CHARACTERISTICS OF FUEL BEDS INVADED BY SMILAX ROTUNDIFOLIA

A Thesis Presented

by

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DEDICATION

Dedicated to Conrad H. Ohman and Betty Boe.

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I am grateful to many for the successful completion of this project. Joel Carlson and David Crary taught me a great deal about fire management and helped steer me toward UMass. The Naushon Trust was generous in allowing me to perform the project on their beautiful island. Bruce Bagley and his staff, especially Jay Hess provided me with a place to stay, food to eat, transportation, equipment, hard work, and good company. Alison Dibble and Robert White of the U.S. Forest Service provided me with technical assistance. The Joint Fire Science Program provided the funding that made my project go. The Nature Conservancy and Cape Cod National Seashore provided equipment and personnel.

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ABSTRACT

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Invasion of grasslands by woody shrubs can alter existing fire regimes and give rise to problem fire behavior. Invaded areas are likely to burn less often but with more intensity. Abandoned pastures on Naushon Island, Massachusetts (USA) which have been invaded by the woody vine *Smilax rotundifolia* follow this pattern. I evaluated the usefulness of standard and custom fuel models for predicting fire behavior observed in a 0.5-acre (0.2-ha) experimental burn. Custom fuel model development required characterizing fuel load and fuel bed depth of the experimental burn plot – a task complicated a dense mat of vines with 100 % cover to a height of 3 to 6 ft (1 to 2 m). This was done by measuring the height of fuel beds, estimating 3-dimensional cover by modified point-intercept sampling, and harvesting live vines and leaves and dead woody and non-woody litter and vines from 1 m^2 cubes. From these data, I developed regression equations to estimate fuel load using fuel bed depth.

Measured 1-hr fuel loads (10 tons/acre, 23 mt/ha) were greater than for any standard fuel model. The fuel bed was composed of mostly dead fuels (7.3 tons/acre, 3.5 mt/ha). Total 1-hr fuel loads were accurately predicted by shrub height (R^2 = 0.81).

All standard fuel models, including SFM 4 (Chapparal), underestimated flame length and rate of spread observed during an experimental burn conducted in mid-June, 2004 under full green-up conditions. Observed values were: flame length 17 ft (5 m) and rate of spread 40 ft/minute (15 m/minute). The custom fuel model predicted flame lengths of 16 ft (5 m) and rates of spread of 38 ft/minute (14 m/minute).

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CHAPTER 1

INTRODUCTION

Smilax rotundifolia (hereafter called by its common name, greenbrier) has been invading grasslands on Naushon Island (Figure 1) since the early 20th century, when agricultural activities largely ceased on the island (Shroeder 2002). Naushon lies southwest of Woods Hole, Massachusetts and is part of the Elizabeth Islands, which collectively form the town of Gosnald. Portions of Naushon's island landscape were historically maintained as grassland by sheep grazing (Shroeder 2002). The absence of sheep grazing has coincided with invasion by greenbrier.

Invasion of grasslands on Naushon Island by woody shrubs such as greenbrier has lead to a decrease in plant species diversity (Shroeder 2002, Richburg 2005, Simmons pers. comm.). When greenbrier invades grasslands it often forms thickets of near 100% cover (Richburg 2005), effectively replacing the grassland with a shrubland. Grasslands are often more desirable for recreation and biodiversity than areas dominated by woody shrubs and vines, which can decrease or eliminate sight lines, hinder foot traffic, out-compete showy or otherwise desirable herbaceous plants, and degrade habitat for grassland bird species.

In addition to ecological and aesthetic concerns, woody shrub invasion can alter fuel beds and the frequency and intensity of fires. Specifically, woody shrub invasion can cause fires to occur less often, with greater intensity when they occur during extreme weather conditions (van Wilgen and Richardson 1985). Changes in fire regimes can affect plant community composition and give rise to difficult-to-control fires that can result in the loss of property and life. Although we know, anecdotally, that fires burn intensely in greenbrier, there has been no published study that documents how greenbrier alters fuel beds or quantifies fire behavior in greenbrier thickets, which are of potential concern in several locations along the North Atlantic coast line. My chief goal in this thesis is to quantify the fuel conditions and fire behavior that result from greenbrier invasion.

Figure 1. **Naushon Island, Massachusetts**

In this study, the effects of greenbrier invasion on fire behavior are addressed in four ways. First, I describe the greenbrier fuel bed (Chapter 3), in the process identifying characteristics that make a greenbrier fuel bed flammable. Next, I propose a method for predicting the total fuel load of a greenbrier monoculture (Chapter 4), thereby providing researchers and managers with a tool for easily estimating this important component of custom fuel models. I then develop a custom fuel model for the Protected Field area on Naushon Island (Chapter 5), where the field work for this study was performed, and compare model predictions to fire behavior observed on a prescribed burn. Finally, I test the custom fuel model's sensitivity to different fuel bed characteristics (Chapter 6). This allows me to rank the relative effects that different fuel characteristics have on fire behavior. Taken together, these steps provide both an in-depth understanding of greenbrier fuel beds and tools for predicting the behavior of fire when these fuel beds burn.

CHAPTER 2

STUDY AREA

The study area consisted of greenbrier thickets in the Protected Field area of Naushon Island. Naushon is approximately 5500 acres (2260 ha) in size, with the Protected Field measuring approximately 92 acres (37.5 hectares). The Protected Field was traditionally maintained as grassland by herbivores, primarily sheep and to a lesser extent cattle, before agricultural activities were largely abandoned on the island in the early 20th Century (Shroeder 2002). In its current condition, the Protected Field has large, nearly impenetrable monocultures of greenbrier, interrupted by patches of grasses and sedges (chiefly *Carex pennsylvanica*), huckleberry (*Gaylussacia baccata*), and the exotic Scotch broom (*Cytisis scoparius*).

Naushon formed as an island approximately 6000-9000 years ago when portions of the Buzzard's Bay Moraine were drowned by rising sea levels. The Moraine itself was formed approximately 18,800 years ago (Balco et al. 2002) as the Laurentide Ice Sheet retreated from its maximum extent on the North Atlantic coast. The glacier's role in the island's formation is reflected in coarse, sandy soils (Anonymous 1983); rolling, hilly topography (Anonymous 1983); kettle holes (Shroeder 2002) and large boulders (Anonymous 1983; Shroeder 2002).

Naushon is privately owned and has approximately 35 residences (Shroeder 2002), most of which are concentrated at the east end of the island. There are no paved roads and traffic is limited to farm and maintenance vehicles. The Naushon Trust (which oversees management of the island), has a strong interest in the stewardship and preservation of the island's unique early-successional landscape.

This interest in preservation is likely the result of both a desire on the part of Trust members to maintain the land in a character similar to the one their ancestors enjoyed and to preserve rare or uncommon species that depend on early-successional landscapes. There is also a concern that proliferation of woody invasive species, such as greenbrier, presents a fire hazard to structures, some of which have cultural or historical significance.

CHAPTER 3

LITERATURE REVIEW

Characteristics of Greenbrier

Greenbrier, also known as catbrier and roundleaf greenbrier, is a native woody vine which commonly invades post-agricultural sites (Hemond et al. 1983). It uses tendrils to climb to heights of 3-6 meters in invaded woodlands (Carey 1994). In open areas, it spreads over shrubs and herbaceous plants, killing them by shading. In this way, it decreases plant species diversity in coastal grasslands and heathlands. Greenbrier is found in 32 states (Carey 1994). It regenerates vegetatively from rhizomes, and its seeds are dispersed by birds (Carey 1994). Following fire, greenbrier resprouts vigorously (Richburg 2005). Rabbits (Niering and Dreyer 1989) and deer (*pers. obs.*) browse succulent post-fire shoots. Greenbrier can form dense thickets (Morong 1894, Niering and Goodwin 1962), with up to 48,000 stems per acre (20,000 stems per hectare) (Carey 1994). Greenbrier has long (approximately 0.8 cm) thorns growing the length of its stem (Carey 1994).

Fuel bed Characteristics of Greenbrier

Understanding the fuel beds is important to modeling, and therefore understanding and predicting, wildland fire behavior. Some of the fuel properties that influence fire behavior include fuel loading, fuel size-class distribution, surface area-to- volume ratio, packing ratio, fuel continuity, and fuel-bed depth. These properties, along with heat content and live fuel characteristics, are the most important determinants of fire behavior (Miller 1994).

