terms of stand history and harvesting techniques did not produce significant differences ($p>0.05$) in PM10 or PM2.5 emissions at year 2000, 2020, or 2080. This lack of significant differences held for all treatments and burn intervals.

Patterns of smoke emissions varied by thinning intensity and by burning interval (Figures 2.2a-b). Emissions from the first burn were high from all four thinning intensities, but decreased with repeated burning as fuel loads decreased. The production of PM10 during the first burns for the no thin treatments averaged 0.16 tons/acre, light thin averaged 0.17 tons/acre, and both medium and heavy thin averaged 0.14 tons/acre. The production of PM2.5 during the initial burns for the no thin treatments averaged 0.13 tons/acre, light thin averaged 0.14 tons/acre, medium and heavy thin averaged 0.12 tons/acre.

Increased thinning resulted in lower future emissions, because less canopy was available to drop fuels. By year 80, emissions for the no thin treatments were approximately twice as high as the heavy thinning treatments. All three thinning treatments resulted in emissions production closer to each other than the no thin treatments. Different burning regimes also led to quantitative differences in emissions. More frequent burning resulted in lower emissions per acre when burned than a less frequent interval, a result of less fuel accumulating between burns. Emissions were also reduced more rapidly when the stand was burned more frequently.

We found no significant difference in emissions from the first burn (year 2000) between treatments. Differences between treatments were most noticeable in the future burns, after the emissions production leveled off and variability decreased. Significant differences ($P<.0001$) tended to appear at the second burn, 5, 10, or 20 years later, between no thin and thinning treatments. By year 2080, significant differences ($P<.0001$) existed between all treatments except for medium and light thin, and medium and heavy thin burned at 20-year intervals. Emissions for all management options showed significant decreases ($P<.0001$) over time between 2000 and 2020 and on to 2080. PM2.5 emissions showed a more rapid decrease with repeated burning than PM10 emissions, corresponding with patterns seen only in duff loading.

Increased frequency of burning led to lower PM emissions per burn, but higher cumulative emissions over the 80-year period (Figures 2.3a-b). When burned less frequently, more biomass is lost to the atmosphere by decomposition than from consumption. Increased thinning intensity also effectively reduced cumulative emissions of PM by reducing the biomass added to the fuel pool over time. The relative effects of each of these treatments are such that the unthinned stands burned on 20-year intervals produce approximately as much cumulative PM as the heavy thin stands burned on 5-year intervals. Heavy thinning combined with a 20-year burning interval produced the lowest cumulative PM overall.

Sensitivity Analysis

FVS-FFE results were relatively insensitive to varying the factors affecting fuel loading and flamelength by +/- 10% (Table 2.3). PM10 emission predictions were least sensitive to flamelength, with the heavy thinned stand averaging less than 1% change over the 80-year period, and the unthinned stand increasing average PM10 emissions by 1.2% with a reduction in flamelength and reducing average emissions by 1.4% with an increase in flamelength.

PM10 emissions were most sensitive to the two alterations of the fuel submodel. Maximum sensitivity was found by reducing the duff production, which reduced PM10 emissions by an average of 8.8% and 9.6% for the heavy thinned and unthinned stands, respectively. Increasing this factor produces a lesser effect, increasing emissions by 1.1% and 1.2%. Reducing the fuel decay rates by 10% effectively increased PM10 emissions by 1.7% and 2.9% for the thinned and unthinned stands, respectively. Increasing this factor results in a reduction of 1.6% and 2.0%. The overall trend of sensitivity with thinning intensity was that the unthinned stand was more sensitive to the three parameters than the heavy thinned stand.

Discussion

FVS-FFE provides an estimate of the amount of smoke emitted, but does not model the important effects of space and time scales. Burning intervals, thinning intensities, and the time span in which we conduct the preliminary burns will determine how rapidly we reduce both smoke levels from prescribed fire and the risk of catastrophic fire, as well as who will be impacted by smoke and for how long. These modeling results can be tentatively extrapolated to Flagstaff's WUI, assuming that the fuel loads, stand structure, and emissions data from Fort Valley are similar to what would be experienced across the entire interface. The Flagstaff Area Wildfire Risk Assessment (Grand Canyon Forest Partnership, 2000) classified the Flagstaff WUI into 78,100 acres of high, medium, and low catastrophic fire potential based on fuel type, fuel loads, forest age and density, access, slope, and aspect. Embedded within this area are 16,000 acres of highly urbanized residential and business areas.

We assumed that the high risk areas possessed stand profiles similar to the unthinned stands, medium risk areas were similar to medium and light thin stands, and low risk areas were similar to heavy thin stands. This classification appeared to most accurately represent the ponderosa pine forests in the WUI. We recognize, however, that this is a simplification in that stand conditions were not the only factor utilized in assessing risk. Other factors included slope, aspect, and proximity to structures. In addition, not all of the WUI will be treated and some dense canopy will be retained for wildlife habitat, screening, and nutrient cycling. In addition, some of the WUI may be thinned, but not burned. Areas located adjacent to homes, for example, may not be broadcast burned to avoid the danger of escaped fire. We calculated the number of acres needing thinning and burning per year under each burning interval (Table 2.4). For example, to treat both the high and medium risk areas and burn at a 5-year burning interval would require the yearly burning of approximately 7,820 acres, whereas to treat the same area with a 20-year burning interval would require burning only 1,955 acres per year. Based on conversations with Forest Service personnel, there are an average of 75-80 days per year suitable for prescribed burning in the general area of Flagstaff. These days are distributed throughout the year, with many falling at times suitable for burning only slash piles (winter). Based on an estimate of 75 burning days per year, burning of both high and medium risk areas on a 5-year interval would require burning 104 acres per burning day, while a 20-year interval would require burning 26 acres per burning day (Table 2.5).

The Arizona Department of Environmental Quality mandates that without special clearance, no more than 50 contiguous acres in the WUI can be burned per day. Burning 50 acres of heavily thinned forest would result in the emission of 7.0 tons of PM10 and 6.0 tons of PM2.5 into the airshed during the first burn. With the first burn of 50 acres of unthinned forest approximately 8.0 tons of PM10 and 6.5 tons of PM2.5 would be emitted. By 2080, differences between burning intervals and thinning treatments would be more apparent. When burned on a 5-year rotation, the unthinned stand produced 1.5 and 1.0 tons of PM10 and PM2.5, respectively, at year 2080,while heavily thinned stands produced 1.0 and 0.5 tons of PM10 and PM2.5, respectively. Unthinned stands burned on a 20 year interval produced 3.5 and 4.5 tons of PM10 and PM2.5, respectively, while heavily thinned stands produced 1.5 tons of both PM10 and PM2.5. When fuel hazards are considered, heavy fuel loads are found in the unburned stands through year 2080. Fuel hazards are reduced with each burn, and remain low with the 5-year intervals, but increase between burns with 20-year intervals. Although the 20-year burning intervals result in approximately twice the smoke emissions per acre as the 5-year intervals, with 5-year intervals each acre is burned 4 times as often.

Smoke emission patterns predicted by our simulation are primarily a result of the amount of fuel consumed, how quickly the fuel load is reduced over time, yearly additions through needle cast and branch-fall, and how long it is allowed to accumulate between burns. Variation in ignition patterns, wind, slope, and fuel moisture would cause shorter or longer flame lengths in some areas. We held flame lengths at a constant 3 feet. Fires of higher intensity (longer flame lengths) produce lower emissions of particulate matter, but with proportionately larger particles than low intensity and smoldering combustion fires (Ward and Hardy 1991). PM2.5 emission factors generally decrease with higher fire intensities.

As duff, ladder fuels, and large logs are consumed over time, there will be a decrease in potential fire intensity, total energy release, and resistance to control (Sackett and Haase 1998). Prescribed burning reduces large logs differently depending on the state of decomposition. Rotten logs are generally almost totally consumed, decreasing firebrand potential and receptive ignition sites. Sound logs generally decrease in diameter when burned, but persist through several fires, leaving the number of logs essentially the same. In ponderosa pine forests, needles are the fuels that cause most of the dynamic fire behavior. Removing them through burning greatly reduces the fire hazard, but needles reaccumulate quickly. Litter loads were reduced substantially with prescribed burning, reducing ignitability and rate-of-spread potential. Over time, all stands and burning intervals experienced an overall reduction in litter load, except the unburned, unthinned stands, which showed an overall increase. This result indicates that even without burning, thinning can reduce future ignitibility and rate-of-spread potential.

To meet the goal of reducing fire hazard, various surface fuel targets are stated in the literature for Fort Valley, ranging from 2 to 8 tons/acre (USDA 1998). In our simulation, the initial burns reduced mean total surface fuel loads to within this range, although all treatments contained stands that remained far above this goal. By the time the burned units reach their next burn (5, 10, or 20 years later), fuel loads increased but remain within this limit for the thinned stands. The unthinned stands were slightly above the upper limit, and by 2079, mean fuel loads are far above this goal for all unburned treatments. All stands burned on 5-year intervals were in the lower end of the range. Unthinned treatments burned on 10- and 20-year intervals were above the limit, with the 20-year intervals higher than the 10-year intervals. Thinning treatments burned on 10 year intervals were within the fuel target, as were the heavy and medium thin treatments burned on 20-year intervals.

PM10 emissions simulated in our study are within the range reported by other researchers. Huff et al. (1995) reported current PM10 emissions from prescribed fires in several watersheds within the Columbia River Basin ranged from 0.14 to 0.18 tons/acre, which also encompasses the means of our first burns. However, wildfires produced 0.28 to 0.36 tons/acre of PM10 within the same watersheds, an amount that was actually surpassed by several higher-end plots during the first burn in our simulations. Einfeld et al. (1991) found that approximately 0.42 tons/acre of PM2.5 were emitted from Northwest Montana logging slash. Hardy (1992) estimated that the Silver Fire, a 96,000 acre wildfire in Southeast Oregon, produced about 0.28 tons/acre of PM2.5. While these amounts are high compared to our mean emission levels, the maximum levels of smoke come close to these high values.

The trend of high initial emissions followed by a rapid decrease with repeated burning is similar to that found by Schaaf (1996), looking at the long-term effects of fuel treatments on annual emissions from both wild and prescribed fires in the Grande Ronde River Basin in Northeast Oregon. Six levels (0-5%) of prescribed fire treatment were simulated over a 100-year period to test if fuel treatments at landscape levels would result in fewer impacts from wildfire to life, property, natural resources, and air quality. Results suggested that annual wildfire emissions could be reduced with increased fuel treatment. Total emissions were found to increase over the first 40 years with increased prescribed burning, then to level off and eventually decrease slightly at 80 years. However, the real tradeoff came with increased control and better dispersion conditions that prescribed fires have over wildfires.

Robinson et al. (2004) collected PM2.5 samples during first entry burns and a maintenance burn in primarily grassland fuel near Flagstaff, Arizona. During first entry burns, ambient concentrations of PM2.5 within the burned area ranged from 2541 and 6459 ug/m3 during the flaming stage, while the concentration during maintenance fires (grassland) was 523 ug/m3. Smoldering particle concentrations were lower (155-904 ug/m3), but began within 4 hours of ignition and continued for several days.

Potter and Fox (1996) describe the two primary components of smoke management as managing the atmosphere for dispersion and the fire itself for production. The first utilizes the atmosphere to dilute and disperse emissions before they impact people and population centers. One aspect of this approach is to generate enough energy in the fire to loft smoke in a plume well above the canopy, as well as burning at times and locations where the wind will transport the smoke away from population centers.

The second component is the management of the fire process itself to minimize pollution generation. Peterson and Leenhouts (1997) discussed various techniques that can be employed to reduce prescribed fire emissions, many of which are currently in use in Flagstaff's WUI. The area burned can be reduced by mechanical treatments such as chipping and crushing. Fuel loading can be reduced by physically removing fuels prior to burning and burning more frequently with low-intensity fires. Thinning treatments fall into this category by reducing yearly fuel accumulation through needle and branch fall. Fuel consumption can be reduced if some fuels are at or above the moisture of extinction where they will not burn; however unless the remaining fuels decompose or are otherwise removed prior to future burning this does not result in long-term emissions reduction. This option is useful for reducing wildfire hazard by removing fine and intermediate fuel while limiting duff and large fuel consumption, and also retains debris for wildlife and nutrient cycling. Protection of large woody fuel from consumption for wildlife and soil productivity is called for by the Fort Valley Environmental Assessment (USDA 1998), which would result in a reduction of smoke emitted from the burn. The final method for reducing emissions is to reduce the emission factor by shifting consumption from smoldering into the flaming phase. Changes in combustion efficiency between flaming and smoldering combustion have a large effect on the character of the resulting emissions. Most pollutant emission factors except for NOx and CO2 are negatively correlated with combustion efficiency, so acting to reduce one pollutant effectively reduces them all (Peterson and Leenhouts 1997). Einfeld et al. (1991) found that smoldering combustion produced about 50% more PM2.5 and CO than flaming combustion. Robinson et al. (2004) also found that concentrations of PM2.5 within a burned area were much less during smoldering than flaming combustion.

Ward and Hardy (1991) found that PM emission factors for long-needled conifer litter burned with backing and heading fires range from 40-100 pounds/ton of fuel consumed, while cured grass emission factors are generally 20 pounds/ton of fuel consumed. This means that as Flagstaff's WUI changes from a closed canopy ponderosa pine forest with fuels almost entirely composed of conifer litter toward a more open landscape of scattered trees and fuels consisting primarily of cured grass, PM emissions would decrease, even if total fuel load remained the same.

Thinning and prescribed burning alone or in combination will not eliminate catastrophic fires, but can substantially reduce the risk of both passive and active crown fire. Fulé et al. (2001) compared potential fire behavior in the same set of thinning prescriptions and concluded that all three thinning treatments resisted crown burning, with the degree of resistance increasing with increased thinning intensity. However, slash fuels must be removed or crown fires can occur in severe wildfire conditions. Fulé et al. (2002) found that a burn only treatment thinned many small trees, reduced fuels, and raised crown base height, but had minor effects on crownfire susceptibility, basal area, canopy cover because the majority of trees >20cm in diameter survived. A full restoration treatment with thinning to emulate reference conditions and prescribed burning resulted in an area much less susceptible to crownfire due to reduced crown bulk density, crown fuel load and increased crown base height. A minimum treatment was intermediate, forming a continuum of forest conditions.

