A Fuel Model for Fire Behavior Prediction in Spotted Knapweed (Centaurea maculosa L.) Grasslands in Western Montana

Gavriil Xanthopoulos

The University of Montana

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A FUEL MODEL FOR FIRE BEHAVIOR PREDICTION
IN SPOTTED KNAPWEED (CENTAUREA MACULOSA L.)
GRASSLANDS IN WESTERN MONTANA

by
Gavriil Xanthopoulos
B.S., Aristotelian University of Thessaloniki,
Greece, 1981

Presented in Partial Fulfillment of the Requirements
for the Degree of
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University of Montana
1986

Approved by
Chairman, Board of Examiners
Dean, Graduate School

Date
Spotted knapweed (Centaurea maculosa L.) is an introduced weed that has invaded grasslands of the northwestern United States. The purpose of this study was to build a fuel model for grasslands dominated by this plant in western Montana, to facilitate efforts to burn this noxious weed.

Total biomass (kg/ha) in knapweed dominated grasslands was broken down to three components: litter and fine grasses, old standing knapweed plants and newly grown ones. Three regression equations were developed for biomass prediction based on sample sizes of 102, 117 and 118 respectively. Independent variables were litter depth and cover, knapweed plant height and percentage of ground cover. Coefficient of determination ($R^2$) ranged from 0.74 to 0.90.

Surface area to volume ratios and plant densities were estimated for spotted knapweed based on detailed measurements of the various plant parts. They were $41.6\, \text{cm}^2/\text{cm}^3$ and $0.45\, \text{gm/cm}^3$ for old knapweed and $53.2\, \text{cm}^2/\text{cm}^3$ and $0.44\, \text{gm/cm}^3$ for new knapweed plants.

Values used in the 13 stylized NFFL (or FBO) fuel models for total and effective mineral content and energy content were also used for spotted knapweed.

Fire behavior observations from three test burns in spotted knapweed infested fields were compared to predictions from the mathematical fire spread model using fuel parameter inputs from the spotted knapweed fuel model. This task was based on BEHAVE, a fire behavior prediction computer system, based on the fire spread model.

A two-model approach is utilized for the explanation of the deviation of fire behavior observations from predictions. Three stylized fuel models for spotted knapweed are suggested and guidelines are offered for safe and effective early spring hazard reduction burns.
ACKNOWLEDGEMENTS

I wish to express my gratitude to the Greek Scholarship Foundation for supporting my graduate studies for a Masters of Science degree in Forestry in the United States. I wouldn’t have started these studies without their help.

I also wish to express my gratitude and appreciation to my major professor Dr. Ronald Wakimoto for his guidance, encouragement and friendship as well as for the support he secured for me from the Blackfoot Forest Protective Association and Northern Montana Forestry Association. My appreciation also goes to the other three members of my committee Dr. Donald Bedunah, Dr. James Brown and Dr. David Patterson for their valuable contributions and comments during the execution of this study as well as their technical and moral support.

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Thanks also go to all the nice people, professors and
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Finally thanks go to my wife Maria for her love and patience, and to my good friends Eva and John Koutelieris and Konstadinos Kalabokidis for their friendship and support during these two years.
DEDICATION

To my delightful wife, Maria who has been my inspiration during the two years of hard work that were needed for this thesis.

and

To our beloved parents who have supported us in every possible way during these two years.
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INTRODUCTION

Spotted knapweed (Centaurea maculosa L.) is the dominant Centaurea species found in western Montana. The other two Centaurea species of importance in Montana are diffuse knapweed (Centaurea diffusa) and Russian knapweed (Centaurea repens). Spotted knapweed was introduced to the North American continent from Eurasia around the beginning of the twentieth century as contaminants of Turkistan alfalfa (Groh 1940). The knapweeds are relatively free of natural enemies and have become widespread in the rangelands of the region. The gradual exclusion of other plants and the high fiber content of knapweed plants, may result in significant reductions in the cattle and wildlife carrying capacity of the infested areas (Maddox 1979, Chicoine 1984). Although animals will graze the rosettes and young flower heads, the spines on the mature flower heads, the bitter taste and the high fiber content of the mature plants make them unpalatable to most livestock. Intensive research on control methods for knapweed has only recently started and focuses mainly on herbicides and biological control.

A. Problem

Spotted knapweed is the most widespread of the knapweeds in the grasslands of western Montana. Ranchers
in the area consider it as their primary weed problem. It mainly invades dry sites with disturbed soil such as roadsides, trails, house yards, construction sites and overgrazed grasslands. In addition to causing grazing problems it constitutes a serious fire hazard problem and to most people it is aesthetically unpleasant.

Although fire does not seem to be a promising control method, predicting fire behavior in knapweed infested fields is desirable for the following reasons:

a. To be able to burn knapweed for fire hazard reduction purposes safely and effectively.

b. To fight wildfires in knapweed safely and effectively.

c. To aid scientists in evaluating the use of fire (alone or combined with other methods) as a knapweed control method.

The stylized grass fuel models developed at the Intermountain Fire Sciences Laboratory - previously Northern Forest Fire Laboratory (NFFL) - of the U. S. Forest Service in Missoula, Montana and currently used by Fire Behavior Officers (FBO) cannot predict fire behavior in knapweed with an acceptable accuracy. This was obvious from personal observations in wildfire situations and prescribed burns (Wakimoto, R. personal communication), as well as from a series of preliminary burns that were
conducted in April, 1985 in knapweed infested fields. Observations from these burns are shown in Table 1. In many cases fire behavior predictions with fuel model 1 (short grass fuel model) can greatly exceed observed fire behavior while in other cases knapweed fires are described best by fuel model 3 (tall grass fuel model) which has a much higher fire potential.

Table 1. Fire behavior observations during preliminary burns in knapweed infested fields in April 1985. Dead fuel moisture and expected flame length values derived from S-390 fire behavior field guide.

<table>
<thead>
<tr>
<th>Burn No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
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<tbody>
<tr>
<td>Dead fuel moisture (%)</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Windspeed (km/hour)</td>
<td>7</td>
<td>12</td>
<td>12</td>
<td>9</td>
<td>5</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>Slope (appr.) (%)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Observed flame length (m)</td>
<td>0.3</td>
<td>1.0</td>
<td>1.0</td>
<td>0.8</td>
<td>0.3</td>
<td>0.3</td>
<td>1.2</td>
</tr>
<tr>
<td>Expected flame length (m)</td>
<td>1.2</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>0.9</td>
<td>0.9</td>
<td>2.4</td>
</tr>
</tbody>
</table>

(Using fuel model 1)

As knapweed continues to spread in the region the number of fires to be fought in knapweed infested areas will probably increase. This can be very important as many of these fires will endanger houses and other buildings in the country and rural-urban interface since these are preferred sites for the invasion of knapweed. Having an adequate fire behavior prediction capability for knapweed fires will be very useful for wildfire fighting and for prescribed burning.
B. Objectives

The main goal of this study was to build a fuel model for spotted knapweed grasslands of western Montana because it forms dense stands with relatively homogeneous characteristics and is widespread in the area.