The amount of live and dead fuel, usually expressed in tons per acre or kilograms per square meter, is known as fuel load. Fuels are often separated by size classes – 1-hour (>0 to 0.25” diameter), 10-hour (>0.25 to 1”), and 100-hour (>1” to 3”) time lags - for the purpose of fuel bed description. Originally, fuels were divided into these size classes as a way of describing of how long they would take to adjust to changes in environmental fuel moisture (Byram 1963 unpublished, Fosberg 1970). However, some (Anderson 1990, Pyne et al 1996) have found that using these classes to describe anything other than the size of the fuel can cause misunderstandings.

Greenbrier vines rarely exceed 0.25” diameter and thus are 1-hr fuels. Fuel size class distribution is an important determinant of fire behavior. A fuel bed made up solely of large particles will not burn as rapidly or intensely as one made up of small, fine fuel particles. Fires usually ignite and spread in fine (1-hr) fuels (Miller 1994). A physical characteristic of fine fuels is a large surface area-to-volume ratio.

A fuel item with a large surface area-to-volume ratio has a large portion of its matter subject to the drying effects of the heat of an approaching fire and is quickly heated to the point of ignition - approximately 620°F (325°C) (Pyne et al. 1996). The surface area-to-volume ratios of individual fuel particles in greenbrier fuel beds are less than in grasslands, as evidenced by stems of a larger diameter. However, the surface area-volume ratio of greenbrier fuel beds is high compared to larger-stemmed woody shrubs such as Scotch broom and huckleberry, which also occur in the Protected Field.

The proportion of the fuel bed that is occupied by fuel is defined as the packing ratio (Burgan and Rothermel 1984). A fuel bed with no fuel has a packing ratio of zero, and a solid block of wood has a packing ratio of one (Burgan and Rothermel 1984, Miller 1994). A very tightly packed (high packing ratio) fuel bed often will not burn well because of a lack of available oxygen. By contrast, a very loosely packed fuel bed will similarly not burn well, because fuel particles are spread so far apart that heat is not transferred readily among particles (Miller 1994) even though oxygen is readily available. Every fuel bed has a theoretically ideal mix of fuel and air, and this mix is referred to as the optimum packing ratio (Burgan and Rothermel 1984).

The way fuel is distributed within a fuel bed influences the rate of spread of a fire. Fires spread best in continuously distributed fuels. Continuity of fuels can be thought of in both horizontal and vertical terms. Horizontal continuity is related to the horizontal distance between fuel particles, which is related to percent cover; whereas vertical continuity is related to the distance between surface and crown fuels (Miller 1994).

Fuel bed depth is the height of available surface fuels above the duff. In two otherwise similar fuel beds, the beds with greater depth will produce longer flame lengths. Greenbrier growing in the Protected Field can produce fuel beds up to 2 meters in depth, and fires burning in these fuels can consume nearly all above-ground biomass, suggesting that the entire fuel bed is available to burn. For the purposes of fire behavior prediction, however, fuel bed depth is defined as the average of the heights of the different fuel strata weighted by their fuel loads. Greenbrier fuel beds have only litter and shrub strata present:

$$D_{fb} = D_l * M_l + D_s * M_s$$

where:

D_{fb} = fuel bed depth
D_l = depth of the litter strata
M_l = percentage of the mass located in the litter strata
D_s = depth of the shrub strata
M_s = percentage of the mass located in the shrub strata

The Fire Behavior of Woody Shrubs

Woody shrubs have been shown to generate extreme fire behavior (Miller 1994) and by invading a grassland can alter its fire regime (its pattern of fire frequency and intensity). Extreme fire behavior is defined in this paper as having any or all of the following characteristics: 1. flame lengths in excess of 8 feet (2.4 meters), 2. frequent release of hot embers which land outside of the main fire causing spot fires, 3. the presence of fire-whirls. Van Wilgen and Richardson (1985) describe invasion of woody plants in South Africa, where invasion reduced fine fuels in the understory by out-competing smaller plants. They found that high intensity fires were needed to ignite shrub crowns, but they also observed that the fuel conditions could cause more intense fire behavior under extreme weather conditions. On the other hand, when small-diameter shrub and grass fuels are mixed within a fuel bed, intensity of fires within the mixed fuel bed can increase.

Several characteristics of shrub fuels can produce difficult-to-control fire behavior (Miller 1994): 1) shrubs often have a higher volatile chemical content which makes them more flammable than many others wildland fuels; 2) shrubs often have a high percentage of dead stems which require less heat to ignite; and 3) stands of shrubs have a ratio of fuel-to-air (i.e. packing ratio) within the shrub canopy that is nearly ideal for promoting fire spread.

Sampling Shrub Fuels

Non-destructive fuel sampling can be advantageous, because they are often less labor and time consuming than destructive methods (Sah et al. 2004). The two most common non-destructive shrub sampling techniques are those that use stem diameter or shrub-canopy volume or height as a predictor of shrub mass (Brown et al. 1982). Using the basal diameter of a shrub stem as an index to the overall mass of the stem, or of specific components (e.g. leaves, stems of a given size class, etc.) can be used to effectively and quickly determine mass (Telfer 1969, Brown 1976, Schlessinger and Gill 1978, Gray and Schlesinger 1981).

The mass of shrubs has been estimated by many from crown diameters and shrub heights (Brown et al. 1982, Ludwig et al. 1975, Rittenhouse and Sneva 1977, Sah et al. 2004). To relate easily measured plant characteristics to mass of common desert plants, Ludwig et al. (1975) measured canopy height, canopy diameter, and canopy shape to calculate canopy volume. Plants were then harvested and dried to obtain a dry weight. Plants were selected for sampling to represent a range of canopy sizes, and canopy volume was correlated with mass with R^2 values above 0.90 for many plants. Big sagebrush (*Artemisia tridentate*) was sampled in a similar manner. (Rittenhouse and Sneva 1977) measured crown width, crown area, and total plant height and related these characteristics to above-ground mass. After log transformation, the predictive equation yielded R^2 values above 0.90.

Modeling Fire Behavior

Resource managers in the Northeast, as elsewhere in the United States, use computer-based fire behavior models to aid in planning for wildfire control. The most common software used in the United States is the Behave fire behavior prediction system, which utilizes user-defined fuel, weather, and topographic inputs to predict wildland fire behavior. Behave comes in three formats: early, DOS-based applications collectively known as BEHAVE (Andrews 1986, Andrews and Chase 1989, Burgan and Rothermel 1984, Burgan 1987, Anderson 1982); the Microsoft Excel spreadsheet add-on, NEXUS and the Windows-based application, BehavePlus3 (Andrews et al 2005). Here, references made to BEHAVE (in all capital letters) refer to the specific DOS-based program. References to Behave (not all capitalized) refer to the fire behavior system, in general.

Behave fire behavior predictions are driven by mathematical algorithms (Rothermel 1972) that have been shown to accurately predict fire behavior characteristics in many fuel types. In one study (Andrews 1980) an analysis of predicted versus observed rates of spread was conducted for three diverse fuel types: conifer logging slash, grass, and southern rough (a palmetto-gallberry shrub complex). A linear regression yielded an R^2 of 0.89, indicating a strong relationship between observed fire behavior and fire behavior predicted using fuel-type-specific models.

Behave can be used either with 13 standard fuel models as described by Anderson (1982) or with custom fuel models developed from parameters entered by the user. Standard fuel models were created to represent an array of fuel types including fine herbaceous fuels (models 1-3), shrubs (models 4-7), timber (models 8-10), and slash (models 11-13). These models allow managers to predict wildfire behavior without directly measuring fuel bed characteristics. Measuring the fuel properties needed for BEHAVE programs is generally too time-consuming for use on individual wildfires (Rothermel 1983). Yet when observations suggest that none of the standard models adequately describe fire behavior for a given fuel type, the option remains to develop custom fuel models unique to that fuel type. Because fire managers have observed difficult-to-control fire behavior associated with burning greenbrier, I chose to develop a custom fuel model in hopes of better describing observed fire behavior. This required detailed characterizations of greenbrier fuel beds.

CHAPTER 4

METHODS

Describing and Quantifying the Greenbrier Fuel Bed

Greenbrier fuel bed characteristics examined included shrub height, fuel loading, greenbrier cover, vertical fuel continuity, fuel particle surface area-to-volume ratio, packing ratio, and volatility (chemical heat content).

