Effects of fire and logging on landscape structure in the Greater Yellowstone Ecosystem
by Henry Bond Wilmer, III

A thesis submitted for partial fulfillment of the requirements for the degree of Master of Science in Biology
Montana State University

Abstract:
Ecologists have recognized disturbance as an important driver of spatial patterns in a landscape and the composition of its species. Wildfire in particular has received special attention as a recurrent, ubiquitous disturbance that has greatly influenced the structure of Rocky Mountain forest ecosystems. However, in recent decades, staggered-setting clearcut logging has altered the spatial and temporal characteristics of historic landscape patterns driven by fire. Increasingly, landscape ecologists are using patterns of natural disturbance as a guide for ecosystem management. My study area in the Greater Yellowstone Ecosystem (GYE) contained patterns of intensive logging in the Targhee National Forest (TNF) directly adjacent to patterns resulting from wildfire in 1988 in Yellowstone National Park (YNP). To compare these disturbance types, I tested hypotheses at two scales. At the landscape scale, spatial patterns of clearcuts and wildfires were subsampled at various extents and quantified using landscape metrics. A finer-scaled field study focused on post-disturbance biological legacy within stands. Results indicate that clearcutting fragmented forests more than wildfire, reducing total core area, while increasing the number of core areas. Patch size, shape and dispersion all revealed differences between clearcutting and wildfire. Furthermore, multi-scaled frequency distributions of 9 landscape metrics revealed thresholds in scaling effects for each disturbance type. The field study demonstrated that clearcutting is a more severe disturbance type than wildfire, removing more CWD and dramatically reducing snag density. These differences between clearcutting and wildfire at both the landscape and stand scales have important ecological consequences for the natural fire regime. At the landscape scale, wildfire is constrained by the clearcutting pattern in TNF, whereas fire risk is higher in YNP. At the stand scale, clearcutting removes CWD and standing snags that provide fuel for future wildfires. Hence, clearcutting disrupts the natural disturbance regime. Recognizing this important consequence, timber harvest strategies can be developed that better mimic natural landscape patterns that perpetuate the natural disturbance regime and sustain levels of biodiversity.

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Henry Bond Wilmer III

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ABSTRACT

Ecologists have recognized disturbance as an important driver of spatial patterns in a landscape and the composition of its species. Wildfire in particular has received special attention as a recurrent, ubiquitous disturbance that has greatly influenced the structure of Rocky Mountain forest ecosystems. However, in recent decades, staggered-setting clearcut logging has altered the spatial and temporal characteristics of historic landscape patterns driven by fire. Increasingly, landscape ecologists are using patterns of natural disturbance as a guide for ecosystem management. My study area in the Greater Yellowstone Ecosystem (GYE) contained patterns of intensive logging in the Targhee National Forest (TNF) directly adjacent to patterns resulting from wildfire in 1988 in Yellowstone National Park (YNP). To compare these disturbance types, I tested hypotheses at two scales. At the landscape scale, spatial patterns of clearcuts and wildfires were subsampled at various extents and quantified using landscape metrics. A finer-scaled field study focused on post-disturbance biological legacy within stands. Results indicate that clearcutting fragmented forests more than wildfire, reducing total core area, while increasing the number of core areas. Patch size, shape and dispersion all revealed differences between clearcutting and wildfire. Furthermore, multi-scaled frequency distributions of 9 landscape metrics revealed thresholds in scaling effects for each disturbance type. The field study demonstrated that clearcutting is a more severe disturbance type than wildfire, removing more CWD and dramatically reducing snag density. These differences between clearcutting and wildfire at both the landscape and stand scales have important ecological consequences for the natural fire regime. At the landscape scale, wildfire is constrained by the clearcutting pattern in TNF, whereas fire risk is higher in YNP. At the stand scale, clearcutting removes CWD and standing snags that provide fuel for future wildfires. Hence, clearcutting disrupts the natural disturbance regime. Recognizing this important consequence, timber harvest strategies can be developed that better mimic natural landscape patterns that perpetuate the natural disturbance regime and sustain levels of biodiversity.