A fuel model is defined as a simulated fuel complex for which all the fuel descriptors required for the solution of the mathematical fire spread model have been specified. To build a fuel model one is required to determine values for a number of parameters that affect the way a fuel burns, as they have been defined by Rothermel (1972) and implemented in existing fire behavior prediction computer systems based on Rothermel's fire spread model. These parameters are (Rothermel 1972, Burgan and Rothermel 1984):

1. Ovendry fuel loading expressed as mass per unit area;
2. Average depth of each fuel model component for the estimation of fuel bed depth;
3. Surface area to volume ratios of the fuel particles;
4. Fuel particle density in mass per unit volume;
5. Fuel particle total mineral content as fraction of dry weight;
6. Fuel particle effective mineral content as fraction of dry weight;
7. Mean fuel energy content for combined fuel mass expressed in energy units per mass unit; and
8. Dead fuel moisture content of extinction expressed as percent of dry weight.

A second objective for this study, was to offer practical help for the utilization of the fuel model in fire behavior predictions by creating fire behavior graphs of typical knapweed fuel situations using the BEHAVE system (Andrews and Latham 1984). This system is a computer program developed at the Intermountain Fire Sciences Laboratory which, when given as inputs the fuel and environmental parameters of a burn, can produce fire behavior predictions for those conditions. The fire behavior graphs can be useful for people who do not have access to BEHAVE. Additionally the fuel model in its general form can be used by those who are interested in more site specific predictions and have access to BEHAVE.

The methods used to meet these two objectives are fundamentally different. The work on the second objective is based on the results of the first one. This fact dictated the separation of the study in two major parts. The first part refers to fuel parameter measurements. The second part refers to fire behavior measurements, and fire behavior graphs and interpretations.
LITERATURE REVIEW

There is practically no literature on the relation of knapweed with fire or on knapweed as a fuel. Most of the literature on spotted knapweed is about its effects on the rangelands it has invaded and examines different methods of control focusing mainly on herbicides and biological control (Watson and Renney 1974, Maddox 1979, Chicoine 1984, Mass 1985).

Current research at the University of Montana is focussed on controlling spotted knapweed by herbicides and considers fire combined with herbicides as one of the alternative treatments. It is hypothesized that burning before spraying can decrease herbicide interception from old standing knapweed plants and can increase knapweed seed germination making knapweed more vulnerable (Carpenter, J., personal communication). In another research project the nutritional content of spotted knapweed has been examined and its energy content has been calculated (Kelsey, R., personal communication). A third project examines the environmental factors associated with the invasion of spotted knapweed (Mooers 1986).

Current knowledge on forest fuel properties and fire behavior modeling is mostly the result of research contacted during the last twenty years. Richard Rothermel
(1972) presented the mathematical fire spread model based on William Frandsen's (1971) analysis of the conservation of energy on a spreading fire. The model is composed of a number of equations which for their solution require as inputs values for the parameters mentioned above and allow the calculation of a rate of spread value for a moving fire front. Much of the work done on fire behavior after this publication was on refinement of the model and on improvement and standardization of the methods to obtain values for these parameters. In addition to that much effort was put into the more efficient utilization of the model mainly through the creation of some standard fuel models and the extensive use of computers for the solution of the complex equations of the model.

Some of the equations in Rothermel's model were slightly modified by Frank Albini (1976a) for correction purposes and for easier and without problems implementation in computer programs.

woody plants - for the prediction of their loading using height and ground cover as the independent variables. Their model for grasses accounted for the least variability with \( R^2 = 0.30 \) and coefficient of variation 67%. They attributed its poor accuracy to the difficulty of ocularly estimating ground cover for grasses and noted that "as different plant sizes and shapes are added to the data base for developing predictive equations poorer accuracy can be expected".

In 1976 Frank Albini published a guide on estimating wildfire behavior and effects (Albini 1976b) based on 13 stylized fuel models that are representative of the most common fuel situations in the United States; they became known as the NFFL models. Fuel models 1 and 3 describe grass fuels in the open. Fuel model 1 is for short grass, while fuel model 3 is for tall grass. The two models differ significantly in their fire behavior potentials as it can easily be seen from the fire behavior nomographs included in the publication. The nomographs Albini created have been used extensively over the past years by Fire Behavior Officers in operational situations and have proved to be a very useful and practical fire fighting tool.

Based on the same principles but using tables instead of nomograms, the National Wildfire Coordinating Group
(1981) produced a training package and field guide on fire behavior - offered as a self-paced training course (S-390) - which incorporates all the basic fire behavior information needed in wildfire fighting.

In the eighties, the knowledge acquired through tedious work in the previous decade was incorporated in an interactive fire behavior prediction computer system called BEHAVE (Andrews and Latham 1984) which was documented by Burgan and Rothermel (1984), and Andrews (1986). The BEHAVE system is made up of two subsystems: the fire behavior prediction subsystem, BURN, and the fuel modeling subsystem, FUEL. This system, particularly the FUEL subsystem, provides opportunities to develop fuel models that can accommodate a wide variety of fire management activities. Rothermel's mathematical model is the core of the BEHAVE system. It also includes Albini's (1976a) modifications and the assumptions he made (1976b) in order to relate Rothermel's model to Byram's (1959) fireline intensity and flame length.

Computer generated predictions of fire behavior can be of little value if they do not match real fire behavior so real world data are necessary to verify the predictive capabilities of a fuel model. Fire behavior monitoring is a very important but not straightforward procedure. Error
enters into the observations of rate of spread and flame length because of subjectivity in differing perceptions of distance and height and lack of adequate portable measuring tools. The importance of these errors cannot be overlooked, since fire behavior observations are crucial for calibrating and refining a fuel model (Omi 1986). Rothermel and Rinehart (1983) offered a useful guide for collecting fire behavior information and Ryan (1981) suggested a feasible and simple technique for measuring flame height and flame-tilt angle for the purpose of calculating flame length.

If major discrepancies between observations and predictions exist the fuel model must be calibrated. Rothermel and Rinehart (1983) describe an approach based on developing correction factors to model outputs. Burgan and Rothermel (1984) offer brief guidelines on using the TSTMDL procedure of the FUEL subsystem in BEHAVE to modify fuel and environmental inputs until predicted fire behavior matches the observed one. Omi (1986) used their guidelines and developed a more detailed algorithm to be followed for the calibration of a fuel model.
PART 1

DETERMINATION OF VALUES

FOR THE PARAMETERS

OF THE FUEL MODEL
A. Accuracy statement

Rothermel's fire spread model and the subsequent fire behavior prediction systems were developed for uniform continuous fuels. This assumption means that the model calculates fire behavior as though the fuel components are mixed and distributed uniformly throughout the specified depth (Rothermel 1972, 1983 Burgan and Rothermel 1984). In nature this is usually not the case. These assumptions, and the use of heuristics (or rules of thumb) in the development of the BEHAVE system, (Andrews and Latham 1984), make the fire behavior predictions obtained from the system represent approximate mean values for an area. On the other hand, the environmental factors that affect the way a fire burns (wind, slope, moisture) are constantly variable so average values are also used for these factors. The result of these approximations is that the predictions obtained from the BEHAVE system although of great value to fire managers, have accuracy limitations. As stated by Burgan and Rothermel (1984) "the infinite variability produced by changes in fuel composition, quantity, depth, continuity, and so on, make it imperative that even site-specific fuel models must represent a rather broad range of conditions".