I determined fuel load by harvesting all fuel particles within a cube that had a 1 meter by 1 meter base and a height equal to that of the top of the shrub canopy. I followed the example of Ludwig et al. (1975) and selected sample stands to represent different fuel conditions (chiefly height of the shrub fuel bed) using a stratified random sampling design. My goal was to create the maximum range of inference for fuel load predictions. Areas were subjectively evaluated as having low (less than approximately 2 feet (0.6 m)), medium (between approximately 2 feet (0.6 m) and 4 feet (1.2m)), or high (greater than approximately 4 feet (1.2 m)) canopy heights. Once an area with uniform heights was identified, I haphazardly tossed a small object to locate a position for the sampling cube.

Fuels were then sampled as follows. First, a PVC sampling cube, measuring 1 meter on each side, was assembled in the area to be sampled. Three sides of a three-dimensional quadrat were cut using a gas-powered hedge trimmer to create a column of greenbrier. The hedge trimmer cleanly cut the greenbrier without snagging or pulling the column allowing it to maintain its vertical and horizontal integrity (Figure 2).

Figure 2. A greenbrier quadrat with three sides freed.

With three sides free, non-destructive sampling for predictive equations was performed. Shrub height was measured by determining the maximum height of a plant intercept for ten different points within each quadrat. Percent cover was simultaneously measured using the point intercept method (Mueller-Dombois and Ellenberg 1974) to record the presence or absence of greenbrier at each of these points. At this time, modified point-intercept sampling (explained further in the next section) was also performed. I characterized vertical continuity by noting the distribution of fine fuels in the column and gaps in potentially available fuels between the litter and crown layers. Sample plots on which a fire originating in the litter would likely carry to the crown fuels were judged to be vertically continuous. Those where fire would likely not carry to crown fuels was judged to be not continuous.

After completing non-destructive sampling, the entire greenbrier column was harvested using the hedge trimmer and hand clippers and stem-stumps were counted

(Figure 3). Clipped greenbrier stems and leaves were placed in 30-gallon trash barrels; the litter on the surface was gathered and placed in paper bags; and the samples were taken to the laboratory where random sections of greenbrier were measured for diameter to determine their size (hour-class) and surface area-to-volume ratio. The greenbrier was then sorted into live stem, live leaf, and dead stem components. It was sometimes difficult to determine the live or dead status of a stem, because a stem can be mostly dead on the outside, but with some living tissue on the inside. If a stem appeared mostly dead, as evidenced by the stem breaking cleanly when snapped or appearing to be porous or dry on the inside when cut, it was classified as dead. Litter samples were sorted into herbaceous (leaf and grass/sedge) and downed wood. The sorted fuels were then dried at 70° Celsius to determine their oven-dry weight. I determined packing ratio by constructing a custom fuel model in BEHAVE's Testmodel module which has packing ratio as an output. Chemical heat content was measured at the U.S. Forest Service Forest Products Laboratory in Madison, WI, using a cone calorimeter (Dibble and White, unpublished data).

Predicting Greenbrier Mass

I developed equations to predict the mass of greenbrier, because mass is difficult to measure, is likely to vary across sites, and influences fire behavior. Non-destructive methods of predicting shrub-fuel mass typically fall into two categories: those that use stem diameter, and those that use canopy volume or height as an index of mass. Because greenbrier does not grow in discrete units, but instead in intertwined jumbles, predicting the mass of individual stems would have little utility. Also, anecdotal observations suggest that greenbrier stems can vary greatly in height, while having similar

Figure 3. Greenbrier quadrat after shrub fuels had been removed.

diameters (W.A. Patterson, pers. comm., personal observation). For these reason, shrub diameter was not measured for the purpose of fuel load prediction. Shrub height, along with two less common methods, was used.

Equations were developed from three easy-to-measure plant characteristics: 3-dimensional cover, stem density, and shrub height. Three-dimensional cover was measured using a modified point-intercept technique. I counted all the instances of greenbrier intercepting a vertical point extending from the top of the canopy to the top of the duff layer. This method differs from the one described by Mueller-Dombois and Ellenberg (1974) in that I counted *each* intercept along the point, rather than simply checking for presence of plant intercepts at defined points along the point

(Figure 4). A method of relating intercepts in three dimensions to mass (Wilson 1959) is similar, though more complex, than the one I used.

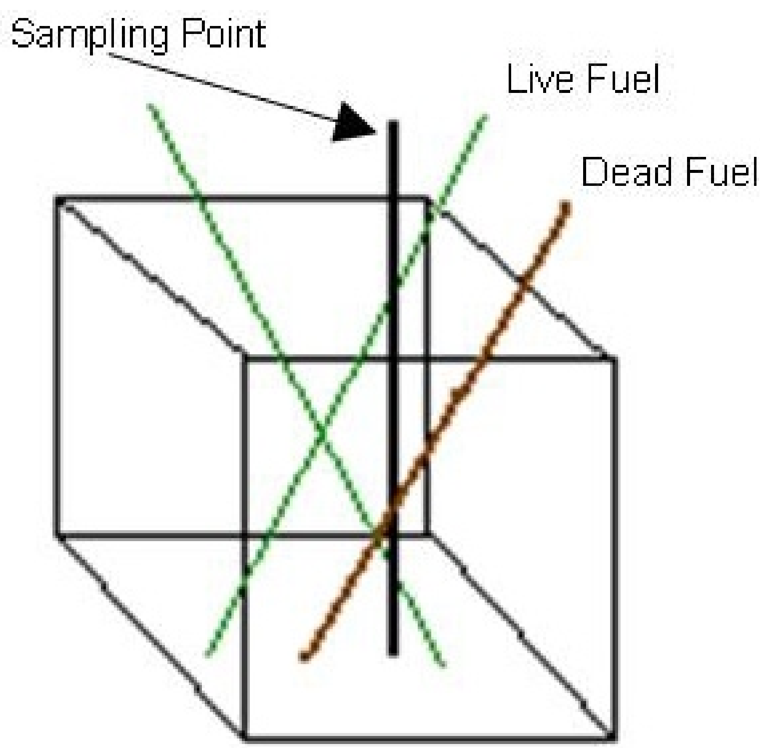

Figure 4. Idealized drawing of 3-dimensional sampling technique. In this example, two live hits and one dead hit would be tallied, meaning that there are two intersections with live fuel particles and one with dead. In Mueller Dombois and Ellenberg (1974), one hit would be tallied, meaning that there is fuel at this point.

At each intercept, I recorded whether the plant was alive or dead, and stem or leaf. A wooden dowel 0.25-inch (0.64-cm) in diameter and 3.3 feet (1 meter) was used to represent the point. The dowel was marked at 1-cm (0.4 in) intervals for the first 10 cm (4 in) above the ground and then in 10-cm intervals thereafter. Ten of these points were measured within each quadrat. Sampling was performed at points with coordinates at 25-cm (9.8-inch) intervals along the south and west lines (Figure

5). A tenth point was selected by randomly generating two numbers between 1 and 100 (representing the 100 cm length of each side of the quadrat). These two numbers were used to define the coordinates of the final sampling point within the square which formed the top of the cube. For instance, if the two randomly generated numbers were 12 and 23, the point was located 12 cm east and 23 cm north of the southwest corner of the sampling square.

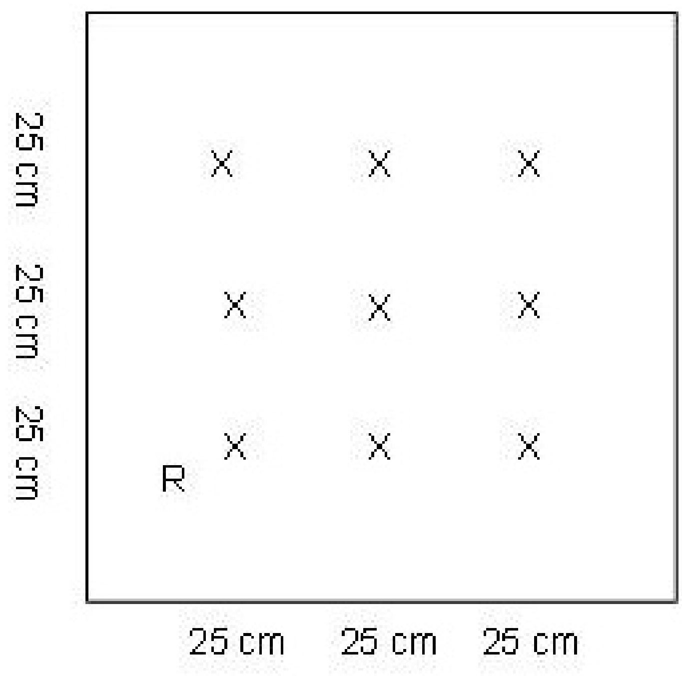

Figure 5. Layout of sampling points within each quadrat. Points are at 25 cm-intervals with the first one located 25 cm north and 25 cm east of the southwest corner. A tenth point ("R") was located randomly within the quadrat.