Wildfires often occur when fuel is dry, fuel consumption greater, and much fuel is consumed during the less efficient smoldering stage, resulting in about 2 times as much PM10 as prescribed burns. Prescribed burning under favorable dispersion conditions can also limit the impact of a wildfire burning through the same area when dispersion conditions are poor (Ottmar 1992). Most of the large wildfires in the Flagstaff area burn with strong winds resulting in relatively good smoke dispersion.

These model results are intended to support decision-making processes by discussing the expected impacts of several available options. One potential problem with relying on a model such as FVS-FFE for long-term predictions is the imprecision of simulation results. The purpose of the modeling analysis was not to compare absolute values, but to compare management alternatives and trends. As illustrated by our sensitivity analysis, the modeling of emission production by the FFE is sensitive to changes in the fuel model parameters. However, as discussed by Scott (1998), the internal consistency of a model will be more reliable than its accuracy. Thus inaccuracies in the model will have a greater effect on absolute values than on the difference between alternative scenarios.

Conclusions

We found that increased thinning intensity can reduce future emissions by reducing fuel inputs from the canopy to the forest floor. However, without burning the fuel reductions are short-term. Increasing the return interval of maintenance fires keeps fuels from accumulating between burns and reduces the smoke produced in the burns. Total emissions produced over time were highest with more frequent burning, but less during any one burn.

Structural and functional changes and the resulting high wildfire risk are problems in many of the forests throughout much of the Western United States. We illustrated the impacts that combinations of thinning intensities and frequencies of prescribed fire may have on smoke emissions and fuel hazards. Prescribed burning can greatly reduce fuel hazard, but only temporarily. Continual burns are needed to remove the accumulated fuels to maintain low fuel hazard. Because fuels are continually entering the surface fuel pool, especially needles, hazard reduction must be an ongoing process, and a single fire can only temporarily reduce the hazard. Our simulation found that after 120 years of fire exclusion, heavy smoke emissions will result from initial prescribed burns. Subsequent burns produce less smoke with each burn, with lower amounts produced by heavier thinning intensities and more frequent burning intervals. With more frequent burning, less fuel accumulates on the forest floor. Heavier thinning reduces the amount of canopy fuel that can fall the forest floor. Over time, more frequent burning will result in more cumulative smoke production than a less frequent burn interval, and heavier thinning can reduce cumulative smoke. Without burning, fuel loads remain high regardless of thinning treatment, although without thinning, they result in very hazardous conditions.

Covington et al. (1994) predicted an acceleration of historic changes in the Inland West such as increasing fuel accumulations, longer fire seasons, and intensified burning conditions, defining a narrow window of 15-30 years for the implementation of restoration treatments. As the scale of disturbance increases, thresholds may be crossed to alternative stable states, such as grasslands or shrublands (Savage and Mast 2005). However, prescribed fire is an excellent tool for restoring fire-related ecosystems. Just as fire is an integral part of the ponderosa pine ecosystems of the Inland West, so is the resulting smoke. Our management of prescribed fire smoke will determine the continued public acceptance of prescribed burning in the wildland urban interface. Poor smoke management can cause health and safety problems for the general public. Flagstaff possesses many smoke sensitive areas such as an airport, highways, Flagstaff Medical Center, and recreational areas. The preliminary steps of restoration and fuel reduction will produce much more smoke than future maintenance, so the question is how much smoke would we accept in order to pass on a landscape with a reduced risk of catastrophic wildfire?

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Tables and Figures

Table 2.1. Stand characteristics before and after thinning by thin intensity blocks.

	No Thin	Light Thin	Medium Thin	Heavy Thin
Pre-thin				
Basal Area (sq. ft./acre)	164.3	148.5	167.7	151.5
Density (trees/acre)	480.6	422.3	603.9	386.7
Post-thin				
Basal Area (sq. ft./acre)	164.3	97.2	77.7	67.8
Density (trees/acre)	480.6	98.3	68.8	56.8

Table 2.2. Thinning intensity and burning interval simulated (16 combinations of management options), and prescribed fire outputs tracked for simulations.

Thinning Treatment	Burning Intervals	Model Fire Outputs
No Thin	Unburned	Fuels
Light	5-year	Fuels, PM2.5, PM10
Medium	10-year	Fuels, PM2.5, PM10
Heavy	20-year	Fuels, PM2.5, PM10

Table 2.3. Sensitivity of FVS-FFE predicted PM10 emissions to changes (±10%) in model parameters (flame length, fuel decay rate, and duff production) for no thin and heavy thin treatments burned on 20-year intervals. Table values are average percentage change over 80 years of simulation.

	No Thin		Heavy Thin	
Parameter / change	-10%	+10%	-10%	+10%
Flame length	1.2	-1.4	0.1	-0.2
Fuel decay rate	2.9	-2.0	1.7	-1.6
Duff production	-9.6	1.2	-8.8	1.0

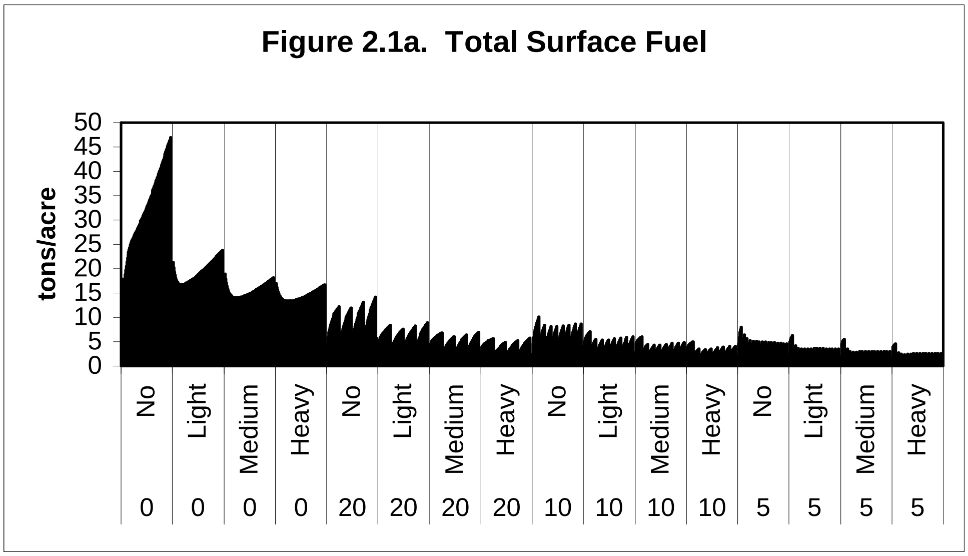
Table 2.4. Total acres and average number of hectares burned in Flagstaff's WUI for each burning interval by risk rating.

Risk Rating	Total Acres	5-Yr Interval	10-Yr Interval	20-Yr Interval
High	23000	4600	2300	1150
Medium	16100	3220	1610	805
Low	39000	7800	3900	1950

Table 2.5. Number of acres burned per burning day in Flagstaff's WUI for different assumptions regarding number of burning days per year by prescribed burning interval and risk rating.

	80 days/year			75 days/year		
Risk / interval	5-Year	10-Year	20- Year	5-Year	10-Year	20- Year
High	58	29	14	61	31	15
Medium	40	20	10	43	21	11
Low	98	49	24	104	52	26
Total	195	98	49	208	104	52

Figure 2.1. Surface fuel loading (tons/acre) by thinning treatment and burn interval from year 0 to year 80. Each category shows the fuel levels from years 0 to year 80 in 5 year intervals.



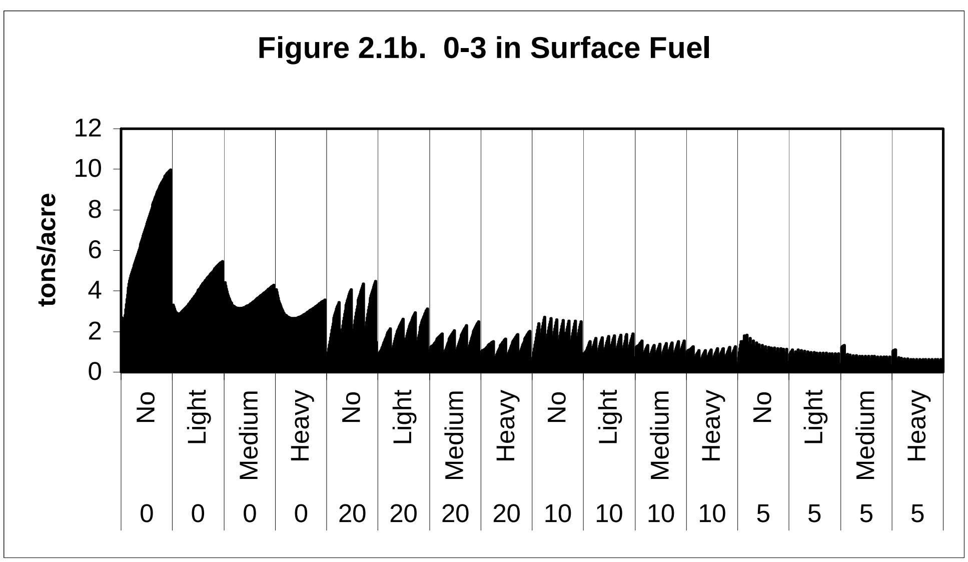


Figure 2.1c. 3 in + Surface Fuel

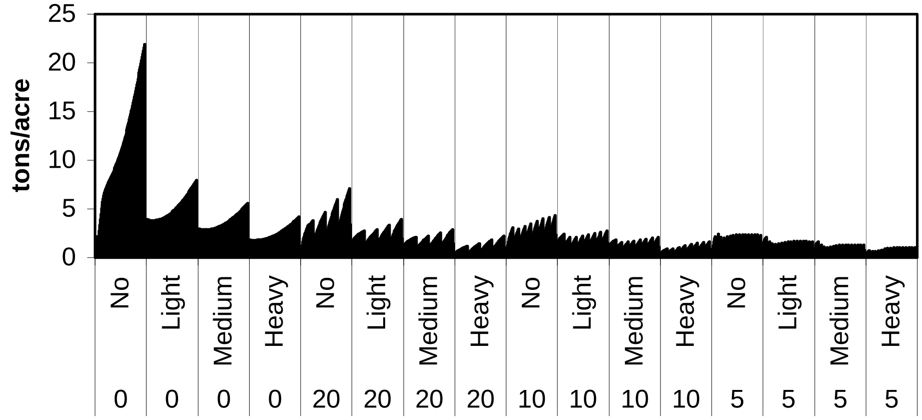
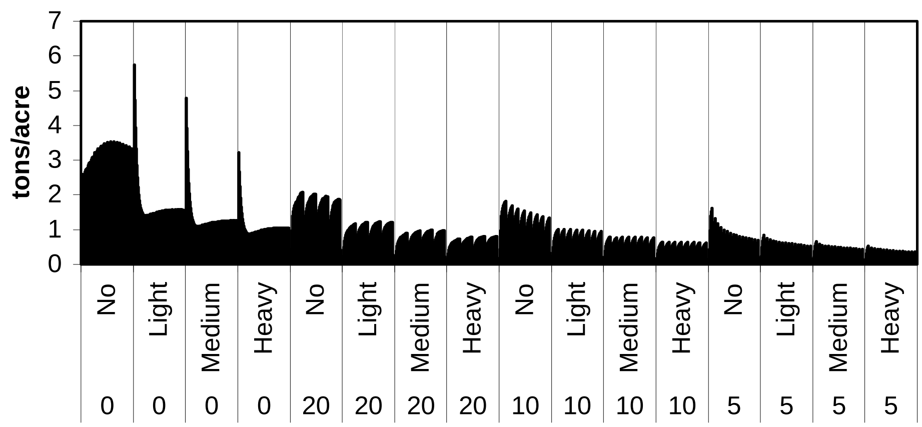


Figure 2.1d. Litter



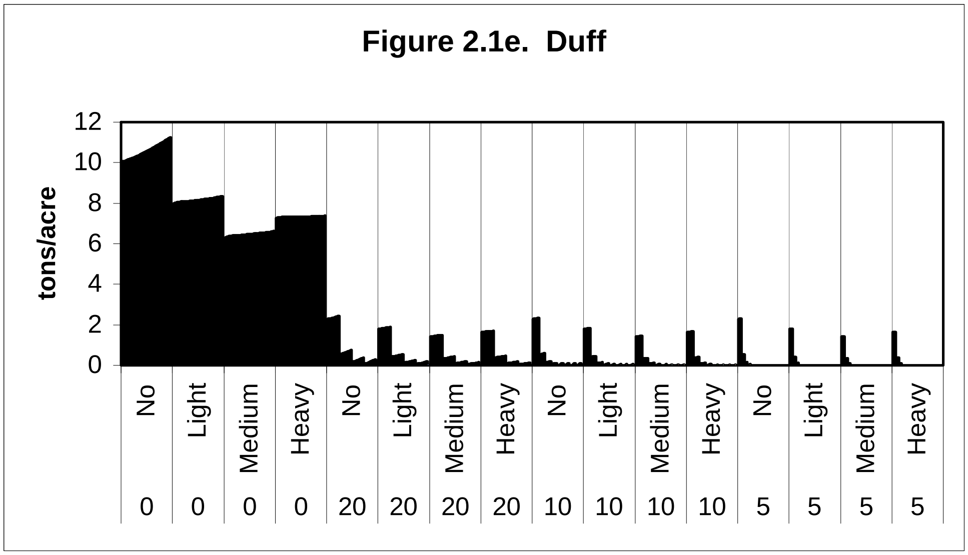
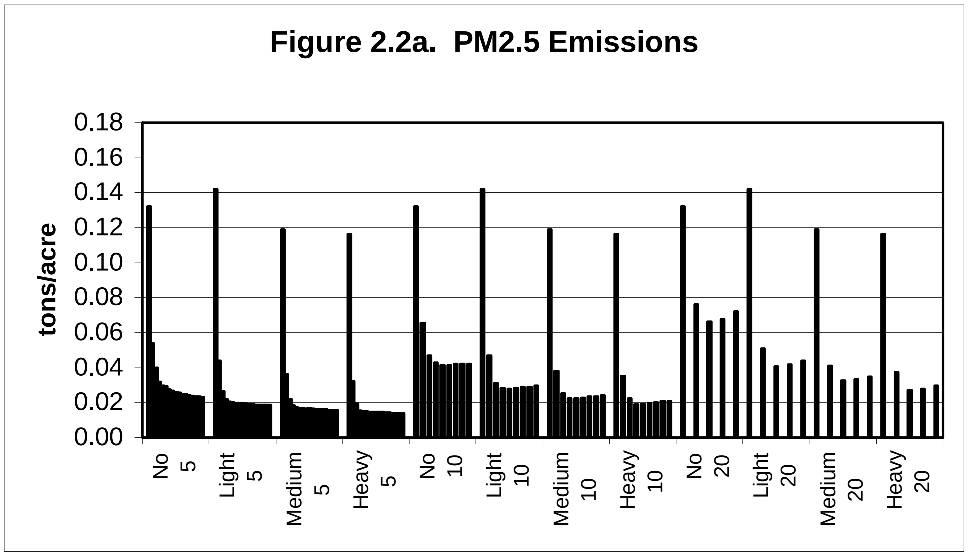


Figure 2.1e. Duff
tons/acre
12
10
8
6
4
2
0
No
Light
Medium
Heavy
No
Light
Medium
Heavy
No
Light
Medium
Heavy
No
Light
Medium
Heavy
0
0
0
0
20
20
20
20
10
10
10
10
5
5
5
5

Figure 2.2. PM2.5 and PM10 emissions (tons/acre) by burn interval and thinning intensity (year 0 to 80).