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From the discussion above it becomes obvious that very strict confidence levels in the estimation of the mean values of the parameters of the fuel model are not necessary. For this study surface-area-to-volume (S/V) ratios of the fuel particles, ash content and energy content were assumed as having a unique - constant - average value, although some variation should be expected both between sites and between years (Brown 1970a). This assumption has also been used in the 13 NFNL models for much more complex fuel situations (Albini 1976b).

A confidence level of 90% and a 10% deviation from the mean were considered acceptable in the calculation of the necessary sample sizes for the estimation of the various parameters. For comparison, the usual approach for the determination of the S/V ratio in BEHAVE system is to let the user choose a value for this ratio following general descriptive guidelines that the system offers (Burgan and Rothermel 1984).

In addition to the above mentioned assumptions, when working with BEHAVE, "some fuel factors essential to the fire model are held constant because they either have a small effect over their naturally occurring range or would be very difficult for the user to determine" (Burgan and Rothermel 1984). This means that the system does not
provide the user with the opportunity to change their assumed average values. These factors and their assumed values are shown in Table 2.

Table 2. Fuel factors held constant in BEHAVE system

<table>
<thead>
<tr>
<th>Fuel factor</th>
<th>Assumed value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle density (gm/cm³)</td>
<td>0.512</td>
</tr>
<tr>
<td>Total mineral content (fraction of dry weight)</td>
<td>0.0555</td>
</tr>
<tr>
<td>Effective mineral content (frac. of dry weight)</td>
<td>0.010</td>
</tr>
<tr>
<td>10-h S/V ratio (cm²/cm³)</td>
<td>3.576</td>
</tr>
<tr>
<td>100-h S/V ratio (cm²/cm³)</td>
<td>0.984</td>
</tr>
</tbody>
</table>

B. Sampling sites

Samples for the study were obtained from a number of sites in western Montana. The sites were subjectively chosen to represent as much of the range of knapweed heights and densities in the region as possible. Because of this, average values of fuel loading over the whole sample are of no importance. The sites from which samples were taken and their characteristics are as follows.

The Clearwater Junction site. A site along highway 83, 4 km from its junction with State Highway 200. It is in section 21 of T15N, R14W. It is a typical rough fescue (Festuca scabrella) grassland invaded by knapweed.

The Harper’s lake site. A site next to Harper’s Lake, in section 33 of T15N, R14W. It is a productive site with a good rough fescue cover.
The Frenchtown site. A site next to the road towards the paper mill near Missoula, 200 m from its junction with the airport road. It is located on the border between sections 21 and 28 of T14N, R20W. It is a disturbed field left uncultivated for a number of years. Spotted knapweed height and density is very high.

The South Hills site. A construction site on the hills south of Missoula in section 7, T12N, R19W. It is a typical disturbed site where knapweed is at its tallest.

The Blue Mountain site. A site at Blue Mountain Recreation Area near Missoula, at the NE quarter of section 3 of T12N, R20W. Samples were taken in large openings in the forest so that no forest litter (needles, twigs, etc) was included.

The Threemile Range site. A site at Threemile Range in the Bitterroot Valley east of Florence in section 17 of T38N, R18W. It is a forested site with large openings occupied by Kentucky bluegrass (*Poa pratensis*). No sites under forest canopy were chosen because forest litter in such sites would increase the variation in the sample significantly.

Preliminary fire behavior observations were conducted in prescribed burns (as described earlier) which were
conducted at the Clearwater Junction and Threemile Range sites and in a knapweed infested pasture in the Bitteroot Valley, two miles south of Lolo in section 10 of T11N, R20W. Two carefully monitored burns were also conducted at the Clearwater Junction site in April 1986 to measure fire behavior and compare it to the predicted one via BEHAVE. A third burn in spring 1986 was conducted in a field at the north fork of the Willow Creek in the Bitteroot Valley east of Corvallis.

C. Fuel loading

Knapweed fuel loading varies substantially between different areas thus affecting fire behavior greatly. Its variability does not allow the use of an average value for fuel loading. To predict fire behavior in a specific knapweed field we should be able to estimate the fuel loading with a reasonable accuracy without having to repeat the tedious and time consuming clipping - drying - weighing sampling process. A multiple regression model with fuel loading as the dependent variable and a number of easily measured field parameters as the independent variables has been used in the past to solve similar problems (Brown and Marsden 1976). The same approach was used in this project. A comparable sample size (90 observations) was used. After considering carefully the situations encountered in the
field it was decided that three different equations had to be developed: one for older standing knapweed that has been on the site through at least one winter; a second one for freshly produced knapweed measured at the end of the growing season; and a third one for the litter component of the knapweed fields. The independent variables used in the first two cases were the height of the knapweed stems and their percent canopy cover which was defined as the vertical projection of plant area (Brown and Marsden 1976). In the third case the independent variables were litter depth and litter cover. The occasional sparse grasses in the sampled areas were included in the litter and they were measured as such in terms of depth and cover. Older standing knapweed, (one or two years old), will be referred to as "old knapweed" hereafter and freshly produced knapweed will be called "new knapweed" for easier reference in the rest of this study.

The selection of cover and height (depth) as independent variables was made to describe the fuels both horizontally (cover) and vertically (height). The breakdown of the fuel loading was made to achieve the following objectives.

a. Describe the fuel bed more accurately. Associated values of fuel loading and fuel bed depth can be estimated simultaneously.
b. Account for the lack of freshly produced knapweed in the spring by not adding this to the total fuel loading.

c. Allow for the assignment of the corresponding S/V ratios to each fuel component. Then BEHAVE can produce a weighted S/V ratio to be used in the fire behavior prediction calculations.

d. Achieve better accuracy in the total fuel loading prediction.

As stated earlier samples were collected from nine spotted knapweed infested areas in western Montana subjectively chosen as representative of the range of naturally occurring fuel loading. Personal observation showed that when the short fine grasses usually associated with knapweed exceed 40-50% cover, fire carries mainly through grass fuel and fire behavior approximates predictions by the short grass fuel model. Therefore areas where ocular estimation showed that grass cover exceeded 50% were not selected for sampling.

Sampling was initiated after the new knapweed plants had completed their growth and had produced flowers - July 19, 1985 - and was complete by the end of September, 1985. In each of the chosen sites ten 40 x 50 cm plots at 5 m intervals on a randomly chosen transect, were established. This plot size was chosen because it is large enough to
include most plants in their entirety and small enough to permit clipping and weighing with reasonable effort. Sampling within each plot included the following observations or measurements.

a. Ocular estimation of height (cm) and ground cover (%), of the present year’s knapweed plants. Ground cover was estimated to the nearest 5 percent (Brown and Marsden 1976).

b. Ocular estimation of height (cm) and ground cover (%) of older standing knapweed plants.

c. Height (cm) and ground cover (%) measurement of the present year’s knapweed plants. Eight plants closer to the corners of the plot frame were measured for height (two at each corner). Cover percent was estimated with the line intercept method on two 40 cm transects inside the plot connecting fixed points between the long (50 cm) sides of the plot at 1/3 and 2/3 of their length.

d. Height (cm) and ground cover (%) measurement of older standing knapweed plants. Measurements were done as in c.

e. Litter cover percentage including grasses. It was estimated on the same two transects inside the plot as knapweed’s ground cover.

f. Litter depth (cm) including grasses. It was measured
at four fixed points inside the plot.

g. Clipping and collection of standing knapweed plants (older and new ones separately). Fine grasses and all litter above the fermentation layer were collected together. They were ovendried for 48 hours at 105° C and weighed.