This modified point-intercept sampling was used to measure shrub height, percent cover, and the number of three-dimensional point-intercepts with greenbrier. After the greenbrier was destructively harvested, the stem density was tallied by counting the plant stumps within the quadrat.

The suitability of each independent variable was determined by weighing its strength in predicting fuel mass and also by the ease with which it could be measured.

The strength of the predictor was determined by performing a linear regression and calculating a coefficient of determination (R^2). The ease of measurement was related to the amount of time and effort expended in sampling.

Custom Fuel Model Development

Custom fuel models can be used by fire managers to help predict fire behavior in advance of wild or prescribed fires. Modeling in this project was accomplished by using Behave software, and inputs included fuel load and depth, surface area-to-volume ratio, and heat content by size class and category (litter, grass, slash and shrubs). A preliminary model was developed using fuel data and predictions were then compared to actual fire behavior. Because Behave programs allow the user to adjust inputs to match observed fire behavior, I fine-tuned my model so that model outputs would better match observed behavior. I evaluated the need for custom fuel models in greenbrier fuels by comparing standard fuel model outputs with observed fire behavior (see Chapter 5).

A prescribed fire was conducted on June 13, 2004 on a 0.5-acre (0.2-ha) research plot in the Protected Field. This fire had been preceded by a smaller experimental burn in October 2003. The first burn was useful in evaluating potential fire behavior. A crew of 11 firefighters and researchers was present for the June 13 burn. The plot was bounded on the north and west by a mowed fire break approximately 15 feet (5 m) wide, on the east by an area of green grass/sedge burned in the October 2003 fire, and on the south by a greenbrier plot that had been burned in April 2002 and had little fuel. An area (approximately one acre) to the north of the June 2004 burn plot was burned during October 2003.

Immediately before ignition, litter was gathered from throughout the plot and placed in eight plastic bags for later fuel moisture determination. Samples of live leaves and live stems were also gathered and placed in sealed plastic bags. Dead stem fuel moisture was measured in the field using a protometer capable of recording fuel moistures greater than 7%. After the burn was complete, the litter and live fuel samples were returned to the laboratory where they were weighed, dried at 70° Celsius for 24 hours (or until dry), and reweighed to yield percent moisture on an oven dry weight basis.

Key weather parameters were measured before, during, and after the burn including state of the weather (an estimate of the degree of cloud cover and precipitation status), ambient air temperature, relative humidity, and wind speed and direction. Wind speed was measured at between five and seven feet (1.5 to 2 m) above the ground (i.e. at approximately midflame height) using a digital anemometer.

The fire was ignited as a head fire with a drip-torch and allowed to burn freely without influence of backing or flanking fires. Flame lengths and rates of spread were measured by placing, at 20-foot (6.1 m) intervals, four iron poles with horizontal arms at one-foot (0.3-m) intervals within and parallel to the expected path of the head fire in the southern one-third of the plot. I recorded the average length of flames as they reached each pole and the time it took the head fire to travel the 20 feet between the poles. The entire burn was video-recorded which allowed verification of field measurements taken during the burn.

Fuel Model Evaluation

The custom fuel model was evaluated by comparing BehavePlus3 outputs for flame length and rate of spread - using as environmental inputs the fuel moisture and weather data at the time of the burn - with observed fire behavior. This process was particularly useful during fuel model construction when estimating surface area-volume ratios, moisture of extinction, and heat content.

Sensitivity Analysis

Sensitivity analysis was performed to evaluate the sensitivity of the Protected Field greenbrier custom fuel model to variations in 1-hr dead fuel load, live fuel load, heat content, fuel bed depth, surface area-volume ratio, and moisture of extinction. Each of these was increased/decreased by +/- 5%, 10%, 20% and 40%, while holding other input parameters constant. Heat contents were increased/decreased by +/- 5%, 10%, and 20%, and to the upper (12000 btus/pound) and lower (6000 btus/pound) acceptable limits. For each run, the resulting flame length and rate of spread were recorded.

Following the example of Dell'Orfano (1996), degree of change was calculated as follows:

$$\Delta I = (I_U - I_L) / I_L$$

$$\Delta O = (O_U - O_L) / O_L$$

where:

I_U = upper limit of the inputs

I_L = lower limit of the inputs

O_U = upper limit of the resulting outputs

O_L = lower limit of the outputs.

I compared the ratio of the degree of change in the output to the change in the input. In this way, I was able to illustrate the effects of a change in fuel parameters on fire behavior characteristics.

CHAPTER 5

RESULTS

Describing and Quantifying Greenbrier Fuel Beds

Nine greenbrier plots were sampled in the Protected Field during June, July and August 2003. The average quadrat sampled was 3.27 feet (1.00 m) tall with a volume of 29.4 ft^3 (0.82 m^3), had 100 percent cover, was vertically continuous (as evidenced by the presence of 1-hr fuels throughout the column), and had 4.9 pounds (2.24 kg) of fuel per sampling cube, which is equivalent to 10.05 tons/acre (23.0 mt/ha) (Table 1) (see Table 2 for component fuel loads). The average diameter of greenbrier stems 2 inches (5 cm) above their base was 0.22 inch (0.56 cm), with none greater than 0.25 inch (0.64 cm). Thus the entire fuel bed was composed of 1-hr (fine) fuels.

Table 1. Mean fuel bed characteristics with 95% Confidence Intervals for greenbrier in the Protected Field.

	Shrub Height	Percent Cover	Total Fuel Load	Ave Basal Stem Diam.	Percent Dead	Relative Packing Ratio	Heat Content
English units	3.27 ft	99%	10.05 t/acre	0.22 in	72%	0.79	8000 btu/lb
N	9	9	9	20	9		
95% Confidence Interval	2.40-4.14	96.4% - 100%	7.06-12.88	0.20-0.22	66% - 79%		
Metric units	1.00 meters		23 mt/ha	0.56 cm			18.61 Mj/kg

Table 2. Component fuel loads for greenbrier fuel beds. Percent of total fuel load are in parentheses.

	Litter	Dead Stems	Live Stems	Live Leaf
English Units	3.77 t/acre (37%)	3.51 t/acre (35%)	2.10 t/acre (21%)	0.67 t/acre (7%)
Metric Units	8.60 mt/ha	8.00 mt/ha	4.79 mt/ha	1.53 mt/ha

Table 3. Surface area-to-volume ratios for greenbrier fuel components.

	Litter	Dead Stems	Live Stems	Live Leaf
Type of measurement	Estimate	Direct	Direct	Estimate
SA/V	2500 ft^{-1}	535 ft^{-1}	535 ft^{-1}	2500 ft^{-1}
Percentage of dead fuel load	52%	48%		
Percentage of live fuel load			76%	24%

I calculated the surface area-to-volume ratio for the greenbrier fuel model by combining directly measured and estimated values. The average diameter of greenbrier stems and branches was 0.09 inch (.23 cm). Assuming vines are a perfect cylinder, this represents a surface area-to-volume ratio of 535 ft^{-1} (17.5 cm^{-1}). This value serves as the surface area-to-volume ratio of live and dead stems. Litter and live leaf material could not be directly measured, so I used a BehavePlus3-estimated value of 2500 ft^{-1} (Table 3).

On average, 72 % (range = 66 to 89 %) of the fuel load was dead stems largely concentrated in the lower 1.3 feet (0.4 m) of the fuel bed. Dead stems in the upper parts of the fuel bed were either dead stems branching off of live stems or dead, broken stems entwined in live greenbrier. Dead greenbrier leaves tend to curl as they dry, and this effect coupled with small stems present in the litter layer kept the litter well aerated.   The average height of litter was 2.0 inches (5.2 cm).

The BEHAVE module Testmodel calculates the packing ratio based on component fuel loads and fuel bed depths. It further calculates a relative packing ratio by dividing the theoretical optimum packing ratio by the calculated observed packing ratio. A relative packing ratio of 1 indicates that there is an optimum ratio of fuel to air. A Behave analysis for the greenbrier fuel bed in the Protected Field yielded a relative packing ratio of 0.79, which is close to the optimal value. For comparison, the three most similar standard fuel models 3, 4, and 7 have relative packing ratios of 0.21, 0.52, and 0.34, respectively. Behave predicts maximum fire behavior outputs for fuel beds with a relative packing ratio of 1, all other factors being constant.