INTRODUCTION

A recent paradigm shift in forestry challenges land managers to meet a wider range of objectives (Franklin and Forman 1987; Swanson and Franklin 1992; Golley 1993; Franklin 1993). While continuing to provide forest products, these managers must now also maintain ecosystem processes and protect viable populations of native species (Jensen and Everett 1993; Hansen et al. 1995; Targhee National Forest 1997). To meet these objectives sustainably, ecologists have studied natural disturbance as an analogue to human management activities (Franklin and Forman 1987; Hunter 1993; Ripple 1994; Cissel et al. 1994; Foster et al. 1998). Disturbances such as wildfire influence ecological processes like nutrient cycling (Stark 1977; Harmon et al. 1986; Turner et al. 1995), succession (Romme and Knight 1981; Tinker et al. 1993; Turner et al. 1997), future disturbances (Romme 1982; Turner 1989), and habitats of many species (Pearson et al. 1995; Romme et al. 1995; Hoffman 1997). Hence, both processes and organisms are dependent upon natural disturbance.

In recent decades, human activities like logging have imposed landscape patterns different from those resulting from natural disturbance (Franklin and Forman 1987; Spies et al. 1994; Reed et al. 1996; Tang et al. 1997; Tinker et al. 1998). It is unknown how well these human-disturbed landscapes will sustain ecosystem processes and native populations. Understanding the differences between human and natural disturbance can allow land managers to design strategies that sustain ecosystem processes, native organisms, and the goods and services they provide.

The Greater Yellowstone Ecosystem (GYE) provides a unique opportunity to study patterns of both natural and human disturbance. Wildfires burned Yellowstone National Park (YNP) in 1988, while the Targhee National Forest (TNF) across the Park boundary has been heavily logged since the 1950's. My study has two objectives: (1) compare the effects of clearcut logging and wildfire on vegetation structure within stands and on spatial patterns of vegetation across landscapes, (2) explore consequences of these vegetation patterns for the spread of future wildfire. I will also recommend management strategies to sustain ecosystem processes, viable populations of native species and forest products and services.

Disturbance and Landscape Pattern

Ecologists have recognized disturbance as an important driver of spatial patterns in the landscape and the types of organisms that occupy the landscape (Romme 1982; Baker 1992b; Pearson et al. 1995). Disturbances such as wildfire (Turner et al. 1994a), windthrow (Kramer 1997) or insect infestation (Romme et al. 1986; Veblen 1997) typically affect some localized areas more than others, resulting in a patchwork mosaic of different vegetation types and ages. This mosaic of "patches" plays a crucial role in ecosystem function and patterns of biodiversity (Pickett and White 1985; Forman and Godron 1986; Turner 1989). Thus, it is important to understand the influence of disturbance on patch dynamics and its consequences for managing ecological processes and biodiversity.

Natural patterns of disturbance typically create a highly variable mosaic of patch types, exhibiting a wide range of patch sizes, return intervals, and severity levels (Swanson and Franklin 1992; Millspaugh and Whitlock 1993; Foster et al. 1998; Brown et al. 1999; Li et al. 1999). This spatial and temporal variability results from numerous interactions of a variety of biotic and abiotic factors (Bessie and Johnson 1995). For example, flooding events are constrained by climate and topography, but are also influenced by riparian vegetation and soil. Similarly, forest patches are susceptible to windthrow where topography interacts with climate, soil and existing vegetation patterns (Kramer 1997). Wildfire, insect infestations, hurricanes, droughts and landslides also represent stochastic and reciprocal interactions of climatic, edaphic and biotic conditions. Thus, patterns of natural disturbance are highly variable both spatially and temporally.