Ocular estimations were recorded before the actual measurements to avoid bias. They were taken in order to examine the possibility of obtaining equally good predictions of fuel loading with less effort. Dry basal leaves of knapweed plants were included in the litter because they cannot be separated easily.

Scatterplots created in winter 1986, during the analysis of the collected data, indicated that very few plots in the sample included tall and dense standing knapweed - either old or new. The samples from these few plots dictated the direction and form of the resulting regression equations for old and new standing knapweed. This fact would allow little confidence in loading predictions from knapweed height and cover values that were not adequately represented in the data set. Therefore it was considered necessary to obtain additional tall knapweed samples to improve confidence on the predictive capability of the equations. Fifteen plots for tall old knapweed
plants were collected in April 1986 at the South Hills site near Missoula. The plots were subjectively chosen to include tall knapweed plants since the objective was to establish a relationship between height, cover and loading rather than obtaining measurements representing the specific site. Similarly fifteen additional plots of new knapweed were clipped in July 1986 at the same site to improve the corresponding equation.

D. Fuel bed depth

Fuel bed depth directly affects the bulk density of a fuel which in turn is one of the main factors influencing the rate of spread of a fire front (Rothermel 1972). It can be measured directly in the field either as the average height of the fuels or as 70% of the maximum height of vegetation (Burgan and Rothermel 1984).

Since fuel bed depth will have to be measured for the calculation of the fuel loading there was no effort to assign a unique average value to it. Such an approach would increase the bulk density erroneously as the fuel loading would increase without a corresponding increase in fuel bed depth.

Once measured - or ocularly estimated - in the field, fuel bed depth can be used both as a direct input to the
BEHAVE system and as an independent variable for the estimation of fuel loading. Since there will be three different values of fuel bed depth available, the average heights of old and new knapweed and the depth of litter, these values will be weighted with their corresponding loadings and produce one value to be used with a corresponding value of total fuel loading (Burgan and Rothermel 1984). Procedure NEWMDL in the BEHAVE system performs this task for the user.

E. Surface-area-to-volume ratio

Random knapweed plant samples were used for the estimation of the surface-area-to-volume ratio (S/V ratio) of the different parts of the plants. These are: central stems, side stems, seed pods, leaves and basal leaves. Twenty samples for each part were initially measured and the variance was calculated. The formula \( n = \frac{t^2 \cdot v}{e^2} \) where \( n \) is the sample size, \( t \) is Student's t statistic, \( v \) is variance and \( e \) is the acceptable error, was used for the estimation of the required sample size for each part. A value \( a = 0.1 \) was used for the selection of \( t \). The value for \( e \) was determined as 10% of the estimate of the mean based on the 20 samples. Additional samples were measured where necessary. The measurements were to the nearest 0.1 mm using inside calipers. Ratios of S/V for old and new
knapweed plant parts were assumed the same and mixed samples from both categories were used in the measurements.

The S/V ratio for the central and side stems was determined using the formula \( S/V = 4/d \) where \( d \) is the average diameter of the particle (Brown 1970a). The average diameter for the central stems was calculated from ten measurements at equal tenths of their length. For the side stems five diameter measurements were used. Additionally the lengths of the stems were recorded and were used for the calculation of the volume of each stem to be used for the calculation of particle densities.

\( S/V \) ratio for the leaves was determined using the formula \( S/V = 2/t \) where \( t \) is the average thickness of the leaf (Burgan and Rothermel 1984). Thickness was measured in one cm lengths along the long axis and the values were averaged. The surface area of each leaf was measured by tracing the perimeter of the leaf on paper and then tracing that with a LASICO Model N-20M planimeter. This measurement was used for the calculation of the volume of each leaf which is necessary for the calculation of its density. Only green knapweed leaves were used for these measurements as dry ones are extremely fragile and warped and do not allow accurate measurements. \( S/V \) ratio was assumed to be the same for fresh and dry leaves although
some change in particle size in shrinking from a green condition to a cured one should be expected (Brown 1970a). In the BEHAVE system the user is advised to use a value 6.6 cm$^2$/cm$^3$ lower for live plants than the one used if the same plants were cured. This would be the magnitude of the expected error resulting from the assumption used in these measurements.

The seed pods were measured as right circular cones. The surface area and volume for each pod were calculated from the measurements of height and diameter of the pod using the corresponding formulas for right circular cones.

Another measurement needed for the calculation of the weighted surface area to volume ratio of the standing knapweed plants is the percent contribution of the plant parts to their total biomass. This was measured separately for old and new knapweed plants. Three samples for each category, composed of 30 randomly chosen plants each, were collected, separated into central stems, side stems, seed pods, and leaves, oven-dried for 48 hours at 105° C and weighed. Then the percentage of these plant parts in the total plant biomass was calculated.

F. Fuel Particle densities

All the plant parts used for S/V ratio measurements
were also ovendried and weighed and this weight was divided by their volume to calculate their ovendry density. This is necessary for the estimation of the overall surface-area-to-volume ratio for knapweed with the method described by Burgan and Rothermel (1984). The particle densities are also used in the mathematical fire spread model for the estimation of packing ratio but in BEHAVE system an average value (0.51 gm/cm³) has been assumed for this variable.

G. Ash and energy content

Ash content of knapweed biomass as well as its energy content have been measured by Dr. Richard Kelsey at the Chemistry Department of the University of Montana for his study on the nutritional content of spotted knapweed in Western Montana. He found that in general they do not vary significantly between areas (Kelsey, R. personal communication). He measured an ash content of 0.065 which is close to the value used in BEHAVE for the total mineral content. He also found that the average energy content of knapweed was 4343 cal/gm or 18182 kj/kg which is very close to the average value of 18604 kj/kg that has been used for all the 13 stylized NFFL fuel models. No additional measurements were made on these factors and it was decided that these values and the average value of 0.01 that BEHAVE
uses for the effective mineral content were adequate for the knapweed fuel model.

H. Dead fuel moisture of extinction

Dead fuel moisture of extinction, which is defined as "the fuel moisture at which the fire ceases to spread", is an important but difficult to measure parameter since it varies with fuel loading, fuel bed depth and probably some other fuel properties (Wilson 1985). Determining it in field trials is difficult. The usual approach is to have this parameter calculated by the BEHAVE system when values for all the other parameters have been entered to it (Burgan and Rothermel 1984). The formula used for this calculation derives dead fuel moisture of extinction from the packing ratio which in turn is a function of the fuel loading and the fuel bed depth. Since these two parameters were not held constant for the knapweed fuel model the dead fuel moisture of extinction will be variable depending on their values.
ANALYSIS AND RESULTS

A. Fuel loading prediction

1. Old knapweed loading prediction

The measured height and ground cover for older knapweed plants, their product, their squares and the product of the square of each with the other were evaluated as possible independent variables for the prediction of old knapweed fuel loading. In addition to those, natural log (ln) transformations of the variables and ocular estimations of height and cover were also tried as independent variables. Stepwise regression analysis was initially used to examine possible forms of the predictive equation. The resulting equations were examined for the percentage of variation explained, as this is denoted by their coefficient of determination ($r^2$) or squared multiple correlation coefficient ($R^2$) value, and for their calculated coefficient of variation about regression (CV) which is the ratio (standard deviation of the residuals)/(mean fuel loading). Standard deviation of the residuals is also called standard error of the estimate. Care was taken if some individual measurements influenced disproportionally the coefficients of the equation. This was done by examining scatter diagrams of the points, Cook’s distance values of the individual points (Norusis
and the standardized residuals calculated after each point was omitted (called standardized deleted residuals). As mentioned earlier additional samples of tall plants had to be obtained to improve reliability at the high end of the equations when it became obvious that the few points there affected the values of the coefficients of the equations significantly. Simplicity of the resulting equation was also a consideration.