Live leaves appeared to be waxy, which suggests the presence of volatile compounds (Burgan and Rothermel 1984). However, bomb calorimeter analysis of greenbrier leaves produced a value of 6554 btu/pound, a value that seems low for green fuels which burn readily. In Chapter 6 I discuss the apparent discrepancy between the plant's waxy leaves (and, thus, the likely presence of volatiles) and the low heat content value that was measured.

Predicting Greenbrier Mass

Stem Density

Six of the nine quadrats were sampled for stem density. The number of stems per quadrat did not prove to be an accurate predictor of fuel load in greenbrier (R^2 = 0.06).

Three-Dimensional Cover Sampling

There were, on average, 49 intercepts per sampling cube. Of these, 27 (55%) were live material and 22 (45%) were dead. The number of hits per sampling cube proved to be a potentially useful predictor of the total mass of fuels in the quadrat (R^2 = 0.80) (Figure 7). Visual inspection of the scatter plot of total fuel mass on total point intercept hits shows that the observations are evenly distributed along the regression line (Figure 6).

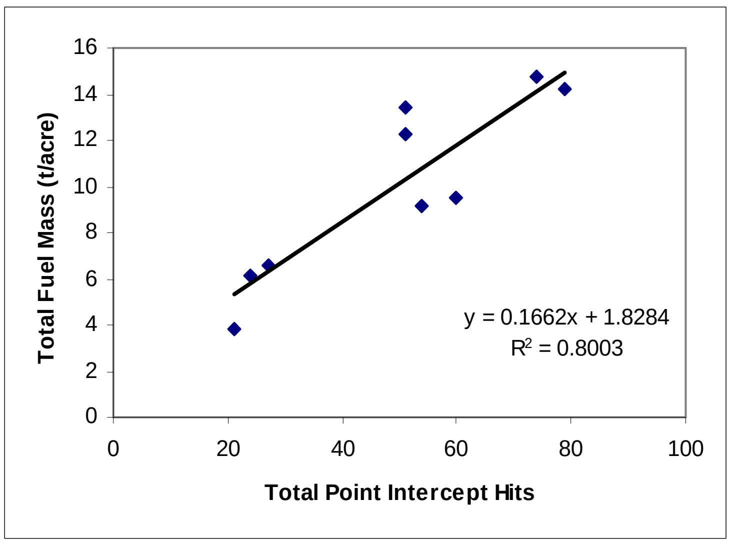

Figure 6. Three-dimensional cover as a predictor of total fuel mass. A linear regression line is fitted and the linear equation and coefficient of determination are in the lower-right.

Attempts to identify a predictive relationship between live intercepts and live mass, and dead intercepts and dead mass were less successful, with R^2 values of 0.73 (Figure 7) and 0.40 (Figure 8), respectively. This finding will be explored further in the DISCUSSION.

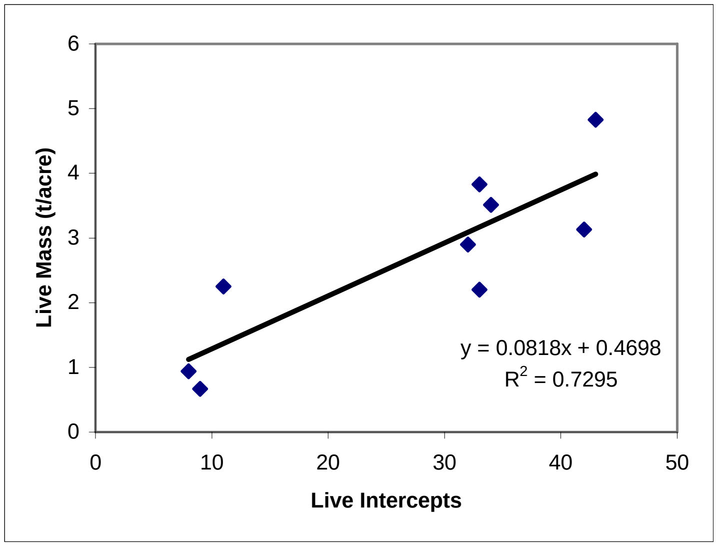

Figure 7. Live plant intercepts as a predictor of live fuel mass. A linear regression line is fitted and the linear equation and coefficient of determination are in the lower-right.

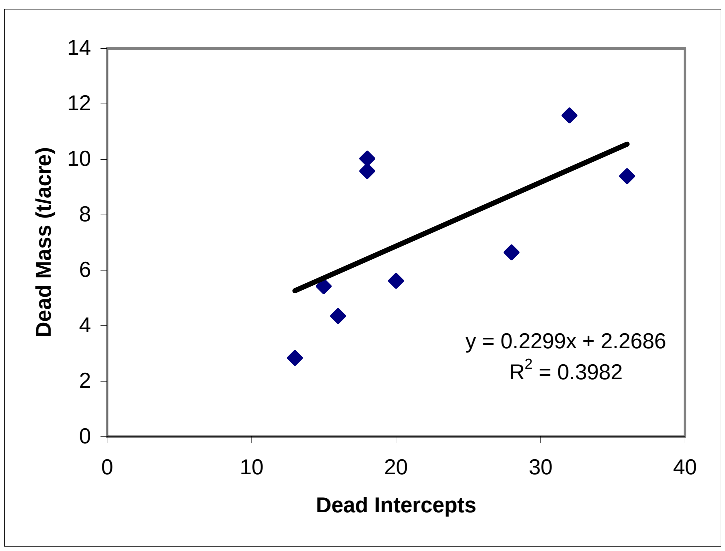

Figure 8. Dead plant intercepts as a predictor for dead fuel mass. A linear regression line is fitted and the linear equation and coefficient of determination are in the lower-right.

Shrub Height

The average shrub height of the greenbrier fuel bed in the Protected Field was 3.27 feet (1.0 meters) with a range of 1.25 - 5.02 feet (0.38 - 1.53 m). Shrub height proved to be a potentially useful predictor of total mass of fuels in the quadrat (R^2 = 0.81), with observations evenly distributed along the regression line (Figure 9).

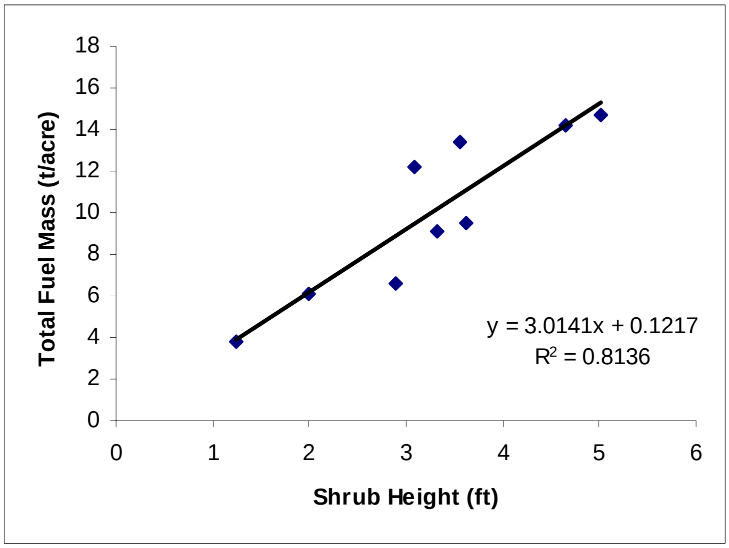

Figure 9. Shrub height as a predictor of total fuel mass. A linear regression line is fitted and the linear equation and coefficient of determination are in the lower-right.

Sampling Effort

Counting stems was relatively simple once all fuel was removed, taking less than five minutes per plot. However, if the stems had not been harvested, counting would have taken much more time. Modified point-intercept sampling was time-intensive and difficult to perform, taking approximately 40 minutes per plot. Measuring shrub height took less time. Approximately ten measurements could be obtained from a quadrat in less than five minutes.

Custom Fuel Model Development

I created a custom fuel model in the windows-based BehavePlus3 and the DOS-based BEHAVE using information from the fuel sampling portion of the project. I then used data from the prescribed fire to verify and modify the inputs. These two programs differ in the way that data are entered and in the detail provided by their output. BehavePlus3 has a simplified input interface that requires less information, and its output report omits estimates of moisture of extinction, packing ratio, and relative packing ratio. However, as long as data are properly entered, these two programs always yield identical predictions of flame length and rate of spread.