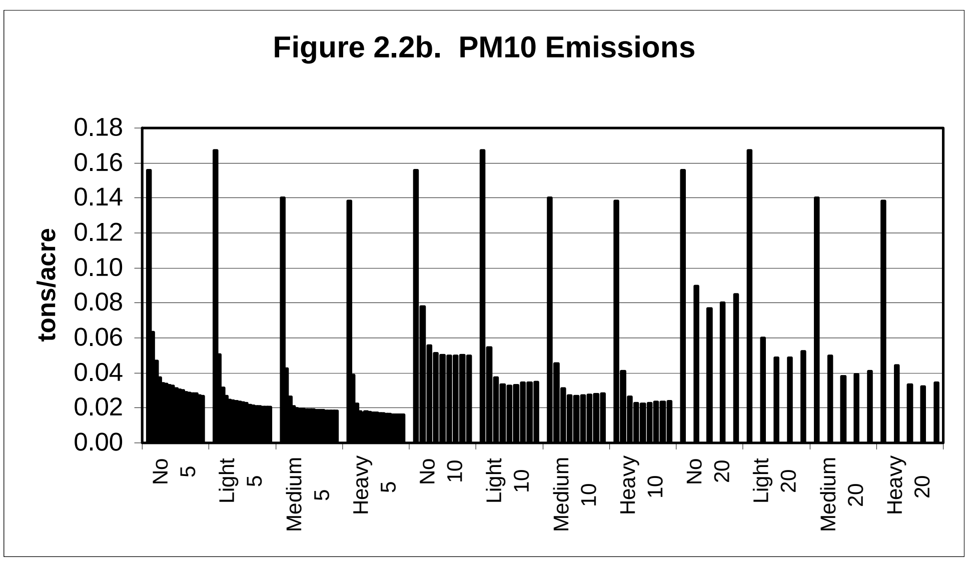
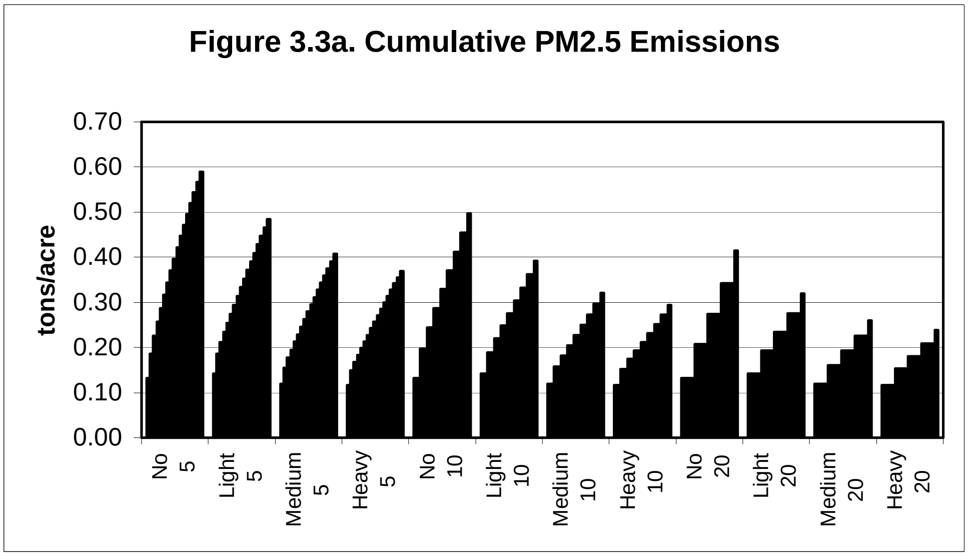
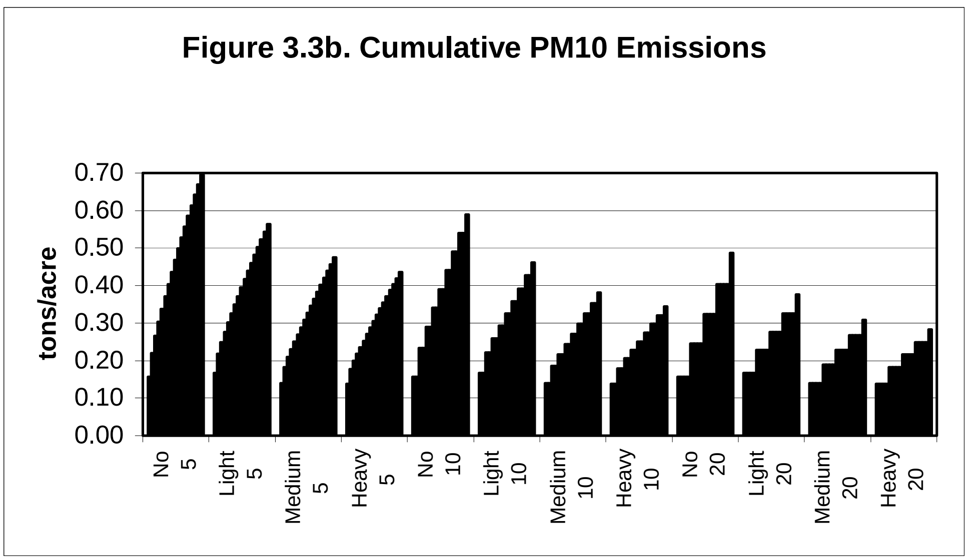


Figure 2.3. Cumulative PM2.5 and PM10 emissions (tons/acre) by burn interval and thinning intensity (year 0 to 80).





Chapter 3

Ecological Restoration in Flagstaff's Wildland-Urban Interface: An Intergenerational Justice and Equity Perspective

Abstract

A variety of management options, many involving prescribed fire, have been proposed as methods of restoring ecosystem health and lowering the risk of catastrophic wildfire in the WUI areas in the Southwestern US. The current generation's ability to affect the future imposes responsibilities involving issues of sustainability, justice, and equity. This paper examines these intergenerational concepts in the context of ecological restoration, focusing on the interplay of fire risk, ecological health, and smoke impacts on human health. We utilize FVS and SASEM to illustrate the transfers of fire hazards and smoke emissions resulting from three prescribed burning intervals (0, 5, and 20 years) applied to heavy thin and no thin treatments. We then discuss these results in the context of intergenerational equity and justice, utilizing a conservation of options approach. No action, represented by unthinned, unburned stands, would result in the transfer of a continually degrading ecosystem with high fire risk, which we argue is both unjust and unethical. Thinning immediately reduce the risk of active crown fire and in the long-term would result in less fuel being added to the forest floor from the canopy. Prescribed fire reduces the forest floor fuels that have accumulated over the last 120 years, but will result in smoke, with its associated health effects. However, as the landscape moves from primarily fuel model 9 into fuel model 2, there is an increasing likelihood of prescribed fires violating current air pollution standards. Restoration utilizing thinning and burning

would benefit both the current and future generations, and transfer the highest amount of natural capital options, but must be balanced against the negative health effects of increased smoke.

Introduction

Our ability to affect future generations imposes an ethical responsibility that involves issues of justice and equity (Norton and Toman 1997). The industrial age's faith in progress held that future generations would inherit a world improved by the labor of their ancestors (Auerbach 1995). We have recently recognized that the welfare and even the existence of future generations can be threatened by public policy. Intergenerational ethics addresses how present actions affect future persons and what the present generation owes to the future. Within intergenerational ethics, the concept of distributive justice focuses on the proper distribution of resources in society over time, while equity focuses on decision-making and the fairness of a given distribution (Young 1992). These important concepts of justice and equity are interrelated and sometimes overlap.

Sustainability requires that we meet our ethical obligation to transfer assets that provide adequate options for future generations, especially by conserving and investing in natural capital (Daly 1994, Folke et al. 1994). Once ecosystem assets are damaged, ecological restoration attempts to restore their productive capacity. As a result of over a century of fire exclusion, ponderosa pine forests throughout the western United States have become dense with small trees, herbaceous production has declined, and fuels have accumulated on the forest floor. The result is a landscape with a high catastrophic wildfire risk and susceptibility to large-scale pathogen outbreaks (Cooper 1960, Cooper 1961, Covington and Moore 1994, Covington et al. 1994, Fulé et al. 1997, Moore et al. 1999). Restoration of ponderosa pine ecosystems improves the ecological health and lowers the risk that these systems will be lost to the future. The restoration involves the reintroduction of fire, with the potential for creating large quantities of pollution. The ethics literature argues that natural capital stocks should be maintained for the future (Aerback 1995, Brown Weisse 1990, Brown Weisse 1994, Church 1999, Costanza et al. 1997, Cumberland 1991, Daly 1994, Norton and Toman 1997, Tacconi 2000, Young 1992), but also asserts that subjecting some to pollutions for the benefit of others is neither equitable nor just.

This paper examines these intergenerational concepts in the context of ecological restoration, focusing on the interplay of fire risk, ecological health, and smoke impacts on human health. We first review intergenerational equity and natural capital concepts. We then introduce Southwestern ponderosa pine ecosystems, historic conditions and changes, and ecological restoration with specific attention to the forest around Flagstaff, Arizona. We then present the methods utilized to model between generational transfers of smoke emissions and fuel hazards with alternate management options. Finally, we present the results and discuss the intergenerational tradeoffs faced by restoration practitioners.

Literature Review

Intergenerational Justice and Equity

The following section briefly discusses intergenerational justice and equity concepts. Justice will be defined within an intergenerational context, and several well-known decision rules designed to address intergenerational equity will be outlined. This limited review of the concepts is designed to justify the equity approach chosen to discuss intergenerational transfers of natural capital in Flagstaff's WUI.

Justice

Justice is a culturally defined concept that places boundaries on interpersonal actions (Aerback 1995). The concepts of justice imply standards of judgment. By labeling something as unjust, a claim is made that is expected to bind the judgments and actions of others. It indicates that others of good conscience ought to condemn the action. Matters of justice are usually discussed with regards to the current generation (Aerback 1995, Barry 1989, Church 1999). It is not often disputed that we have an obligation to act justly towards those unable to defend themselves, such as the mentally handicapped. Because future generations depend on us and can do us no harm, they fall under a similar obligation. Intergenerational justice may be defined as "what we owe to remote (not alive at the same time) past and future generations as a matter of justice" (Aerback 1995). Two core issues of intergenerational justice are how our actions affect remote generations and what we owe to remote generations. The decision must both analyze how it will affect remote generations, and include a standard for judging the predicted impacts. Justice is based upon doing the analysis; if tradeoffs are not analyzed, there is no justice.

There are two main classes of justice: corrective and distributive (Solum 2001). Intergenerational justice is concerned primarily with distributive justice. Barry (1989) classified distributive justice into justice as mutual advantage and justice as impartiality.

Mutual advantage describes a hypothetical contract based on self-interest. This position requires voluntary cooperation, and results in a more even distribution of benefits than if parties do not cooperate. Justice as impartiality is not based on self-interest, but rather on the idea of an impartial observer. The motive can be either a direct moral concern for others, or a concern for the opinion of others. Intergenerational justice must be based on impartiality because mutual cooperation between past and future generations cannot occur (Church 1999). The impartiality approach must address the problem of accurately predicting future needs (Gower 1995). We can only attempt to act justly towards future generations, because they may not conceptualize or value justice as we do. Decisions made with a moral concern for future generations have to be made with respect to the standards of the current generations (Auerbach 1995). Church (1999) argued that forest management should include intergenerational justice framework in decision analysis. This approach addresses the two previously mentioned core concepts of intergenerational justice: 1. the decision must analyze how it affects remote generations, and 2. it must include a standard for judging the predicted impact. A forest management decision can be considered just if it reflects a moral concern for the welfare of future generations.

Equity

Equity approaches are decision rules concerned with the consequences of policy alternatives and how they affect the distribution of resources, rights, and wealth. The neoclassical economic approach to intergenerational equity involves discounting future values to the present. This approach assumes that the historic trend of increasing per-capita income will continue indefinitely. However, convincing arguments exist against utilizing discounting to make provisions for future generations. Howarth and Norgaard (1992) demonstrated that the distribution of rights and assets across generations determines whether the efficient allocation of resources results in sustainability. They demonstrated that the economically efficient allocation changes as the distribution of rights changes across generations, and therefore is not an independent criteria for judging equity. As asserted by Cumberland (1991), neoclassical economics does not strongly support the case for equitable intergenerational transfers of natural resources.

