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Effects of Disturbance and Fuelbed Succession on Spatial Patterns of Fuel, Fire Hazard, and Carbon; and Fuel Consumption in Shrub-dominated Ecosystems

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Abstract

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A state and transition approach was used to model and map fuelbed, fire hazard, and carbon change under different management and fire regimes for the Okanogan-Wenatchee National Forest in central Washington. Landscape metrics showed different patterns of change over time depending upon the metric considered and the fire and management regime modeled. Fuelbeds characteristic of older forest conditions became more common during the first ~100 years of simulation (coverage increased 5 – 20%), except in those locations where wet forests subject to stand-replacement fire occur (coverage decreased 6 – 12%). In general, mean fuelbed patch size decreased (mean patch size 12 – 18 ha smaller in year 200), and patches of like type became more aggregated (contagion index increased 2 – 4% in year 200) under current and elevated fire and management regimes; absence of management did not cause the same level of change in mean fuelbed patch size. Low fire hazard patches tended to become larger and occupy more of the landscape over time, whereas high fire hazard patches generally became smaller and less common. Management activities had only small effects on mean patch size and landscape class composition; however, simulated management generally produced landscapes with less aggregated patches. The Okanogan-Wenatchee National Forest could be expected to be a sink for carbon, much of it in pools of dead material, for at least ~100 years if the current fire and management regime persists. If, as expected, annual area burned increases, the Forest is likely to become a source of carbon.

Management activities that encourage preservation of large, fire-resistant trees could mitigate projected carbon releases if annual area burned increases.

Fuel consumption predictions are necessary to accurately estimate fire effects, including pollutant emissions during wildland fires. Fuel and environmental measurements on a series of operational prescribed fires were used to develop models for predicting fuel consumption in big sagebrush (*Artemisia tridentata*) and pine flatwoods ecosystems. Models predicted independent consumption measurements within 2% (fall) and 5% (spring) for big sagebrush fires, and 8% (dormant season) and 67% (growing season) for pine flatwoods fires. A general model for predicting fuel consumption in shrub-dominated types is also proposed.

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CHAPTER 1: INTRODUCTION

Recognition of the effects of past policies and actions, and of the beneficial aspects of fire as an ecosystem process, is contributing to changes in land and fire management philosophy and policy. Effective wildland resource planning and management require advances in our ability to map and model fuel succession and fire effects dynamically over a range of spatio-temporal domains. With the ability to dynamically map and model fuel succession, scientists and managers will be able to evaluate and weigh the effects of different management choices and treatments on fuels, carbon fluxes, potential fire hazard, potential fire effects, and potential wildfire behavior.

Land managers have used and will continue to use mechanical methods (harvesting, thinning, mastication, etc.) and prescribed fire as treatments at a variety of spatial scales for a number of specific purposes, including fuel and fire hazard reduction, wildlife habitat improvement, and ecosystem restoration. Adoption of science-based land management policy and methods requires a full evaluation of regulatory requirements and potential impacts using the best available information. Quantification of fuel characteristics (both in space and over time) and fuel consumption is critical for effective predictive modeling of fire hazard (flammability and fire behavior potential), fire behavior (rate of spread, flame length, and fire intensity), and fire effects (fuel consumption, smoke emissions, regional haze, nutrient cycling, plant succession, erosion, and carbon cycling).

The research presented herein is driven by Federal regulations and policy mandates to develop techniques and products necessary to predict fuel and fire hazard and the effects of prescribed fire and other fuel management activities (e.g., Sandberg et al. 1999, Joint Fire Science Program 2000). This dissertation focuses on two elements necessary for effective resource management in fire-influenced wildlands: dynamic mapping and analysis of fuel, fuel succession, fire hazard, and carbon (Chapter 2 and

Chapter 3), and fuel consumption in shrub-dominated ecosystems (Chapter 4). Chapter 2 is a review of landscape fire modeling approaches to provide context for Chapter 3, which presents the results of a modeling experiment to assess the effects of potential future fire and land management scenarios by using a spatially explicit fuelbed succession model developed for the purpose of simulating landscape fuel, fire potential, and carbon patterns. Chapter 4 reports models for predicting fuel consumption in shrub-dominated big sagebrush and pine flatwoods fuel types. Appendices to this dissertation include: suggestions for further landscape fuelbed succession model development, and documentation of the results of fuelbed succession model simulations (Appendix A); documentation of site-level data describing fuel characteristics, conditions, and consumption, and regression diagnostics used to develop the big sagebrush and pine flatwoods fuel consumption models reported in Chapter 4 (Appendix B).

CHAPTER 2: REVIEW OF LANDSCAPE SUCCESSION MODELS

SUMMARY

Models that simulate vegetation change and disturbance over large areas and long timeframes contribute to a better understanding of the manner in which process and pattern interact. This chapter reviews different ways that landscape succession models have been classified and some of the common methods that have been used to simulate vegetation succession and disturbance.

INTRODUCTION

Biogeochemical, ecological, and disturbance processes interact to drive vegetation succession and to determine the composition and pattern of landscape patches in space and over time. Landscape succession models, especially those that can integrate human and natural disturbances, are useful for studying landscape dynamics and related issues that cannot be addressed completely with field studies because of logistical and social limitations on experiments (i.e., size, type, and duration) and the amount of time that may be required before results can be observed (Baker 1989, Peterson 1998, Mladenoff and Baker 1999). Models that simulate landscape change over large spatial and long temporal domains inform science and resource management by providing a more complete understanding of the potential changes to landscape characteristics under a variety of future land use, disturbance, and climatic scenarios.

Most field studies are at the spatial extent of stands or smaller for a few years or less, while many questions and issues of interest to scientists and resource managers must consider large areas (i.e., landscapes 10^4 ha and larger) over long time periods (i.e., decades to centuries). Landscape succession models can be used as a way to broaden inferences to larger and longer scales from smaller and shorter studies and observations (Peterson 1998, Urban et al. 1999).

Landscape succession models have been developed to address a variety of questions and are valuable tools for testing hypotheses and "what if" scenarios (Franklin 1979, He 2008, Perry and Millington 2008). A large number of different models have been developed with variable scope (both spatiotemporal and inferential), assumptions, limitations, and purposes. Models have been used to examine: the effects of environmental conditions on species composition (Botkin et al. 1972, Frelich and Reich 1995, Mladenoff and He 1999); the manner in which different forest management strategies contribute to landscape structure and composition (Franklin and Forman 1987, Gustafson and Crow 1999, Strand et al. 2009); the dynamics of forest age and cover classes under historical disturbance regimes (Keane et al. 1990, He and Mladenoff 1999, Hessburg et al. 1999b, Wimberly 2002, Keane et al. 2006, Wimberly and Kennedy 2008); the interaction between vegetation succession, fuel characteristics, fire regimes, and weather (Baker et al. 1991, Miller and Urban 1999, Perera et al. 2004, Yang et al. 2004); the historical range of variability of landscape patterns (Hessburg et al. 1999b, Keane et al. 2002), and the effects of landscape properties on fire spread (Turner et al. 1989), hazard and risk (Hessburg et al. 2007a, Keane et al. 2010) for example, in addition to other purposes and variations too numerous to list fully. Landscape succession models have also been used to develop and test hypotheses concerning the potential effects of a changing climate on landscape properties (Baker 1995), including vegetation composition and distribution (Lenihan et al. 1998, Bachelet et al. 2001). Cushman et al. (2007) outline methods to leverage the strengths of different landscape models and modeling approaches to generate fine-scale predictions of landscape composition and pattern under potential future climate and disturbance regimes.

OBJECTIVE

The objective of this chapter is to outline and describe the conceptual range and evolution of landscape succession models. Rather than inventory all landscape

succession models, I will briefly describe several model classification schemes and note examples that illustrate some of the approaches model developers have employed.

MODEL CLASSIFICATIONS

A large number of simulation-based landscape succession models have been developed over the last several decades with a common goal of addressing questions regarding how landscapes patterns and processes change over time. The spatial and temporal domains simulated vary depending on the specific questions or phenomena a given model was designed to examine and its theoretical and computational underpinnings, assumptions, and limitations. Several different organizational frameworks have been presented to try to categorize models that have been developed for different purposes and with different approaches. For example, landscape succession models have been classified based on: their methodological approach, especially the distinction between non-spatial and spatially explicit models (Baker 1989); the computational approach (Keane et al. 2004); and the amount of ecological process included in the model design and execution (Scheller and Mladenoff 2007).

METHODOLOGICAL

Landscape succession models have been grouped by whether they require and produce a spatially explicit representation of the landscape (Baker 1989, He 2008). For non-spatial models, landscape composition and structure are considered in total (e.g., the number of different states in a landscape or the proportion of a landscape in different states), whereas spatial models derive the characteristics of the landscape from spatially explicit representations of some landscape characteristic (i.e., maps) in which the value (and change in value), interaction effects, and location of each unit or pixel are tracked (Baker 1989). Baker (1989) divided non-spatial models into two groups: differential equation and difference equation. Differential equation models evaluate landscape composition at various points in time based on birth, change, and death rates

of different landscape states and the starting sizes or proportions of different states in the original landscape. In difference equation models, landscape composition and state changes are based on stochastic or deterministic transition probabilities between states (e.g., Markov chain, semi-Markov). Spatially explicit simulations can be achieved by modeling changes to individual landscape units or pixels using differential equation, stochastic, and deterministic techniques or by modeling ecological processes and the response of individual organisms, for example trees of different species and size, to their environment and spatial neighborhood (Baker 1989, He 2008). Like Baker (1989), He (2008) also distinguished between spatial and non-spatial models, and further divided models with different levels of temporal resolution from fine (hours, days, seasons) to coarse (1 year and greater), which had the effect of loosely classifying models into groups most suitable for tactical, strategic, and theoretical uses. The continued development of faster and more powerful computers, geographic information systems, and remote sensing technologies have facilitated the development of spatial models since Baker's (1989) review.

COMPUTATIONAL

Keane et al. (2004) used cluster analysis and ordination to semi-quantitatively classify 44 landscape succession models into 12 different groups based on the degree of stochasticity, complexity, and mechanism included in each model's computational approach to simulating vegetation succession, fire ignition, fire spread, and fire effects. Four different vegetation succession simulation designs were identified in order of increasing complexity and computational demand: frame (a.k.a., state and transition), ecological process, plant functional type, and individual plant models. The degree of complexity within each vegetation succession design is also variable. In addition to distinctions between vegetation succession approaches, Keane et al.'s (2004) classification takes into account three elements necessary to effectively simulate disturbance events (in this case, fire): fire ignition, fire spread and fire effects. Most

models employ a stochastic process to initiate a disturbance on the model landscape. Fire starts may be located randomly or influenced to varying degrees by biotic, climatic, topographic, and demographic characteristics of the simulation landscape. Fire size and shape may be applied without taking into account spatial information (the so-called "cookie cutter" approach), or fires may spread across the simulation landscape by using raster or vector methods. Raster and vector models simulate spread to adjacent pixels or areas; spread direction and rate may be stochastic or influenced by vegetation (fuel type, amount, and moisture content) and environmental (wind, terrain) characteristics and conditions. Modeled effects of fire at a point on the simulation landscape can be rule-based or mechanistic. While the effect of fire on vegetation composition and structure is of particular importance for simulating succession, smoke emissions, fuel consumption, soil heating and other fire effects may also be of interest. Rule-based methods for specifying transitions among states or changes to vegetation composition or structure following a fire may be used to describe the characteristics of the post-fire vegetation, and to determine the successional trajectory of the landscape unit or pixel. Alternatively, with a mechanistic approach, fire effects derive from simulated fire behavior (i.e., fire intensity, flame length, duration) to model change in vegetation (i.e., mortality) and fuel consumption, for example.

ECOLOGICAL

Whereas Baker (1989), He (2008), and Keane et al. (2004) classified models by virtue of how they were implemented, Scheller and Mladenoff (2007) proposed a classification of eight groups based on how ecological processes are represented, focusing on three criteria: spatial interactions (included or not), community dynamics (static or dynamic), and ecosystem processes (included or not). Spatial interactions among landscape units or pixels, such as those associated with disturbance (i.e., fire), seed dispersal, and competition for light, water, and nutrients are computationally expensive, particularly as landscape grain decreases and extent increases, but are

important drivers of spatial patterning. He (2008) estimated that spatial implementations of process-based model simulations incurred computation loads that were two to five orders of magnitude greater than landscape succession models that simulated vegetation change by aggregating and implicitly modeling succession dynamics. How ecosystem processes (e.g., nutrient cycling, photosynthesis, water balance, competition, decomposition) are implemented in model designs determines whether a model uses static vegetation assemblages or generates them dynamically. Whether vegetation assemblages are modeled as dynamic or static influences the composition of future landscape states. In models with static assemblages, landscape units or pixels exhibit a degree of spatially and temporally dynamic behavior as they can transition from one state to another within an *a priori* succession pathway framework., Individual species neither respond to their environment nor interact spatially in models that represent vegetation statically, and therefore, novel vegetation assemblages cannot develop as is the case with models in which changes to species composition and structure at the individual and cohort level create dynamic assemblages.

MODELING APPROACHES

The preceding section describing model classifications mentioned various methods for specifying vegetation change and integrating disturbance into landscape succession models. In this section I will describe some of the different approaches that have been used for simulating succession and integrating disturbance in spatially explicit landscape succession models.

METHODS FOR SIMULATING SUCCESSION

Methods for simulating vegetation change over time can be divided into two broadly defined philosophical approaches: succession pathways and ecosystem processes (Table 2.1)[1]. Succession pathway models define vegetation states and simulate

[1] Model names associated with citations throughout the text can be found in tables 2.1 and 2.2.

state-to-state transitions without explicitly modeling within-state transitions. Ecosystem process models simulate the equivalent of within-state vegetation dynamics by tracking individual plant or species-specific interactions and responses to ecological and biogeochemical inputs. These categories encompass a range of specific computational and theoretical methods for simulating vegetation succession. Different models based on both approaches use variable levels of detail and complexity and are designed to work at a variety of spatial and temporal scales, although much larger computational requirements typically constrain either the size, resolution, or detail of the area that is modeled with process-driven models (He 2008).

Succession Pathways – In frame or state and transition models vegetation states are defined by age, time since last disturbance, community type, or a combination of dominant cover type and structural stage; transitions are driven by the passage of a defined period of time or the occurrence of a natural or anthropogenic disturbance (Figure 2.1). Succession pathways may be simple (e.g., Figure 2.1) or quite complex where multiple trajectories are specified and chosen using stochastic, probabilistic, or mechanistic criteria to better represent ecological and management-based state changes (Figure 2.2). Transitions between states may be a function of empirically or theoretically defined relationships between states and transition rates (i.e., Markov models; Shugart et al. 1973). Pathway models designed to simulate vegetation dynamics for landscapes where vegetation type is relatively homogeneous, disturbances have simple outcomes (e.g., stand replacing fire or clearcutting), or age structure is the landscape trait of interest often simulate changes only in the age of a landscape unit, and thus the spatial arrangement of different vegetation age classes on the landscape (Baker et al. 1991, Gustafson and Crow 1999, Wimberly et al. 2000). Based on ecological theory or empirical evidence supporting a given approach, probability of a disturbance-caused transition may be constant (Boychuk and Perera 1997) or may change with age (Baker 1992, Ratz 1995, Keane and Long 1998), as has been postulated for sites in which the age class composition of a landscape follows a Weibull distribution (with shape parameter, c

> 1; Johnson and Van Wagner 1985); may incorporate elements of age-dependent and uniform probability of disturbance (Gustafson and Crow 1999, Li et al. 2000); or may be simulated as a conditional probability that is a function of site factors (slope, aspect, elevation), in addition to vegetation type and age (Baker et al. 1991, Baker 1995, Yemshanov and Perera 2002, Perera et al. 2003). As vegetation composition and disturbance dynamics become more complex, so do model pathways. Complex interactions between vegetation age and structure, fire spread, and fire severity were modeled for the Coast Range and for dry forests typical of central Oregon (Wimberly 2002, Wimberly and Kennedy 2008). Succession pathway models can also accommodate multiple disturbance types by increasing the complexity of the succession pathway (e.g., Keane and Long 1998, Kurz et al. 2000, Keane et al. 2002). For example, Hemstrom et al. (2007) used TELSA (Kurz et al. 2000) to evaluate the effects of wildfire, insect activity, grazing, and various management treatments on landscape composition for a 178,000 ha landscape in northeastern Oregon under three different hypothetical scenarios: historical natural disturbance, active fuel treatment, and fire suppression only.

Ecosystem Processes – Ecosystem process models simulate vegetation succession by specifying the effects of physical and ecological variables (e.g., temperature, moisture, competition, regeneration, seed dispersal, nutrient cycling) on vegetation development and composition. Ecosystem process models generally take two forms: biogeochemical (BGC) models and gap models. BGC models simulate the overall flow and allocation of carbon, nutrients, water, and energy via photosynthesis, evapotranspiration, and decomposition at a location (Running and Coughlan 1988, Running and Gower 1991, Peng and Apps 1999). Gap models, beginning with JABOWA (Botkin et al. 1972), simulate vegetation composition, structure, and change for individual trees on a small plot (<0.025 ha) under the assumption that individuals achieve optimal growth when none of the required resources (light, nutrients, water, energy) are limiting, but experience reduced growth or vigor when conditions are suboptimal either because of resource limitations in the modeled plot or competition

with neighbors. BGC models may be used to drive the underlying responses of individual plants and species in gap models (Keane et al. 1996). As computing technology has advanced, gap models have been reformulated to link multiple "plots" to model larger areas, but are generally still limited to small model domains (e.g., 9 ha; Miller and Urban 1999). Gap models have also evolved to include routines to initiate, spread, and simulate the effects of disturbances on vegetation composition (Miller and Urban 1999). These models take into account the characteristics and condition of the vegetation and the physical environment to link vegetation dynamics, climate, and disturbance (Figure 2.3). Gap models require parameterization of species attributes and spatiotemporal databases describing site and climatic conditions for the modeled domain. Because of their substantial data requirements, parameterization data may be insufficient or incomplete, which can introduce considerable uncertainty into model behavior and outputs (McKenzie et al. 1996, McKenzie 1998).

Mladenoff and He (1999) developed LANDIS, a spatially explicit landscape simulation model that is "conceptually related" to gap models (Mladenoff and He 1999, p. 126). LANDIS incorporates the ecosystem processes of seed dispersal and germination, decomposition, disturbance (wind, fire, harvesting), and intra-specific competition through use of species-specific life history attributes (seed dispersal; regeneration; longevity; tolerance to shade, wind, and fire). However, compared to gap models it makes concessions in temporal resolution (10-year time step, although newer versions accommodate a user-specified time step as short as one year) and vegetation detail (presence or absence of species age cohorts). Because its vegetation succession module simulates only the presence or absence of species age cohorts, and does not track birth, growth, death, and biomass of individual trees, LANDIS requires far fewer computations than gap models, allowing it to perform multi-century simulations on large landscapes (10^3 to 10^7 ha, depending on cell size) with reasonable run times. LANDIS has proven to be a very adaptable modeling format and has been modified to add more detailed approaches for simulating tree succession (Schumacher et al. 2004)

and fire processes (Yang et al. 2004). LANDIS has been parameterized for a variety of ecosystems and has been used to explore a number of topics, including: an investigation of the effects of different fire regimes on species mixes on a 500,000 ha landscape in northern Wisconsin (He and Mladenoff 1999); a comparison of modeled and observed species and age distributions under an empirically derived fire regime for a 2,516 ha nature preserve in Finland (Pennanen and Kuuluvainen 2002); a test of the effects of different model assumptions regarding establishment, seed dispersal, and disturbance for oak-pine forests that typify a landscape in which disturbance regime and vegetation pattern are connected in the Georgia Piedmont (Wimberly 2004); and a Monte Carlo analysis of the effects of uncertainty associated with assigning age cohorts to cells in the simulation landscape for a 937,244 ha cool temperate conifer forest in northeastern China (Xu et al. 2004).

Process-based models project vegetation change as the outcomes of biogeochemical processes and interactions among multiple individual trees of different size and species, so composition is an emergent landscape property in contrast to pathway models for which composition is determined by the definition of successional pathways, transitions, and discrete states. Gap models are very computationally expensive so cannot be readily used to model large and complex landscapes directly, but can be used as tools to parameterize coarser-scale landscape succession models (He et al. 1999), or to define more complex states and transitions of pathway models (Acevedo et al. 2001). Using models that operate at very fine spatial scales with high levels of mechanism and detail to inform models that operate at a coarser scale with reduced detail, may contribute to greater simulation realism of larger domains and longer time periods for cases in which environmental drivers (e.g., climate, atmospheric chemistry, nutrient status, hydrology) are expected to change over the term of the simulation (Urban et al. 1999, Cushman et al. 2007).

METHODS FOR INTEGRATING DISTURBANCE

Landscape patterns are a result of spatial variation in environmental and biophysical conditions, as well as acute or chronic disturbances, such as fires, floods, landslides, windthrow events, tree falls, insect or disease outbreaks, timber harvesting, grazing, and species invasions (Pickett and White 1985). Because of its fundamental role in affecting vegetation dynamics and in shaping landscape patterns (especially in North America), I will focus on how fire has been integrated into the simulation framework of spatially explicit landscape succession models. Some of the conceptual approaches are generic and have also been used to simulate other disturbance types.

Simulating fires (and other disturbances) is typically modeled in three steps: initiation, spread, and effects (Table 2.2; Keane et al. 2002, Keane et al. 2004). Stochastic and deterministic strategies have been used for simulating the aforementioned steps. Deterministic strategies yield identical simulations given the same inputs, whereas stochastic strategies introduce an element of randomness (e.g., a random draw from a statistical distribution, or a randomly selected pixel) into model calculations such that unique simulations are produced given the same inputs. Algorithms that randomly determine number of fire starts, fire sizes, probability of spread, direction of spread, and probability of fire type (e.g., low, medium, high severity) subject model outcomes to varying degrees of chance. Fire behavior models based on physical principles, such as Rothermel (1972, 1991) and Van Wagner (1973, 1977) are examples of mechanistic models with deterministic outcomes.[2] The distinction I make (akin to that of He and Mladenoff 1999) is between models that simulate fire as a function of mechanistic physical processes and interactions among fuels, weather, and topography that drive initiation, spread, and effects (deterministic), and models that simulate fire location,

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[2] Spatially explicit models like FARSITE (Finney 1998), FLAMMAP (Finney 2006), and FIREHARM (Keane et al. 2010) simulate fuel moisture dynamics, fire initiation, and fire spread (and fire effects in the case of FIREHARM) but do not simulate changes to vegetation composition or fuel characteristics and have been intentionally omitted from this discussion even though they may be components of landscape succession models (e.g., FIRE-BGC).

frequency, size, and shape using probability distributions and random number generators (stochastic). As with vegetation succession, these categories encompass a range of specific computational and theoretical methods for starting and spreading fires and for enumerating their effects. Most landscape succession models use a combination of stochastic and deterministic methods to simulate individual fires.

Fire Initiation – In most cases landscape succession models randomly place ignitions on the simulation landscape, and specify the number of fire starts by drawing randomly from an empirically-parameterized probability distribution at each model time step. Mechanism can be introduced by relating the effects of weather (wind), topography (slope), vegetation characteristics (fuel type, amount, and arrangement), and vegetation condition (fuel moisture as influenced by vegetation characteristics, weather, and topography) to the probability of ignition at a given location (Keane et al. 2004). SEM-LAND (Li et al. 2000), BFOLDS (Perera et al. 2003) and MC-FIRE (Lenihan et al. 1998) are examples of models that incorporate feedbacks between simulated weather, fuel moisture, and vegetation characteristics to influence fire occurrence at different points on the simulation landscape. Approaches to fire initiation that incorporate mechanistic influences require much greater data input and computation. Typically, spatially-explicit and temporally dynamic algorithms with hourly or daily time steps are necessary to simulate the weather variables that drive fuel condition, which contributes to the probability of ignition and of subsequent cell to cell spread (He and Mladenoff 1999).

Fire Spread – Landscape succession models create fire patches on the simulation landscape in various ways. It is desirable to generate patches with realistic sizes and shapes that represent empirical or theoretical frequency and size distributions (Keane et al. 2002). By virtue of their inclusion in landscape succession models, fires feed back on vegetation succession, sometimes simply by returning a landscape unit or pixel to its original state, but also by diverting succession along alternate successional trajectories (e.g., Figure 2.2). The landscape composition and pattern that result from fires during

each time step influence simulated spread of future fires. Increasingly complex landscape succession models incorporate feedbacks between simulated or input environmental variables (weather, topography) and fire spread dynamics through effects on the physical properties that dictate susceptibility of the landscape unit or pixel and its neighbors to fire initiation and spread.

Because they require computationally efficient algorithms to simulate multiple disturbances over large areas and long time periods, most landscape succession models use stochastic or probabilistic cellular methods (i.e., cellular automata) to "spread" fire to adjacent cells or polygons that are eligible for burning under the weather and fuel conditions in effect during the time step being simulated (e.g., Baker et al. 1991, Ratz 1995, Keane and Long 1998, He and Mladenoff 1999, Hargrove et al. 2000, Kurz et al. 2000, Rupp et al. 2000, Keane et al. 2002, Wimberly 2002, Chew et al. 2004, Schumacher et al. 2006). The flammability or availability of individual landscape units to burn and their quantity and arrangement on the simulation landscape affect the properties of resulting fires (size, shape, severity) and landscape patterns (Turner et al. 1989). For example, Turner et al. (1989) found that whether more or less than 41 percent of an abstract heterogeneous landscape was considered susceptible to disturbance (i.e., above or below the percolation threshold) affected the size and arrangement of patches that developed under different levels of probability of spread (what Turner et al. (1989) refer to as intensity) and frequency. Fire spread based on computation of the physical or mechanistic processes that control fire behavior, as in fire behavior modeling systems for which the objective is to predict single fires with high spatial and temporal fidelity (e.g., FARSITE; Finney 1998), is computationally expensive and is generally not used in landscape succession modeling where simulation of many fires over large areas and long time horizons is demanded (except see Keane et al. 1996).

The size of individual fires may be a random draw from a probability distribution where fires are "spread" until the specified size is achieved or no additional burnable cells or polygons are available (Baker et al. 1991, Keane and Long 1998, He and

Mladenoff 1999, Kurz et al. 2000, Rupp et al. 2000, Keane et al. 2002, Wimberly 2002, Keane et al. 2006), or an emergent property of the landscape given mechanistically-derived parameters that control the probability of a fire igniting adjacent cells (and continuing to spread) or extinguishing (Keane et al. 1996, Li et al. 2000, Perera et al. 2003). Spread from the initially seeded location to neighboring landscape units or pixels is determined using stochastic methods to derive the final size and shape. In an effort to generate realistic fire shapes and to emulate fire spread mechanisms, many models add complexity to algorithms controlling spread direction (and therefore the final fire shape), by specifying spread to be a function of vegetation characteristics (flammability or probability of ignition) and vegetation conditions (fuel moisture) of individual cells (He and Mladenoff 1999). The effects of terrain (slope) and weather (wind) may also influence the likelihood of a fire spreading in a particular direction at a particular rate (e.g., Baker et al. 1991, Keane and Long 1998, He and Mladenoff 1999, Hargrove et al. 2000, Li et al. 2000, Wimberly 2002). Mechanistic approaches to integrating fire in landscape succession models, although rare, often use the fire spread equations proposed by Rothermel (1972) or the Canadian Forest Fire Behavior Prediction System (Forestry Canada 1992) in conjunction with simulated fuel characteristics (derived from a description of the simulated vegetation type and age), fuel condition (derived from the effects of simulated weather and fuel characteristics), underlying topography, and input or modeled wind data (He and Mladenoff 1999).

Fire Effects – Fires create patterns on a simulation landscape; exploration of the linkages between patterns and processes requires the modeling of fire effects in landscape succession models. The manner in which the effects of individual fires are simulated is dictated primarily by the vegetation succession strategy that is applied and the level of detail of both the modeled vegetation and fire severity data. State and transition modeling systems effectively reset or divert successional trajectories. Simpler models track just the time since the last fire and evaluate the age mosaic that is created by multiple fires over the term of the simulation under varying assumptions governing

fire ignition and fire spread (Baker et al. 1991, Ratz 1995, Boychuk et al. 1997); the effect of fire is to re-set the pixel or polygon age to zero. Other kinds of stand replacing disturbances are also simulated this way (e.g., Gustafson and Crow 1999). For succession pathway models that simulate fires of different severity, various methods and model data, including time since last fire, fuel or vegetation type, prevailing weather, fire size, and probability of fire type, determine which state transition a burned landscape unit will follow.

Landscape succession models that use a model of physical processes to quantify the effects of fuel, weather and topography on fire behavior (Keane et al. 1996, Lenihan et al. 1998, Miller and Urban 1999) can use theoretical or empirical models to simulate fire effects, such as tree mortality (Peterson and Ryan 1986, Ryan and Reinhardt 1988) and fuel consumption (Brown et al. 1985), as a function of the modeled fire behavior. A categorical system that correlates fire behavior with mortality and vegetation change is also used (He and Mladenoff 1999).

CONCLUSIONS

Researchers investigating the mechanisms and effects of landscape change have approached questions and issues relating to the dynamics of ecosystem processes and spatial patterns in many different ways as evidenced by the proliferation of different landscape succession models (Tables 2.1 and 2.2). The specific approach and the level of detail and complexity encoded in each model are a function of the ambition of model objectives, state of knowledge about a required ecological process, and technical limitations (both data and computational). Great strides have been made in the development of higher resolution remote sensing and field measurement technologies; bigger, faster, and more powerful computer hardware; more sophisticated understanding of a variety of physical and ecological processes; and more efficient and elegant software. While these advancements are notable, knowledge gaps and technical

obstacles to parameterizing models, characterizing landscapes, and computing complex functions still limit landscape succession modeling.

Despite their shortcomings, landscape succession models contribute to our understanding of the manner in which pattern and process interact at larger and longer scales than we are capable of addressing with controlled, field-based experiments (Baker 1992). Using landscape succession models to understand the effects of different potential land use, treatment, disturbance, and climate change scenarios on landscape properties provides resource managers and policy makers with a scientific foundation upon which to base resource management decisions. Continued development and creative integration (e.g., Cushman et al. 2007) of existing landscape succession models will be necessary as the scale, scope, and complexity of management and policy issues evolve.

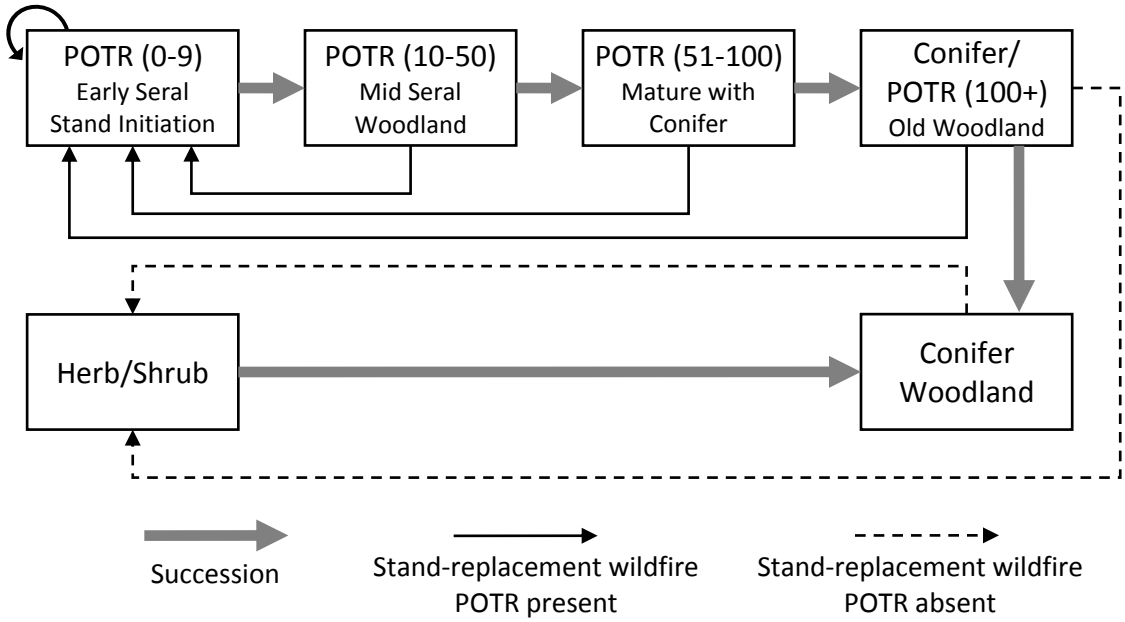

Figure 2.1. *Example simple state and transition model pathway for quaking aspen (*Populus tremuloides – POTR*) sites in Idaho. The range of time between state transitions is indicated in parentheses for each state. Fires are specified probabilistically. Redrawn from Strand et al. (2009).*

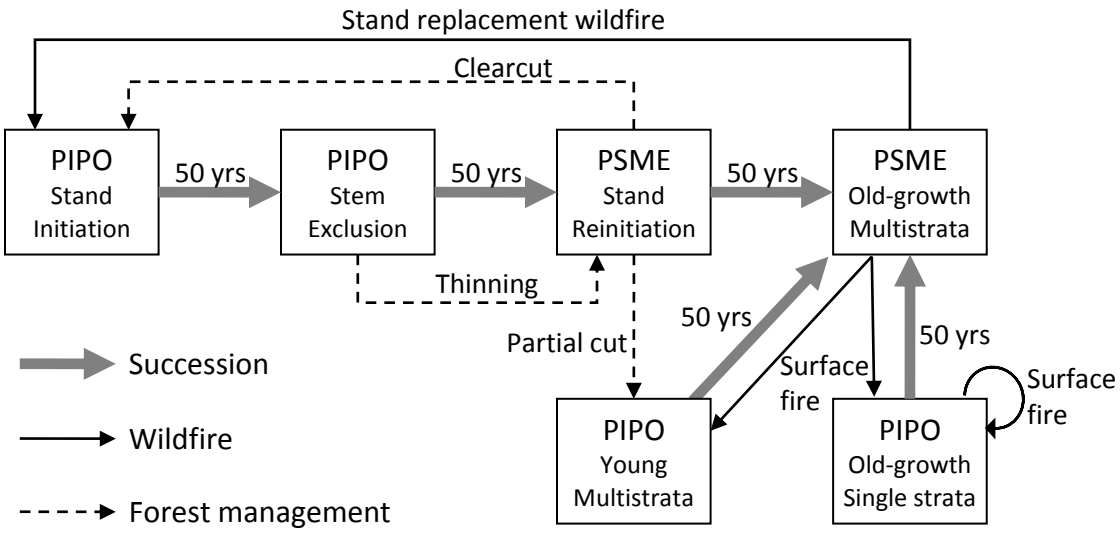

Figure 2.2. *Example state and transition model pathway for theoretical Douglas-fir (*Pseudotsuga menziesii – PSME*) potential vegetation type in the Interior Columbia River Basin with multiple natural and human disturbance types.* PIPO = *Ponderosa pine* (Pinus ponderosa). *Redrawn from Keane and Long (1998).*

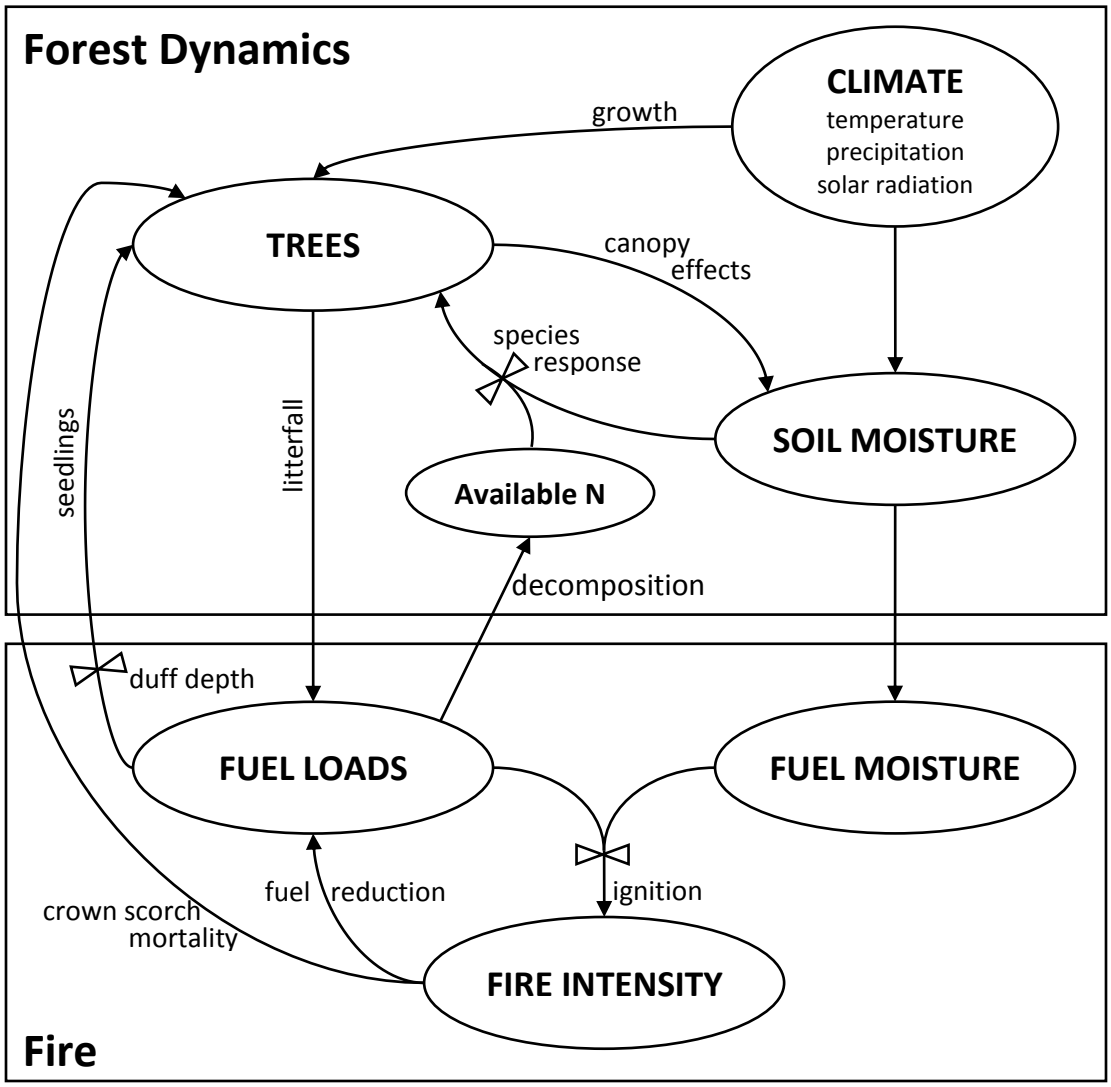

Figure 2.3. *Example of the physical and ecological interactions driving landscape composition of a gap model (ZELIG). Redrawn from Miller and Urban (1999).*

Table 2.1. *Examples of spatial landscape succession models with succession approach categories after Keane et al. (2004).*

Approach	Description	Model	Citation[1]
I. Succession Pathway	Landscape units (polygons or pixels) change states (age, structure/cover class) according to the transition rules specified by a pathway structure.	ALFRESCO	Rupp et al. (2000)
		BFOLDS	Perera et al. (2003)
		CRBSUM	Keane and Long (1998)
		CRBSUM2	Keane and Long (1998)
	Transitions are deterministic.	DISPATCH	Baker et al. (1991)
	Disturbances divert successional trajectories.	FIREPAT	Keane and Long (1998)
		FLAP-X	Boychuk et al. (1997)
		HARVEST	Gustafson and Crow (1999)
		LADS	Wimberly (2002)
		LANDSUM	Keane et al. (2002)
		RATZ	Ratz (1995)
		SEM-LAND	Li et al. (2000)
		SIMPPLLE	Chew et al. (2004)
		TELSA	Kurz et al. (2000)
II. Ecosystem Process	Biogeochemical processes or individual species requirements control vegetation composition and successional development.	FIRE-BGC	Keane et al. (1996)
		LANDIS	He and Mladenoff (1999)
		LANDCLIM	Schumacher et al. (2006)
		MC-FIRE	Lenihan et al. (1998)
	Disturbances change status of individuals or species-age cohorts.	ZELIG	Miller and Urban (1999)

[1]Main citation for the indicated model given the context of this review. Several models are documented in multiple citations that do not appear in this table.

Table 2.2. *Examples of spatial landscape succession models with algorithms for including fire in landscape dynamics after Keane et al. (2004). Whether the model uses stochastic, deterministic, or a mixture of stochastic and deterministic methods for fire initiation, fire spread and fire effects is indicated.*

Model	Citation[1]	Fire Initiation	Fire Spread	Fire Effects
ALFRESCO	Rupp et al. (2000)	Stochastic	Mixed	Deterministic
BFOLDS	Perera et al. (2003)	Mixed	Mixed	Deterministic
CRBSUM	Keane and Long (1998)	Stochastic	NA	Deterministic
CRBSUM2	Keane and Long (1998)	Stochastic	Stochastic	Mixed
DISPATCH	Baker et al. (1991)	Stochastic	Stochastic	Deterministic
EMBYR	Hargrove et al. (2000)	Stochastic	Stochastic	Deterministic
FIRE-BGC	Keane et al. (1996)	Stochastic	Deterministic	Deterministic
FIREPAT	Keane and Long (1998)	Stochastic	Stochastic	Mixed
FLAP-X	Boychuk et al. (1997)	Stochastic	Stochastic	Deterministic
LADS	Wimberly (2002)	Stochastic	Mixed	Mixed
LANDCLIM	Schumacher et al. (2006)	Stochastic	Mixed	Deterministic
LANDIS	He and Mladenoff (1999)	Stochastic	Mixed	Deterministic
LANDSUM	Keane et al. (2002)	Stochastic	Stochastic	Mixed
MC-FIRE	Lenihan et al. (1998)	Mixed	Unknown	Deterministic
RATZ	Ratz (1995)	Stochastic	Deterministic	Deterministic
SEM-LAND	Li et al. (2000)	Stochastic	Mixed	Deterministic
SIMPPLLE	Chew et al. (2004)	Stochastic	Stochastic	Deterministic
TELSA	Kurz et al. (2000)	Stochastic	Stochastic	Deterministic
ZELIG	Miller and Urban (1999)	Mixed	NA	Deterministic

[1]Main citation for the indicated model given the context of this review. Several models are documented in multiple citations that do not appear in this table.

CHAPTER 3: EFFECTS OF DISTURBANCE AND FUELBED SUCCESSION ON SPATIAL PATTERNS OF FUEL, FIRE HAZARD, AND CARBON

SUMMARY

Effective land management planning requires a better understanding of the manner in which landscape patterns of fuel, fire potential, and carbon stocks change with time and disturbance (both human-caused and natural) under different management and fire regimes. Past efforts to map fuels have converted vegetation descriptions to fire behavior or fire danger rating system fuel models (i.e., simplified, stylized representations of surface fuels designed for fire behavior and fire danger rating modeling). A state and transition approach was used to model and map fuelbed (i.e., collections of data that describe all aboveground fuels), fire hazard, and carbon dynamics directly under different management and fire regimes for the Okanogan-Wenatchee National Forest in north-central Washington and evaluate the landscape patterns that evolved. Landscape metrics describing spatial patterns of fuelbeds, fire potential, and carbon stock showed different patterns of change over time depending upon the metric considered and the fire and management regime modeled. Fuelbeds characteristic of older forest conditions became more common across the study area during the first ~100 years of simulation (coverage increased 5 – 20%), except in those locations where wet forests subject to stand-replacement fire occur (coverage decreased 6 – 12%). In general, mean fuelbed patch size decreased (mean patch size 12 – 18 ha smaller in year 200), and patches of like type became more aggregated (contagion index increased 2 – 4% in year 200) under current and elevated fire and management regimes; absence of management did not cause the same level of change in mean fuelbed patch size. Low fire hazard patches tended to become larger and occupy more of the landscape over time, whereas high fire hazard patches generally became smaller and less common. Mean patch size of low flame length, low rate of spread, and low crown fire potential patches increased 29 – 405 ha in year 200 (landscape coverage increased 2 –

17%), and decreased 4 – 587 ha in year 200 for high flame length, high reaction intensity, and high crown fire potential patches (landscape coverage decreased 0 – 12%). Management activities had only small effects on mean patch size and landscape class composition; however, simulated management generally produced landscapes with less aggregated patches. The Okanogan-Wenatchee National Forest could be expected to be a sink for carbon, much of it in pools of dead material, for at least ~100 years if the current fire and management regime persists. If annual area burned increases, as expected, the Forest is likely to become a source of carbon. Carbon stored in live trees is essentially removed as a source of emissions from decomposition and future combustion, so management activities that encourage preservation of large, fire-resistant trees could mitigate projected carbon releases from the landscape if annual area burned increases.

INTRODUCTION

Location, landform, soils, climate, and disturbances, both natural and human-caused, shape vegetation, and thus fuel type and structure (Daubenmire 1962, Franklin and Dyrness 1987) resulting in dynamic patterns at a variety of spatial scales (Forman and Godron 1986, Turner et al. 2001). Simulation and quantitative evaluation of landscape spatial patterns allows for study of potential connections between ecosystem pattern and process (Franklin and Forman 1987, Turner 1989, Keane et al. 1999, McGarigal et al. 2009) and changes in pattern through time (Romme 1979, Romme and Knight 1982, Baker 1992, Keane et al. 2001a, Miller 2007).

The concept of a landscape is spatially relative (Turner 1989, Allen 1998, Lertzman and Fall 1998, Turner et al. 2001); in the context of forest and fire management a landscape is typically considered to be large enough to capture heterogeneity in spatial patterns, and therefore is larger than the typical fire or stand (10^1-10^3 hectares), but smaller than the region (10^6 - 10^7 hectares). A variety of metrics have been developed

and calculated to characterize different aspects of landscape pattern (McGarigal and Marks 1995, Gustafson 1998, McGarigal et al. 2009), often in response to natural or human disturbances such as timber harvesting (Franklin and Forman 1987) and wildland fire (Romme 1982, Romme and Knight 1982, Hessburg et al. 1999b, Hessburg et al. 1999a, Keane et al. 1999, Collins and Stephens 2010).

Vegetation, fuel, and landscape properties are affected by resource management activities, such as thinning, harvesting, and prescribed burning, and by natural disturbances, such as wildfire (Toumey and Korstian 1958, Pickett and White 1985, Oliver and Larson 1996, Brown and Smith 2000, Turner et al. 2001). The type, severity, and time since disturbance, whether natural or human-caused, affect vegetation and fuel characteristics (Oliver 1981, Agee and Huff 1987, Turner et al. 1999). The size, frequency, and nature of disturbances affect landscape composition and pattern and related ecosystem processes over a wide range of spatial and temporal scales (Pickett and White 1985, Lertzman and Fall 1998). Within the context of disturbance effects on vegetation, fuels, and landscapes, policy makers and land management practitioners are asked to conceive, plan, and implement resource management actions to accomplish specific outcomes (Rykiel 1998), such as preservation of species, maintenance of ecosystem patterns and processes, and protection of air quality and human health (Peterson and Parker 1998). In so doing, they must evaluate the potential cumulative effects of increasingly complex decisions over large areas (i.e., 10^4 - 10^6 hectares) and long time scales (i.e., decades to millennia) to achieve desired future conditions that meet various legal obligations and management missions (Gustafson and Crow 1999).

Effective natural resource policy and planning require that those responsible anticipate landscape changes over time (e.g., Dunn et al. 1999), particularly with respect to fuels, for regions in which fire is a common disturbance agent. Change to the characteristics, conditions, and spatial patterns of vegetation and fuels associated with management, disturbance, and succession affect fire hazard (Fahnestock and Dieterich 1962, Agee and Huff 1987, Stephens 1998, Youngblood et al. 2007), carbon dynamics

(Smithwick et al. 2002, Smithwick et al. 2005, Harmon et al. 2009, Hurteau and North 2009), and other ecosystem properties. Landscape succession modeling can be used to evaluate the effects of management and disturbance on spatial patterns and ecosystem processes (e.g., He and Mladenoff 1999, Keane et al. 1999, Li et al. 2000, Wimberly 2002, Perera et al. 2004, Wimberly 2007, Wimberly and Kennedy 2008). Technological advances, especially increased computing power and more widely available spatial data, are creating opportunities to model ecological systems and disturbance regimes, and to evaluate landscapes over larger spatial and longer temporal scales (Baker 1999, Keane et al. 2004, Scheller and Mladenoff 2007, He 2008).

Fuel Succession

Generally, fuel succession research has sought to quantify temporal patterns of change to the surface fuel strata (i.e., leaf and needle litter, and dead and down woody material) following a natural or human-caused disturbance (Childs 1939, Fahnestock and Dieterich 1962, Fahnestock 1968, Abbott and Crossley 1982, Carlton and Pickford 1982, Agee and Huff 1987, Spies et al. 1988, Schimmel and Granström 1997, Brown et al. 1998, Fraver et al. 2002), although changes to other fuel strata (i.e., standing live and dead trees, shrubs, herbs, mosses) have also been studied (Agee and Huff 1987, Schimmel and Granström 1997). All aboveground biomass, however, represents fuel that is potentially available for combustion, either presently or in a future state, so a broader definition of what constitutes fuel and fuel succession is necessary.

Typical landscape succession models focus on quantifying how vegetation characteristics change or succeed over time; assumptions may be used to crosswalk a particular vegetation state or states to some corresponding fuel state. Davis et al. (2009), for example, proposed a simple state and transition-type approach for modeling fuel succession at national parks in the Sierra Nevada in California wherein data and expert opinion were used to classify the vegetation into 18 generic fuel states (i.e., standard fire behavior fuel models). In Davis et al.'s (2009) Sierra Nevada Fuel Succession Model,

successional pathways determine region-specific, time- and disturbance-caused transitions between different fire behavior fuel models, although changes to different elements that make up a fuel complex are not modeled explicitly.

Fuel Mapping

Fuels are dynamic and constantly changing as vegetation grows, decays, accumulates, is disturbed, and changes condition. Maps of fuels, however, capture characteristics and conditions at only one instant in time. Keane et al. (2010) partially address the static nature of spatial fuels data by generating temporally dynamic fuel conditions over the course of a fire season with the model FIREHARM. In their approach to modeling fire behavior and effects, however, only fuel condition (i.e., fuel moisture) varies; fuel characteristics (i.e., type, amount, and arrangement) are static. Spatially explicit methods for projecting changes to fuel characteristics, and landscape composition and pattern through time for large landscapes, are necessary to evaluate the potential effects of future disturbances and management on ecosystem properties, including landscape patterns, fire hazard, carbon dynamics, and potential prescribed and wildfire effects. Development of methods to dynamically map fuels is an important research priority that can also contribute to analysis and modeling of disturbance and carbon dynamics in a changing climate (McKenzie et al. 2007).

Characterizing Fuels

Fuel Models – Until recently, fuel mapping has been concerned primarily with Northern Forest Fire Laboratory (NFFL) fire behavior or National Fire Danger Rating System (NFDRS) fuel models (Burgan et al. 1998, Keane and Long 1998, Keane et al. 2001a), which are used as inputs for predicting surface fire spread with the Fire Area Simulator (i.e., FARSITE; Rothermel 1972, Finney 1998) and other fire spread models (e.g., HFire; Morais 2001, Peterson et al. 2009). There are 13 original NFFL fire behavior fuel models (Albini 1976, Anderson 1982), 40 new standard fire behavior fuel models

(Scott and Burgan 2005), and 20 NFDRS fuel models (Deeming et al. 1977) in widespread use in the United States, all of which will be referred to generically as *fuel models*. Some significant shortcomings of using fuel models to characterize complex fuelbeds are:

1) Fuel models are general representations of fuels based on expected fire behavior and do not necessarily correspond to actual measured fuel characteristics.
2) Fuel models require developers to adjust characteristics (i.e., fuelbed depth, characteristic surface area-to-volume ratio, moisture of extinction, fuel loading, etc.) in a circular fashion such that modeled fire behavior meets expectations under different weather and fuel moisture conditions (Sandberg et al. 2007).
3) Models for predicting fire effects, such as CONSUME (Prichard et al. no date), FOFEM (Keane et al. no date), BURNUP (Albini and Reinhardt 1997), and others require fuels data, particularly fuel loading, "as measured" and not adjusted to yield expected fire behavior.[3]
4) Estimates of carbon pools and fluxes in response to fuel treatments and wildland fire require fuels data as measured.
5) Subtle and even moderate (and sometimes large) differences in fuel characteristics are generally not captured by the limited number of fuel models (Sandberg et al. 2007).[4]

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[3] Lutes et al. (2009) proposed a framework for evaluating fire effects with what amount to "fire effects fuel models" (i.e., Fuel Loading Models). FIREHARM (Keane et al. 2010) evaluates fire effects by using Fuel Loading Models in a spatial domain, although this approach still lacks the detail necessary to fully characterize the entire fuelbed. The fire effects fuel model approach does not distinguish among different fuelbeds that might produce similar fire effects. For example, fuel types with high woody fuel loading might be considered the same as those with a deep forest floor or organic soil horizon because they exhibit similar soil heating and smoke emissions when burned under dry conditions, when in fact their fuel characteristics are quite different.

[4] For example, fuel loading in pine-dominated ecosystems in the southeast United States can vary by an order of magnitude depending on site and age (Ottmar and Vihnanek 2000, Ottmar et al. 2003), but is represented by a single fire behavior or fire danger rating fuel model (i.e., NFFL 7 or NFDRS D), although it should be noted that Hough and Albini (1978) developed a "dynamic fuel model" to accommodate the variability in fuel characteristics in palmetto-gallberry fuel types.

Fuel Characteristic Classification System (FCCS) – This study used a different approach for quantifying fuels. The Fuel Characteristic Classification System (FCCS; Sandberg et al. 2001, Ottmar et al. 2007a) is a method for describing fuels that addresses some of the aforementioned shortcomings of fuel models. In the FCCS, data characterizing fuelbeds[5] are organized into six strata: canopy, shrubs, herbs and grasses, dead and down woody debris, litter, which also includes lichens and mosses, and duff or ground fuels. Numerous quantities (e.g., coverage, density, height, size, species composition, biomass, etc.) describe modal properties for variables in each stratum for each fuelbed as appropriate (Riccardi et al. 2007). Thus, each *fuelbed* includes a full accounting of all of the combustible material (aboveground only at this point), in contrast to fire behavior, fire danger, and fire effects *fuel models* which only characterize a fraction of the fuel present, and which may or may not equate with actual measured conditions on the ground. A modified version of the Rothermel (1972) surface fire behavior algorithm (Sandberg et al. 2007) and a conceptual model for assessing crown fire potential (Schaaf et al. 2007) capitalize on the more complete description of fuels embodied in the FCCS fuelbed to calculate potential surface and crown fire behavior from measured fuel characteristics. Allometric methods are used to estimate biomass and carbon content for each fuelbed component and stratum.

The marriage of FCCS fuelbeds with surface and crown fire behavior models preserves more of the specificity, detail, and infinite variability in fuels and predicted fire behavior that is otherwise lost when collapsing detailed vegetation and fuels data for use in fuel model-based fire behavior prediction systems. FCCS fuelbeds can describe fuels on a continuous scale, allowing the user to resolve and detect differences in fuel characteristics and fire potentials among fuel types not possible with fuel models.

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[5] FCCS fuelbeds are scale-independent, but are intended to describe "…a relatively uniform unit on the landscape that represents a distinctive fire environment (Sandberg et al. 2001, Sandberg et al. 2007)." (Riccardi et al. 2007, p. 2395).

OBJECTIVES AND QUESTIONS

The objective of this research was to examine how disturbance and succession might affect landscape patterns by using a landscape modeling framework (Figure 3.1) capable of exploiting existing data to project landscape fuel, fire potential, and carbon stocks using relatively fine-grain spatial data (4 ha) over a very large area (>10^6 ha) and long time period (200 years). Landscape metrics and carbon stocks were compared across different fire and management regime levels to better understand how disturbances, both natural and human-caused, might affect future spatial patterns of fuels, fire hazard, and carbon dynamics. The objective was to examine general patterns, not to assess the effectiveness of specific fuel treatments in modifying fire occurrence, fire spread, or fire severity. For the purposes of the dissertation I confined my inquiries to the following questions:

Over time, how do different patterns of wildfire and management affect:

1) landscape patterns of fuels?
2) landscape fire hazard?
3) carbon pools and dynamics?

METHODS

OVERVIEW

I conducted a modeling experiment to explore how different levels of simulated fire occurrence and management activity might affect landscape patterns of fuel, and thus potential fire hazard and carbon stock on the Okanogan-Wenatchee National Forest (OKA-WEN) in north-central Washington. The simulations incorporated an existing map (Figure 3.2; Raymond et al. 2006, McKenzie et al. 2007) and library of FCCS fuelbeds linked by successional pathways (Table 3.1; R.D. Ottmar, unpublished data) in a spatially explicitly landscape succession model. The landscape succession model simulated fuelbed change and generated raster maps of FCCS fuelbeds under user-

specified fire and management regimes. Maps of future fuelbed patterns under two fire occurrence levels and three management levels were produced. Associated with each fuelbed (and thus each map pixel) are attributes describing the fuel characteristics, fire potential, and carbon stock, allowing maps of FCCS fuelbeds to represent selected fuelbed attributes (surface fire behavior, crown fire behavior, carbon stock). Landscape metrics (mean patch size, percentage of landscape in a class, contagion index, clumpiness index) and carbon stock were calculated from FCCS fuelbed and reclassified maps. Differences in landscape metrics and carbon stock associated with fire and management levels specified in the model simulations were compared statistically.

STUDY AREA

The simulation landscape was defined by the boundaries of the Okanogan-Wenatchee National Forest (OKA-WEN). The OKA-WEN occupies a fairly contiguous approximately 40-80 km wide (E/W) by 300 km long (N/S) area along the eastern flank of the Cascade Range south of the Canadian border in central Washington (Figure 3.2). The OKA-WEN abuts other federal lands to the west (Mt. Baker-Snoqualmie National Forest, North Cascades National Park, and Lake Chelan National Recreation Area) and south (Gifford Pinchot National Forest, Mt. Rainier National Park, and Yakama Nation). The study area extent was 1.62 million ha, and included all lands that are administered by the OKA-WEN even if officially part of an adjoining national forest with the exception of a portion of the Tonasket Ranger District. The eastern portion of the Tonasket Ranger District in the Okanogan Highlands was not included owing to its fragmented ownership pattern and lack of connectivity with the main block of the OKA-WEN. A large portion of the OKA-WEN is federally designated as wilderness (some or all of the Pasayten, Glacier Peak, Lake Chelan-Sawtooth, Henry M. Jackson, Alpine Lakes, Norse Peak, William O. Douglas, and Goat Rocks Wilderness Areas) where mechanized equipment is banned and other management-related restrictions apply.

Because of its location on the eastern side of the north/south-trending Cascade Range, west-to-east gradients of decreasing precipitation (>250 to ~20 cm annually) and winter-time temperature (-13 to -7 °C mean January minimum), and increasing summer-time temperature (22.5 to 31 °C mean July maximum) are typical (Franklin and Dyrness 1987). In general, the OKA-WEN is a mountainous environment where elevation declines as one moves east from the Cascade Crest (ranges from 2900 to ~350 m). The combination of elevation and topography associated with mountain environments largely dictates ecosystem, and thus in a general sense, fuelbed type at specific locations on the landscape. Forests are characterized by a number of predominantly coniferous species (Franklin and Dyrness 1987, Lillybridge et al. 1995). Upper elevation forests are composed of mountain hemlock (*Tsuga mertensiana*), Pacific silver fir (*Abies amabilis*), subalpine fir (*A. lasiocarpa*), subalpine larch (*Larix lyallii*), and whitebark pine (*Pinus albicaulis*). Montane forests include mixtures of Douglas-fir (*Pseudotsuga menziesii*), grand fir (*A. grandis*), ponderosa pine (*Pinus ponderosa*), western larch (*L. occidentalis*), lodgepole pine (*P. contorta*), and Engelmann spruce (*Picea engelmannii*) depending upon environmental conditions. At lower elevations, ponderosa pine and Douglas-fir forests grade into grasslands and big sagebrush (*Artemisia tridentata*) and antelope bitterbrush (*Purshia tridentata*) steppe communities. Alpine communities occur above timberline in locations where mountains reach a sufficient elevation.

Fire regimes are associated with ecosystem and fuelbed types and likewise tend to reflect differences in temperature and precipitation. In a general sense, relatively infrequent, but severe fires occur in cooler and wetter landscape positions, and grade to relatively frequent and low severity fires in warmer and drier landscape positions with intermediate locations experiencing various mixes of low and high severity and frequency (Agee 1994, Hessl et al. 2004, Wright and Agee 2004).

MODELING FRAMEWORK

The modeling framework assembled for this study included a fuelbed succession model, a library of FCCS fuelbeds, fuelbed successional pathways (i.e., state and transition models), and a map of FCCS fuelbeds, each of which will be described in greater detail in the following sections.

Fuelbed Succession Model – The fuelbed succession model was developed in the R programming environment (R Development Core Team 2010) and uses a state and transition approach (i.e., Kurz et al. 2000, Wimberly 2002, Chew et al. 2004, Keane et al. 2006). Instead of fixed polygons and transition probabilities, however, individual pixels "succeed" deterministically among states either as a result of age or stochastically determined fire- or management-related transitions specified by data- and expert opinion-derived successional pathways (Figures 3.3 and A.1) that were developed and validated by local fire and fuel management personnel familiar with the fire and vegetation ecology of the study area. The model operates on an annual time step, and identifies "stands" (contiguous patches of pixels of the same fuelbed type using an 8-neighbor rule) at each year throughout the course of the simulation period. These stands, and the pixels of which they are composed, depending upon their stage of succession in the simulation, are maintained in their current state, transition to the next successional state, burn in a wildfire and transition to the appropriate post-fire state, or are designated for a management action and transition to the appropriate post-management state. Where more than one age-based transition is possible, the successor fuelbed is chosen randomly from among the candidate fuelbeds in the current version of the model. Stands can be burned or receive a management action either wholly or in part. Fires or management events can cross stand boundaries if adjacent fuelbed types are also eligible for burning or for the specified management activity. Thus, stand boundaries are dynamic, as they are redefined based on the occurrence and placement of each fire and management event.