This landscape heterogeneity influences ecosystem processes like nutrient cycling (Stark 1977; Harmon et al. 1986; Spies et al. 1988; Turner et al. 1995), succession (Romme and Knight 1981; Tinker et al. 1993; Turner et al. 1997), dispersal success (Lavorel et al. 1995; Bascompte and Solé 1996; Boone and Hunter 1996; Gustafson and Gardner 1996; Bellhumuer and Legendre 1998; With and King 1999) and future disturbances (Romme 1982; Bessie and Johnson 1995; Tang et al. 1997). For example, downed logs within disturbance patches act as banks within the carbon budget, (Harmon et al. 1986; Turner et al. 1995). These logs decay slowly and release nutrients that are used by regenerating vegetation (Chappell and Agee 1996). The high levels of light, nutrients and other resources in disturbance patches favor the growth of early seral plants (Halpern 1989; Chen et al. 1995; Turner et al. 1997; Gray and Spies 1997). Future disturbances like wildfire (Romme 1982; Turner et al. 1989a; Renkin and Despain 1992), insect infestations (Romme et al. 1986; Veblen 1997), or windthrow (Kramer 1997; Tang et al. 1997) are frequently dependent upon mature or old-growth forest structure. Hence, as disturbances across the landscape reset the successional clock, varying proportions of the landscape are susceptible to future disturbances. Thus, ecosystem processes are dependent upon landscape heterogeneity.

Biodiversity is also affected by landscape heterogeneity. A highly variable spatial pattern across the landscape can provide a greater diversity of ecological niches (Hansen et al. 1991; Hansen et al. 1993; Halpern and Spies 1995; Hargis 1997). For example, a forest consists of a wide variety of vegetation types, ages, and sizes along with varying amounts of woody debris and standing snags. This variety of characteristics interact and vary spatially across the stand, creating a diversity of ecological niches (Rose and Muir, 1997). Hence, a Black-backed woodpecker (*Picoides arctus*) requiring standing snags can coexist with an American marten (*Martes americana*) that requires long, coarse woody debris. Similarly, at a broader scale, patch size can influence those species that require a large territory for breeding. Edge-adapted species can thrive in a highly fragmented habitat at the expense of those adapted to the forest core interior. Hence, the spatial pattern of the vegetation patches influences the diversity of habitat types available to native forest animals.

Human disturbance, on the other hand, is hypothesized to fragment ecosystems into smaller patches, exhibiting a less variable pattern both within patches and across the landscape. Forest fragmentation has been particularly well documented in the Pacific

Northwest of the United States, where traditional, staggered-setting clearcutting patterns have reshaped the landscape (Franklin and Forman 1987; Swanson and Franklin, 1992; Spies et al. 1994; Wallin et al. 1994; Hansen et al. 1995). For example, following a clearcut, the variety of tree types, ages and densities is commonly replaced by a single, even-aged, fast-growing species (Halpern and Spies 1995). This strategy quickly renders a high volume of marketable board feet (Hansen et al. 1995). However, these structurally simple stands lack the standing snags, woody debris, and surviving, large trees that provide not only fuel for the natural fire regime but also a diversity of ecological niches for native species (Hansen et al. 1995; Rose and Muir 1997).

Across the landscape, a staggered-setting pattern of small clearcuts resulted from antiquated objectives to promote ecotonal game species and road construction, while dispersing the damaging hydrologic and aesthetic effects of clearcuts (Swanson and Franklin 1992). However, these small patches exhibit less core area, increased edge density and more simple shapes than the presettlement pattern (Reed et al. 1997; Tinker et al. 1998). This alteration of landscape pattern may bear important consequences for the disturbance regime (Franklin and Forman 1987; Turner et al. 1994b; Wallin et al. 1994; Tang et al. 1995) and for species that require large, connected territories (Buskirk and Ruggerio 1994; Boone and Hunter 1996; Edenius and Elmberg 1996).