Equations based on ocular estimations were discarded because they had lower $R^2$ values. Ln transformations did not offer improvement to the $R^2$ values and they were also discarded. The equation chosen included only the product of height and cover (height-cover interaction term) as independent variable thus having the form of a linear equation. This equation was preferred to more complex ones produced by stepwise procedure which had slightly higher $R^2$ values (less than 0.01 difference) and lower CV but included squared terms and were not linear. It satisfies the simplicity criterion and also verifies the initial assumption that loading is a function of knapweed height and cover. A total of 117 measurements was used for the evaluation procedure. The equation developed was:
$$Y_1 = 44.2 + (1.044 \times X_1 \times Z_1)$$

where $Y_1$ is old knapweed loading (in kg/ha)

$X_1$ is old knapweed height (in cm)

$Z_1$ is old knapweed cover (in %).

with adjusted coefficient of determination $r^2 = 0.889$

standard deviation of the residuals = 659.1

mean observed old knapweed loading = 1128.4

coefficient of variation = $659.1/1128.4 = 0.58$

prob-value < 0.0001

The null hypothesis for this and all the subsequent regression equations was $H_0: b = 0$, tested against the one-sided alternative hypothesis $b > 0$. Since the prob-value was so low, $H_0$ was rejected at 0.01% level of significance in favor of the alternative hypothesis. This can also be interpreted that using the regression equation is preferable to using the mean for the prediction of fuel loading.

A scatterplot of the actual loading data with the corresponding height-cover interaction values is shown (Figure 1). The straight line fitted to these data is also shown in the graph. The graph shows that the straight line fits the data well (no obvious violation of the assumption of linearity).
Figure 1. Old knapweed loading prediction equation fit on the complete (n = 117) data set.
Figure 2. Plot of the standardized residuals versus the values of the independent variable.

Figure 3. Percent error of each prediction plotted versus actual old knapweed loading.
A second graph shows the standardized residuals, 
\[
\frac{\text{observed-predicted loading values}}{\text{standard deviation of the residuals}}^3,
\] plotted against height-cover interaction values (Figure 2). The pattern observed in this graph indicates that the assumption of homogeneity of variance is not completely met by these data. It indicates that the error variance of the dependent variable \(Y_1\) increases with the independent variable. The observed pattern shows no departure from linearity and there is no pattern reflecting a need for curvilinear terms in the regression model (Kleinbaum and Kupper 1978). These observations support the choice of the linear equation but also suggest that predictions for high values of the independent variable may have less reliability than the rest.

A third graph was formed by calculating the ratio 
\[
\frac{\text{actual residual} \times 100}{\text{observed loading}}
\] for each point and plotting it against the observed loading (Figure 3). This graph allows the observation of the percent error that individual predicted values of loading may have when compared to the observed loading values. This error is more meaningful for fire behavior prediction purposes than the actual values of the residuals. Some of the percent values in this graph are quite large implying that the equation can potentially predict values that are far from actual loading values. This is generally true for very
small values of loading only and is the result of the small value of the denominator of this ratio and of the small size of the sampling plot (0.2 m²). The latter makes the effects of natural variation and of any inaccuracy in the measurements of the dependent or independent variables very pronounced. The two sources of error when predicting an individual observation for a value X₀ of the independent variable are (Norusis 1985):

a. the individual value may differ from the population mean of Y for X₀, and
b. the estimate of the population mean at X₀ may differ from the population mean.

When estimating the mean response, only the second error component is considered. The variation observed in Figure 3 is a result of the first error component and is exaggerated by the small size of the sampling frame. The prediction equation is intended for use over large areas. Values of the independent variable should be the average of a large number of measurements so that potential errors would be minimized.

The equation is valid for spotted knapweed infested grasslands in western Montana with an infestation heavy enough to reduce the grass cover to less than 40%. Its limits of applicability are also determined by the range of height and cover measurements that were included in the
samples. One should not try to apply the equation to heights less than 20 cm and cover values less than 5%, as the nonzero constant value in the equation would significantly bias the outcome. Height values over 90 cm were not included in the sample so one should avoid extrapolating the equation beyond this value.

2. New knapweed loading prediction

The equation for the prediction of new knapweed fuel loading was developed in the same way as the equation for old standing knapweed. The same variables and their combinations were used - as measured for new knapweed standing plants - and the same criteria for the selection of the best predictive equation. Additional samples for tall plants had to be taken for new knapweed to improve reliability at the high end of the equation.

The equation chosen has the same form as the one for old knapweed having only the product of height and cover (height-cover interaction term) as independent variable. It was preferred to a more complex equation that resulted from stepwise procedure which had slightly higher $R^2$ values and lower CVs but included squared terms and was not linear. A total of 118 measurements was used for the evaluation procedure. The equation developed was:
\[ Y_2 = -71.0 + (1.472 \times X_2 \times Z_2) \]

where \( Y_2 \) is new knapweed loading in \( \text{kg/ha} \)

\( X_2 \) is new knapweed height (in cm)

\( Z_2 \) is new knapweed cover (in %).

with adjusted coefficient of determination \( r^2 = 0.88 \)

standard deviation of the residuals = 1169.5

mean observed old knapweed loading = 1953.4

coefficient of variation = 1169.5/1953.4 = 0.60

prob-value < 0.0001.

New knapweed loading data are plotted with corresponding height-cover interaction values (Figure 4). The straight line representing the equation fitted to them is included in the graph. The standardized residuals after fitting the line are also plotted against the height-cover interaction values (Figure 5). The homogeneity of variance assumption does not appear clearly violated from this graph. A third graph allows the observation of the percent error that individual predicted values of new knapweed loading may have when compared to the observed ones (Figure 6). The observations made on the corresponding graph for old knapweed apply for this graph also.

As before, the equation is valid for spotted knapweed infested grasslands in Western Montana with an infestation heavy enough to reduce the grass cover to less than 40%.
Figure 4. New knapweed loading prediction equation fit on the complete (n = 118) data set.
Figure 5. Plot of the standardized residuals versus the values of the independent variable.

Figure 6. Percent error of each prediction plotted versus actual new knapweed loading.
Its limits of applicability are also determined by the range of height and cover measurements that were included in the samples. One should not try to apply the equation to heights less than 20 cm and cover values less than 5%, as the nonzero constant value in the equation would significantly bias the outcome. Height values over 100 cm were not included in the sample so one should be careful when extrapolating the equation beyond this value.

3. Litter/grass loading prediction

Stepwise regression analysis was also used for the development of the litter/grass loading prediction equation. The independent variables evaluated were litter depth (in cm), litter cover (percent), their product, their squares, and the products of the square of each with the other. Ln transformations of height and cover were also tried. The criteria used for the selection of the variables to be included in the equation were the same as in the other two cases.