An alternative approach, Rawlsian equity (Rawls 1971, Young 1992), proposes using the original position under a veil of ignorance to decide equity questions. People collectively decide on societal rules without knowing what position they will occupy in society, or what generation they will be part of (Young 1992). From this exercise the principle of maxi-min was developed, which emphasizes raising the welfare of the worst off person or generation (Costanza et al. 1997). Each policy is analyzed in turn for the worst thing (minimum) that could happen if we pursue that policy, and the policy with the largest (maximum) minimum is chosen. This approach is useful for deciding on potential resource use patterns to be followed to achieve intergenerational equity (Tacconi 2000). It cannot provide definitive answers to questions of intergenerational resource distribution, because it is impossible to know the exact conditions of sustainability or to accurately estimate the welfare, values, and preferences of future generations (Young 1992). Thus it is biased toward the values of the present generation. It may also entail the current generation making a large sacrifice to increase future welfare, which is unlikely to occur.

Brown Weiss (1990, 1994) argued that future preference and value assumptions should be avoided, and outlined three principles for intergenerational equity decisions: conservation of options, conservation of equality, and conservation of access. Conservation of options requires each generation to conserve the diversity of the natural and cultural resource base so they do not overly restrict future options for solving problems and satisfying values, i.e., each generation is entitled to diversity comparable to that of previous generations. Other things being equal, more available options increase the potential welfare of future generations. To conserve equality, each generation should pass on the planet in no worse condition than it received it. To conserve access, each generation should provide its members with equitable access rights to the resource base and conserve this access for future generations.

Implementing approaches to address intergenerational equity can be problematic. Church (1999) argued that a conservation of options approach possesses the most potential for incorporating an intergenerational justice framework, as it avoids the necessity of the current generation predicting or assuming the values and preferences of future generations. We agree and propose that we define management options which represent transfers of different levels and qualities of natural capital to future generations.

Natural Capital, Sustainability, and Southwestern Ponderosa Pine Ecosystems

Economists define capital as a stock that yields a flow of goods or services (Costanza et al. 1997). Natural capital consists of assets in the natural world that yield the flow of natural resources consisting of nonrenewable resources, renewable resources, and ecosystem services (Daly 1994, Odum 1994). Biodiversity, the diversity of life at all levels, is an important attribute of natural capital that contributes to the maintenance of ecosystem functions and is a prerequisite for economic adaptability and provides a diversity of options for economic development (Tacconi 2000). Humans depend on healthy ecosystems for survival, as these systems provide the basis for economic development and sustainability (Costanza et al. 1997, Folke et al. 1994, Jasson and Jasson 1994).

Sustainable development requires meeting current needs as fully as possible while ensuring that the opportunities of future generations are undiminished relative to the present (Howarth and Norgaard 1992). Because achievement of sustainability can only be recognized in retrospect, and the planning horizon verges upon perpetuity, a great amount of uncertainty exists as to what future generations will require in terms of natural capital (Cumberland 1991). Given this uncertainty, intergenerational transfers may be required to guarantee sustainability and prevent welfare decline of future generations (Costanza et al. 1997, Cumberland 1991). Natural capital stocks that are transferred can be positive transfers, such as intact, large-scale ecosystems, or negative, in the form of degraded ecologies and polluted environments. Like human-made capital, natural capital can depreciate through use or be conserved and augmented through investment to help keep life support ecosystems and interrelated socio-economic systems resilient to change (Folke et al. 1994, Segura and Boyce 1994). Divestment occurs when natural capital stocks are liquidated or ecosystem processes are altered. This action reduces future options and the ability to benefit from natural capital.

In selecting the stock of environmental resources to transfer, emphasis should be given to resources that may be scarce in the future, such as large-scale ecosystems, intact and undamaged, with species diversity, complex interspecies relationships, and supporting of evolutionary processes to provide for flexibility and adaptability (Costanza et al. 1997, Cumberland 1991). Costanza et al. (1997) believed that ecosystem services and other forms of natural capital will be in shortest supply in the distant future, and by actively transferring these assets we help increase the welfare of the most distant generations. Although the functional form of future human welfare production functions is very uncertain, one can reasonably assume that the supply of environmental assets will be both inelastic, and a source of diminishing returns (Costanza et al. 1997). This is also a mechanism for compensating future generations for past ecological damage (Cumberland 1991). Society has already begun making these transfers by setting aside areas such as designated wilderness areas and national parks. In cases where natural capital has been degraded, it may be necessary to invest in its restoration.

In the ponderosa pine dominated forests of Flagstaff, Arizona's WUI, ecological restoration attempts to restore the capacity of the system to self-regulate, by recreating the forest structure that characterized reference conditions, which allow ecosystem processes, especially frequent, low-intensity fires, to resume (Ecological Restoration Institute 2000). Combining prescribed fire with structural restoration alters fire behavior, reducing the risk of crown fires and producing an increase in herbaceous productivity and old growth tree response (Covington et al. 1997, Covington and Moore 1994, Fulé et al. 2001, Kolb et al. 2001). In fire adapted ecosystems, prescribed fire reduces fuel hazards and produces other effects which mechanical or chemical treatments cannot fully imitate (USDA FS 1993). The use of fire produces smoke, which constrains its use as a management tool. When prescribed fire is considered for fuel management, it is necessary to consider the production and effects of smoke.

Methods

Our analysis addresses the approximately 180,000-acre landscape delineated as the greater Flagstaff wildland-urban interface (Grand Canyon Forest Partnership 2000). Flagstaff, AZ, is located in the largest contiguous ponderosa pine (*Pinus ponderosa*) forest in the world. Flagstaff, founded in 1881, has experienced rapid growth in recent years. The population in was 52,894 in 2000, and was estimated to have reached 55,173 by 2002 (www.epodunk.com). Most of the growth involves expansion of suburban developments into previous forested areas and meadows, such as the community of Kachina Village. The Wildland-Urban Interface (WUI) exists as a continuum where urban areas mix with the forest (Feary and Neuenschwander 1998). Large severe fires are especially destructive in the interface between wildlands and communities, as exampled by the Cerro Grande Fire in Los Alamos, NM in 2000 (US DOI 2000). Flagstaff's urban area lies within the WUI, and is at risk of destruction from wildfire. About 600 wildfires per year occur in the Flagstaff area (Grand Canyon Forest Partnership 2000).

Flagstaff's WUI contains chaparral, desert scrub, grassland, mixed conifer, pinyon/juniper, ponderosa pine, ponderosa pine/Gambel oak, urban and water, and riparian ecological types (Figure 3.1) (USDA FS 2000c). The chaparral, desert scrub, grassland, pinyon/juniper, urban and water, and riparian types were excluded from analysis, based on the assumption that restoration treatments in these types are not priority. Only the ponderosa pine and ponderosa pine/Gambel oak types were utilized in this analysis, as these vegetation types are the most likely to be at high risk of losing one or more key components of their ecology. As illustrated by Figure 3.2 and Table 3.1, the majority of the WUI's ponderosa pine and ponderosa pine/Gambel oak are in the 0-35 year fire return interval and currently at high risk, almost a third is in the moderate risk category, and a small percentage are in the low risk category and the 35-100 year return interval high risk category (USDA FS 2000b).

Estimation of Restoration Impacts: Fuel Hazard and Smoke

The reduction of fuel hazards is the primary impetus behind thinning and burning treatments in Flagstaff's WUI. The effectiveness of these treatments lies in their ability to not only reduce fuel loads in the short-term, but to keep fuels low, and thereby reducing fire hazards and risk to the community into the future. Treatment effectiveness can be discussed using changes in fuel load and model, which relate to risk of catastrophic loss, and can be altered in a variety of ways such as varying prescriptions of thinning and burning.

However, smoke from prescribed burning poses a relevant and serious threat to public health. This threat is related to the quantity and concentration of smoke, the various chemical species, and particulate matter size (Koenig et al. 1988, Morgan 1989). In this study, we are focusing on the various fractions of particulate matter, especially PM2.5 and PM10, that pose significant health risks, and are monitored by the US Environmental Protection Agency (United States Environmental Protection Agency 1997). Generally, 70% of wood smoke particulates are <2.5 microns in diameter (PM2.5), 20% between 2.5 and 10 microns (PM10), and 10% are greater than 10 microns (Morgan 1989). We will address both PM10 and PM2.5, because PM10 can penetrate the respiratory tract, and PM2.5 is small enough to reach the alveolar region of the lungs and also has the maximum effect on visibility. We will then briefly address the health effects of several other smoke constituents in the discussion.

Simulation of Restoration Treatments

We modeled changes in fire risk (fuel loading and fuel model) and smoke particulate matter using the Central Rockies Variant of the Forest Vegetation Simulator (FVS) (Dixon 2001, Wykoff et al. 1982). The Fire and Fuels Extension (FFE) integrates FVS with elements from existing fire behavior and effects models to simulate fire effects, fuel loading, and snag dynamics (Beukema et al. 1998). The model calculates smoke production (PM2.5 and PM10) using emission factors applied to the amount of fuel consumed.

Input data were based on restoration treatments conducted on the Fort Valley Experimental Forest. Two initial conditions and four burning cycles were simulated to develop per acre level of outputs. The original restoration treatments incorporated two intermediate thinning treatments, however, we have limited our investigation to the two extremes. The full restoration (heavy thin) treatment and control (no thin) were replicated three times using a block design. We used tree and fuel loading data collected on twenty plots in each replica to initialize the restoration simulations. (Table 3.2 illustrates initial and post treatment condition of the treatments simulated.) The heavy thin (full restoration) treatment leaves all presettlement trees and 1.5-3 postsettlement replacement trees for each evidence of a dead presettlement tree. The no thin treatment retained dense stands of small trees with interspersed yellow pines.

Simulations were initiated with the post-treatment conditions and run for 80 years with varying prescribed fire intervals: 0 (no prescribed fire), 5, and 20 years. Simulations were individually run on each of the twenty plots representing the initial condition, and the results were averaged. The 5-year interval is within the historic range of variability for most Northern Arizona ponderosa pine forests (2-8 years) (Fulé et al. 1997, Moore et al. 1999). The 20-year interval is included to look at a longer interval that may serve the management goal of reducing fire hazard, and is within the 2-20 year range of variability for all Southwest ponderosa pine forests (Swetnam and Baisan 1996). Prescribed fires were simulated using 3-foot flame lengths, throttle-back burn, and no crowning. To compare the effects of thinning on fuel loads we simulated the stands with fire exclusion. These treatment combinations were chosen to represent several options available for use in Flagstaff's WUI (Table 3.3) (USDA FS 1998, USDA FS 2000a). Outputs included PM 10, PM 2.5, fuel load (total, 100-hour, 1000-hour, litter, and duff), and fuel model (Anderson 1982).

We utilized the per acre results given by FVS, and extrapolated out to the WUI as previously defined to estimate the percent of the landscape in each model, and the PM emitted at year 1, 5, 20, and 80. (Chapter 2 discusses the stand level results.) These four time periods provide excellent illustrations of the scale of change over time. We compared a heavy thin treatment burned at 5 year intervals and implemented in 5 years, a heavy thin treatment burned at 20 year intervals implemented in 20 years, and an unthinned, unburned control scenario. We will not discuss fire only treatments, because local, long-term experimentation has indicated that burning alone is unlikely to restore the natural forest structure of ponderosa pine forests in the study region (Covington and Sackett 1992, Fulé et al. 2002, Harrington and Sackett 1990).

We utilized the Simple Approach Smoke Estimation Model (SASEM) (Sestak and Riebau 1988) as a means to address smoke impacts and equity concerns. SASEM utilizes a straight line Gaussian plume model and emissions based on the Emission Production Model (EPM) (Sandberg and Peterson 1984) or internal algorithms. The model assumes meteorological conditions do not change, that atmospheric distributions can be estimated by point values, and that a fixed ratio of smoke entrained in a plume to unentrained is 60:40. SASEM estimates maximum ground-level concentrations of TPM, PM 10, and

PM 2.5, the distances at which this concentration would occur, and the range of distance over which ambient standards would be exceeded.

The PM 2.5 national ambient air quality standards are 65 ug/m3 and 15.0 ug/m3 for 24-hours and annually, and the PM10 standards are 150 ug/m3 and 50 ug/m3 for 24-hours and annually (US EPA 1997). The 24-hour standards were used in the simulation; 150 ug/m3 for TSP and PM10, and 65 ug/m3 for PM2.5. Potential PM10 and PM2.5 concentrations were calculated by SASEM for excellent to poor atmospheric stability (ventilation index) for 50 acres of heavy thin or unthinned stands for 5 and 20 year burning intervals. The 50 acres were chosen to represent the generalized upper area allowed by the Arizona Department of Environmental Quality (1996) before special measures must be taken. We utilized three fuel models to represent current and potential future conditions. While FVS utilizes Anderson's (1982) fuel models, SASEM utilizes NFDRS (Bradshaw et al 1984, Deeming et al. 1977) fuel models for default fuel parameters. Fuel model C typifies open pine stands where grasses and forbs are the primary ground fuel along with needles and branches, and correspond to Anderson's (1982) fire behavior model 2. Fuel model K describes slash from light thinnings where slash is scattered under an open overstory, which relates well to post-thinning conditions and Anderson's fuel model 11. Fuel model U describes closed stands of pines, which relates well to unthinned stands, and relates to Anderson's (1982) fuel model 9. The conditions utilized for the SASEM simulation are illustrated in Appendix I.

Results

We approached the risk of catastrophic fire by utilizing fuel hazard as described by fuel load and fuel model (both Anderson and NFDRS). Our results for fuel loads and models were consistent with both experimental observations (Sackett and Haase 1998) and computer simulations (Covington et al. 2001) of the study area (see Chapter 2 for a discussion of stand level results). All fuels were reduced with burning, followed by a subsequent rise (see Chapter 2, Figure 2.1a-e). Thinning and the amount of time between burns determined the magnitude of fuel accumulation. There was a clear difference between the no thin and the heavy thin treatments, as thinning serves to reduce future available fuel. Burning on a 5-year interval does not allow much fuel build-up on any unit, even the unthinned stands, while a 20-year interval allows time for a larger fuel buildup.