Beyond the physical characteristics of individual patch types and sizes, ecologists suggest that humans comprehensively reduce the range of variability in spatial patterns across the landscape (Forman and Godron 1986; Swanson et al. 1993). Whereas wildfire burns small patches in one area and large patches in another, clearcutting is likely to homogenize the landscape in a uniform dispersion of small patches. This "rescaling" of the disturbance regime into regular, homogenous patterns is due to administrative and logistical constraints aimed at maximizing human resource extraction. Such scaling thresholds are common among disturbance types (Urban et al. 1987; Delcourt and Delcourt 1988; Turner et al. 1993b; Li et al. 1999), but quantifying spatial heterogeneity across a landscape remains a challenge (Scheiner 1992; McGarigal and Marks 1994; Gustafson 1998; Meisel and Turner 1998).

Landscape Metrics and Scale

In comparing natural and human landscape patterns, attention must be paid to methods of quantifying landscape pattern. Landscape metrics have emerged as important tools for quantifying spatial pattern (Turner 1990; Turner and Gardner 1991; McGarigal and Marks 1994; Riitters et al. 1995; O'Neill et al. 1997; Tinker et al. 1998). Such metrics provide a dizzying number of measurements, including the number of patches, mean patch size, edge density, total core area, shape indices, and fractal dimension, to name only a few. Ecologists are increasingly interested in linking landscape metrics with ecological processes like dispersal (Turner et al. 1989a; With and King 1999), habitat selection (McGarigal and Marks 1994; Edenius and Elmberg 1996; Beauvais and Buskirk 1997), and population viability (Murphy and Noon 1992; Bascompte and Solé 1996)

However, clear interpretation of landscape metrics is often obscured by the effect of scale (Allen and Starr 1982; Turner et al. 1989b; MacGarigal and Marks 1994; Ritters et al. 1995; O'Neill et al. 1996; Hargis et al. 1998; Meisel and Turner 1998). Scale is defined by two components, grain and extent (Turner et al. 1989b). Turner (1989b) illustrated how analysis of landscape pattern is strongly influenced by each of these components. For example, as grain size increases and the landscape coarsens, rare and small patches drop out of the sample. Hence, as landscape metrics are calculated, the sample distribution is skewed by the resolution of the spatial analysis. Thus, measures of landscape pattern are influenced by scale. Similarly, extent influences the measurement of landscape pattern. Landscape metrics like dominance and contagion increase as the extent of analysis grows (Turner 1989b). However, it remains unclear how to choose the appropriate extent of analysis for the process of interest.

Hence, a challenge to ecologists is to interpret landscape metrics while controlling for the effects of scale (Allen and Starr 1982; Pickett and White 1985; Forman and Godron 1986; Urban et al. 1987; McGarigal and Marks 1994; Allen and Roberts 1998). More precisely, ecologists want to understand how scale influences the behavior of landscape metrics (Turner 1989b; Hargis et al. 1998). With this understanding, land managers can select an appropriate scale for achieving ecological objectives.

OBJECTIVES AND HYPOTHESES

Objective 1: Determine the relative influence of staggered-setting clearcut logging and wildfire on both stand structure and landscape spatial pattern. Three hypotheses were formulated to meet this objective.

Hypothesis 1

Forest patches are more fragmented by logging than wildfire. In particular, clearcutting creates more edge in the surviving forest than wildfire. Clearcutting produces smaller and less variable patch sizes of surviving forest than wildfire. Clearcutting reduces core area of surviving forest more than wildfire. Clearcut patches themselves are smaller, exhibit less core area and variability in patch size and shape, and show a different distribution of patch sizes from wildfire.

The Yellowstone wildfires of 1988 exhibited a highly variable range of patch sizes and shapes (Christensen et al. 1989). Turner et al. (1994a) demonstrated that fire influenced the degree of spatial patterning at two scales. Driven by strong winds and extreme drought conditions, severe canopy fires created large, aggregated, elliptical patches across most of the Park (Turner and Romme 1994). Around the periphery of these large patches, many smaller patches were burned as embers landed in younger, wetter stands or in less windy conditions. These smaller patches were more numerous, less severe, and exhibited more complex shapes than the larger canopy fires (Turner et al. 1994a). Thus, natural fire patterns are highly variable due to the wide range of conditions and factors that can influence fire spread.