The amount of fire that occurs at each model time step is stochastically generated from probability distributions derived from the fire history record of the landscape for which fuelbed succession is being simulated. The number of fires simulated per year, and the area per fire are based on random draws from Poisson and log-normal distributions, respectively (sensu He and Mladenoff 1999, Wimberly 2002), parameterized such that the process yields individual fire areas and natural fire rotations reflective of the fire history record from which they were derived. The model first determines the number of fires per time step by drawing randomly from a Poisson distribution whose mean (λ) is defined by fire frequency (FF):

$$\mathrm{FF} = \mathrm{A}/(\mathrm{MFS} \times \mathrm{NFR})$$

where A is the total landscape area, MFS is the mean fire size, and NFR is the natural fire rotation (Wimberly 2002). The NFR is the number of years required to burn an area equal in size to the study landscape as determined from maps of historical fire occurrence (Heinselman 1973). In a second step, a list of fire sizes of the length specified by the previous step is generated for each year by drawing randomly from a log-normal distribution for which the parameters that define the shape of the log-normal curve (μ and σ) are calculated as:

$$\mu = 2ln(\mathrm{MFS}) - \tfrac{1}{2}ln(\mathrm{SDFS}^2 + \mathrm{MFS}^2)$$

$$\sigma = \sqrt{ln(\mathrm{SDFS}^2 + \mathrm{MFS}^2) - 2ln(\mathrm{MFS})}$$

where MFS is the mean fire size, as above, and SDFS is the standard deviation of fire size of historical fires (Yang et al. 2004). Number of fires and fire sizes are truncated such that individual fire sizes cannot exceed a user-specified maximum and annual area burned cannot exceed 75 percent of the size of the burnable area on the landscape. The probability that fire size will be truncated increases as mean and maximum fire sizes approach the size of the study landscape. Given a very large study landscape (i.e., ~1.6 million ha for this simulation experiment) and modest mean fire frequency and size (i.e., 4.3 to 6.1 fires yr^{-1} and 2,520 to 3,567 ha $year^{-1}$ for this simulation experiment) it is unlikely that the area specified to burn in a given year will exceed 75 percent. It is

possible, however, that randomly drawn individual fire events will exceed the user-specified maximum fire size and be truncated depending upon the criteria used to set the maximum fire size.

Eligibility for wildfire depends on stand age and the time since the most recent non-stand-replacement wildfire or management activity involving fire (i.e., pre-commercial thin, selection cut, or clearcut followed by prescribed fire). Areas burned by prescribed fires or wildfires are ineligible to burn again for a user-specified number of years under the assumption that fine fuels removed by the previous fire require a specified period of time before they are of sufficient amount and continuity to again allow fire spread. Fuelbeds within federal wilderness boundaries are eligible to burn during a wildfire if sufficient time has passed since they previously burned in a wildfire.

For individual wildfires, sampling is performed to select a fuelbed in which a wildfire will start from among all eligible fuelbeds. The specific initiation point is then selected by sampling from among all eligible pixels in the selected fuelbed. The initial fuelbed selection is weighted by a probability that reflects the area occupied by a given fuelbed and the spread contrast, a measure of the relative ease with which wildfire is expected to spread in a given fuelbed derived by relativizing by the maximum (McCune and Grace 2002) potential rate of spread from among all fuelbeds in the successional pathways as predicted by the FCCS surface fire spread algorithm of Sandberg et al., (2007) under benchmark environmental conditions.[6] Fires are more likely to be initiated in fuelbeds with higher predicted rates of spread that are more abundant using this method.

Wildfire shapes are derived by using cellular automata methods to model fires as contagious events that spread stochastically to adjacent cells (potential spread is to an 8-cell neighborhood). Random draws from a binomial distribution weighted by the

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[6] Benchmark environmental conditions used to estimate potential fire behavior: slope = 0%, windspeed = 1.8 m sec^{-1}. Benchmark fuel moisture conditions are the D2L2 scenario of Scott and Burgan (2005): 1-hr = 6%, 10-hr = 7%, 100-hr = 8%, 1000-hr = 12%, grass/forbs = 60%, shrubs = 90%, tree crowns = 90%, duff = 50%.

aforementioned area-weighted spread contrasts are used to determine into which neighboring pixels a fire will spread. Area-weighted spread contrasts cause fires to expand more readily in the direction of more common fuelbeds that are expected to burn with greater rates of spread. Wildfires spread until they achieve a pre-defined size or they exhaust the supply of adjacent and contiguous cells that are eligible to burn. In a case where a simulated wildfire cannot be completely mapped because the eligible contiguous area is exhausted before the specified fire size is reached, additional initiation points are selected in the manner specified above, and fire is spread until the sum of the area of all patches related to a given wildfire event reaches the specified size, or the eligible area in the landscape is exhausted. The effects of fire weather (i.e., windspeed and direction) and topography (i.e., slope) on fire spread are not modeled.

The annual area subject to management activity and the number and size distribution of individual events are user-specified (a list of management events by type and their respective sizes is specified for each year of the simulation). Any management activity can be specified in the fuelbed succession model as long as the appropriate states and transitions (i.e., fuelbeds and their successors) are defined in the successional pathways. In this experiment, various forms and combinations of thinning, harvesting, and prescribed burning were simulated.

Fuelbed age and fuelbed pathway type affect which locations are eligible for each management event. Fuelbeds in wilderness areas are restricted to "natural" succession pathways (i.e., transitions because of fuelbed age or wildfire) in model simulations, thus only locations outside of wilderness areas are eligible to receive a management event. Sampling is performed to select a specific initiation point from among all pixels eligible for the prescribed management event. Management events are spread to adjacent eligible cells until they achieve a pre-defined size or they exhaust the supply of adjacent and contiguous cells that are eligible for the prescribed management action. As with wildfires, in cases where a management event cannot be completely mapped because the eligible contiguous area is exhausted before the prescribed event size is reached,

additional initiation points are selected and the management activity is spread until the sum of the area of all patches related to a given event reaches the specified size, or the eligible area in the landscape is exhausted.

OKA-WEN Fuelbed Succession Simulation Parameters – The effects of contemporary and elevated (double the contemporary area) levels of fire occurrence and management activities were simulated. Doubling the area subjected to wildfire and management actions was intended to test the effect of elevated wildfire and management levels on landscape patterns of fuels, fire potential, and carbon stock. The number and size of fires per time step were based on the historical fire record for the 30-year period from 1977-2006 (Table 3.2). Area burned was effectively doubled by adjusting the fire frequency and mean fire size such that the contemporary fire rotation was halved for the elevated fire level. The maximum fire size was limited to 200,000 ha, which is approximately the size of the largest fire to occur in the Pacific Northwest region in recent decades (i.e., the Biscuit Fire in southern Oregon in 2002). In comparison, the largest fire in the study area during the 30-year historical period was approximately 71,000 ha (the Tripod fire in north-central Washington in 2006). Although fire suppression is not modeled explicitly, its effects are implicit in the fire history data used to parameterize the modeling procedures that generate the number of fires and the area burned in simulations. The number and area specified for each management event were based on forest records (average number and area per management type from 2004-2008) for each management type for the contemporary management level (Table 3.2); the number and event areas were adjusted to achieve a halving of the contemporary management rotation for the elevated management level.

FCCS Fuelbeds and Successional Pathways – This project used a library of 262 fuelbeds developed jointly by the OKA-WEN and the USFS Pacific Northwest Research Station. Fuelbeds were created from field data, fuels photo series, plant association descriptions, and expert knowledge and validated by local fire and fuel management personnel (Tables 3.1 and A.2). The OKA-WEN fuelbeds are temporally linked in

successional pathways such that fuel characteristics change logically through time with "natural" succession (i.e., time or wildfire) or prescribed management activities based on principles of silviculture, forest stand development, and community ecology (Figures 3.3 and A.1). For example, shrubs and herbaceous vegetation tend to dominate following stand-replacement, but decline in quantity as the forest canopy closes and the understory light environment changes (Daubenmire 1962, Whelan 1995); prescribed fire reduces the quantities of dead and down woody material through fuel consumption (Stephens and Moghaddas 2005); high-severity wildfire increases the number of standing snags, which transfer to the dead and down woody fuel stratum over time as they decay and fall (McIver and Ottmar 2007), and thinning reduces tree density.

As with other state and transition models for vegetation succession, this approach effectively incorporates vegetation development and change into the fuelbed characteristics and successional transitions removing the computational burden of modeling fuelbed development mechanisms and processes explicitly, which enables analysis at higher resolution (200 m pixel size and annual time step), and larger spatial (10^6 hectares) and longer temporal (multi-century) scales. Although this modeling experiment relied on inventory data and expert opinion to develop fuelbeds and successional pathways, vegetation succession models capable of incorporating natural and human disturbances, such as the Fire and Fuels Extension to the Forest Vegetation Simulator (Reinhardt and Crookston 2003) could potentially be used to help define states and transition pathways (Acevedo et al. 2001).

A review of fuelbeds and succession logic in consultation with two of the primary fuelbed and pathway developers (R.D. Ottmar, USFS, Pacific Northwest Research Station and T.L. Leuschen, FireVision LLC and former fire management officer for the USFS, Okanogan National Forest) dictated the following modifications:

1) Revisions to some fuelbeds where stand, vegetation, or fuel characteristics were suspect or erroneous, or where the characteristics of antecedent or successor fuelbeds were inconsistent.

2) Assignment of "natural," age-related succession transitions to fuelbeds for which management activity was required to initiate a state change in the original successional pathways.
3) Addition of new fuelbeds to represent undescribed states that could result from transitions that were unspecified in the original successional pathways (e.g., fuelbeds to represent immediately post-harvest or post-stand-replacement fire conditions, and fuelbeds to represent unique fuel and stand characteristics resulting from assignment of new "natural" succession transitions as described in #2, above).

A wide variety of fuelbed and stand management actions have been and are currently used on the OKA-WEN (e.g., precommercial and commercial thinning, pruning, lop and scatter, whole-tree yarding, mastication, prescribed fire, pile and burn, grazing, etc.), however, the type and timing of management treatments in the successional pathway framework are limited for this modeling experiment. In general, fuelbeds can be thinned (both precommercially and commercially), prescribe burned, thinned and prescribe burned, commercially harvested, commercially harvested and prescribe burned, salvaged (following stand-replacing wildfire), or salvaged and prescribe burned as is appropriate based on their age and management regime. Thus, for example, high elevation subalpine fir forests do not include pathway options with management interventions, while Douglas-fir and ponderosa pine-dominated types may have multiple pathway options that could lead to a wide variety of fuelbeds at different stages of development (Figure A.1). Only fuelbeds composed of merchantable species that are older than a specified age (generally 80-90 years per T.L. Leuschen, personal communication) are eligible for commercial harvesting, which acts to return a fuelbed to the earliest successional state. Thinning, thinning followed by prescribed fire, and prescribed fire alone (without prior thinning), cause fuelbeds to transition to new states as specified in the successional pathways. Fuelbeds are eligible for management actions

only as they near the end of the age range that defines a given state, thus fuelbeds cannot receive successive management actions at intervals shorter than the full length of the age range of the state specified in the successional pathways.

Fuelbeds experience one of two levels of fire severity when a wildfire is modeled depending on fuel characteristics: stand-replacement surface or crown fire, or non-stand-replacement surface fire. In the case of stand-replacement, succession is effectively reset and a burned fuelbed reverts to a recently burned state with subsequent development following the prescribed successional pathway. Fuelbeds burned in stand-replacement wildfires are eligible for salvage operations for two years following the fire. Transitions resulting from non-stand-replacing wildfire were not explicitly specified in the original fuelbed successional pathways; to add this transition type without a wholesale revision of the OKA-WEN fuelbeds and successional pathways, fuelbeds were specified to change to new states following the same successional transitions as management activities that include prescribed fire as a component of the treatment (i.e., prescribed fire, and thinning followed by prescribed fire). Though not an ideal solution, this approach represents a workable compromise as it is not unreasonable to assume that a non-stand-replacing surface wildfire will have a similar effect on fuel and stand characteristics as a prescribed fire (i.e., reduction of fuel loading) or a mechanical thinning followed by a prescribed fire (reduction in tree density and reduction of fuel loading). For cases in which prescribed fire was not a component of any of the management activities for which a fuelbed was eligible, transition to a successor fuelbed that was the product of management transitions involving prescribed fire from other fuelbeds in the same pathway and age range was specified. For example, fuelbed #163 and #164, which lack management transitions involving prescribed fire, change to fuelbed #165 in the event of a non-stand-replacing wildfire because #165 results from thinning and prescribed burning fuelbed #162, which is part of the same fuelbed pathway and age range as fuelbeds #163 and #164 (i.e., Douglas-fir/ninebark, 41-80 years; Figure 3.3).

OKA-WEN FCCS Fuelbed Map – A map of FCCS fuelbeds for the entire administrative boundary of the OKA-WEN was derived from Landsat Thematic Mapper imagery, photo-interpreted vegetation cover types, and a rule-based classification (D. McKenzie, personal communication); the fuelbed map used in this modeling experiment was refined to include a more complete fuelbed library than was used in the development of a preliminary map used by Raymond et al. (2006) and McKenzie et al. (2007). Eighty-three fuelbeds were mapped at 25-m resolution with the rule-based classification; 62 fuelbeds were retained in the map that was used as a starting point for all of the simulations after the following modifications were performed. In general, very rare fuelbeds that occurred only as very small patches and fuelbeds not associated with a successional pathway were eliminated from the original map. The original 25-m resolution map was modified for use in the fuelbed succession experiment with the following steps in ArcMap 9.2 (ESRI 2009):

1) The map extent was adjusted to exclude a portion of the Tonasket Ranger District, a disconnected area in the Okanogan Highlands to the east of the main block of the OKA-WEN.
2) Stands less than 4 ha were re-assigned to their nearest neighbor fuelbed on a pixel-by-pixel basis. Mapped fuelbeds that were not associated with a successional pathway were also reassigned to the nearest neighbor fuelbed that was part of a successional pathway. Re-assignments were made by using the NIBBLE function, which replaces targeted pixels with the value of the nearest neighbor.
3) The 25-m resolution raster was aggregated to 200-m resolution by using the RESAMPLE function, set to assign the value of the majority of pixels that were aggregated to make the new cell. The speed of the fuelbed succession model is strongly affected by the number of pixels in the map; 200-m resolution was chosen to maintain a relatively fine grain and still produce reasonable simulation run times (4.5-44 hours per simulation depending on fire and management level).

4) Individual stands were randomly assigned an age from a uniform distribution bounded by the minimum and maximum possible age for the fuelbed type of which that stand was composed.

Because the OKA-WEN fuelbed map was derived from older imagery (2001) it is not a spatially accurate or completely up-to-date representation of the OKA-WEN landscape. It does, however, capture the composition of the OKA-WEN reasonably well based on comparisons with systematically collected field data (Raymond et al. 2006). The most recent version of this map (produced in July 2009), modified as noted above, served as a starting point from which fuelbed succession was simulated and the baseline from which change was measured.

The comprehensive, quantitative FCCS fuelbed characteristics, and the related potential fire behavior attributes, can also be mapped enabling examination of landscape patterns and metrics for a variety of different purposes (McKenzie et al. 2007). Simulation output maps of fuelbed type were re-classified to represent fire behavior (surface fire flame length, surface fire rate of spread, surface fire reaction intensity, crown fire initiation potential, and crown fire transmissivity potential) and carbon stock (live, dead, and total). Flame length, rate of spread and reaction intensity are all well defined measures of surface fire intensity (Keeley 2009). Crown fire initiation potential and crown fire transmissivity potential require explanation. Crown fire initiation potential (Schaaf et al. 2007) is related to the ease with which surface fires can transition to crown fires, and is a conceptual analog of the critical fireline intensity of Van Wagner (1977) and the torching index of Scott and Reinhardt (2001). Crown fire transmissivity potential (Schaaf et al. 2007) is a measure of the capacity of canopy fuels to sustain crown fire, and is analogous to the critical rate of spread for active crowning (Van Wagner 1977) and the crowning index (Scott and Reinhardt 2001). Both crown fire potential calculations yield a value on a relative scale from 0 to 9, with larger numbers indicating higher potential. Fire behavior maps were further categorized into groups

representing low, medium, and high fire behavior predictions (Table 3.3). Live, dead, and total fuelbed carbon stock per pixel was summed to determine landscape carbon stocks at 25-year intervals for the entire OKA-WEN.

Fuelbed Succession Simulation Experiment

A simulation experiment with two factors was performed that yielded six replicated time-series projections of landscape composition and pattern that were used to examine how different levels of wildfire area burned (contemporary [F1], elevated [F2]) and area managed (no management [T0], contemporary [T1], elevated [T2]) might affect the OKA-WEN landscape (Table 3.2). For each year in the simulation, the number and size of wildfires for the contemporary period were randomly drawn from statistical distributions parameterized with fire occurrence data for the study area (1977-2006). The elevated fire regime level represents a doubling of the area burned based on projections for the 2080's by Littell et al. (2009) for Bailey's Eastern Cascades ecosection.

Three levels of management regime were simulated. A management level with no management activities was specified as a control of sorts againsts which to assess the effect contemporary and elevated levels of management might have on landscape patterns going forward. A contemporary management activity level was prescribed based on 2004-2008 records for the OKA-WEN from the Forest Service, Pacific Northwest Region forest operations and fuel treatment inventory database. Management activities included commercial harvests, and a variety of fuel treatments (thinning, thinning with prescribed fire, and prescribed fire only). Management activities performed by the forest, but not included in the successional pathways were excluded (e.g., piling and prescribed burning, pruning, and surface fuel and understory mastication). The annual area for each type of management activity specified in the contemporary management level was doubled to represent a case in which management actions were implemented at an elevated level that reflects a potentially attainable, if ambitious, management program.

All simulations began with the same FCCS fuelbed base map and ran on an annual time step for 200 years with output evaluated at 25-year intervals. Each year, the model randomly determined the sequence and placement of wildfires and management activities on the landscape (occurrence, size, shape, and location). Each fire/management treatment combination was replicated 10 times to generate a distribution of possible future landscape states with mean and variance of computed landscape metrics.

Landscape Metrics

Landscape ecology seeks to quantify spatial patterns and relate those patterns to ecological processes (O'Neill et al. 1988, Gustafson 1998, Turner et al. 2001). McGarigal and Marks (1995) note that perhaps hundreds of metrics have been proposed for quantifying aspects of landscape pattern, composition, and structure. They, and others, also note, however, that metrics should be chosen because of their ecological relevance or ability to enhance our understanding of ecological functions and processes (Gustafson 1998, Li and Wu 2004, Leitão et al. 2006). Landscape spatial patterns, while a product of the larger biophysical environment, are also a reflection of disturbance, such as fire, and succession processes that affect fuel development and change over time (Hessburg et al. 2007b). The following class and landscape metrics are considered useful for assessing and comparing disturbance-prone landscapes in an ecosystem management context (Keane et al. 2001b), and were calculated for each re-classified map for each 25-year time interval and combination of fire and management regime level by using the landscape analysis program FRAGSTATS v.3 (McGarigal et al. 2002):

Mean patch size – Groupings of contiguous pixels of the same class constitute a patch (8-neighbor rule), and mean patch size is calculated as the sum of the area of all patches of a given class (or landscape) divided by the number of patches in that class (or landscape). As an example of the ecological relevance of patch size, an increase over time in the mean size of patches with a high probability of crown fire initiation or spread

on a landscape historically characterized by small crown fires would suggest a change in fire regime that may warrant management action if such a change was deemed undesirable.

Patch size standard deviation – Patches are defined as above for mean patch size, and patch size standard deviation is calculated as the square root of the sum of the squared difference in area between each patch and the mean patch size for a given class or landscape divided by the total number of patches of the given class or landscape (i.e., population standard deviation). Classes or landscapes for which the patch size standard deviation increases over time could indicate that type-altering events of widely varying size are shaping the patch structure of the landscape.

Percentage of landscape – Percentage of landscape is calculated as the percentage of the area of interest in a given class, and may be useful, for example, to understand the effects of potential increases in area burned by wildfire as climate changes (McKenzie et al. 2004, Littell et al. 2009). Under a fire regime in which area burned increases, resource managers may be able to assess the relative resilience of a landscape over time by calculating the percentage of the landscape that is characterized by generally benign potential fire behavior (e.g., low flame length, slow rate of spread, low probability of crown fire initiation and spread).

Contagion index – The contagion index (O'Neill et al. 1988, Li and Reynolds 1993) is an indicator of the degree of landscape fragmentation (or aggregation), and is calculated as the product of the probabilities that two randomly selected adjacent pixels belong to two selected patch types. Increasing values of the contagion index over time suggest the development of a more connected landscape.

Clumpiness index – As the contagion index is a measure of fragmentation or aggregation for the landscape as a whole, the clumpiness index is for landscape classes. The clumpiness index (McGarigal et al. 2002) is scaled from maximum aggregation (1), to completely random arrangement (0), to maximum disaggregation (-1). The clumpiness index is calculated as:

1) the difference between the proportion of pixels of the focal class with like adjacencies (i.e., neighboring pixels of the same class) and the proportion of the landscape in the focal class, divided by the proportion of the landscape in the focal class, if the focal class occupies less than one half of the landscape, or
2) the difference between the proportion of pixels of the focal class with like adjacencies and the proportion of the landscape in the focal class, divided by one minus the proportion of the landscape in the focal class, if the focal class occupies more than one half of the landscape.

Increasing values of the clumpiness index for a class of high crown fire probability could be indicative of an increase in the contiguity of areas susceptible to crown fire initiation or spread.

Carbon Stock

Fuelbed carbon stock is the sum of the carbon content of the biomass of all aboveground fuel elements that make up a given fuelbed. Live and undecayed, dead biomass is considered 50% carbon (Ragland et al. 1991), and decayed, dead biomass is considered 40% carbon. Landscape carbon stock is the sum of the product of the area occupied by each fuelbed and its carbon stock, for all fuelbeds on the landscape. Although not a metric for describing spatial pattern, potential changes in landscape carbon pools over time could be important for assessing the potential for a landscape to be a source or sink for carbon in the future. Note that this definition does not include carbon in the soil or belowground pools.

Data Analysis

Fuelbed succession simulations for combinations of two fire and three management regimes yielded annual maps of fuelbeds, associated fire potentials, and carbon stocks. Landscape properties were analyzed at 25-year intervals. As with other similar modeling experiments (e.g., Li et al. 2005), the stochastic application of

disturbance (fire) and management activity allowed for replication of each fire/management regime "treatment" level thereby making possible statistical analysis of treatment effects and interactions.

The analytical focus was on evaluating trends over time and testing for the statistical significance of changes to the mean patch size, percentage of the landscape, and clumpiness index in a given class with respect to potential fire behavior (flame length, rate of spread, reaction intensity, crown fire initiation potential, and crown fire transmissivity potential) and carbon stock (live, dead, and total aboveground carbon) as individual pixels on the OKA-WEN landscape succeeded. At each 25-year time step, mean landscape metrics for each fire/management regime level were compared using a fixed-effects two-factor analysis of variance (ANOVA) with equal replication; a Tukey HSD test was used to make pairwise comparisons among the three levels of management treatment, and among the interactions in the case of a significant main effects or interaction F-test (Zar 1984, Quinn and Keough 2002, Gotelli and Ellison 2004). The data for each 25-year time step were tested to make sure they met the assumptions of ANOVA. Homogeneity of variance was confirmed with Levene's test (Levene 1960). Shapiro-Wilk tests on the ANOVA residuals (Shapiro and Wilk 1965) suggested that the data were often not normally distributed, so permutation techniques were used to determine ANOVA significance without the requirement that the data come from a normally distributed population (Anderson 2001, Legendre 2007). All statistical tests were carried out in the R programming environment (R Development Core Team 2010) with α=0.05. To determine the time required for landscape metrics to diverge from the initial condition under different fire/management regime combinations, the differences of mean landscape metrics from the initial conditions (i.e., year zero of the simulation) were plotted at 25-year intervals and determined to have changed significantly if their 95% confidence interval no longer included zero (sensu Baker 1992, 1993).

RESULTS

Modeled fire sizes and annual area burned were heavily skewed (Figure 3.4). By design, the model produced predominantly relatively small fires that generated years of mostly relatively modest annual area burned. Size of individual fire events ranged from 4 to 200,000 ha (median fire size = 672 ha and 944 ha for current and elevated fire regime simulations, respectively) and only a small number of fires were truncated at the arbitrarily set limit of 200,000 ha (34 out of 62,182 fires simulated). Area burned was annually variable, ranging from 0 to 279,008 ha (median annual area burned = 5,836 ha) and 0 to 290,136 ha (median annual area burned = 13,322 ha) for the current and elevated fire regimes, respectively (Figure 3.4).

The area subjected to different management activities was simulated as specified in Table 3.2 with the exception of prescribed fire only and post-fire salvage. Only three out of a possible 262 fuelbeds were eligible to receive prescribed fire only treatments (fuelbed #126, #131, and #138; Figure A.1), none of which was part of the original FCCS fuelbed map. Succession of their precursor fuelbeds was necessary before the initial modeled landscape contained stands that were eligible for treatment with prescribed fire only. Prescribed fire only management actions were only partially applied in the simulations, as the OKA-WEN landscape lacked eligible fuelbeds for 50% of simulation years. Similarly, areas that were recently burned by stand-replacing wildfire were eligible to be salvaged for up to two years post-fire, so the supply of area eligible for salvage fluctuated with respect to how recently a fire had occurred. When little or no area burned for two or more successive years insufficient area was available to fully implement specified levels of post-fire salvage (11% of simulation years among all simulations).

FUELS

Succession, disturbance by wildfire, and management activities led to changes in landscape pattern and composition of fuelbeds over time (Figures 3.5 to 3.7). Fuelbeds

representing older conditions (i.e., >80 years since stand origin) increased in dry (dry Douglas-fir/ponderosa pine/grand fir, ponderosa pine, western larch, Douglas-fir/ninebark, ponderosa pine/western larch/Douglas-fir, western larch/Douglas-fir, western larch/Douglas-fir/lodgepole pine, and western larch/lodgepole pine fuelbed pathways), mesic (Douglas-fir/moist grand fir, moist grand fir/western hemlock, and dry western hemlock fuelbed pathways), montane (lodgepole pine and subalpine fir fuelbed pathways), and subalpine (Engelmann spruce/whitebark pine/subalpine larch fuelbed pathway) forest types, and decreased in wet (western hemlock/Pacific silver fir/mountain hemlock fuelbed pathway) forest types. The proportion of the landscape in young (i.e., <81 years since stand origin) and old classes in dry forest types not subject to any management activity converged at approximately 175 years. Where management was specified in dry forests, more older fuelbeds persisted. Elevated levels of management activity promoted an increase in the percentage of the landscape in older mesic forest fuelbeds. Fuelbeds in young, wet forest types increased at the expense of older wet types for approximately 75 years and then their coverage on the landscape remained constant for the remainder of the simulation period for both fire levels and all management levels. Landscape composition of montane and subalpine fuelbeds changed very little over time under an elevated fire regime regardless of management level, but showed reciprocal changes in old (increase) and young (decrease) fuelbed types under the current fire regime, regardless of management level.

For simulations in which no management activities were specified under both the current and elevated levels of fire occurrence mean size of landscape patches composed of the same fuelbed initially increased from 57.4 ha followed by very little change (Figure 3.8a). The OKA-WEN landscape experienced a general reduction in mean patch size for simulations where management activities were specified. Mean patch size was significantly smaller under an elevated fire regime than the current fire regime for a given management level for all years (ANOVA, $p<0.01$), and under an elevated management regime for a given fire level in years 25 and 50 (Tukey HSD,

$p<0.04$). Except for a brief increase for current fire regime/no management simulations (F1/T0), patch size standard deviation declined sharply from 593.4 ha over the first 75-100 years at which point it stabilized (Figure 3.8b). Even though they became smaller and more uniform in size on average, patches of the same type became more aggregated. Contagion index showed an immediate increase and remained above the initial level (44.9%) for the duration of the simulation. After the initial increase, contagion index gradually declined until year 100, after which little change occurred (Figure 3.8c). Patches were significantly less aggregated (i.e., lower contagion index) where no management activity was prescribed for a given fire level for all years (Tukey HSD, $p<0.01$).

Fire Hazard

Mean patch size – Reclassifying the fuelbed maps to represent different measures of fire hazard revealed varied landscape patterns (mean patch size, percentage of landscape, clumpiness index) by fire behavior measure (potential flame length, rate of spread, reaction intensity, crown fire initiation , crown fire transmissivity) and class (low, medium, high). Mean patch size generally increased or decreased for 50-100 years before returning partially to initial conditions and then changing relatively little for the final approximately 100 years of the simulation. Measures of low fire behavior showed a pattern of increasing mean patch size to a peak level after 50-75 years followed by a slight decrease and then a period of little change that was still in excess of initial conditions, with the exception of low reaction intensity (Figure 3.9). In contrast, the mean size of high fire behavior patches decreased for all measures of fire hazard, with the exception of rate of spread. Medium fire behavior patches increased (reaction intensity and crown fire transmissivity potential), decreased (flame length and rate of spread), or both increased and decreased (crown fire initiation potential). Simulations with an elevated fire regime showed more extreme changes (both positive and negative)

in mean patch size than simulations with the current fire regime, with the exception of the high flame length and high crown fire initiation classes.

As a main effect, fire regime level (i.e., current vs. elevated) consistently yielded a significant difference in mean patch size regardless of fire hazard measure or fire hazard class, whereas tests for differences in the mean patch size attributable to different management levels were inconsistently significant (Table A.8). A significant interaction between fire regime level and management level was observed rarely (4 of a possible 105 tests) until year 200, when 6 of 15 possible tests were significant (ANOVA, $p<0.05$).

Mean patch sizes in the original (i.e., simulation year 0) landscape were quite different among classes for the different measures of fire hazard (Table 3.4). The mean size of patches with high crown fire transmissivity potential was very large initially (861.5 ha), especially in comparison with the initial mean size of high crown fire initiation potential patches (132.3 ha). Mean patch size of both high crown fire transmissivity potential and high crown fire initiation potential patches declined overall during the simulation, although the mean patch size for high crown fire initiation potential did regain some its original area after approximately 75 years (Figure 3.9). The mean size of patches in the high flame length category started out quite small (28.9 ha) and declined over time. Mean patch size of high flame length patches declined significantly less for the final 100 years in simulations for which no management activities were specified (Tukey HSD, $p<0.01$).

Percentage of landscape – As with mean patch size, the percentage of the original OKA-WEN landscape in low, medium, and high fire behavior classes varied depending on the choice of fire behavior measure considered (Table 3.4). The simulation year 0 landscape was composed of a fairly even mix of fuelbeds that would burn with low and medium flame length and rate of spread, with only a small percentage composed of fuelbed types that would burn with high flame length (0.3%) and rate of spread (6.1%). Fuelbeds characteristic of medium levels of fire behavior all initially occupied more than 40% of the OKA-WEN landscape, with the exception of medium crown fire

transmissivity potential fuelbeds. Despite a large initial amount of the landscape in a high crown fire transmissivity potential state, fuelbeds characteristic of high flame length and high crown fire initiation potential were among the least abundant types. Only approximately 0.1% of the landscape was composed of fuelbeds that would produce surface fire flame length >2.5 m under the benchmark fuel moisture and environmental conditions used to classify fuelbeds after approximately 100 years regardless of fire or management regime (Figure 3.10). A majority of the original landscape (55.8%) was composed of fuelbeds with high crown fire transmissivity potential, although as with mean patch size, this quantity decreased significantly during the simulation (Figure 3.10).

Temporal patterns of change in landscape proportions in different fire behavior classes were very similar to those observed for mean patch size, with the exception of the high flame length and high rate of spread categories. The percentage of the landscape in the low reaction intensity class showed a significant decline through year 50, but returned to the original level by year 75 for all combinations of fire and management regime. Except for an early approximately 75-year reduction, the percentage of the landscape in the medium crown fire transmissivity potential class did not change for all management levels under the current fire regime, but did increase and sustain an increase by year 75 for all management levels under an elevated fire regime. Similar to mean patch size, significant interaction between fire regime level and management activity level was rare for the first 175 years of the simulation (8 of a possible 105 tests), but was observed for 5 of 15 possible tests in year 200 (ANOVA, $p<0.05$).

Clumpiness index – The clumpiness index showed quite different temporal patterns of change in comparison to the mean patch size and percentage of the landscape (Figure 3.11). Patches expected to burn with low flame length, medium rate of spread, and high reaction intensity, crown fire initiation potential, and crown fire transmissivity potential were the most aggregated (highest clumpiness index) in the

original landscape (Table 3.4). Whereas plots of change in mean patch size and percentage of the landscape over time separated on the basis of current and elevated fire regimes, plots of change in clumpiness index separated on the basis of whether management was specified. When management level was a significant main effect, simulations for which current and elevated management activity levels were specified were significantly less aggregated than simulations with no management activity, although sometimes all treatment levels differed significantly (Tukey HSD, $p<0.05$). Although the patterns of change in clumpiness index differed from those observed for mean patch size and percentage of the landscape, similar ANOVA results were observed for clumpiness index after 200 years of simulated succession; interactions between fire regime level and management activity level for 7 of 15 possible tests were statistically significant (ANOVA, $p<0.05$) compared to 8 of 105 possible tests for the first 175 years.

CARBON

The original 1.62 million ha OKA-WEN landscape held a total of 243.5 Tg of carbon, of which 171.2 Tg was live and 72.3 Tg was dead (Table 3.5). Fuelbed succession led to changes in live, dead, and total landscape carbon stocks over time (Figure 3.12). Compared to simulations for which management was specified, simulations with no management activities accumulated the most live, dead, and total carbon by year 200 under the current fire regime, but the least live, dead, and total carbon by year 200 under an elevated fire regime (Table 3.5). Total carbon stock ranged from a high of 294.8 Tg after 150 years of fire at the current level with no management activity to a low of 199.8 Tg after 75 years of fire and management at elevated levels. The elevated fire regime significantly reduced live carbon from than the current fire regime (ANOVA, $p<0.05$ for all years). For the current fire regime, live carbon stock was maintained or increased slightly over time. Except for a short-lived decrease in dead carbon stock associated with all fire/management regime combinations, dead carbon stock increased from the initial level. Management at an elevated level produced a smaller average increase in

dead carbon stock over time under both fire regimes. Different levels of management produced significantly different amounts of live and dead carbon for a given fire regime level in all years (Tukey HSD, $p<0.05$). The effect on live carbon stock of the interaction between fire regime level and management activity level was significant after 125 years (ANOVA, $p<0.05$; Table A.11).

DISCUSSION

Variability in size, shape, location, periodicity, and successional effects of disturbances (fires and management activities) created complex spatial patterns through time, and added a dynamic aspect to previous efforts to map fuels and fire hazard (Burgan and Shasby 1984, Hardy et al. 1998, McKenzie et al. 2007). Fuelbeds change as vegetation establishes, competes, grows, dies, and decomposes. Transitions among fuelbed states associated with disturbances and succession affected potential landscape fire hazard and carbon dynamics. Effective land and fire management require that managers anticipate the cumulative effects of disturbances, succession, and fuel changes on landscape patterns of fire hazard, biomass accumulation, carbon dynamics, and other properties. Simulation modeling and landscape analysis, as was performed here, is useful for assessing landscape composition, landscape change, and landscape heterogeneity under alternate disturbance and management scenarios (Gustafson 1998, Leitão et al. 2006) .

LANDSCAPE COMPOSITION

Spatial patterns of fuels, fire behavior potential, and carbon stock changed as fire, management, and succession were simulated. Fires and management activities affect fire potential (Finney et al. 2007), and carbon pools and dynamics (Hurteau et al. 2008, Meigs et al. 2009, Mitchell et al. 2009, Wiedinmyer and Hurteau 2010) as a result of changes in landscape composition (Miller and Urban 2000).

Because of the legacy of historic disturbances and forest management, the study landscape began with abundant young dry forest type fuelbeds and old wet forest type fuelbeds. Fuelbeds characteristic of wet forest types tend to support stand-replacement fires in the successional pathways defined for the OKA-WEN. In contrast, fuelbeds characteristic of drier forest types more often support non-stand-replacement surface fires; stand-replacement fires occur only in the absence of regular fire or management when fuelbeds succeed to a state with heavy fuel accumulation. Thus, differential susceptibility to stand-replacement fires among fuelbed types led to a marked change in landscape composition over time with a general increase in the proportion of the landscape in older fuelbeds in drier types (i.e., dry, mesic, montane), but a decrease in the proportion of the landscape in older fuelbeds in wet types.

Change in age structure of the landscape should be interpreted in the context of the way fires were placed by the fuelbed succession model. Fires were initiated at random points weighted by fuelbed abundance and relative rate of spread. Although the simulated number and size of fires were parameterized using fire frequency, mean fire size, and natural fire rotation values derived from recent fire records for the entire study area, weighted random placement distributed area burned unreaslistically among wet and dry landscape positions. Wetter and higher elevation fuelbed types, in which fires were historically rare (Hemstrom and Franklin 1982, Agee et al. 1990, Morrison and Swanson 1990), had modeled rates of spread among the upper one-third of all fuelbeds, which likely simulated too much fire in wetter types and at high elevations and thus not enough fire in dry and mesic types at low and medium elevations. However, if changing climate increases the susceptibility to fires of currently "wet" locations (e.g., Camp et al. 1997), as could happen with lengthening fire seasons (Wotton and Flannigan 1993, Westerling et al. 2006), increases in area burned in wetter fuelbed types might occur. Changes in the distribution of stand ages for the OKA-WEN could have a range of ecological effects. For example, an increase in the area burned by stand-replacement fire could lead to loss of late-successional forests that are suitable habitat for the

Northern Spotted Owl (*Strix occidentalis caurina*), a federally threatened species (Spies et al. 2006).

Like some wildfires, harvesting is also a stand-replacing disturbance in the successional pathways defined for the OKA-WEN. Compared to fire, however, small quantities of harvesting were modeled (100 or 200 ha yr^{-1}), and so had a minimal effect on age structure of the overall landscape.

Many of the management activities specified in the successional pathways were designed to reduce stand-scale fire hazard (i.e., reduction in surface fuels and promotion of forests with fewer, but larger trees), by decreasing fire intensity and severity in the event of a wildfire (e.g., Agee et al. 2000, Agee and Skinner 2005). By virtue of modeling spatially explicit successional changes among FCCS fuelbeds, I was able to simultaneously assess various aspects of landscape fire potential, including crown fire, for the entire OKA-WEN landscape under different fire and management regimes. Elevated levels of management activity promoted an increase in the proportion of the landscape in older fuelbeds, particularly among dry and mesic fuelbed types. Thus, activities that alter fire behavior and effects at the stand scale may also affect fire hazard at larger scales and contribute to the resilience of landscapes in fire-influenced ecosystems. For example, Prichard et al. (*in press*) noted that the 2006 Tripod fire in the northern portion of the study area failed to spread into an area that had been burned in a previous wildfire, creating a large unburned island within the fire's perimeter. Similarly, they noted that areas that had been treated to reduce fuels provided sites from which to initiate fire fighting operations (i.e., back-burning) to prevent the fire from spreading toward nearby communities. These two examples from the Tripod fire illustrate that the legacy of fuel spatial patterns can be an important factor affecting fire occurrence and effects.

The simulation approach of this study provided a method to assess the potential effects of fires and other disturbances on fuel and carbon dynamics. Pacific Northwest forests can store large amounts of carbon aboveground, but are subject to fires of

varying severity and frequency that affect carbon pools and fluxes. Smithwick et al. (2002) estimated that in old-growth forests similar to those found on the OKA-WEN, 66 to 71 percent of total ecosystem carbon is stored aboveground. Quantities of total aboveground carbon of the OKA-WEN fuelbeds were comparable to other regional estimates (e.g., Janisch and Harmon 2002, Smithwick et al. 2002, Meigs et al. 2009, Van Deusen and Heath 2010) ranging from 0.3 to 29.9 Mg C ha^{-1} for grassland and steppe communities, and from 8.8 to 487.8 Mg C ha^{-1} for forest types of varying age, species composition, and disturbance and management history (Table A.1).

Carbon pools vary in size for fuelbeds of different age, species composition, management history, fire regime, and time since last fire, although in general, older forested fuelbeds store more carbon than younger forested and non-forest fuelbeds by virtue of the large carbon fraction stored in large live and dead tree boles (Janisch and Harmon 2002, Smithwick et al. 2002). To understand carbon source and sequestration potential, it is critical to understand and quantify within-stand carbon fluxes attributable to succession, management activities, and fire, as well as within-landscape carbon dynamics related to changes in fuelbed type in response to succession, management, and the effects of wildfire.

Landscape Change

Changes in landscape metrics appear almost immediately in response to the modeled fire and management regimes. Though mostly of a modest size given the distribution parameters in the model, fire are occasionally much larger than the largest management events. Thus, initially the effect of fire on patch size and composition tends to overwhelm the effect of the smaller-scale management events. However, forest (and therefore fuel) dynamics are a function of complex interactions between disturbances of varying size and severity (Spies and Franklin 1989, Morrison and Swanson 1990, Frelich and Reich 1995, Lertzman and Fall 1998). Significant statistical interactions between fire and management that occurred late in the simulation (i.e., at

year 200) suggest that many relatively small management events over time do have a measurable effect on how wildfires shape landscape patterns of fuels and the resulting fire hazard. The relatively smaller changes in clumpiness index in simulations with no management activity further support this notion that even small disturbances have a cumulative effect on some landscape properties.

Landscapes subjected to repeated disturbances may have a shifting mosaic of patch types and ages with a relatively stable composition over time when in equilibrium with their disturbance regime (Bormann and Likens 1979, White and Pickett 1985). Without exception, the different metrics used to describe landscape characteristics showed a pattern of significant change for the first 50-100 years of simulation followed by a period of relatively little change for the remainder of the simulation. The eastern Cascades experienced a large reduction in annual area burned beginning in the early 1900's (Everett et al. 2000, Hessl et al. 2004, Wright and Agee 2004) causing much of the land area of the OKA-WEN to miss one or more fires over the last century. The initial changes observed in simulated time series of landscape metrics may represent recovery from this altered fire regime of roughly the past century, with stabilizing landscape metrics later in the simulations suggesting a landscape moving toward equilibrium with the simulated disturbance regime. Of course, compared to these simulations, which modeled landscape change under constant levels of disturbance, real landscapes may never achieve equilibrium with their disturbance regimes, particularly if the disturbance regimes are subject to change in response to fluctuations in climate, land use, and other factors as is frequently the case where regularly occurring fire is the dominant disturbance type (Baker 1995, Dunn et al. 1999). In light of the uncertainty of future fire regimes and biophysical environments, simulation studies such as this should be viewed as a method to develop insights into the effects of ecosystem processes (i.e., fire) on landscape pattern, and *vice versa*, rather than as a specific prediction of a future landscape state.

Area burned is not the only important fire statistic or measure of fire's impact. Fire intensity and severity are also important, particularly for assessing potential fire effects (Agee 1998). This study modeled changes in mean patch size, landscape composition, and aggregation of patches on landscapes composed of fuelbeds with different potential fire hazard. Increases in the mean patch size and percentage of the landscape with low fire behavior potential suggest that the modeled fire and management regimes could produce a landscape on which fires might burn with lower intensity and severity, even when area burned is elevated above current levels.

Patches with high fire behavior potential showed a corresponding decrease in mean patch size and percentage of the landscape for all metrics, except rate of spread. A variety of fuel characteristics can promote accelerated rates of spread, including increases in the loading, coverage, and depth of fine woody, herbaceous, and shrub fuels (Sandberg et al. 2007). The increase in mean patch size for high rate of spread patches resulted from the modeling of fires in areas with >30 year old fuelbeds in the Engelmann spruce/whitebark pine/subalpine larch (ES/WBP/SL) fuelbed pathway. Replacing >30-year-old fuelbeds with the <31-year-old fuelbed by way of stand-replacing fires caused burned patches to shift from medium (1.2 to 3.1 m min^{-1}) to high (5.0 m min^{-1}) potential rate of spread (Figures 3.6, 3.7, A.4 and A.5), as the younger ES/WBP/SL fuelbed (fuelbed #230) is characterized by a continuous shrub layer (90% coverage).

This study attempted to use a fuelbed succession model to quantify how multiple stochastic disturbances in a variety of forest and range types might affect carbon stocks for a very large landscape over a multi-century time scale. Modeling disturbance regimes, succession, and landscape change is uncertain over decadal, much less centennial and longer time scales. Modeling fires on a natural fire rotation of 150 years (i.e., the "current" fire regime), where modeled fire locations are generated stochastically, led to modest fluctuations in live carbon stock when considered for the entire landscape. In comparison, doubling the amount of fire over the same period (i.e., the "elevated" fire regime) significantly decreased the size of the live carbon pool, a

result that has been observed in field studies (Tilman et al. 2000). If annual area burned increases as the regional climate warms, as has been predicted (McKenzie et al. 2004, Littell et al. 2009), then the OKA-WEN may sequester less carbon in the future than it does today.

Relative to the current fire regime, increasing area burned produced a landscape populated by more fuelbeds that were a product of surface fire that have less dead carbon, and thus lower dead fuel loading. This could potentially reduce the amount of future carbon emissions through heterotrophic and combustion pathways by reducing the supply of dead biomass subject to decomposition and rapid oxidation by fire. Although the more frequently burned landscape might sequester less total carbon, in the long term (i.e., after approximately 100 years when landscape carbon stocks are modeled to stabilize), less dead carbon will be available for liberation during decomposition and wildfire, potentially reducing average landscape carbon emissions. The net effect of lower levels of dead carbon may be the development of a landscape of fuelbeds that when burned, experience reduced intensity and severity, maintaining relatively more carbon in a living state (Mitchell et al. 2009).

Landscape Heterogeneity

Fuel characteristics and conditions are heterogeneous across a range of spatial and temporal scales (Hiers et al. 2009, Keane et al. 2010). Increased fuel heterogeneity and fragmentation have been shown to negatively affect fire propagation (Duguy et al. 2007), and management that reduces tree density and surface fuels, even when applied to a small area, has been observed to reduce fire severity (Raymond and Peterson 2005, Prichard et al. *in press*). Related to this is the idea of strategically placed fuel treatments (Finney 2001), which are predicated on the idea that altering landscape patterns by intermixing fuel types with reduced fire potential can affect future wildfire spread and severity patterns even when alterations are made to only small areas or proportions of the landscape (Finney et al. 2007). The OKA-WEN has experienced several large and

uncharacteristically severe wildfires recently, including the Tyee fire in 1994 (56,734 ha) and the Tripod fire in 2006 (70,894 ha). In both of these fires, some areas that historically supported low and medium intensity and severity surface fires burned as crown fires because of changes in fuel characteristics (e.g., accumulated surface fuels and increased tree density). Owing in part to an altered twentieth century fire regime, a majority of the area (55.8%) of the contemporary OKA-WEN landscape (i.e.., simulation year 0) had high crown fire transmissivity potential in large patches, perhaps providing some explanation for the recent occurrence of large crown fires in historically surface fire regimes.

Management activity fragmented high crown fire transmissivity patches over time, and the overall area and mean patch size in this fire behavior class declined. Reductions in the amount, mean patch size, and aggregation of patches with high crown fire transmissivity potential, in response to management at the current and elevated levels, appears as though it could have a moderating effect on crown fire hazard by creating landscape fuel patterns less likely to support widely spreading crown fire. Management activities designed to reduce crown fire behavior, even when implemented in small patches on a very limited area, could have the desirable effect of constraining potential crown fire size by reducing the contiguity of fuelbeds able to sustain crown fire spread (i.e., areas with high crown fire transmissivity potential). In addition to a susceptible canopy layer, high surface-fire intensity and flame length are typically necessary for crown fire initiation and spread (Van Wagner 1977, Scott and Reinhardt 2001). The cumulative effects of management activities at both the current and elevated levels that made high flame length and high reaction intensity patches smaller, less common, and less aggregated could also reduce crown fire potential.

The management activity level had a small but significant effect on live and dead carbon pools. Less live carbon was stored (current fire level) or lost (elevated fire level), and less dead carbon was stored (both fire levels) as the amount of management activity increased. The amount of area subjected to management activities annually was quite

small, both as a fraction of the overall OKA-WEN landscape (0.2 to 0.4%), and compared to the area affected by wildfire. Except for a small amount of commercial harvesting (100 to 200 ha yr^{-1}), most management activities changed fuelbeds to new states rather than initiating new stands. Transitions resulting from management typically yield fuelbeds with less carbon when compared to transitions resulting from succession alone. Thus the elevated management level produced more lower-carbon fuelbeds than the current management level, and a net decrease in landscape carbon stocks. Simulations with no management promoted the greatest carbon accumulation (or retention) suggesting that the cumulative effects of even a relatively small amount of management can affect carbon dynamics when assessed over a large area.

Compared to non-stand replacement fires, high severity, stand-replacement fires liberate more carbon during combustion, and also increase heterotrophic carbon emissions by shifting large amounts of carbon from live pools to dead pools for a number of years post-fire (Agee and Huff 1987, Janisch and Harmon 2002, Meigs et al. 2009). Management activities to reduce crown fire, therefore, will create a more stable carbon stock over time by creating fuelbeds in which potential fire intensity is minimized, and carbon is concentrated in larger but fewer live trees. Recurrent low-severity surface fires in forest types where they occurred historically, whether of natural or management origin, can produce similar changes in stand and fuel properties. Fuelbeds with these characteristics will be less likely to burn with intensity sufficient to cause high mortality and a shifting of carbon from live to dead pools. Preserving landscape carbon in large live trees essentially removes it as a source of emissions from decomposition and future combustion.

Most of the area in fuelbeds with large amounts of carbon, or with the potential to accumulate large amounts of carbon, occurred in wet forest types (i.e., western hemlock/Pacific silver fir/mountain hemlock pathway fuelbeds) that burn with stand-replacement severity. More of these areas burned under the elevated fire regime producing a net decrease in the amount of carbon sequestered on the OKA-WEN.

Fuelbeds in wet forest types on the OKA-WEN historically have long (100-300+ years or longer) fire-return intervals (Agee 1993). Given the stochastic manner in which fires were located in model simulations, more fire than was realistic was probably simulated for these fuelbed types, although some fire histories have suggested that periods when very large areas burned did occur in similar forest types elsewhere in Washington over the last millennium, perhaps during periods of warmer, drier climate (Hemstrom and Franklin 1982, Henderson et al. 1989). Of course, if the model simulated too much fire in wet fuelbed types, it likely did not simulate enough fire in mesic and dry fuelbed types that have much shorter fire return intervals (Agee 1994, Hessl et al. 2004, Wright and Agee 2004). Additional model development and testing is necessary to determine the degree to which landscape carbon dynamics are sensitive to fire placement.

MODELING LIMITATIONS

The simulation approach is particularly useful for examining the influence of different model parameters and assumptions on relative differences in landscape patterns even if one is unable to assess a model's absolute accuracy (Keane et al. 2004). However, output and analysis should be interpreted with full knowledge of the design and execution limitations and assumptions inherent in the model framework.

Fires - The manner in which fires are simulated in the model used here borrows from well established approaches in other landscape succession models (e.g., He and Mladenoff 1999, Wimberly 2002). Fire locations were weighted by fuelbed abundance and potential rate of spread in this model however, and did not stratify the landscape into different fire regime classes (i.e., areas or fuelbed types with different fire frequency, fire rotation, and mean fire size), so it is almost certain that too much of the total area burned occurred in wetter, relatively non-flammable fuel types that support stand-replacement fire. Comparisons of the effects on landscape metrics and properties of different fire and treatment regimes can still be made, but one must recognize the assumptions under which the landscapes developed. Shifting too much area burned to

wetter fuelbed types for which fires were historically rare changed landscape age structure for those types and affected the successional dynamics of drier fuelbed types that experienced a deficit of area burned. Wimberly and Kennedy (2008) found a similar pattern when they tested the sensitivity to different fire spread probabilities of different forest cover types and successional stages for a hypothetical forest type with a mixed-severity fire regime typical of the east Cascades of Oregon.

Older, wetter, and less severely burned fuelbed types store more carbon than younger, drier, and more severely burned fuelbed types (Smithwick et al. 2002, Meigs et al. 2009). An anomalously high area burned by high-severity fire in old, wet types likely changed carbon pools more than if the same area had burned less severely in drier types. The fire deficit in drier types would have also affected landscape fuel patterns. Too much area in drier types may have changed to states with increased stand density and heavier fuel loading, as relatively too little area would have followed non-stand-replacement fire trajectories, potentially affecting fuelbed characteristics, fire hazard, and carbon.

Also related to modeled fires, the two simulated fire regime levels (current and elevated) were assumed to vary around a constant frequency and size for the duration of the simulation. Given historical evidence of fire regime variability over time (Heyerdahl et al. 2002, Wright and Agee 2004, Prichard et al. 2009), and uncertainty about how future climate and landscape composition and pattern will affect fire regimes, this is a not uncommon, but likely overly simple assumption. Fuelbed transitions that result from modeled wildfires and management activities do not feed back on simulated fire size in the current model, although fire shape, and to some degree, the locations that actually burn are functions of the effects of succession, fire, and management on fuelbed type. Making the fire regime an emergent property of landscape fuel patterns (e.g., Perera et al. 2004) would help test and strengthen inferences about pattern and process interactions.

Fuels – Only fuelbed characteristics determined whether a fire was modeled to burn with stand-replacing severity. Many fuelbed types, particularly those in which fire behavior potential could be characterized as medium, might burn with stand replacement under some environmental conditions and might burn less severely under more moderate conditions. The version of the model used here was not able to incorporate this variability into projections of landscape change.

The way fire behavior category ranges were defined affected how landscape fire hazard was characterized. Changing the break points between fire behavior categories could affect landscape composition and patch dynamics. The values of category breaks may explain why temporal patterns of landscape metrics for low and medium reaction intensity levels are opposite the patterns for low and medium flame length and rate of spread levels, the other measures of surface fire behavior. Sensitivity of landscape properties to fire behavior class definitions was not examined in this study.

While combined as a single management entity currently, the Okanogan National Forest and the Wenatchee National Forest were independent land management units at the time the vegetation data and maps underlying the original FCCS fuelbed maps were produced (Raymond et al. 2006), potentially affecting the landscape patterns that were simulated to an unknown degree. Aggregation of the original 25-m resolution FCCS fuelbed map to 200-m resolution also likely affected simulations. Patch detail less than 4 ha was lost, and several rare fuelbeds were eliminated, or their coverage was reduced when pixels were combined using the methods outlined previously.

Carbon – Recall that fuelbeds burned by non-stand-replacement fires follow the same successional transitions as management activities that include prescribed fire as a component of the treatment, which may cause an underestimate of dead landscape carbon stocks. A number of these management treatments include commercial thinning (i.e., thinned material is removed from the site). In the case of a non-stand-replacing wildfire, the trees that are removed during commercial thinning may have otherwise been killed and shifted to the dead carbon pool as snags, but remained on the landscape.

No effort was made to compensate for this missing component from fuelbeds that were burned with non-stand-replacing surface fire.

In addition to factors already mentioned that affect assessment of landscape carbon stock (e.g., spatial distribution of fires, simplistic method to determine fire type, compromise method to specify non-stand-replacement fire transition), this analysis also does not include an accounting of the carbon costs of implementing management activities or the carbon storage that results from harvesting and production of commercial wood products. Although both factors are important for a full carbon accounting, they do not affect measures of standing landscape carbon stock so were not considered.

Implications and Conclusions

Fire behavior measures and landscape pattern metrics were used to examine how disturbance processes and fuelbed patterns interact. The composition and arrangement of fuelbeds on the simulated OKA-WEN landscape were affected by disturbance and succession, changing patterns of fuels, fire hazard, and carbon stock. The OKA-WEN is proposing a management approach to "provide for more sustainable and resilient forests" that recognizes the importance of planning and implementing project- and stand-level activities to accomplish multiple goals in the context of the larger landscape (Okanogan-Wenatchee National Forest 2010, p. 11). Balancing competing management objectives across a range of spatial and temporal scales for a diverse and dynamic landscape, however, is inherently complex. The modeling framework developed for this project is sufficiently generic that it could be used to test a variety "what if" scenarios on the OKA-WEN and elsewhere to inform management of large landscapes (e.g., national forests, national parks, etc.). Simulation results could be used to help understand what kinds of management activities preserve carbon or lessen the likelihood of large severe fire occurrence. Restoring an open forest structure and low severity fire regime in dry forest types through thinning and prescribed burning, for

example, may limit total carbon sequestration potential, but may reduce the magnitude of carbon stock fluctuations over long time scales while still providing ecosystem and economic benefits (Hurteau and North 2009). With further development, this fuelbed succession modeling framework could become a useful tool with which resource managers can test and evaluate the different landscape configurations that result from alternative management approaches and expected changes in fire regimes.