The fuel model mode of untreated stands began at fuel model 9, while heavy thinning resulted in a fuel model mode of 2 (Table 3.4). Outliers of fuel models 10 and 12 were also observed. Unthinned, unburned stands changed into fuel model 10 by year 40. Burning unthinned stands allows the fuel model to remain at 9, with 5 year burning eventually reaching fuel model 2. Thinning and burning at 5-year intervals resulted in a fuel model of 2 through year 80. Thinning and burning at 20-year intervals also resulted in a fuel model mode of 2, however, the maximum fuel model was 9 and 10. Thinning followed by no burning resulted in a mode fuel model of 2, with maximums of 10 and 12.

The no action alternative was represented by the unthinned, unburned stands in our simulation. This option would allow dense stands persist, continually increasing amounts of both the fine fuels which increase fire ignitability and rate-of-spread and the large fuels and duff which contribute to smoke emissions (Table 3.5). These conditions contribute to an increasing risk of catastrophic wildfire and the potential of much higher smoke emissions as the landscape moves from predominantly fuel model 9 into fuel models 10 and 12. As the amount of thinning and burning increases across the landscape, more of the landscape is moved into fuel model 2 (Table 3.5). The speed at which restoration is implemented affects the speed of movement into fuel model 2, retention in fuel model 9, or movement into more hazardous fuel models (Table 3.5). Heavy thinning, with a 20-year fire return interval implemented over a 20 year period would result in fuel model 2 covering the majority of the WUI in 20 years. Increasing the rate of thinning and burning will result in a lower landscape-level fire hazard, as illustrated with the 5-year implementation and fire return interval. However, increased burning will lead to increased smoke in the atmosphere, as illustrated in Table 3.6.

Thinning and fire return interval affected the pattern of smoke emissions (Table 3.5; see Chapter 2, Figure 2.2a-e,). Initial per acre emissions were high, but decreased with repeated burning as fuel loads decreased. Thinning resulted in lower future emissions per acre burned, because less canopy was available to drop fuels. By year 80, emissions for the no thin treatments were approximately twice as high as the heavy thin treatments. The frequency of the fire return interval produced quantitative differences in emissions. More frequent burning resulted in lower emissions per acre when burned than a less frequent interval; a result of less fuel accumulating between burns. Although increased frequency of prescribed burning resulted in lower emissions by the second burn, this resulted in higher cumulative emissions (see Chapter 2, Figure 2.3a-e). The relative effects are such that the unthinned stands burned on 20-year intervals produce approximately as much cumulative PM as the heavy thin stands burned on 5-year intervals.

Stand level emissions of PM were shown to differ dramatically with thinning and burning interval (Table 3.5; Chapter 2, Figures 3.4a-b). The SASEM predicted maximum concentrations and exceedences of the national ambient air quality standards for TPM, PM 10, and PM 2.5 are depicted in Appendix I. When burning 50 acres of fuel model K, TPM, PM 10, and PM 2.5 standards were exceeded only during poor stability conditions. In fuel model U, TPM and PM 2.5 standards were exceeded during poor stability conditions, while PM 10 standards were exceeded during poor stability conditions at wind speeds <4 mi/hr. However, burning 50 acres of fuel model C resulted in both TPM and PM 2.5 exceeding the standards at most combinations of wind speed and stability, while PM 10 standards were exceeded during poor stability and wind speed < 5 mi/hr. Fuel model C burned under non-poor stability conditions was predicted to exceed standards primarily between 0.5 and 2 miles, allowing for a high potential to affect human health. The exceedence distances predicted under poor stability were large for each fuel model, often exceeding 13 miles.

Although FVS modeled the areas restored with heavy thinning and frequent burning to emit lower quantities of PM, the SASEM results indicated that burning these areas could result in more frequently exceeding air quality standards than either the initial burns or burning with a longer fire return interval. Fuel model C resulted in more potential violations of air quality standards than fuel model K or U, differing in the lower heat content of the fuel, lower heat release rate, smaller fireline width, and increased number of smoke plumes (Appendix 1). The increased conditions over which standards are exceeded decrease the ability to time prescribed burns.

Discussion

Ecological restoration attempts to improve the natural capital which is passed to future generations as an intergenerational transfer. Ecological restoration in Flagstaff's WUI, and generally throughout the fire-adapted ecosystems of the West, involves reintroduction of fire, which produces smoke. Restoration changes the risk of property damage and ecosystem loss. In order to be considered just, we must analyze both the positive and negative effects (tradeoffs) these actions have on current and future generations, and include a standard for judging the predicted impacts. Here, we discuss the tradeoffs in terms of options that the current generation can pass on to the future, including the fire hazard and fire risk; intergenerational transfers of smoke, with the associated potential for health impacts; and intact ecosystems providing ecosystem services, such as biodiversity and nutrient cycling. The management options discussed represent transfers of different levels and qualities of this natural capital to future generations.

Full restoration with 5-year fire return intervals implemented as rapidly as possible (here within 5 years) would entail heavy thinning throughout the WUI and burning on approximately 5 year intervals indefinitely into the future. This option would result in the highest and most rapid return on the investment by rapidly reducing fire hazard and increasing ecosystem health. Experimental observations of restoration treatments have shown ecological benefits rapidly accrue, including increased herbaceous production (Covington et al. 1997), increased tree growth, increased carbon and nitrogen uptake, increased insect resistance (Feeney et al. 1998), and increased soil respiration rates and N transformation (Covington and Sackett 1986, Kaye and Hart 1998a, b). The increase in herbaceous understory production is important for its contribution to biodiversity, as it represents the majority of the plant species diversity. The understory ecosystem component also restrains tree regeneration, and its diversity and biomass are important for many ecosystem components and processes, including surface fire propagation and pollinators (Allen et al. 2002). However, the cost to both the current and future generations may be the highest with respect to the potential costs of smoke emitted from the fires. One of the costs of the smoke may be an increased cost of health care in the future.

As illustrated with SASEM, as the fuel models change from closed stands and heavy fuel loads to open stands dominated by grass, ground level concentrations of smoke may actually increase during burns, leading to unhealthy smoke exposures. The low intensity burns fail to develop strong convection columns and smoke is dispersed locally

(Reinhardt and Ottmar 1997). Higher intensity fires tend to develop enough heat to pull the smoke away.

Fulé et al. (2001, 2002) found that forest restoration treatments of thinning young trees followed by prescribed burning resulted in significantly lower stand density, lower crown fuel load, and higher crown base height than untreated stands. Simulated fire under extreme weather conditions caused 48% more canopy burning and higher flame lengths, heat/area, and rate of spread in untreated stands. Wind speeds required for passive crown fire (torching) were twice as high in treated stands. In a landscape dominated by fuel model 2 (grass and timber litter, Anderson 1982), forest structures are open and dominated by large, fire resistant trees with few shrubs or small trees to act as ladder fuel. In these conditions, torching is rare and active crownfire almost impossible. This allows a much wider prescription window than denser stands because the risk of intense fire behavior is low, allowing a greater ability to plan for smoke dispersion and minimize smoke episodes.

Flagstaff possesses good air quality at the present time, except when burning results in smoke episodes. Robinson et al. (2004) found that background PM2.5 concentrations ranged from 19 to 69 ug/m3. As an air pollutant, smoke affects both workers (firefighters, burning crews) and the general public. Because the WUI is by definition close to homes, burning would likely result in episodes of unhealthy smoke exposure. By instituting large-scale, long-term burning programs, we are instituting the long-term exposure of people to substances which are linked to short- and long-term health problems, including asthma and cancer. In this paper, we are primarily concerned with particulate matter, although other hazardous components of wood smoke include carbon monoxide (Reinhart and Ottmar 2000), irritants such as aldehydes (Koenig et al. 1988, Reinhart and Ottmar 2000), and mutagenic and carcinogenic polycyclic aromatic hydrocarbons (Koenig et al. 1988, Morgan 1989). PM10 is collected in the upper respiratory system (throat and nose), and can enter the lower respiratory system, reaching deeper with reduced size. The finest PM can deposit in the alveoli and remain indefinitely, causing structural and chemical changes. In addition, other toxic and mutagenic compounds attached to the PM can enter at the same time (Koenig et al. 1988, Morgan 1989). Prescribed burns in the Flagstaff area produce PM2.5 with high organic carbon levels (>90% by mass), as well as K+, NH4+, and NO3-, chlorine, sulfur, and silicon, titanium and chromium (Robinson et al. 2004). The primary acute effects of ambient PM include premature mortality, aggravation of respiratory and cardiovascular disease (indicated by increased hospital admissions and emergency room visits, school absences, lost work days, and restricted activity days), aggravated asthma, acute respiratory symptoms (aggravated coughing and difficult or painful breathing), chronic bronchitis, eye irritation, and decreased lung function often experienced as shortness of breath (Morgan 1989, Pierson et al. 1989, Reinhart and Ottmar 2000). Pierson et al. (1989) found that for every 100 ug/m3 of TPM in the environment, the risk of dying goes up 32% from emphysema, 19% from bronchitis and asthma, 12% from pneumonia, and 9% from cardiovascular disease. Schwartz (1993) found an average 6% increase in mortality and an 18.5% increase in respiratory hospital emissions for every 50 ug/m3 of TPM.

Robinson et al. (2004) collected PM2.5 samples during first entry burns and a maintenance burn in primarily grassland fuel near Flagstaff, Arizona. During first entry burns, ambient concentrations of PM2.5 within the burned area ranged from 2541 and 6459 ug/m3 during the flaming stage, while the concentration during the maintenance fire was 523 ug/m3. Smoldering particle concentrations were lower (155-904 ug/m3), but began within 4 hours of ignition and continued for several days. These concentrations would decrease with mixing as distance form the burn increased. However, as described above, these emissions may be high enough to have a significant effect on the health of Flagstaff's citizens and visitors.

The health effects of wood smoke are not only relevant outdoors, as most people spend 80-90% of their time indoors (Pierson et al. 1989). Smaller smoke particles remain suspended for long periods of time and about 50-70% of outdoor wood smoke penetrates into buildings. Unusually sensitive members of the population such as those with underlying respiratory or cardiovascular disease may be unable to tolerate additional stress imposed by smoke exposure (Morgan 1989). Infants, children, pregnant women, senior citizens, smokers, ex-smokers, and those suffering from allergies, asthma, bronchitis, emphysema, pneumonia, or any other heart or lung illness are sensitive to low levels of smoke. In Coconino county there are an estimated 931 people with emphysema, 4,410 with chronic bronchitis, 6,855 with adult asthma, and 2,908 cases of pediatric asthma (American Lung Association 2003). These groups must receive special attention in assessing smoke risk, because not to do so would be unjust, as they are relatively less capable of defending themselves against the negative effects of smoke. A lack of consideration would also violate the equity premises of equality and access.

The impacts could be minimized and dispersed in several ways. Thinning could be minimized in terms of thinning intensity or how quickly the initial thinning treatments are accomplished, spreading the initial cost of investment in the natural capital restoration farther over time. Reduced thinning intensity would provide minimal initial crown fire resistance, and allow the canopy to close faster and higher fuel inputs to the forest floor, allowing hazardous conditions to rapidly return (Covington et al. 2001, Fulé et al. 2001, Fulé et al. 2002). By thinning at a slower pace (20-year implementation period), costs could be spread out, but high fire hazards would persist over the landscape for a longer time period with the potential of much higher costs associated with catastrophic wildfire. These options do not appear optimal in terms of maximizing the transfer of options to the future.

The current generation could increase burning intervals (20 years), resulting in lower cumulative smoke emissions than short burning intervals (5 years). Increased burn intervals allow more time for fuel to accumulate, leading to a higher fire risk between burns and more smoke when the stand is burned. As illustrated with FVS and SASEM, these changes in fuel hazard are of small magnitude and may be better in terms of health impacts and reduce the risk of exceeding air quality standards. The smaller annual number of prescribed burns could be implemented during the best possible dispersion conditions, thereby reducing impacts to sensitive individuals.

Doing nothing is a policy decision, and it may have a worse effect on future generations than any other option. This is especially true for Flagstaff's WUI. The possibility that large-scale restoration treatments will not occur is an option by inaction, which would allow the continued decline of the forest's ecological health, measured by structure and function. In a landscape dominated by untreated stands, with high vertical and horizontal fuel continuity, low crown base height, and high canopy density, passive and active crownfires are likely in the dry fire conditions characteristic of spring and early summer. High fire risk would continue indefinitely, if protected from allogenic disturbance, or until the occurrence of a stand-replacing disturbance, resulting in acutely high smoke emissions and ecosystem damage. Crownfires are likely even under average prescribed fire conditions. For this reason, introducing fire into unthinned stands is not a good management alternative for Flagstaff's WUI.

In addition, understory vegetation in unthinned stands will continue to decline, as it has since fire exclusion began with the subsequent increase in overstory density and heavy forest floor accumulations (Biswell 1972 , Cooper 1960). There is a concern that the very low decomposition rate in absence of fire reduces productivity and nutrient cycling by binding nitrogen in forms unavailable for plant uptake (Arnold 1950, Cooper 1960, Biswell 1972, Harrington and Sackett 1992). If we do nothing, future generations will endure the cost of fire suppression, poor ecosystem health, and wildfire smoke production. The ecosystem may even be irreversibly changed or lost. Thus, the current ecosystem appears to be a poor choice for transfer to future generations, and the no action alternative would appear to be unjust and unethical, by both the conservation of options standard and the Rawlsian standard. With the potential loss of ecological function the current generation is not acting to conserve the natural resource base and there are reduced choices over time. Therefore the conservation of options standard is not met. Because the window of opportunity for restoration is shrinking (15 – 30 years) (Covington et al. 1994) and the fire risk will continue to increase until a catastrophic fire removes the fuel load, each consecutive generation is worse off. Therefore the Rawlsian standard is failed. However, there is ample evidence that we can restore the WUI specifically, and the short-interval fire adapted ecosystems of the west in general, to a condition in which there is a lower fire risk as well as ability to persist as it did for at least 300-500 years before Euro-American settlement.