Clearcutting, however, operates within a narrower range of human-imposed constraints. Traditionally, a uniform, staggered-setting pattern resulted from antiquated objectives to promote ecotonal game species, seed rain from nearby stands, and road-building for fire suppression, while dispersing the damaging hydrological effects, and unpleasant aesthetics of clearcuts.

Many studies have demonstrated quantifiable trends among the spatial patterns of human fragmentation of forested landscapes (Harris 1987; Swanson and Franklin 1992; Mladenoff et al. 1993; Spies et al. 1994; Reed et al. 1996; O'Neill et al. 1997; Tinker et al. 1998). Franklin and Forman (1987) demonstrated in simulated landscapes how a checkerboard pattern of disturbance patches introduced more edge and decreased the average patch size and core area more than an aggregated pattern of large patch sizes. These results were confirmed in the Pacific Northwest (Swanson and Franklin 1992; Spies et al. 1994; Wallin et al. 1994), and in the upper Midwest (Baker 1992b; Mladenoff et al. 1993). Studies of Rocky Mountain landscapes exhibit similar patterns of fragmentation. (Reed et al. 1996; Tinker et al. 1998). Table 1 represents a suite of measures used by these studies to assess landscape fragmentation.

Table 1. List of measures of fragmentation.

Measure	Fragmentation Effect
Number of patches	Increases
Patch size	Decreases
Patch shape	Simplifies
Total edge	Increases
Core Area	Decreases
Number of core areas	Increases
Nearest neighbor distance	Increases

Studies comparing human with natural disturbance on real landscapes are few however (Mladenoff et al. 1993). Swanson et al. (1993) hypothesized that clearcutting reduces variability across these measures relative to the natural range of variability due to wildfire. Tinker et al. (1998) have compared landscape patterns of clearcutting with pre-settlement patterns by digitally removing human features from the landscape using geographic information systems (GIS). Similarly, simulated human and natural patterns have been generated using neutral landscape models and fractal techniques (With 1997). However, no previous efforts have been made to compare the spatial patterns of human and natural disturbance on real landscapes in Rocky Mountain ecosystems.

Hypothesis 2

The relationship between landscape extent and certain landscape metrics (patch size, core area, edge density) is nonlinear. As extent increases beyond a threshold, the variability of landscape metrics will decrease. This threshold will be achieved at a smaller extent of analysis for logging than for wildfire, indicating a difference between the scales of these disturbance mechanisms.

An emergent theme within landscape ecology is the role of scale in measuring landscape pattern (Allen and Starr 1982; Turner et al. 1989b; Turner et al. 1993b; Allen and Roberts 1998). Ecologists study scale because they are interested in knowing if a measured pattern is due to an ecological process or merely an artifact of the scale of analysis. Previous studies have suggested scaling tendencies of disturbance mechanisms (Allen and Starr, 1982; Urban et al. 1987; Delcourt and Delcourt 1988; Romme and Despain 1989), habitat selection (Wiens and Milne 1989), and dispersal abilities (Lavorel et al. 1995; Bellehumeur and Legendre 1998), but few have attempted to explicitly quantify thresholds in disturbance scaling.

Meisel and Turner (1998) searched for such thresholds using semivariance analysis to assess patterns of spatial autocorrelation in real and artificial landscapes. However, results from this technique were difficult to interpret for real patterns and did not address landscape metrics. O'Neill et al. (1996) determined that subsampling the landscape was necessary to assess spatial variability within landscapes. They determined that an appropriate extent of analysis was 2-5 times greater than the feature of interest. However, this study addressed only broad landscape-level indices like dominance and contagion.