A total of 102 measurements were used for the evaluation procedure. They included the initial 90 measurements, 3 additional ones collected in October 1985 at the Blue Mountain site and 9 measurements collected in April 1986 for the measurement of fuel loading before the
first test burn (Part 2). The independent variables chosen were litter depth and litter cover. The equation formed with these variables was preferred to a more complex one with almost the same \( R^2 \) value but much more complex form. Using the product of depth and cover instead of each of them separately, produced a linear equation with the same \( R^2 \) and coefficient of variation, but with a much higher y-intercept value which made it a lot less sensitive in predicting lower fuel loadings. The equation developed was:

\[
Y_3 = 791.5 + (695.85 \times X_3) + (15.784 \times Z_3)
\]

Where \( Y_3 \) is litter loading (in Kg/ha)

\( X_3 \) is litter depth (in cm)

\( Z_3 \) is litter cover (in percent)

with adjusted multiple correlation coefficient \( R^2 = 0.74 \)

standard deviation of the residuals = 795.5

mean observed litter loading = 2915.7

coefficient of variation = 795.5/2915.7 = 0.27

prob-value for coefficient for \( X_3 < 0.0001 \)

prob-value for coefficient for \( Z_3 < 0.0001 \)

The standardized residuals from this equation are plotted versus each independent variable (Figures 7 and 8). The basic assumptions for regression do not appear to be violated from these plots. A graph of the percent error of
Figure 7. Plot of the standardized residuals versus litter depth.

Figure 8. Plot of the standardized residuals versus litter cover.
Figure 9. Percent error of each prediction plotted versus actually observed litter loading is also included (Figure 9).

Predictions from this equation in the range 800-1000 kg/ha should be of questionable reliability. The high constant value in the equation makes it inappropriate for the prediction of litter/grass loading in fields where this loading is very low.
B. Surface-area-to-volume ratio and fuel particle density

The mean surface area to volume ratio of each plant particle was calculated (Table 3). The sample sizes used for the estimation of these mean values are also included. Additional measurements to the twenty made initially for each plant part were found to be necessary for the leaves and for the central stems only.

Table 3. Surface area to volume ratio (S/V) and density for spotted knapweed plant particles

<table>
<thead>
<tr>
<th>Plant particle</th>
<th>mean S/V cm²/cm³</th>
<th>mean density gm/cm³</th>
<th>sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed pods</td>
<td>10.80</td>
<td>0.1987</td>
<td>20</td>
</tr>
<tr>
<td>Side stems</td>
<td>39.25</td>
<td>0.7196</td>
<td>20</td>
</tr>
<tr>
<td>Central stems</td>
<td>15.73</td>
<td>0.5936</td>
<td>21</td>
</tr>
<tr>
<td>Leaves</td>
<td>80.58</td>
<td>0.5454</td>
<td>30</td>
</tr>
</tbody>
</table>

S/V ratio for the basal leaves of knapweed was found to be 79.11 cm²/cm³. This value is very close to the average value of 82.02 cm²/cm³ that was used for the litter and since dry basal leaves were included in the litter during sampling it was decided to exclude them from the calculation of the weighted S/V ratio of standing knapweed plants.

The mean volume of each plant part and its mean weight were used for the calculation of the density of the part. Although an assumed average value of 0.51 gm/cm³ is used in BEHAVE, plant part densities are necessary for the
calculation of the weighted surface area to volume ratio for the whole plant. An overall density for the whole plant was also calculated as shown in tables 5 and 6, to be compared to the value assumed by BEHAVE.

Table 4. Old and new knapweed plant particle percentages in their total biomass.

<table>
<thead>
<tr>
<th>Plant particle</th>
<th>Old knapweed (%)</th>
<th>New knapweed (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed pods</td>
<td>15.75</td>
<td>17.30</td>
</tr>
<tr>
<td>Side stems</td>
<td>6.35</td>
<td>8.80</td>
</tr>
<tr>
<td>Central stems</td>
<td>65.42</td>
<td>50.10</td>
</tr>
<tr>
<td>Leaves</td>
<td>12.48</td>
<td>23.80</td>
</tr>
<tr>
<td></td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

A separate weighted surface-area-to-volume ratio for the whole plant was calculated for old knapweed plants and for new ones because the percent contributions of each plant part to the total loading differed between the two categories. Another reason is that using the two separate equations developed, one can estimate a separate fuel loading for each category. Then the corresponding S/V ratio for each loading can be assigned and a weighted S/V ratio for the whole loading can be calculated manually or via BEHAVE.

The weighting procedure was based on the fuel surface each plant part contributes in a fixed amount of fuel - usually the one included in a square foot of fuel bed.
The total plant biomass was assumed to be 100 mass units so the percent value that each plant part contributes in the total plant loading was used as loading of the corresponding part in the calculations. The volume each part contributes to the total volume was calculated from the formula: Volume = loading/density. The surface of each part was calculated using its S/V ratio as follows: Surface = (S/V) X Volume. The sum of these surface values is the total fuel surface in this assumed biomass. Each surface area estimate was multiplied by the S/V ratio for the corresponding plant part, the products were summed up and divided by the total fuel surface yielding the weighted S/V ratio for the whole plant (Tables 5 and 6).

Table 5. Calculation of S/V ratio and density for old knapweed.

<table>
<thead>
<tr>
<th>Plant Particle</th>
<th>Density gm/cm³</th>
<th>Loading gm</th>
<th>Volume cm³</th>
<th>S/V cm²/cm³</th>
<th>Vol*(S/V) cm²</th>
<th>Vol*(S/V)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed pods</td>
<td>0.1987</td>
<td>15.75</td>
<td>79.265</td>
<td>10.80</td>
<td>856</td>
<td>9246</td>
</tr>
<tr>
<td>Side stems</td>
<td>0.7196</td>
<td>6.35</td>
<td>8.824</td>
<td>39.25</td>
<td>346</td>
<td>13594</td>
</tr>
<tr>
<td>Central stems</td>
<td>0.5936</td>
<td>65.42</td>
<td>110.209</td>
<td>15.73</td>
<td>1736</td>
<td>27269</td>
</tr>
<tr>
<td>Leaves</td>
<td>0.5454</td>
<td>12.48</td>
<td>22.882</td>
<td>80.58</td>
<td>1844</td>
<td>148578</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.00</strong></td>
<td><strong>221.180</strong></td>
<td><strong>4779</strong></td>
<td></td>
<td><strong>198687</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Weighted S/V ratio = 198687/4779 = 41.57 cm²/cm³**

**Average density = 100/221.18 = 0.45 gm/cm³**

44
Table 6. Calculation of S/V ratio and density for new knapweed.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Density Loading</th>
<th>Volume</th>
<th>S/V</th>
<th>Vol*S/V</th>
<th>Vol*(S/V)^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle</td>
<td>gm/cm³</td>
<td>gm</td>
<td>cm³</td>
<td>cm²/cm³</td>
<td></td>
</tr>
<tr>
<td>Seed pods</td>
<td>0.1987</td>
<td>17.30</td>
<td>87.066</td>
<td>10.80</td>
<td>940</td>
</tr>
<tr>
<td>Side stems</td>
<td>0.7196</td>
<td>8.80</td>
<td>12.229</td>
<td>39.25</td>
<td>480</td>
</tr>
<tr>
<td>Central stems</td>
<td>0.5936</td>
<td>50.10</td>
<td>84.400</td>
<td>15.73</td>
<td>1328</td>
</tr>
<tr>
<td>Leaves</td>
<td>0.5454</td>
<td>23.80</td>
<td>43.638</td>
<td>80.58</td>
<td>3516</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>227.330</td>
<td>6264</td>
<td>333223</td>
<td></td>
</tr>
</tbody>
</table>

Weighted S/V ratio = 333223/6264 = 53.19 cm²/cm³

Average density = 100/227.33 = 0.44 gm/cm³

It should be noted that the numbers in Tables 3-6 have more significant digits than needed. Three or four significant digits is all that is realistic for the accuracy used in the measurements. It was decided to include the numbers in the Tables as they were used in the computations for easier verification of the results.