The components of the custom fuel model are presented in Table 4. No fuels larger than 0.25 inch (0.64 cm) basal diameter were present, so the loads for 10-hr and 100-hr fuels were zero. In constructing the model, I considered all fuel particles in the leaf litter, including dead greenbrier stems, to be litter. All fuels above the litter layer, including dead stems, live stems, and live leaves were entered into the fuel model as part of the shrub component. The live shrub component is made up of all the live fuel particles in the fuel bed, including live leaves. A slash component was not used in this model. As discussed earlier, the directly measured heat content value was lower than I expected, and I instead used a value of 8000 btu/lb. This value is widely used in fire modeling (Pyne et al.1996) and is used for all 13 standard fuel models.

The prescribed fire burned without interruption across the plot and consumed most biomass above the duff (Figure 11). Variations in fire behavior were probably due largely to minor variations in wind speed. Overall, flame lengths averaged 17 feet (5

Table 4. Protected Field greenbrier custom fuel model inputs.

Fuel Component	Category	Size Class	Load (t/acre)	SA/V (ft-1)	Heat Content (Btu/ft^2)	Moisture of Extinction	Fuel Strata Depth (ft)
Litter	dead	1 hr	3.77	2500	8000	32	0.17
Shrub	dead	1 hr	3.51	545	8000	32	3.27
Shrub	live	1 hr	2.77	983	8000	32	3.27

meters) with rates of spread of 40 ft/minute (15 m/minute) at wind speeds of 10 mph (16.1 km/hr). Fuel moisture and weather conditions at the time of the burn are summarized in Table 5.

Figure 10. Pictured is a headfire with approximately 20-foot (6.1-m) flame lengths during a June 13, 2004 controlled burn.

Figure 11. Research plot immediately after fire.

Table 5. Fuel moisture and weather conditions present during the June 13, 2004 burn in greenbrier at the Protected Field. Moisture values are presented on an oven-dry weight basis (ODWB).

AverageWind Speed (mph) (range in parenth.)	Litter Moisture (% ODWB)	Slash Moisture (% ODWB)	Live Fuel Moisture (% ODWB)	State of the Weather
10 (8 – 15)	19	8	175	0 (clear)

When time-of-the-burn fuel moisture and weather conditions are used with BehavePlus3, the custom fuel model predicts rates of spread and flame lengths that closely match observed fire behavior. The relevant standard fuel models all under-predict flame length and, with the exception of fuel model 3, under-predict rate of spread (Table 6).

Table 6. Standard and custom fuel model predictions of flame length and rate of spread compared with actual (observed) fire behavior.

	Flame Length (ft)	Rate of Spread (ft/min)
Observed	17 (range = 15-20)	40 (range = 30-45)
Protected Field CFM – Greenbrier	16	38
SFM 3 - Tall Grass	10	79
SFM 4 - Chaparral	7	20
SFM 7 - Southern Rough	4	16

Sensitivity Analysis

Rate of spread and flame length reacted differently to changes in input parameters (using environmental variables from the June 2004 burn – see Table 5) than the custom fuel model, with rate of spread generally changing more. That is, a change in an input parameter usually caused the model to predict a greater change, percentage-wise, in rate of spread than flame length. I also calculated an average sensitivity by adding the sensitivity values for rate of spread and flame length together and dividing by two for each input parameter I tested (Table 7)

Generally, the custom fuel model was least sensitive to live fuel load and moisture of extinction. Decreasing the moisture of extinction by 40% increased flame length by 12%, whereas increasing the moisture of extinction by 40% did not affect flame length. Similarly, reducing live fuel load by 40% had no effect on predicted flame length, whereas increasing the live fuel load by 40% decreased flame length by only 6%.

The model was most sensitive to changes in surface area-to-volume ratio and fuel bed depth. With all other fuel parameters held constant, increasing fuel bed depth decreases the packing ratio and vice versa. The net result is a 45% increase in rate of spread with a 40% increase in fuel bed depth and a 45% decrease with a 40% decrease in fuel bed depth. Similarly, a 40% increase in dead fuel surface area-to-volume ratio caused a 53% increase in predicted rate of spread, whereas a 40% decrease in surface area-to-volume caused rate of spread to decrease by 42%..

Table 7. Sensitivity of the greenbrier custom fuel model predictions to changes in tested fuel inputs. Sensitivity is measured as the ratio of the degree of change in the output parameter (the predicted fire behavior) to the degree of change in the input parameter (fuel characteristic). Combined sensitivity is the mean of the rate of spread sensitivity and the flame length sensitivity.

Fuel Input	Combined Sensitivity	Rate of Spread Sensitivity	Flame Length Sensitivity
Fuel Bed Depth	0.79	1.21	0.38
Surface area-Volume	0.68	1.23	0.13
Heat Content	0.55	0.47	0.62
1-Hr Fuel Mass	0.30	0.29	0.31
Live Fuel Mass	0.17	0.26	0.09
Moisture of Extinction	0.13	0.15	0.11

CHAPTER 6

DISCUSSION

Describing and Quantifying Greenbrier Fuel Beds

Characteristics That Contribute to Extreme Fire Behavior

Several characteristics of the greenbrier fuel bed can help to explain the observed extreme fire behavior. Among these is the absence of a large fuel component which would act as a heat sink and hence slow rates of spread. The absence of 10-, 100-, and 1000-hour fuels means that more of the fire's energy is expended in the flaming stage of combustion and less in drying fuels to the point where flaming combustion is possible. Further, 72% of the fuel in the greenbrier fuel beds I sampled is dead, and this dominance of dead material means that little of the fire's energy is being used to drive water from live fuels.

The study average 1-hr dead fuel load (the sum of litter and dead stem fuels) of 7.28 tons/acre is unusually large. All standard fuel models, including the three most similar to greenbrier - SFMs 3, 4 and 7 - have lower 1-hr fuel loads (Table 9). This also helps to explain the extreme fire behavior observed in greenbrier.

Table 8. One-hour dead fuel load (in tons/acre) for several brush and tall grass standard fuel models.

Fuel Model	1 Hour Dead Fuel Load
Greenbrier Custom Fuel Model	7.28
SFM 3 Long Grass	3.01
SFM 4 Chaparral	5.01
SFM 7 Southern Rough	1.13

Other findings help to explain the extreme fire behavior that can occur in a greenbrier fuel bed. Among these is a near ideal mixing of fuel and air in the fuel bed as suggested by the estimated relative packing ratio of 0.79.

Conflicting heat content values

The calculated heat content reported by the Forest Products Lab (6554 btu/lb) is near the lowest heat content value acceptable to BehavePlus3 for custom fuel model construction (minimum 6000 btu/lb) and is less than the value used for all of the standard fuel models (8000 btu/lb). Fuels with waxy leaves are assumed to have higher heat content than those with non-waxy leaves (Burgan and Rothermel 1984), so one might expect greenbrier to have a heat content greater than 8000 btu/lb. While constructing the CFM, I used a heat content value of 8000 btu/lb, and the model performed well. When the value of 6554 btu/lb was used in BehavePlus3, predictions for flame length (13 ft) and rate of spread (33 ft/min) were lower than those observed on the test burn.

Predicting Greenbrier Mass

Stem density poorly predicts fuel load for the Protected Field. Counting stems is also impractical, because stems must first be harvested to allow counting of individual stumps.

Three-dimensional cover samples accurately predicted the total mass of greenbrier stems on my sample plots, but the procedure required approximately 40 minutes/plot to perform. Attempts to correlate live intercepts with live fuel load and dead intercepts with dead fuel load were less successful due to the difficulty in determining whether a greenbrier stem was alive or dead under field conditions. A greenbrier stem that was determined to be dead in the lab could easily have been mistakenly identified as live under field conditions.

Shrub height is a good predictor of the mass of greenbrier. Sampling can be performed quickly with minimal equipment (a stick for measuring height and brush chaps for walking through the thorny vines). This method represents what is likely to be the most accurate and least time-consuming method of predicting greenbrier fuel load. Mass has, however, little utility in predicting fire behavior unless fuel load can be broken down into fuel categories (i.e. shrub, slash, litter, and grass), size classes (1-, 10-, and 100-hr), and live or dead status. To predict fuel loads for custom fuel modeling using shrub height as a predictor, one would have to estimate how much of the fuel bed is live and dead, what percentage of the fuel load is litter versus shrubs. One could do this by noting the percentages reported in the RESULTS (Table 5), or by independently determining this information at the research or management site by applying the sampling protocol I outlined in the METHODS.