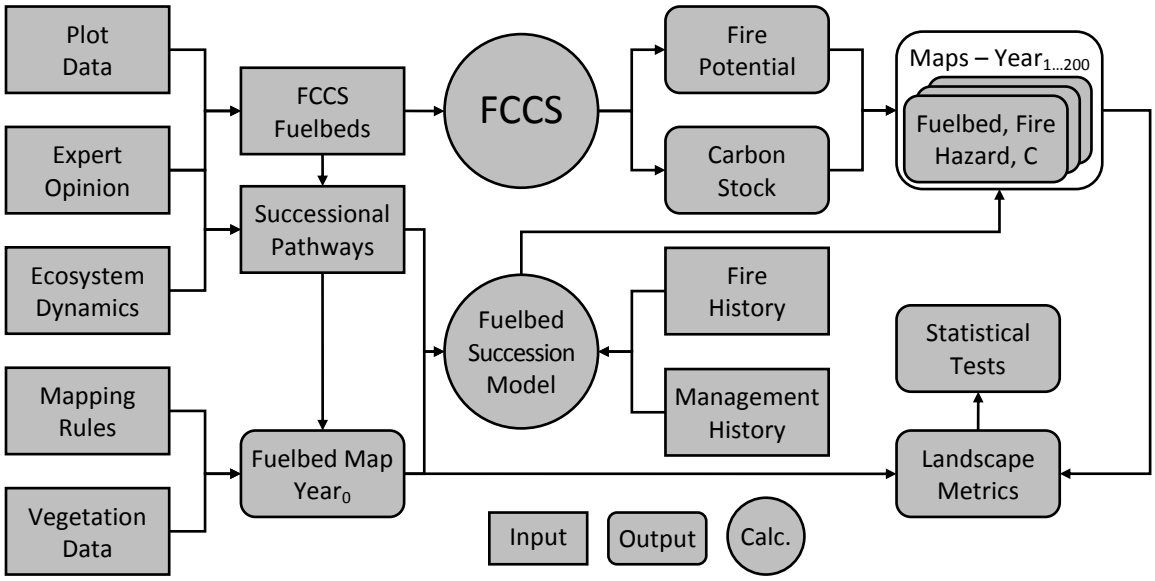

Figure 3.1. *Conceptual diagram of modeling framework for fuelbed succession mapping and analysis project. FCCS is the Fuel Characteristic Classification System.*

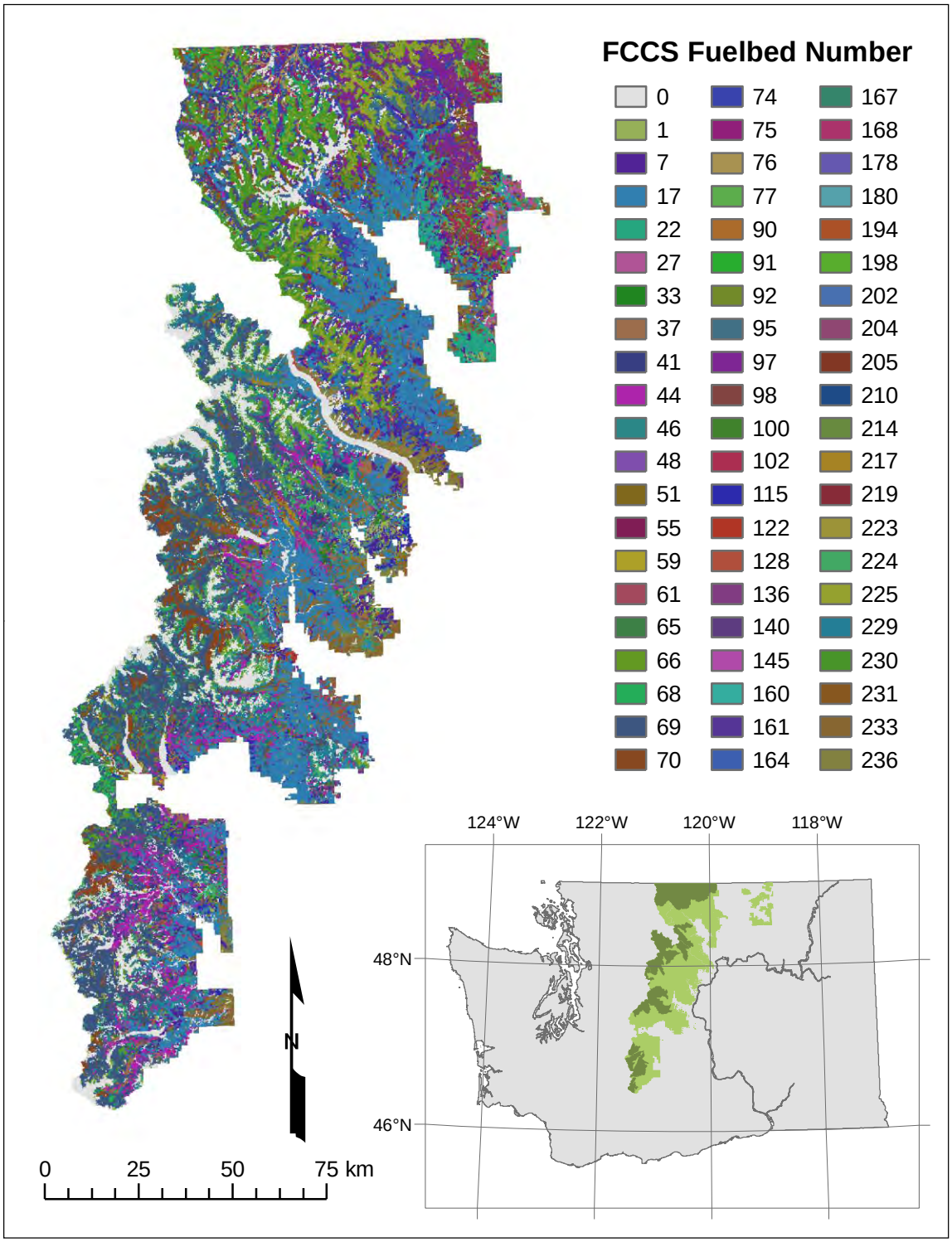

Figure 3.2. *Map of Fuel Characteristic Classification System (FCCS) fuelbeds for the Okanogan-Wenatchee National Forest. Map represents fuelbed composition and arrangement at simulation year 0. The extent of the Okanogan-Wenatchee National Forest is indicated in green shading on the inset map. Dark green shading indicates federally designated wilderness areas. FCCS Fuelbed names and characteristics can be found in Tables A.1 and A.2. Fuelbed 0 indicates water, rock, or ice.*

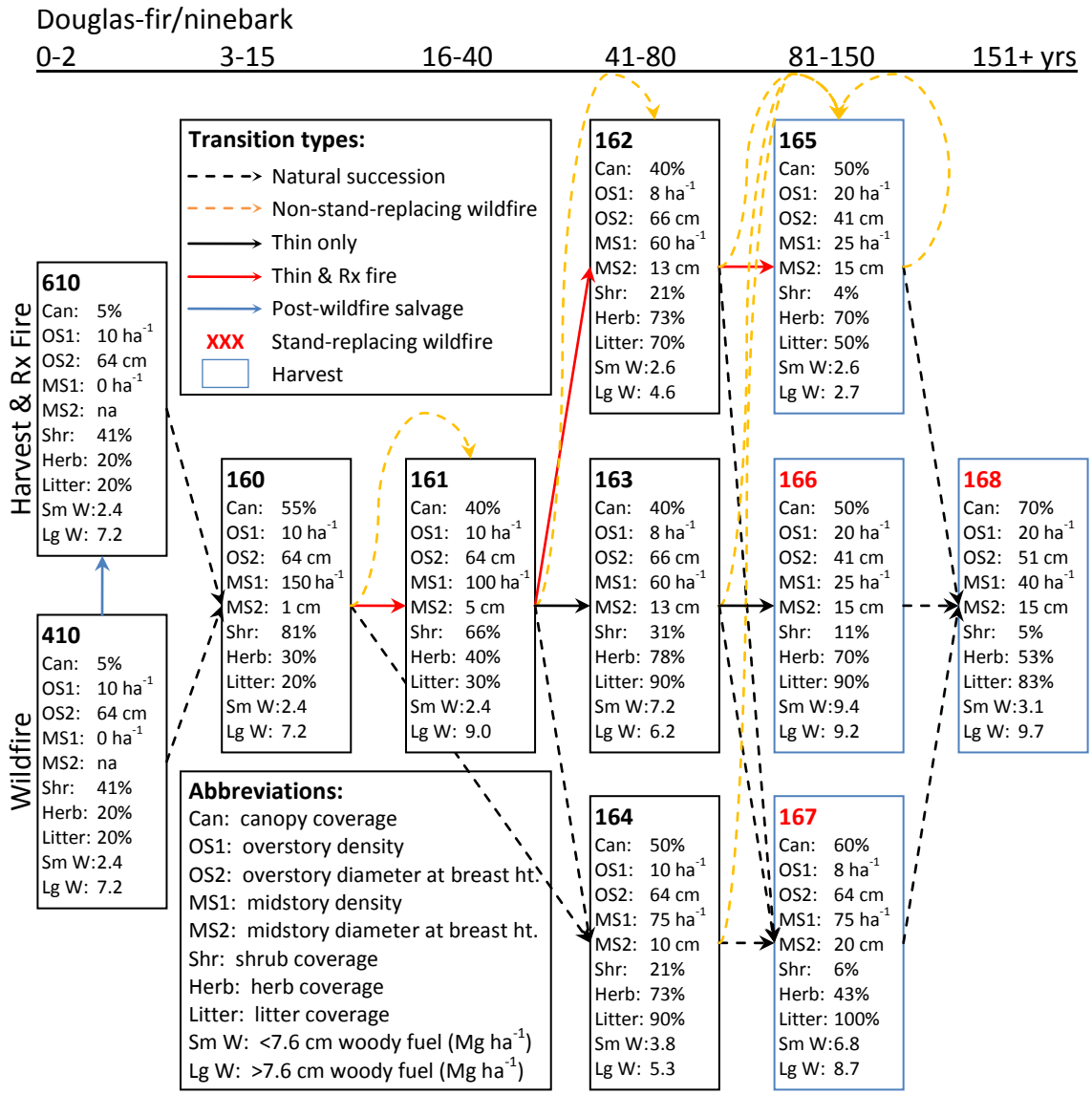

Figure 3.3. *Okanogan-Wenatchee National Forest Douglas-fir/ninebark FCCS fuelbed successional pathway. The DF/ninebark pathway is one of 19 pathways that describe changes to fuelbeds on the OKA-WEN. FCCS fuelbeds succeed from left to right, but return to the 0-2 year state when a stand replacing event is simulated (i.e., stand-replacing wildfire or harvest). The pathway choice is dependent on the transition type that occurs (natural, stand-replacing wildfire, non-stand-replacing wildfire, thinning, thinning and prescribed burning, and harvesting). Fuel and stand characteristics change logically from one fuelbed to the next based on the type of disturbance or management that occurs.*

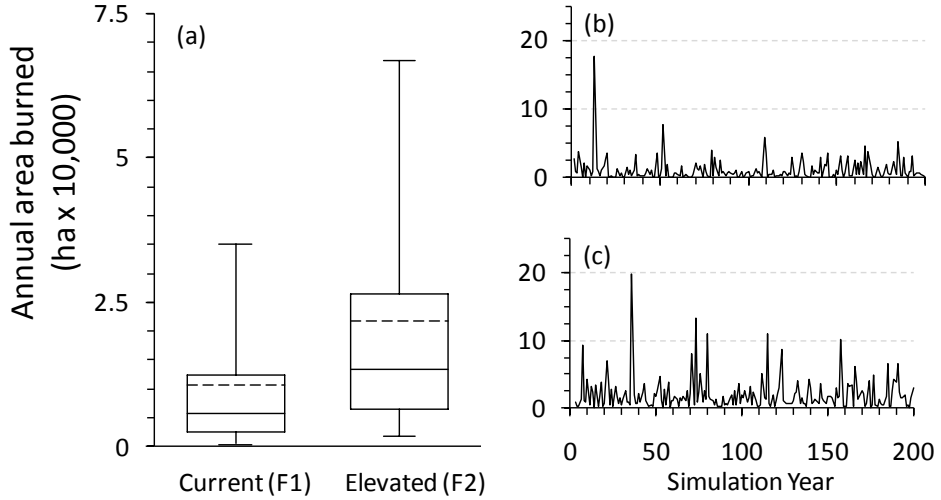

Figure 3.4. *Range in simulated annual area burned (a), and sample time series under the current (b) and elevated (c) fire regimes. For the box and whisker plot, the box shows the interquartile range, with the median indicated as a solid line and the mean as a dashed line. The ends of the whiskers enclose the 5th and 95th percentiles. The full range of annual area burned is 0 to 279,008 ha for the current fire regime (F1) and 0 to 290,136 ha for the elevated fire regime (F2).*

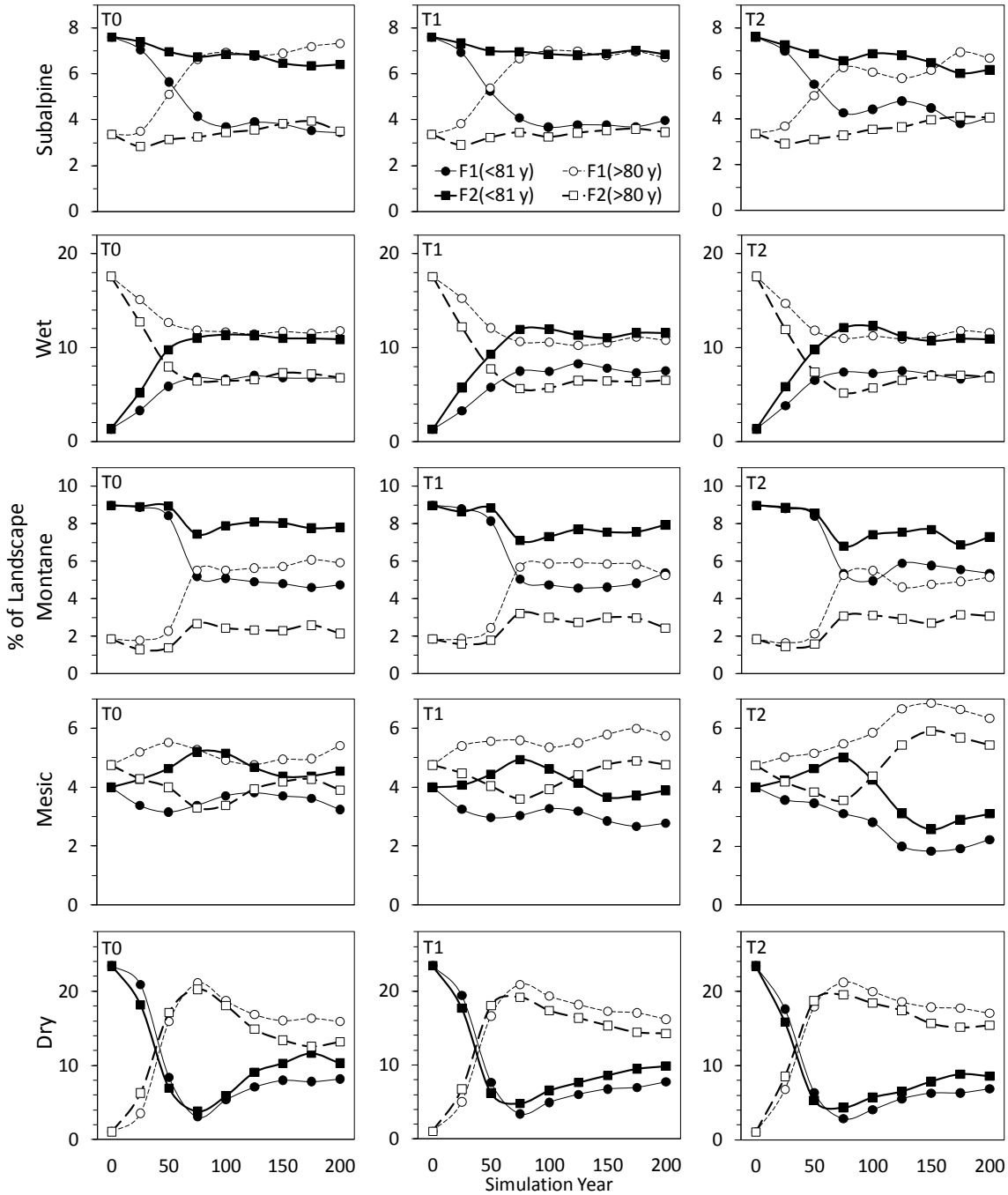

Figure 3.5. *Trends in the percentage of the landscape in FCCS fuelbeds grouped by forest type and age (older or younger than 80 years) for replicated 200-year fuelbed succession simulations under combinations of current (F1) and elevated (F2) fire regimes, and no (T0; left column), current (T1; middle column), and elevated (T2; right column) management regimes for the Okanogan-Wenatchee National Forest. Forest types include fuelbeds from the following successional pathways: Subalpine = ES/WBP/SL; Wet = WH/PSF/MH; Montane = LP, SF; Mesic = DF/moist GF, Moist GF/WH, and dry WH; Dry = Dry DF/PP/GF, PP, WL, DF-ninebark, PP/WL/DF, WL/DF, WL/DF/LP, and WL/LP. See Table 3.1 for a list of abbreviations.*

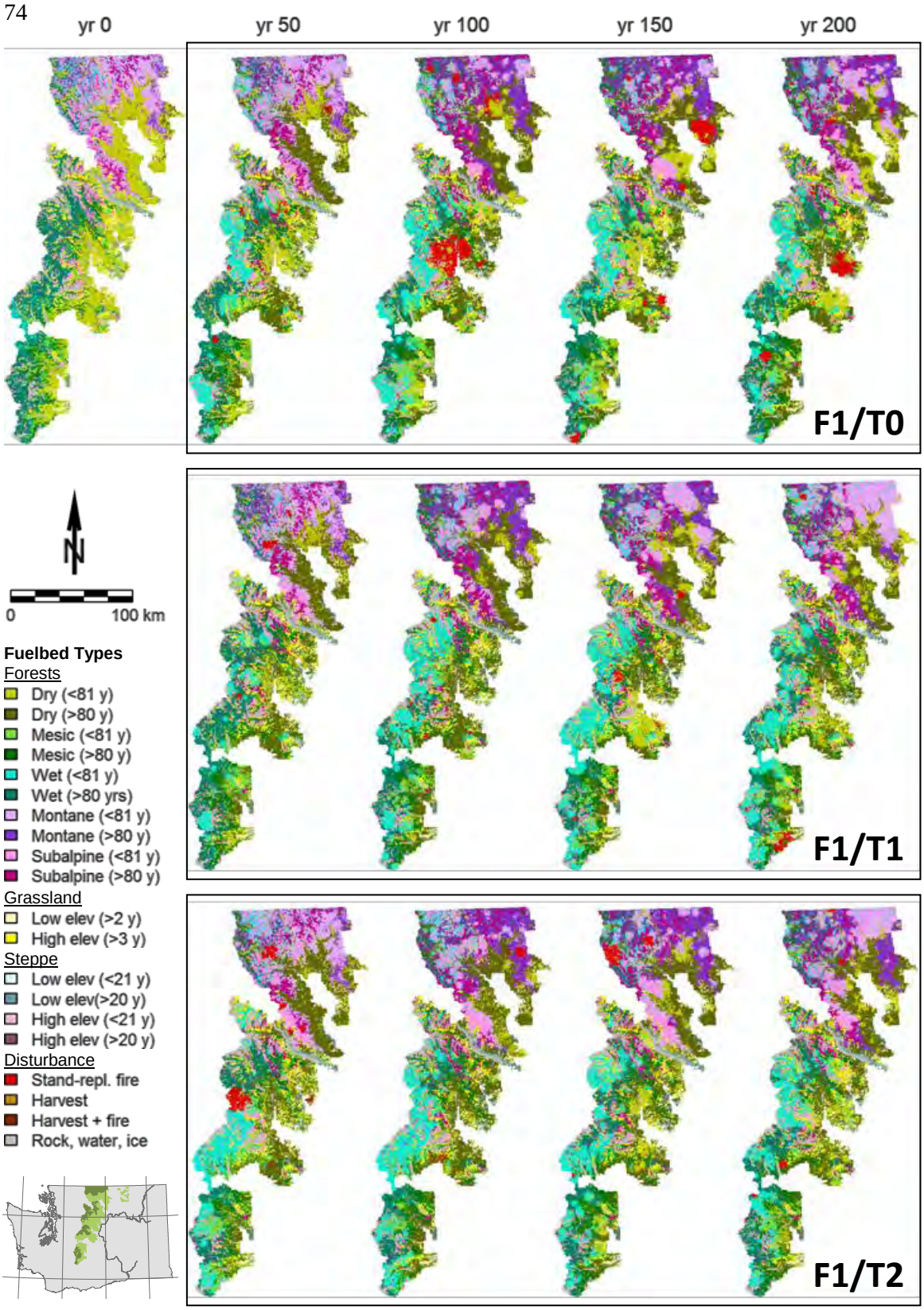

Figure 3.6. *Simulated fuelbed succession under the combinations of the current fire regime (F1) and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

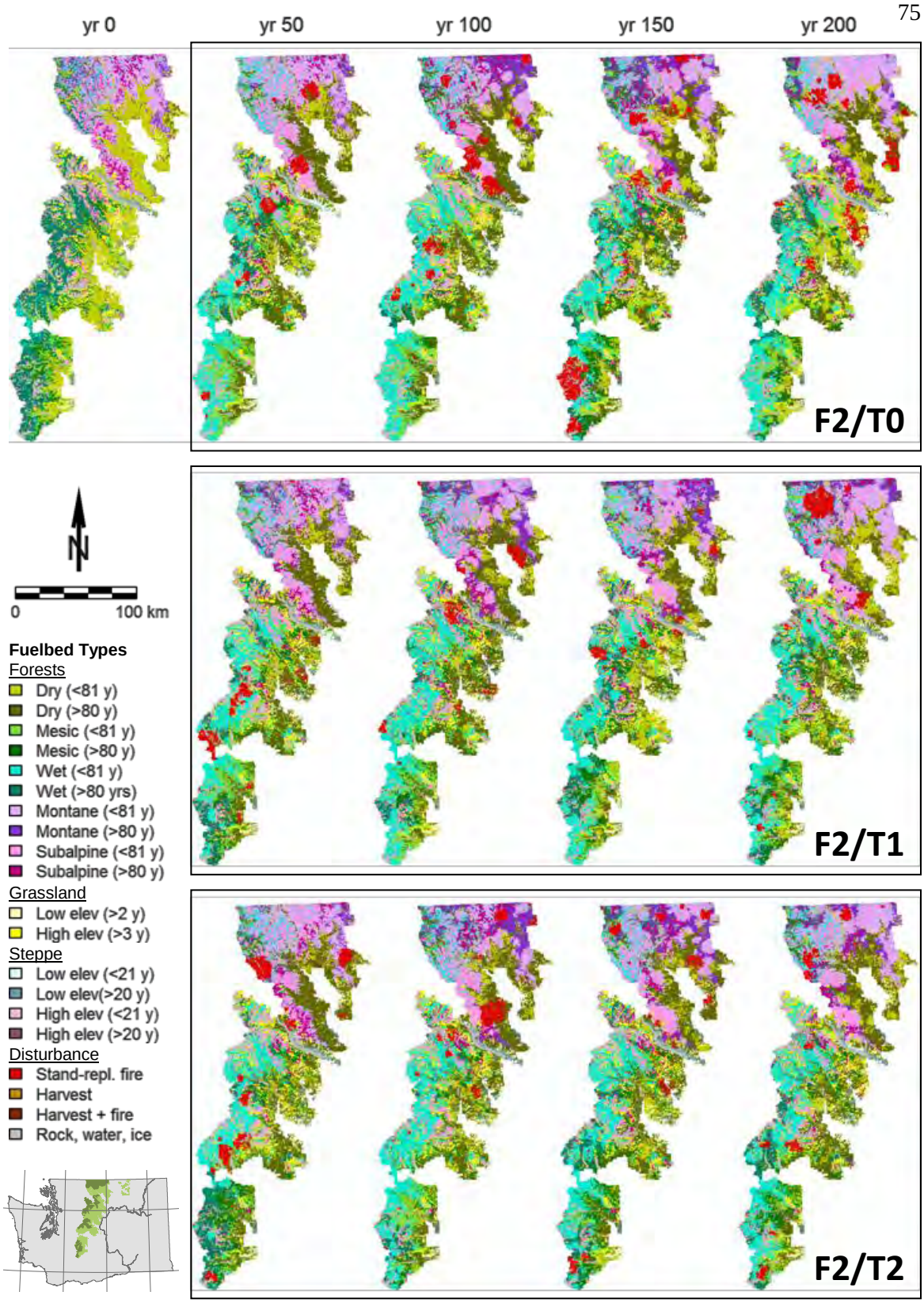

Figure 3.7. *Simulated fuelbed succession under the combinations of the elevated fire regime (F1) and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

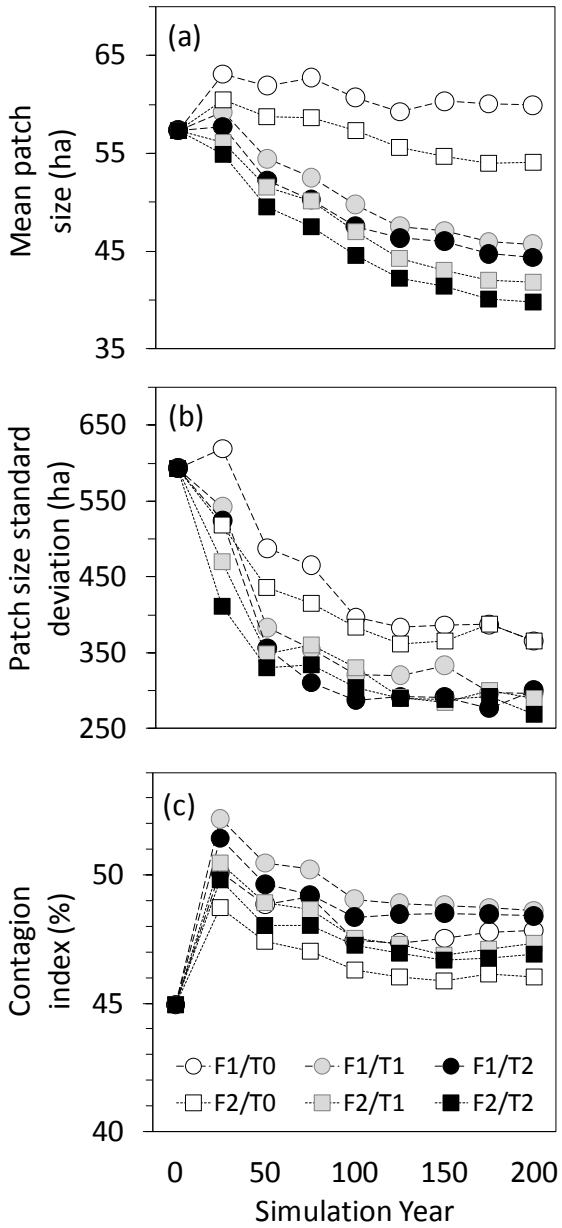

Figure 3.8. *Trends in FCCS fuelbed (a) mean patch size, (b) patch size standard deviation, and (c) contagion index for replicated 200 year fuelbed succession simulations under combinations of current (F1) and elevated (F2) fire regimes, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

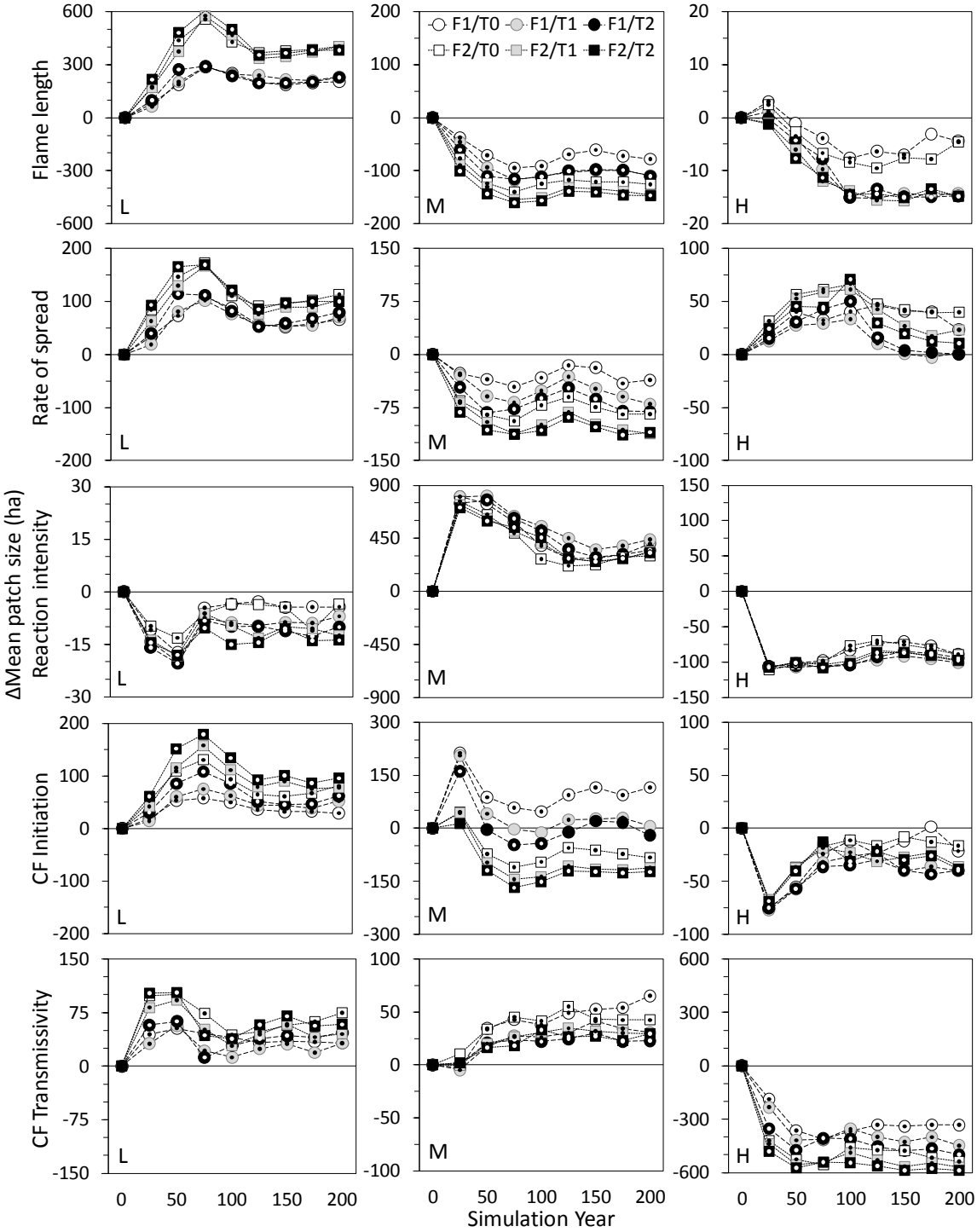

Figure 3.9. *Change in mean patch size of landscape patches of low (L), medium (M) and high (H) flame length (row 1), rate of spread (row 2), reaction intensity (row 3), crown fire initiation potential (row 4), and crown fire transmissivity potential (row 5) over time for replicated 200 year fuelbed succession simulations under combinations of current (F1) and elevated (F2) fire regimes, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest. Dots within symbols indicate a statistically significant departure from the initial (year 0) condition.*

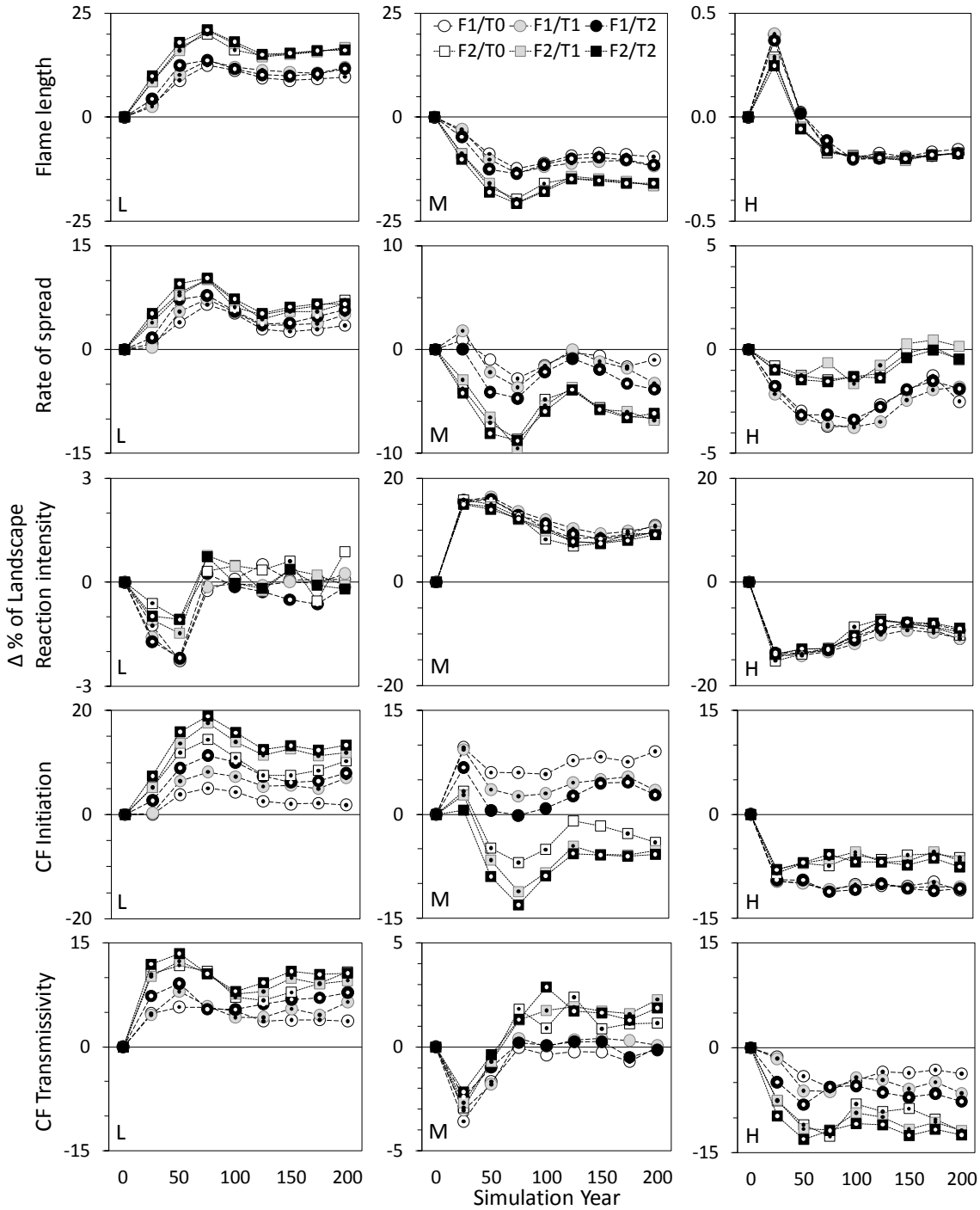

Figure 3.10. *Change in percentage of the landscape in patches of low (L), medium (M) and high (H) flame length (row 1), rate of spread (row 2), reaction intensity (row 3), crown fire initiation potential (row 4), and crown fire transmissivity potential (row 5) over time for replicated 200 year fuelbed succession simulations under combinations of current (F1) and elevated (F2) fire regimes, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest. Dots within symbols indicate a statistically significant departure from the initial (year 0) condition.*

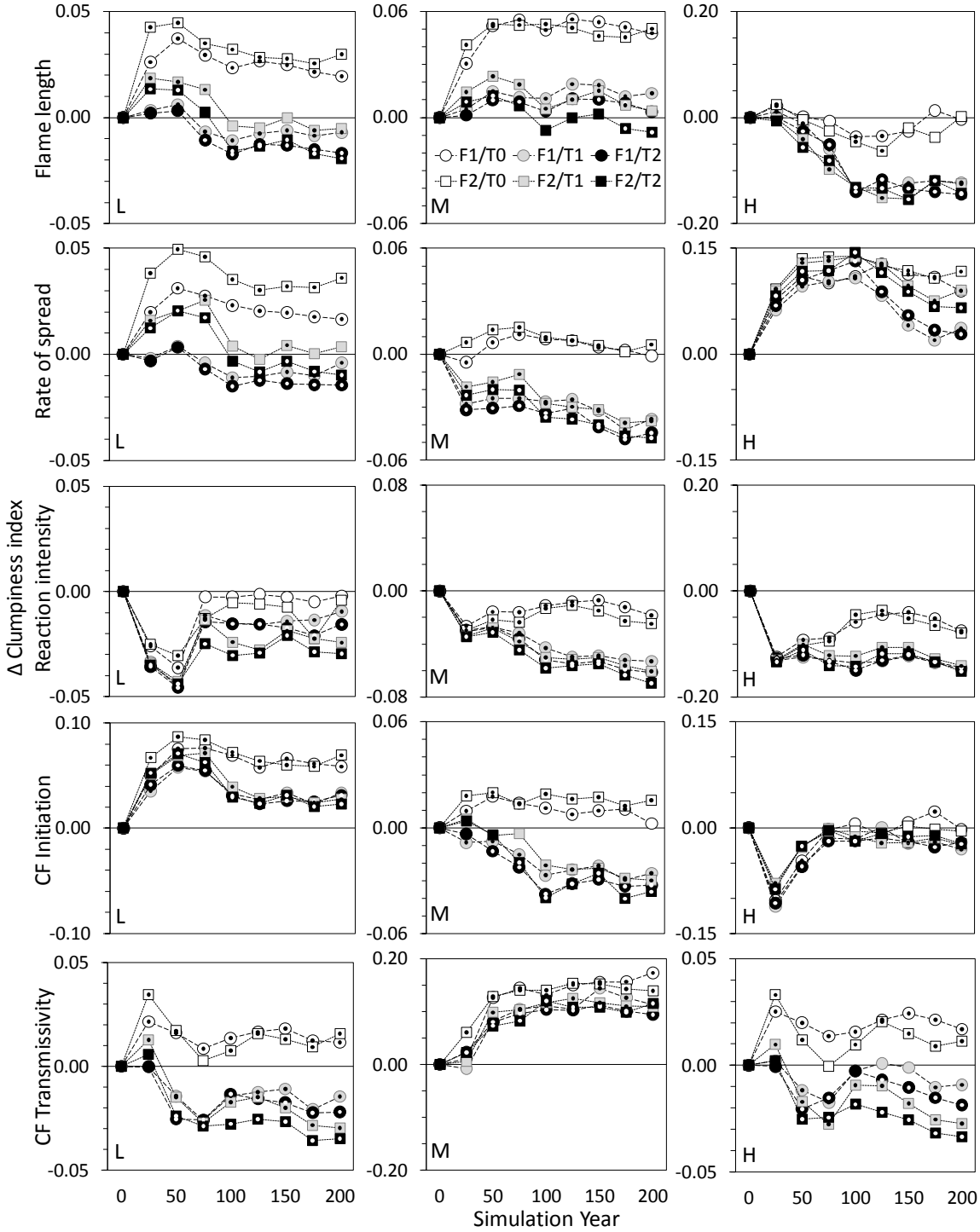

Figure 3.11. *Change in clumpiness index of patches of low (L), medium (M) and high (H) flame length (row 1), rate of spread (row 2), reaction intensity (row 3), crown fire initiation potential (row 4), and crown fire transmissivity potential (row 5) over time for replicated 200 year fuelbed succession simulations under combinations of current (F1) and elevated (F2) fire regimes, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest. Dots within symbols indicate a statistically significant departure from the initial (year 0) condition.*

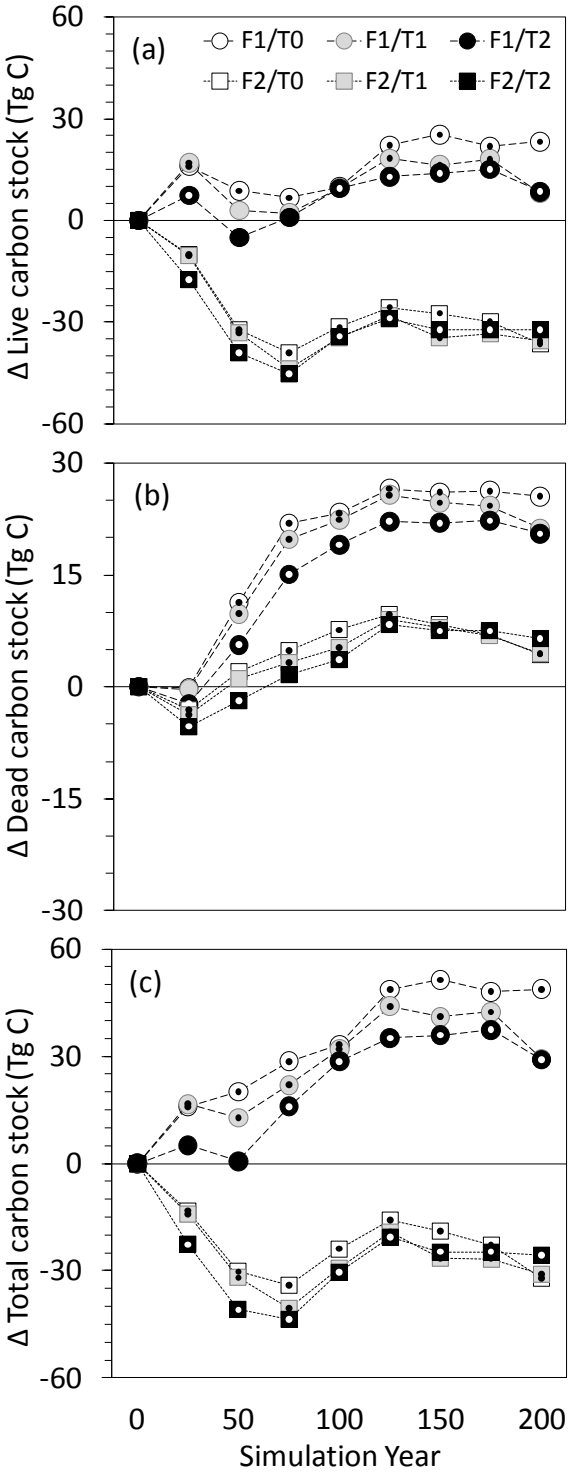

Figure 3.12. *Change in (a) live, (b) dead, and (c) total aboveground carbon stock over time for replicated 200 year fuelbed succession simulations under combinations of current (F1) and elevated (F2) fire regimes, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest. Dots within symbols indicate a statistically significant departure from the initial (year 0) condition.*

Table 3.1. *FCCS fuelbed successional pathways and landscape composition for the Okanogan-Wenatchee National Forest at the start of the simulation period. BS=Big sagebrush; DF=Douglas-fir; ES=Engelmann spruce; GF=grand fir; LP=lodgepole pine; MH=mountain hemlock; PP=ponderosa pine; PSF=Pacific silver fir; SF=subalpine fir; SL=subalpine larch; WBP=whitebark pine; WH=western hemlock; WL=western larch.*

Pathway	**Area occupied**		**Fuelbeds**
	ha	*percentage*	*number pathway*$^{-1}$
Dry DF, PP, GF	351,844	24.4	39
DF, Moist GF	129,056	9.0	17
Moist GF, WH	12,252	0.9	18
WH, PSF, MH	305,996	21.2	10
SF	97,404	6.8	10
Dry WH	188	< 0.1	7
LP	77,928	5.4	10
PP	19,136	1.3	41
WL	0	0.0	16
DF - Ninebark	11,432	0.8	11
PP, WL, DF	164	< 0.1	23
WL, DF	2,336	0.2	18
WL, DF, LP	11,056	0.8	18
WL, LP	28	< 0.1	5
ES, WBP, SL	177,556	12.3	5
Grass (high elevation)	97,334	6.8	2
Grass (low-mid elevation)	52,040	3.6	2
BS (high elevation)	63,108	4.4	5
BS (low-mid elevation)	32,140	2.2	5

Table 3.2. *Okanogan-Wenatchee National Forest data used to define fuelbed succession experiment treatments (fire and management regimes) and levels (contemporary and elevated). The contemporary fire regime reflects fire occurrence data from 1977 to 2006; the elevated fire regime represents a doubling of the total area burned per simulation. Management activities in successional pathways and simulations included: commercial harvest, commercial harvest followed by prescribed fire, thin (precommercial and commercial), thin (precommercial and commercial) followed by prescribed fire, prescribed fire only, and post-wildfire salvage. The contemporary management regime is based on management activity data from 2004 to 2008; the elevated management regime was derived by doubling the annual area of the contemporary management regime for each management activity. Whether precommercial or commercial thinning was simulated depended on the transitions associated with the fuelbeds chosen at random to receive the thinning.*

	Contemporary		**Elevated**	
Fire regime				
Natural fire rotation	149.4 yrs		74.7 yrs	
Fire frequency	4.3 yr^{-1}		6.1 yr^{-1}	
Mean fire size	2,520 ha		3,567 ha	
Fire size standard deviation	9089 ha		12,909 ha	
Log-normal mean fire size[a]	6.51 ha		6.86 ha	
Log-normal fire size standard deviation[a]	1.62 ha		1.63 ha	
Management regime	*number yr^{-1}*	*area (ha yr^{-1})*	*number yr^{-1}*	*area (ha yr^{-1})*
Commercial harvest	3	50	4	100
Commercial harvest + prescribed fire	2	50	3	100
Thin	15	1000	20	2000
Thin + prescribed fire	26	1500	36	3000
Prescribed fire only[b]	14	500	20	1000
Post-wildfire salvage	4	500	6	1000

[a] Parameter values for the log-normal distribution used for simulating individual fire sizes were calculated from equations 11 and 12, respectively, in Yang et al. (2004).

[b] In most years less than the prescribed number of hectares was treated owing to the rarity of fuelbeds for which 'prescribed fire only' was a management option.

Table 3.3. *Predicted fire behavior reclassification categories. Fire behavior categories were adapted from Rothermel (1983), Agee (1993), and Scott and Burgan (2005). Flame length, rate of spread, and reaction intensity are measures of surface fire intensity. The crown fire initiation potential is a relative measure of how readily a surface fire will transition to a crown fire, and the crown fire transmissivity potential is a relative measure of how readily crown-to-crown fire spread can occur (Schaaf et al. 2007).*

Fire behavior metric	**Low**	**Medium**	**High**
Flame length (m)	< 1.0	1.0-2.5	> 2.5
Rate of spread (m min^{-1})	< 1.5	1.5-3.5	> 3.5
Reaction intensity (kW m^{-2})	< 250.0	250.0-750.0	> 750.0
Crown fire initiation potential (0-9)	< 3.0	3.0-6.0	> 6.0
Crown fire transmissivity potential (0-9)	< 3.0	3.0-6.0	> 6.0

Table 3.4. *Initial (year 0) landscape class metrics for different fire potential attributes for the Okanogan-Wenatchee National Forest.*

Fire potential attribute	Class	Mean patch size (ha)	Percentage of landscape*	Clumpiness index
Flame length	L	223.8	44.2	0.64
	M	268.4	44.5	0.63
	H	28.9	0.3	0.53
Rate of spread	L	214.8	42.4	0.64
	M	275.1	40.5	0.67
	H	51.7	6.1	0.60
Reaction intensity	L	72.2	10.5	0.63
	M	403.4	55.4	0.63
	H	156.0	23.0	0.72
Crown fire initiation	L	94.4	24.1	0.59
	M	315.2	47.7	0.66
	H	132.3	17.2	0.71
Crown fire transmissivity	L	138.7	28.8	0.65
	M	36.3	4.4	0.54
	H	861.5	55.8	0.68

*Pixels with no fuels (i.e., rock, water, and ice) made up 11.0% of the original landscape and were assumed to be static for the duration of the simulations.

Table 3.5. *Simulated live, dead, and total carbon stock under combinations of current (F1) and elevated (F2) fire regimes, and no (T0), current (T1), and elevated (T2) management regimes over time for the Okanogan-Wenatchee National Forest. Values are mean ± standard deviation of 10 simulations per fire/management treatment combination.*

Fire/Mgt					**Simulation year**				
Level	**0**	**25**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
					Live carbon stock in Tg C (SD)				
F1/T0	171.2	187.3 (10.2)	180.0 (7.6)	177.9 (7.3)	181.1 (13.2)	193.4 (11.5)	196.5 (11.8)	193.0 (12.3)	194.4 (6.1)
F1/T1	171.2	188.2 (5.6)	174.2 (11.5)	173.4 (10.5)	180.8 (10.9)	189.5 (12.8)	187.6 (14.1)	189.3 (13.4)	179.2 (11.7)
F1/T2	171.2	178.6 (11.4)	166.2 (13.7)	172.0 (11.2)	180.7 (7.2)	184.1 (14.0)	185.2 (13.3)	186.3 (10.2)	179.7 (12.6)
F2/T0	171.2	161.1 (12.3)	138.9 (14.0)	132.2 (14.4)	139.7 (11.5)	145.6 (11.7)	143.9 (14.2)	141.3 (15.3)	134.8 (12.5)
F2/T1	171.2	160.9 (12.5)	138.1 (10.9)	127.5 (10.4)	136.7 (10.3)	143.0 (9.1)	136.6 (11.0)	137.7 (6.6)	135.8 (11.6)
F2/T2	171.2	153.8 (11.6)	132.1 (7.0)	126.0 (10.0)	137.0 (10.9)	142.3 (3.4)	139.0 (9.2)	139.0 (7.8)	139.0 (11.1)
					Dead carbon stock in Tg C (SD)				
F1/T0	72.3	72.2 (1.2)	83.6 (3.2)	94.2 (3.5)	95.6 (3.6)	98.8 (4.1)	98.3 (4.2)	98.5 (3.5)	97.8 (3.5)
F1/T1	72.3	71.9 (0.6)	82.1 (2.1)	92.1 (2.9)	94.7 (3.4)	98.0 (4.7)	97.0 (4.8)	96.5 (4.3)	93.5 (4.2)
F1/T2	72.3	70.0 (0.8)	77.9 (2.6)	87.4 (4.6)	91.3 (3.5)	94.5 (5.4)	94.2 (5.5)	94.5 (4.7)	92.8 (4.8)
F2/T0	72.3	69.2 (1.5)	74.3 (3.5)	77.1 (4.7)	79.9 (4.2)	82.0 (4.3)	80.6 (3.7)	79.3 (4.7)	76.6 (4.6)
F2/T1	72.3	68.5 (1.2)	73.4 (2.1)	75.6 (3.0)	77.5 (3.0)	81.2 (2.9)	80.2 (4.1)	79.2 (3.2)	76.7 (2.2)
F2/T2	72.3	67.0 (1.9)	70.5 (2.1)	73.8 (3.5)	75.9 (3.9)	80.6 (1.8)	79.8 (1.9)	79.8 (1.7)	78.8 (2.6)
					Total carbon stock in Tg C (SD)				
F1/T0	243.5	259.4 (11.3)	263.5 (10.2)	272.0 (9.6)	276.7 (15.9)	292.2 (14.6)	294.8 (15.2)	291.5 (13.7)	292.3 (8.7)
F1/T1	243.5	260.1 (5.9)	256.3 (13.3)	265.4 (12.3)	275.4 (13.2)	287.5 (17.3)	284.5 (17.6)	285.9 (17.0)	272.7 (15.2)
F1/T2	243.5	248.6 (12.0)	244.1 (16.1)	259.4 (15.5)	272.0 (10.3)	278.6 (19.1)	279.4 (18.2)	280.9 (14.0)	272.5 (16.7)
F2/T0	243.5	230.3 (13.5)	213.2 (16.8)	209.3 (18.3)	219.6 (15.2)	227.6 (15.3)	224.5 (17.4)	220.6 (19.4)	211.5 (15.4)
F2/T1	243.5	229.4 (13.5)	211.5 (11.8)	203.0 (12.4)	214.3 (12.6)	224.3 (11.0)	216.9 (14.5)	216.8 (8.3)	212.5 (13.1)
F2/T2	243.5	220.8 (13.1)	202.5 (8.3)	199.8 (11.9)	213.0 (14.0)	222.9 (3.6)	218.8 (10.7)	218.8 (8.8)	217.8 (13.1)

CHAPTER 4: FUEL CONSUMPTION IN SHRUB-DOMINATED ECOSYSTEMS

SUMMARY

Fuel consumption predictions are necessary to accurately estimate or model fire effects, including pollutant emissions during wildland fires. Fuel and environmental measurements on a series of operational prescribed fires were used to develop empirical models for predicting fuel consumption in big sagebrush (*Artemisia tridentata*) and pine flatwoods ecosystems. Models predicted independent consumption measurements within 2.2% (fall) and 5.1% (spring) for sagebrush fires, and 8.0% (dormant) and 67.2% (growing) for flatwoods fires. A general model for predicting fuel consumption in shrub-dominated types is also proposed.

INTRODUCTION

Regularly occurring fires are common and represent a natural process for numerous ecosystems in which shrubs are the primary form of combustible biomass. Past policies and management practices have contributed to altered vegetation structure and composition, accumulations of fuel, and changes to historical fire regimes (Tilman et al. 2000, Fellows and Goulden 2008). Recent wildfires in shrub-dominated types have exhibited extreme fire characteristics (intensity, severity, size) that may exceed the historical range of variability (Table 4.1). Recognition of fire as a keystone process in ecosystems generally, and in shrub-dominated types specifically, has led to an increase in the use of prescribed fire to preserve or enhance ecosystem properties (Hiers et al. 2007), promote specific compositional or structural changes (Beardall and Sylvester 1976, Outcalt and Foltz 2004, Moore et al. 2006, Bates et al. 2009), and reduce fuels and potential fire behavior to desired levels (Biswell 1989, Brose and Wade 2002, Raymond and Peterson 2005).

Despite the many potentially beneficial aspects of fire in ecosystems, pollutant emissions from wildland fires degrade air quality, potentially impairing visibility and

negatively affecting human health. The federal Clean Air Act regulates air pollutants, including emissions produced during prescribed fires (Sandberg et al. 2002). Measurements or estimates of emissions from fires are necessary to manage fire-related air quality impacts and to set, and assess compliance with, regulatory standards (Hardy et al. 2001a). Fires that occur in locations with high shrub fuel loading or that cover large areas of shrub-dominated vegetation can produce substantial emissions and degrade air quality (Phuleria et al. 2005, Hu et al. 2008).

Prescribed fires and wildfires are widespread in vegetation types where shrubs are the dominant fuel, including arid rangelands composed of various species of sagebrush (*Artemisia* spp.) and their associates; chaparral shrublands and woodlands; pocosins; coastal sage scrub; pitch pine (*Pinus rigida*) and oak (*Quercus* spp.) scrub; and pine forests in the southeastern United States (i.e., southern pine forests), especially longleaf pine (*P. palustris*), pond pine (*P. serotina*), and slash pine (*P. elliottii*) flatwoods types. Shrub biomass varies with site quality, species composition, and successional status. Standing shrub loading can exceed 10 Mg ha^{-1} in southern pine forests with shrubby understories (McNab et al. 1978, Ottmar and Vihnanek 2000, Ottmar et al. 2003), 20 Mg ha^{-1} in sagebrush and coastal sage scrub types (Ottmar et al. 2000), 40 Mg ha^{-1} in Western pine forests with shrub-dominated understories (Ottmar et al. 2004), and 100 Mg ha^{-1} in chaparral (Ottmar et al. 2000). A variable proportion of shrub biomass is consumed during fires (Hough 1968, Southern Forest Fire Laboratory Staff 1976, Wright and Prichard 2006). Quantifying and developing models to predict fuel consumption in big sagebrush and pine flatwoods ecosystems are the objectives of this study.

An increasing awareness of environmental issues by the public mandates that resource managers fully evaluate regulatory requirements and potential effects of land management decisions using the best available information. Furthermore, many shrub-dominated types occur adjacent to urban and suburban areas or serve as habitat for highly valued flora and fauna. Accurate assessments or estimates of fuel consumption

and related fire effects (i.e., emissions, altered vegetation structure and composition, nutrient flux) are important for estimating and mitigating potential human and environmental impacts of fires.

Prescribed fire is used in a wide variety of shrub-dominated ecosystems for a number of specific purposes, including, fuel and fire hazard reduction, wildlife habitat improvement, and ecosystem restoration (Biswell 1989, Wade and Lunsford 1989, Keeley et al. 2009). Linking the physical and mechanistic aspects of fuel and fire science to potential fire effects contributes to informed resource management for ecological benefit. Fire effects (e.g., smoke emissions, regional haze, nutrient cycling, plant succession, species composition changes, plant/tree mortality, wildlife habitat restoration and maintenance, erosion, soil heating, carbon fluxes, and nutrient cycling) are determined in large part by fuel characteristics and conditions, and the energy and other by-products released upon combustion. Quantification of fuel consumption in shrub-dominated vegetation types during prescribed fires and wildfires is therefore critical for modeling fire effects and for meeting management objectives for terrestrial and atmospheric resources.

Prescribed Fire and Big Sagebrush

In planning prescribed fire in big sagebrush ecosystems, one often needs to consider sage grouse (*Centrocercus urophasianus*) habitat and post-fire establishment of non-native grasses. Applied in select circumstances, prescribed fire can positively affect sage grouse (and other sagebrush-steppe fauna) by favoring important native perennial forb and grass species (Petersen and Best 1987, Crawford et al. 2004). Crawford et al. (2004) noted that fire's role in sagebrush-steppe ecosystems is complex, however, and can have very different impacts on landscape and vegetation, structure, recovery, and composition (and thus sage grouse and other wildlife habitat) depending on the floristic and environmental conditions of the vegetation communities in which it occurs.

Prescribed fire is widely used in western North America to limit tree establishment in sagebrush-steppe habitats, create a mosaic of vegetation conditions, and improve and reinvigorate grazed rangelands (Bock and Bock 1988, Severson and Rinne 1988, Holechek et al. 1995, Bates et al. 2009). Fires in sagebrush systems are frequently patchy, creating a mosaic of vegetation ages and structures at sub-meter to multiple-hectare scales, which tends to favor avian diversity (Wiens and Rotenberry 1981, Petersen and Best 1987, West 1999). Application of prescribed fire where size, severity, and spread can be controlled to some degree may maintain a patchy landscape structure in sagebrush-steppe habitats that limits potential wildfire size and severity by disrupting fuel continuity (Pellant 1999).

Prescribed Fire and Pine Flatwoods

In pine forests of the southeastern United States, prescribed fire is used to control excessive growth of understory and midstory vegetation in order to limit the accumulation of fuel, promote ecosystem restoration, and improve and maintain habitat for fire-adapted plants and animals (Wade and Lunsford 1989, Wade et al. 2000). Maintenance of southern pine forests through regular application of fire under conditions prescribed to minimize adverse impacts on site productivity limits fuel accumulation and also reduces potential severity of wildfires should they occur (Wade and Lunsford 1989, Abrahamson and Hartnett 1990).

Plant-species diversity in southern pine forests is promoted by frequent prescribed fire, and several wildlife species, including the federally endangered red-cockaded woodpecker (*Picoides borealis*) benefit from mature pine forests lacking a hardwood understory that are maintained by frequent, low-intensity surface fires (Wade and Lunsford 1989, Robbins and Myers 1992, Wade et al. 2000). Prescribed fire creates mineral seed beds necessary for longleaf, slash, and pond pine regeneration, releases suppressed species with small stature such as shiny blueberry (*Vaccinium myrsinites*) and dwarf huckleberry (*Gaylussacia dumosa*) that are otherwise overtopped by unrestrained

growth of taller understory species, and promotes flowering of wiregrass (*Aristida stricta*) and other important herbaceous species (Abrahamson and Hartnett 1990).

Southern pine flatwoods grow on minerally deficient soils where substantial quantities of nutrients become sequestered in live vegetation, such as saw palmetto and its associates, and pine needle litter that is relatively slow to decompose (Gholz and Fisher 1982, Hough 1982, Gholz et al. 1985, Abrahamson and Hartnett 1990). Prescribed fire accelerates nutrient turnover, releasing minerals in plant-available forms and stimulating nitrogen fixation by the post-fire biota, which compensates for nitrogen losses through volatilization (Lewis 1974, Wade and Lunsford 1989). Fire-induced effects on nutrient dynamics are thought to positively influence timber productivity over the long term, although there is conflicting evidence on this topic (Wade and Johansen 1986).

Fuel Consumption Research

Early research to quantify fuel consumption yielded empirical models for predicting consumption of dead and down woody material, leaf and needle litter (i.e., the O_i horizon), and duff (i.e., the O_e and O_a horizons, composed of fermented and decomposed organic material that develops beneath the O_i horizon). Initial investigations to quantify fuel consumption in the Pacific Northwest sought strategies for minimizing air pollution from prescribed burning for hazard reduction and site preparation following clearcut logging (Sandberg 1980, Ottmar et al. 1985). To improve the accuracy of emissions estimates, additional studies were conducted to determine the proportion of consumption that occurs during the flaming and smoldering phases of combustion under different environmental and fuel conditions (Ottmar 1983, Ferguson and Hardy 1994). These findings were extended to develop models for predicting fuel consumption of dead and down woody material, litter, and duff in unharvested coniferous forest types (Prichard et al. 2006).

Other research to quantify fuel consumption during prescribed fires using theoretical and empirical methods has been conducted primarily on dead and down woody, litter, and duff fuels in forested types in the Pacific Northwest and elsewhere (Sweeney and Biswell 1961, Van Wagner 1972, Brown et al. 1985, Little et al. 1986, Kauffman and Martin 1989, Reinhardt et al. 1989, Ottmar et al. 1990, Brown et al. 1991, Hall 1991, Reinhardt et al. 1991, Albini and Reinhardt 1997, Miyanishi and Johnson 2002). With the exception of a small part of the work of Hough (Hough 1968, Hough 1978, Hough and Albini 1978) and Ward (1983) in southern pine forests, very little research has documented consumption of understory vegetation.

In ecosystems where shrubs are the primary fuel, data and models for predicting fuel consumption (and emissions) from commonly or easily measured fuel and weather variables are scarce (i.e., Hough 1978, Wright and Prichard 2006). Estimates of fuel consumption and emissions from live shrub fuels are based primarily on expert opinion or rules-of-thumb. For example 50-90 percent of shrub fuels are predicted to be consumed in the First Order Fire Effects Model (FOFEM v5.5; Keane et al. no date) depending upon ecosystem type and season of burn regardless of fuel characteristics, fuel conditions, or fire weather, and 70 percent of shrub fuels are predicted to be consumed in CONSUME[7] v2.1 (Ottmar et al. no date), while a preliminary model for big sagebrush (Wright and Prichard 2006) is employed universally for all shrub types in CONSUME v3.0 (Prichard et al. no date). The *Southern Forestry Smoke Management Guidebook* (Southern Forest Fire Laboratory Staff 1976) does include tables for estimating 'available fuel' in southern pine forests, which is assumed here to be equivalent to predicted fuel consumption, under variable fuel loading and fuel moisture conditions. However, the *Guidebook* provides no scientific documentation for the contents of these tables, the data used to derive them, or the development of the relationships expressed.

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[7] CONSUME is decision-support software for prescribed fire practitioners and planners that predicts fuel consumption and emissions during prescribed fires and wildfires.

Inadequate models for predicting or estimating shrub fuel consumption may lead to inaccurate emissions estimates or inventories. Shrub consumption over-predictions could trigger unnecessary regulatory limitations on the use of prescribed fire in certain settings and circumstances. Similarly, estimates of fire-related emissions after an event may indicate a greater or lesser impact than was actually experienced. For example, Clinton et al. (2006) estimated emissions from seven large wildfires in southern California in 2003 by using the shrub fuel consumption model implemented in FOFEM (Keane et al. no date), which simply assumes that 80 percent of biomass is consumed in chaparral fuel types regardless of fuel characteristics, fuel conditions, or fire weather at the time and place of burning. Likewise, Stephens et al. (2007) used FOFEM to estimate emissions for the state of California prior to Euro-American settlement. They estimated that 38 percent of the land area (~16.02 million ha) and 55 percent of the annual area burned (~1.26 million ha) was in a variety of shrub-dominated vegetation types. Although analyses that employ an expert-opinion model may provide a crude emissions inventory, they lack a scientific foundation and fail to take into account variability of fuels and fire effects (specifically in these cases fuel loading and consumption), variability caused by location (i.e., fuel loading and characteristics), and variability related to the timing of fires (i.e., season, fuel moisture, and fire weather).

OBJECTIVE

Emissions of a particular pollutant from a fire are calculated as the product of the area burned, the mass of the fuel consumed per unit area burned, and an emission factor[8]. Total emissions are the sum of all pollutants emitted. Fuel consumption is the quantity of biomass fully combusted and converted to carbon gases, water vapor, other

[8] Emission factors are the ratio of the mass of a particular pollutant's emissions per unit mass of fuel consumed and vary depending upon combustion phase (flaming vs. smoldering) and fuel type (e.g., woody material vs. duff vs. sagebrush) but are considered constants when calculating pollutant emissions as a function of area burned and fuel consumption.

volatile gases, and airborne particulate matter, and is typically determined by measuring the difference between the pre-fire and post-fire fuel mass or loading. The ability to accurately predict fuel consumption enables fire, air-quality, and natural-resource professionals to plan for and manage smoke from fires, and to mitigate negative impacts associated with air pollution.

This study addresses a recognized knowledge gap in the ability of the fire science and management communities to predict fuel consumption during fires in shrub-dominated ecosystems. The objective of this research was to develop empirical models to predict fuel consumption for big sagebrush rangeland and pine flatwoods forest ecosystems based on field measurements of pre-fire fuel loading, composition and arrangement, day-of-burn fuel and weather conditions, and fuel consumption. Such models will be used to enhance the functionality of CONSUME (Prichard et al. no date) and its successors, which can allow for more informed and effective fire planning and fire use in these ecosystem types.

METHODS

STUDY AREAS

Study sites were located in big sagebrush rangelands in southeastern Oregon, northwestern Nevada, northwestern Wyoming, northern California, and western Montana, and in pine flatwoods forests in northern Florida and southern Georgia. Sagebrush sampling in western Montana was conducted to supplement the data from Oregon, Nevada, Wyoming and California, which were reported in Wright and Prichard (2006).

Sites were selected to span a range of fuel loadings and were burned under varying weather and fuel moisture to attempt to capture the range in fuel and environmental conditions typically encountered during operational prescribed burning activities in these ecosystems. Selection of sites to represent a wide range of conditions

within types maximizes the breadth of conditions for which application of the models reported here is appropriate. Although no wildfires were sampled for this project, the models should be applicable for wildfires (or wildland fire use fires) in which the fuel characteristics and environmental variables fall within the range of the data used to develop the models.

In total, fuel characteristics, fuel moisture content, fire weather, and fuel consumption were measured *in situ* on operational prescribed fires at 26 sites in 9 burn units in big sagebrush ecosystems, and at 31 sites in 16 burn units in pine flatwoods ecosystems (Table 4.2). In several instances, multiple locations were sampled within burn units. For burn units within which multiple locations were sampled, sites were selected to represent different fuel characteristics and conditions (e.g., vegetation coverage and composition, fuel loading, fuel moisture content). In multi-site burn units, sites were often widely separated (hundreds to thousands of meters), were ignited at different times or on different days during burning operations, and typically burned under different weather and fuel moisture conditions. Therefore, for modeling purposes, sites were considered independent observations even though some were nominally part of the same fire event.

Big sagebrush – Sites with a broad range of coverage and biomass of all three recognized subspecies of big sagebrush were sampled: Wyoming big sagebrush (*A. t.* ssp. *wyomingensis*), mountain big sagebrush (*A. t.* ssp. *vaseyana*), and basin big sagebrush (*A. t.* ssp. *tridentata*). Big sagebrush subspecies occur on sites with different ranges of precipitation; Wyoming big sagebrush occupies the driest sites (20 to 32 cm annual precipitation), mountain big sagebrush occupies the wettest sites (31 to 149 cm annual precipitation) and basin big sagebrush is found on intermediate sites (Francis 2004). In all cases, sampling occurred within the perimeter of larger operational units that were burned under a variety of fire weather and fuel moisture conditions during the fall and

spring (Table 4.3). Sampling occurred on moderate slopes on all aspects at elevations ranging from 1,331 to 2,356 m.

Pine flatwoods – Longleaf pine (*Pinus palustris)*, slash pine (*P. elliottii*), and pond pine (*P. serotina*) forests with a typical understory of predominantly saw palmetto (*Serenoa repens*) and gallberry (*Ilex glabra*) were sampled in northern Florida and southern Georgia. Sites included various mixtures of other common flatwoods species, including wiregrass (*Aristida stricta*) and runner oak (*Quercus margarettae*). Non-industrial forest managers may apply prescribed fire as often as every year in flatwoods, but more typically areas are burned on a three to four year cycle (Sackett 1975, Wade and Lunsford 1989). Sites sampled for this study had all been burned within the previous five years. Sites were sampled and burned during the dormant and growing seasons under a variety of fire weather and fuel moisture conditions (Table 4.4).

Data Collection

Fuel characteristics and consumption – Fuel mass, or loading, was measured by destructively sampling 9 to 18 pre-fire and 9 to 18 post-fire plots. *Plots* were systematically arranged in an evenly spaced grid pattern at *sites* with relatively uniform vegetation within the boundaries of planned prescribed burn *units*. Each set of plots characterized average fuels, vegetation, and consumption within a 0.5 to 1 ha site within burn units that ranged in size from tens to hundreds and even thousands of hectares. Within sites, vegetation uniformity was assessed visually, and sharp changes or discontinuities in composition and structure were avoided.

Fuels were collected or clipped at ground level from within a square plot frame that ranged in size from 1.0 to 4.0 m^2. Harvested and collected fuels were separated into different categories in the field. Categories included: grasses, forbs, live and dead shrub material by species or species group and size class (i.e., <2.5 and >2.5 cm stem diameter), dead and down woody fuels by size class (i.e., <0.6, 0.6-2.5, 2.5-7.6, and >7.6 cm diameter), and litter. Harvested or collected material was oven-dried to a constant

weight (100 °C for a minimum of 48 hours) and weighed directly or weighed undried in the field and adjusted to reflect ovendry weight by using moisture content subsamples that were representative of the field-weighed material.