If burned in a wildfire, smoke emissions may be worse than with prescribed fire. Wildfires generally occur when fuels are dry, consumption greater, and more fuel is consumed during the less efficient smoldering combustion stage resulting in approximately twice the PM10 of a prescribed fire (Pyne et al. 1996). Prescribed fires are planned in advance and can be ignited when dispersion is best, so fuel is consumed with more efficiency and less smoke production than wildfires (Pyne et al. 1996). The area burned with a prescribed fire can also be controlled; wildfires generally burn a much larger area. Fuel treatments which alter height-to-crown ratio and the abundance and continuity of canopy fuels have been shown to moderate extreme fire behavior (Omi and Martinson 2002). Altering the fuel model of the WUI with thinning and burning treatments will not prevent wildfire from occurring but will reduce the associated risks.

According to Daly (1994), “investing in natural capital is a prerequisite for sustainability”. Ecological restoration of natural capital should be considered an important component for any sustainable development strategy designed to be proof against risk, both future and present. While the decision to restore Flagstaff’s WUI is primarily based on the intragenerational concerns of wildfire risk and ecological values, the effects will extend into future generations. Before we implement a policy we need to consider its effects on the future, because some policies will only be reversible at high cost to future generations, if they are reversible at all (Auerbach 1995). If we are going to be just, we must concern ourselves with and address future impacts of current management. In addition, each future generation is better off if there is continued maintenance in the present. We can help insure the continued maintenance of our natural capital by acting in such a way that “future generations are most likely to honor the commitments and build upon the moral traditions of their ancestors” (Auerbach 1995). If we establish a tradition of acting justly towards future generations, it is likely that the next generation will also act justly towards the future.

In conducting this discussion of tradeoffs with a focus on intergenerational justice and equity, we have taken a step towards acting justly towards the future, as well as the present. This document is not meant as a planning document, but as an aid to planning efforts. Restoration treatment location and scheduling should be and will continue to be an exercise in adaptive management. We have presented and argument that justice and equity need to characterize the appropriateness of the intergenerational transfer of natural capital in the Flagstaff WUI utilizing the chosen equity approach. The final decision is up to society. However, as stated by Auerbach (1995), “It is not enough to understand how we ought to act, we must actually act that way”.

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Tables and Figures

Table 3.1. Area and percentage of ponderosa pine and ponderosa pine/Gambel oak by historic fire frequency and current condition class.

Description	Acres	Percent
0-35 yrs; Condition Class 3	62020	62
0-35 yrs; Condition Class 2	28442	28
0-35 yrs; Condition Class 1	5413	5
35-100+ yrs; Condition Class 3	4256	4
sum total	100130	100

Table 3.2. Stand characteristics before and after thinning.

	No Thin	Heavy Thin
Pre-thin		
Basal Area (sq. ft./acre)	164.3	151.5
Density (trees/acre)	480.6	386.7
Post-thin		
Basal Area (sq. ft./acre)	164.3	67.8
Density (trees/acre)	480.6	56.8

Table 3.3. Thinning intensity and burning interval simulated and prescribed fire outputs tracked for simulations.

Thinning Treatment	Burning Intervals	Model Fire Outputs
No Thin	Unburned	Fuels
Heavy	5-year, 20-year	Fuels, PM2.5, PM10

Table 3.4. Fuel model changes over time for unthinned and heavily thinned stands burned at 0, 5, 10, and 20 year intervals.

Thinning Treatment	No Thin					
Fire Return Interval	0	0	5	5	20	20
Year	MODE	MAX	MODE	MAX	MODE	MAX
00	9	12	9	12	9	10
10	9	12	9	9	9	9
20	9	12	9	9	9	9
30	10	12	9	9	9	9
40	10	12	2	9	9	9
50	10	12	2	9	9	9
60	10	12	2	9	2	9
70	10	12	2	9	9	9
80	10	12	2	9	2	9

Thinning Treatment	Heavy Thin					
Fire Return Interval	0	0	5	5	20	20
Year	MODE	MAX	MODE	MAX	MODE	MAX
00	2	12	2	12	2	12
10	2	10	2	9	2	10
20	2	10	2	9	2	10
30	2	10	2	9	2	10
40	2	10	2	9	2	10
50	2	10	2	9	2	9
60	2	10	2	9	2	10
70	2	10	2	9	2	9
80	2	10	2	9	2	10

Table 3.5. Amount of the Flagstaff, AZ WUI in each fuel model (Anderson 1982) for three levels of treatment.

No burning, no thinning				Heavy thin, 5 year burn intervals, 5 year implementation				Heavy thin, 20 year burn intervals, 20 year implementation			
Year	%	Median	Max	Year	%	Median	Max	Year	%	Median	Max
1	95%	9	12	1	24%	2	12	1	5%	2	10
	5%	2	9		76%	9	12		90%	9	12
									5%	2	9
5	95%	9	12	5	20%	2	12	5	50%	2	10
	5%	2	9		80%	2	9		20%	2	9
									75%	9	12
20	95%	9	12	20	100%	2	9	20	5%	2	10
	5%	9	12						95%	2	9
80	95%	10	12	80	100%	2	9	80	100%	2	9
	5%	9	12								

Table 3.6. Changes in PM emissions over time for two levels of treatment: per acre, day (based on 80 burning days per year), and year over the landscape from year 0 to 80.

Heavy thin, 5 year burn intervals, 5 year implementation

Year			per acre	per year	per day
0	Yearly	PM10	0.14	2547.23	31.84
		PM2.5	0.12	2142.62	26.78
	Cumulative	PM10	0.14	2547.23	31.84
		PM2.5	0.12	2142.62	26.78
5	Yearly	PM10	0.04	714.21	8.93
		PM2.5	0.03	594.66	7.43
	Cumulative	PM10	0.73	13450.36	168.13
		PM2.5	0.61	11307.74	141.35
20	Yearly	PM10	0.02	318.79	3.98
		PM2.5	0.01	272.81	3.41
	Cumulative	PM10	1.11	20334.93	254.19
		PM2.5	0.93	17147.06	214.34
80	Yearly	PM10	0.02	294.26	3.68
		PM2.5	0.01	254.42	3.18
	Cumulative	PM10	2.11	38901.20	486.27
		PM2.5	1.79	32960.73	412.01

Heavy thin, 20 year burn intervals, 20 year implementation

Year			per acre	per year	per day
0	Yearly	PM10	0.14	636.81	7.96
		PM2.5	0.12	535.65	6.70
	Cumulative	PM10	0.14	636.81	7.96
		PM2.5	0.12	535.65	6.70
5	Yearly	PM10	0.14	636.81	7.96
		PM2.5	0.12	535.65	6.70
	Cumulative	PM10	0.28	3184.04	39.80
		PM2.5	0.23	2678.27	33.48
20	Yearly	PM10	0.18	839.88	10.50
		PM2.5	0.15	707.31	8.84
	Cumulative	PM10	0.46	12939.23	161.74
		PM2.5	0.39	10884.74	136.06
80	Yearly	PM10	0.03	158.63	1.98
		PM2.5	0.03	135.64	1.70
	Cumulative	PM10	0.78	22979.48	287.24
		PM2.5	0.65	19308.83	241.36

Figure 3.1. Ecotypes within the Flagstaff, Arizona Wildland-Urban Interface (WUI).

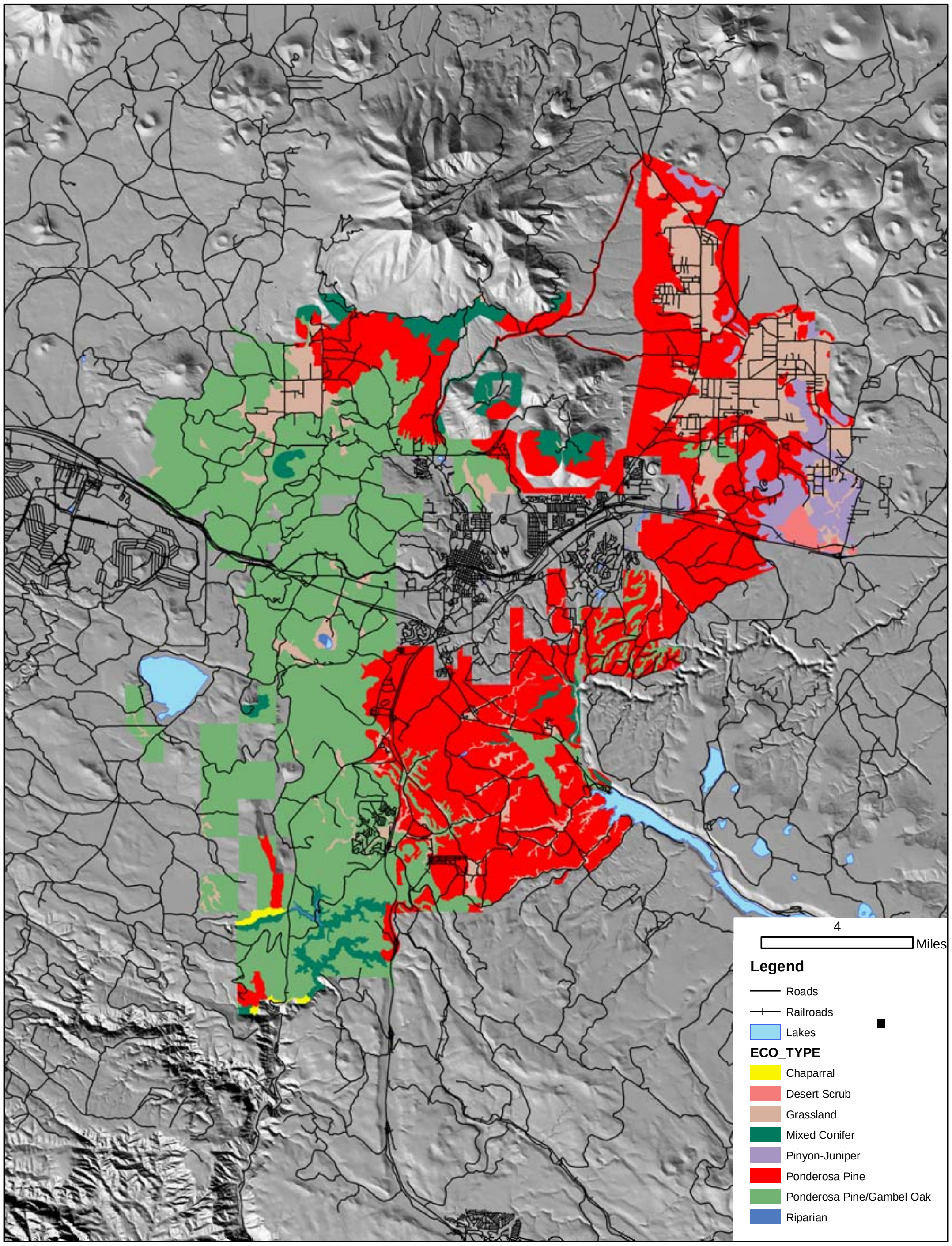
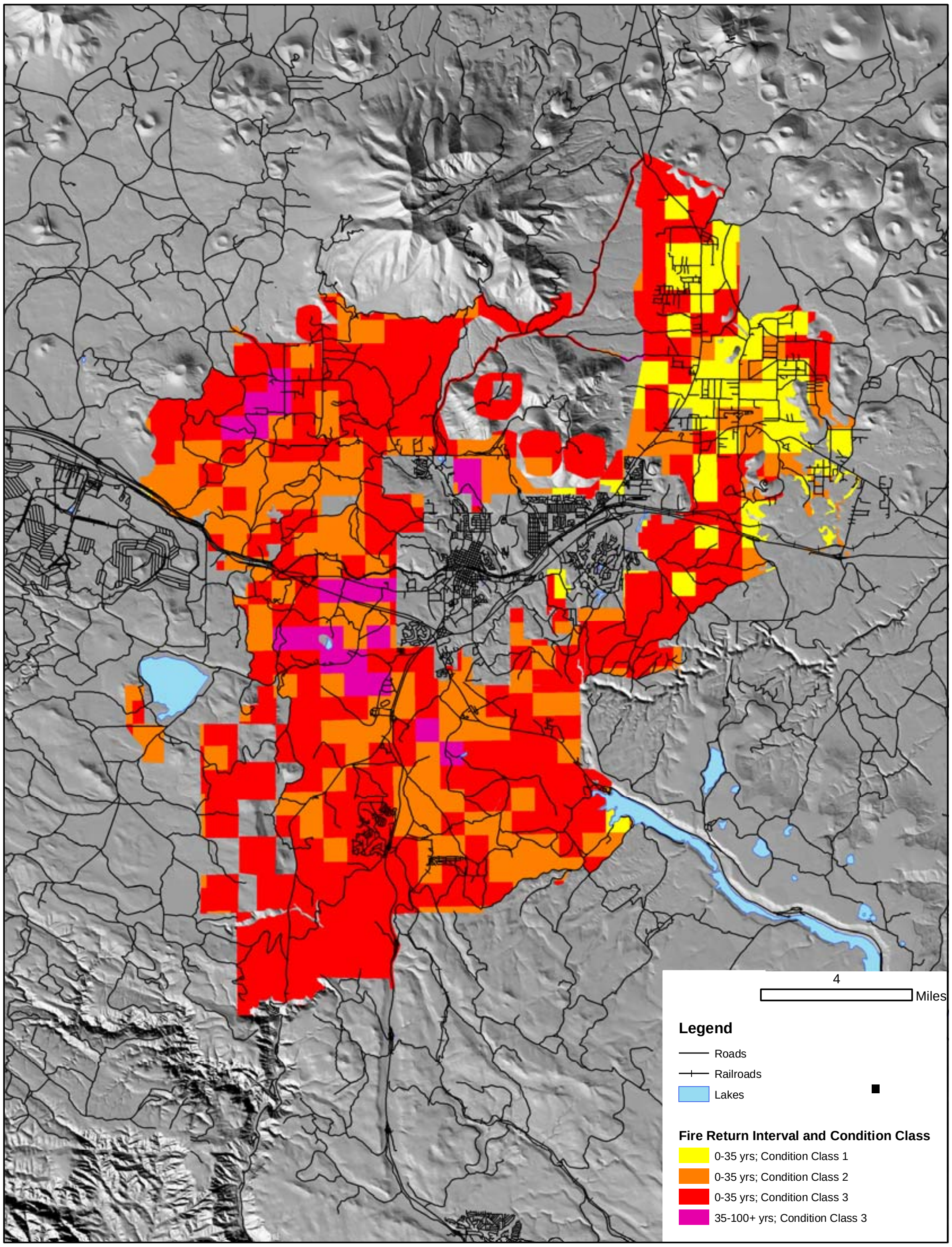


Figure 3.2. Fire regime and condition class of ponderosa pine and ponderosa pine/Gambel oak ecotypes within the Flagstaff, AZ Wildland-Urban Interface (WUI).