For this study, grain size is fixed, while the extent of a sample window is varied. As the size of this sample window increases, we would expect more patches to be included in the calculation of an average measure. For example, window sizes that are smaller than a single patch express no variance, while a large sampling window will allow numerous patches to contribute toward a more representative mean.

However, disturbances occur as scaled processes themselves (Urban et al. 1987; Delcourt and Delcourt 1988). Thus, large disturbances would require a larger sample window to characterize the average landscape pattern than smaller disturbance types. An accurate measure of disturbance pattern could be achieved when the variance of the response is no longer strongly influenced by the size of the sampling window. This multi-scaled technique could not only identify scaling thresholds among disturbance types, but in doing so, could also help determine an appropriate scale for future analyses.

Hypothesis 3

Stands disturbed by wildfire exhibit more snags and downed logs than clearcut stands. This biological legacy is also more variable in burns than clearcuts.

Increasingly, "new forestry" techniques are focused on protecting the important ecological role of biological legacy (Swanson and Franklin 1992; Franklin 1992). This biological legacy includes standing live trees and coarse woody debris (CWD), which includes standing dead trees (snags) and downed logs. Post-disturbance live trees have been shown to increase structural complexity, and hence biodiversity, within stands and across successional stages (Hansen et al. 1991; Franklin 1992). The importance of coarse woody debris (CWD) for ecosystem function had previously been overlooked in ecological studies because generation and decay processes are slow and require long time periods to monitor (Harmon et al. 1986). However, recent studies have demonstrated that CWD, influences nutrient cycling (Turner et al. 1995), succession (Gray and Spies 1997), habitat availability (Hoffman 1997), stream morphology (Franklin 1992), and biodiversity (Hansen et al. 1991). In their seminal article, Harmon et al. (1986) provide an excellent, comprehensive review of the ecology of CWD and its importance for these ecosystem processes and characteristics.

Particularly, studies (Harmon et al. 1986; Maser et al. 1988) have modeled persistence of CWD through time and successional stages in Pacific Northwest forests. Initially after a disturbance occurs, a surge of CWD results from high mortality. This residual wood is slow to decompose, especially if snags remain standing for a long time or if logs are suspended in a lattice above the ground, which harbors more moisture and decomposers (Despain, pers. comm). As the stand ages, this woody material eventually fragments, sags, and decomposes, reaching lowest levels of abundance after the post-disturbance surge has decomposed, but before the regenerating stand has aged sufficiently to contribute large trees to CWD levels. Over the long term, CWD resulting from the initial disturbance is replaced by CWD resulting from natural senescence of a mature stand (Harmon et al. 1986). The combination of these two mechanisms for input of CWD represents a natural cycle that is ubiquitous across systems and natural disturbance types.

Post-fire levels of CWD are high because fire typically consumes fine debris and bark, leaving thick logs and standing snags. This is true of most disturbance types, which consume smaller pieces of wood than larger. Additionally, post-fire CWD reflects pre-disturbance tree density and primary productivity which is driven by numerous factors including disturbance type, soil nutrient levels and depth, slope, aspect, elevation, and microclimatic variables. Hence, post-fire CWD is highly variable (Harmon et al. 1986).

Clearcutting, on the other hand, imposes a uniform severity, removing all standing trees and then piling and burning any remaining slash. This strategy reduces the pre-disturbance variability in CWD to allow for efficient extraction of timber and also the quick regeneration of even-aged stands, free of competition for light and nutrients. Thus, it is logical to assume that silvicultural techniques that specifically remove larger logs will decrease the amount and variability of CWD more than wildfire. However, few studies have quantified the loss of CWD due to clearcut logging (Tritton 1980). Additionally, to my knowledge, no such studies have been attempted in Rocky Mountain ecosystems. Hence, I aim to estimate the amount of CWD removed from National Forests in the Greater Yellowstone Ecosystem. Consequences of this removal of CWD are explored by hypothesis 4.

Objective 2: Examine ecological consequences of these hypothesized differences between clearcutting and wildfire for the natural fire regime.