C. Final fuel model parameters for spotted knapweed dominated grasslands in western Montana

The final fuel model for knapweed has some parameters with fixed values and some variable ones that will have to be estimated on site for site specific fire behavior predictions. The three loading prediction equations provide the ability to calculate fuel loadings with an acceptable accuracy based on measurements of stem height and cover and litter depth and cover. Fuel bed depth is
also determined from these measurements.

For easier reference the complete fuel model parameters for spotted knapweed are given in summary below.

FUEL LOADING: Estimated in the field as follows:

Fuel loading = old standing knapweed loading (Y1) + new standing knapweed loading (Y2) + litter and grass loading (Y3)

\[ Y1 = 44.2 + (1.044 \times X1 \times Z1) \]

\[ Y1 = \text{old knapweed fuel loading (kg/ha)} \]

\[ X1 = \text{old knapweed height (cm)} \]

\[ Z1 = \text{old knapweed cover (\%)} \]

\[ Y2 = -71.0 + (1.472 \times X2 \times Z2) \]

\[ Y2 = \text{new knapweed fuel loading (kg/ha)} \]

\[ X2 = \text{new knapweed height (cm)} \]

\[ Z2 = \text{new knapweed cover (\%)} \]

\[ Y3 = 791.5 + (695.85 \times X3) + (15.784 \times Z3) \]

\[ Y3 = \text{litter/grass fuel loading (kg/ha)} \]

\[ X3 = \text{litter and grasses depth (cm)} \]

\[ Z3 = \text{litter and grasses cover (\%)} \]

FUEL BED DEPTH: Measured in the field for each fuel loading component separately (in cm).

SURFACE AREA TO VOLUME RATIO: Fixed values for each fuel loading component as follows:

Old knapweed S/V ratio: 41.6 cm²/cm³

New knapweed S/V ratio: 53.2 cm²/cm³
Litter and grass S/V ratio: 82.0 cm²/cm³ — (Assumed value. Can be changed if better information on this value is available in a specific situation).

FUEL PARTICLE DENSITY: Assumed to be 0.51 gm/cm³ and held constant in BEHAVE.

It was calculated as:

Old knapweed density: 0.45 gm/cm³
New Knapweed density: 0.44 gm/cm³

FUEL PARTICLE TOTAL MINERAL CONTENT: Assumed to be 5.55% and held constant in BEHAVE.

It was measured as 6.49%.

FUEL PARTICLE EFFECTIVE MINERAL CONTENT: Assumed to be 1% and held constant in BEHAVE.

No effort to measure it in this study.

MEAN FUEL ENERGY CONTENT: Assumed to be 18604 Kj/Kg for the 13 stylized NFFL fuel models.

It was measured as 18182 Kj/kg for knapweed.

DEAD FUEL MOISTURE CONTENT: It is affected by fuel loading and fuel bed depth which are both variable.

No effort to define a value for it in this study.

Should be calculated with BEHAVE when the other fuel parameters have been assigned values.
PART 2

FIRE BEHAVIOR MODELING
METHODS

A. Fire behavior measurements

Once the fuel model was complete a series of test burns were planned in April 1986 to obtain fire behavior measurements under carefully monitored conditions. These measurements were then used to examine the agreement between observed fire behavior and predicted one via BEHAVE using the fuel model developed.

Three test burns on three different days were conducted on April 4, 8 and 10, 1986. Burns 1 and 2 were contacted at the Clearwater Junction site, and burn 3 was done at a site near Corvallis, MT. Unusually early growth start for the cool season grasses and forbs, because of earlier snow melt in March, caused unexpected problems. The burns were conducted as early as possible to avoid further grass growth on days with unfavorable weather for the lighting of an intense fire. This fact, and the high moisture content of the live grasses, resulted in marginal burns which created monitoring difficulties but also allowed some useful observations that offer some insight on the peculiar fire behavior usually observed in knapweed fields.

The burns were conducted on 50 X 50 m plots with low
to medium spotted knapweed loadings with grass cover less than 40%. The fires were ignited with two handheld flame torches along the upwind side of the plots and were allowed to burn as headfires. Flame height measurements were taken on fire retardant treated cotton strings (Ryan 1981), hanging at five meter intervals from two metal strings that were positioned 10 m apart, 3 m above the ground. Visual estimation of flame-tilt angle was recorded by two teams of observers at the time fire reached each string and flame length was calculated after the burn from these data. The observers also recorded the time that fire reached each string, and the windspeed at that time measured with a Dwyer anemometer.

Wooden stakes at 10 m interval, marked with fluorescent flagging, were used for the estimation of rate of spread. An independent observer recorded the time that the fire front reached each of these sticks. Windspeed was continuously recorded in two minute intervals on a Davis anemometer which measures feet in a given length of time. The anemometer was positioned 50 m upwind from the fire. Rate of spread was calculated by dividing known distances between two sticks or strings by the time the fire needed to move from one to the other. The selection of these intervals was done so that the calculated rates of spread correspond to fairly stable simultaneous windspeeds. In
the first and third burns the plots were not burned completely. In the third burn fire tended to go out where there were even small interruptions in the fuel continuity. It had to be re-ignited and only two reliable spread measurements were possible in that burn.

Table 7. Fire behavior observations for three test burns.

<table>
<thead>
<tr>
<th>BURN # 1</th>
<th>BURN # 2</th>
<th>BURN # 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROS</td>
<td>wind</td>
<td>FL</td>
</tr>
<tr>
<td>0.64</td>
<td>8.0</td>
<td>0.12</td>
</tr>
<tr>
<td>0.63</td>
<td>8.0</td>
<td>0.67</td>
</tr>
<tr>
<td>1.54</td>
<td>8.0</td>
<td>0.12</td>
</tr>
<tr>
<td>0.56</td>
<td>8.0</td>
<td>0.18</td>
</tr>
<tr>
<td>0.79</td>
<td>8.0</td>
<td>0.12</td>
</tr>
<tr>
<td>0.71</td>
<td>8.0</td>
<td>0.23</td>
</tr>
<tr>
<td>1.26</td>
<td>8.0</td>
<td>0.42</td>
</tr>
<tr>
<td>2.72</td>
<td>9.0</td>
<td>12.21</td>
</tr>
<tr>
<td>1.32</td>
<td>9.5</td>
<td>13.20</td>
</tr>
<tr>
<td>4.00</td>
<td>12.0</td>
<td>14.34</td>
</tr>
<tr>
<td>4.48</td>
<td>13.0</td>
<td>14.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.57</td>
</tr>
</tbody>
</table>

Rate of spread (ROS) in m/min,
Flame length (FL) in meters and
Wind measurements in km/hour.