Vegetation coverage is one measure of horizontal fuel continuity, and was estimated by lifeform category (grass, forb, and shrub coverage) using the line intercept method (Canfield 1941) along 152.4 or 304.8 m of transect per site. Grass, forb and shrub heights were measured at regular intervals within the sample site. Shrub coverage and height were recorded by species or morphologically similar species group where multiple shrub species were present. Proportion of the area burned by the fire was measured along transects that were offset 3 m from the original grid layout to assess the patchiness of each fire.

Fuel consumption was calculated as the difference between average pre-fire and post-fire loading by category of all of the plots that were harvested at a site, with the exception of non-sagebrush fuels (i.e., herbaceous vegetation, litter, and dead and down woody material) on sagebrush sites. Non-sagebrush fuel consumption was estimated by multiplying the average pre-fire biomass by the proportion of the area burned. Most non-sagebrush fuel is consumed during fires, however, because the non-sagebrush consumption was derived from pre-fire loading and proportion of the area burned (i.e., the response and predictors were not independent) rather than from direct measurements of pre- and post-fire loading I was unable to use regression to model non-sagebrush consumption.

Fuel moisture and fire weather – Multiple (n = 5 to 10) samples of different kinds of live and dead fuels were collected from within and adjacent to the plot area in airtight containers immediately prior to the fires to quantify fuel moisture content. This addressed the hypothesis that moisture content may be an important predictor of fuel consumption, especially among live fuels that typically only partially consume during fires. Fuel moisture samples were weighed shortly after being collected, oven-dried to a

constant weight (100 °C for a minimum of 48 hours), and re-weighed after oven drying to determine moisture content as a fraction of dry weight. A single set of fuel moisture samples were sometimes collected and used to represent multiple sites if they were close to one another and being burned at the same time.

Temperature, relative humidity, and wind speed were measured immediately prior to and every 15-30 minutes during burning operations with a sling psychrometer, a handheld electronic weather station, or an automated weather station. Temperature and relative humidity measurements made with the sling psychrometer and electronic or automated weather stations taken at the same time in the same location often differed. Psychrometer-measured values were used preferentially for consideration in predictive models as this is the device used most commonly to measure temperature and relative humidity by fireline personnel. Fire type (i.e., backing, heading, flanking) and fire behavior (flame length, rate of spread) were estimated visually and noted where safety allowed.

Ignition – The prescribed fires used for this study were operational in nature, so plots were burned during the course of daily firing activities. Burn units were either ignited by hand with drip torches or by helicopter with incendiary plastic spheres. In most cases plot areas were burned as heading or flanking fires that originated from either of the aforementioned ignition sources.

Data Analysis

Individual models – Ordinary least squares regression models were developed from measured fuel and environmental variables to predict fuel consumption in big sagebrush and pine flatwoods fuel types; the model for big sagebrush builds on the preliminary model of Wright and Prichard (2006). Pearson product moment correlation analysis and exploratory plots of response variables against predictors were used to evaluate the nature and strength of the relationships among variables (Table 4.5). Monotonic transformations (natural log, square root, and arcsine-square root) of the

response and predictor variables were examined and used if they helped linearize relationships and homogenize variance. Plots of the standardized residuals, quantiles of the normal distribution, and Cook's distance were examined to identify outliers and values with high leverage, and to determine whether the data and model met the assumptions of regression analysis (Neter et al. 1990, Gotelli and Ellison 2004). Sites that were outliers (i.e., standardized residuals greater than two standard deviations above or below the fitted value), or that exerted strong leverage (i.e., Cook's D > 0.4) were identified and removed for final model development to minimize the influence of extreme values on modeled relationships and to improve compliance with the assumption of regression that residual variance is homoscedastic. Model development and diagnostic analyses were performed in the R programming environment (R Development Core Team 2010).

Each model was developed by starting with the raw or transformed response and predictor variables that were the most strongly correlated. Additional predictor variables were added one at a time by using a manual forward selection procedure in which the raw or transformed variable with the most significant partial regression coefficient (i.e., the lowest p-value less than α_{crit}=0.10) was retained. This procedure continued until no significant predictors could be added. Variables with non-significant partial regression coefficients were also retained in some cases if there was a reasonable physical rationale to support their inclusion in the final model. The pool of possible predictors was limited to those that made sense based on underlying physical principles of fire behavior and heat transfer that were not collinear. Given the degree of freedom reduction that accompanies the addition of each predictor variable and the relatively small sample size, final models were selected to balance parsimony (three or fewer predictor variables) with variance explanation (maximized R^2). Predictive capability was evaluated by comparing modeled consumption estimates to independently

collected data (e.g., R.D. Ottmar unpublished data, Taylor and Wendel 1964, Kauffman and Cummings 1989, Sapsis and Kauffman 1991, Sparks et al. 2002).

General model – Fuel composition and arrangement vary in different shrub-dominated ecosystems; a model that employs generic variables to estimated fuel consumption would have the benefit of providing consumption estimates for fuel complexes where type-specific models are unavailable. Most fuels in shrub ecosystems are of small diameter, have high surface area-to-volume ratios, and therefore burn primarily during the flaming phase of combustion. Reaction intensity and fireline intensity are two measures of fire energy that are determined, in part, by the amount of fuel that is consumed during flaming combustion. Reaction intensity (I_R) is a measure of the rate of energy release per unit area of flaming fire front and is correlated with fire propagation and spread rate. Reaction intensity is function of net fuel consumption (w_n, mineral- and moisture-free loading of fuel particles <7.6 mm in diameter and a potential proxy for the variable in which we are interested), heat of combustion (h, adjusted for moisture and mineral content), the potential reaction velocity (Γ', a function of fuel particle size and arrangement), and the moisture (η_M) and mineral (η_s) damping coefficients of the burning fuels ($I_R = w_n h \Gamma' \eta_M \eta_s$; Rothermel 1972). Similarly, fireline intensity (I_B) is a measure of the rate of energy release in the flaming front per unit length of fire line. Fireline intensity is a function of heat of combustion (h), flaming fuel consumption (w_f, loading of fuel particles that contribute to flaming combustion and a potential proxy for the variable in which we are interested), and rate of spread (R) of the flaming front ($I_B = h w_f R$; Byram 1959). Byram (1959) also noted that flame length (L_f) could be approximated by fireline intensity ($L_f = 0.45\ I_B^{0.46}$); van Wagtendonk (2006) derived metric coefficients to approximate fireline intensity from flame length ($I_B = 258\ L_f^{2.17}$). Can estimates of modeled fire behavior (i.e., reaction intensity, fireline intensity, flame length, rate of spread) be used to predict fuel consumption given information about fuel quantity (i.e., loading), condition (i.e., moisture content), and characteristics

(i.e., surface-area-to-volume ratio, heat of combustion, mineral content) as implied by re-arranging Rothermel's equation for calculating reaction intensity ($w_n = I_R/h\Gamma'\eta_M\eta_s$) or Byram's equation for calculating fireline intensity ($w_f = I_B/hR$)?

Potential fire behavior was modeled for all big sagebrush and pine flatwoods sites based on pre-fire fuel loading, day-of-burn fuel conditions and fire weather, and slope by using the modified version of the Rothermel fire behavior model (Rothermel 1972, Sandberg et al. 2007) that is implemented in the Fuel Characteristic Classification System (FCCS; Ottmar et al. 2007a). In contrast to Rothermel's original formulation, which combines the bulk properties of all fuel components into single values describing the fuel characteristics, this modification considers the heat source and heat sink strength of the litter, woody, herbaceous, and shrub fuels individually and sums them to derive measures of fire behavior. Sandberg et al.'s (2007) modification, as implemented in the FCCS, frees users from the limitations of stylized fuel models and allows computation of fire behavior metrics from inventoried data. Reaction intensity, fireline intensity, flame length, rate of spread (and combinations suggested by re-arranging Rothermel's and Byram's intensity equations), and total fuel loading were considered as independent variables to explore the possibility of creating a general model to predict fuel consumption.

RESULTS

Data collection occurred at 26 big sagebrush and 31 pine flatwoods sites. Pre-fire fuel characteristics, fuel consumption, model form, and model performance are reported for big sagebrush and pine flatwoods separately, followed by results from an effort to develop a general model that could be used for any shrub-dominated type.

BIG SAGEBRUSH

Pre-fire fuel characteristics – Total pre-fire fuel loading for big sagebrush ranged from 5.3 to 23.6 Mg ha^{-1}; on average 76.0 percent of the total biomass present was shrubs

(Table 4.6). Big sagebrush sites had a variable but substantial percentage of dead shrub material (24.2 to 64.2 percent of total fuel loading). Shrub coverage ranged from 13.5 to 81.3 percent (Table 4.7), and vegetation stature, as measured by shrub height, averaged 0.3 to 0.9 m, although many plants were taller than the average height (Table B.5). The pre-fire herbaceous component ranged from 0.1 to 4.0 Mg ha^{-1} and 4.6 to 79.9 percent coverage (Tables 4.6 and 4.7). Most sites had little or no litter (0.2 to 2.7 Mg ha^{-1}), and variable amounts of woody surface fuels <7.6 cm diameter (0.2 to 3.1 Mg ha^{-1}, Table B.4).

Fuel consumption – Both the absolute amount of fuel consumed and the proportion of the pre-fire loading that was consumed varied from site to site (Table B.6). Shrub consumption ranged from 0.2 to 19.9 Mg ha^{-1}, and total biomass consumption ranged from 0.8 to 22.3 Mg ha^{-1} (Table 4.8). Big sagebrush prescribed fires were often patchy with 11.3 to 100 percent of the area burned. Area burned exceeded 85 percent on only 7 out of 26 sagebrush sites (Table 4.7). Season of burning did seem to influence consumption of the shrub fuels with greater consumption occurring on fall sagebrush fires. Most dead fuels and fine live fuels (i.e., grasses and forbs) were consumed in portions of the sites that burned, although it is unknown whether consumption of these fuelbed elements affected the amount of consumption of the adjacent and overtopping live shrub component.

Model variables – Multiple linear regression models for estimating fuel consumption by fuelbed component are reported in Table 4.9 and illustrated in Figure 4.1. An equation for estimating total fuel consumption is also included in Table 4.9 and illustrated in Figure 4.2a. Patchiness of the fire and the amount of pre-fire shrub loading were important for estimating shrub consumption. The proportion of the area burned was best modeled as a function of the coverage of fine live fuels, windspeed, slope, 10-hr fuel moisture content, and season of burn (Figure 4.3). Season of burn significantly improved models of shrub consumption for the big sagebrush type.

Most non-sage biomass is consumed when burned. Because post-fire non-sage biomass (i.e., herbaceous vegetation, litter, and dead and down woody fuel) was not measured directly, however, independence between the response and predictor variables was lacking. Data from Kauffman and Cummings (1989) were used to estimate the mean proportion of non-sage biomass consumed weighted by the proportion of the area burned by season (proportion consumed during spring fires = 0.80, proportion consumed during fall fires = 0.89; Table 4.10) to be able to predict consumption of the non-sage fuel component. Non-shrub consumption was modeled by multiplying the pre-fire loading by the proportion consumed and the proportion of the area burned, where the proportion consumed is chosen based upon the season of burning.

Model performance – Given the relatively small sample size (n = 26), I chose to use all data to develop the models rather than to split the data into separate sets for model development and model validation (Quinn and Keough 2002). Model performance was evaluated by comparing model predictions to measured values for two independently gathered data sets. Agreement between measurements and modeled estimates of fuel consumption was overall quite good (Table 4.10). Modeled consumption was within 2.7 and 5.1 percent of measured values on average for fall and spring big sagebrush fires, respectively (Kauffman and Cummings 1989, Sapsis and Kauffman 1991).

PINE FLATWOODS

Pre-fire fuel characteristics – Total pre-fire fuel loading ranged from 4.6 to 23.7 Mg ha^{-1} (Table 4.6). Shrub biomass, including various species of woody-stemmed shrubs and saw palmetto, was on average only 32.9 percent of total biomass; 87.3 percent on average was live (Table B.11). Shrub coverage ranged from 24.4 to 100 percent (Table 4.7), and vegetation stature averaged 0.3 to 1.2 m as measured by shrub and saw palmetto height, although many plants were taller than the average height (Table B.12). The pre-fire herbaceous component ranged from <0.1 to 3.7 Mg ha^{-1} and 0.6 to 62.6

percent coverage (Tables 4.6 and 4.7). Litter loading was half of total loading on average (Table B.11), and ≤7.6 cm diameter woody surface fuels ranged from 0.2 to 3.1 Mg ha^{-1}.

Fuel consumption – Both the absolute amount of fuel consumed and the proportion of the pre-fire loading that was consumed varied from site to site (Tables B.6 and B.13). Shrub consumption ranged from 0.2 to 6.3 Mg ha^{-1}, and total biomass consumption ranged from 1.3 to 15.7 Mg ha^{-1} (Table 4.8). Area burned exceeded 85 percent on all flatwoods sites, with one exception (Table 4.7). Season of burning did influence consumption of the shrub fuels; greater consumption occurred for growing season (i.e., spring/summer) fires. Most (mean 86.1 percent) fine dead (dead saw palmetto, litter, and <0.6 cm woody material) and fine live fuels (grasses and forbs) were consumed, although it is unknown whether consumption of these fuelbed elements affected the amount of consumption of the dominant woody shrub and live saw palmetto components.

Model variables – Multiple linear regression models for estimating fuel consumption by fuelbed component are reported in Table 4.9 and illustrated in Figure 4.4. An equation for estimating total fuel consumption is also included in Table 4.9 and illustrated in Figure 4.2b. Pre-fire shrub loading was the variable with the greatest predictive power in shrub consumption equations for flatwoods sites. Season of burn significantly improved the model for shrub consumption. Non-shrub vegetation was almost entirely consumed in burned areas; non-shrub vegetation consumption was modeled as the sum of pre-fire grass and herbaceous vegetation loading multiplied by the average proportion consumed (i.e., mean 0.9944 for sites in which >85 percent of the site burned), and the proportion of the area burned for the rare cases when burned area is <85 percent. Loading and moisture content were significant predictors in litter (litter loading and litter moisture) and down woody fuel (total woody fuel loading and 10-hr fuel moisture) consumption models.

Model performance – Given the relatively small sample size (n = 31), I chose to use all data to develop the models rather than to split the data into separate sets for model development and model validation (Quinn and Keough 2002). Model performance was evaluated by comparing model predictions to measured values for several independently gathered data sets. Agreement between measurements and modeled estimates of fuel consumption were overall quite good (Table 4.10). For dormant season flatwoods fires, modeled values were within 8.0 percent on average (R.D. Ottmar unpublished data, Sparks et al. 2002). For growing season flatwoods fires, modeled values overestimated consumption for the fires for which I had independently collected data (pond pine pocosin and shortleaf pine-mixed oak) by 67.2 percent on average (Taylor and Wendel 1964, Sparks et al. 2002).

General Model

I explored whether the relationships defined by Rothermel (1972) and Byram (1959) that, as a function of consumed fuel, fire behavior could be used to model fuel consumption in a general sense. Predicted rate of spread, flame length, reaction intensity, and fireline intensity ranged from <0.01 to 0.51 m sec^{-1}, 0.2 to 4.7 m, 481 to 1,788 kW m^{-2}, and 9 to 7,290 kW m^{-1}, respectively for sagebrush sites (Table B.3) and from <0.01 to 0.03 m sec^{-1}, 0.1 to 0.9 m, 162 to 1,372 kW m^{-2}, and 3 to 228 kW m^{-1}, respectively for flatwoods sites (Table B.10) using measured fuels data, day-of-burn fuel moisture and windspeed measurements, and actual slope for each site as inputs for the modified Rothermel (1972) fire behavior equations (Sandberg et al. 2007) encoded in the Fuel Characteristic Classification System (Ottmar et al. 2007a). Fireline intensity divided by rate of spread (I_B/R), the quantity suggested by rearranging Byram's (1959) equation, was a significant predictor of fuel consumption (Table 4.9 and Figure 4.5), but explained only approximately 11 percent of the variability in the observations. The relationship between fire behavior and fuel consumption appears to differ for the two shrub-dominated fuel types sampled for this study (Figure 4.5).

DISCUSSION

Post-fire fuel loading and fuel consumption are a function of the amounts of three fuel states in a given area: (1) unburned, (2) burned and fully combusted, and (3) burned but only partially combusted. Accounting for the proportion of the area that burns and the proportion of the pre-fire loading that is consumed in the areas that burn are therefore important for generating an accurate estimate of overall unit-wide fuel consumption. I chose to model total fuel consumption as the sum of consumption predictions for each fuelbed component. I also developed models that predicted total fuel consumption from total loading for both big sagebrush and pine flatwoods, and a general model that could, hypothetically, be used for any shrub-dominated type provided that fuel loading and potential fire behavior fall within the range of the data sampled as part of this study.

BIG SAGEBRUSH

Proportion of area burned – Prescribed fires (and wildfires) can create a mosaic of burned and unburned patches in some ecosystems or burn the entire area in others. Whether a fire is patchy or continuous appears to be related to the horizontal continuity of fine fuels. Patchy prescribed fires are common (and even objectives of fire and resource management and burning operations) in sagebrush ecosystems. Thus, determining how much of an area is likely to burn is key in big sagebrush ecosystems. Models for predicting proportion of area burned during spring fires and fall fires were similar to the model proposed by Wright and Prichard (2006), and include variables that are readily available to resource managers (Table 4.9): coverage of herbaceous vegetation, 10-hr fuel moisture content, windspeed, and slope.

Windspeed and slope are important drivers of fire spread (Rothermel 1972, Albini 1976); when in alignment, wind amplifies the effect of slope in rate of spread models (Curry and Fons 1938, Fons 1946, Weise and Biging 1997, Nelson 2002). The

windspeed × slope (or slope category) variable in the models to predict proportion of area burned is meant to reflect this complementary effect of aligned wind and slope on successful fire spread; it is included as a combination variable rather than as a statistical interaction. The slope category multiplier incorporated into the equation for spring fires is comparable to the values suggested by Brown (1982) for rate of spread.

Fine herbaceous fuels provide a vector for fire spread (Britton et al. 1981), and may be particularly important where the distance between big sagebrush plants is too far, or the heat transfer and flame contact effect of windspeed and slope is insufficient to sustain fire spread. These models will allow fire planners to develop site-specific prescriptions that are likely to meet their management objectives with respect to fire coverage or patchiness (and subsequent fuel consumption and emissions production) across a range of conditions in big sagebrush ecosystems. For example, where and when fire is an appropriate landscape treatment, prescriptions can be developed for specific projects and for coordinated groups of projects to preserve a desired level of shrub coverage for sage grouse or other sensitive wildlife species at a variety of spatial and temporal scales (Crawford et al. 2004). At the same time, these models can be used to assess potential air quality, site hydrology, erosion, and range quality impacts associated with fuel consumption, which causes an immediate fire-induced loss of vegetative biomass, and a subsequent shift from dominance by shrubs to dominance by herbaceous vegetation immediately following fire that can persist for several decades (Paysen et al. 2000, Bates et al. 2009).

Fuel consumption models – Pre-fire biomass was consistently the most important variable for predicting fuel consumption for all fuelbed components. Pre-fire biomass can be determined directly from field measurements using allometric (e.g., Brown 1982, Frandsen 1983) or destructive methods, or it can be estimated using published guides (Ottmar et al. 2000, Ottmar et al. 2007b) or expert knowledge. Fuel amount was the strongest predictor variable, but variation in fuel condition (i.e., dead fuel moisture

content) and environment (i.e., season, windspeed, slope) increased or decreased the proportion of the area burned and subsequent fuel consumption, probably because of their effects on the energetics of the combustion process. That is, burning drier fuels under windier conditions on steeper slopes during the fall enhanced fire spread and increased fuel consumption.

Live fuel moisture affects flammability and fire behavior, but it was generally not correlated with fuel consumption for big sagebrush, as one might expect based on the importance of moisture content as a predictor for consumption of dead fuels (e.g., Sandberg 1980, Sandberg and Ottmar 1983, Little et al. 1986, Harrington 1987, Brown et al. 1991). In this regard, the findings of this study agree with other studies in shrub-dominated ecosystems that also failed to observe a relationship between live fuel moisture and live fuel consumption (Hough 1978, Bilgili and Saglam 2003, Wright and Prichard 2006).

Season of burn and weather have been shown to affect fire behavior, fire effects and vegetation response following fire (Bragg 1982, Brown 1982, Sparks et al. 2002, Outcalt and Foltz 2004), which suggests that they may also have an effect on fuel consumption. In fact, Ottmar et al. (1990) were better able to predict consumption of large woody fuels (1000-hr and larger) upon discovering that they responded differently under spring vs. summer fuel moisture and burning conditions. Season of burn was an important predictor of proportion of area burned and of consumption of shrub fuels in big sagebrush types. Day-of-burn weather observations were not useful for predicting fuel consumption, although windspeed was an important variable in the equations for predicting how much of an area was likely to burn. The inclusion of season in the consumption prediction models may have effectively captured the long- and short-term fluctuations in weather and fire environment that instantaneous day-of-burn weather and fuel moisture measurements did not. Seasonal differences may represent a threshold effect on fuel consumption in a manner that different continuous observations

of fire weather (i.e., temperature, relative humidity, days since rain, etc.) and fuel condition (live and dead fuel moisture content) cannot.

Addition of spring prescribed-fire data and inclusion of season as a categorical predictor for big sagebrush systems expanded the range for which the model is applicable and improved upon the model performance reported by Wright and Prichard (2006) as measured against the same independent data set.

Fire type (i.e., heading vs. backing vs. flanking) has a pronounced effect on fire behavior and may also influence fuel consumption (Sackett 1975, Brown 1982). The sites sampled for this study were burned during operational prescribed fires, however, and I had no control over how burn sites were ignited or the type of fire used in their burning. Given this limitation, I was not able to investigate whether fire type, lighting method, or firing pattern affected fuel consumption. Further data collection with a more experimental approach to control fuel characteristics, fuel conditions, and fire weather would be necessary to better understand the effects of fire type and application method on fuel consumption.

PINE FLATWOODS

Proportion of area burned – Prescribed fires (and wildfires) typically burn the entire area in pine flatwoods (Abrahamson and Hartnett 1990 , personal observation), due to the horizontal continuity of vegetation and fine live and dead fuels. However, variation in vegetation composition with subtle changes in topography, hydrology, soils, and disturbance history create patches of unburned vegetation in the larger landscape mosaic, leaving refugia and recolonization sites for flora and fauna.

Fuel consumption models – Pre-fire biomass was consistently the most important variable for predicting fuel consumption for all fuelbed components. Pre-fire biomass can be determined directly from field measurements using allometric (e.g., McNab et al. 1978, Gholz et al. 1999) or destructive methods, or it can be estimated using published guides (Southern Forest Fire Laboratory Staff 1976, Albrecht and Mattson 1977, Wade et

al. 1993, Ottmar and Vihnanek 2000, Ottmar et al. 2003) or expert knowledge. Fuel amount was the strongest predictor variable, but variation in fuel condition (i.e., dead fuel moisture content) and environment (i.e., season) increased or decreased fuel consumption, probably because of their effects on the energetics of the combustion process. That is, more fuel was consumed when fuels were drier or when sites burned during the growing season when ambient temperatures are typically higher.

Live fuel moisture affects flammability and fire behavior, but it was generally not correlated with live fuel consumption for pine flatwoods as one might expect based on the importance of moisture content as a predictor for consumption of dead fuels (e.g., Sandberg 1980, Sandberg and Ottmar 1983, Little et al. 1986, Harrington 1987, Brown et al. 1991). In this regard, the findings of this study agree with other studies in shrub-dominated ecosystems that also failed to observe a relationship between live fuel moisture and live fuel consumption (Hough 1978, Bilgili and Saglam 2003, Wright and Prichard 2006), however, live shrub stem moisture did slightly improve the coefficient of determination of the model to predict consumption of total aboveground biomass.

Season of burn and weather have been shown to affect fire behavior, fire effects and vegetation response following fire (Bragg 1982, Brown 1982, Sparks et al. 2002, Outcalt and Foltz 2004), which suggests that they may also have an effect on fuel consumption. In fact, Ottmar et al. (1990) were better able to predict consumption of large woody fuels (1000-hr and larger) upon discovering that they responded differently under spring vs. summer fuel moisture and burning conditions. Season of burn was an important predictor of consumption of shrub fuels in flatwoods. Day-of-burn weather observations were not useful for predicting fuel consumption, although the inclusion of season in the prediction models may have effectively captured the long- and short-term fluctuations in weather and fire environment that instantaneous day-of-burn weather and fuel moisture measurements did not. Seasonal differences may represent a threshold effect on fuel consumption in a manner that different continuous observations

of fire weather (i.e., temperature, relative humidity, days since rain, Keetch-Byram Drought Index, etc.) and fuel condition (live and dead fuel moisture content) cannot.

The models predicted fuel consumption for the independent flatwoods data very well for dormant season prescribed fires (Table 4.10), and with limited success for the growing-season fires. The independent growing season fire data are from fires in the southeastern United States, but not in flatwoods fuel types (pond pine pocosin and shortleaf pine-mixed oak), so do not represent good test cases, perhaps explaining the large differences between observed and modeled consumption.

Fire type (i.e., heading vs. backing vs. flanking) has a pronounced effect on fire behavior and may also influence fuel consumption (Sackett 1975). Experimental burning trials in saw palmetto-gallberry fuels in the southeastern United States (Hough 1968, Southern Forest Fire Laboratory Staff 1976, Hough 1978) were equivocal with respect to differences in fuel consumption between backing and heading fires. The sites sampled for this study were burned during operational prescribed fires, and I had no control over how burn sites were ignited or the type of fire used in their burning. Given this limitation, I was not able to investigate whether fire type, lighting method, or firing pattern affected fuel consumption. Further data collection with a more experimental approach to control fuel characteristics, fuel conditions, and fire weather would be necessary to better understand the effects of fire type and application method on fuel consumption.

The models presented here can be used to provide rigorous estimates of fuel consumption and changes in aboveground biomass in the post-fire environment. In addition to providing information critical for assessing changes in fire hazard, fire risk (Wade and Lunsford 1989, Abrahamson and Hartnett 1990, Brose and Wade 2002), and air quality impacts (Hu et al. 2008, Tian et al. 2008), better estimates of fuel consumption are important for assessing heat, nutrient, and carbon fluxes and their impacts on productivity (Gholz et al. 1985, Wade and Johansen 1986, Outcalt and Foltz 2004).

General Model

Albini (1975) tested whether consumption of duff fuels was driven by the energy flux from burning logging slash, but was unable to show a correlation with measured and modeled heat release from two sites in Montana despite supporting evidence that this might be the case. He speculated that reaction intensity (Rothermel 1972) represented the flaming combustion of fine fuels, while the bulk of the heat load in slash fuelbeds is contributed by the larger woody fuel particles that are not well represented. I investigated whether estimates of modeled fire behavior could be used in models to estimate fuel consumption in shrub-dominated fuel types. This approach yielded a significant model with a term for fireline intensity divided by rate of spread, although the proportion of the variance explained was much lower than for component-specific or type-specific models (Table 4.9). Compared to logging slash, fuel consumption in shrub-dominated fuel complexes occurs mostly during the flaming phase of combustion, offering one possible explanation for why this study found a relationship, albeit weak, where Albini (1975) did not. The relatively weak relationship between fireline intensity and total fuel consumption observed in this study, however, may indicate that more glowing and smoldering combustion occurs than one might be led to believe from simple visual observation of fires in shrub-dominated fuel types.

Models for predicting fire intensity and spread are based on laboratory fires in artificial fuelbeds (e.g., Byram 1959, Rothermel 1972, Sandberg et al. 2007) and thus assume that fuel characteristics and conditions are homogeneous. This may be a reasonable assumption for ecosystems in which the predominant fuel is made up of a uniform and continuous layer of needles or leaves, however, fuelbeds in many ecosystems exhibit considerable spatially heterogeneity as is frequently the case in which shrubby vegetation makes up some or all of the available fuel. Thus, modeled fire behavior may not be a perfect (or even a marginal) reflection of the actual fuel characteristics and conditions, which may also contribute to the relatively low

correlation between fuel consumption and modeled estimates of fire behavior that were observed in this study.

A general model to predict fuel consumption from modeled estimates of fire behavior was intended for use in ecosystems that lack type-specific fuel consumption models. Fire behavior is affected by fuel structure as well as amount (Cheney 1990, Catchpole et al. 1993), however, and the relationship between modeled fire behavior and fuel consumption appears to be different for big sagebrush and flatwoods types. Flatwoods fires were modeled to be less intense and spread more slowly for comparable levels of consumption (Figure 4.5). Although the observed range of consumption was similar for sagebrush and flatwoods fires, a portion of the consumed fuel was composed of needle litter in flatwoods fires, whereas consumed fuel was almost exclusively shrubby and herbaceous vegetation in sagebrush fires. Being more tightly packed than vegetation, the pine litter component in flatwoods fuelbeds may effectively dampen modeled fire behavior compared to big sagebrush for equivalent amounts of fuel consumption (Nelson and Adkins 1986).

MANAGEMENT IMPLICATIONS

Big sagebrush and pine flatwoods fuels are composed and arranged differently yet have comparable overall fuel loadings (Table 4.6). Despite differences in fuel and environment (arid vs. humid), total pre-fire loading is the most important variable for predicting total fuel consumption for both fuelbed types. Type-specific models to predict total fuel consumption explained as much or more of the variance in the data as models for individual fuelbed components, but they were not as good at modeling independent data (Table 4.10), sometimes by a large amount.

The models presented here are based on correlations between field-measured variables; they do not prove cause and effect. Such models are considered phenomenological in that the response (i.e., fuel consumption and proportion of area burned) is statistically related to physically sensible explanatory variables using

observational data, but the mechanisms are not measured or modeled directly (e.g., Higgins et al. 2008). Variables were considered for inclusion in the final models only if there was a reasonable physical explanation for the modeled correlation. For example, consumption of litter and woody fuels in flatwoods decreases with increasing fuel moisture content as has been observed by others, and as one might expect from the principles governing ignition, pyrolysis and combustion. Similarly, windspeed and slope are included in models for predicting proportion of area burned as they influence convective and radiant heat transfer and flame contact to adjacent unburned fuels affecting the spread of fire. Differences between the scale of the processes that influence fuel combustion and consumption (i.e., at the fuel particle scale) and the variables that are being used as a proxy for those processes (i.e., at the plot/stand scale) may affect the amount of variability that is explained by each model.

Land managers utilize prescribed fire to achieve a variety of objectives. Regardless of the objective, and whether they are prescribed or wild, however, fires consume biomass and produce smoke. Consumption of dead and living biomass during wildland fires has the potential to alter ecosystem structure, composition, and function in a variety of ways, and the resulting emissions have the potential to impact air quality, visibility, and human health and safety.

This study documented the physical conditions that influence live shrub consumption, and led to models that will improve fuel consumption predictions during prescribed fires in big sagebrush and pine flatwoods ecosystems. Fire managers will be able to develop data-based estimates of fuel consumption based on quantitative information rather than relying on expert opinion and the 'rules-of-thumb' that are currently used. More accurate estimates of consumption will contribute to better estimates of emissions during prescribed fires in two widespread and commonly burned shrub-dominated types. Empirically based fuel consumption estimates will (1) allow

fire practitioners to employ smoke management techniques[9] that utilize an understanding of the effects of varying fuel and environmental conditions on the amount of fuel consumed, (2) improve emissions and air quality inventories and models that are based on inadequate fuel consumption models, and (3) develop fire management prescriptions to meet ecological and resource management objectives. The ability to predict the consumption of fuels of a variety of types, amounts, arrangements, and moisture contents under different burning conditions will allow fire, land, and air quality managers in jurisdictions with big sagebrush and pine flatwoods fuel types to better plan for and if necessary mitigate the effects of prescribed fires and anticipate the effects of wildfires.

[9] Common smoke management techniques seek to minimize the overall amount of fuel consumed and/or to minimize the amount of smoldering combustion that occurs. For forested types this can involve burning under conditions when larger fuels and/or duff are relatively wet to minimize overall consumption or altering ignition patterns to maximize the amount of consumption that occurs during the more efficient flaming phase of combustion.

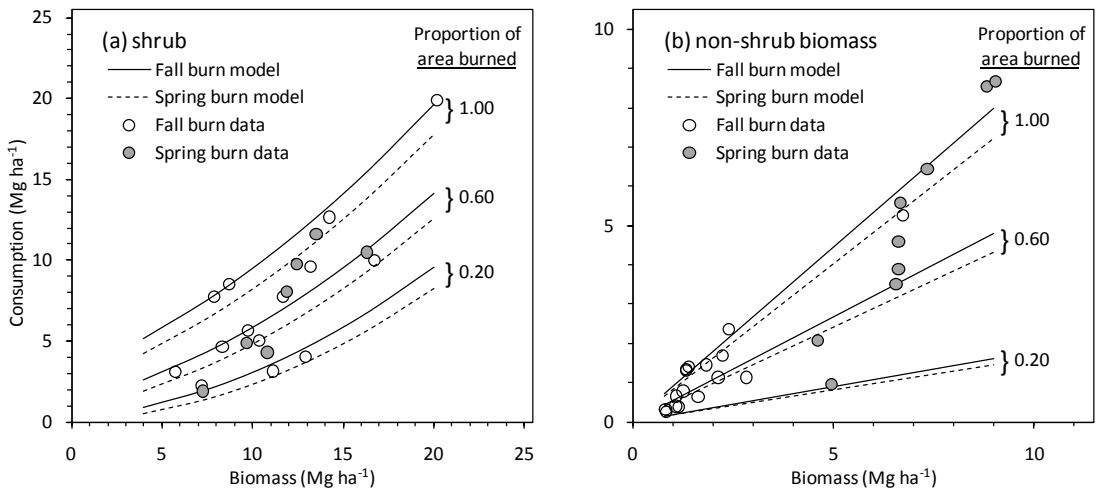

Figure 4.1. *(a) Multiple linear regression model showing shrub consumption as a function of pre-fire shrub biomass and season of burn for a range of values of proportion of area burned for big sagebrush ecosystems. (b) Simple relationship proposed for estimating non-shrub fuel consumption (litter, dead and down woody fuel, and herbaceous vegetation) as a function of proportion of area burned and season of burn for big sagebrush ecosystems.*

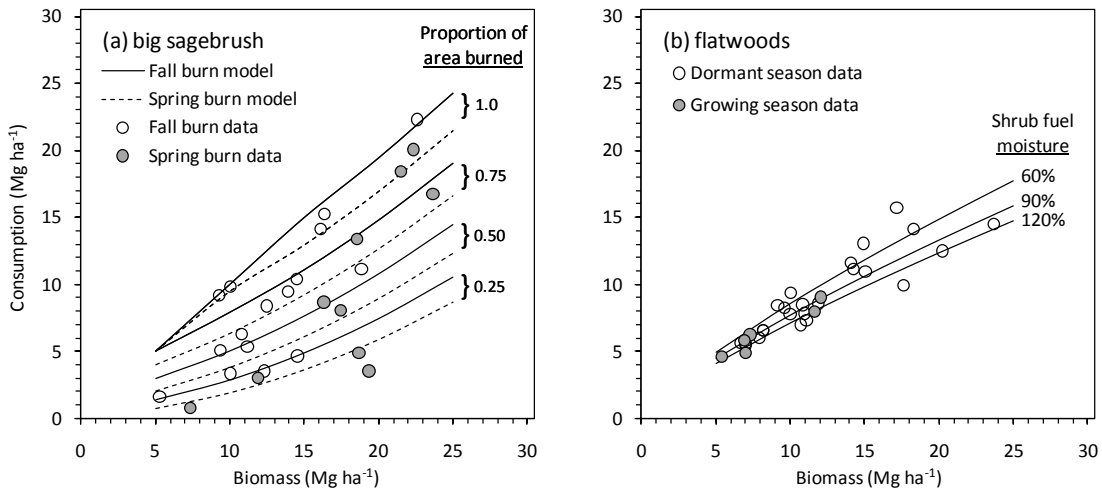

Figure 4.2. *Multiple linear regression models showing (a) total aboveground biomass consumption in big sagebrush systems as a function of pre-fire biomass and season of burn for a range of values of proportion of area burned, and (b) total aboveground biomass consumption in flatwoods systems as a function of pre-fire biomass for a range of values of live shrub fuel moisture.*

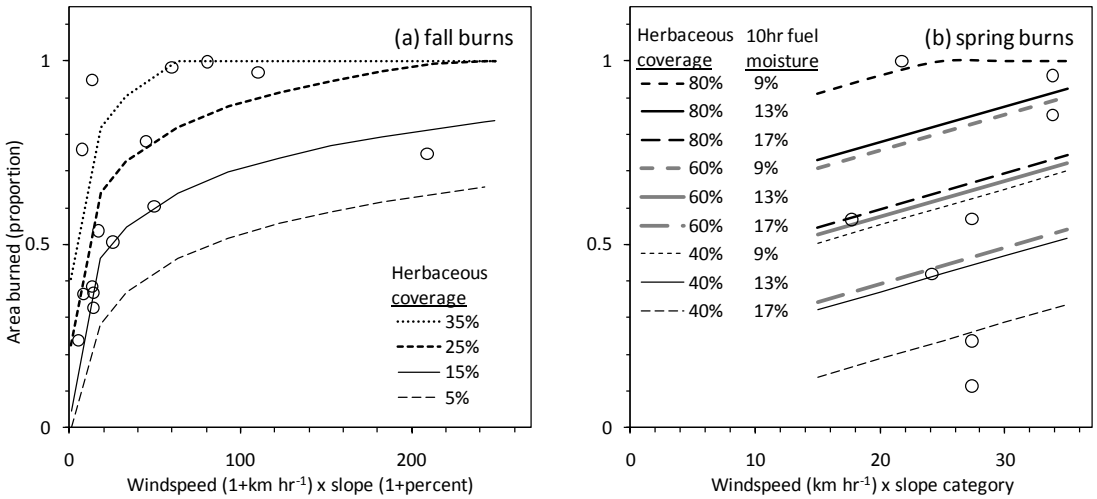

Figure 4.3. *Multiple linear regression models showing proportion of area burned in big sagebrush systems for (a) fall burns as a function of windspeed and slope for a range of values for herbaceous species coverage, and (b) spring burns as a function of windspeed and slope category for a range of values of herbaceous species coverage and 10-hr fuel moisture. See footnote in Table 4.9 for definition of slope categories.*

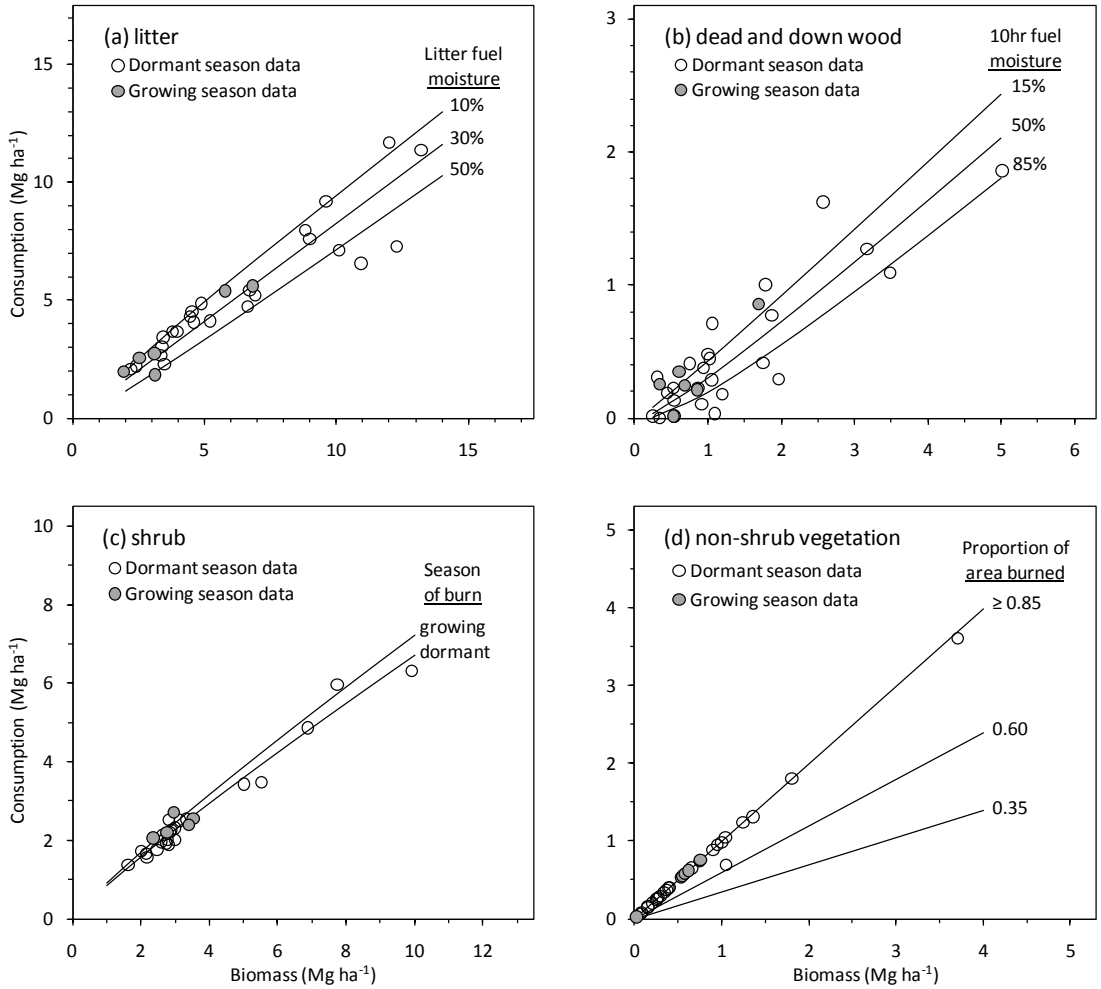

Figure 4.4. *Multiple linear regression models showing (a) litter consumption as a function of pre-fire litter biomass for a range of values of litter fuel moisture, (b) dead and down woody fuel consumption as a function of pre-fire woody fuel biomass for a range of values of 10hr woody fuel moisture, and (c) shrub consumption (including saw palmetto) as a function of pre-fire shrub biomass and season of burn for pine flatwoods ecosystems. (d) A simple relationship proposed for estimating non-shrub vegetation (i.e., grasses and forbs) consumption as a function of pre-fire non-shrub vegetation biomass for a range of values of proportion of area burned for pine flatwoods ecosystems.*

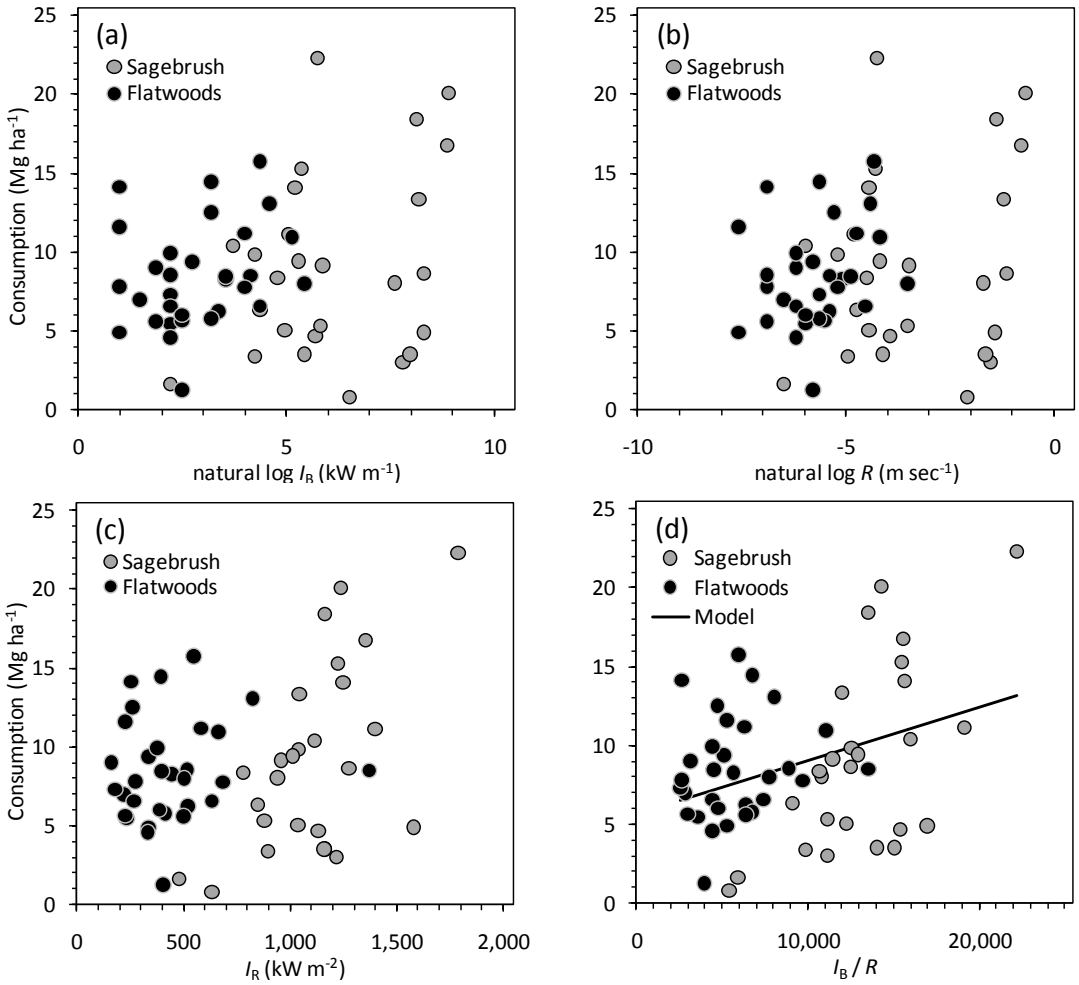

Figure 4.5. *Scatter plots depicting the relationship between total aboveground fuel consumption and (a) fireline intensity (I_B, in kW m^{-1}), (b) rate of spread (R, in m sec^{-1}), (c) reaction intensity (I_R, in kW m^{-2}), and (d) fireline intensity divided by rate of spread as predicted by the Fuel Characteristic Classification System using actual fuel characteristics, fuel conditions, slope, and weather data. The general fuel consumption model based on fireline intensity divided by the rate of spread is indicated in panel (d). Fireline intensity and rate of spread were natural log transformed for clarity of display.*

Table 4.1. *Recent examples of uncharacteristic wildfires in several widespread shrub-dominated ecosystems. While large wildfires are common in California chaparral, the Cedar and Zaca fires are notable because of their uncharacteristic cost, duration, and the amount of damage they caused to private property.*

Fire name	Year	Size (ha)	Fuel type	Location	Notable features
24 Command/ Two Forks	2000	66,297	Sagebrush	Eastern WA	Extremely rapid fire spread; burned in three days
Cedar	2003	113,424	Chaparral	East of San Diego, CA	Largest in California history; 15 fatalities; burned 2,820 buildings
Zaca	2007	97,208	Chaparral	North of Santa Barbara, CA	$118.3 mil suppression costs; 118 days from ignition to containment
Warren Grove	2007	6,800+	Pitch pine scrub	Central NJ	Extreme fire spread and flame length; 6,000 evacuations
Big Turnaround Complex	2007	206,921	Southern rough	Northeast FL/ Southeast GA	Extreme fire behavior; largest fire in Florida history

Table 4.2. *Summary information for big sagebrush and pine flatwoods fires.*

Burn unit	Latitude	Longitude	Sites per unit	Dominant species[a]	Burn season	State
Big sagebrush						
Flook Lake	N 42° 36′	W 119° 32′	3	ARTRWY	Fall	Oregon
Stonehouse	N 42° 56′	W 118° 26′	1	ARTRVA	Fall	Oregon
V-Lake	N 42° 28′	W 118° 44′	5	ARTRVA	Fall	Oregon
Gold Digger	N 41° 46′	W 121° 34′	2	ARTRVA	Fall	California
Escarpment	N 41° 52′	W 119° 40′	2	ARTRWY, ARTRTR	Fall	Nevada
Sagehen	N 41° 56′	W 119° 15′	1	ARTRTR	Spring	Nevada
Heart Mtn	N 44° 42′	W 109° 09′	3	ARTRVA, ARTRWY	Fall	Wyoming
Dyce Creek	N 45° 19′	W 113° 01′	4	ARTRVA	Spring	Montana
N Black Cyn	N 44° 55′	W 113° 21′	5	ARTRVA	Spring	Montana
Pine flatwoods						
A-214	N 30° 24′	W 84° 31′	3	SERE, QUMA, ILGL	Dormant	Florida
A-215	N 30° 24′	W 84° 30′	3	SERE, QUMA, ILGL	Growing	Florida
A-302	N 30° 17′	W 84° 26′	3	SERE, ILGL	Dormant	Florida
A-303	N 30° 18′	W 84° 27′	1	SERE, ILGL	Dormant	Florida
A-342	N 30° 05′	W 84° 36′	2	SERE, ILGL	Dormant	Florida
A-343	N 30° 25′	W 84° 36′	2	SERE, ILGL	Growing	Florida
BW-204	N 30° 51′	W 84° 01′	1	ARST, SERE, ILGL	Dormant	Georgia
BW-215	N 30° 52′	W 84° 02′	1	SERE, ARST	Dormant	Georgia
E-502B-1	N 30° 27′	W 86° 46′	3	SERE, ILGL, QUMA	Dormant	Florida
E-502B-2	N 30° 27′	W 86° 44′	3	SERE, ILGL	Dormant	Florida
E-807B	N 30° 29′	W 86° 16′	3	SERE, ILGL	Dormant	Florida
PH-1N	N 30° 28′	W 81° 29′	1	SERE, QUCH	Dormant	Florida
PH-1V	N 30° 28′	W 81° 30′	1	ILGL, SERE	Dormant	Florida
SM-P17A	N 30° 05′	W 84° 22′	1	SERE, ILGL	Dormant	Florida
SM-P18A	N 30° 05′	W 84° 22′	1	SERE, ILGL	Dormant	Florida
SM-S1A	N 30° 09′	W 84° 09′	1	ILGL, SERE	Dormant	Florida
SM-S1H	N 30° 09′	W 84° 09′	1	ILGL, SERE	Growing	Florida

[a]ARTRWY=*Artemisia tridentata* ssp. *wyomingensis*; ARTRVA= *A. t.* ssp. *vaseyana*; ARTRTR=*A. t.* ssp. *tridentata*; SERE=*Serenoa repens*; QUMA=*Quercus margarettae*; ILGL=*Ilex glabra*; ARST=*Aristida stricta*; QUCH=*Quercus chapmanii*

Table 4.3. *Day-of-burn weather and fuel moisture data for prescribed fires in big sagebrush units. The range of weather and fuel moisture measurements is reported for burn units in which more than one site was sampled.*

	Weather				Fuel moisture		
Burn unit	**Temp**	**RH**	**Windspeed**	**Days since rain[a]**	**Grass**	**Sagebrush foliage**	**Dead 10hr**
	°C	*percent*	*km hr⁻¹*		---------- *percent* ----------		
Flook Lake	17.2-17.8	17-34	12.1-12.9	1.5-2.5	9.8-10.2	59.9-61.8	9.2
Stonehouse	7.2	40	6.4	7	29.9	78.7	8.4
V-Lake	21.1-23.9	22-28	3.2-12.1	5-10	19.9-38.7	60.6-74.9	2.8-6.2
Gold Digger	16.7	25-26	7.2	30.5	13.7	71.9	7.7
Escarpment	17.8	35	6.4	3.5	10.6	68.9	6.8
Heart Mtn	16.1-20.6	24-28	4.0-12.1	18	30.3	73.6	5.7
Sagehen	17.2	23	16.1	32	14.5	77.1	10.8
Dyce Creek	12.8-15.6	28-34	7.2-11.3	2.5-3.5	12.8-45.3	88.7-106.0	9.3-14.4
N Black Cyn	13.9	30	12.1-13.7	2.5	41.3-54.2	107.4-110.1	11.9-16.9

[a]Days since >2.5 mm of measured rainfall at the nearest Remote Automated Weather Station.

Table 4.4. *Day-of-burn weather and fuel moisture data for prescribed fires in pine flatwoods units. The range of weather and fuel moisture measurements is reported for burn units in which more than one site was sampled.*

	Weather					Fuel moisture			
Burn unit	**Temp**	**RH**	**Windspeed**	**Days since rain[a]**	**KBDI[b]**	**Grass**	**Shrub stems**	**Pine litter**	**Dead 10hr**
	°C	*percent*	*km hr⁻¹*			---------- *percent* ----------			
A-214	15.6-17.2	51-53	5.6-6.1	3.5	223	42.5-50.8	89.8-94.2	27.0-31.8	40.7-52.3
A-215	22.2-27.8	39-65	1.4-3.5	13	189	44.5-56.0	88.1-101.8	18.8-31.7	13.7-18.3
A-302	22.7-23.1	72-73	4.3-5.0	2	149	31.6-61.8	85.5-91.6	22.7-38.8	74.1-83.5
A-303	12.2	64	2.4	2	180	44.2	86.4	35.2	69.2
A-342	21.7-24.4	48-56	4.0-4.8	5.5	162	38.4-45.2	81.0-87.6	21.2-24.9	43.2-46.0
A-343	35.0	49	2.4	3	201	113.2	123.5	10.0	12.0
BW-204	16.7	12	4.0	4.0	234	37.6	89.3	13.7	25.0
BW-215	13.9	50	4.8	1.0	31	39.6	129.2	45.0	62.5
E-502B-1	15.0-16.7	45-52	3.2	3.5	20	37.0	73.9	36.8	55.0
E-502B-2	17.8	56	6.4	3.5	20	35.4	71.6	23.0	53.7
E-807B	14.4-17.2	31-55	2.4-4.8	2.5	92	42.1	75.9-83.6	48.8	62.2
PH-1N	22.8	68	4.8	12.0	70	24.9	62.2	13.3	15.9
PH-1V	21.1	71	4.8	12.0	70	24.9	101.0	19.2	15.9
SM-P17A	26.1	53	4.8	2.5	198	37.8	92.9	23.5	53.9
SM-P18A	15.6	44	3.2	2.5	122	41.9	89.9	33.9	71.2
SM-S1A	25.3	46	2.9	3.5	116	63.9	87.9	37.6	53.5
SM-S1H	29.7	51	15.3	2.5	311	214.5	104.0	19.0	20.0

[a]Days since >6 mm of measured rainfall at the nearest Remote Automated Weather Station.
[b]KBDI = Keetch-Byram Drought Index; lower numbers indicate wetter conditions.

Table 4.5. *Potential dependent and independent variables for model development.*

Dependent variables	**Independent variables**
Total fuel consumption	Total fuel loading
Shrub fuel consumption	Live fuel loading by species or life form
Live fuel consumption	Dead fuel loading by species
Dead fuel consumption	Down woody fuel loading by size class
Litter consumption	Litter loading
Fine fuel consumption	Vegetation coverage by species or life form
Down woody fuel consumption	Vegetation height by life form
Fuel consumption by species/lifeform	Proportion of area burned
Proportion of area burned	Fire type
	Season of burning
	Slope (big sagebrush)
	Windspeed
	Relative humidity
	Fuel moisture by fuel type
	Keetch-Byram Drought Index (flatwoods)
	Soil moisture
	Days since rain

Table 4.6. *Pre-fire fuel loading for big sagebrush and pine flatwoods units. The range of pre-fire fuel loading measurements is reported for burn units in which more than one site was sampled.*

Burn unit	Herbaceous vegetation	Live shrub[a]	Dead shrub	All vegetation	Surface fuels[b]	All fuels
	---------- *Mg ha^{-1}* ----------					
Big sagebrush						
Flook Lake	0.11-0.29	5.52-7.14	4.21-5.76	10.47-13.01	0.71-1.52	11.19-14.54
Stonehouse	0.61	4.62	1.99	7.81	2.21	10.02
V-Lake	0.16-0.27	3.24-11.11	1.16-5.18	4.60-16.88	0.07-1.97	5.27-18.86
Gold Digger	0.57-0.73[c]	4.52-6.35[d]	3.40-3.80[d]	9.05-10.31	0.34-0.51	9.39-10.83
Escarpment	0.28-4.03[c]	3.09-7.62	2.65-6.63	9.78-14.53	1.56-2.71	12.49-16.09
Heart Mtn	0.36-0.41	4.52-12.71	2.94-7.49	8.28-20.59	0.97-1.99	9.27-22.59
Sagehen	0.11[c]	6.08	10.92	17.11	2.23	19.34
Dyce Creek	0.66-0.98	6.02-9.83	4.81-6.46	11.48-17.16	5.96-8.29	17.45-23.64
N Black Cyn	0.59-1.83	1.59-7.31	0.79-4.81	3.19-13.96	3.30-6.08	7.34-18.69
Pine flatwoods						
A-214	0.07-0.29	2.29-2.62	0.19-0.46	2.89-3.11	3.91-8.01	7.02-11.08
A-215	0.02-0.55	2.56-2.79	0.12-0.97	3.31-3.55	3.72-8.52	7.03-12.07
A-302	0.37-1.00	2.29-2.82	0.50-0.86	3.69-4.15	4.51-5.45	8.20-9.60
A-303	3.71	1.76	0.86	6.33	4.51	10.84
A-342	0.20-0.39	2.40-3.31	0.38-1.05	2.98-4.76	3.68-5.27	6.66-10.03
A-343	0.58-0.62	2.00-2.89	0.35-0.52	2.93-4.03	2.48-2.89	5.41-6.91
BW-204	0.90	1.62	<0.01	2.52	5.67	8.19
BW-215	1.050	1.06	0.03	2.15	2.40	4.55
E-502B-1	0.25-0.34	1.91-2.36	0.25-0.50	2.50-3.11	8.47-15.18	10.97-18.30
E-502B-2	1.24-1.81	1.65-2.34	0.09-0.36	3.37-4.39	10.52-13.79	14.28-17.16
E-807B	0.08-0.57	2.57-7.12	0.41-1.07	3.54-7.89	14.10-15.79	17.64-23.68
PH-1N	0.40	6.02	0.87	7.29	2.71	10.01
PH-1V	0.28	8.55	1.36	10.19	4.87	15.06
SM-P17A	0.65	2.88	0.12	3.66	4.28	7.94
SM-P18A	1.04	2.84	0.05	3.93	3.06	6.99
SM-S1A	0.75	5.37	0.15	6.27	5.65	11.92
SM-S1H	0.77	4.03	0.23	5.03	6.63	11.66

[a]Includes *Serenoa repens* (saw palmetto) for flatwoods units.
[b]Includes litter and dead and down woody fuels.
[c]Includes *Chrysothamnus* spp.
[d]Includes *Purshia tridentata*.

Table 4.7. *Pre-fire coverage, proportion of area burned, and vegetation height for big sagebrush and pine flatwoods units. The range of pre-fire coverage and height measurements is reported for burn units in which more than one site was sampled.*

	Pre-fire coverage and area burned					Height	
Burn unit	**Herbaceous vegetation**	**Shrub**	**Saw palmetto**	**All vegetation**	**Area burned**	**Grass**	**Shrub[a]**
	percent					*m*	
Big sagebrush							
Flook Lake	4.6-20.1	29.2-38.1		33.8-58.1	32.7-38.6	0.12-0.17	0.39-0.50
Stonehouse	20.0	42.6		62.5	39.8	0.24	0.55
V-Lake	12.3-23.0	62.6-36.0		51.2-85.6	23.9-96.9	0.11-0.36	0.37-0.70
Gold Digger	25.0-25.7[b]	27.3-31.6[c]		53.0-56.6	36.4-60.4	0.22-0.23	0.40-0.49
Escarpment	22.5-32.8[b]	13.5-35.1		46.3-57.6	75.9-78.2	0.17-0.41	0.64-0.69
Heart Mtn	31.5-37.6	32.4-66.8		66.7-98.3	94.8-99.8	0.12-0.16	0.29-0.51
Sagehen	10.9[b]	43.3		54.2	14.5	0.22	0.92
Dyce Creek	59.0-79.9	64.9-81.3		92.2-98.7	56.7-100.0	0.11-0.16	0.56-0.70
N Black Cyn	43.5-49.0	51.5-63.8		84.2-99.0	11.3-80.0	0.08-0.16	0.46-0.53
Pine flatwoods							
A-214	2.6-8.3	27.7-70.7	29.9-35.5	71.5-100.0	97.0-100.0	0.27-0.37	0.40-1.07
A-215	1.2-9.0	42.2-55.1	14.3-20.9	64.3-78.4	99.4-100.0	0.24-0.40	0.40-0.98
A-302	13.1-62.6	41.7-46.3	28.7-35.2	92.7-100.0	99.6-100.0	0.37-0.52	0.40-0.85
A-303	39.0	28.9	18.9	86.8	98.5	0.61	0.98
A-342	11.9-14.4	43.0-50.6	29.8-35.6	92.3-93.0	100.0	0.40-0.46	0.55-0.82
A-343	12.4-21.1	38.2-45.2	26.2-37.1	83.8-96.4	91.0-99.1	0.34-0.37	0.37-0.88
BW-204	24.2	25.3	5.6	55.1	100.0	0.46	0.70
BW-215	19.1	28.0	4.0	51.1	33.8	0.34	0.67
E-502B-1	7.9-35.3	37.1-47.4	12.8-30.7	72.4-85.2	99.3-100.0	0.21	0.27-0.79
E-502B-2	28.0-62.5	15.8-37.7	8.6-16.8	52.4-100.0	100.0	0.30-0.46	0.46-0.82
E-807B	0.6-5.8	29.9-68.7	16.2-28.4	52.1-99.8	87.6-94.5	0.15-0.46	0.85-1.04
PH-1N	8.8	59.1	31.8	99.7	97.5	0.34	0.67
PH-1V	1.4	45.4	48.4	95.2	100.0	0.24	0.88
SM-P17A	13.7	47.0	14.3	75.0	99.2	0.27	0.30
SM-P18A	18.9	49.3	27.7	95.9	91.0	0.46	0.52
SM-S1A	14.9	63.2	26.2	100.0	98.0	0.40	1.10
SM-S1H	11.0	38.8	32.9	82.7	100.0	0.43	0.85

[a]Includes *Serenoa repens* (saw palmetto) for flatwoods units.
[b]Includes *Chrysothamnus* spp.
[c]Includes *Purshia tridentata*.