Hypothesis 4

Under certain climate conditions, wildfire has a higher probability of spreading through landscape patterns generated by previous fires than landscapes disturbed by clearcut logging. Only when even-aged clearcut stands reach maturity do fuels become connected. A burned landscape is contiguous throughout successional stages.

Many landscape ecologists have suggested that the probability of future disturbances, like wildfire, is altered by spatial patterns (Tang et al. 1997; Turner and Romme 1994; Turner et al. 1989a; Franklin and Forman 1987; Picket and White 1985; Forman and Godron 1986). Specifically, it has been suggested that after ignition the fragmenting pattern of clearcuts and roads would act as fire breaks, inhibiting the natural fire pattern.

A challenge to fire ecologists is to identify a threshold in burning conditions where the spatial pattern of fuels influences fire spread (Turner and Romme 1994; Gardner et al. 1996). Identifying this threshold could provide insight for forest managers to prescribe fire to effect desired levels of landscape heterogeneity. Therefore, it is important to explore the mechanisms of fire spread.

Climate is the primary determinant of fire size, shape, severity, and dispersal. When weather conditions are extremely dry, hot and windy, crown fires burn large, elliptical patches dominated by severe canopy burn (Turner et al. 1994a). These wind-driven fires spread primarily through "fire spotting", the lofting of embers downwind by convection currents generated by the fire itself (Turner and Romme 1994). In simulated fires, Hargrove et al. (1994) observed that fire spotting increased the rate of spread 4-8 times faster than surface diffusion alone. Under these conditions, the spatial distribution of fuels is overridden by intense, wind-driven, canopy fire.

Less extreme weather conditions allow forests to burn more moderately. Instead of fire spotting as a primary mechanism, these moderate burns are more dependent on diffusion processes governed by variations in fuel ages, conditions, and distributions (Turner and Romme, 1994). Therefore, a closer examination of fuel conditions is warranted.

Canopy fires develop in mature forests that exhibit a developed understory with high levels of dead wood and standing snags (Romme 1982; Despain 1990; Turner and Romme 1994, Hargrove et al. 1994). The role of this coarse woody material has been overlooked by most mechanistic, fire simulation models. These models focus primarily on surface diffusion through accumulated fine litter and duff (Rothermel 1972; Burgan and Rothermel 1984). Van Wagner (1977) and Turner and Romme (1994) have examined the conditions needed for crown fires. However, these studies failed to explicitly examine the role of coarse woody debris in the generation of embers.

Within stands, I suggest that the amount of coarse woody material contributes to the generation of embers and higher temperatures to promote fire spotting. Across the landscape, this fire spotting is more likely to initiate a second ignition if the spatial pattern of mature fuels exhibits large, contiguous core areas. I tested these hypotheses with field studies and simulation modeling in the GYE.

STUDY AREA

The study area includes 540,516 ha along the boundary of Yellowstone National Park (YNP) with Targhee National Forest (TNF) (Fig. 1). This area was selected to represent three types of spatial patterns: (1) staggered-setting clearcut logging in TNF, (2) patterns created by the 1988 wildfires in YNP, and (3) areas without major disturbance in the last century.

The 100,606 ha study site in the TNF contains clearcuts resulting from salvage logging efforts after a pine beetle infestation during the 1970's. The TNF study site extends east from US Highway 191 to the YNP boundary. The north-south extent of the TNF study area ranges from the southern boundary of YNP to the southern extent of Montana.

The 383,707 ha YNP study site contains the Fan and North Fork fires of 1988. These fires range from the Bechler River source in the south to the northern YNP boundary. The YNP study site extends from the TNF boundary to the eastern extent of the North Fork Fire near the Grand Canyon of the Yellowstone. The undisturbed portion of the study area includes 56,203 ha in YNP. The Southern and Western boundaries are the same as YNP. The Northern boundary adjoins the Southern extent of the YNP study site near the Bechler River source. The Eastern extent is 552,586 m in UTM zone 12.