Chapter 4

Overall Conclusions

Structural and functional changes and the resulting high wildfire risk are problems in many of the forests throughout much of the Western United States. These problems are especially pronounced in the wildland-urban interface (WUI). Focusing on the WUI of Flagstaff, AZ, we have analyzed how several management options consisting of different thinning intensities and burning intervals would likely affect both the current and remote generations, and included a standard for judging the predicted impacts. As previously stated, justice is based upon doing the analysis; if the tradeoffs are not analyzed, there is no justice. We chose a conservation of options approach for discussing intergenerational equity issues, focusing on the interplay of fire risk, ecological health, and smoke impacts on human health.

The no treatment option would transfer the least options to the future in terms of natural capital, and therefore is both unjust and unethical to the future as well as the present. Thinning immediately reduce the risk of active or passive crown fire and in the long-term would result in less fuel being added to the forest floor from the canopy, reducing future emissions. However, without burning the fuel reductions are short-term. Prescribed burning can greatly reduce fuel hazard, but only temporarily. Because fuels are continually entering the surface fuel pool, especially needles, hazard reduction must be an ongoing process, and a single fire can only temporarily reduce the hazard. In addition, the use of fire will produce smoke, with its associated health effects. Although FVS modeled the areas restored with heavy thinning and frequent burning to emit lower quantities of PM, the SASEM results indicated that burning these areas could result in more frequently exceeding air quality standards than either the initial burns or burning with a longer fire return interval. Restoration utilizing thinning and burning would benefit both the current and future generations, and transfer the highest amount of natural capital options, but must be balanced against the negative health effects of increased smoke.

As we have illustrated, models can be useful for exploring risks and tradeoffs. However, they are only approximations of reality and are subject to different degrees of uncertainty and error, adding an element of risk to decisions based upon modeling exercises. Uncertainties abound when the potential for smoke impacts, escaped prescribed fires, and changes in ecological health are considered, but ought to be compared to the certainty of lost ecological, economic, and social values from catastrophic wildfires in these fire-prone ecosystems.

Because future generations are unlikely to conceptualize or value justice as we do, we can only attempt to act justly towards toward them. Thus decisions made with a moral concern for future generations will be made with respect to the standards of the current generations (Auerbach 1995). Auerbach (1995) argued that "we ought to act toward future generations in such a way that future generations are most likely to honor the commitments and build upon the moral traditions of their ancestors." This recognizes the intergenerational nature of civilization and is especially meaningful for those concerned with the judgment of history. If we establish a tradition of acting justly towards future generations, it is likely that the next generation will also act justly towards the future. A moral obligation to act justly will not be created unless concern for the future is transformed into action. “The fact that proposed actions so strongly emphasize restoration of native biological diversity reflect high value placed on ecological integrity by Flagstaff’s community” (Covington et al. 1998).

While the decision to restore Flagstaff’s WUI is primarily based on the intragenerational concerns of wildfire risk and ecological values, the effects will extent into future generations. Planning effective means for making transfers to future generations must be centered no only upon monetary and fiscal measures, but more importantly upon real resources relevant to ecological sustainability, especially large-scale complex ecologies. Ecological restoration offers an excellent way to repair damaged capital before it depreciates beyond use. With these two manuscripts, we have attempted to illustrate that any action is better for current and future generations than no action at all. Just as fire is an integral part of the ponderosa pine ecosystems of the Inland West, so is the resulting smoke.

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Appendix I:

SASEM simulated concentrations and exceedences of the national ambient air quality standards for TPM, PM 10, and PM 2.5.

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FUEL MODEL C

SASEM 4.0 Results

 Using NewSasem input and calculations.

 Burn Name ........................     New Burn
 Burn Date ........................     4/20/2000
 Burn Type ........................     BROADCAST
 Fuel Model .......................     C
 Fine Fuel Loading ................     3.854 T/A
 Small Fuel Loading ...............     0.000 T/A
 Large Fuel Loading ...............     0.000 T/A
 Very Large/Live Fuel Loading .....     0.482 T/A
 Extra Large Fuel Loading .........     0.000 T/A
 Stump Fuel Loading ...............     0.000 T/A
 Duff Depth  ......................     0.044 in
 Burn Duration ....................     4.000 Hr
 Burn Area ........................     20.000 Hectares

 Wind Speed Min ...................     1.0 mi/hr
 Wind Speed Max ...................     10.0 mi/hr
 Wind Speed Inc ...................     1.0 mi/hr
 Wind Direction Min ...............     SE
 Wind Direction Max ...............     SW
 Stability Type ...................     Dispersion Day
 Stability Min ....................     Excellent
 Stability Max ....................     Poor
 Mixing Height ....................     1500.0 m
 Met Limitation ...................     Only Valid
Combinations

 Total Fuel Consumed ..............     3.516 T/A
 TSP Emission Factor ..............     8.385 g/kg
 PM-10 Emission Factor ............     5.545 g/kg
 PM-2.5 Emission Factor ...........     4.700 g/kg
 TSP Emission Rate ................     0.205 g/s/m
 PM-10 Emission Rate ..............     0.136 g/s/m
 PM-2.5 Emission Rate .............     0.115 g/s/m
 TSP Total Emissions ..............     1.457 T
```

PM-10 Total Emissions .... 0.963 T
PM-2.5 Total Emissions .... 0.817 T
Fireline Length .... 447.22 m
Fire Rate of Spread .... 0.031 m/s
Heat Content of Fuel .... 5000. Btu/lb
Fireline Width .... 3.73 m
Number of Plumes .... 120.
Heat Release Rate .... 253383. cal/s
Wind Persistence Factor 0.167
Portion of smoke which rises ..... 60.00 %

Total Suspended Particulates (TSP)

Stability	Wind Speed (mi/hr)	Maximum Concen (ug/m**3)	Distance to Maximum Concen (mi)	Exceedences Distance From (mi)	Exceedences Distance To (mi)	Plume Rise (m)
EXC	1.0	184.0	0.97	0.59	1.65	255.
EXC	2.0	183.3	0.56	0.56	0.87	128.
EXC	3.0	161.3	0.56	0.56	0.62	85.
EXC	4.0	124.1	0.62	No Exceedence		64.
EXC	5.0	103.7	0.62	No Exceedence		51.
GOOD	2.0	184.0	0.93	0.62	1.80	128.
GOOD	3.0	184.0	0.62	0.56	1.12	85.
GOOD	4.0	179.1	0.56	0.56	0.81	64.

GOOD	5.0	165.1	0.56	0.56	0.62	51.
GOOD	6.0	140.5	0.62	No Exceedence		43.
GOOD	7.0	125.9	0.62	No Exceedence		36.
GOOD	8.0	113.5	0.62	No Exceedence		32.
GOOD	9.0	103.0	0.62	No Exceedence		28.
GOOD	10.0	94.0	0.62	No Exceedence		26.
FAIR	4.0	184.0	1.13	0.57	2.68	64.
FAIR	5.0	184.1	0.81	0.56	1.93	51.
FAIR	6.0	184.0	0.62	0.56	1.49	43.
FAIR	7.0	183.2	0.56	0.56	1.18	36.
FAIR	8.0	178.8	0.56	0.56	0.99	32.
FAIR	9.0	172.3	0.56	0.56	0.81	28.
FAIR	10.0	164.7	0.56	0.56	0.68	26.
POOR	1.0	619.1	2.93	0.57	13.87	76.
POOR	2.0	390.0	2.06	0.56	13.86	60.
POOR	3.0	297.6	1.64	0.58	13.88	53.
POOR	4.0	245.7	1.44	0.57	9.02	48.
POOR	5.0	211.7	1.23	0.61	5.15	44.

* The TSP standard used is 150. micrograms per cubic meter.

PM-10

Stability	Wind Speed (mi/hr)	Maximum Concen (ug/m**3)	Distance to Maximum Concen (mi)	Exceedences Distance From (mi)	Exceedences Distance To (mi)	Plume Rise (m)
EXC	1.0	113.2	0.72	No Exceedence		255.
EXC	2.0	118.9	0.62	No Exceedence		128.
EXC	3.0	99.9	0.62	No Exceedence		85.
EXC	4.0	82.1	0.62	No Exceedence		64.
EXC	5.0	68.6	0.62	No Exceedence		51.
GOOD	2.0	113.5	1.36	No Exceedence		128.
GOOD	3.0	121.7	0.62	No Exceedence		85.
GOOD	4.0	115.0	0.62	No Exceedence		64.
GOOD	5.0	103.9	0.62	No Exceedence		51.
GOOD	6.0	92.9	0.62	No Exceedence		43.
GOOD	7.0	83.2	0.62	No Exceedence		36.
GOOD	8.0	75.0	0.62	No Exceedence		32.
GOOD	9.0	68.1	0.62	No Exceedence		28.
GOOD	10.0	62.2	0.62	No Exceedence		26.
FAIR	4.0	116.0	1.69	No Exceedence		64.
FAIR	5.0	119.2	0.62	No Exceedence		51.

FAIR	6.0	121.7	0.62	No Exceedence		43.
FAIR	7.0	119.9	0.62	No Exceedence		36.
FAIR	8.0	115.8	0.62	No Exceedence		32.
FAIR	9.0	110.6	0.62	No Exceedence		28.
FAIR	10.0	105.0	0.62	No Exceedence		26.
POOR	1.0	409.4	2.93	0.57	13.87	76.
POOR	2.0	257.9	2.06	0.56	13.86	60.
POOR	3.0	196.8	1.64	0.64	5.92	53.
POOR	4.0	162.4	1.44	0.82	2.49	48.
POOR	5.0	133.3	1.98	No Exceedence		44.

* The PM-10 standard used is 150. micrograms per cubic meter.

PM-2.5

Stability	Wind Speed (mi/hr)	Maximum Concen (ug/m**3)	Distance to Maximum Concen (mi)	Exceedences Distance From (mi)	Exceedences Distance To (mi)	Plume Rise (m)
EXC	1.0	103.2	0.97	0.59	2.27	255.

EXC	2.0	102.8	0.56	0.56	1.24	128.
EXC	3.0	90.4	0.56	0.56	0.87	85.
EXC	4.0	75.8	0.56	0.56	0.62	64.
EXC	5.0	58.2	0.62	No Exceedence		51.
GOOD	2.0	103.2	0.93	0.62	2.67	128.
GOOD	3.0	103.1	0.62	0.56	1.74	85.
GOOD	4.0	100.4	0.56	0.56	1.24	64.
GOOD	5.0	92.5	0.56	0.56	0.99	51.
GOOD	6.0	83.8	0.56	0.56	0.81	43.
GOOD	7.0	75.8	0.56	0.56	0.68	36.
GOOD	8.0	63.6	0.62	No Exceedence		32.
GOOD	9.0	57.7	0.62	No Exceedence		28.
GOOD	10.0	52.7	0.62	No Exceedence		26.
FAIR	4.0	103.2	1.13	0.57	5.04	64.
FAIR	5.0	103.2	0.81	0.56	3.36	51.
FAIR	6.0	103.2	0.62	0.56	2.55	43.
FAIR	7.0	102.7	0.56	0.56	1.99	36.
FAIR	8.0	100.3	0.56	0.56	1.68	32.
FAIR	9.0	96.6	0.56	0.56	1.37	28.
FAIR	10.0	92.3	0.56	0.56	1.18	26.
POOR	1.0	347.0	2.93	0.57	13.87	76.
POOR	2.0	218.6	2.06	0.56	13.86	60.
POOR	3.0	166.8	1.64	0.58	13.88	53.

| POOR 4.0 137.7 1.44 0.57 13.87 48. |
| POOR 5.0 118.7 1.23 0.61 10.18 44. |

|____|

* The PM-2_5 standard used is 65. micrograms per cubic meter.

FUEL MODEL K

SASEM 4.0 Results

Using NewSasem input and calculations.

Burn Name .... New Burn
Burn Date 4/20/2000
Burn Type .... BROADCAST
Fuel Model .... K
Fine Fuel Loading .... 1.200 T/A
Small Fuel Loading .... 3.600 T/A
Large Fuel Loading .... 6.000 T/A
Very Large/Live Fuel Loading ..... 0.000 T/A
Extra Large Fuel Loading .... 0.000 T/A
Stump Fuel Loading .... 0.000 T/A
Duff Depth .... 0.110 in
Burn Duration .... 4.000 Hr
Burn Area .... 20.000 Hectares

Wind Speed Min .... 1.0 mi/hr
Wind Speed Max .... 10.0 mi/hr
Wind Speed Inc .... 1.0 mi/hr
Wind Direction Min .... SE
Wind Direction Max .... SW
Stability Type .... Dispersion Day
Stability Min .... Excellent
Stability Max .... Poor
Mixing Height .... 1500.0 m
Met Limitation .... Only Valid Combinations

Total Fuel Consumed	7.559 T/A
TSP Emission Factor	13.071 g/kg
PM-10 Emission Factor	9.733 g/kg
PM-2.5 Emission Factor	8.223 g/kg
TSP Emission Rate	0.688 g/s/m
PM-10 Emission Rate	0.512 g/s/m
PM-2.5 Emission Rate	0.433 g/s/m
TSP Total Emissions	4.883 T
PM-10 Total Emissions	3.636 T
PM-2.5 Total Emissions	3.072 T
Fireline Length	447.22 m
Fire Rate of Spread	0.031 m/s
Heat Content of Fuel	7000. Btu/lb
Fireline Width	29.81 m
Number of Plumes	15.
Heat Release Rate	6101865. cal/s
Wind Persistence Factor	0.167
Portion of smoke which rises	60.00 %

Total Suspended Particulates (TSP)

Stability	Wind Speed (mi/hr)	Maximum Concen (ug/m**3)	Distance to Maximum Concen (mi)	Exceedences Distance From (mi)	Exceedences Distance To (mi)	Plume Rise (m)
EXC	1.0	65.6	5.04	No Exceedence		2233.
EXC	2.0	65.6	2.70	No Exceedence		1116.
EXC	3.0	65.6	1.88	No Exceedence		744.
EXC	4.0	65.6	1.45	No Exceedence		558.

EXC	5.0	65.6	1.19	No Exceedence		447.
GOOD	2.0	70.5	10.08	No Exceedence		1116.
GOOD	3.0	65.6	4.42	No Exceedence		744.
GOOD	4.0	65.6	3.22	No Exceedence		558.
GOOD	5.0	65.4	2.52	No Exceedence		447.
GOOD	6.0	65.4	4.42	No Exceedence		372.
GOOD	7.0	65.4	3.73	No Exceedence		319.
GOOD	8.0	65.4	3.22	No Exceedence		279.
GOOD	9.0	65.5	2.83	No Exceedence		248.
GOOD	10.0	65.5	2.52	No Exceedence		223.
FAIR	4.0	51.5	12.49	No Exceedence		558.
FAIR	5.0	51.5	8.41	No Exceedence		447.
FAIR	6.0	65.6	11.25	No Exceedence		372.
FAIR	7.0	65.6	8.56	No Exceedence		319.
FAIR	8.0	70.5	12.49	No Exceedence		279.
FAIR	9.0	70.5	10.14	No Exceedence		248.
FAIR	10.0	70.5	8.41	No Exceedence		223.
POOR	1.0	677.0	13.84	1.72	13.84	219.
POOR	2.0	451.2	13.86	1.62	13.86	174.
POOR	3.0	345.5	12.14	1.64	13.88	152.
POOR	4.0	285.2	9.95	1.75	13.86	138.
POOR	5.0	245.7	8.49	1.84	13.89	128.

* The TSP standard used is 150. micrograms per cubic meter.

PM-10

Stability	Wind Speed (mi/hr)	Maximum Concen (ug/m**3)	Distance to Maximum Concen (mi)	Exceedences Distance From (mi)	Exceedences Distance To (mi)	Plume Rise (m)
EXC	1.0	48.8	5.04	No Exceedence		2233.
EXC	2.0	48.8	2.70	No Exceedence		1116.
EXC	3.0	48.8	1.88	No Exceedence		744.
EXC	4.0	48.8	1.45	No Exceedence		558.
EXC	5.0	48.8	1.19	No Exceedence		447.
GOOD	2.0	52.5	10.08	No Exceedence		1116.
GOOD	3.0	48.8	4.42	No Exceedence		744.
GOOD	4.0	48.8	3.22	No Exceedence		558.
GOOD	5.0	48.7	2.52	No Exceedence		447.
GOOD	6.0	48.7	4.42	No Exceedence		372.
GOOD	7.0	48.7	3.73	No Exceedence		319.
GOOD	8.0	48.7	3.22	No Exceedence		279.

GOOD	9.0	48.7	2.83	No Exceedence		248.
GOOD	10.0	48.8	2.52	No Exceedence		223.
FAIR	4.0	38.3	12.49	No Exceedence		558.
FAIR	5.0	38.3	8.41	No Exceedence		447.
FAIR	6.0	48.8	11.25	No Exceedence		372.
FAIR	7.0	48.8	8.56	No Exceedence		319.
FAIR	8.0	52.5	12.49	No Exceedence		279.
FAIR	9.0	52.5	10.14	No Exceedence		248.
FAIR	10.0	52.5	8.41	No Exceedence		223.
POOR	1.0	504.1	13.84	2.09	13.84	219.
POOR	2.0	336.0	13.86	2.11	13.86	174.
POOR	3.0	257.2	12.14	2.26	13.88	152.
POOR	4.0	212.3	9.95	2.49	13.86	138.
POOR	5.0	183.0	8.49	2.83	13.89	128.

* The PM-10 standard used is 150. micrograms per cubic meter.

PM-2.5

Stability	Wind Speed	Maximum Concen	Distance to Maximum Concen	Exceedences Distance From	To	Plume Rise

	(mi/hr)	(ug/m**3)	(mi)	(mi) (mi)	(m)
EXC	1.0	41.2	5.04	No Exceedence	2233.
EXC	2.0	41.2	2.70	No Exceedence	1116.
EXC	3.0	41.2	1.88	No Exceedence	744.
EXC	4.0	41.2	1.45	No Exceedence	558.
EXC	5.0	41.2	1.19	No Exceedence	447.
GOOD	2.0	44.3	10.08	No Exceedence	1116.
GOOD	3.0	41.2	4.42	No Exceedence	744.
GOOD	4.0	41.2	3.22	No Exceedence	558.
GOOD	5.0	41.2	2.52	No Exceedence	447.
GOOD	6.0	41.1	4.42	No Exceedence	372.
GOOD	7.0	41.1	3.73	No Exceedence	319.
GOOD	8.0	41.1	3.22	No Exceedence	279.
GOOD	9.0	41.2	2.83	No Exceedence	248.
GOOD	10.0	41.2	2.52	No Exceedence	223.
FAIR	4.0	32.4	12.49	No Exceedence	558.
FAIR	5.0	32.4	8.41	No Exceedence	447.
FAIR	6.0	41.2	11.25	No Exceedence	372.
FAIR	7.0	41.2	8.56	No Exceedence	319.
FAIR	8.0	44.3	12.49	No Exceedence	279.
FAIR	9.0	44.3	10.14	No Exceedence	248.