Table 4.8. *Fuel consumed during big sagebrush and pine flatwoods prescribed fires. The range of fuel consumption measurements is reported for burn units in which more than one site was sampled.*

Burn Unit	Herbaceous vegetation	Shrub[a]	All vegetation	Surface fuels: Litter	Surface fuels: Dead wood	All fuels
	Mg ha^{-1}					
Big sagebrush						
Flook Lake	0.04-0.10	3.13-5.01	3.23-5.06	0.27-0.59		3.52-5.34
Stonehouse	0.25	2.22	2.47	0.89		3.35
V-Lake	0.05-0.22	1.34-13.95	1.39-14.17	1.09		15.26
Gold Digger	0.27-0.35[b]	4.66-5.66[c]	4.93-6.00	0.31		6.31
Escarpment	0.22-3.15[b]	3.12-12.66	6.26-12.88	1.23-2.11		8.38-14.11
Heart Mtn	0.36-0.41	7.75-19.92	8.16-20.31	0.97-1.98		9.15-22.28
Sagehen	0.02	2.74	2.76	0.76		3.52
Dyce Creek	0.37-0.94	4.29-11.59	4.66-12.53	3.38-7.93		8.04-20.06
N Black Cyn	0.09-0.77	0.22-8.04	0.31-8.51	0.47-4.87		0.78-13.38
Pine flatwoods						
A-214	0.07-0.29	2.74-3.01	2.07-2.18	3.04-5.22	0.03-0.22	5.44-7.32
A-215	0.02-0.55	2.76-3.52	2.57-3.27	1.84-2.74	0.25-0.86	4.92-9.04
A-302	0.37-0.98	2.82-3.32	2.90-3.49	3.65-4.87	0.02-0.48	6.57-8.46
A-303	3.61	2.62	5.74	2.30	0.45	8.49
A-342	0.20-0.39	2.78-4.37	2.21-4.43	3.43-4.53	0.02-0.41	5.66-9.37
A-343	0.58-0.62	2.35-3.41	2.63-3.01	1.95-2.54	0.01-0.26	4.60-5.81
BW-204	0.89	1.62	2.26	4.12	0.19	6.58
BW-215	0.70	1.10	0.88	0.39	0.00	1.27
E-502B-1	0.25-0.34	2.16-2.86	1.99-2.47	5.43-11.39	0.29-1.63	7.84-14.14
E-502B-2	1.24-1.81	2.01-2.59	2.80-3.76	7.59-11.70	0.10-1.00	11.17-15.74
E-807B	0.08-0.57	2.98-7.73	2.11-6.11	6.57-7.28	1.09-1.86	9.95-14.48
PH-1N	0.40	6.89	5.26	2.21	0.31	7.77
PH-1V	0.28	9.91	6.59	3.67	0.71	10.97
SM-P17A	0.65	3.00	2.96	2.65	0.38	6.00
SM-P18A	1.04	2.89	3.31	2.06	0.23	5.60
SM-S1A	0.74	5.52	4.22	4.06	0.29	8.57
SM-S1H	0.76	4.26	2.40	5.39	0.21	8.00

[a]Includes *Serenoa repens* (saw palmetto) for flatwoods sites
[b]Includes *Chrysothamnus* spp.
[c]Includes *Purshia tridentata*.

Table 4.9. *Type-specific equations for predicting shrub, non-shrub, and all aboveground biomass consumption, and proportion of area burned for big sagebrush fires. Type-specific equations for predicting shrub, non-shrub vegetation, dead and down woody material, litter, and all aboveground biomass consumption for flatwoods fires. General equation for predicting all aboveground biomass consumption.*

Equations[a]	**n**	**F-ratio**	**RSE**[b]	**Adj. R^2**
Big sagebrush				
$\sqrt{C_s} = 0.0556 + 0.1351(L_s) + 1.6730(B) - 0.2196(Season)$	23	89.19	0.23	0.92
If *Season* = fall,				
$C_n = 0.8890(L_n) \times B$	na	na	na	na
$B = -0.2217 + 0.0179(P_h) + 0.1433\left(\ln\left((W+1) \times (S+1)\right)\right)$	15	27.46	0.12	0.79
If *Season* = spring,				
$C_n = 0.8027(L_n) \times B$	na	na	na	na
$B = 0.3597 + 0.0102(P_h) - 0.0456(F_{10}) + 0.0098(W \times S_c)$	10	10.82	0.16	0.77
$\sqrt{C_a} = 0.0929 + 0.1036(L_s) + 2.2451(B) - 0.2985(Season)$	25	146.50	0.23	0.95
Flatwoods				
$\ln C_s = -0.1682 + 0.9008(\ln L_s) + 0.0717(Season)$	27	196.70	0.10	0.94
If $B < 0.85$, $C_n = 0.9944(L_n) \times B$; If $B \geq 0.85$, $C_n = 0.9944(L_n)$	na	na	na	na
$\sqrt{C_w} = -0.0276 + 0.7309\left(\sqrt{L_w}\right) - 0.0031(F_{10})$	31	35.48	0.19	0.70
$\sqrt{C_l} = 0.2871 + 0.9140\left(\sqrt{L_l}\right) - 0.0101(F_l)$	30	176.40	0.16	0.92
$\ln C_a = 1.4253 + 0.7881(\ln L_a) - 0.2661(\ln F_s)$	30	119.00	0.11	0.89
General				
$C_a = 5.7079 + 0.0003(I_B/R)$	57	7.77	4.35	0.11

[a]Symbols:

B = area burned, proportion of total area;
C_a = consumption of all aboveground biomass, Mg ha^{-1};
C_l = consumption of litter biomass, Mg ha^{-1};
C_n = consumption of non-shrub biomass (herbaceous vegetation, litter, and dead and down woody biomass for big sagebrush) or non-shrub vegetation (herbaceous vegetation only for flatwoods), Mg ha^{-1};
C_s = consumption of shrubs, Mg ha^{-1};
C_w = consumption of dead and down woody biomass, Mg ha^{-1};
F_{10} = day-of-burn 10hr fuel moisture, percentage by dry weight;
F_s = day-of-burn shrub fuel moisture (woody shrub stems), percentage by dry weight;
I_B = fireline intensity, kW m^{-1};
L_a = pre-fire loading of all aboveground biomass; Mg ha^{-1};
L_l = pre-fire loading of litter biomass; Mg ha^{-1};
L_n = pre-fire loading of non-shrub biomass (herbaceous vegetation, litter, and dead and down woody biomass for big sagebrush) or non-shrub vegetation (herbaceous vegetation only for flatwoods), Mg ha^{-1};
L_s = pre-fire loading of shrubs (including saw palmetto for flatwoods), Mg ha^{-1};
L_w = pre-fire loading of dead and down woody biomass; Mg ha^{-1};
P_h = pre-fire coverage of herbaceous vegetation, percentage;
S = slope, percent;
S_c = slope category, <5% = 1, 5-15% = 2, 16-25% = 3, 26-35% = 4, >35% = 5;
Season = season of burn, spring burn in big sagebrush and growing season burn in flatwoods = 1, all else = 0;
R = rate of spread, m sec^{-1};
W = day-of-burn windspeed, km hr^{-1}.

[b]Residual standard error from regression; in units of the dependent variable.

Table 4.10. *Comparisons of measured and modeled fuel consumption.*

		Pre-fire loading				Measured consumption						
Data source[a]	Burn season	Shrub	Non-shrub	Total	Area burned	Shrub	Non-shrub	Total	Modeled consumption[b]		Difference[b]	
		----- *Mg ha*$^{-1}$ -----			*percent*	---------- *Mg ha*$^{-1}$ ----------					*percent*	
Big sagebrush												
John Day	Fall	6.07	4.52	10.59	100	--	--	9.80	10.09	(10.59)	2.9	(8.1)
Prineville	Fall	7.35	5.38[c]	12.73	100	6.80	4.50	11.30	12.13	(12.73)	7.4	(12.7)
Prineville	Fall	11.83	7.49[c]	19.32	100	11.08	6.71	17.79	17.73	(18.84)	-0.4	(5.9)
Prineville	Fall	12.34	10.85[c]	23.19	100	11.02	10.14	21.16	21.18	(22.48)	0.1	(6.2)
All fall	Fall										2.7	(8.2)
John Day	Spring	2.93	3.30	6.23	100	--	--	5.23	5.58	(6.23)	6.7	(19.1)
Prineville	Spring	9.44	8.12	17.56	47	3.93	3.22	7.15	6.61	(7.08)	-7.5	(-1.0)
Prineville	Spring	11.66	8.52	20.18	51	4.44	4.59	9.03	8.59	(9.16)	-4.9	(1.4)
Prineville	Spring	11.43	7.19	18.62	100	8.54	6.34	14.88	15.09	(15.75)	1.4	(5.9)
All spring	Spring										5.1	(6.9)
Pine flatwoods												
Stamper Tract[d]	Growing	14.73[e]	14.68[f]	29.41	100	10.76	2.74	13.50	23.70	(15.75)	75.6	(16.7)
Ouachita[g]	Growing	0.93[h]	8.62[i]	9.55	100	--	--	3.91	6.21	(7.05)	58.7	(80.3)
All growing	Growing										67.2	(48.5)
Ouachita[g]	Dormant	0.24[h]	10.95[i]	11.19	100	--	--	5.48	6.91	(7.72)	26.1	(40.9)
Okeefenokee	Dormant	7.23	5.80[j]	13.03	100	4.69	3.68	8.37	8.59	(9.15)	2.7	(9.4)
Piedmont A	Dormant	0.47	5.57[j]	6.04	100	0.28	3.86	4.14	4.23	(5.20)	2.1	(25.6)
Piedmont B	Dormant	0.27	5.35[j]	5.62	100	0.14	3.73	3.87	3.94	(4.80)	1.7	(24.0)
Piedmont C	Dormant	0.32	6.84[j]	7.16	100	0.13	4.22	4.35	4.75	(5.80)	9.3	(33.4)
FL Panther 2	Dormant	0.84	3.96[j]	4.80	100	0.58	3.82	4.40	4.66	(4.06)	6.0	(-7.5)
All dormant	Dormant										8.0	(23.5)

[a]Data are from: John Day (Sapsis and Kauffman 1991); Prineville (Kauffman and Cummings 1989); Stamper Tract (Taylor and Wendel 1964); Ouachita (Sparks et al. 2002); Okeefenokee, Piedmont, Florida Panther (R.D. Ottmar, unpublished data)

[b]Based on the sum of individual component estimates (left column), and total aboveground (C_a) estimates (right column, in parens)

[c]Does not include duff

[d]Pond pine pocosin vegetation type

[e]Includes all vegetation

[f]Noted as litter, but most likely also includes duff

[g]Shortleaf pine-mixed oak forest type with sparse shrub understory

[h]Assumed all 'live fuels' were shrubs

[i]Assumed 1/3 of '1hr timelag fuel' was litter

[j]Includes herbaceous vegetation, litter, and woody material ≤7.6 cm diameter

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APPENDIX A: SUPPLEMENTAL MATERIAL FOR CHAPTER 3

FUTURE LANDSCAPE FUELBED SUCCESSION MODEL DEVELOPMENT

The modeling framework described in Chapter 3 is a starting point; further research and development could improve the utility of this approach in the science, policy, and planning environments. Several potential improvements are listed below:

- Develop a method to weight simulation landscapes such that fires start with higher probability in landscape positions and fuelbed types with a higher probability of ignition.
- Implement a function in the fire spread algorithm that minimizes the differences in spread contrast between fuelbeds in fire years when a very large area is projected to burn under the assumption that top-down processes (i.e., weather) override bottom-up controls (i.e., fuels) on fire spread in extreme fire years (e.g., Bessie and Johnson 1995).
- Incorporate a probability function to determine fire type (stand replacement vs. non-stand replacement), where a fuelbed's probability of burning as a certain fire type is based on fire hazard (e.g., Wimberly and Kennedy 2008) and extremity of fire year.
- Interpolate fuelbed characteristics between successional states to represent state changes as a continuous rather than abrupt occurrence.
- Incorporate a more comprehensive list of fuelbeds and successional trajectories into fuelbed pathways. For example, specify prescribed fire only as a viable management option for all fuelbed types in which it is used and add piling and burning as a new fuelbed management transition option. Also, develop and incorporate specific non-stand-replacement wildfire fuelbeds.
- Incorporate a fire spread model, such as FARSITE (Finney 1998) or HFire (Morais 2001), that would allow the fire regime to be an emergent property of the fuels present throughout the simulation period. That is, the fire regime would change as

appropriate in response to fuels, (e.g., Perera et al. 2004) and allow landscape pattern to feedback on fire frequency, size, and shape.

- Test more sophisticated fire and management regimes. For example, simulate a fire regime that varies over time, or a management regime in which a portion of management activities are focused in the wildland-urban interface, in areas that exceed a threshold fire hazard level, or in areas with an undesirable fire regime condition class (FRCC; Hardy et al. 2001b).
- Integrate the effects of climate change on vegetation development and disturbance regimes. A first approximation of the effects of climate change could potentially be incorporated into the modeling framework by determining how fuelbeds might transition to an alternate fuelbed pathway given assumptions about how changing climate affects the suitability of sites to support different vegetation and fuelbed types.

Okanogan-Wenatchee FCCS Fuelbed Successional Pathways

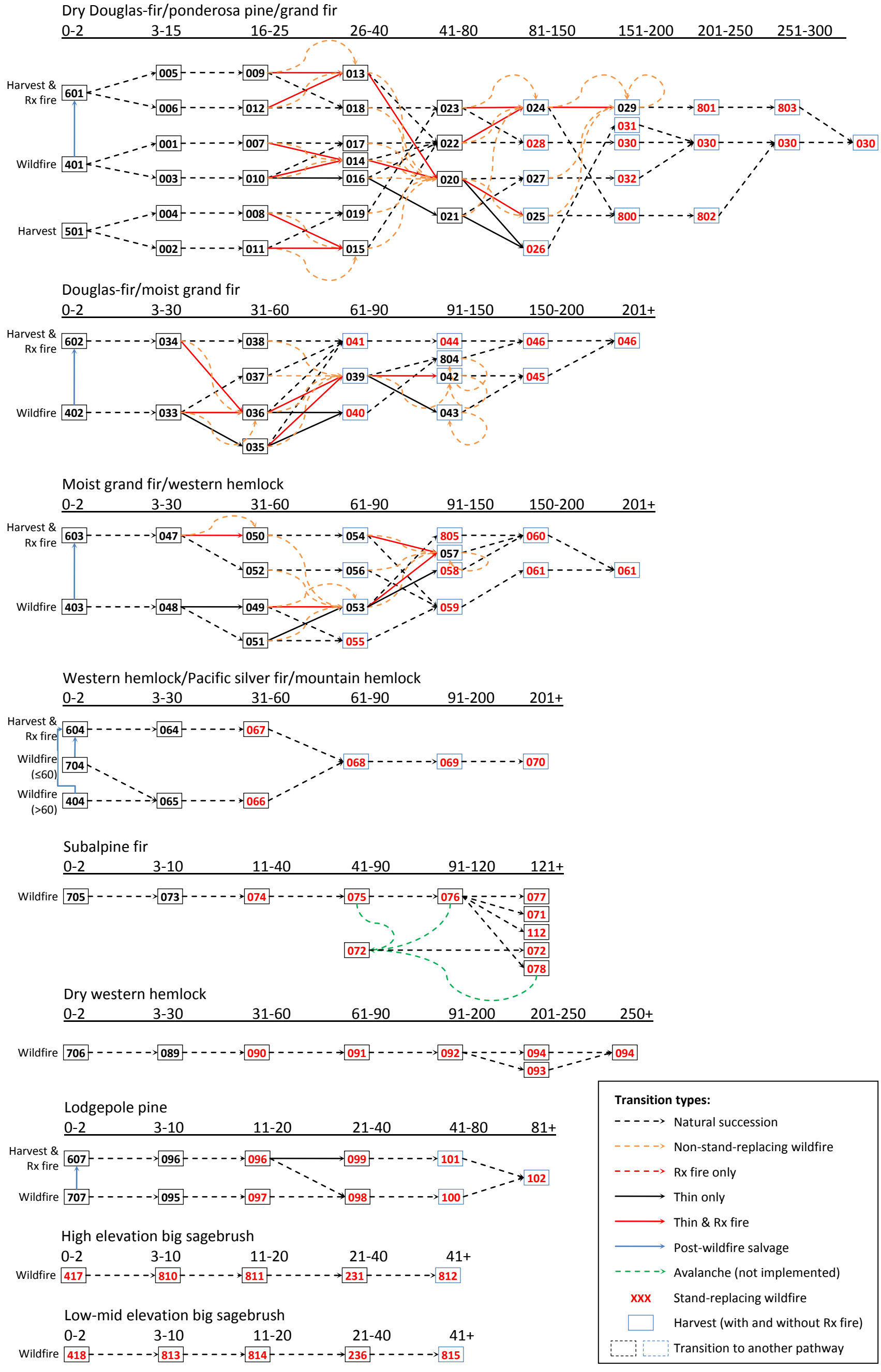

Figure A.1. Okanogan-Wenatchee National Forest fuelbed successional pathways.

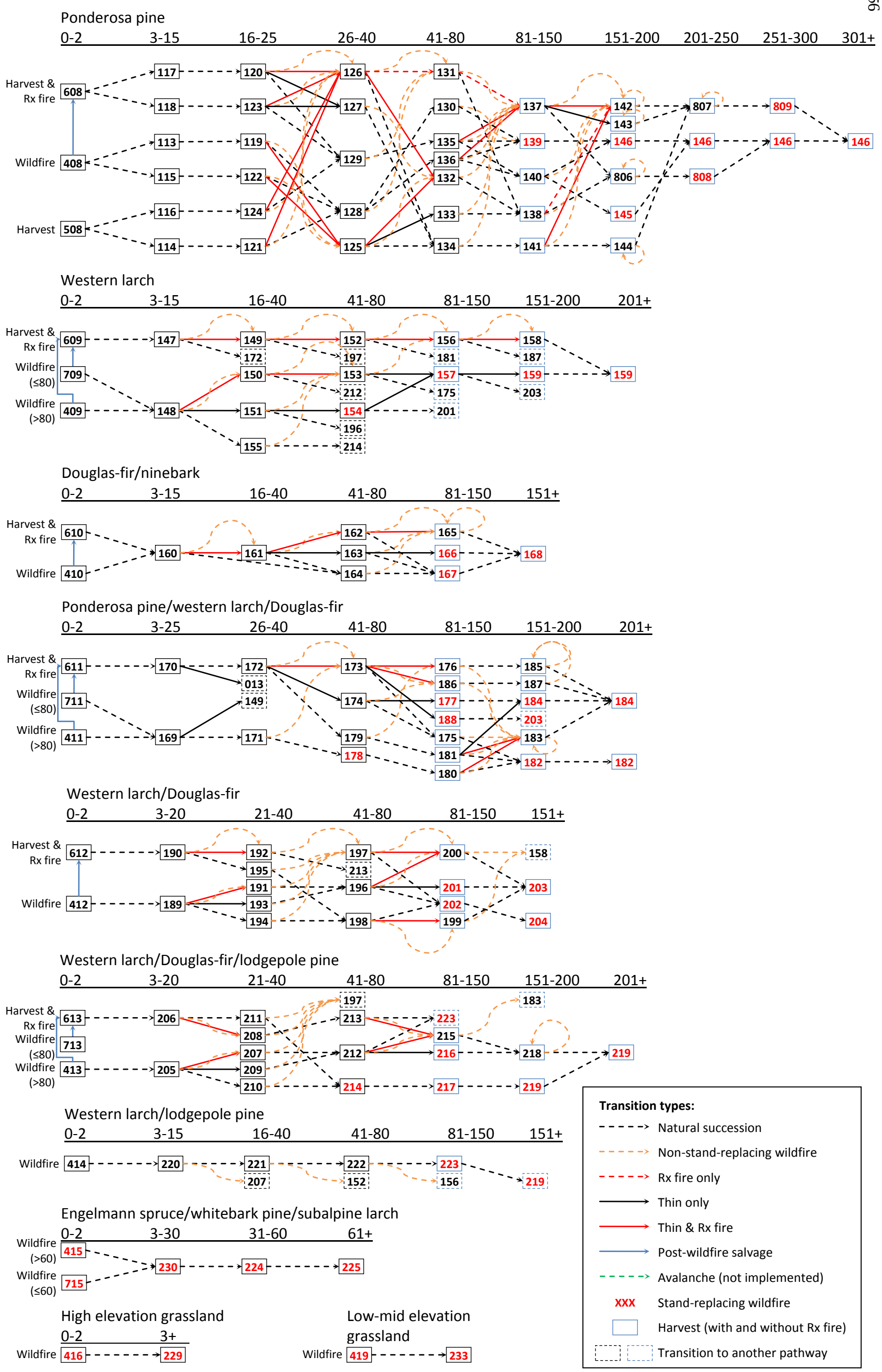

Figure A.1. (continued). *Okanogan-Wenatchee National Forest fuelbed successional pathways.*

FUELBED SUCCESSION SIMULATION RESULTS

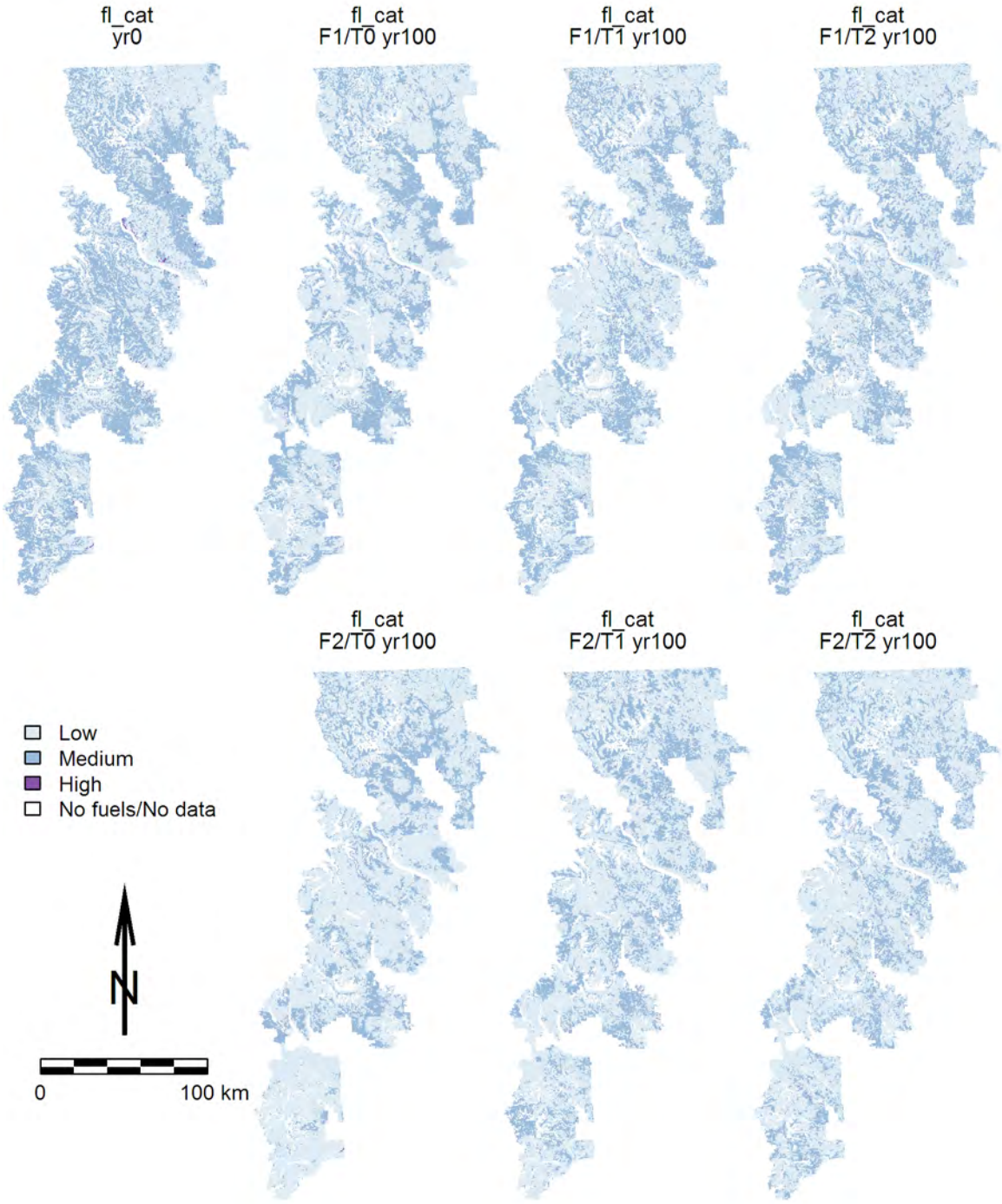

Figure A.2. *Simulated change in potential flame length category (fl_cat) after 100 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

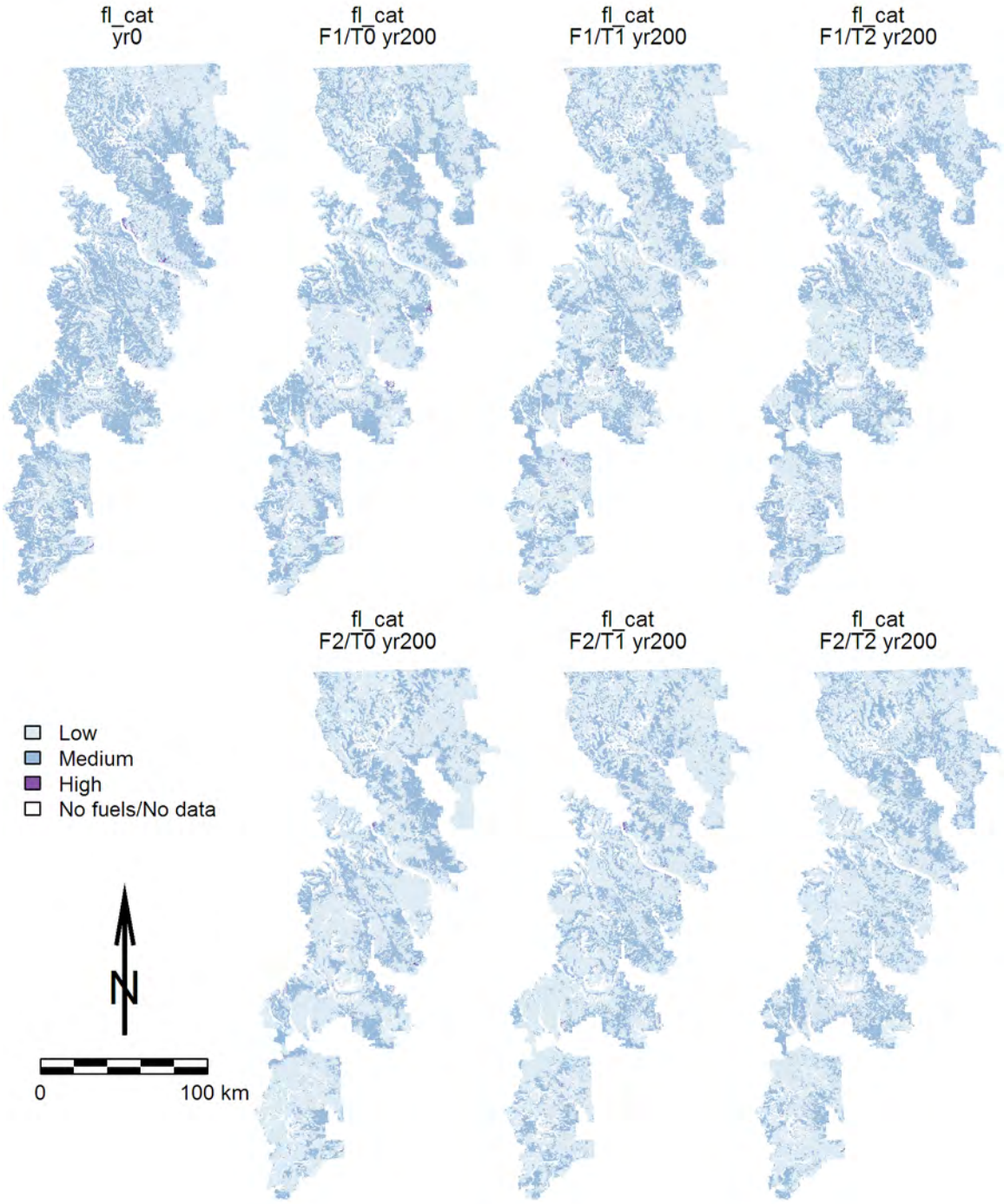

Figure A.3. *Simulated change in potential flame length category (fl_cat) after 200 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

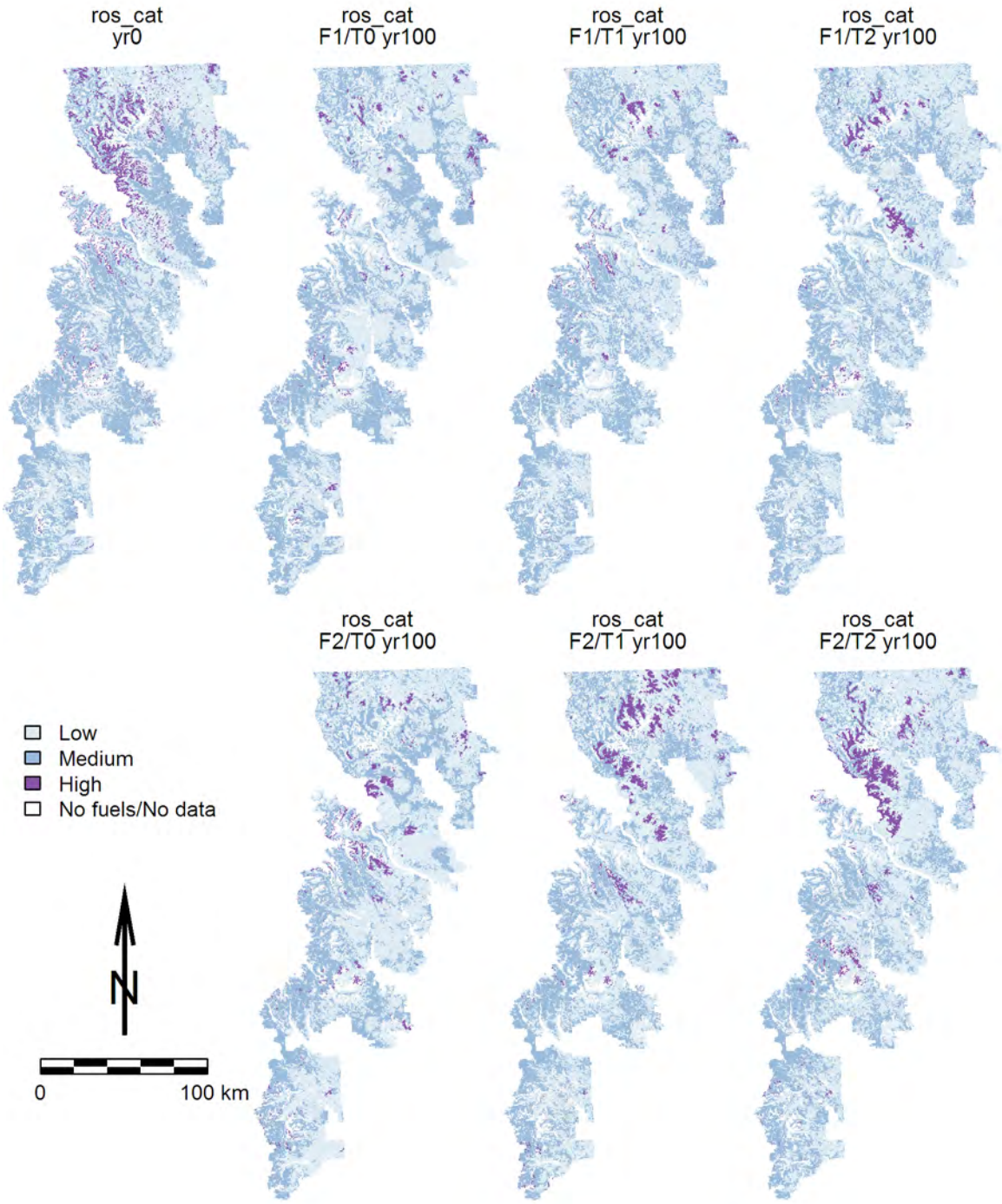

Figure A.4. *Simulated change in potential rate of spread category (ros_cat) after 100 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

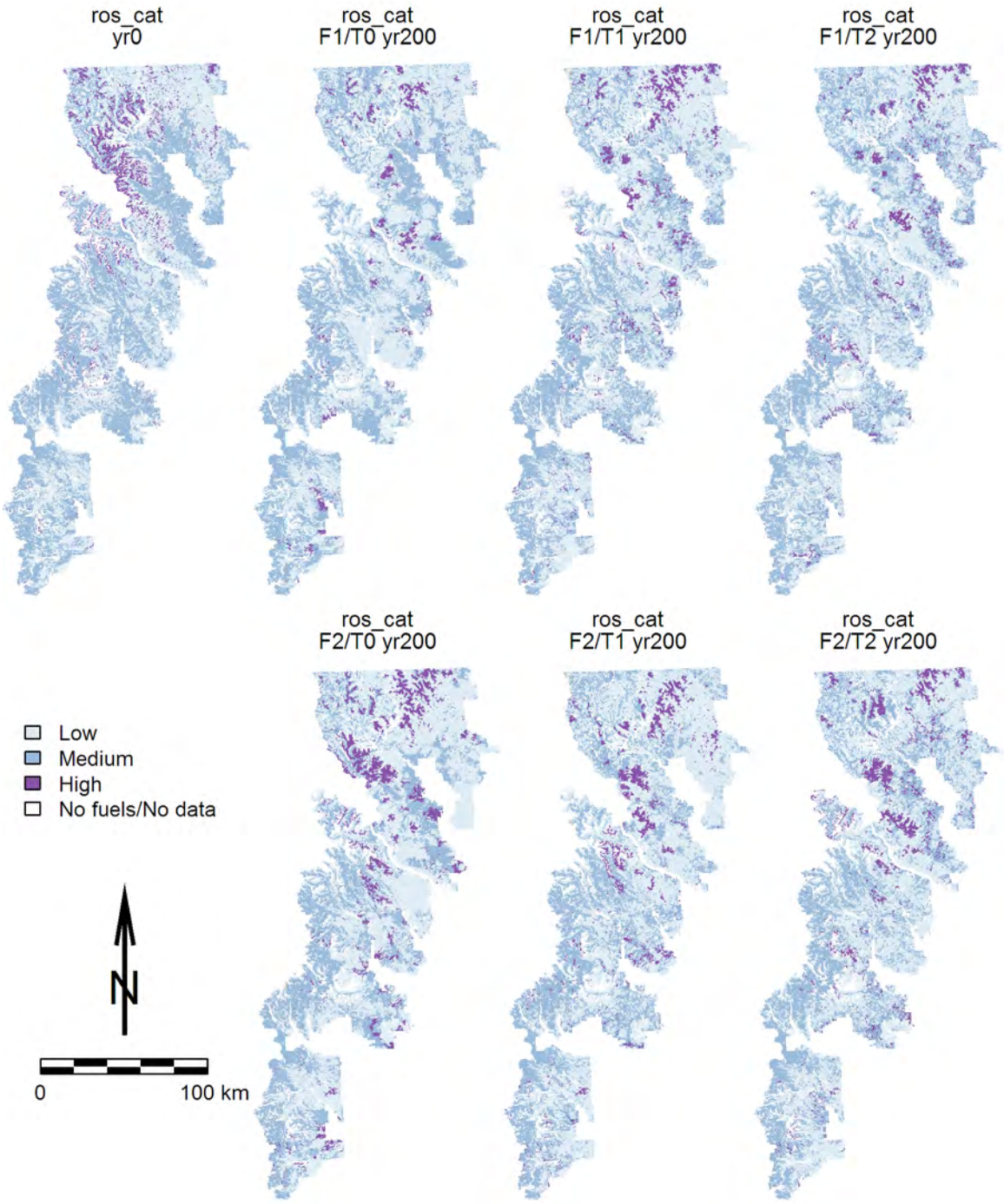

Figure A.5. *Simulated change in potential rate of spread category (ros_cat) after 200 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

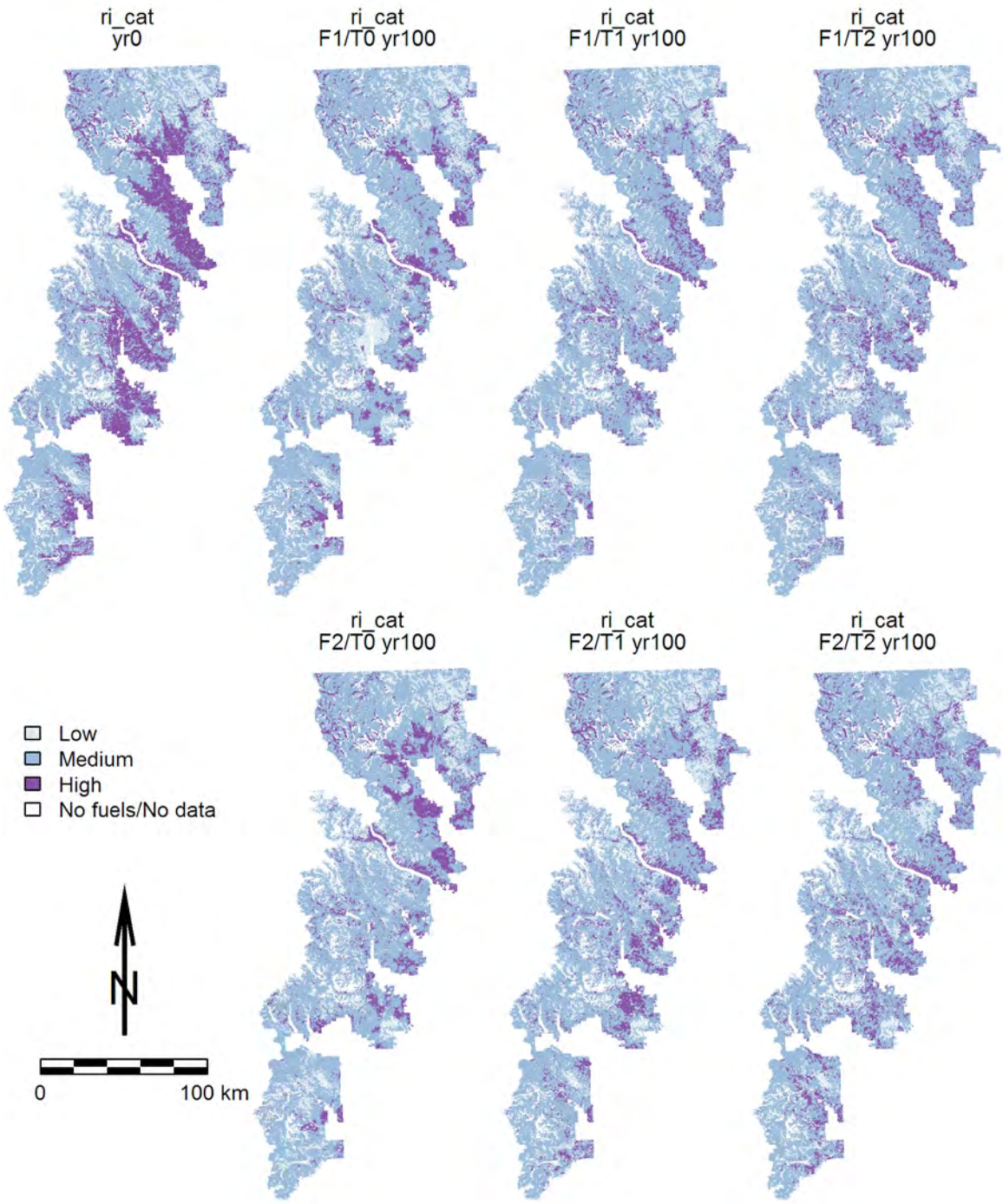

Figure A.6. *Simulated change in potential reaction intensity category (ri_cat) after 100 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

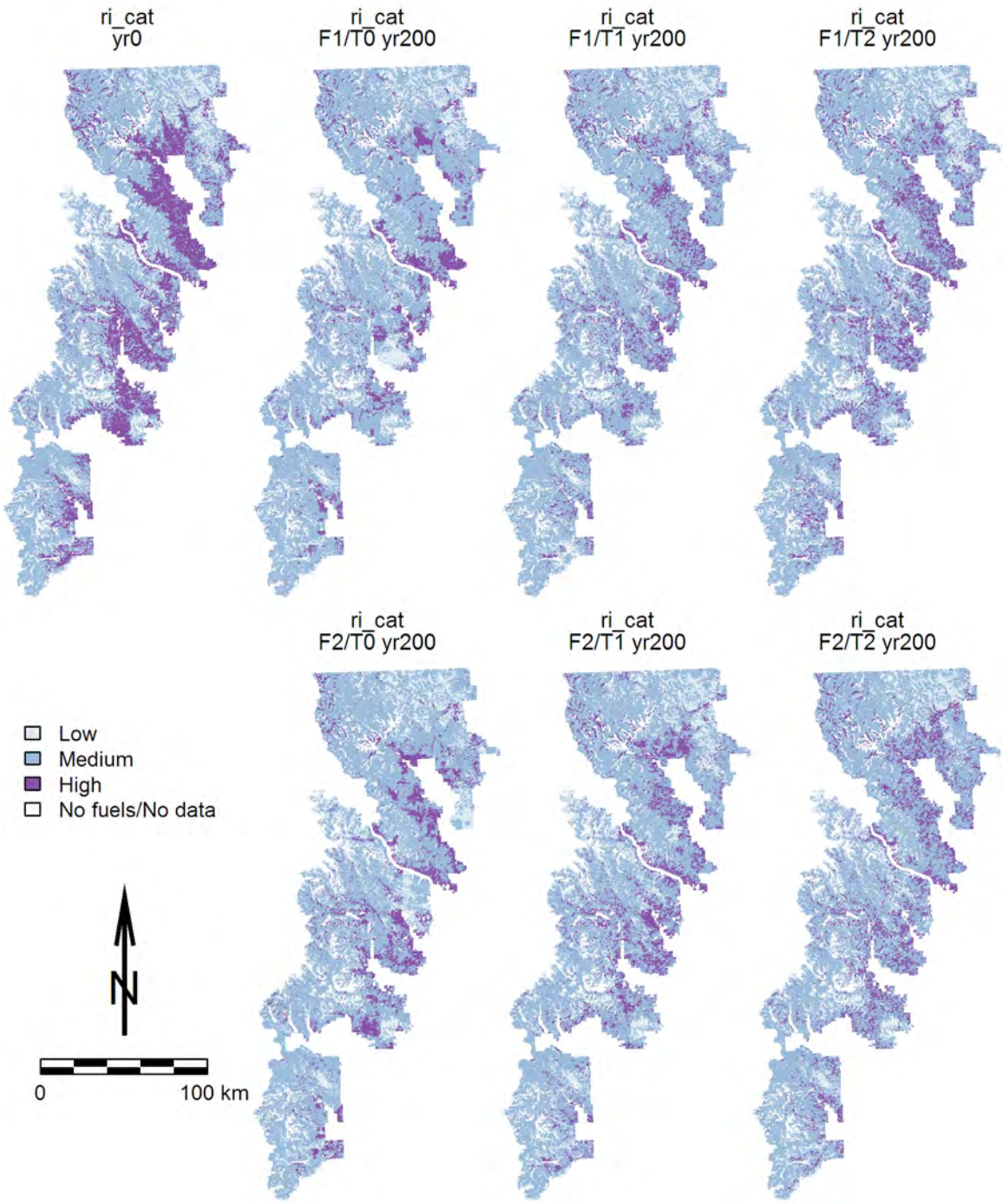

Figure A.7. *Simulated change in potential reaction intensity category (ri_cat) after 200 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

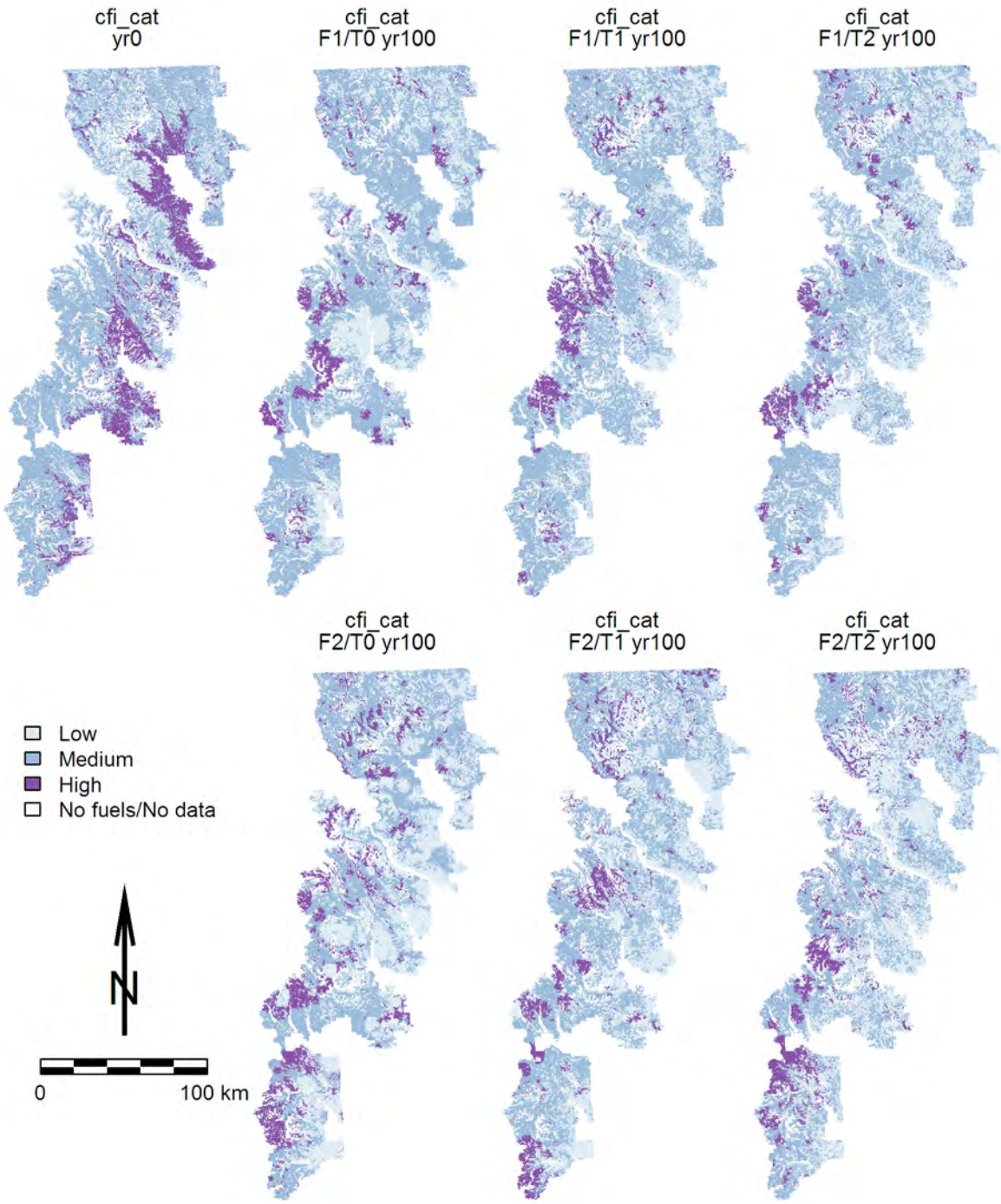

Figure A.8. *Simulated change in crown fire initiation potential category (cfi_cat) after 100 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

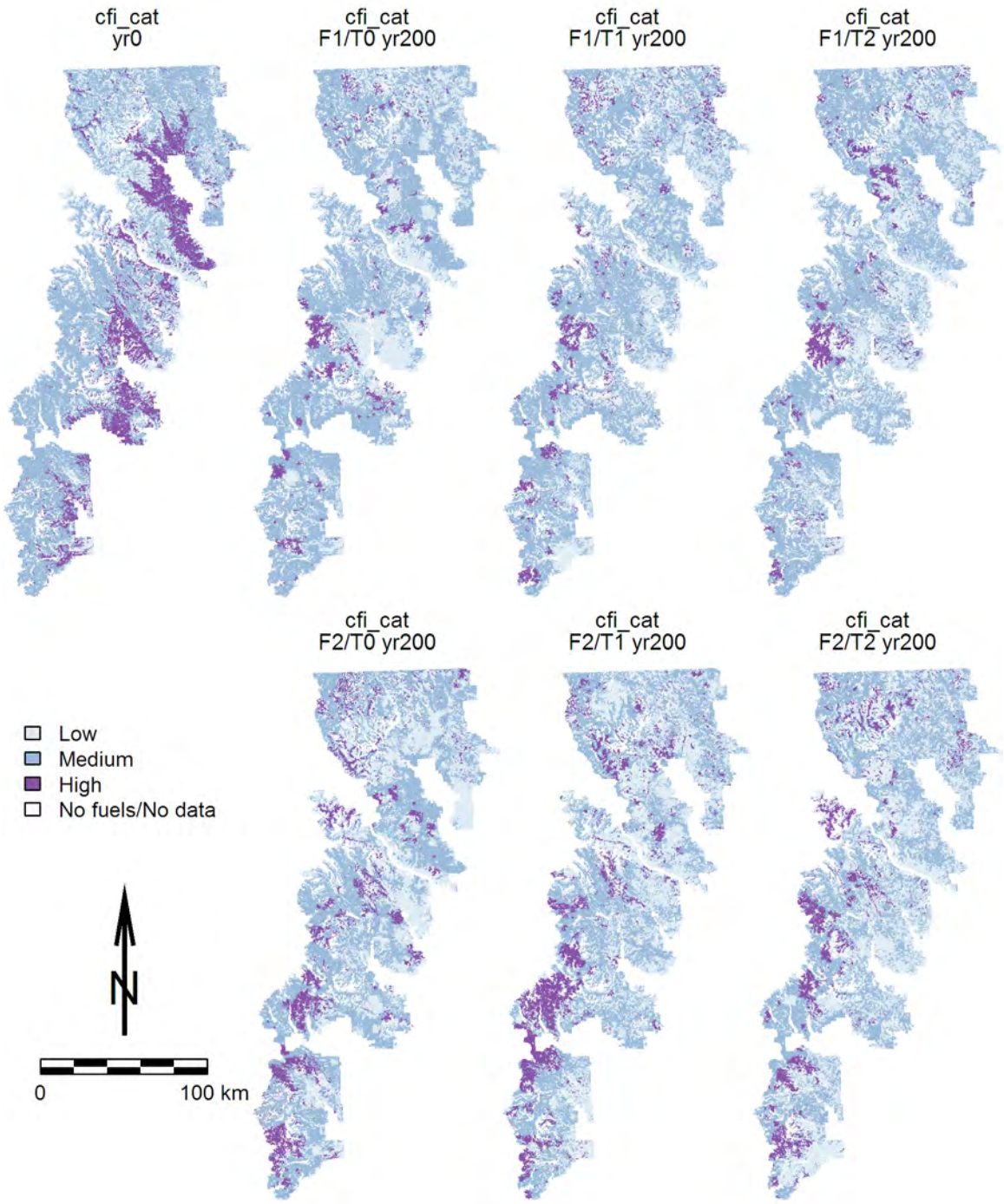

Figure A.9. *Simulated change in crown fire initiation potential category (cfi_cat) after 200 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

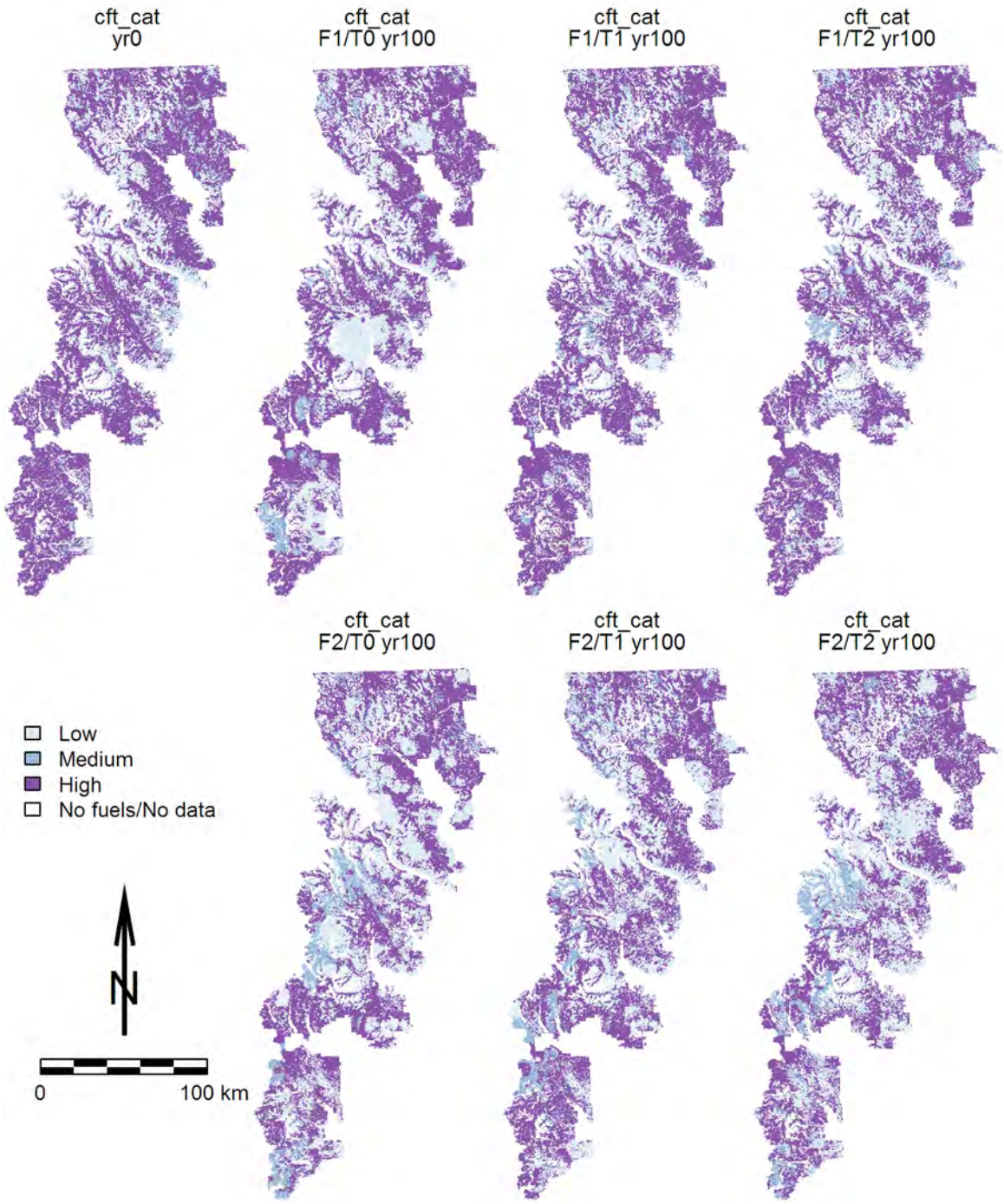

Figure A.10. *Simulated change in crown fire transmissivity potential category (cft_cat) after 100 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

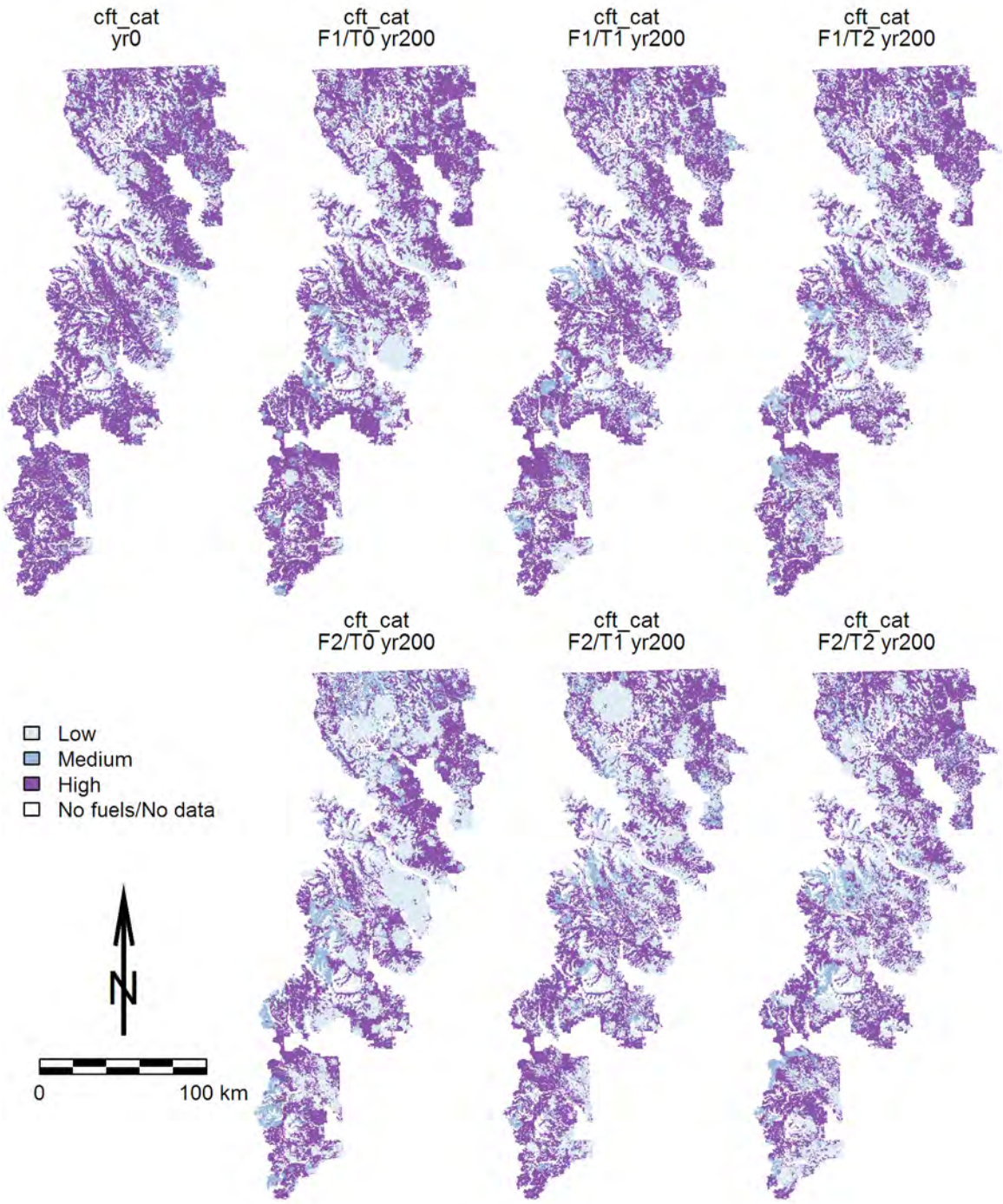

Figure A.11. *Simulated change in crown fire transmissivity potential category (cft_cat) after 200 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

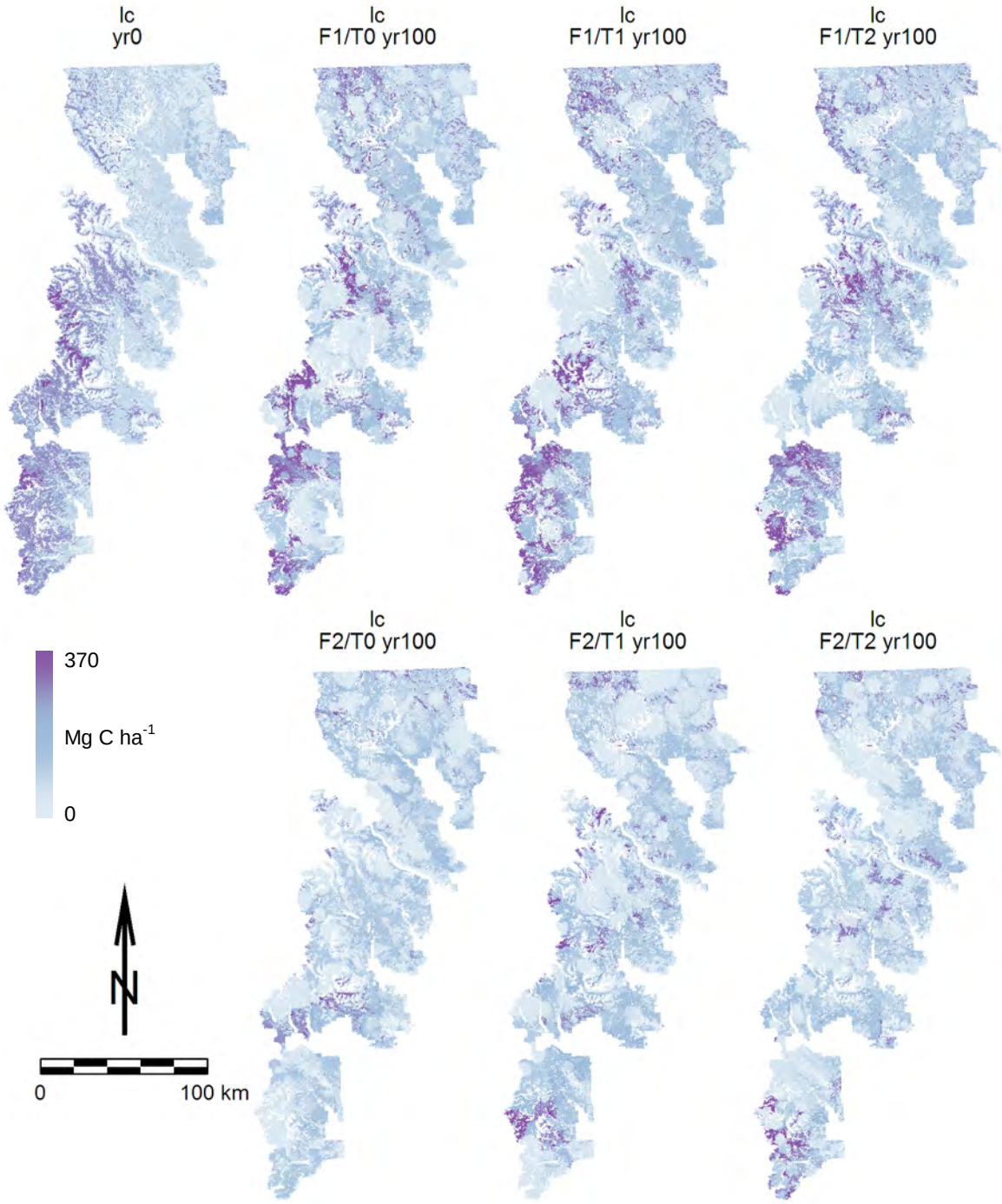

Figure A.12. *Simulated change in live carbon stock (lc) after 100 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