Custom Fuel Model Development

The custom fuel model accurately predicted the fire behavior of the prescribed burn that was conducted in June 2004. The predicted flame length of 16 feet closely matched the actual observed flame length of approximately 17 feet. The CFM predicted a rate of spread of 38 ft/minute, close to the observed rate of 40 ft/minute. These custom fuel model predictions were superior to those produced by the standard fuel models (see Table 7 in the RESULTS) which under-predicted flame length and rate of spread (except for SFM 3, which over-predicts rate of spread). The custom fuel model clearly outperformed the standard fuel models. Indeed, in a related study

(Richburg et al. 2004) compared observed versus custom-fuel-model-predicted flame lengths for a variety of shrubs across several controlled burns and found an overall R^2 of 0.93. The fact that these custom fuel models predict fire behavior well, coupled with the fact that standard fuel model predictions were generally much poorer, supports the use of custom fuel models for greenbrier.

The June 2004 prescribed fire was useful in confirming the accuracy of the greenbrier monoculture custom fuel model, and the extreme fire behavior was effective in showing the potential danger of this fuel condition. There was some speculation among the experienced fire researchers at the June 14 burn about whether the plot would burn completely given the relatively high moisture content of the dead fuels and the fact that the greenbrier plants were fully leafed out. Had fire behavior predictions been generated *a priori*, they would have confirmed our need to proceed with caution.

Sensitivity Analysis

Sensitivity analysis shows that the Protected Field greenbrier custom fuel model was most sensitive, considering rate of spread and flame length together, to changes in fuel bed depth and least sensitive to moisture of extinction. This is fortuitous in that fuel bed depth can be easily and accurately measured as opposed to moisture of extinction which is difficult to measure (so a BEHAVE-generated calculation was used instead).

By manipulating fuel bed depth while holding fuel load constant I altered the estimated packing ratio. Packing ratio is a very important determinate of fire behavior, and we have found that increasing the packing ratio (by reducing the fuel bed depth) can be an effective method of reducing fire behavior (Richburg et al. 2004). The fact that fuel bed depth had a greater effect on fire behavior than fuel load is an interesting finding that has potential utility for fuel management. In many instances, it would be easier for managers to manipulate the fuel bed depth by mowing, than to try to physically remove fuel. Reducing fuel bed depth might not only be easier, but also more effective, than reducing fuel load.

After fuel bed depth, surface area-volume ratio was the next most sensitive, when considering both rate of spread and flame length. I was able to directly measure greenbrier stems for surface area-volume ratio, and this provided support for the value used for the custom fuel model, although the surface area-volume ratio of the litter fuels had to be approximated.

After surface area-volume ratio, heat content caused the greatest change in rate of spread plus flame length. This causes some concern, because of the difference between what I assumed the heat content might be and the value produced by bomb calirometry. Although this conflict does exist, I do not believe that it lessens the utility of the custom fuel model because the model performs well.

Although 1-hour fuel load has less effect on rate of spread than most fuel characteristics, it is next in importance (after heat content) in its effect on flame length. I measured 10-hr fuel load directly and have confidence in the accuracy of the custom fuel model. The coefficients of determination (Table 10) show that we can accurately predict 1-hr fuel load either by three-dimensional-cover sampling or by measuring shrub heights.

Live fuels, because of their characteristically high moisture content, often suppress fire behavior. This effect is illustrated in the sensitivity analysis. Increasing the live fuel load reduces both rate of spread and flame length, and decreasing live fuel load increases fire behavior.

CHAPTER 7

MANAGEMENT IMPLICATIONS/AREAS FOR FURTHER STUDY

This study shows that greenbrier monocultures present a unique fuel condition for which fire behavior is not well explained by any standard fuel model. This fact, coupled with the extreme fire behavior that can occur in greenbrier monocultures demonstrates a need for a custom fuel model. This is particularly true in situations where greenbrier monocultures grow near structures or where land managers intend to use prescribed fire as a management tool.

This study also shows that fuel bed mass of greenbrier monocultures can be predicted with shrub height. Shrub height is much easier to determine than taking a direct measurement of fuel bed mass. This predictive relationship can be used by managers/researchers at other sites to help develop their own, site-specific custom fuel models.

The custom fuel modeling and prescribed fire exercises undertaken as part of my research showed that the custom fuel model predicted observed fire behavior well. Had this custom fuel model been developed before the prescribed fire was performed, it could have informed us of a potential hazard. Evaluating site-specific custom fuel models with additional burns merits further work.

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APPENDIX A

3-DIMENSIONAL COVER INTERCEPTS

These data show the location of 3-dimensional cover intercepts, with the height of intercept above the duff layer presented in centimeters. Sampling was performed during the summer of 2003.

APPENDIX A

PLOT 1		PLOT 2		PLOT 3		PLOT 4		PLOT 5	
live	dead	live	dead	live	Dead	live	dead	live	dead
35	5	42	12	86	10	34	6	30	14
48	6	76	28	74	10	36	10	46	30
50	10	78	48	70	10	38	10	46	36
60	12	116	32	80	16	46	12	30	38
64	13	98	8	110	18	48	14	32	48
65	14	100	32	74	22	48	14	40	50
66	15	126	34	64	30	50	14	44	50
67	15	130	40	78	38	50	16	56	52
68	16	60	8	68	60	52	16		54
70	18	96	24		70	54	22		56
70	18	120	118		74	58	32		58
76	18	130	62		86	58	32		60
78	20	138	28		88	60	44		68
78	20	70	30		92	60	58		
78	22	94	46		98	62	72		
78	24	122	48			64	80		
80	25	130	10			64	106		
80	25	160	52			66	106		
82	26	112	12			68			
85	27	116	22			76			
85	29	138	38			76			
86	30	150	66			82			
88	30	92	14			86			
88	30	110	16			90			
90	38	122	20			92			
92	38	42	22			92			
92	48	118	46			94			
94	49	128	50			94			
95	50	112	94			96			
102	50	124	108			98			
104	52	130	24			100			
105	60	140	32			104			
107	65	86				104			
107	68	100							
108	75	110							
110	97	112							
112		134							
114		144							
		152							
		94							
		138							
		152							

APPENDIX A

PLOT 6		PLOT 7		PLOT 8		PLOT 9	
live	dead	live	dead	live	dead	live	dead
32	20	58	28	46	12	30	14
46	22	66	34	78	20	76	18
50	24	84	38	80	60	80	20
64	28	68	48	58	82	86	20
82	30	80	48	78	10	94	22
102	32	30	48	80	34	106	22
62	32	40	50	110	18	52	30
70	34	64	52	138	24	88	30
80	34	60	58	82	46	116	36
92	38	70	58	84	54	60	38
42	38	74	60	104	60	108	40
76	46		62	118	76	116	40
64	48		66	122	80	60	42
70	50		66	72	14	82	44
76	52		70	96	38	102	46
80	54		78	108	98	34	52
84	56			110	130	84	52
108	58			114	10	90	54
76	62			64	12	64	58
82	64			66	14	84	62
88				88	15	86	64
90				100	18	90	72
62				110	32	20	72
74				138	34	60	74
78				72	40	74	76
34				74	54	76	78
72				88	92	90	80
90				122	20	96	88
96				94	74	100	
56				120	86	46	
58				14	14	64	
10				64	28	86	
78				70	96		
90				118	16		
				122	24		
				126	98		
				42			
				120			
				132			
				134			
				138			
				78			
				102			

APPENDIX B

QUADRAT MASSES

These data show the mass of fuel in each quadrat sampled. Data are presented in metric and english units. Sampling was performed during the summer of 2003. The following abbreviations are used:

Gram	g
Metric Ton	mt
Hectare	ha
Ton	t

APPENDIX B

PLOT 1							
	live stem	live leaf	total live fuels	litter	dead stem	total dead fuels	total fuels
g per quadrat	488	0	488	965	1263	2228	2716
mt/ha	0.488	0	0.488	0.965	1.263	2.228	2.716
t/acre	2.196	0	2.196	4.3425	5.6835	10.026	12.222

PLOT 2							
	live stem	live leaf	total live fuels	litter	dead stem	total dead fuels	total fuels
g per quadrat	568	130	698	1396	1197	2593	3291
mt/ha	0.568	0.13	0.698	1.396	1.197	2.593	3.291
t/acre	2.556	0.585	3.141	6.282	5.3865	11.6685	14.8095