```
 | FAIR   10.0       44.3       8.41        No Exceedence
223. |
 | POOR    1.0      425.9      13.84       1.35    20.42
219. |
 | POOR    2.0      283.9      13.86       1.24    13.86
174. |
 | POOR    3.0      217.3      12.14       1.26    13.88
152. |
 | POOR    4.0      179.4       9.95       1.25    13.86
138. |
 | POOR    5.0      154.6       8.49       1.22    13.89
128. |

|__________________________________________________________
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   * The PM-2_5 standard used is   65. micrograms per cubic
meter.


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FUEL MODEL U

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 SASEM 4.0 Results

 Using NewSasem input and calculations.

 Burn Name ........................     New Burn
 Burn Date ........................     4/20/2000
 Burn Type ........................     BROADCAST
 Fuel Model .......................     U
 Fine Fuel Loading ................     4.202 T/A
 Small Fuel Loading ...............     1.401 T/A
 Large Fuel Loading ...............     0.000 T/A
 Very Large/Live Fuel Loading .....     0.700 T/A
 Extra Large Fuel Loading .........     0.000 T/A
 Stump Fuel Loading ...............     0.000 T/A
 Duff Depth  ......................     0.064 in
 Burn Duration ....................     4.000 Hr
 Burn Area ........................     20.000 Hectares

 Wind Speed Min ...................     1.0 mi/hr
 Wind Speed Max ...................     10.0 mi/hr
 Wind Speed Inc ...................     1.0 mi/hr
 Wind Direction Min ...............     SE
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Wind Direction Max .... SW
Stability Type .... Dispersion Day
Stability Min .... Excellent
Stability Max .... Poor
Mixing Height .... 1500.0 m
Met Limitation .... Only Valid Combinations

Total Fuel Consumed .... 5.811 T/A
TSP Emission Factor .... 10.859 g/kg
PM-10 Emission Factor .... 7.773 g/kg
PM-2.5 Emission Factor .... 6.560 g/kg
TSP Emission Rate .... 0.439 g/s/m
PM-10 Emission Rate .... 0.314 g/s/m
PM-2.5 Emission Rate .... 0.265 g/s/m
TSP Total Emissions .... 3.119 T
PM-10 Total Emissions .... 2.232 T
PM-2.5 Total Emissions .... 1.884 T
Fireline Length .... 447.22 m
Fire Rate of Spread .... 0.031 m/s
Heat Content of Fuel .... 7000. Btu/lb
Fireline Width .... 29.81 m
Number of Plumes .... 15.
Heat Release Rate .... 4690880. cal/s
Wind Persistence Factor 0.167
Portion of smoke which rises ..... 60.00 %

Total Suspended Particulates (TSP)

Stability	Wind Speed (mi/hr)	Maximum Concen (ug/m**3)	Distance to Maximum Concen (mi)	Exceedences Distance From (mi)	To (mi)	Plume Rise (m)

```
 | EXC      1.0         49.0        4.37        No Exceedence
1907. |
 | EXC      2.0         49.0        2.35        No Exceedence
953. |
 | EXC      3.0         49.0        1.63        No Exceedence
636. |
 | EXC      4.0         49.0        1.26        No Exceedence
477. |
 | EXC      5.0         49.0        1.03        No Exceedence
381. |
 | GOOD     2.0         49.0        5.80        No Exceedence
953. |
 | GOOD     3.0         49.0        3.71        No Exceedence
636. |
 | GOOD     4.0         49.0        2.71        No Exceedence
477. |
 | GOOD     5.0         48.9        4.54        No Exceedence
381. |
 | GOOD     6.0         48.9        3.71        No Exceedence
318. |
 | GOOD     7.0         48.9        3.14        No Exceedence
272. |
 | GOOD     8.0         49.0        2.71        No Exceedence
238. |
 | GOOD     9.0         49.0        2.38        No Exceedence
212. |
 | GOOD    10.0         49.0        2.12        No Exceedence
191. |
 | FAIR     4.0         38.5        9.44        No Exceedence
477. |
 | FAIR     5.0         49.0       11.75        No Exceedence
381. |
 | FAIR     6.0         49.0        8.51        No Exceedence
318. |
 | FAIR     7.0         52.7       11.96        No Exceedence
272. |
 | FAIR     8.0         52.7        9.44        No Exceedence
238. |
 | FAIR     9.0         52.7        7.66        No Exceedence
212. |
 | FAIR    10.0         49.0        3.44        No Exceedence
191. |
 | POOR     1.0        486.3       13.85       1.92    13.85
201. |
 | POOR     2.0        315.6       13.37       1.93    13.87
159. |
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POOR	3.0	240.8	10.12	2.11	13.85	139.
POOR	4.0	198.8	8.31	2.41	13.84	126.
POOR	5.0	171.3	7.09	2.87	13.86	117.

* The TSP standard used is 150. micrograms per cubic meter.

PM-10

Stability	Wind Speed (mi/hr)	Maximum Concen (ug/m**3)	Distance to Maximum Concen (mi)	Exceedences Distance From (mi)	Exceedences Distance To (mi)	Plume Rise (m)
EXC	1.0	35.1	4.37	No Exceedence		1907.
EXC	2.0	35.1	2.35	No Exceedence		953.
EXC	3.0	35.1	1.63	No Exceedence		636.
EXC	4.0	35.1	1.26	No Exceedence		477.
EXC	5.0	35.1	1.03	No Exceedence		381.
GOOD	2.0	35.1	5.80	No Exceedence		953.
GOOD	3.0	35.1	3.71	No Exceedence		636.
GOOD	4.0	35.0	2.71	No Exceedence		477.

GOOD	5.0	35.0	4.54	No Exceedence		381.
GOOD	6.0	35.0	3.71	No Exceedence		318.
GOOD	7.0	35.0	3.14	No Exceedence		272.
GOOD	8.0	35.1	2.71	No Exceedence		238.
GOOD	9.0	35.1	2.38	No Exceedence		212.
GOOD	10.0	35.1	2.12	No Exceedence		191.
FAIR	4.0	27.5	9.44	No Exceedence		477.
FAIR	5.0	35.1	11.75	No Exceedence		381.
FAIR	6.0	35.1	8.51	No Exceedence		318.
FAIR	7.0	37.7	11.96	No Exceedence		272.
FAIR	8.0	37.7	9.44	No Exceedence		238.
FAIR	9.0	37.7	7.66	No Exceedence		212.
FAIR	10.0	35.1	3.44	No Exceedence		191.
POOR	1.0	348.1	13.85	2.48	13.85	201.
POOR	2.0	225.9	13.37	2.80	13.87	159.
POOR	3.0	172.4	10.12	3.91	13.85	139.
POOR	4.0	142.3	8.50	No Exceedence		126.
POOR	5.0	122.6	7.28	No Exceedence		117.

* The PM-10 standard used is 150. micrograms per cubic meter.

PM-2.5

Stability	Wind Speed (mi/hr)	Maximum Concen (ug/m**3)	Distance to Maximum Concen (mi)	Exceedences Distance From (mi)	Exceedences Distance To (mi)	Plume Rise (m)
EXC	1.0	29.6	4.37	No Exceedence		1907.
EXC	2.0	29.6	2.35	No Exceedence		953.
EXC	3.0	29.6	1.63	No Exceedence		636.
EXC	4.0	29.6	1.26	No Exceedence		477.
EXC	5.0	29.6	1.03	No Exceedence		381.
GOOD	2.0	29.6	5.80	No Exceedence		953.
GOOD	3.0	29.6	3.71	No Exceedence		636.
GOOD	4.0	29.6	2.71	No Exceedence		477.
GOOD	5.0	29.6	4.54	No Exceedence		381.
GOOD	6.0	29.6	3.71	No Exceedence		318.
GOOD	7.0	29.6	3.14	No Exceedence		272.
GOOD	8.0	29.6	2.71	No Exceedence		238.
GOOD	9.0	29.6	2.38	No Exceedence		212.
GOOD	10.0	29.6	2.12	No Exceedence		191.
FAIR	4.0	23.2	9.44	No Exceedence		477.
FAIR	5.0	29.6	11.75	No Exceedence		381.

FAIR	6.0	29.6	8.51	No Exceedence		318.
FAIR	7.0	31.8	11.96	No Exceedence		272.
FAIR	8.0	31.8	9.44	No Exceedence		238.
FAIR	9.0	31.8	7.66	No Exceedence		212.
FAIR	10.0	29.6	3.44	No Exceedence		191.
POOR	1.0	293.8	13.85	1.48	13.85	201.
POOR	2.0	190.7	13.37	1.44	13.87	159.
POOR	3.0	145.5	10.12	1.49	13.85	139.
POOR	4.0	120.1	8.31	1.54	13.84	126.
POOR	5.0	103.5	7.09	1.62	13.86	117.

* The PM-2_5 standard used is 65. micrograms per cubic meter.