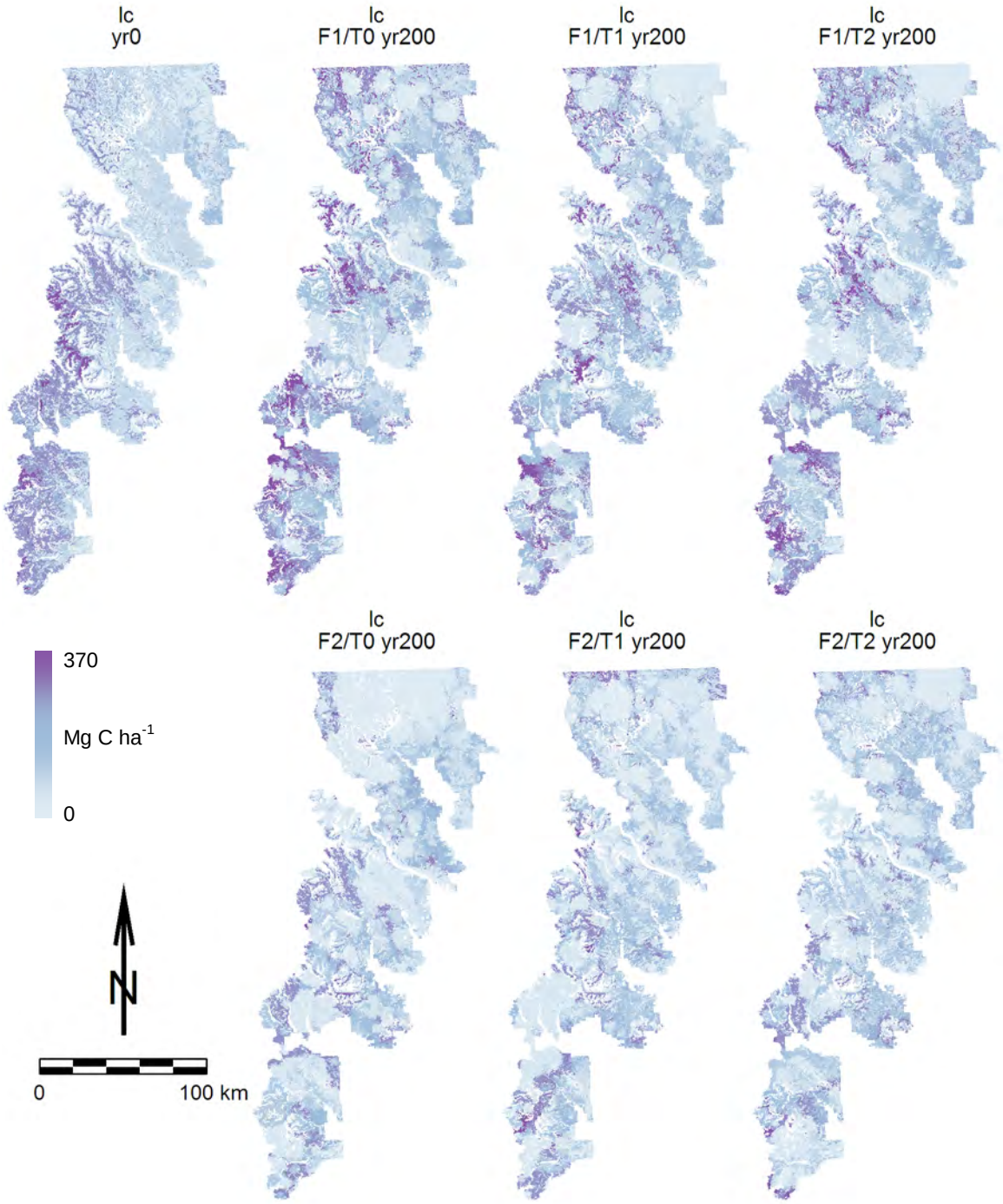

Figure A.13. *Simulated change in live carbon stock (lc) after 200 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

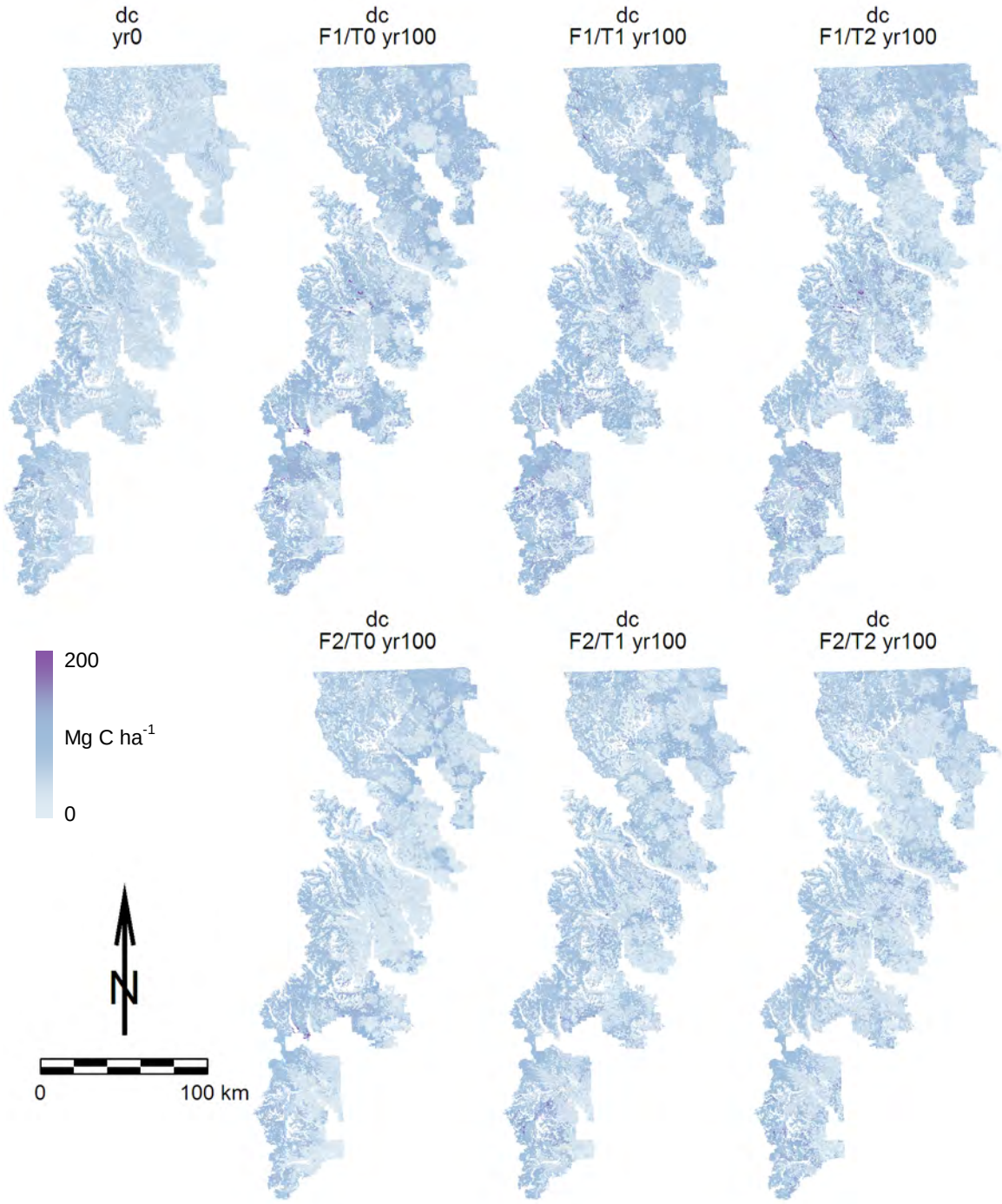

Figure A.14. *Simulated change in dead carbon stock (dc) after 100 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

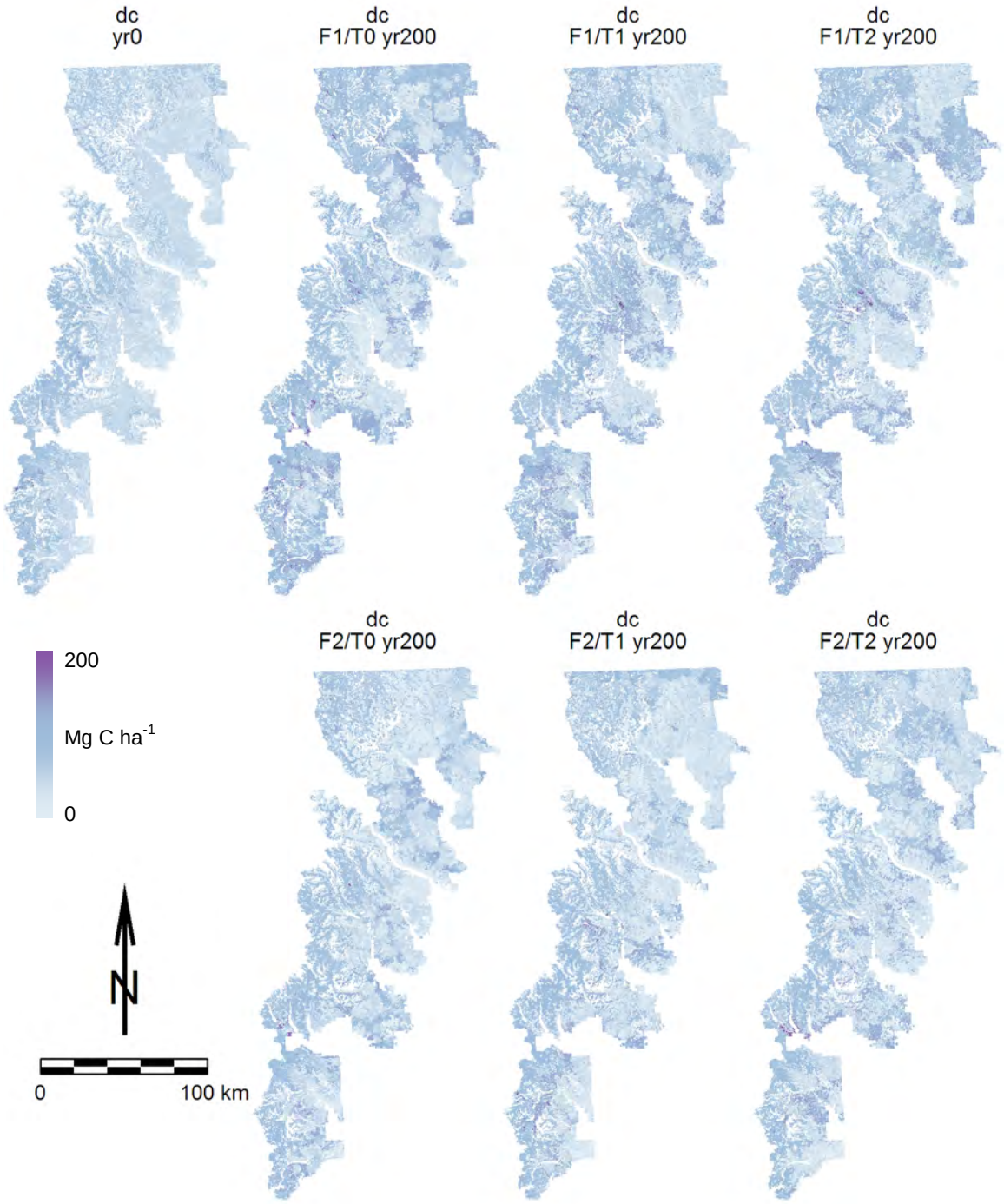

Figure A.15. *Simulated change in dead carbon stock (dc) after 200 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

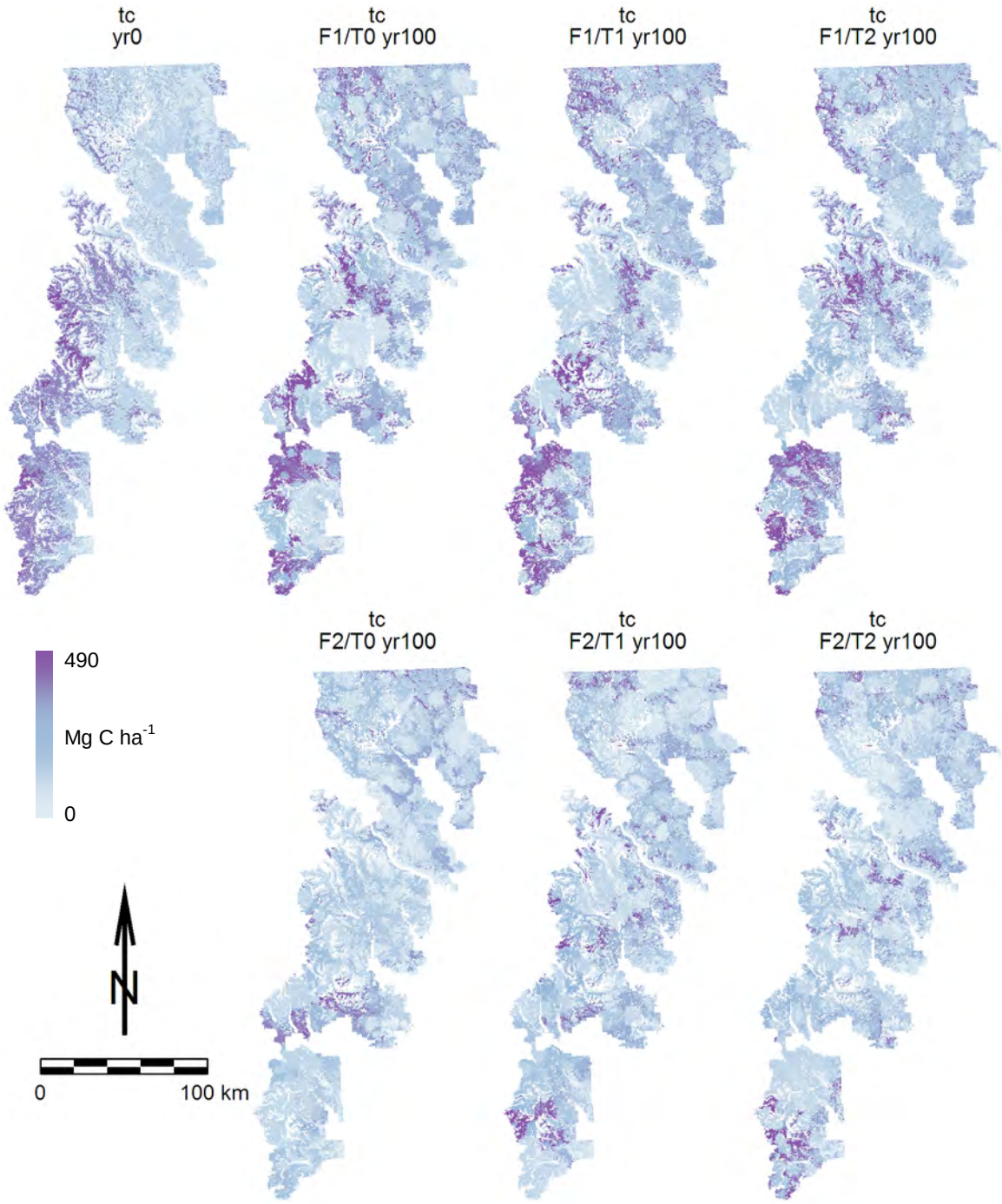

Figure A.16. *Simulated change in total carbon stock (tc) after 100 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

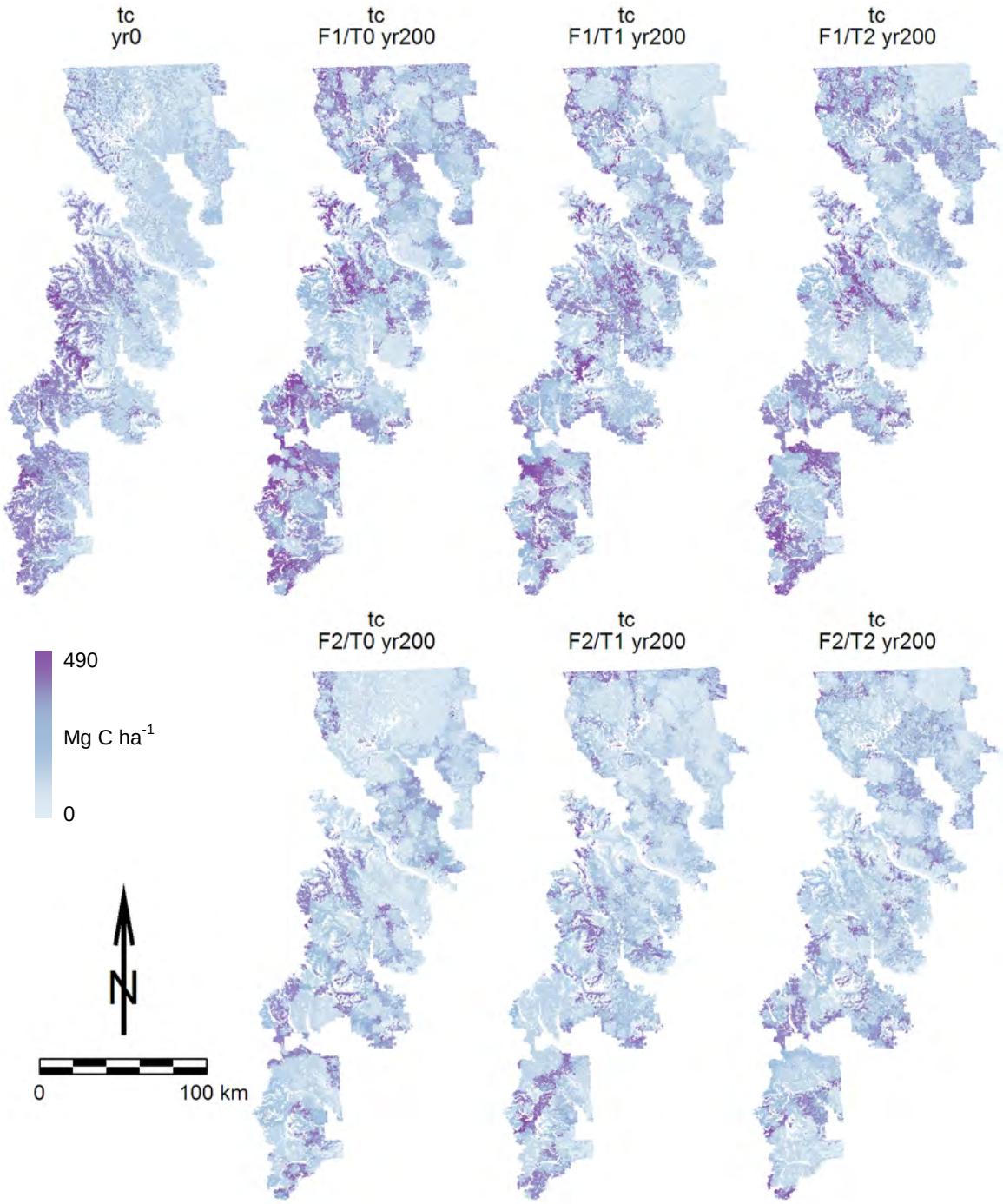

Figure A.17. *Simulated change in total carbon stock (tc) after 200 years of fuelbed succession under combinations of the current (F1) and elevated (F2) fire regime, and no (T0), current (T1), and elevated (T2) management regimes for the Okanogan-Wenatchee National Forest.*

Table A.1. *Okanogan-Wenatchee National Forest FCCS fuelbed fire behavior and carbon attributes listed by fuelbed identification (ID) number. FL = flame length, ROS = rate of spread, RI = reaction intensity, CFI = crown fire initiation potential, CFT = crown fire transmissivity potential, LC = live carbon stock, DC = dead carbon stock, TC = total carbon stock.*

ID	Fuelbed pathway	ROS	FL	RI	CFI	CFT	LC	DC	TC
	pathway name (age range) misc.	*m min^{-1}*	*m*	*kW m^{-2}*			------*Mg ha^{-1}*------		
001	Dry DF/PP/GF (3-15) shrubland	2.7	2.3	1604.5	2.6	0.0	41.5	49.1	90.6
002	Dry DF/PP/GF (3-15) shrubland	4.4	2.9	1949.5	2.9	0.0	42.0	69.4	111.4
003	Dry DF/PP/GF (3-15) grassland	0.5	0.6	626.6	1.9	0.0	20.5	48.2	68.7
004	Dry DF/PP/GF (3-15) grassland	2.5	1.4	859.4	2.1	0.0	33.9	48.4	82.4
005	Dry DF/PP/GF (3-15) shrubland	2.5	1.9	1308.0	3.3	0.0	28.6	29.7	58.3
006	Dry DF/PP/GF (3-15) grassland	1.4	0.8	589.9	2.2	0.0	20.5	25.3	45.9
007	Dry DF/PP/GF (16-25)	0.3	0.3	297.7	3.9	5.8	135.3	42.3	177.7
008	Dry DF/PP/GF (16-25)	0.4	0.4	320.8	4.2	5.8	60.8	19.3	80.0
009	Dry DF/PP/GF (16-25)	0.9	0.6	356.3	2.9	7.2	43.0	19.4	62.5
010	Dry DF/PP/GF (16-25)	1.3	0.6	261.3	5.2	8.9	86.9	62.5	149.3
011	Dry DF/PP/GF (16-25)	1.2	0.4	128.1	4.2	8.9	86.9	50.1	136.9
012	Dry DF/PP/GF (16-25)	1.5	0.7	425.9	3.1	0.0	35.4	25.3	60.7
013	Dry DF/PP/GF (26-40)	0.9	0.6	343.0	2.3	0.0	36.0	21.0	57.0
014	Dry DF/PP/GF (26-40)	0.8	0.5	429.8	2.9	0.0	75.6	21.2	96.7
015	Dry DF/PP/GF (26-40)	0.9	0.6	416.2	2.9	0.0	75.5	22.3	97.8
016	Dry DF/PP/GF (26-40)	1.8	1.5	920.3	4.5	0.0	75.6	68.2	143.7
017	Dry DF/PP/GF (26-40)	3.0	2.1	1473.0	9.0	9.0	89.7	50.3	139.9
018	Dry DF/PP/GF (26-40)	0.2	0.3	388.5	2.2	9.0	57.5	23.5	81.0
019	Dry DF/PP/GF (26-40)	1.0	0.5	236.2	4.8	9.0	157.2	33.5	190.7
020	Dry DF/PP/GF (41-80)	1.0	0.7	451.5	5.7	0.0	106.6	13.1	119.6
021	Dry DF/PP/GF (41-80)	2.0	1.6	875.3	3.7	0.0	106.4	65.4	171.8
022	Dry DF/PP/GF (41-80)	1.6	1.1	588.9	3.5	8.5	197.9	38.3	236.2
023	Dry DF/PP/GF (41-80)	2.1	1.2	565.8	2.8	8.9	188.7	49.7	238.4
024	Dry DF/PP/GF (81-150)	1.0	0.5	501.9	1.6	0.0	57.7	9.7	67.5
025	Dry DF/PP/GF (81-150)	0.4	0.7	1151.7	1.9	0.0	100.0	8.5	108.6
026	Dry DF/PP/GF (81-150)	2.4	2.0	1591.0	3.1	0.0	100.0	69.8	169.9
027	Dry DF/PP/GF (81-150)	2.2	1.5	993.0	5.6	7.2	145.4	32.5	177.9
028	Dry DF/PP/GF (81-150)	1.6	1.0	521.6	3.3	8.5	180.4	114.2	294.7
029	Dry DF/PP/GF (151-200)	0.2	0.3	382.9	1.4	8.2	164.1	14.5	178.6
030	Dry DF/PP/GF (151+)	1.9	1.1	503.9	3.7	8.1	234.0	129.5	363.6
031	Dry DF/PP/GF (151-200)	1.5	1.1	654.5	2.6	6.6	164.2	66.3	230.5
032	Dry DF/PP/GF (151-200)	4.3	2.2	1058.7	5.5	8.9	198.1	94.9	293.0
033	DF/moist GF (3-30)	0.9	0.7	454.7	5.5	0.0	20.5	59.0	79.6
034	DF/moist GF (3-30)	0.6	0.6	475.8	5.2	0.0	20.5	19.2	39.8
035	DF/moist GF (31-60)	1.8	1.6	914.7	4.2	5.8	44.7	39.4	84.1
036	DF/moist GF (31-60)	0.3	0.3	330.6	2.1	5.8	44.7	11.8	56.5
037	DF/moist GF (31-60)	0.9	0.8	421.4	4.6	9.0	158.1	22.9	181.0
038	DF/moist GF (31-60)	1.0	0.8	451.0	5.8	9.0	16.2	16.9	33.1
039	DF/moist GF (61-90)	0.2	0.3	157.3	2.1	0.0	90.1	14.2	104.3
040	DF/moist GF (61-90)	1.9	1.7	1032.8	4.7	0.0	91.8	45.3	137.1
041	DF/moist GF (61-90)	1.3	0.9	409.7	4.4	9.0	208.0	37.8	245.8
042	DF/moist GF (91-150)	0.4	0.4	323.9	1.7	0.0	73.5	32.0	105.5
043	DF/moist GF (91-150)	0.8	0.7	436.9	2.1	0.0	73.5	40.5	114.0
044	DF/moist GF (91-150)	1.3	0.9	371.4	3.9	9.0	275.5	68.5	344.0

Table A.1. *Continued.*

ID	Fuelbed pathway	ROS	FL	RI	CFI	CFT	LC	DC	TC
	pathway name (age range) misc.	*m min^{-1}*	*m*	*kW m^{-2}*			------*Mg ha^{-1}*------		
045	DF/moist GF (151-200)	0.9	0.8	393.9	3.1	8.5	219.3	132.1	351.4
046	DF/moist GF (151+)	1.0	0.8	382.7	3.1	9.0	288.0	130.0	417.9
047	Moist GF/WH (3-30)	0.5	0.4	210.2	4.3	0.0	20.6	20.8	41.4
048	Moist GF/WH (3-30)	0.8	0.6	301.1	5.1	0.0	15.5	48.7	64.3
049	Moist GF/WH (31-60)	1.7	1.5	869.3	4.5	7.2	64.3	37.7	102.0
050	Moist GF/WH (31-60)	0.8	0.6	297.7	3.0	7.2	64.3	27.1	91.4
051	Moist GF/WH (31-60)	0.9	0.7	365.9	4.9	9.0	158.0	27.6	185.6
052	Moist GF/WH (61-90)	1.3	1.1	551.2	5.0	9.0	84.5	21.0	105.5
053	Moist GF/WH (61-90)	0.8	0.7	443.9	2.8	7.2	143.6	18.5	162.1
054	Moist GF/WH (61-90)	0.7	0.6	337.5	2.5	7.2	143.6	32.8	176.4
055	Moist GF/WH (61-90)	1.4	1.0	399.4	4.7	9.0	181.4	40.2	221.6
056	Moist GF/WH (61-90)	0.9	0.6	253.7	3.8	9.0	168.2	26.8	195.1
057	Moist GF/WH (91-150)	0.5	0.5	340.9	2.2	0.0	72.9	27.4	100.3
058	Moist GF/WH (91-150)	1.8	1.4	667.6	3.5	0.0	104.9	55.4	160.3
059	Moist GF/WH (91-150)	1.3	0.8	350.3	4.9	9.0	206.5	111.4	317.9
060	Moist GF/WH (151-200)	1.3	0.9	437.6	3.4	8.5	169.9	62.7	232.5
061	Moist GF/WH (151+)	1.3	0.8	309.2	3.2	9.0	193.6	200.6	394.2
064	WH/PSF/MH (3-30)	2.1	0.8	298.4	5.9	7.2	26.9	28.6	55.4
065	WH/PSF/MH (3-30)	2.8	0.9	304.8	6.3	7.2	26.9	109.4	136.4
066	WH/PSF/MH (31-60)	1.5	0.7	291.4	5.7	5.8	130.9	92.0	222.9
067	WH/PSF/MH (31-60)	1.3	0.9	452.2	6.2	7.2	97.1	54.4	151.5
068	WH/PSF/MH (61-90)	1.7	1.3	623.1	4.0	9.0	192.6	87.7	280.4
069	WH/PSF/MH (91-200)	1.6	1.3	708.4	4.1	9.0	266.5	99.6	366.2
070	WH/PSF/MH (201+)	1.7	1.3	621.0	4.1	9.0	367.5	120.3	487.8
071	SF (121+)	1.2	0.8	579.8	6.1	8.1	208.6	33.7	242.4
072	SF (41+) quaking aspen	0.7	0.5	354.4	3.7	0.0	15.0	20.6	35.5
073	SF (3-10)	0.9	0.7	422.2	5.6	5.8	6.4	74.9	81.3
074	SF (11-40)	1.2	0.9	581.3	2.9	8.9	23.5	50.7	74.2
075	SF (41-90)	1.3	0.9	558.8	4.1	8.9	138.7	32.3	171.0
076	SF (91-120)	1.2	0.8	438.8	3.0	8.1	119.6	88.6	208.2
077	SF (121+)	1.7	0.8	375.9	2.7	8.1	286.8	99.6	386.5
078	SF (121+)	2.8	1.2	517.6	3.4	8.5	310.2	111.9	422.1
089	Dry WH (3-30)	1.1	0.9	665.2	6.2	8.1	100.0	51.5	151.5
090	Dry WH (31-60)	0.6	0.6	480.2	5.3	8.5	157.3	30.3	187.6
091	Dry WH (61-90)	0.8	0.7	446.1	4.6	7.2	218.1	28.1	246.1
092	Dry WH (91-200)	1.0	0.8	502.3	6.0	5.8	263.5	45.2	308.7
093	Dry WH (201+)	1.4	0.4	141.2	3.1	8.1	280.3	68.2	348.5
094	Dry WH (201+)	1.5	1.0	468.1	3.8	8.5	337.5	83.8	421.3
095	LP (3-10)	0.6	0.5	240.9	4.8	8.1	4.8	28.0	32.9
096	LP (3-20)	0.4	0.2	125.0	3.4	8.1	4.8	8.8	13.6
097	LP (11-20)	0.6	0.5	235.6	4.7	8.1	14.6	27.7	42.3
098	LP (21-40)	0.8	0.5	243.0	5.0	8.9	20.8	27.9	48.7
099	LP (21-40)	1.9	1.4	627.7	7.7	5.8	10.2	29.8	39.9
100	LP (41-80)	1.0	0.6	253.7	2.9	9.0	71.2	54.7	125.9
101	LP (41-80)	1.1	0.7	284.3	3.0	8.1	52.7	49.5	102.2
102	LP (81+)	1.1	0.6	232.0	2.6	7.2	58.1	104.0	162.1
112	SF (121+)	1.7	1.0	605.3	6.7	8.5	99.1	176.4	275.5

Table A.1. *Continued.*

ID	Fuelbed pathway	ROS	FL	RI	CFI	CFT	LC	DC	TC
	pathway name (age range) misc.	*m min^{-1}*	*m*	*kW m^{-2}*			------*Mg ha^{-1}*------		
113	PP (3-15) shrubland	0.9	1.0	878.9	2.8	0.0	43.6	20.7	64.3
114	PP (3-15) shrubland	2.5	1.8	1235.8	3.2	0.0	14.2	20.0	34.2
115	PP (3-15) grassland	0.2	0.3	354.9	1.6	0.0	38.6	9.9	48.5
116	PP (3-15) grassland	0.9	0.7	538.5	2.1	0.0	9.0	17.8	26.9
117	PP (3-15) shrubland	0.6	0.9	1054.0	2.3	0.0	14.2	13.1	27.3
118	PP (3-15) grassland	0.2	0.3	366.0	1.7	0.0	12.2	11.4	23.7
119	PP (16-25)	1.3	1.1	798.9	3.1	0.0	45.7	19.0	64.7
120	PP (16-25)	0.5	0.9	1211.5	2.3	0.0	31.0	20.3	51.3
121	PP (16-25)	2.5	1.8	1191.1	3.9	0.0	34.4	20.7	55.0
122	PP (16-25)	1.7	1.4	949.4	3.4	0.0	48.6	23.7	72.4
123	PP (16-25)	0.4	0.4	438.8	2.1	0.0	36.8	10.8	47.6
124	PP (16-25)	1.2	0.8	616.3	2.8	0.0	37.0	18.2	55.2
125	PP (26-40)	2.6	2.2	1891.9	4.2	0.0	50.9	17.4	68.3
126	PP (26-40)	0.2	0.5	876.3	2.1	0.0	38.3	15.4	53.7
127	PP (26-40)	2.9	2.3	1669.0	4.3	0.0	39.5	29.2	68.7
128	PP (26-40)	4.9	2.8	1764.4	5.7	0.0	64.3	20.2	84.5
129	PP (26-40)	1.8	1.4	1009.9	3.5	0.0	87.3	27.0	114.3
130	PP (41-80)	4.9	3.2	2368.7	8.9	0.0	137.5	36.3	173.8
131	PP (41-80)	1.5	0.8	455.4	2.9	8.9	35.2	15.7	50.8
132	PP (41-80)	0.7	0.7	568.0	2.6	0.0	97.2	10.0	107.1
133	PP (41-80)	1.9	1.5	961.1	3.6	0.0	98.1	23.0	121.0
134	PP (41-80)	1.9	1.7	1751.8	3.8	5.8	83.7	13.2	96.9
135	PP (41-80)	2.1	1.3	720.0	3.4	9.0	133.7	23.5	157.2
136	PP (41-80)	1.8	1.3	911.0	4.3	9.0	137.5	19.6	157.1
137	PP (81-150)	1.8	1.0	591.6	2.9	6.6	98.4	16.3	114.7
138	PP (81-150)	2.2	2.0	1956.2	4.1	0.0	126.4	14.1	140.5
139	PP (81-150)	1.8	1.3	790.3	3.8	4.7	109.3	78.5	187.8
140	PP (81-150)	3.3	2.3	1584.8	4.8	9.0	177.1	30.6	207.7
141	PP (81-150)	3.3	2.5	2013.6	4.5	5.8	202.1	14.7	216.9
142	PP (151-200)	0.4	0.4	316.9	1.5	0.0	105.6	9.9	115.5
143	PP (151-200)	0.7	0.6	353.0	1.7	0.0	68.6	20.0	88.6
144	PP (151-200)	1.0	1.3	1657.6	2.5	7.2	217.3	10.9	228.1
145	PP (151-200)	1.9	1.2	613.0	2.6	8.9	205.7	47.1	252.8
146	PP (151+)	3.0	2.3	1756.0	3.5	7.2	186.4	93.1	279.4
147	WL (3-15)	0.4	0.4	301.9	1.9	0.0	28.9	13.0	41.8
148	WL (3-15)	0.4	0.5	434.6	2.2	0.0	29.6	69.2	98.7
149	WL (16-40)	0.3	0.3	295.5	1.8	7.2	34.5	9.9	44.5
150	WL (16-40)	0.4	0.4	294.0	1.9	7.2	34.5	51.3	85.9
151	WL (16-40)	0.7	0.6	389.3	2.3	7.2	34.5	62.2	96.8
152	WL (41-80)	0.3	0.3	250.1	1.8	8.1	86.5	7.7	94.2
153	WL (41-80)	0.4	0.3	250.4	1.9	8.1	86.5	28.4	114.9
154	WL (41-80)	1.1	1.0	555.8	3.1	8.5	86.5	45.0	131.5
155	WL (16-40)	0.4	0.3	196.7	1.8	0.0	48.5	60.4	108.8
156	WL (81-150)	0.6	0.5	526.4	1.7	5.8	94.0	6.8	100.8
157	WL (81-150)	0.8	0.7	544.0	2.0	5.8	106.2	31.3	137.5
158	WL (151-200)	0.8	0.5	407.8	1.9	0.0	130.4	10.8	141.2
159	WL (151+)	0.8	0.7	563.0	2.8	0.0	149.9	38.5	188.4

Table A.1. *Continued.*

ID	Fuelbed pathway	ROS	FL	RI	CFI	CFT	LC	DC	TC
	pathway name (age range) misc.	*m min^{-1}*	*m*	*kW m^{-2}*			------*Mg ha^{-1}*------		
160	DF/ninebark (3-40)	0.7	0.6	513.8	2.1	0.0	79.9	26.0	105.9
161	DF/ninebark (16-40)	0.9	0.6	486.6	2.2	0.0	80.3	22.5	102.8
162	DF/ninebark (41-80)	0.6	0.6	678.6	2.6	0.0	75.8	23.9	99.7
163	DF/ninebark (41-80)	1.7	1.3	1042.8	3.8	0.0	76.1	33.6	109.7
164	DF/ninebark (41-80)	0.5	0.8	1030.0	2.4	0.0	82.6	28.9	111.5
165	DF/ninebark (81-150)	0.5	0.5	600.5	2.6	5.8	55.4	16.4	71.8
166	DF/ninebark (81-150)	2.2	1.4	928.2	4.2	5.8	55.5	34.8	90.3
167	DF/ninebark (81-150)	1.6	1.3	831.8	2.5	7.2	84.8	37.5	122.3
168	DF/ninebark (151+)	0.9	0.7	510.8	2.6	8.1	123.1	29.6	152.8
169	PP/WL/DF (3-25)	0.1	0.2	409.2	1.6	0.0	47.2	30.5	77.7
170	PP/WL/DF (3-25)	0.2	0.3	511.6	1.7	0.0	44.7	10.8	55.5
171	PP/WL/DF (26-40)	0.3	0.5	635.5	2.6	7.2	80.0	34.8	114.7
172	PP/WL/DF (26-40)	0.7	0.6	772.8	2.9	0.0	84.6	10.8	95.4
173	PP/WL/DF (41-80)	1.1	0.7	746.0	3.6	6.6	118.7	15.1	133.8
174	PP/WL/DF (41-80)	2.1	1.8	1517.4	5.4	6.6	118.7	37.8	156.5
175	PP/WL/DF (81-150)	1.8	1.0	789.5	2.8	8.9	173.3	25.9	199.1
176	PP/WL/DF (81-150)	0.5	0.7	1171.5	2.9	7.2	214.7	10.7	225.3
177	PP/WL/DF (81-150)	1.6	1.6	1678.0	4.1	7.2	168.9	30.5	199.4
178	PP/WL/DF (41-80)	1.4	0.9	512.5	2.8	8.5	123.9	45.3	169.3
179	PP/WL/DF (41-80)	1.3	1.2	1206.9	3.2	9.0	131.1	28.6	159.7
180	PP/WL/DF (81-150)	1.3	1.0	886.1	3.6	8.9	179.6	43.0	222.6
181	PP/WL/DF (81-150)	0.7	0.8	989.5	2.2	7.7	168.0	29.2	197.2
182	PP/WL/DF (151+)	3.0	1.5	927.3	3.9	8.9	206.8	56.1	262.8
183	PP/WL/DF (151-200)	1.5	0.8	699.1	2.7	0.0	138.1	16.9	155.0
184	PP/WL/DF (151+)	1.5	1.3	1080.0	3.3	6.6	193.0	51.1	244.0
185	PP/WL/DF (151-200)	1.1	1.1	1403.0	2.8	7.2	257.1	13.7	270.8
186	PP/WL/DF (81-150)	1.2	1.0	1081.9	3.0	0.0	144.2	15.3	159.6
187	PP/WL/DF (151-200)	1.2	1.2	1242.8	3.1	5.8	181.4	19.7	201.1
188	PP/WL/DF (81-150)	3.2	2.0	1595.1	4.5	0.0	144.5	34.4	178.8
189	WL/DF (3-20)	0.4	0.4	281.3	1.8	0.0	37.6	91.0	128.6
190	WL/DF (3-20)	0.4	0.3	253.9	1.7	0.0	20.9	15.8	36.7
191	WL/DF (21-40)	1.5	0.8	692.4	2.6	0.0	48.1	14.2	62.3
192	WL/DF (21-40)	0.7	0.6	703.6	2.2	0.0	35.8	14.6	50.4
193	WL/DF (21-40)	1.9	1.5	1108.9	4.0	0.0	52.5	28.5	81.0
194	WL/DF (21-40)	1.6	0.8	665.4	3.1	8.1	60.9	24.4	85.3
195	WL/DF (21-40)	0.7	0.6	724.8	2.7	8.1	48.4	12.3	60.7
196	WL/DF (41-80)	1.4	1.1	1089.6	4.1	7.2	90.2	37.6	127.8
197	WL/DF (41-80)	1.1	0.9	1066.3	3.8	5.8	93.8	20.5	114.3
198	WL/DF (41-80)	1.1	0.8	443.6	3.8	8.9	84.9	36.4	121.3
199	WL/DF (81-150)	0.4	0.5	682.0	2.1	5.8	85.7	11.0	96.7
200	WL/DF (81-150)	0.4	0.5	901.4	1.7	0.0	119.5	11.5	131.0
201	WL/DF (81-150)	2.4	1.7	1511.5	2.9	5.8	119.2	45.2	164.3
202	WL/DF (81-150)	1.0	0.8	446.9	3.0	9.0	137.2	34.0	171.2
203	WL/DF (151+)	1.3	1.1	582.8	3.0	9.0	181.9	41.1	222.9
204	WL/DF (151+)	1.3	1.0	569.2	3.0	9.0	188.7	66.8	255.5
205	WL/DF/LP (3-20)	0.4	0.5	438.5	2.2	0.0	48.3	63.9	112.2
206	WL/DF/LP (3-20)	0.4	0.4	312.8	1.9	0.0	48.3	17.5	65.8

Table A.1. *Continued.*

ID	Fuelbed pathway	ROS	FL	RI	CFI	CFT	LC	DC	TC
	pathway name (age range) misc.	*m min^{-1}*	*m*	*kW m^{-2}*			------*Mg ha^{-1}*------		
207	WL/DF/LP (21-40)	0.9	0.7	672.4	2.5	0.0	55.0	18.4	73.3
208	WL/DF/LP (21-40)	0.7	0.5	565.4	2.3	0.0	51.5	17.2	68.8
209	WL/DF/LP (21-40)	1.6	1.3	1053.3	4.1	0.0	55.0	27.4	82.3
210	WL/DF/LP (21-40)	1.0	0.9	877.3	2.8	8.1	61.4	21.6	83.0
211	WL/DF/LP (21-40)	0.4	0.6	829.8	2.4	0.0	58.1	20.8	78.9
212	WL/DF/LP (41-80)	0.6	0.5	408.5	2.6	7.2	101.5	13.8	115.3
213	WL/DF/LP (41-80)	0.7	0.6	455.3	2.0	7.2	97.3	12.8	110.1
214	WL/DF/LP (41-80)	1.1	0.9	566.7	3.1	8.9	111.8	21.4	133.2
215	WL/DF/LP (81-150)	1.0	0.8	911.0	2.4	0.0	106.8	13.1	119.9
216	WL/DF/LP (81-150)	2.2	1.4	878.9	3.0	0.0	106.2	26.6	132.8
217	WL/DF/LP (81-150)	2.0	1.4	717.6	2.5	8.9	144.7	33.8	178.5
218	WL/DF/LP (151-200)	2.7	1.1	779.0	3.0	0.0	174.5	21.8	196.2
219	WL/DF/LP (201+)	1.8	1.2	497.1	3.8	9.0	196.3	42.9	239.2
220	WL/LP (3-15)	0.5	0.5	422.0	2.3	0.0	48.3	21.6	69.9
221	WL/LP (16-40)	0.7	0.6	378.5	2.8	8.5	61.1	20.9	82.0
222	WL/LP (41-80)	1.1	0.9	552.5	3.4	8.9	103.9	37.8	141.7
223	WL/LP (81-150)	1.5	1.1	649.3	3.2	8.9	133.3	41.9	175.1
224	ES/WBP/SL (31-60)	3.1	1.0	408.8	6.6	0.0	20.3	53.2	73.6
225	ES/WBP/SL (61+)	1.2	0.8	514.3	5.5	0.0	126.6	86.4	213.0
229	High elevation grassland (3+)	0.2	0.1	115.2	0.0	0.0	0.3	0.5	0.8
230	ES/WBP/SL (3-30) shrubland	5.0	1.6	604.8	0.0	0.0	6.3	6.2	12.5
231	High elevation sagebrush (21-40)	0.7	1.0	1550.0	4.7	0.0	22.7	7.3	29.9
233	Low elevation grassland (3+)	0.7	0.3	284.6	0.0	0.0	0.3	0.3	0.6
236	Low elevation sagebrush (21-40)	0.7	0.8	1605.7	0.0	0.0	2.9	3.4	6.3
401	Dry DF/PP/GF (0-2) post-wildfire	0.1	0.1	108.4	1.0	0.0	19.1	40.9	60.1
402	DF/moist GF (0-2) post-wildfire	0.4	0.4	352.7	0.0	0.0	1.0	59.0	60.1
403	Moist GF/WH (0-2) post-wildfire	0.3	0.3	236.3	0.0	0.0	0.8	48.7	49.5
404	WH/PSF/MH (0-2) post-wildfire	3.2	1.3	591.8	0.0	0.0	5.0	109.3	114.3
408	PP (0-2) post-wildfire	0.2	0.3	256.0	1.6	0.0	38.3	17.4	55.8
409	WL (0-2) post-wildfire	0.3	0.3	342.6	1.5	0.0	24.5	69.1	93.6
410	DF/ninebark (0-2) post-wildfire	0.4	0.4	326.5	1.5	0.0	74.7	25.7	100.4
411	PP/WL/DF (0-2) post-wildfire	0.1	0.1	251.5	1.0	0.0	15.6	30.3	46.0
412	WL/DF (0-2) post-wildfire	0.2	0.2	214.6	1.2	0.0	17.5	90.9	108.4
413	WL/DF/LP (0-2) post-wildfire	0.4	0.5	378.0	1.7	0.0	43.1	63.9	106.9
414	WL/LP (0-2) post-wildfire	0.4	0.5	385.5	2.1	0.0	46.4	21.6	68.0
415	ES/WBP/SL (0-2) post-wildfire	0.9	0.5	311.1	3.3	0.0	13.0	27.6	40.5
416	High elev. grassland (0-2) post-wildfire	0.1	0.0	51.2	0.0	0.0	0.1	0.5	0.6
417	High elev. sagebrush (0-2) post-wildfire	0.1	0.1	185.5	0.0	0.0	0.2	0.8	1.0
418	Low elev. sagebrush (0-2) post-wildfire	0.1	0.1	162.9	0.0	0.0	0.2	0.7	0.9
419	Low elev. grassland (0-1) post-wildfire	0.1	0.0	54.9	0.0	0.0	0.1	0.3	0.3
501	Dry DF/PP/GF (0-2) post-harvest	1.2	1.1	707.6	0.0	0.0	1.2	68.9	70.1
508	PP (0-2) post-harvest	1.1	1.0	540.4	0.0	0.0	0.6	21.1	21.7
601	Dry DF/PP/GF (0-2) post-harvest+Rx fire	0.4	0.4	279.0	0.0	0.0	0.6	25.2	25.8
602	DF/moist GF (0-2) post-harvest+Rx fire	0.3	0.3	286.0	0.0	0.0	0.4	19.2	19.6
603	Moist GF/WH (0-2) post-harvest+Rx fire	0.1	0.2	116.1	0.0	0.0	0.5	20.8	21.3
604	WH/PSF/MH (0-2) post-harvest+Rx fire	1.3	0.9	591.0	0.0	0.0	0.7	34.4	35.2
607	LP (0-2) post-harvest+Rx fire	0.2	0.2	125.0	0.0	0.0	0.0	8.8	8.8

Table A.1. *Continued.*

ID	Fuelbed pathway	ROS	FL	RI	CFI	CFT	LC	DC	TC
	pathway name (age range) misc.	*m min^{-1}*	*m*	*kW m^{-2}*			------*Mg ha^{-1}*------		
608	PP (0-2) post-harvest+Rx fire	0.1	0.3	428.6	0.0	0.0	0.7	12.3	13.0
609	WL (0-2) post-harvest+Rx fire	0.3	0.3	298.4	0.0	0.0	0.4	13.0	13.3
610	DF/ninebark (0-2) post-harvest+Rx fire	0.4	0.4	326.5	1.5	0.0	74.7	25.7	100.4
611	PP/WL/DF (0-2) post-harvest+Rx fire	0.2	0.3	490.2	1.7	0.0	16.9	10.8	27.7
612	WL/DF (0-2) post-harvest+Rx fire	0.2	0.2	186.3	0.0	0.0	0.4	15.7	16.1
613	WL/DF/LP (0-2) post-harvest+Rx fire	0.3	0.3	297.0	0.0	0.0	0.2	15.5	15.7
704	WH/PSF/MH (0-2) post-wildfire	3.2	1.3	591.8	0.0	0.0	5.0	109.3	114.3
705	SF (0-2) post-wildfire	0.5	0.5	346.5	0.0	0.0	1.0	74.8	75.8
706	Dry WH (0-2) post-wildfire	0.5	0.5	376.1	0.0	0.0	0.6	51.4	52.0
707	LP (0-2) post-wildfire	0.4	0.4	217.9	0.0	0.0	0.0	28.0	28.0
709	WL (0-2) post-wildfire	0.3	0.3	342.6	1.5	0.0	24.5	69.1	93.6
711	PP/WL/DF (0-2) post-wildfire	0.1	0.1	251.5	1.0	0.0	15.6	30.3	46.0
713	WL/DF/LP (0-2) post-wildfire	0.4	0.5	378.0	1.7	0.0	43.1	63.9	106.9
715	ES/WBP/SL (0-2) post-wildfire	0.9	0.5	311.1	3.3	0.0	13.0	27.6	40.5
800	Dry DF/PP/GF (151-200)	1.9	1.5	995.7	4.6	8.9	198.4	95.7	294.0
801	Dry DF/PP/GF (201-250)	1.9	1.5	995.7	4.6	8.9	198.4	95.7	294.0
802	Dry DF/PP/GF (201-250)	4.3	2.2	1058.7	5.5	8.9	198.1	94.9	293.0
803	Dry DF/PP/GF (251-300)	4.3	2.2	1058.7	5.5	8.9	198.1	94.9	293.0
804	DF/moist GF (91-150)	0.6	0.5	318.9	2.6	7.2	164.7	32.7	197.3
805	Moist GF/WH (91-150)	1.3	0.9	430.0	4.4	8.1	192.8	43.3	236.2
806	PP (151-200)	1.6	1.2	829.1	3.2	6.6	170.0	17.8	187.8
807	PP (201-250)	1.6	1.2	829.1	3.2	6.6	170.0	17.8	187.8
808	PP (201-250)	1.9	1.2	613.0	2.6	8.9	205.5	47.1	252.6
809	PP (251-300)	1.9	1.2	613.0	2.6	8.9	205.5	47.1	252.6
810	High elevation sagebrush (3-10)	0.4	0.4	610.5	0.0	0.0	0.8	1.7	2.5
811	High elevation sagebrush (11-20)	0.2	0.4	972.1	7.0	0.0	3.3	4.3	7.6
812	High elevation sagebrush (41+)	0.2	0.5	1398.7	3.8	0.0	16.0	7.6	23.6
813	Low elevation sagebrush (3-10)	0.3	0.3	515.2	0.0	0.0	0.6	1.3	1.9
814	Low elevation sagebrush (11-20)	0.2	0.4	845.3	0.0	0.0	1.7	3.1	4.8
815	Low elevation sagebrush (41+)	0.5	0.7	1195.9	0.0	0.0	2.5	5.5	8.0

Table A.2. *Okanogan-Wenatchee National Forest FCCS fuelbed stand, vegetation, and woody fuel characteristics listed by fuelbed identification (ID) number. Overstory (OS), midstory (MS), and understory (US) tree density and diameter at breast height are modal values.*

	Tree density			**Tree diameter**			**Coverage**				**Woody fuels**	
ID	**OS**	**MS**	**US**	**OS**	**MS**	**US**	**Trees**	**Shrubs**	**Herbs**	**Litter**	**Small**	**Large**
	----- *trees ha^{-1}* -----			---------- *cm* ----------			---------- *percentage* ----------				--- *Mg ha^{-1}* ---	
001	10	0	400	51		3	10	80	5	80	5.3	27.9
002	10	0	400	51		3	10	80	75	75	5.3	27.9
003	10	0	200	41		3	10	10	70	28	4.8	15.2
004	10	0	400	51		3	10	10	70	80	5.3	27.9
005	10	0	200	41		3	10	85	10	50	3.0	18.9
006	10	0	200	41		3	10	10	85	50	3.0	17.1
007	175	0	100	15		2	50	25	40	46	1.5	25.6
008	175	0	100	15		2	50	25	40	46	1.5	13.4
009	10	150	100	43	13	2	60	25	10	45	1.5	6.4
010	400	0	200	13		1	80	5	20	100	1.5	25.6
011	400	0	200	13		1	80	5	20	100	6.5	20.3
012	10	150	100	43	8	2	60	10	85	45	1.5	18.0
013	10	60	75	46	13	2	40	20	10	97	1.9	10.6
014	109	0	50	20		1	40	30	30	85	1.6	10.2
015	109	0	50	20		1	40	30	40	90	1.6	10.2
016	109	0	50	20		1	40	30	30	90	11.2	27.5
017	350	0	500	18		3	85	30	10	99	6.8	16.4
018	9	250	70	46	10	1	85	30	40	55	3.7	10.9
019	200	150	100	15	5	1	85	25	20	95	5.7	16.1
020	75	0	100	28		1	40	45	20	88	3.3	2.6
021	75	0	100	28		1	40	45	20	90	11.2	25.9
022	125	300	200	30	18	1	75	40	20	100	6.2	16.1
023	200	0	400	30		1	80	40	20	100	4.7	29.9
024	51	0	50	33		1	40	4	92	96	0.8	4.0
025	40	0	50	46		1	35	15	92	90	0.8	2.2
026	40	0	50	46		1	35	15	92	90	13.0	27.6
027	50	50	200	36	15	2	60	45	15	60	4.0	10.0
028	75	75	150	43	15	1	75	10	15	100	4.7	32.0
029	50	0	50	51		3	71	29	40	40	1.2	6.2
030	75	75	150	48	15	1	70	10	15	100	4.7	42.6
031	50	0	50	51		3	55	29	60	90	7.3	21.3
032	40	40	200	43	23	2	80	45	15	100	9.5	24.4
033	0	0	800			5	30	30	15	50	2.4	18.6
034	0	0	800			5	30	30	15	40	2.4	13.0
035	120	0	0	20			50	20	20	100	14.2	17.8
036	120	0	0	20			50	20	20	50	2.4	5.4
037	400	200	80	20	8	1	90	10	10	100	5.4	10.3
038	0	200	80		8	1	90	5	6	100	2.4	10.3
039	60	0	80	36		1	40	5	1	50	2.4	6.3
040	60	0	80	36		1	40	25	25	90	14.7	23.0
041	200	80	80	30	10	1	90	5	1	100	6.2	19.2
042	20	0	80	51		1	40	20	10	50	2.4	5.4
043	20	0	80	51		1	40	20	10	60	3.5	11.9
044	150	80	100	36	23	1	90	5	1	100	7.4	29.5

Table A.2. *Continued.*

	Tree density			Tree diameter			Coverage				Woody fuels	
ID	**OS**	**MS**	**US**	**OS**	**MS**	**US**	**Trees**	**Shrubs**	**Herbs**	**Litter**	**Small**	**Large**
	----- *trees ha^{-1}* -----			---------- *cm* ----------			---------- *percentage* ----------				--- *Mg ha^{-1}* ---	
045	20	20	250	56	38	8	75	5	1	100	6.1	9.6
046	30	20	100	56	38	5	90	5	1	100	6.1	50.6
047	0	0	900			5	30	30	20	50	1.2	9.3
048	0	0	800			5	30	30	20	50	2.4	18.6
049	120	0	0	20			60	20	20	100	14.2	17.8
050	120	0	0	20			60	20	20	85	2.4	19.7
051	400	200	80	20	8	1	90	5	1	100	5.4	13.9
052	400	200	80	15	8	1	90	5	1	100	8.4	7.6
053	100	0	80	30		1	60	5	20	85	4.5	7.7
054	100	0	80	30		1	60	5	10	85	2.4	19.7
055	175	60	80	30	10	1	90	5	1	100	6.2	19.2
056	250	80	80	25	10	1	90	5	1	100	2.7	16.6
057	20	0	80	51		1	40	5	20	50	2.7	8.3
058	20	0	80	51		1	40	10	25	85	10.3	24.5
059	80	40	200	36	23	1	90	5	1	100	7.4	29.5
060	20	150	50	53	15	1	75	20	10	100	6.1	16.4
061	30	40	50	46	30	8	90	5	1	100	6.1	40.7
064	0	0	750			8	60	40	15	90	1.8	20.8
065	0	0	750			8	60	40	15	100	1.8	41.9
066	20	56	181	46	25	8	50	14	21	100	2.7	38.4
067	200	0	181	23		8	60	14	21	100	2.7	29.6
068	76	75	50	36	20	8	100	6	15	100	10.0	24.3
069	75	50	50	43	30	8	100	6	15	100	10.0	24.4
070	65	40	70	51	36	8	100	3	15	100	10.0	36.8
071	250	0	100	25		5	70	7	45	100	4.3	14.0
072	72	0	11619	11		2	97	6	9	36	1.8	1.3
073	0	0	1000			1	50	40	7	30	4.8	15.6
074	100	400	0	13	8		80	30	7	90	9.4	14.8
075	85	450	50	30	18	4	80	30	7	90	4.5	14.8
076	35	200	100	46	30	10	70	20	7	100	2.9	17.3
077	15	100	100	51	33	5	70	20	10	100	2.1	29.6
078	25	100	100	51	30	5	75	50	40	100	3.4	38.2
089	400	0	1000	11		1	70	60	45	60	6.4	17.6
090	500	0	800	13		1	75	55	25	75	5.7	10.3
091	225	0	200	20		1	60	28	15	45	5.7	5.0
092	100	0	250	30		5	50	28	15	86	4.5	8.7
093	70	100	0	36	10		70	14	10	100	11.0	5.1
094	60	80	0	41	15		75	5	5	100	6.7	20.0
095	650	0	4800	3		1	70	1	2	50	4.8	12.3
096	650	0	4800	3		1	70	1	2	50	0.8	4.2
097	650	0	3000	8		3	70	1	2	70	4.8	17.9
098	500	500	2000	10	5	3	80	1	2	80	3.6	18.3
099	250	0	1000	10		1	50	1	2	70	10.3	14.3
100	400	400	200	20	10	1	90	1	2	80	3.6	20.4
101	250	500	200	20	10	1	70	1	2	80	6.4	14.1

Table A.2. *Continued.*

	Tree density			Tree diameter			Coverage				Woody fuels	
ID	**OS**	**MS**	**US**	**OS**	**MS**	**US**	**Trees**	**Shrubs**	**Herbs**	**Litter**	**Small**	**Large**
	----- *trees ha^{-1}* -----			---------- *cm* ----------			---------- *percentage* ----------				--- *Mg ha^{-1}* ---	
102	150	250	200	25	15	1	60	1	2	90	3.6	50.3
112	2	40	800	53	30	5	75	65	9	100	3.9	32.3
113	18	0	200	61		1	10	60	30	28	4.1	7.4
114	10	0	20	41		1	10	60	44	50	5.3	7.2
115	18	0	100	61		1	10	10	70	50	1.3	4.7
116	10	0	20	41		1	10	10	70	50	5.3	7.2
117	10	0	20	41		1	10	60	44	20	1.9	5.3
118	10	0	100	41		3	10	10	70	50	2.7	2.6
119	18	0	400	61		5	20	30	15	95	4.1	4.8
120	10	0	400	61		5	30	60	44	80	4.5	7.6
121	10	0	400	61		5	30	60	44	50	4.5	7.6
122	18	0	1000	61		5	60	30	10	95	5.3	7.8
123	10	0	1000	61		5	60	10	70	60	2.7	2.5
124	10	0	1000	61		5	60	10	70	55	4.5	7.6
125	18	0	150	64		10	30	30	30	30	3.5	7.7
126	10	0	150	64		10	30	30	30	40	1.7	5.5
127	10	0	150	64		10	30	45	30	90	10.3	7.1
128	18	18	1200	64	23	8	90	15	20	96	4.0	8.9
129	10	0	1000	61		8	60	30	20	96	4.5	7.6
130	12	500	34	69	23	18	40	40	30	90	5.0	11.9
131	15	60	10	51	23	3	80	3	11	95	1.7	2.4
132	10	70	20	69	30	3	30	20	20	50	2.9	2.7
133	10	70	20	69	30	3	30	30	30	75	5.6	10.6
134	15	150	10	69	25	3	50	40	30	96	2.9	3.6
135	10	600	0	69	15		95	10	20	95	5.3	8.7
136	15	600	100	69	20	18	95	16	10	100	4.0	7.7
137	10	50	20	69	36	3	55	3	50	95	1.7	2.4
138	10	70	10	69	36	3	40	20	50	70	3.5	3.8
139	5	200	0	69	23		45	10	20	90	6.5	24.9
140	10	200	0	69	28		95	10	10	100	5.7	9.5
141	10	150	10	69	33	3	50	40	30	90	3.5	3.8
142	50	10	10	56	43	3	40	5	40	50	2.9	1.6
143	20	30	10	61	43	3	40	5	40	95	3.5	4.4
144	100	10	10	61	43	3	60	20	40	90	2.9	1.6
145	200	0	0	46			80	5	10	100	5.7	15.4
146	75	0	20	46		3	60	10	40	90	6.9	29.5
147	10	0	400	51		3	70	10	31	40	1.7	2.4
148	10	0	500	51		3	70	10	31	40	4.8	5.8
149	4	150	100	51	10	1	60	3	35	40	2.4	1.8
150	4	150	100	51	10	1	60	3	35	40	2.4	5.9
151	4	150	100	51	10	1	60	3	35	75	5.2	11.0
152	10	90	50	51	20	1	70	10	45	40	1.1	1.5
153	10	90	50	51	20	1	70	10	45	40	1.1	9.6
154	10	90	50	51	20	1	75	10	45	85	7.3	16.1
155	10	0	700	51		1	85	1	15	60	5.6	10.5
156	50	21	50	36	10	1	50	10	45	30	1.1	1.5

Table A.2. *Continued.*

	Tree density			Tree diameter			Coverage				Woody fuels	
ID	**OS**	**MS**	**US**	**OS**	**MS**	**US**	**Trees**	**Shrubs**	**Herbs**	**Litter**	**Small**	**Large**
	----- *trees ha^{-1}* -----			---------- *cm* ----------			---------- *percentage* ----------				--- *Mg ha^{-1}* ---	
157	55	21	50	36	15	1	50	15	65	70	7.8	9.8
158	35	10	15	46	25	10	35	20	75	30	1.1	2.8
159	35	10	50	48	25	10	35	25	65	60	9.5	13.2
160	10	0	150	64		1	55	81	30	20	2.4	7.2
161	10	100	75	64	5	1	40	66	40	30	2.4	9.0
162	8	60	25	66	13	5	40	21	73	70	2.6	4.6
163	8	60	25	66	13	5	40	31	78	90	7.2	6.2
164	10	75	50	64	10	1	50	21	73	90	3.8	5.3
165	20	25	25	41	15	5	50	4	70	50	2.6	2.7
166	20	25	25	41	15	5	50	11	70	90	9.4	9.2
167	8	75	90	64	20	1	60	6	43	100	6.8	8.7
168	20	40	50	51	15	3	70	5	53	83	3.1	9.7
169	3	3	600	51	25	8	60	10	40	10	2.0	3.5
170	3	0	600	51		8	50	5	53	10	1.2	3.0
171	3	400	150	51	13	3	60	5	33	20	3.1	11.2
172	3	400	300	51	13	5	75	3	33	25	1.2	1.3
173	100	75	70	28	13	3	55	5	73	60	0.7	0.7
174	100	75	70	28	13	3	55	5	73	80	8.6	12.7
175	105	50	50	33	13	3	80	30	43	95	2.6	6.3
176	90	20	10	38	25	1	60	5	43	18	1.4	3.4
177	65	30	10	38	25	1	60	5	43	83	9.8	9.4
178	150	200	50	20	15	1	75	3	23	100	5.6	14.6
179	150	200	100	23	13	1	85	15	33	85	5.6	4.9
180	120	50	50	30	20	1	80	3	53	100	5.4	5.3
181	100	30	10	33	20	1	65	3	53	68	5.6	3.1
182	100	40	20	36	20	8	80	3	53	100	5.4	25.9
183	70	5	10	36	30	1	35	3	53	35	1.8	5.0
184	100	5	10	36	30	1	55	3	53	90	9.2	21.3
185	90	20	25	41	30	8	60	5	73	63	1.8	1.7
186	65	30	0	36	25		40	5	73	60	2.4	1.7
187	90	10	50	36	30	1	50	5	73	80	3.9	1.2
188	65	30	0	36	25		40	5	73	80	9.5	10.2
189	4	0	350	51		8	70	20	23	60	2.0	5.4
190	2	0	350	41		8	60	20	23	60	1.1	4.4
191	4	110	50	51	15	3	40	20	33	50	1.1	5.2
192	2	110	0	41	15		40	20	43	80	1.1	3.6
193	4	110	50	56	15	3	40	20	33	80	10.4	5.4
194	4	250	100	51	13	1	70	20	33	80	1.1	12.8
195	2	250	100	41	13	1	70	20	33	80	1.1	3.6
196	80	60	25	25	20	1	60	25	53	80	2.7	17.0
197	110	80	25	23	15	1	50	25	53	80	2.0	2.5
198	150	100	100	20	10	1	80	10	18	80	3.0	16.8
199	60	10	50	30	20	1	50	30	63	40	1.7	2.6
200	60	10	25	36	25	1	40	25	53	40	1.7	2.5
201	60	10	25	36	25	1	50	25	53	80	9.3	18.7
202	120	80	4	28	15	5	90	10	13	80	6.1	12.6