PLOT 3							
	live stem	live leaf	total live fuels	litter	dead stem	total dead fuels	total fuels
g per quadrat	119	30	149	887	317	1204	1353
mt/ha	0.119	0.03	0.149	0.887	0.317	1.204	1.353
t/acre	0.5355	0.135	0.6705	3.9915	1.4265	5.418	6.0885

PLOT 4							
	live stem	live leaf	total live fuels	litter	dead stem	total dead fuels	total fuels
g per quadrat	670	183	853	1270	861	2130	2983
mt/ha	0.67	0.183	0.853	1.27	0.861	2.13	2.983
t/acre	3.015	0.8235	3.8385	5.715	3.8745	9.585	13.4235

PLOT 5							
	live stem	live leaf	total live fuels	litter	dead stem	total dead fuels	total fuels
g per quadrat	131	78	209	295	334	629	838
mt/ha	0.131	0.078	0.209	0.295	0.334	0.629	0.838
t/acre	0.5895	0.351	0.9405	1.3275	1.503	2.8305	3.771

APPENDIX B

PLOT 6							
	live stem	live leaf	total live fuels	litter	dead stem	total dead fuels	total fuels
g per quadrat	*579*	*199*	778	*772*	*477*	1249	2027
mt/ha	0.579	0.199	0.778	0.772	0.477	1.249	2.027
t/acre	2.6055	0.8955	3.501	3.474	2.1465	5.6205	9.1215

PLOT 7							
	live stem	live leaf	total live fuels	litter	dead stem	total dead fuels	total fuels
g per quadrat	350	152	502	379	586	965	1467
mt/ha	0.35	0.152	0.502	0.379	0.586	0.965	1.467
t/acre	1.575	0.684	2.259	1.7055	2.637	4.3425	6.6015

PLOT 8							
	live stem	live leaf	total live fuels	litter	dead stem	total dead fuels	total fuels
g per quadrat	813	261	1074	767	1322	2089	3163
mt/ha	0.813	0.261	1.074	0.767	1.322	2.089	3.163
t/acre	3.6585	1.1745	4.833	3.4515	5.949	9.4005	14.2335

PLOT 9							
	live stem	live leaf	total live fuels	litter	dead stem	total dead fuels	total fuels
g per quadrat	475	175	650	810	667	1477	2127
mt/ha	0.475	0.175	0.65	0.81	0.667	1.477	2.127
t/acre	2.1375	0.7875	2.925	3.645	3.0015	6.6465	9.5715

APPENDIX C

LITTER DEPTHS

Litter depths are presented below in both metric and English units. Sampling was performed during the summer of 2003. The following abbreviations are used:

Centimeters	cm
Feet	ft

APPENDIX C

PLOT 1		PLOT 2		PLOT 3		PLOT 4		PLOT 5	
cm	ft	cm	ft	cm	ft	cm	ft	cm	ft
3	0.10	3	0.10	7	0.23	5	0.16	4	0.13
10	0.33	4	0.13	6	0.20	5	0.16	4	0.13
4	0.13	6	0.20	4	0.13	3	0.10	3	0.10
3	0.10	6	0.20	5	0.16	3	0.10	2	0.07
7	0.23	7	0.23	7	0.23	9	0.30	4	0.13
4	0.13	5	0.16	4	0.13	4	0.13	6	0.20
2	0.07	9	0.30	6	0.20	10	0.33	3	0.10
6	0.20	5	0.16	7	0.23	5	0.16	3	0.10
5	0.16	11	0.36	4	0.13	5	0.16	3	0.10
3	0.10	6	0.20	7	0.23	4	0.13	3	0.10
4.7	0.15	6.2	0.20	5.7	0.19	5.3	0.17	3.5	0.11

PLOT 6		PLOT 7		PLOT 8		PLOT 9	
cm	ft	cm	ft	cm	ft	Cm	ft
6	0.20	2	0.07	7	0.23	8	0.26
8	0.26	2	0.07	9	0.30	7	0.23
6	0.20	2	0.07	5	0.16	5	0.16
7	0.23	3	0.10	6	0.20	5	0.16
6	0.20	3	0.10	6	0.20	6	0.20
6	0.20	3	0.10	9	0.30	5	0.16
5	0.16	2	0.07	6	0.20	8	0.26
4	0.13	3	0.10	5	0.16	8	0.26
6	0.20	5	0.16	7	0.23	7	0.23
6	0.20	4	0.13	12	0.39	5	0.16
6	0.20	2.9	0.10	7.2	0.24	6.4	0.21

APPENDIX D

FUEL MOISTURES AT JUNE 2004 RESEARCH FIRE

Presented below is fuel moisture conditions present immediately before the June 13, 2004 research fire.

Table D.1. Live fuel moistures. Each sample was gathered from throughout the plot. Weights are presented in grams. Moisture percentages are presented on an oven-dry weight basis.

Table D.2. Dead fuel moistures as measured by a protometer. Samples were measured from throughout the shrub canopy. Values are presented as percentages.

APPENDIX D

Table D.1. Live Fuels.

	SAMPLE	WET (g)	DRY (g)	TOTAL WET (g)	TOTAL DRY (g)	% MOIST ODWB
STEM	A	72.3	36.4			
	B	119.0	43.3	191.3	79.7	140%
LEAF	A	79.2	21.1			
	B	69.3	18.0	148.5	39.1	280%
LITTER	A	42.2	36.2			
	B	40.6	33.8			
	C	39.4	32.7	122.2	102.7	19%

Table D.2. Dead Fuels.

9	9
9	7
9	7
7	10
7	7
9	7
9	7
7	8
7	7
9	7

APPENDIX E

SUMMARY OF FUEL SAMPLING DATA

Presented below is a summary of fuels data gathered from 9 sample plots in the Protected Field area of Naushon during the summer of 2003. Blank fields indicate that the value was not measured.

APPENDIX E

PLOT	LITTER (T/AC)	DEAD STEM (T/AC)	DEAD FUELS (T/AC)	LIVE STEM (T/AC)	LIVE LEAF (T/AC)	LIVE FUELS (T/AC)	TOTAL FUEL (T/AC)
1	4.34	5.69	5.69	2.20	0.00	2.20	7.89
2	6.28	5.31	5.31	2.55	0.58	3.13	8.44
3	3.47	2.15	2.15	2.61	0.90	3.51	5.66
4	3.99	1.43	1.43	0.54	0.13	0.67	2.10
5	1.33	1.51	1.51	0.59	0.35	0.94	2.45
6	5.71	3.87	3.87	3.01	0.82	3.83	7.70
7	3.65	3.00	3.00	2.14	0.76	2.90	5.90
8	3.45	5.95	5.95	3.66	1.17	4.83	10.78
9	1.71	2.64	2.64	1.57	0.68	2.25	4.89
AVE	**3.77**	**3.51**	**7.28**	**2.10**	**0.67**	**2.77**	**10.05**

PLOT	LITTER DEPTH (FT)	MAX DEAD HIT (FT)	MAX LIVE HIT (FT)	DEAD HITS (#)	LIVE HITS (#)	TOTAL HITS	PERCENT COVER (%)	STEM COUNT (#)	PERCENT DEAD (MASS)
1	0.15	1.46	3.09	18.00	33.00	51.00	100.00		72.12%
2	0.20	1.99	5.02	32.00	42.00	74.00	100.00		62.91%
3	0.20	1.44	3.32	20.00	34.00	54.00	100.00	94.00	37.99%
4	0.18	1.86	2.00	15.00	9.00	24.00	100.00		68.10%
5	0.11	1.15	1.25	13.00	8.00	21.00	90.00	76.00	61.63%
6	0.17	1.55	3.56	18.00	33.00	51.00	100.00	55.00	50.26%
7	0.21	2.22	3.62	28.00	32.00	60.00	100.00	102.00	50.85%
8	0.24	2.68	4.65	36.00	43.00	79.00	100.00	80.00	55.19%
9	0.10	1.61	2.90	16.00	11.00	27.00	100.00	81.00	53.99%
AVE	**0.17**	**1.77**	**3.27**	**21.78**	**27.22**	**49.00**	**98.89**	**81.33**	**72.42%**

APPENDIX F

SUMMARY OF WEATHER CONDITIONS AT JUNE 2004 RESEARCH FIRE

June 13, 2004, Greenbrier leaves fully-formed and green.

State of the weather: 0 (clear skies)

Total burn time: 9 minutes, 53 seconds

Wind directions: 220° True

Average wind seed for entire burn: 10 mph

Average wind seed between fire poles: 10 mph

Distance between fire poles: 20 feet

Elapsed time between fire poles: 30 seconds

Flame length at fire poles: 17 feet.