Table A.2. *Continued.*

	Tree density			Tree diameter			Coverage				Woody fuels	
ID	**OS**	**MS**	**US**	**OS**	**MS**	**US**	**Trees**	**Shrubs**	**Herbs**	**Litter**	**Small**	**Large**
	----- *trees ha^{-1}* -----			---------- *cm* ----------			---------- *percentage* ----------				--- *Mg ha^{-1}* ---	
203	50	40	4	43	25	5	90	10	15	80	9.4	13.2
204	90	70	4	36	20	1	90	30	6	100	9.9	35.4
205	10	0	500	51		3	70	10	31	40	5.3	8.3
206	10	0	500	51		3	70	10	31	40	1.7	5.5
207	10	10	150	51	8	8	40	30	31	80	2.5	3.7
208	10	20	180	51	8	5	40	30	41	40	1.2	2.0
209	10	10	150	51	8	8	40	30	31	80	10.5	4.6
210	10	100	300	51	10	5	70	15	46	80	3.6	6.1
211	10	20	500	51	10	5	70	30	41	40	2.8	4.7
212	10	200	25	51	13	3	60	40	21	85	4.0	3.7
213	10	180	25	51	13	3	60	40	21	85	4.0	2.7
214	10	175	275	56	13	3	80	30	21	85	6.4	5.1
215	90	10	25	25	13	3	30	40	81	40	3.0	3.7
216	90	10	25	25	13	3	30	30	51	80	9.1	8.6
217	125	100	25	28	13	3	80	30	21	85	13.3	4.8
218	75	10	25	38	25	3	40	30	81	70	1.6	3.9
219	125	20	0	33	15		85	3	14	85	10.5	15.2
220	10	0	500	51		3	70	10	31	40	5.3	5.5
221	10	500	100	51	8	3	75	10	31	60	4.3	8.4
222	200	150	25	20	8	3	80	10	11	80	5.7	8.8
223	150	100	25	25	13	5	80	45	11	80	8.1	12.5
224	10	0	200	36		5	20	40	60	61	2.5	35.8
225	30	0	100	56		15	40	15	40	61	2.5	22.6
229	0	0	0				0	0	65	5	0.0	0.0
230	8	0	0	20			5	90	0	80	0.1	0.4
231	15	0	0	25			10	75	8	20	0.1	0.3
233	0	0	0				0	0	90	12	0.0	0.0
236	0	0	0				0	40	50	10	0.2	0.0
401	10	0	0	41			10	5	10	20	4.3	9.6
402	0	0	0				0	15	15	25	2.4	18.6
403	0	0	0				0	15	10	25	2.4	18.6
404	0	0	0				0	20	10	70	1.8	41.9
408	18	0	0	61			10	10	20	25	2.8	5.8
409	10	0	0	51			5	5	16	25	4.8	5.8
410	10	0	0	64			5	41	20	20	2.4	7.2
411	3	3	0	51	25		2	5	20	10	2.0	3.5
412	4	0	0	51			5	10	13	25	2.0	5.4
413	10	0	0	51			2	5	16	40	5.3	8.3
414	10	0	0	51			2	5	16	25	5.3	5.5
415	10	0	0	36			5	20	10	51	1.1	10.1
416	0	0	0				0	0	35	5	0.0	0.0
417	0	0	0				0	3	20	3	0.0	0.0
418	0	0	0				0	3	20	3	0.0	0.0
419	0	0	0				0	0	50	5	0.0	0.0
501	0	0	0				0	10	5	100	5.7	28.9
508	0	0	0				0	5	15	65	6.4	8.2

Table A.2. *Continued.*

	Tree density			Tree diameter			Coverage				Woody fuels	
ID	**OS**	**MS**	**US**	**OS**	**MS**	**US**	**Trees**	**Shrubs**	**Herbs**	**Litter**	**Small**	**Large**
	----- *trees ha^{-1}* -----			---------- *cm* ----------			---------- *percentage* ----------				--- *Mg ha^{-1}* ---	
601	0	0	0				10	5	5	25	3.0	17.1
602	0	0	0				0	5	10	25	2.4	13.0
603	0	0	0				0	10	10	25	1.2	9.3
604	0	0	0				0	10	10	50	1.8	20.8
607	0	0	0				0	1	2	25	0.8	4.2
608	0	0	0				0	5	30	25	3.9	3.9
609	0	0	0				0	10	21	25	1.7	2.4
610	10	0	0	64			5	41	20	20	2.4	7.2
611	3	0	0	51			2	5	53	10	1.2	3.0
612	0	0	0				0	10	13	30	1.1	4.4
613	0	0	0				0	5	16	25	1.7	5.5
704	0	0	0				0	20	10	70	1.8	41.9
705	0	0	0				0	20	5	25	4.8	15.5
706	0	0	0				0	20	15	25	6.4	17.6
707	0	0	0				0	1	2	25	4.8	12.3
709	10	0	0	51			5	5	16	25	4.8	5.8
711	3	3	0	51	25		2	5	20	10	2.0	3.5
713	10	0	0	51			2	5	16	40	5.3	8.3
715	10	0	0	36			5	20	10	51	1.1	10.1
800	40	40	200	43	23	2	80	20	15	90	7.3	21.3
801	40	40	200	43	23	2	80	20	15	90	7.3	21.3
802	40	40	200	43	23	2	80	45	15	100	9.5	24.4
803	40	40	200	43	23	2	80	45	15	100	9.5	24.4
804	60	0	80	46		4	60	10	10	60	2.8	6.5
805	60	20	50	41	23	3	70	5	20	90	5.8	16.7
806	10	70	20	76	41	3	55	10	50	85	3.4	4.0
807	10	70	20	76	41	3	55	10	50	85	3.4	4.0
808	200	0	0	46			80	0	10	100	5.7	15.4
809	200	0	0	46			80	0	10	100	5.7	15.4
810	0	0	0				0	12	40	3	0.0	0.0
811	15	0	0	8			5	40	20	5	0.3	0.0
812	15	0	0	28			10	65	10	10	0.4	0.0
813	0	0	0				0	12	40	3	0.0	0.0
814	0	0	0				0	30	40	5	0.3	0.0
815	20	0	0	3			2	50	10	10	0.4	0.0

Table A.3. *Simulated mean patch size, percentage of the landscape, and clumpiness index for low (L), medium (M), and high (H) flame length classes under combinations of current (F1) and elevated (F2) fire regimes, and no (T0), current (T1), and elevated (T2) management regimes over time for the Okanogan-Wenatchee National Forest. Values are mean of 10 simulations per fire/management treatment combination.*

	F1/T0			F1/T1			F1/T2			F2/T0			F2/T1			F2/T2		
Year	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**
									Mean patch size (ha)									
0	224	268	29	224	268	29	224	268	29	224	268	29	224	268	29	224	268	29
25	306	231	32	286	222	30	322	208	29	398	191	31	394	179	28	439	168	28
50	411	198	28	426	175	25	496	158	25	661	144	26	598	138	23	704	125	21
75	509	173	25	513	150	19	514	153	21	781	128	22	800	113	17	830	108	18
100	474	177	21	469	158	14	461	157	14	652	143	20	691	117	15	724	112	14
125	424	199	23	463	165	14	420	168	15	590	151	19	558	137	13	578	129	14
150	409	207	22	440	169	15	419	170	14	601	147	21	569	135	13	589	128	14
175	422	196	26	432	168	14	426	169	14	608	147	21	596	129	15	606	122	15
200	428	190	24	454	159	15	452	158	14	628	142	24	628	122	14	606	121	14
									Percentage of landscape									
0	44.2	44.5	0.3	44.2	44.5	0.3	44.2	44.5	0.3	44.2	44.5	0.3	44.2	44.5	0.3	44.2	44.5	0.3
25	47.2	41.1	0.7	46.7	41.6	0.7	48.6	39.8	0.6	52.7	35.7	0.6	52.8	35.7	0.5	54.1	34.4	0.5
50	53.0	35.7	0.3	54.4	34.3	0.3	56.7	32.0	0.3	61.1	27.7	0.2	60.2	28.6	0.2	62.3	26.5	0.2
75	56.7	32.2	0.1	57.9	31.0	0.1	57.9	31.0	0.1	64.1	24.8	0.1	65.0	23.9	0.1	65.2	23.7	0.1
100	55.5	33.5	0.1	56.3	32.6	0.1	55.8	33.1	0.1	60.4	28.6	0.1	62.0	27.0	0.1	62.3	26.6	0.1
125	53.6	35.3	0.1	55.5	33.4	0.1	54.4	34.5	0.1	59.1	29.8	0.1	58.6	30.3	0.1	59.2	29.7	0.1
150	53.0	35.9	0.1	55.1	33.9	0.1	54.1	34.8	0.1	59.5	29.4	0.1	59.3	29.6	0.1	59.6	29.3	0.1
175	53.4	35.5	0.1	54.8	34.1	0.1	54.6	34.3	0.1	60.1	28.9	0.1	59.9	29.0	0.1	60.3	28.6	0.1
200	53.9	35.0	0.1	56.2	32.7	0.1	55.9	33.0	0.1	60.8	28.2	0.1	61.0	28.0	0.1	60.3	28.6	0.1
									Clumpiness index									
0	0.64	0.63	0.53	0.64	0.63	0.53	0.64	0.63	0.53	0.64	0.63	0.53	0.64	0.63	0.53	0.64	0.63	0.53
25	0.67	0.66	0.55	0.64	0.63	0.54	0.64	0.63	0.53	0.68	0.67	0.56	0.66	0.64	0.53	0.65	0.64	0.53
50	0.68	0.68	0.53	0.65	0.64	0.52	0.64	0.64	0.51	0.69	0.68	0.53	0.66	0.65	0.49	0.65	0.64	0.48
75	0.67	0.68	0.53	0.63	0.64	0.47	0.63	0.64	0.48	0.68	0.68	0.51	0.65	0.65	0.43	0.64	0.64	0.45
100	0.66	0.68	0.50	0.63	0.64	0.40	0.62	0.63	0.39	0.67	0.68	0.49	0.64	0.63	0.40	0.63	0.62	0.40
125	0.67	0.68	0.50	0.63	0.65	0.40	0.63	0.64	0.42	0.67	0.68	0.47	0.64	0.64	0.38	0.63	0.63	0.40
150	0.67	0.68	0.51	0.64	0.65	0.41	0.63	0.64	0.40	0.67	0.68	0.51	0.64	0.64	0.38	0.63	0.63	0.38
175	0.66	0.68	0.55	0.63	0.64	0.41	0.63	0.64	0.39	0.67	0.67	0.49	0.64	0.64	0.41	0.62	0.62	0.41
200	0.66	0.68	0.53	0.63	0.64	0.41	0.62	0.63	0.39	0.67	0.68	0.53	0.64	0.63	0.41	0.62	0.62	0.39

Table A.4. *Simulated mean patch size, percentage of the landscape, and clumpiness index for low (L), medium (M), and high (H) rate of spread classes under combinations of current (F1) and elevated (F2) fire regimes, and no (T0), current (T1), and elevated (T2) management regimes over time for the Okanogan-Wenatchee National Forest. Values are mean of 10 simulations per fire/management treatment combination.*

	F1/T0			**F1/T1**			**F1/T2**			**F2/T0**			**F2/T1**			**F2/T2**		
Year	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**
									Mean patch size (ha)									
0	215	275	52	215	275	52	215	275	52	215	275	52	215	275	52	215	275	52
25	249	248	71	234	246	64	254	229	67	299	209	83	278	207	77	308	193	76
50	288	240	92	296	216	79	329	193	82	361	190	109	345	179	104	381	168	97
75	324	229	84	317	207	81	327	198	95	387	181	113	382	163	111	384	162	97
100	302	242	92	291	224	85	297	213	102	325	203	118	333	176	113	336	168	123
125	271	260	98	271	244	62	267	228	68	306	215	99	291	193	94	300	186	82
150	267	256	93	269	227	52	274	212	55	310	201	94	304	176	78	312	172	71
175	273	234	92	270	215	49	283	195	54	317	190	91	304	168	69	315	161	64
200	280	239	75	285	205	53	294	194	52	328	191	91	317	163	75	315	165	62
									Percentage of landscape									
0	42.4	40.5	6.1	42.4	40.5	6.1	42.4	40.5	6.1	42.4	40.5	6.1	42.4	40.5	6.1	42.4	40.5	6.1
25	43.3	41.4	4.3	42.8	42.3	3.9	44.2	40.5	4.3	47.0	36.7	5.3	46.3	37.6	5.1	47.6	36.3	5.1
50	46.4	39.5	3.1	48.0	38.3	2.8	49.7	36.4	2.9	50.7	33.4	4.9	50.3	33.9	4.7	52.0	32.4	4.6
75	48.9	37.7	2.4	49.7	36.8	2.5	50.3	35.8	2.9	52.6	31.8	4.6	52.6	31.0	5.4	52.8	31.7	4.6
100	47.7	38.9	2.4	47.8	38.8	2.3	48.0	38.3	2.7	48.5	35.7	4.8	49.5	35.0	4.4	49.7	34.5	4.8
125	45.4	40.2	3.4	46.0	40.4	2.6	46.1	39.6	3.3	47.5	36.6	4.9	46.9	36.8	5.3	47.7	36.6	4.7
150	45.1	39.9	4.1	46.0	39.3	3.6	46.3	38.6	4.2	48.2	34.9	5.9	47.9	34.7	6.4	48.6	34.7	5.7
175	45.4	38.8	4.8	46.2	38.7	4.1	47.2	37.2	4.6	48.8	34.0	6.2	48.0	34.5	6.6	49.0	33.9	6.1
200	45.9	39.5	3.6	47.5	37.2	4.3	48.2	36.6	4.2	49.5	33.8	5.6	49.1	33.6	6.3	49.0	34.3	5.6
									Clumpiness index									
0	0.64	0.67	0.60	0.64	0.67	0.60	0.64	0.67	0.60	0.64	0.67	0.60	0.64	0.67	0.60	0.64	0.67	0.60
25	0.66	0.67	0.67	0.64	0.64	0.66	0.64	0.64	0.66	0.68	0.68	0.69	0.66	0.65	0.69	0.65	0.65	0.68
50	0.67	0.68	0.71	0.65	0.65	0.69	0.64	0.64	0.70	0.69	0.69	0.73	0.66	0.66	0.72	0.66	0.65	0.71
75	0.67	0.68	0.70	0.64	0.65	0.70	0.63	0.64	0.71	0.69	0.69	0.73	0.67	0.66	0.73	0.66	0.65	0.71
100	0.66	0.68	0.71	0.63	0.64	0.70	0.63	0.64	0.73	0.68	0.68	0.73	0.65	0.64	0.73	0.64	0.64	0.74
125	0.66	0.68	0.72	0.63	0.65	0.68	0.63	0.64	0.68	0.67	0.68	0.72	0.64	0.64	0.72	0.63	0.63	0.71
150	0.66	0.68	0.71	0.63	0.64	0.64	0.63	0.63	0.65	0.67	0.68	0.71	0.65	0.64	0.69	0.64	0.63	0.68
175	0.66	0.67	0.70	0.63	0.63	0.62	0.63	0.62	0.63	0.67	0.67	0.70	0.64	0.63	0.67	0.63	0.63	0.66
200	0.66	0.67	0.68	0.64	0.63	0.63	0.63	0.63	0.62	0.68	0.68	0.71	0.65	0.63	0.69	0.63	0.62	0.66

Table A.5. *Simulated mean patch size, percentage of the landscape, and clumpiness index for low (L), medium (M), and high (H) reaction intensity classes under combinations of current (F1) and elevated (F2) fire regimes, and no (T0), current (T1), and elevated (T2) management regimes over time for the Okanogan-Wenatchee National Forest. Values are mean of 10 simulations per fire/management treatment combination.*

	F1/T0			**F1/T1**			**F1/T2**			**F2/T0**			**F2/T1**			**F2/T2**		
Year	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**
									Mean patch size (ha)									
0	72	403	156	72	403	156	72	403	156	72	403	156	72	403	156	72	403	156
25	61	1,207	48	58	1,206	49	56	1,151	50	62	1167	45	58	1,142	48	58	1,115	48
50	55	1,144	55	52	1,214	49	52	1,179	51	59	1,056	52	54	1,022	56	54	1,001	55
75	68	989	58	65	1,040	50	64	1,023	50	66	898	56	66	913	52	62	946	48
100	69	791	73	63	957	53	62	916	52	69	678	79	63	813	58	57	861	54
125	69	681	83	63	855	59	62	759	63	68	621	86	59	683	72	58	682	69
150	68	683	85	63	759	65	61	694	71	68	630	81	62	656	70	62	656	69
175	68	716	79	63	789	61	60	717	68	61	695	75	62	679	64	58	685	66
200	68	808	67	65	843	55	62	752	62	69	706	67	60	741	58	58	731	59
									Percentage of landscape									
0	10.5	55.4	23.0	10.5	55.4	23.0	10.5	55.4	23.0	10.5	55.4	23.0	10.5	55.4	23.0	10.5	55.4	23.0
25	9.3	71.2	8.5	8.9	71.0	9.1	8.8	70.8	9.4	9.9	71.2	7.9	9.4	70.6	9.0	9.6	70.4	9.1
50	8.3	71.4	9.4	8.3	71.8	8.8	8.3	71.3	9.3	9.5	70.4	9.1	9.1	69.8	10.1	9.5	69.4	10.2
75	10.3	68.6	10.1	10.4	69.0	9.6	10.8	68.3	9.9	10.8	67.9	10.2	11.3	67.4	10.3	11.3	67.6	10.1
100	10.6	65.8	12.6	10.5	67.4	11.1	10.4	66.7	11.9	11.0	63.6	14.3	11.0	65.2	12.8	10.5	65.8	12.7
125	11.0	63.8	14.2	10.4	65.7	12.8	10.3	64.6	14.1	10.9	62.3	15.8	10.3	63.2	15.6	10.3	63.2	15.5
150	10.6	63.9	14.5	10.5	64.7	13.7	10.0	63.7	15.2	11.1	62.9	15.0	10.9	62.9	15.2	10.9	62.8	15.3
175	10.6	64.7	13.7	10.5	65.2	13.3	9.9	64.3	14.8	10.0	64.7	14.3	10.7	63.8	14.4	10.4	63.4	15.1
200	10.6	66.3	12.1	10.8	66.1	12.1	10.4	64.9	13.7	11.4	64.8	12.8	10.4	65.2	13.4	10.3	64.6	14.1
									Clumpiness index									
0	0.63	0.63	0.72	0.63	0.63	0.72	0.63	0.63	0.72	0.63	0.63	0.72	0.63	0.63	0.72	0.63	0.63	0.72
25	0.60	0.61	0.59	0.59	0.60	0.58	0.59	0.60	0.59	0.60	0.60	0.58	0.59	0.60	0.58	0.59	0.60	0.58
50	0.59	0.62	0.62	0.58	0.61	0.59	0.58	0.61	0.59	0.60	0.61	0.61	0.58	0.61	0.61	0.58	0.60	0.60
75	0.62	0.62	0.63	0.62	0.60	0.59	0.61	0.60	0.58	0.61	0.61	0.62	0.61	0.59	0.59	0.60	0.59	0.57
100	0.62	0.62	0.66	0.61	0.59	0.58	0.61	0.58	0.57	0.62	0.62	0.67	0.60	0.58	0.59	0.60	0.57	0.57
125	0.63	0.62	0.67	0.61	0.58	0.58	0.61	0.58	0.58	0.62	0.62	0.68	0.60	0.58	0.61	0.60	0.58	0.60
150	0.62	0.63	0.67	0.61	0.58	0.59	0.61	0.58	0.59	0.62	0.62	0.66	0.61	0.58	0.61	0.61	0.58	0.60
175	0.62	0.62	0.66	0.61	0.58	0.58	0.61	0.57	0.58	0.60	0.61	0.65	0.60	0.58	0.59	0.60	0.57	0.58
200	0.62	0.61	0.64	0.62	0.58	0.57	0.61	0.57	0.57	0.62	0.61	0.64	0.60	0.57	0.57	0.60	0.56	0.56

Table A.6. *Simulated mean patch size, percentage of the landscape, and clumpiness index for low (L), medium (M), and high (H) crown fire initiation potential classes under combinations of current (F1) and elevated (F2) fire regimes, and no (T0), current (T1), and elevated (T2) management regimes over time for the Okanogan-Wenatchee National Forest. Values are mean of 10 simulations per fire/management treatment combination.*

	F1/T0			**F1/T1**			**F1/T2**			**F2/T0**			**F2/T1**			**F2/T2**		
Year	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**
									Mean patch size (ha)									
0	94	315	132	94	315	132	94	315	132	94	315	132	94	315	132	94	315	132
25	113	528	57	108	521	55	125	476	57	147	361	63	136	359	65	155	329	64
50	148	403	77	155	356	75	180	311	75	204	243	95	210	218	95	246	196	92
75	152	373	108	170	312	100	203	268	96	225	205	115	252	171	114	273	147	119
100	144	362	120	157	303	105	180	272	97	188	220	121	206	178	109	228	164	101
125	130	409	108	138	339	109	146	304	102	159	260	116	174	209	101	187	194	110
150	126	430	120	139	341	92	140	335	93	156	253	124	184	199	105	195	192	102
175	127	409	134	133	344	96	141	331	89	162	242	120	170	198	109	181	188	106
200	124	431	111	147	321	92	156	295	93	176	232	116	173	203	96	190	191	94
									Percentage of landscape									
0	24.1	47.7	17.2	24.1	47.7	17.2	24.1	47.7	17.2	24.1	47.7	17.2	24.1	47.7	17.2	24.1	47.7	17.2
25	24.1	57.4	7.5	24.4	57.1	7.6	26.8	54.5	7.7	29.3	51.0	8.7	29.3	50.5	9.2	31.5	48.3	9.2
50	27.9	53.7	7.3	30.5	51.3	7.2	33.0	48.3	7.7	36.0	42.9	10.2	37.7	41.1	10.1	40.0	38.8	10.2
75	29.1	53.7	6.1	32.3	50.3	6.4	35.4	47.5	6.0	38.5	40.7	9.8	41.7	36.6	10.7	43.0	34.6	11.4
100	28.4	53.5	7.1	31.4	50.7	6.9	34.1	48.6	6.3	35.0	42.6	11.3	38.0	39.2	11.7	39.8	38.8	10.4
125	26.6	55.5	6.9	29.5	52.3	7.2	31.5	50.4	7.2	31.6	46.7	10.7	35.5	43.1	10.4	36.6	42.1	10.3
150	26.1	56.0	6.9	29.7	52.7	6.6	30.3	52.2	6.5	31.6	46.0	11.3	36.7	41.9	10.4	37.3	41.8	9.8
175	26.3	55.3	7.4	29.0	53.2	6.8	30.5	52.3	6.2	32.5	45.0	11.5	35.4	41.8	11.8	36.4	41.7	10.9
200	25.9	56.8	6.3	31.1	51.2	6.7	32.0	50.5	6.5	34.4	43.7	11.0	36.0	42.4	10.5	37.4	41.9	9.6
									Clumpiness index									
0	0.59	0.66	0.71	0.59	0.66	0.71	0.59	0.66	0.71	0.59	0.66	0.71	0.59	0.66	0.71	0.59	0.66	0.71
25	0.64	0.66	0.61	0.63	0.65	0.60	0.64	0.65	0.61	0.66	0.67	0.63	0.64	0.66	0.63	0.65	0.66	0.63
50	0.67	0.67	0.67	0.65	0.65	0.66	0.65	0.64	0.66	0.68	0.68	0.69	0.66	0.65	0.68	0.67	0.65	0.69
75	0.67	0.67	0.71	0.65	0.64	0.70	0.65	0.63	0.69	0.68	0.67	0.71	0.67	0.65	0.71	0.66	0.64	0.71
100	0.66	0.67	0.72	0.63	0.63	0.70	0.62	0.62	0.69	0.67	0.67	0.71	0.63	0.63	0.70	0.62	0.62	0.69
125	0.65	0.66	0.70	0.62	0.63	0.71	0.62	0.62	0.70	0.66	0.67	0.71	0.62	0.63	0.69	0.62	0.62	0.70
150	0.66	0.67	0.72	0.63	0.63	0.69	0.62	0.63	0.69	0.65	0.67	0.72	0.62	0.63	0.69	0.63	0.63	0.70
175	0.66	0.67	0.74	0.62	0.63	0.69	0.62	0.62	0.69	0.65	0.67	0.71	0.62	0.63	0.70	0.61	0.62	0.70
200	0.65	0.66	0.71	0.63	0.63	0.68	0.63	0.62	0.69	0.66	0.67	0.71	0.62	0.63	0.69	0.62	0.62	0.69

Table A.7. *Simulated mean patch size, percentage of the landscape, and clumpiness index for low (L), medium (M), and high (H) crown fire transmissivity potential classes under combinations of current (F1) and elevated (F2) fire regimes, and no (T0), current (T1), and elevated (T2) management regimes over time for the Okanogan-Wenatchee National Forest. Values are mean of 10 simulations per fire/management treatment combination.*

	F1/T0			**F1/T1**			**F1/T2**			**F2/T0**			**F2/T1**			**F2/T2**		
Year	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**
									Mean patch size (ha)									
0	139	36	862	139	36	862	139	36	862	139	36	862	139	36	862	139	36	862
25	183	33	675	170	32	629	196	38	509	237	47	442	221	36	424	241	38	381
50	192	71	497	195	54	443	201	57	388	239	70	336	231	57	305	242	53	289
75	185	79	447	160	64	447	151	60	455	212	82	305	190	63	320	182	55	320
100	179	74	494	151	63	507	168	58	451	182	78	402	167	67	373	177	70	316
125	172	85	530	163	67	461	177	61	407	187	92	388	183	71	331	197	63	299
150	173	89	522	170	78	433	181	66	385	196	80	385	197	68	295	209	63	273
175	173	90	530	158	71	461	179	59	396	201	79	344	179	66	315	195	59	286
200	171	102	529	171	67	414	186	59	362	214	79	325	184	66	292	197	66	274
									Percentage of landscape									
0	28.8	4.4	55.8	28.8	4.4	55.8	28.8	4.4	55.8	28.8	4.4	55.8	28.8	4.4	55.8	28.8	4.4	55.8
25	33.6	0.8	54.6	33.4	1.4	54.3	36.1	2.0	50.9	39.3	1.5	48.2	38.9	1.7	48.3	40.7	2.2	46.0
50	34.5	2.7	51.8	36.7	2.6	49.6	37.9	3.4	47.7	40.5	3.7	44.8	41.1	3.7	44.2	42.2	4.0	42.7
75	34.5	4.4	50.1	34.6	4.8	49.5	34.2	4.6	50.2	39.6	6.2	43.1	39.3	5.7	44.0	39.3	5.7	44.0
100	33.9	4.0	51.1	33.0	4.4	51.5	34.2	4.5	50.4	35.9	5.3	47.8	36.4	6.2	46.5	36.8	7.3	44.9
125	32.5	4.2	52.3	33.0	4.7	51.2	34.9	4.6	49.4	35.5	6.8	46.7	36.8	6.3	45.9	38.1	6.1	44.8
150	32.6	4.2	52.2	34.3	4.8	49.9	35.6	4.7	48.7	36.6	5.3	47.1	38.7	6.1	44.1	39.7	6.1	43.3
175	32.7	3.7	52.6	33.4	4.7	50.9	35.8	3.9	49.2	37.9	5.5	45.6	37.8	6.0	45.2	39.2	5.7	44.1
200	32.5	4.4	52.1	35.2	4.5	49.3	36.6	4.3	48.1	39.6	5.6	43.9	38.3	6.7	44.0	39.4	6.3	43.3
									Clumpiness index									
0	0.65	0.54	0.68	0.65	0.54	0.68	0.65	0.54	0.68	0.65	0.54	0.68	0.65	0.54	0.68	0.65	0.54	0.68
25	0.67	0.55	0.71	0.65	0.53	0.68	0.65	0.56	0.68	0.69	0.60	0.71	0.66	0.55	0.69	0.66	0.56	0.68
50	0.67	0.67	0.70	0.64	0.62	0.67	0.63	0.62	0.66	0.67	0.67	0.69	0.64	0.64	0.66	0.63	0.61	0.66
75	0.66	0.69	0.69	0.63	0.65	0.66	0.63	0.64	0.67	0.65	0.68	0.68	0.62	0.64	0.65	0.62	0.62	0.66
100	0.67	0.67	0.70	0.64	0.65	0.68	0.64	0.64	0.68	0.66	0.68	0.69	0.63	0.66	0.67	0.62	0.66	0.66
125	0.67	0.69	0.70	0.64	0.65	0.68	0.64	0.64	0.67	0.67	0.69	0.70	0.64	0.67	0.67	0.63	0.65	0.66
150	0.67	0.70	0.70	0.64	0.68	0.68	0.63	0.65	0.67	0.66	0.69	0.70	0.63	0.66	0.66	0.63	0.65	0.65
175	0.66	0.70	0.70	0.63	0.67	0.67	0.63	0.64	0.67	0.66	0.68	0.69	0.62	0.65	0.65	0.62	0.64	0.65
200	0.66	0.71	0.70	0.64	0.65	0.67	0.63	0.63	0.66	0.67	0.68	0.69	0.62	0.65	0.65	0.62	0.66	0.65

Table A.8. *Results of two-factor analysis of variance tests for differences in mean patch size for patches classified to represent low (L), medium (M), and high (H) potential flame length (FL), rate of spread (ROS), reaction intensity (RI), crown fire initiation potential (CFI), and crown fire transmissivity potential (CFT) under different fire and management levels. Fire df = 1, Management df = 2; Interaction df = 38*

		FL			ROS			RI			CFI			CFT		
Yr	**Effect**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**
		Mean patch size - F statistic (p<0.05 in bold)														
25	Fire	**60.1**	**49.5**	**159.8**	**8.3**	**62.0**	**7.0**	**117.8**	**77.4**	**77.9**	**26.7**	**64.6**	**87.6**	**88.6**	**44.2**	**28.0**
	Mgt	3.1	**5.6**	**4.5**	0.0	**4.5**	2.5	**15.2**	2.4	2.4	0.9	3.0	**9.7**	**3.4**	1.3	**5.5**
	Fire×Mgt							**3.3**								
50	Fire	**91.8**	**81.9**	**203.9**	**18.3**	**54.5**	0.1	**104.6**	**99.8**	**100.0**	**29.8**	**40.5**	**105.7**	**98.6**	**55.7**	**17.0**
	Mgt	**5.7**	**12.5**	**17.3**	0.1	0.8	**6.9**	**12.2**	**5.7**	**5.8**	0.1	**8.6**	**18.4**	**7.1**	0.4	0.3
	Fire×Mgt															
75	Fire	**146.1**	**196.8**	**305.9**	**9.4**	**75.0**	0.1	**210.3**	**158.3**	**157.0**	**13.6**	**71.8**	**116.6**	**185.0**	**83.5**	**8.4**
	Mgt	0.4	**28.2**	**33.4**	0.4	**31.6**	**15.4**	0.5	1.5	1.6	**5.3**	1.6	**11.0**	2.6	1.1	1.4
	Fire×Mgt															
100	Fire	**113.1**	**98.1**	**245.6**	0.3	**8.8**	**5.1**	**89.6**	**118.5**	**119.3**	**5.8**	**17.7**	**109.7**	**111.4**	**92.0**	2.9
	Mgt	0.7	**21.3**	**29.2**	**6.5**	**13.8**	**7.4**	**10.2**	2.2	2.2	0.7	1.7	**18.1**	2.3	0.8	1.3
	Fire×Mgt															
125	Fire	**102.7**	**73.8**	**176.4**	0.3	**22.4**	1.2	**114.0**	**100.4**	**100.4**	0.6	**20.5**	**118.3**	**74.0**	**92.3**	0.1
	Mgt	0.3	**9.3**	**27.0**	0.6	**4.2**	**17.6**	**27.0**	0.9	0.9	1.8	0.8	**22.6**	0.6	0.5	**4.9**
	Fire×Mgt														**4.8**	
150	Fire	**97.6**	**70.0**	**239.8**	**4.3**	**27.5**	**4.8**	**153.8**	**129.9**	**128.9**	0.7	**66.9**	**150.8**	**161.5**	**68.3**	**9.1**
	Mgt	0.0	**9.6**	**25.2**	**14.3**	2.2	**11.5**	**50.2**	1.3	1.2	0.4	2.5	**23.4**	1.5	0.0	1.4
	Fire×Mgt												**4.1**			
175	Fire	**102.4**	**81.4**	**243.3**	1.1	**30.8**	3.1	**140.8**	**106.5**	**107.2**	0.3	**36.8**	**117.8**	**147.8**	**37.1**	0.1
	Mgt	0.0	**5.8**	**17.5**	**12.2**	**9.9**	**26.7**	**20.0**	0.6	0.6	0.2	**3.3**	**15.0**	**3.5**	0.2	1.7
	Fire×Mgt				**3.8**											
200	Fire	**110.7**	**48.5**	**180.8**	0.4	**24.0**	1.7	**149.3**	**97.4**	**96.8**	0.9	**24.5**	**137.7**	**75.3**	**53.4**	0.4
	Mgt	0.2	**6.6**	**26.8**	**5.7**	**4.5**	**15.6**	**32.4**	1.7	1.7	1.0	1.5	**25.9**	**3.3**	2.4	2.7
	Fire×Mgt			**8.2**		**4.9**	**4.1**	**9.4**				**4.0**		**4.8**		

Table A.9. *Results of two-factor analysis of variance tests for differences in percentage of landscape for patches classified to represent low (L), medium (M), and high (H) potential flame length (FL), rate of spread (ROS), reaction intensity (RI), crown fire initiation potential (CFI), and crown fire transmissivity potential (CFT) under different fire and management levels. Fire df = 1, Management df = 2; Interaction df = 38*

		FL			ROS			RI			CFI			CFT		
Yr	**Effect**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**
		Percentage of landscape - F statistic (p<0.05 in bold)														
25	Fire	3.7	**8.1**	**78.7**	**88.6**	**14.7**	**75.3**	**15.6**	**5.1**	**78.4**	**48.4**	**25.6**	2.9	**61.3**	**46.7**	**10.8**
	Mgt	**6.2**	**29.7**	**8.1**	**6.7**	0.4	**5.5**	**26.9**	**13.3**	**8.9**	**66.1**	**108.7**	**24.3**	**50.4**	**153.6**	1.1
	Fire×Mgt															
50	Fire	**22.7**	3.9	**138.8**	**168.7**	**36.4**	**85.2**	**9.2**	**8.5**	**105.6**	**24.6**	**4.4**	**8.7**	**68.5**	**27.2**	**9.8**
	Mgt	1.0	0.8	**17.5**	**12.6**	0.2	**7.7**	1.5	**7.9**	**9.9**	**126.1**	**179.1**	**9.9**	**80.1**	**168.0**	1.0
	Fire×Mgt															
75	Fire	**13.3**	2.4	**270.3**	**286.6**	**87.7**	**151.7**	**15.5**	**15.0**	**159.8**	**40.2**	0.1	**12.3**	**119.6**	**29.4**	**9.3**
	Mgt	0.5	0.4	**34.3**	**21.0**	1.0	0.2	0.1	**20.3**	0.3	**120.7**	**129.6**	**21.2**	**78.0**	**204.1**	0.0
	Fire×Mgt										**4.1**				**2.9**	
100	Fire	**49.9**	**31.5**	**143.5**	**234.2**	**119.4**	**40.5**	**47.6**	0.2	**75.4**	**12.7**	3.6	0.0	**50.4**	0.1	**9.6**
	Mgt	**17.6**	**13.2**	**33.1**	**13.7**	2.4	1.3	**6.2**	**35.2**	**4.1**	**285.7**	**209.0**	**35.4**	**170.4**	**241.2**	1.6
	Fire×Mgt											**3.3**				
125	Fire	**33.6**	**54.9**	**120.1**	**159.3**	**48.9**	**62.5**	**29.7**	3.5	**104.8**	0.4	**14.8**	3.0	**12.6**	4.0	**11.8**
	Mgt	**6.5**	**3.3**	**35.3**	**17.6**	0.0	**12.4**	0.1	**31.6**	**7.6**	**146.3**	**194.4**	**26.3**	**120.9**	**211.7**	**5.1**
	Fire×Mgt															**4.2**
150	Fire	**14.2**	**4.5**	**131.9**	**177.0**	**72.8**	**69.0**	**17.6**	0.6	**96.2**	**7.1**	**16.8**	1.5	**57.5**	0.5	**18.8**
	Mgt	1.0	2.3	**30.1**	**11.0**	1.5	**12.2**	2.5	**30.0**	**15.4**	**248.0**	**284.9**	**41.5**	**181.1**	**351.8**	**17.0**
	Fire×Mgt															**4.1**
175	Fire	**4.7**	**6.1**	**166.4**	**218.8**	**95.1**	**82.8**	**30.2**	0.6	**108.1**	0.8	**20.1**	0.8	**31.6**	0.8	**17.3**
	Mgt	2.5	**7.1**	**25.3**	**7.2**	1.5	**8.6**	2.3	**31.0**	**6.0**	**182.8**	**243.5**	**43.8**	**148.0**	**302.1**	**31.9**
	Fire×Mgt								**3.4**				**3.5**			**5.7**
200	Fire	**12.1**	**14.8**	**95.6**	**127.6**	**83.5**	**71.1**	**24.8**	0.1	**130.4**	**4.3**	**10.1**	0.0	**34.1**	0.2	**34.3**
	Mgt	**5.0**	**20.2**	**18.6**	**7.8**	0.8	**5.0**	1.0	**62.8**	**6.1**	**276.7**	**243.8**	**85.5**	**157.0**	**295.2**	**24.5**
	Fire×Mgt						**7.4**			**4.1**	**6.1**	**5.1**		**6.2**		

Table A.10. *Results of two-factor analysis of variance tests for differences in clumpiness index for patches classified to represent low (L), medium (M), and high (H) potential flame length (FL), rate of spread (ROS), reaction intensity (RI), crown fire initiation potential (CFI), and crown fire transmissivity potential (CFT) under different fire and management levels. Fire df = 1, Management df = 2; Interaction df = 38*

		FL			ROS			RI			CFI			CFT		
Yr	**Effect**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**
		Clumpiness index - F statistic (p<0.05 in bold)														
25	Fire	0.0	**75.3**	**7.4**	**59.6**	**22.4**	**16.9**	**11.2**	**25.8**	**5.2**	**12.3**	**155.8**	**90.9**	**89.6**	**94.7**	**112.1**
	Mgt	**14.8**	**41.1**	0.8	**5.5**	**9.2**	**17.1**	0.1	**56.1**	**5.5**	**100.6**	**206.9**	**46.4**	**3.9**	**17.1**	**9.6**
	Fire×Mgt															
50	Fire	1.0	**6.1**	2.1	**65.0**	**10.6**	**4.2**	**16.0**	0.1	0.2	**8.5**	**103.4**	**91.7**	**169.8**	**153.0**	**107.9**
	Mgt	**4.3**	**22.7**	**4.9**	**9.2**	**10.6**	**52.8**	0.2	**109.0**	**9.8**	**126.3**	**387.1**	**31.9**	**4.6**	**17.4**	**31.1**
	Fire×Mgt			**3.7**												**4.2**
75	Fire	**9.1**	**62.8**	0.2	**123.9**	**20.4**	3.6	2.6	3.1	0.6	**30.4**	**99.6**	**124.6**	**277.8**	**257.2**	**161.4**
	Mgt	**7.8**	**167.3**	**52.0**	0.5	**30.1**	**66.0**	0.6	**126.2**	**15.5**	**83.6**	**532.5**	**28.3**	1.7	**9.1**	**20.7**
	Fire×Mgt												**3.3**			
100	Fire	**11.0**	**21.7**	**11.9**	**50.4**	1.5	3.1	0.1	**10.9**	2.4	**18.9**	**132.6**	**80.5**	**245.7**	**299.9**	**173.9**
	Mgt	**19.1**	**556.8**	**317.1**	0.2	**111.1**	**222.3**	**4.4**	**66.8**	**5.4**	**42.2**	**916.0**	**35.6**	0.2	**6.6**	**33.1**
	Fire×Mgt															
125	Fire	**11.1**	1.7	**16.3**	**36.5**	0.7	1.6	0.6	**4.7**	1.3	**25.4**	**238.2**	**117.2**	**261.3**	**228.8**	**144.6**
	Mgt	**16.2**	**349.4**	**202.0**	0.8	**61.6**	**127.0**	0.1	**125.5**	**11.1**	**142.6**	**1222**	**37.7**	1.7	2.7	**22.1**
	Fire×Mgt										**5.8**					
150	Fire	2.1	**4.6**	0.2	**92.7**	0.2	1.4	0.1	**11.4**	3.2	**39.3**	**384.3**	**184.8**	**249.0**	**230.0**	**201.6**
	Mgt	**8.3**	**247.1**	**118.1**	1.0	**41.9**	**89.3**	**10.1**	**100.6**	**16.2**	**106.5**	**1298**	**27.1**	2.9	1.8	**40.8**
	Fire×Mgt			**3.3**								**3.7**				
175	Fire	**14.9**	**30.7**	0.4	**39.7**	0.5	0.4	0.0	**14.3**	2.7	**72.3**	**373.8**	**157.0**	**302.4**	**291.0**	**190.6**
	Mgt	**4.8**	**537.1**	**224.6**	1.5	**71.4**	**169.2**	**12.7**	**140.8**	**19.5**	**194.4**	**1370**	**18.2**	0.9	1.0	**43.4**
	Fire×Mgt			**3.7**				**5.1**				**6.3**				
200	Fire	**9.8**	**47.2**	0.2	**31.7**	0.1	0.6	0.0	**11.6**	0.4	**39.4**	**311.2**	**91.4**	**276.3**	**315.7**	**106.2**
	Mgt	**12.4**	**611.1**	**309.6**	0.1	**40.9**	**124.4**	**4.3**	**126.6**	**15.1**	**144.3**	**1233**	**14.8**	2.2	1.7	**32.5**
	Fire×Mgt						**5.6**		**6.9**	**3.7**	**3.3**	**4.5**		**4.2**	**4.6**	

Table A.11. *Results of two-factor analysis of variance tests for differences in live, dead, and total carbon stock under different fire and management levels. Fire df = 1, Management df = 2; Interaction df = 38*

Year	Effect	Live C	Dead C	Total C
			F statistic (p<0.05 in bold)	
25	Fire	**149.8**	**43.7**	**106.8**
	Mgt	**189.7**	**1745.7**	**13.3**
	Fire×Mgt			
50	Fire	**105.4**	**16.4**	**72.5**
	Mgt	**362.0**	**1915.5**	**15.3**
	Fire×Mgt			
75	Fire	**101.8**	**25.9**	**62.3**
	Mgt	**507.2**	**2787.4**	**13.2**
	Fire×Mgt			**8.4**
100	Fire	**129.5**	**10.4**	**28.3**
	Mgt	**770.7**	**1830.7**	**8.3**
	Fire×Mgt			**7.6**
125	Fire	**248.9**	**29.8**	**42.8**
	Mgt	**1041.9**	**2286.5**	1.7
	Fire×Mgt	**8.2**		
150	Fire	**369.9**	**42.4**	**70.3**
	Mgt	**1058.8**	**2191.1**	**4.9**
	Fire×Mgt	**3.6**		
175	Fire	**397.1**	**74.5**	**55.6**
	Mgt	**1235.7**	**2925.8**	**6.5**
	Fire×Mgt	**3.9**		
200	Fire	**303.6**	**59.6**	**46.9**
	Mgt	**1009.4**	**2410.0**	**6.3**
	Fire×Mgt	**3.8**	**3.5**	

APPENDIX B: SUPPLEMENTAL MATERIAL FOR CHAPTER 4

Table B.1. *Big sagebrush site information for shrub consumption study.*

Burn site	Date	Burn season	Latitude	Longitude	Elevation	Slope	State	Admin. unit[a]
			degrees N	*degrees W*	*m*	*percent*		
Flook Lake 1	10/13/2001	Fall	42.597742	119.543326	1,542	0	Oregon	FWS1
Flook Lake 2	10/12/2001	Fall	42.594769	119.541321	1,540	0	Oregon	FWS1
Flook Lake 3	10/13/2001	Fall	42.597661	119.533690	1,541	0	Oregon	FWS1
Stonehouse 1	10/17/2001	Fall	42.930576	118.431207	1,937	15	Oregon	BLM1
V-Lake A	9/23/2001	Fall	42.460194	118.729875	2,050	5	Oregon	Private
V-Lake 1	9/23/2001	Fall	42.479847	118.723311	2,049	15	Oregon	Private
V-Lake 2	9/23/2001	Fall	42.460063	118.731193	2,056	3	Oregon	Private
V-Lake 3	9/30/2001	Fall	42.460040	118.734864	2,042	0	Oregon	Private
V-Lake 4	9/30/2001	Fall	42.469944	118.739075	2,018	10	Oregon	Private
Gold Digger 1	10/25/2001	Fall	41.761465	121.569964	1,331	0	California	NPS
Gold Digger 2	10/25/2001	Fall	41.757153	121.572142	1,346	5	California	NPS
Escarpment 1	9/28/2001	Fall	41.869722	119.672413	1,672	0	Nevada	FWS2
Escarpment 2	9/28/2001	Fall	41.866967	119.665315	1,693	5	Nevada	FWS2
Heart Mountain	10/2/2001	Fall	44.684389	109.159229	1,823	8	Wyoming	BLM2
Old Tanker	10/2/2001	Fall	44.700974	109.129910	1,771	0	Wyoming	BLM2
Sand Coulee	10/2/2001	Fall	44.718922	109.148771	1,764	15	Wyoming	BLM2
Sagehen 2	3/21/2002	Spring	41.923856	119.243801	1,717	0	Nevada	FWS2
Dyce Creek A	4/13/2004	Spring	45.318060	113.022670	2,356	15	Montana	BLM3
Dyce Creek B	3/31/2004	Spring	45.317050	113.023110	2,335	17	Montana	BLM3
Dyce Creek C	3/31/2004	Spring	45.309480	113.022980	2,294	20	Montana	BLM3
Dyce Creek D	3/31/2004	Spring	45.308430	113.022980	2,262	15	Montana	BLM3
NBC 1a	4/23/2004	Spring	44.915650	113.351190	2,228	16	Montana	BLM3
NBC 1b	4/23/2004	Spring	44.916050	113.351190	2,228	9	Montana	BLM3
NBC 2a	4/23/2004	Spring	44.910370	113.354800	2,310	14	Montana	BLM3
NBC 2b	4/23/2004	Spring	44.910620	113.354570	2,307	14	Montana	BLM3
NBC 2c	4/23/2004	Spring	44.910910	113.354220	2,300	14	Montana	BLM3

[a]FWS1 = U.S. Fish and Wildlife Service, Hart Mountain National Antelope Refuge; FWS2 = U.S. Fish and Wildlife Service, Sheldon National Wildlife Refuge; BLM1 = Bureau of Land Management, Burn, OR; BLM2 = Bureau of Land Management, Cody, WY; BLM3 = Bureau of Land Management, Butte, MT; NPS = National Park Service, Lava Beds National Monument; Private = Roaring Springs Ranch.

Table B.2. *Site weather and fuel moisture data for big sagebrush study sites.*

	Weather				Fuel moisture		
Burn site	**Temp**	**RH**	**Windspeed**	**Days since rain[a]**	**Grass**	**Live foliage**	**Dead 10hr**
	°C	*percent*	*km hr⁻¹*		---------- *percent* ----------		
Flook Lake 1	17.8	21	12.9	2.5	10.2	59.9	9.2
Flook Lake 2	17.2	34	12.1	1.5	9.8	61.8	9.2
Flook Lake 3	17.8	17	12.9	2.5	10.2	59.9	9.2
Stonehouse 1	7.2	40	6.4	7.0	29.9	78.7	8.4
V-Lake A	22.2	22	3.2	10.0	19.9	60.6	2.8
V-Lake 1	23.9	24	12.1	10.0	38.7	70.9	3.4
V-Lake 2	22.2	22	3.2	10.0	19.9	60.6	2.8
V-Lake 3	21.7	26	4.0	5.0	22.6	74.9	6.1
V-Lake 4	21.1	28	9.0	5.0	22.6	74.9	6.1
Gold Digger 1	16.7	26	7.2	30.5	13.7	71.9	7.7
Gold Digger 2	16.7	25	7.2	30.5	13.7	71.9	7.7
Escarpment 1	17.8	35	6.4	3.5	10.6	68.9	6.8
Escarpment 2	17.8	35	6.4	3.5	10.6	68.9	6.8
Heart Mountain	16.1	25	5.6	18.0	30.3	73.6	5.7
Old Tanker	16.7	28	12.1	18.0	30.3	73.6	5.7
Sand Coulee	20.6	24	4.0	18.0	30.3	73.6	5.7
Sagehen 2	17.2	23	16.1	32.0	14.5	77.1	10.8
Dyce Creek A	15.6	34	8.8	3.5	45.3	106.0	14.4
Dyce Creek B	12.8	28	11.3	2.5	36.7	94.3	11.6
Dyce Creek C	12.8	28	11.3	2.5	12.8	88.7	9.3
Dyce Creek D	12.8	28	7.2	2.5	12.8	88.7	9.3
NBC 1a	13.9	30	12.1	2.5	54.2	110.1	11.9
NBC 1b	13.9	30	12.1	2.5	54.2	110.1	11.9
NBC 2a	13.9	30	13.7	2.5	41.3	107.4	16.9
NBC 2b	13.9	30	13.7	2.5	41.3	107.4	16.9
NBC 2c	13.9	30	13.7	2.5	41.3	107.4	16.9

[a]Days since >2.5 mm of measured rainfall at the nearest Remote Automated Weather Station.

Table B.3. *Modeled potential fire behavior for big sagebrush study sites.*

Burn site	Flame length	Rate of spread	Fireline intensity	Reaction intensity
	m	*m sec*$^{-1}$	*kW m*$^{-1}$	*kW m*$^{-2}$
Flook Lake 1	0.94	0.02	228.1	1161.6
Flook Lake 2	1.07	0.02	296.9	1133.1
Flook Lake 3	1.13	0.03	334.9	878.5
Stonehouse 1	0.55	0.01	70.1	898.3
V-Lake A	0.88	0.02	155.7	1010.6
V-Lake 1	0.43	0.00	197.4	1117.0
V-Lake 2	0.21	0.00	40.6	480.6
V-Lake 3	0.91	0.01	9.0	1224.7
V-Lake 4	0.79	0.01	212.5	1399.4
Gold Digger 1	0.76	0.01	143.0	1036.9
Gold Digger 2	0.58	0.01	78.9	850.7
Escarpment 1	0.70	0.01	119.4	778.5
Escarpment 2	0.85	0.01	182.9	1248.3
Heart Mountain	1.10	0.01	315.6	1788.3
Old Tanker	1.16	0.03	354.9	956.7
Sand Coulee	0.55	0.01	70.1	1041.2
Sagehen 2	3.05	0.19	2896.9	1159.3
Dyce Creek A	2.56	0.18	1984.4	940.5
Dyce Creek B	4.60	0.45	7084.6	1353.2
Dyce Creek C	4.66	0.51	7289.8	1238.0
Dyce Creek D	3.26	0.25	3355.0	1162.2
NBC 1a	3.35	0.30	3562.5	1043.7
NBC 1b	3.57	0.24	4072.8	1580.2
NBC 2a	1.55	0.12	672.0	634.3
NBC 2b	2.80	0.22	2417.4	1215.6
NBC 2c	3.54	0.32	3997.7	1276.7

Table B.4. *Pre-fire fuel loading for big sagebrush sites.*

Burn site	Herbaceous vegetation	Live sagebrush	Dead sagebrush	Other shrubs	All vegetation	Surface fuels[c]	All fuels
	----------	----------	----------	*Mg ha*$^{-1}$	----------	----------	----------
Flook Lake 1	0.290	5.521	5.623	0.002	11.435	0.866	12.300
Flook Lake 2	0.109	7.141	5.763	0.000	13.013	1.523	14.536
Flook Lake 3	0.106	6.087	4.214	0.063	10.471	0.714	11.185
Stonehouse 1	0.614	4.621	1.995	0.580	7.810	2.211	10.021
V-Lake A	0.156	11.113	5.177	0.440	16.885	1.975	18.860
V-Lake 1	0.273	7.919	3.514	0.236	11.942	1.974	13.916
V-Lake 2	0.206	9.207	3.787	0.229	13.430	1.052	14.481
V-Lake 3	0.158	3.239	1.162	0.043	4.602	0.672	5.274
V-Lake 4	0.224	11.062	3.635	0.312	15.233	1.122	16.356
Gold Digger 1	0.733[a]	4.522[b]	3.796[b]	0.000	9.052	0.339	9.391
Gold Digger 2	0.570	6.348[b]	3.396[b]	0.000	10.314	0.511	10.825
Escarpment 1	4.033[a]	3.094	2.652	0.000	9.780	2.709	12.488
Escarpment 2	0.282[a]	7.619	6.626	0.000	14.527	1.562	16.088
Heart Mountain	0.393	12.709	7.492	<0.001	20.594	1.994	22.588
Old Tanker	0.411	4.520	2.937	0.409	8.277	0.992	9.269
Sand Coulee	0.361	5.531	3.193	0.003	9.088	0.968	10.056
Sagehen 2	0.113[a]	6.081	10.919	0.000	17.112	2.231	19.343
Dyce Creek A	0.659	6.016	4.810	0.000	11.485	5.963	17.448
Dyce Creek B	0.863	9.834	6.464	0.000	17.161	6.482	23.643
Dyce Creek C	0.977	7.599	5.925	0.000	14.501	7.847	22.348
Dyce Creek D	0.746	6.210	6.124	0.110	13.190	8.293	21.483
NBC 1a	0.587	7.099	4.805	0.000	12.492	6.085	18.576
NBC 1b	1.833	7.313	4.811	0.000	13.957	4.733	18.690
NBC 2a	0.813	1.593	0.785	0.000	3.191	4.151	7.342
NBC 2b	1.321	4.655	2.592	0.000	8.567	3.301	11.868
NBC 2c	1.293	5.727	3.967	0.000	10.987	5.326	16.313

[a]Includes *Chrysothamnus* spp.
[b]Includes *Purshia tridentata*.
[c]Includes litter and dead and down woody fuels.

Table B.5. *Pre-fire coverage, height, and area burned for big sagebrush sites.*

	Pre-fire coverage and area burned					Height	
Burn Site	**Herbaceous vegetation**	**All sagebrush**	**Other shrubs**	**All vegetation**	**Area burned**	**Grass**	**Sagebrush**
	percent					*m*	
Flook Lake 1	10.8	35.9	0.2	46.8	32.7	0.12	0.39
Flook Lake 2	20.1	38.1	0.0	58.1	38.6	0.17	0.50
Flook Lake 3	4.6	29.0	0.2	33.8	36.9	0.15	0.39
Stonehouse 1	20.0	35.7	6.9	62.5	39.8	0.24	0.55
V-Lake A	20.0	49.8	6.1	75.8	50.6	0.11	0.50
V-Lake 1	12.3	43.9	9.3	65.4	74.6	0.36	0.70
V-Lake 2	14.8	43.2	3.7	61.7	53.7	0.16	0.48
V-Lake 3	15.1	34.5	1.5	51.2	23.9	0.15	0.37
V-Lake 4	23.0	59.5	3.1	85.6	96.9	0.22	0.48
Gold Digger 1	25.7[a]	24.5[b]	2.8	53.0	36.4	0.22	0.40
Gold Digger 2	25.0	30.3[b]	1.3	56.6	60.4	0.23	0.49
Escarpment 1	32.8[a]	13.5	0.0	46.3	75.9	0.17	0.64
Escarpment 2	22.5[a]	35.1	0.0	57.6	78.1	0.41	0.69
Heart Mountain	37.6	66.5	0.3	98.3	98.3	0.16	0.51
Old Tanker	34.3	29.7	2.7	66.7	94.8	0.14	0.32
Sand Coulee	31.5	42.0	0.1	73.6	99.8	0.12	0.29
Sagehen 2	10.9[a]	43.3	0.0	54.2	14.5	0.22	0.92
Dyce Creek A	59.0	64.9	0.0	92.2	56.7	0.11	0.56
Dyce Creek B	66.1	81.3	0.0	97.7	85.2	0.16	0.70
Dyce Creek C	77.8	66.0	0.0	94.4	96.0	0.15	0.69
Dyce Creek D	79.9	65.7	0.0	98.7	100.0	0.13	0.58
NBC 1a	47.6	52.9	0.0	93.6	80.0	0.14	0.53
NBC 1b	48.3	55.9	0.0	84.2	41.9	0.14	0.50
NBC 2a	46.8	52.2	0.0	99.0	11.3	0.08	0.46
NBC 2b	43.5	63.4	0.4	92.6	23.7	0.14	0.46
NBC 2c	49.0	51.5	0.0	87.7	57.0	0.16	0.52

[a]Includes *Chrysothamnus* spp.
[b]Includes *Purshia tridentata*.

TableB.6. *Fuel consumption for big sagebrush sites.*

Burn site	Herbaceous vegetation	All sagebrush	Other shrubs	All vegetation	Surface fuels[a]	All fuels
	---------- *Mg ha* $^{-1}$ *(percentage of pre-fire loading)* ----------					
Flook Lake 1	0.097 (33.6)	3.132 (28.1)	0.001 (33.6)	3.230 (28.2)	0.291 (33.6)	3.521 (28.6)
Flook Lake 2	0.042 (38.6)	4.020 (31.2)	0.000	4.062 (31.2)	0.588 (38.6)	4.650 (32.0)
Flook Lake 3	0.040 (38.0)	4.999 (48.5)	0.024 (38.0)	5.064 (48.4)	0.271 (38.0)	5.335 (47.7)
Stonehouse 1	0.246 (40.0)	1.992 (30.1)	0.232 (40.0)	2.469 (31.6)	0.885 (40.0)	3.354 (33.5)
V-Lake A	0.082 (53.0)	9.750 (59.9)	0.233 (53.0)	10.065 (59.6)	1.046 (53.0)	11.112 (58.9)
V-Lake 1	0.205 (75.3)	7.571 (66.2)	0.177 (75.3)	7.954 (66.6)	1.486 (75.3)	9.440 (67.8)
V-Lake 2	0.129 (62.4)	9.457 (72.8)	0.143 (62.4)	9.728 (72.4)	0.656 (62.4)	10.384 (71.7)
V-Lake 3	0.050 (31.6)	1.322 (30.0)	0.013 (31.6)	1.385 (30.1)	0.212 (31.6)	1.597 (30.3)
V-Lake 4	0.218 (97.2)	13.648 (92.9)	0.304 (97.2)	14.170 (93.0)	1.091 (97.2)	15.260 (93.3)
Gold Digger 1	0.271 (37.0)	4.660 (56.0)	---	4.931 (54.5)	0.125 (37.0)	5.057 (53.8)
Gold Digger 2	0.346 (60.7)	5.655 (58.0)	---	6.001 (58.2)	0.310 (60.7)	6.311 (58.3)
Escarpment 1	3.148 (78.1)	3.116 (54.2)	---	6.264 (64.1)	2.114 (78.1)	8.379 (67.1)
Escarpment 2	0.222 (78.6)	12.662 (88.9)	---	12.884 (88.7)	1.227 (78.6)	14.111 (87.7)
Heart Mountain	0.390 (99.2)	19.916 (98.6)	0.000 (99.2)	20.306 (98.6)	1.978 (99.2)	22.284 (98.7)
Old Tanker	0.411 (100)	7.341 (98.4)	0.409 (100)	8.161 (98.6)	0.992 (100)	9.153 (98.8)
Sand Coulee	0.361 (100)	8.525 (97.7)	0.003 (100)	8.889 (97.8)	0.968 (100)	9.857 (98.0)
Sagehen 2	0.023 (20.5)	2.737 (16.1)	---	2.761 (16.1)	0.763 (34.2)	3.524 (18.2)
Dyce Creek A	0.374 (56.7)	4.287 (39.6)	---	4.661 (40.6)	3.383 (56.7)	8.044 (46.1)
Dyce Creek B	0.735 (85.2)	10.495 (64.4)	---	11.230 (65.4)	5.522 (85.2)	16.751 (70.9)
Dyce Creek C	0.938 (96.0)	11.589 (85.7)	---	12.527 (86.4)	7.533 (96.0)	20.060 (89.8)
Dyce Creek D	0.746 (100)	9.646 (78.2)	0.110 (100)	10.502 (79.6)	7.930 (95.6)	18.432 (85.8)
NBC 1a	0.470 (80.0)	8.043 (67.6)	---	8.512 (68.1)	4.868 (80.0)	13.380 (72.0)
NBC 1b	0.768 (41.9)	2.155 (17.8)	---	2.923 (20.9)	1.984 (41.9)	4.908 (26.3)
NBC 2a	0.092 (11.3)	0.218 (9.2)	---	0.310 (9.7)	0.470 (11.3)	0.780 (10.6)
NBC 2b	0.313 (23.7)	1.902 (26.2)	---	2.215 (25.9)	0.782 (23.7)	2.997 (25.3)
NBC 2c	0.737 (57.0)	4.894 (50.5)	---	5.632 (51.3)	3.038 (57.0)	8.670 (53.1)

[a]Includes litter and dead and down woody fuels.

Table B.7. *Pine flatwoods site information for shrub consumption study.*

Burn site	Date	Burn season[a]	Latitude	Longitude	State	Admin. Unit[b]
			degrees N	*degrees W*		
A214E	2/17/2005	Dormant	30.38825	84.50228	Florida	USFS
A214NE	2/17/2005	Dormant	30.39500	84.50447	Florida	USFS
A214W	2/17/2005	Dormant	30.39989	84.52228	Florida	USFS
A215N	4/20/2005	Growing	30.40306	84.49900	Florida	USFS
A215NW	4/20/2005	Growing	30.40347	84.50550	Florida	USFS
A215S	4/20/2005	Growing	30.38944	84.50142	Florida	USFS
A302C	2/5/2005	Dormant	30.29717	84.44028	Florida	USFS
A302N	2/5/2005	Dormant	30.30120	84.43127	Florida	USFS
A302S	2/5/2005	Dormant	30.27414	84.43444	Florida	USFS
A303E	1/31/2005	Dormant	30.30075	84.45650	Florida	USFS
A342N	2/8/2005	Dormant	30.07986	84.60169	Florida	USFS
A342S	2/8/2005	Dormant	30.07642	84.60364	Florida	USFS
A343N	7/24/2005	Growing	30.07986	84.60169	Florida	USFS
A343S	7/24/2005	Growing	30.07644	84.60472	Florida	USFS
BW204A	2/18/2005	Dormant	30.84536	84.01928	Georgia	Private
BW215A	2/4/2005	Dormant	30.86381	84.03761	Georgia	Private
E502B-1A	2/6/2005	Dormant	30.45306	86.76336	Florida	DOD
E502B-1B	2/6/2005	Dormant	30.45272	86.76319	Florida	DOD
E502B-1C	2/6/2005	Dormant	30.45242	86.76306	Florida	DOD
E502B-2A	2/6/2005	Dormant	30.45353	86.73847	Florida	DOD
E502B-2B	2/6/2005	Dormant	30.45325	86.73872	Florida	DOD
E502B-2C	2/6/2005	Dormant	30.45322	86.73953	Florida	DOD
E807B-3A	2/17/2004	Dormant	30.48744	86.26294	Florida	DOD
E807B-3B	2/17/2004	Dormant	30.48694	86.26431	Florida	DOD
E807B-3C	2/17/2004	Dormant	30.48608	86.26383	Florida	DOD
PH1N	2/16/2006	Dormant	30.47464	81.49064	Florida	FDRP
PH1V	2/16/2006	Dormant	30.47322	81.49231	Florida	FDRP
SM-P17A	2/16/2005	Dormant	30.08556	84.37200	Florida	USFWS
SM-P18A	2/5/2005	Dormant	30.08447	84.37122	Florida	USFWS
SM-S1A	1/26/2005	Dormant	30.15550	84.15158	Florida	USFWS
SM-S1H	5/23/2005	Growing	30.14289	84.15803	Florida	USFWS

[a]The dormant and growing seasons are from approximately November 1 to March 31 and April 1 to October 31, respectively.
[b]USFS = U.S. Forest Service, Apalachicola National Forest; DOD = Department of Defense, Eglin Airforce Base; FDRP = Florida Division of Recreation and Parks, Pumpkin Hill Creek Preserve State Park; USFWS = U.S. Fish and Wildlife Service, St. Marks National Wildlife Refuge; Private = Greenwood Plantation.

Table B.8. *Site weather information for pine flatwoods study sites.*

Burn site	Temperature	RH	Windspeed	Days since rain[a]	KBDI[b]
	°C	*percent*	*km hr⁻¹*		
A214E	17.2	51	5.6	3.5	223
A214NE	15.6	53	6.1	3.5	223
A214W	17.2	51	5.6	3.5	223
A215N	22.2	65	1.4	13.0	189
A215NW	22.8	65	1.4	13.0	189
A215S	27.8	39	3.5	13.0	189
A302C	23.1	72	5.0	2.0	149
A302N	23.1	72	4.3	2.0	149
A302S	22.7	73	4.3	2.0	149
A303E	12.2	64	2.4	2.0	180
A342N	24.4	48	4.0	5.5	162
A342S	21.7	56	4.8	5.5	162
A343N	35.0	49	2.4	3.0	201
A343S	35.0	49	2.4	3.0	201
BW204A	16.7	12	4.0	4.0	234
BW215A	13.9	50	4.8	1.0	31
E502B-1A	15.0	52	3.2	3.5	20
E502B-1B	16.7	45	3.2	3.5	20
E502B-1C	16.7	45	3.2	3.5	20
E502B-2A	17.8	56	6.4	3.5	20
E502B-2B	17.8	56	6.4	3.5	20
E502B-2C	17.8	56	6.4	3.5	20
E807B-3A	17.2	55	2.4	2.5	92
E807B-3B	14.4	34	4.0	2.5	92
E807B-3C	17.2	31	4.8	2.5	92
PH1N	22.8	68	4.8	12.0	70
PH1V	21.1	71	4.8	12.0	70
SM-P17A	26.1	53	4.8	2.5	198
SM-P18A	15.6	44	3.2	2.5	122
SM-S1A	25.3	46	2.9	3.5	116
SM-S1H	29.7	51	15.3	2.5	311

[a]Days since >6 mm of measured rainfall at the nearest Remote Automated Weather Station.
[b]KBDI = Keetch-Byram Drought Index; lower numbers indicate wetter conditions.

Table B.9. *Site fuel moisture information for pine flatwoods study sites.*

Burn site	Pine litter	Dead 10hr	Grass	Shrub leaves	Shrub stems	Palmetto leaves	Palmetto stems
	percent						
A214E	31.8	40.7	42.5	98.2	94.2	112.9	150.8
A214NE	27.0	52.3	50.8	110.2	89.8	119.5	163.4
A214W	29.4	46.5	46.7	104.2	92.0	116.2	157.1
A215N	25.2	16.0	49.6	113.3	95.0	109.0	160.6
A215NW	31.7	18.3	56.0	116.6	101.8	110.8	162.4
A215S	18.8	13.7	44.5	110.0	88.1	107.2	158.8
A302C	38.8	83.5	46.5	123.1	91.0	108.2	161.1
A302N	22.7	74.1	31.6	118.1	85.5	104.6	149.3
A302S	30.8	75.6	61.8	120.6	91.6	126.4	163.1
A303E	35.2	69.2	44.2	121.0	86.4	114.1	156.2
A342N	21.2	46.0	38.4	118.7	81.0	101.8	147.0
A342S	24.9	43.2	45.2	111.5	87.6	113.2	150.2
A343N	10.0	12.0	113.2	162.9	123.5	146.0	194.8
A343S	10.0	12.0	113.2	162.9	123.5	146.0	194.8
BW204A	13.7	25.0	37.6	115.2	89.3	106.2	150.8
BW215A	45.0	62.5	39.6	129.2	113.5	114.9	163.0
E502B-1A	36.8	55.0	37.0	97.6	73.9	100.3	156.8
E502B-1B	36.8	55.0	37.0	97.6	73.9	100.3	156.8
E502B-1C	36.8	55.0	37.0	97.6	73.9	100.3	156.8
E502B-2A	23.0	53.7	35.4	103.8	71.6	102.8	153.5
E502B-2B	23.0	53.7	35.4	103.8	71.6	102.8	153.5
E502B-2C	23.0	53.7	35.4	103.8	71.6	102.8	153.5
E807B-3A	48.8	62.2	42.1	130.6	75.9	116.9	---
E807B-3B	48.8	62.2	42.1	130.6	83.6	116.9	---
E807B-3C	48.8	62.2	42.1	130.6	79.4	116.9	---
PH1N	13.3	15.9	24.9	110.5	62.2	111.7	160.8
PH1V	19.2	15.9	24.9	99.0	101.0	121.0	177.8
SM-P17A	23.5	53.9	37.8	102.2	92.9	109.4	158.6
SM-P18A	33.9	71.2	41.9	100.5	89.9	114.6	150.4
SM-S1A	37.6	53.5	63.9	128.0	87.9	106.2	155.6
SM-S1H	19.0	20.0	214.5	150.0	104.0	132.4	189.1

Table B.10. *Modeled potential fire behavior for pine flatwoods study sites.*

Burn site	Flame length	Rate of spread	Fireline intensity	Reaction intensity
	m	*m sec*$^{-1}$	*kW m*$^{-1}$	*kW m*$^{-2}$
A214E	0.21	<0.01	9.0	235.49
A214NE	0.15	<0.01	4.4	217.35
A214W	0.21	<0.01	9.0	176.34
A215N	0.12	<0.01	2.7	335.29
A215NW	0.18	<0.01	6.5	162.35
A215S	0.37	<0.01	29.1	520.13
A302C	0.40	0.01	34.6	444.15
A302N	0.40	0.01	34.6	398.22
A302S	0.21	<0.01	9.0	266.11
A303E	0.52	<0.01	61.9	1371.76
A342N	0.24	<0.01	12.1	227.93
A342S	0.27	<0.01	15.6	333.96
A343N	0.21	<0.01	9.0	331.88
A343S	0.34	<0.01	24.1	414.29
BW204A	0.58	0.01	78.9	632.58
BW215A	0.24	<0.01	12.1	404.08
E502B-1A	0.12	<0.01	2.7	225.86
E502B-1B	0.12	<0.01	2.7	273.67
E502B-1C	0.12	<0.01	2.7	253.07
E502B-2A	0.58	0.01	78.9	548.29
E502B-2B	0.49	0.01	54.3	582.31
E502B-2C	0.64	0.01	98.0	824.04
E807B-3A	0.34	<0.01	24.1	393.12
E807B-3B	0.21	<0.01	9.0	377.62
E807B-3C	0.34	0.01	24.1	261.39
PH1N	0.49	0.01	54.3	684.18
PH1V	0.82	0.02	169.0	666.04
SM-P17A	0.24	<0.01	12.1	387.83
SM-P18A	0.18	<0.01	6.5	501.80
SM-S1A	0.21	<0.01	9.0	517.86
SM-S1H	0.94	0.03	228.1	503.50

Table B.11. *Pre-fire fuel loading for pine flatwoods sites.*

Burn site	Herbaceous vegetation	Shrub	Live palmetto	Dead palmetto	All vegetation	Pine litter	All dead wood	All fuels
	----------	----------	----------	*Mg ha*$^{-1}$	----------	----------	----------	----------
A214E	0.294	2.813	0.453	0.191	3.107	3.383	0.527	7.017
A214NE	0.150	2.744	1.143	0.455	2.894	6.624	1.195	10.713
A214W	0.069	3.006	1.222	0.408	3.076	6.913	1.094	11.083
A215N	0.545	2.764	0.289	0.119	3.309	3.118	0.605	7.032
A215NW	0.022	3.524	1.076	0.966	3.546	6.833	1.690	12.069
A215S	0.551	2.952	0.599	0.161	3.504	3.107	0.688	7.299
A302C	1.000	3.150	0.971	0.856	4.149	4.450	0.998	9.597
A302N	0.946	2.816	0.697	0.509	3.762	4.869	0.536	9.166
A302S	0.368	3.320	0.771	0.500	3.688	3.959	0.551	8.198
A303E	3.706	2.623	0.742	0.863	6.328	3.484	1.024	10.836
A342N	0.204	2.780	0.489	0.377	2.984	3.430	0.247	6.660
A342S	0.392	4.365	1.484	1.051	4.757	4.526	0.746	10.029
A343N	0.576	2.352	0.392	0.347	2.928	1.950	0.529	5.407
A343S	0.619	3.407	0.536	0.522	4.026	2.540	0.347	6.913
BW204A	0.897	1.621	0.152	0.002	2.517	5.230	0.442	8.189
BW215A	1.049	1.098	0.177	0.034	2.148	2.067	0.336	4.551
E502B-1A	0.251	2.461	0.374	0.267	2.712	8.830	2.571	14.114
E502B-1B	0.336	2.163	0.341	0.253	2.499	6.716	1.753	10.969
E502B-1C	0.256	2.856	0.664	0.498	3.111	13.213	1.970	18.295
E502B-2A	1.358	2.013	0.412	0.359	3.372	12.004	1.787	17.162
E502B-2B	1.244	2.179	0.152	0.094	3.423	8.985	1.874	14.282
E502B-2C	1.805	2.589	0.383	0.244	4.394	9.606	0.912	14.912
E807B-3A	0.152	7.734	0.679	0.612	7.886	12.302	3.486	23.675
E807B-3B	0.565	2.977	0.630	0.410	3.542	10.928	3.168	17.638
E807B-3C	0.081	5.006	1.307	1.074	5.086	10.115	5.017	20.218
PH1N	0.401	6.891	0.903	0.870	7.292	2.405	0.309	10.007
PH1V	0.278	9.908	2.170	1.363	10.186	3.806	1.065	15.058
SM-P17A	0.655	3.004	0.460	0.123	3.658	3.342	0.939	7.940
SM-P18A	1.042	2.887	0.361	0.052	3.930	2.197	0.861	6.987
SM-S1A	0.749	5.524	0.453	0.155	6.272	4.595	1.051	11.919
SM-S1H	0.767	4.259	1.421	0.233	5.027	5.775	0.859	11.660

Table B.12. *Pre-fire coverage, height, and area burned for pine flatwoods sites.*

	Pre-fire coverage and area burned					Height		
Burn Site	**Herbaceous vegetation**	**Saw palmetto**	**Shrub**	**All vegetation**	**Area burned**	**Grass**	**Saw palmetto**	**Shrub**
	percentage					*m*		
A214E	8.3	29.9	70.7	100.0	97.0	0.37	0.73	0.40
A214NE	6.9	36.9	27.7	71.5	100.0	0.34	1.01	0.52
A214W	2.6	35.5	44.5	82.6	100.0	0.27	1.07	0.67
A215N	9.0	14.3	55.1	78.4	100.0	0.40	0.79	0.43
A215NW	1.2	20.9	42.2	64.3	99.4	0.24	0.98	0.55
A215S	6.2	20.5	50.5	77.2	100.0	0.37	0.85	0.40
A302C	37.0	35.2	46.0	100.0	100.0	0.52	0.85	0.55
A302N	62.6	28.7	41.7	100.0	100.0	0.40	0.64	0.40
A302S	13.1	33.3	46.3	92.7	99.6	0.37	0.70	0.49
A303E	39.0	18.9	28.9	86.8	98.5	0.61	0.98	0.55
A342N	11.9	29.8	50.6	92.3	100.0	0.40	0.79	0.55
A342S	14.4	35.6	43.0	93.0	100.0	0.46	0.82	0.55
A343N	12.4	26.2	45.2	83.8	99.1	0.34	0.73	0.37
A343S	21.1	37.1	38.2	96.4	91.0	0.37	0.88	0.49
BW204A	24.2	5.6	25.3	55.1	100.0	0.46	0.70	0.58
BW215A	19.1	4.0	28.0	51.1	33.8	0.34	0.67	0.46
E502B-1A	35.3	12.8	37.1	85.2	100.0	0.21	0.79	0.55
E502B-1B	10.0	26.0	47.4	83.4	99.3	0.21	0.52	0.27
E502B-1C	7.9	30.7	33.8	72.4	100.0	0.21	0.64	0.37
E502B-2A	62.5	16.5	37.7	100.0	100.0	0.40	0.76	0.58
E502B-2B	30.0	16.8	36.0	82.8	100.0	0.46	0.82	0.67
E502B-2C	28.0	8.6	15.8	52.4	100.0	0.30	0.55	0.46
E807B-3A	2.7	28.4	68.7	99.8	86.4	---	1.04	1.16
E807B-3B	5.8	16.2	43.4	65.4	94.5	0.46	0.82	0.94
E807B-3C	0.6	21.6	29.9	52.1	87.6	0.15	0.98	0.85
PH1N	8.8	31.8	59.1	99.7	97.5	0.34	0.61	0.67
PH1V	1.4	48.4	45.4	95.2	100.0	0.24	0.85	0.88
SM-P17A	13.7	14.3	47.0	75.0	99.2	0.27	0.55	0.30
SM-P18A	18.9	27.7	49.3	95.9	91.0	0.46	0.76	0.52
SM-S1A	14.9	26.2	63.2	100.0	98.0	0.40	1.01	1.10
SM-S1H	11.0	32.9	38.8	82.7	100.0	0.43	1.04	0.85

Table B.13. *Fuel consumption for pine flatwoods sites.*

Burn site	Herbaceous vegetation	Shrub	Saw palmetto	All vegetation	Pine litter	All dead wood	All fuels
	---------- *Mg ha $^{-1}$ (percentage of pre-fire loading)* ----------						
A214E	0.291 (99.2)	1.648 (75.9)	0.242 (37.6)	2.181 (70.2)	3.038 (89.8)	0.224 (42.6)	5.443 (77.6)
A214NE	0.150 (100)	0.724 (63.2)	1.208 (75.6)	2.083 (72.0)	4.728 (71.4)	0.182 (15.2)	6.992 (65.3)
A214W	0.067 (96.8)	0.827 (60.1)	1.172 (71.9)	2.067 (67.2)	5.216 (75.5)	0.033 (3.1)	7.317 (66.0)
A215N	0.536 (98.4)	2.078 (88.2)	0.117 (28.6)	2.730 (82.5)	1.840 (59.0)	0.346 (57.1)	4.917 (69.9)
A215NW	0.022 (100)	0.769 (51.9)	1.782 (87.3)	2.573 (72.6)	5.609 (82.1)	0.859 (50.8)	9.041 (74.9)
A215S	0.549 (99.6)	2.060 (94.0)	0.657 (86.4)	3.266 (93.2)	2.735 (88.0)	0.247 (35.8)	6.248 (85.6)
A302C	0.984 (98.4)	0.910 (68.8)	1.592 (87.1)	3.486 (84.0)	4.291 (96.4)	0.480 (48.1)	8.256 (86.0)
A302N	0.946 (100)	1.401 (87.0)	1.110 (92.0)	3.457 (91.9)	4.869 (100)	0.135 (25.1)	8.460 (92.3)
A302S	0.368 (100)	1.444 (70.5)	1.089 (85.7)	2.901 (78.7)	3.652 (92.2)	0.016 (2.8)	6.568 (80.1)
A303E	3.609 (97.4)	0.697 (68.5)	1.437 (89.5)	5.743 (90.8)	2.302 (66.1)	0.446 (43.5)	8.492 (78.4)
A342N	0.204 (100)	1.323 (69.1)	0.684 (79.0)	2.210 (74.1)	3.430 (100)	0.016 (6.4)	5.656 (84.9)
A342S	0.392 (100)	1.679 (91.8)	2.358 (93.0)	4.430 (93.1)	4.526 (100)	0.410 (55.0)	9.366 (93.4)
A343N	0.576 (100)	1.459 (90.5)	0.596 (80.6)	2.632 (89.9)	1.950 (100)	0.013 (2.5)	4.595 (85.0)
A343S	0.619 (100)	1.760 (74.9)	0.634 (60.0)	3.013 (74.8)	2.540 (100)	0.255 (73.3)	5.808 (84.0)
BW204A	0.890 (99.3)	1.258 (85.8)	0.117 (75.4)	2.264 (89.9)	4.122 (78.8)	0.188 (42.6)	6.575 (80.3)
BW215A	0.695 (66.2)	0.152 (17.2)	0.034 (16.0)	0.881 (41.0)	0.390 (18.9)	0.000 (0.0)	1.271 (27.9)
E502-1A	0.251 (100)	1.222 (67.1)	0.531 (82.9)	2.004 (73.9)	7.969 (90.3)	1.625 (63.2)	11.599 (82.2)
E502-1B	0.336 (100)	1.206 (76.9)	0.453 (76.2)	1.995 (79.8)	5.429 (80.8)	0.412 (23.5)	7.837 (71.4)
E502-1C	0.256 (100)	1.231 (72.6)	0.980 (84.4)	2.466 (79.3)	11.386 (86.2)	0.289 (14.7)	14.141 (77.3)
E502-2A	1.311 (96.5)	1.004 (80.9)	0.720 (93.3)	3.035 (90.0)	11.697 (97.4)	1.002 (56.1)	15.735 (91.7)
E502-2B	1.244 (100)	1.453 (75.2)	0.108 (43.6)	2.804 (81.9)	7.593 (84.5)	0.771 (41.1)	11.168 (78.2)
E502-2C	1.805 (100)	1.484 (75.7)	0.473 (75.4)	3.762 (85.6)	9.193 (95.7)	0.103 (11.3)	13.058 (87.6)
E807-3A	0.152 (100)	5.183 (80.4)	0.778 (60.2)	6.113 (77.5)	7.277 (59.1)	1.092 (31.3)	14.481 (61.2)
E807-3B	0.565 (100)	0.679 (35.1)	0.863 (83.0)	2.107 (59.5)	6.568 (60.1)	1.270 (40.1)	9.945 (56.4)
E807-3C	0.081 (100)	1.491 (56.8)	1.939 (81.5)	3.511 (69.0)	7.135 (70.5)	1.858 (37.0)	12.504 (61.8)
PH1N	0.401 (100)	3.298 (64.4)	1.560 (88.0)	5.259 (72.1)	2.210 (91.9)	0.305 (98.6)	7.774 (77.7)
PH1V	0.278 (100)	4.636 (72.7)	1.675 (47.4)	6.588 (64.7)	3.667 (96.3)	0.711 (66.7)	10.966 (72.8)
SM-P17A	0.652 (99.7)	1.941 (80.2)	0.370 (63.5)	2.964 (81.0)	2.654 (79.4)	0.379 (40.3)	5.997 (75.5)
SM-P18A	1.042 (100)	2.134 (86.2)	0.132 (32.1)	3.309 (84.2)	2.062 (93.9)	0.226 (26.3)	5.598 (80.1)
SM-S1A	0.744 (99.4)	3.311 (67.4)	0.168 (27.7)	4.223 (67.3)	4.057 (88.3)	0.287 (27.3)	8.568 (71.9)
SM-S1H	0.756 (98.6)	0.897 (34.4)	0.746 (45.1)	2.400 (47.7)	5.387 (93.3)	0.211 (24.5)	7.997 (68.6)

Sagebrush – Shrub Consumption

$R^2 = 0.9337$
Adjusted $R^2 = 0.9232$
RSE = 0.2299
$F_{3, 19} = 89.19$ ($p < 0.001$)
n = 23 (Sagehen 2, N Black Cyn 1b, N Black Cyn 2a removed as outliers)

Coefficients	b	SE	t-value	Pr(>|t|)
(Intercept)	0.0556	0.1664	0.334	0.74
shrub biomass	0.1351	0.0145	9.323	<0.01
prop. burned	1.6730	0.2098	7.974	<0.01
season (spr=1)	-0.2196	0.1056	-2.079	0.05

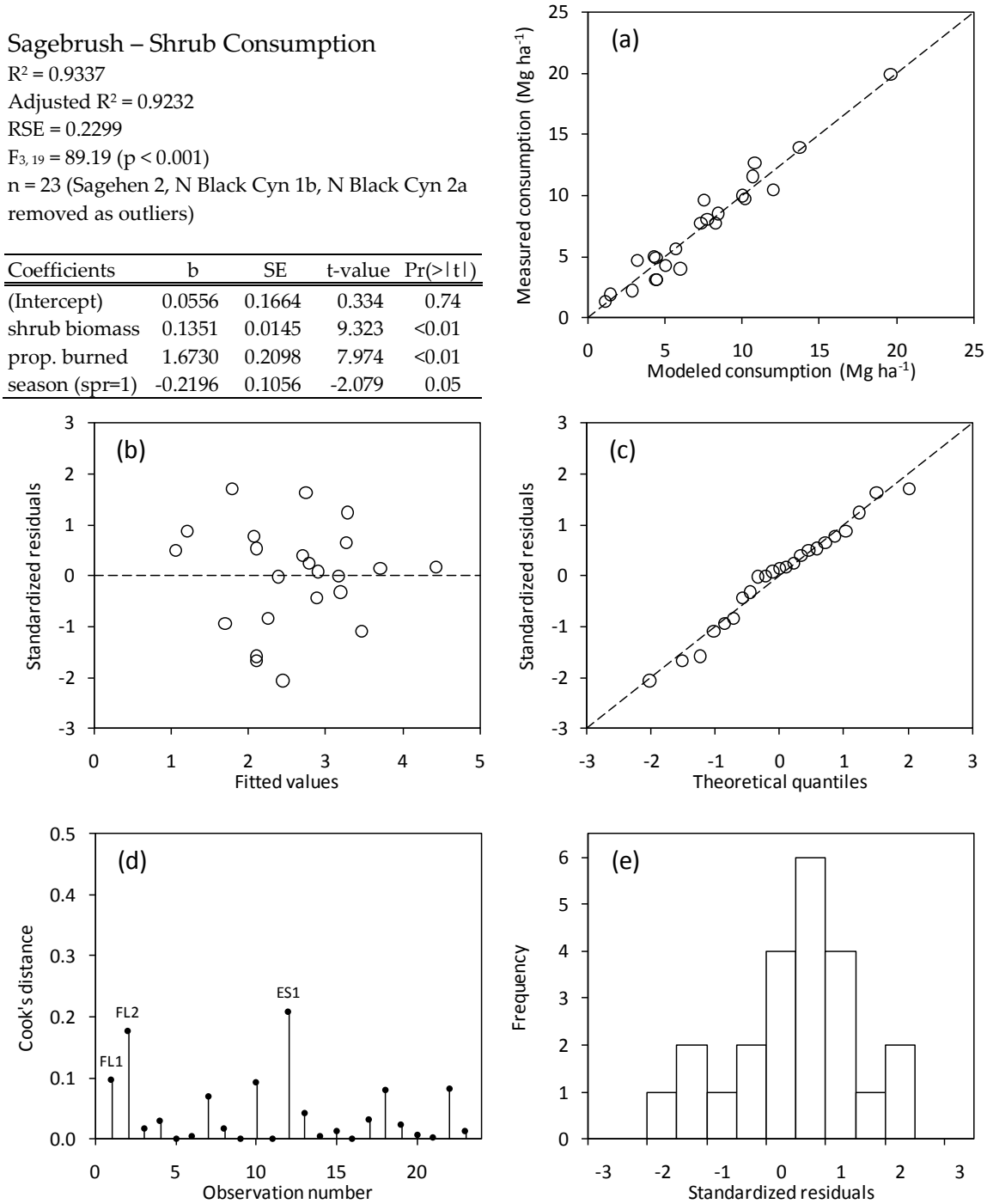

Figure B.1. *Sagebrush shrub consumption model diagnostics. Plots of (a) measured vs. modeled consumption, (b) standardized residuals vs. fitted values, (c) standardized residuals vs. theoretical quantiles of the normal distribution, (d) Cook's distance, and (e) distribution of standardized residuals. FL1 = Flook Lake 1, FL2 = Flook Lake 2, ES1 = Escarpment 1*

Sagebrush – All Biomass Consumption

$R^2 = 0.9523$
Adjusted $R^2 = 0.9458$
RSE = 0.2334
$F_{3, 22} = 146.50$ ($p < 0.001$)
n = 26

Coefficients	b	SE	t-value	Pr(>|t|)
(Intercept)	0.0929	0.1519	0.611	0.55
all biomass	0.1036	0.0130	7.997	<0.01
prop. burned	2.2451	0.1996	11.246	<0.01
season (spr=1)	-0.2985	0.1161	-2.572	0.02

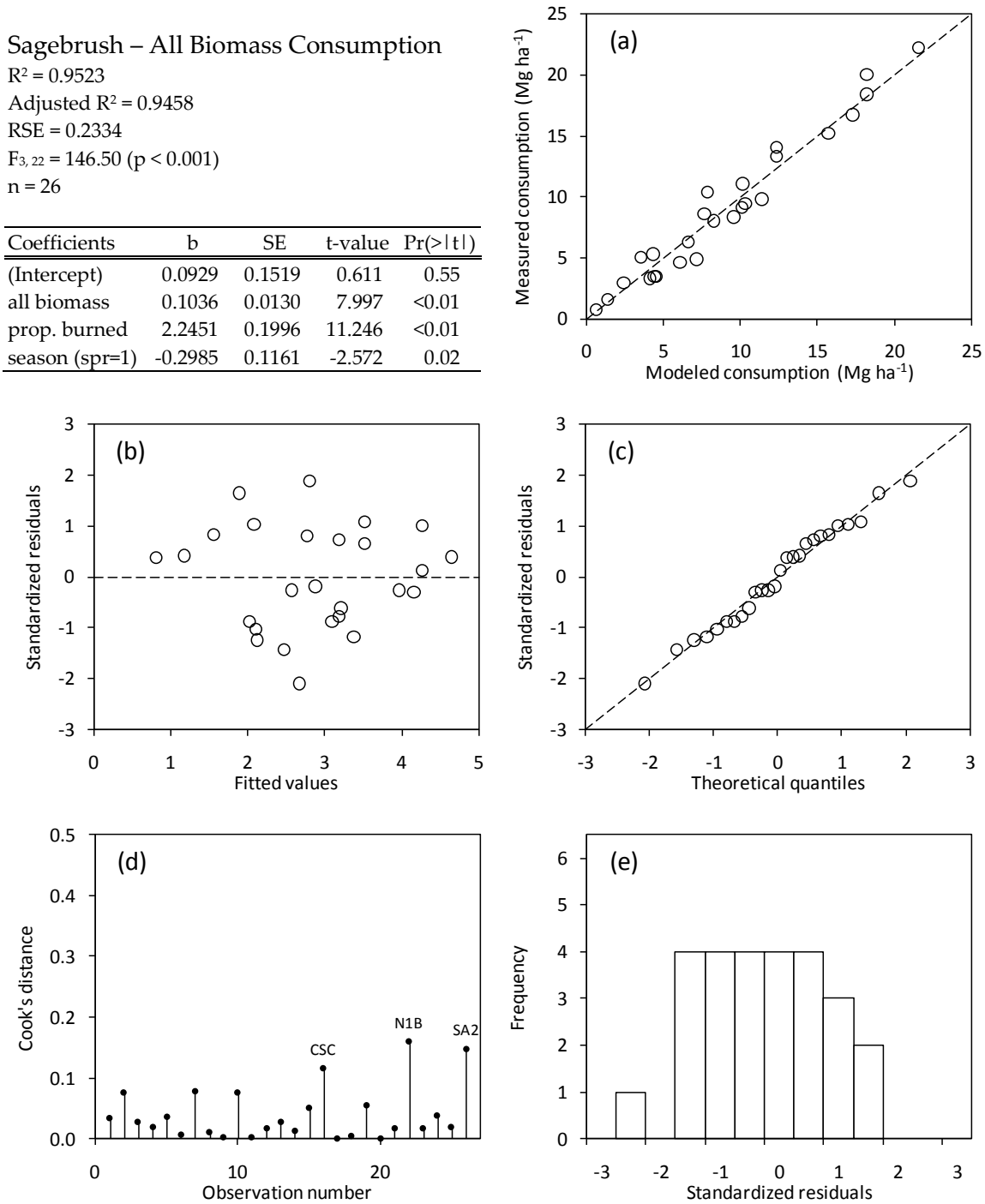

Figure B.2. *Sagebrush all biomass consumption model diagnostics. Plots of (a) measured vs. modeled consumption, (b) standardized residuals vs. fitted values, (c) standardized residuals vs. theoretical quantiles of the normal distribution, (d) Cook's distance, and (e) distribution of standardized residuals. CSC = Sand Coulee, N1B = N Black Cyn 1b, SA2 = Sagehen 2*

Sagebrush – Proportion Burned (fall)

$R^2 = 0.8207$
Adjusted $R^2 = 0.7908$
RSE = 0.1221
$F_{2, 12} = 27.46$ ($p < 0.001$)
n = 15 (Stonehouse 1 removed as outlier)

Coefficients	b	SE	t-value	Pr(>|t|)
(Intercept)	-0.2217	0.1214	-1.826	0.09
herb. coverage	0.0179	0.0035	5.168	<0.01
windspeed × slope	0.1433	0.0301	4.759	<0.01

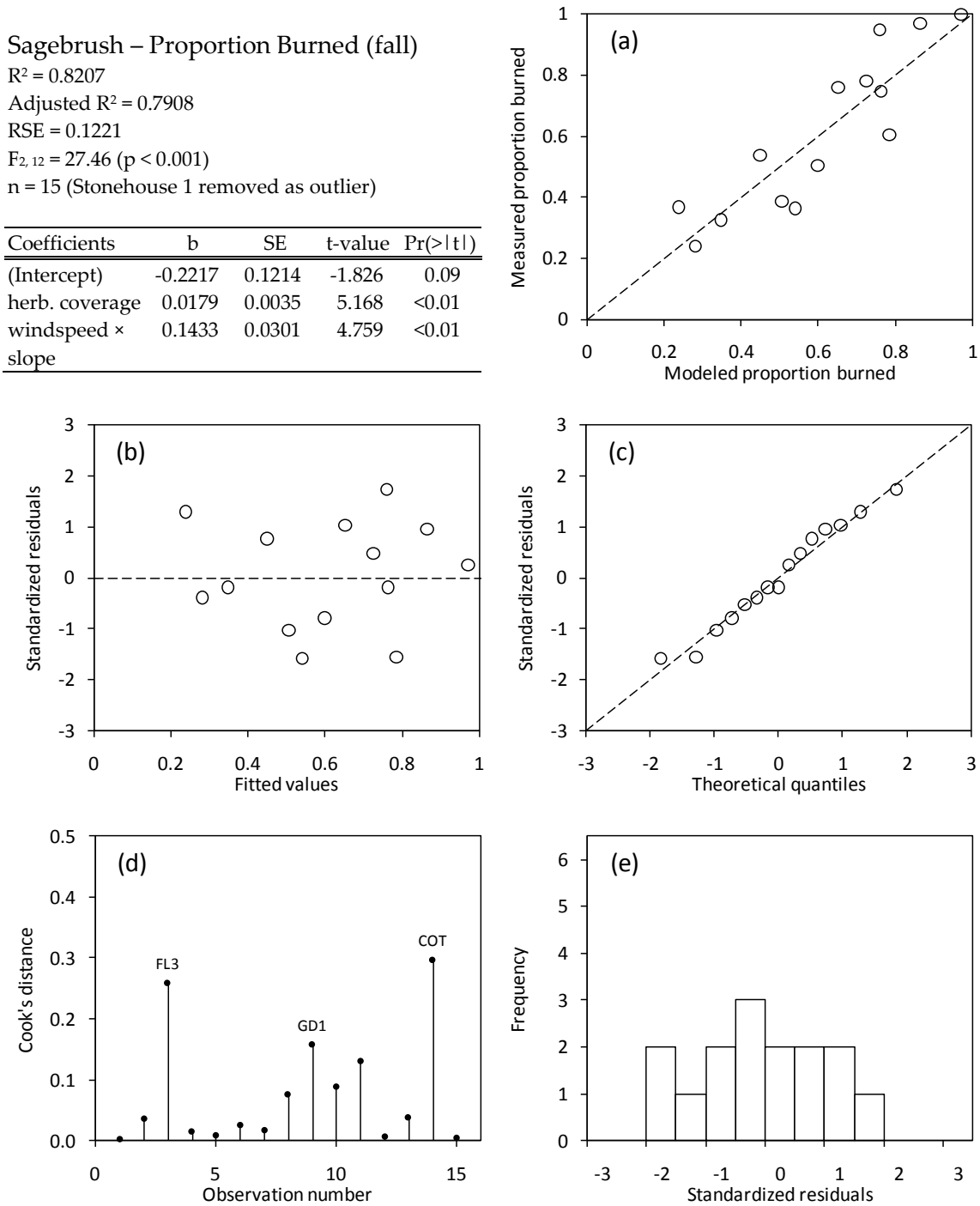

Figure B.3. *Sagebrush proportion of area burned (fall) model diagnostics. Plots of (a) measured vs. modeled consumption, (b) standardized residuals vs. fitted values, (c) standardized residuals vs. theoretical quantiles of the normal distribution, (d) Cook's distance, and (e) distribution of standardized residuals. FL3 = Flook Lake 3, GD1 = Gold Digger 1, COT = Old Tanker*

Sagebrush – Proportion Burned (spring)

$R^2 = 0.8440$
Adjusted $R^2 = 0.7660$
RSE = 0.1606
$F_{3, 6} = 10.82$ ($p = 0.008$)
n = 10

Coefficients	b	SE	t-value	Pr(>|t|)
(Intercept)	0.3597	0.3531	1.019	0.35
herb. coverage	0.0102	0.0031	3.267	0.02
10hr moisture	-0.0456	0.0186	-2.447	0.05
windspeed × slope category	0.0098	0.0086	1.140	0.30

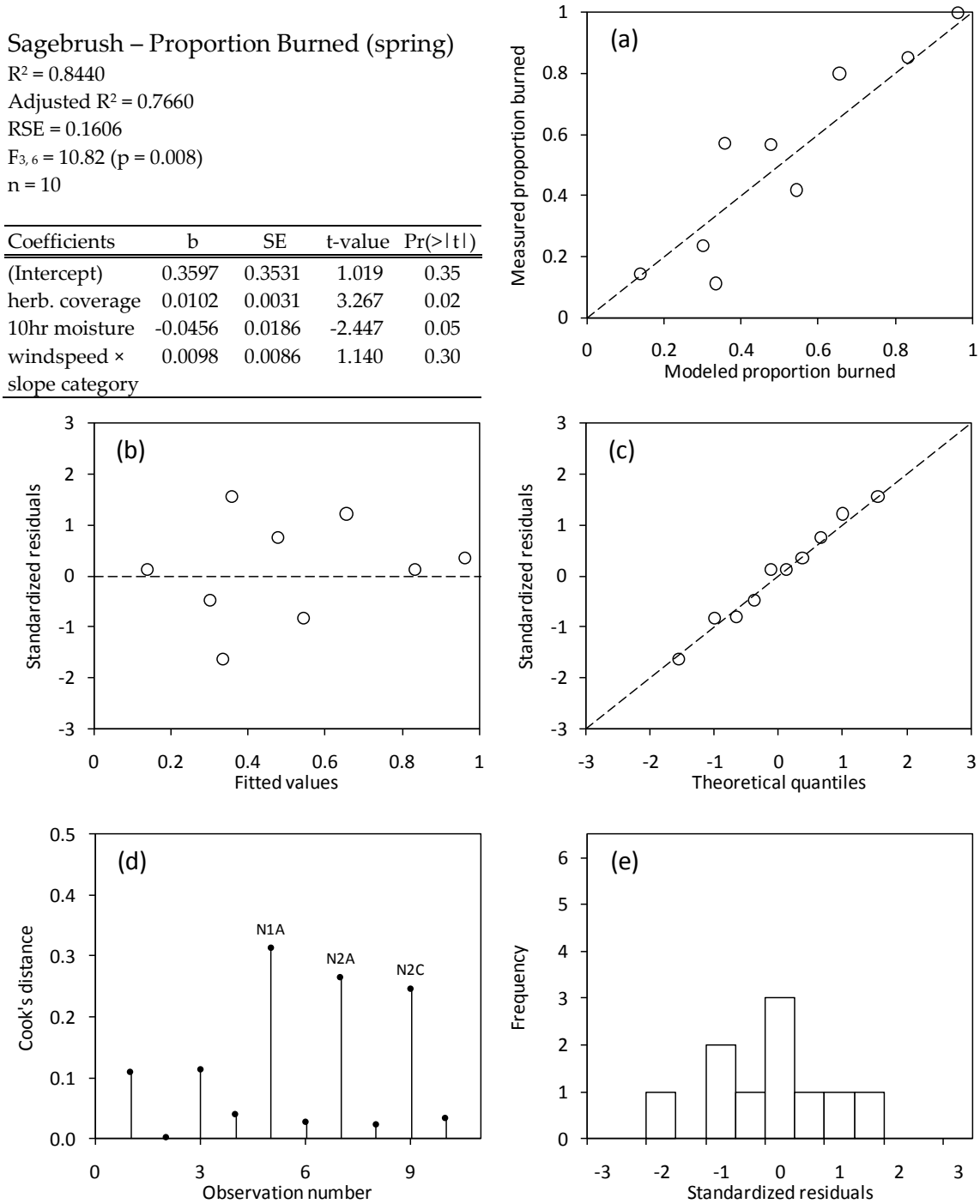

Figure B.4. *Sagebrush proportion of area burned (spring) model diagnostics. Plots of (a) measured vs. modeled consumption, (b) standardized residuals vs. fitted values, (c) standardized residuals vs. theoretical quantiles of the normal distribution, (d) Cook's distance, and (e) distribution of standardized residuals. N1A = N Black Cyn 1a, N2A = N Black Cyn 2a, N2C = N Black Cyn 2c*

Flatwoods – Shrub Consumption

$R^2 = 0.9425$

Adjusted $R^2 = 0.9377$

RSE = 0.0969

$F_{2, 24} = 196.70$ ($p < 0.001$)

n = 27 (A342S, E807B-3B, BW215A, SM-S1H removed as outliers)

Coefficients	b	SE	t-value	Pr(>|t|)
(Intercept)	-0.1682	0.0578	-2.910	<0.01
shrub biomass	0.9008	0.0455	19.800	<0.01
season (growing=1)	0.0717	0.0529	1.355	0.19

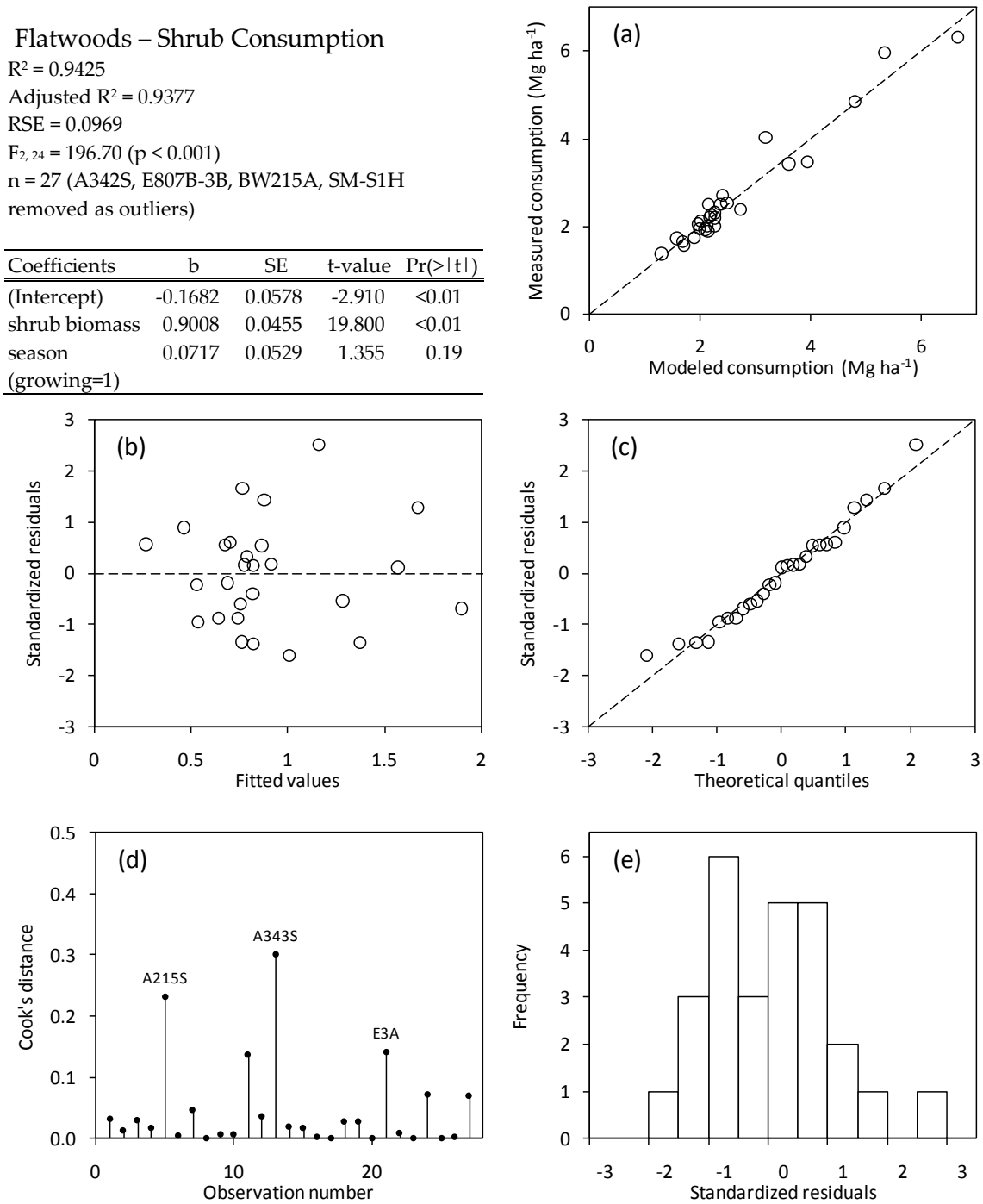

Figure B.5. *Flatwoods shrub consumption model diagnostics. Plots of (a) measured vs. modeled consumption, (b) standardized residuals vs. fitted values, (c) standardized residuals vs. theoretical quantiles of the normal distribution, (d) Cook's distance, and (e) distribution of standardized residuals. E3A = E807B-3A*

Flatwoods – All Biomass Consumption

$R^2 = 0.8981$

Adjusted $R^2 = 0.8905$

RSE = 0.1114

$F_{2, 27} = 119.00$ ($p < 0.001$)

n = 30 (BW215A removed as outlier)

Coefficients	b	SE	t-value	Pr(>|t|)
(Intercept)	1.4253	0.8091	1.762	0.09
all biomass	0.7881	0.0660	11.939	<0.01
shrub moisture	-0.2661	0.1597	-1.667	0.11

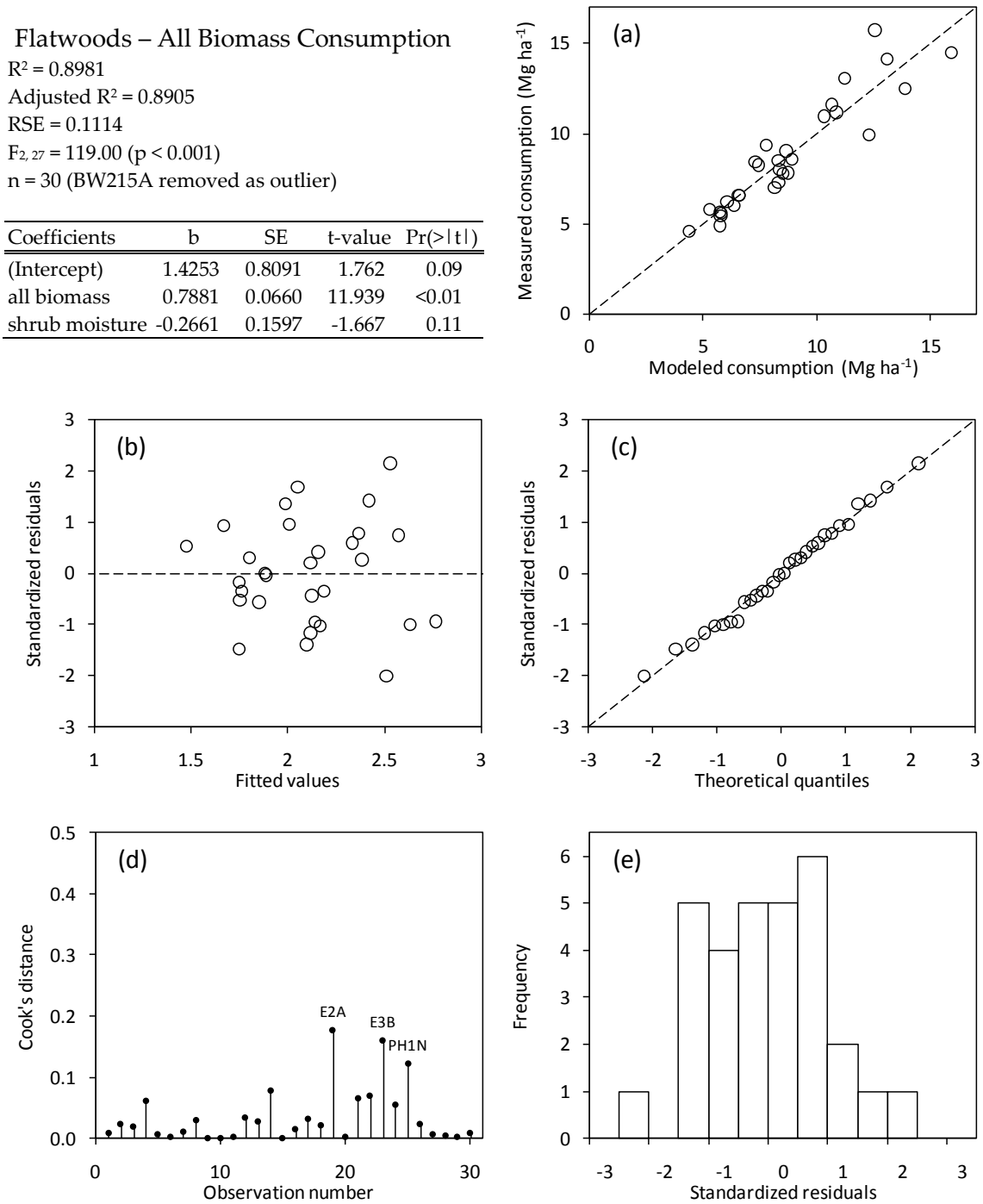

Figure B.6. *Flatwoods all biomass consumption model diagnostics. Plots of (a) measured vs. modeled consumption, (b) standardized residuals vs. fitted values, (c) standardized residuals vs. theoretical quantiles of the normal distribution, (d) Cook's distance, and (e) distribution of standardized residuals. E2A = E502B-2A, E3B = E807B-3B*

Flatwoods – Litter Consumption

$R^2 = 0.9289$

Adjusted $R^2 = 0.9236$

RSE = 0.1570

$F_{2, 27} = 176.40$ ($p < 0.001$)

n = 30 (BW215A removed as outlier)

Coefficients	b	SE	t-value	Pr(>|t|)
(Intercept)	0.2871	0.1108	2.593	0.02
litter biomass	0.9140	0.0533	17.155	<0.01
litter moisture	-0.0101	0.0032	-3.103	<0.01

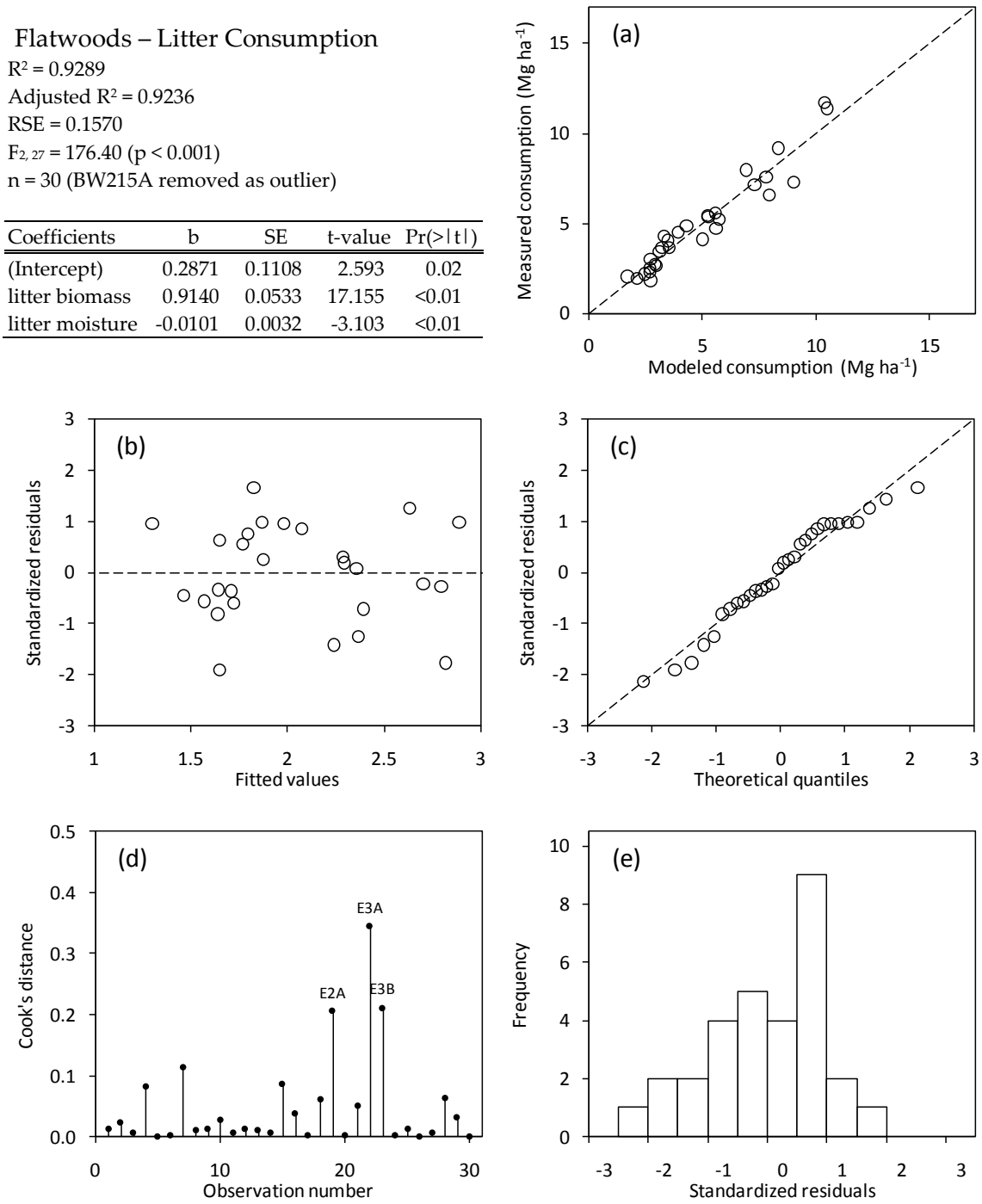

Figure B.7. *Flatwoods litter consumption model diagnostics. Plots of (a) measured vs. modeled consumption, (b) standardized residuals vs. fitted values, (c) standardized residuals vs. theoretical quantiles of the normal distribution, (d) Cook's distance, and (e) distribution of standardized residuals. E2A = E502B-2A, E3A = E807B-3A, E3B = E807B-3B*

Flatwoods – All Woody Consumption

$R^2 = 0.7171$

Adjusted $R^2 = 0.6968$

RSE = 0.1860

$F_{2, 28} = 35.48$ ($p < 0.001$)

n = 31

Coefficients	b	SE	t-value	Pr(>|t|)
(Intercept)	-0.0276	0.1035	-0.267	0.79
wood biomass	0.7309	0.0875	8.357	<0.01
10hr moisture	-0.0031	0.0017	-1.851	0.07

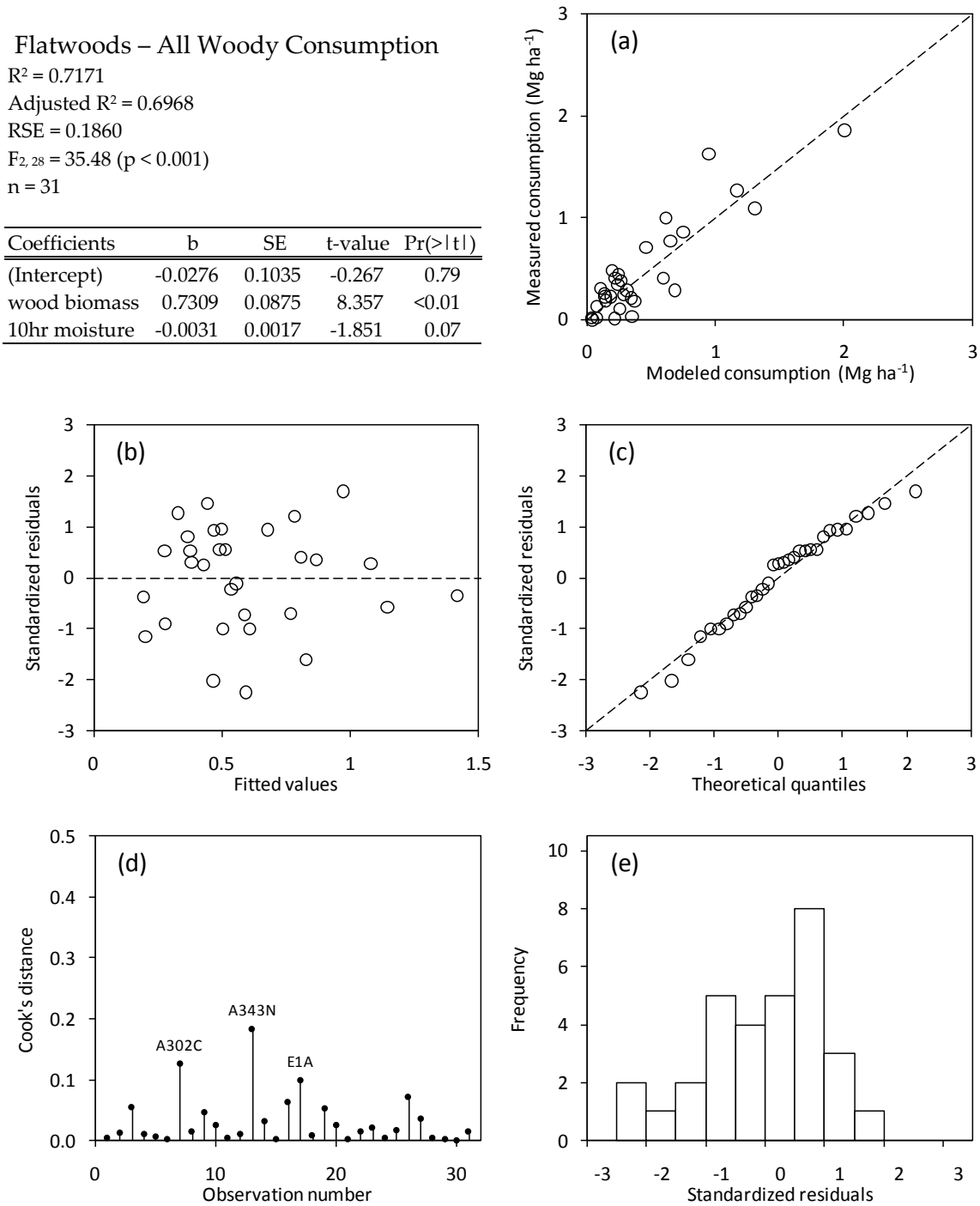

Figure B.8. *Flatwoods dead and down woody material consumption model diagnostics. Plots of (a) measured vs. modeled consumption, (b) standardized residuals vs. fitted values, (c) standardized residuals vs. theoretical quantiles of the normal distribution, (d) Cook's distance, and (e) distribution of standardized residuals. E1A = E502B-1A*

All data – All Biomass Consumption

$R^2 = 0.1237$

Adjusted $R^2 = 0.1078$

RSE = 4.352

$F_{1, 55} = 7.77$ ($p = 0.007$)

n = 57

Coefficients	b	SE	t-value	Pr(>|t|)
(Intercept)	5.7080	1.2399	4.604	<0.01
I_B / R	0.0003	0.0001	2.787	<0.01

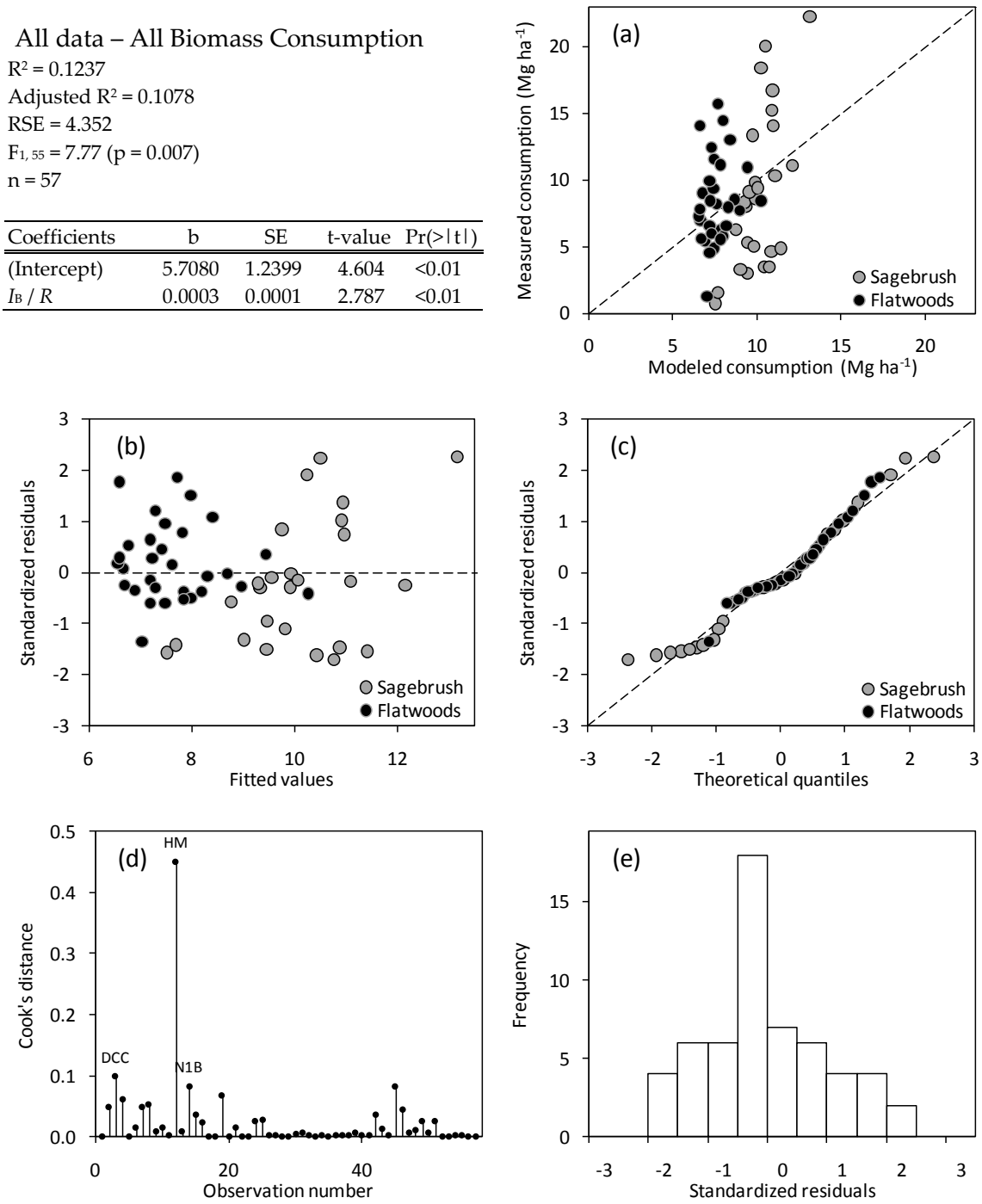

Figure B.9. *General all biomass consumption model diagnostics. Plots of (a) measured vs. modeled consumption, (b) standardized residuals vs. fitted values, (c) standardized residuals vs. theoretical quantiles of the normal distribution, (d) Cook's distance, and (e) distribution of standardized residuals.* I_B *= fireline intensity, R = rate of spread; DCC = Dyce Creek C, HM = Heart Mountain, N1B = N Black Cyn 1b*

CURRICULUM VITAE

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