The environmental parameters, dry and wet bulb temperatures, cloud cover, wind speed and direction changes, were recorded before and during the burns. Immediately before burning, both dead fuel and live grass samples were obtained for the verification of the predictions of fuel moisture obtained from the National Wildfire Coordinating Group S-390 fire behavior Tables 3A and 3C. The samples were weighed, oven dried at 105° C and re-weighed. Dead fuel moisture contents were found to be
within 0.5% of the values predicted from the tables (reference moisture content corrected for aspect and time).

Fire behavior measurements from these burns are given in table 8. They include observed rate of spread (ROS) and flame length (FL) and the corresponding midflame windspeeds for each observation.

Prior to burning the first plot, 9 sample plots (40 X 50 cm) were randomly located in it and were sampled for fuel loading. Green forbs and grasses were separated from litter to permit the estimation of the percent of live fuel in the litter present on the site at the time of the burn. It was found that live plants contributed 18% of the total litter - grass loading in this burn. These measurements were among the data used in the calculation of the old knapweed and litter prediction equations as described in Part one of the study.

A 30 m transect was also located in the plot. Measurements to be used with the prediction loading equations were taken on one meter spacings on the transect. The closest standing old knapweed plant to every meter mark and the litter depth under the mark were measured. Knapweed and litter cover measurements were recorded for the first 40 cm after each mark. A total of 30 measurements were done for each variable which then
produced an average value that was used with the corresponding loading prediction equations. Table 9 compares loading values predicted from these equations to actually measured loading, as the mean of nine sample plots, in the same burn plot.

Table 8. Comparison of predicted vs measured loadings for test burn No 1.

<table>
<thead>
<tr>
<th>Predicted</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old knapweed loading (kg/ha)</td>
<td>672</td>
</tr>
<tr>
<td>Litter/grass loading (kg/ha)</td>
<td>3494</td>
</tr>
</tbody>
</table>

Fuel loading for the other two burn plots was estimated using the prediction equations for old knapweed and litter loading. Data were collected with the same method (30 m transect) before the burns, resulting in 30 measurements for each variable.
ANALYSIS

The actual fuel loading measurements from the first plot were used for the development of a fuel model representative of that plot with the help of the NEWMDL procedure of the BEHAVE system. For reference purposes it was given the number 31. This model and all the subsequent models were developed using the branch of NEWMDL that allows for "2 sizes of fine fuels in one or more components". All dead fuel loading was included in the 1-hr timelag fuel class although a small percentage of knapweed central stems may exceed 0.6 cm in diameter near their base. It would be difficult to assign part of the standing knapweed loading to 10-hr timelag fuel class and this part would be extremely small. Fire behavior predictions obtained from BEHAVE for various environmental conditions were used as guidelines for the execution of the burn. Fuel loadings for the fuel models for second and third burns were based on calculations using the old knapweed and litter loading prediction equations. Of the predicted litter - grass loading, twenty percent was assumed to be live grasses using approximately the same percentage as measured in the first burn plot. Grass depth for NEWMDL procedure was calculated from the average knapweed height of thirty knapweed plants measured along the 30 m transect and 3 cm depth ocularly estimated as a
mean value for green grasses. They were weighted with their corresponding fuel loadings. The value used as litter depth for NEWMDL was the average of thirty litter depth measurements along the 30 m transect. The models were given the numbers 32 for the second test burn and 33 for the third test burn.

Table 9. Environmental conditions during the three test burns.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Burn #1</th>
<th>Burn #2</th>
<th>Burn #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (°C)</td>
<td>12</td>
<td>21</td>
<td>15</td>
</tr>
<tr>
<td>Cloud cover</td>
<td>Cloudy</td>
<td>Sunny</td>
<td>Cloudy</td>
</tr>
<tr>
<td>1-hr dead fuel moisture (%)</td>
<td>11.6</td>
<td>9</td>
<td>10.6</td>
</tr>
<tr>
<td>Live fuel moisture (%)</td>
<td>300</td>
<td>311</td>
<td>353</td>
</tr>
<tr>
<td>Midflame windspeed (km/hour)</td>
<td>5-13</td>
<td>5-20</td>
<td>4-12</td>
</tr>
<tr>
<td>Slope (%)</td>
<td>0</td>
<td>0</td>
<td>7</td>
</tr>
</tbody>
</table>

Environmental conditions during the three test burns are shown in Table 9. Using BEHAVE separate graphs for flame length and rate of spread were produced for each burn. BEHAVE produces results only in the English system of units. The graphs shown (Figures 10 - 15) are the metric versions of BEHAVE’s graphs. A computer program was written in Microsoft GWBASIC Version 3.11, for this purpose that generated the values for the graphs and then the graphs were created using Lotus Development Corporation’s LOTUS 123 system. These graphs were compared to the ones created with BEHAVE for correctness. The computer program used is listed in Appendix II. The independent variable
was windspeed since it was the factor varying most during the burns. The graphs were made for actual dead fuel moisture content and slope. Live fuel moisture used was 300% which is the maximum value accepted in BEHAVE’s BURN subsystem. It was apparent that in most cases BEHAVE over-predicted fire behavior in each one of the burns. On the other hand some flame length and rate of spread measurements in each burn reached or even exceeded the predicted ones. This was generally true at higher windspeeds.

Burgan and Rothermel (1984) in the documentation of BEHAVE provide guidelines on adjustment of fuel models to get fire behavior predictions from BEHAVE that match observed fire behavior. Since fuel loading, fuel bed depth, S/V ratio and heat content had been estimated with an acceptable confidence in the first part of this study the only remaining parameter for adjustment was dead fuel moisture of extinction.

The burns were conducted at fuel moisture contents that appeared very close to the dead fuel moisture of extinction. Fire spread sporadically and without a continuous front. Hence, the values tried for this variable ranged between the actual fuel moisture at the time of the burn and the dead fuel moisture of extinction.
value predicted by BEHAVE. In this way most fire behavior predictions were matched to the observed ones but the more intense fire behavior observed at high windspeeds was by far underestimated. Thus changing fuel moisture of extinction was abandoned as a method of adjusting the model.

To solve the problem a new approach based on personal observations during the burns was tried. It was observed that under lower windspeeds fire was not intense enough (5 - 20 cm flame length) to ignite standing knapweed stems because their packing ratio is far from optimum. As the windspeed increased and flame lengths exceeded 30 cm flames engulfed standing stems which in turn were ignited, produced even higher flame lengths and facilitated the spread of the fire. In order to model these behavior changes a second model was created for each test burn (named 21, 22, 23 and corresponding to models 31, 32, 33 respectively), that did not include old standing knapweed stems (Table 10).

Removing old standing knapweed not only affected fuel loading but fuel bed depth as well. As a result, the ratio (packing ratio / optimum packing ratio) which in the initial models had a value close to two, changed to values close to five. This fuel bed, being more compacted showed
a much lower fire potential, in spite of its very high calculated dead fuel moisture content of extinction.

Table 10. Description of site specific fuel models for test burns # 1, 2 and 3.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>MODEL 21</th>
<th>MODEL 31</th>
<th>MODEL 22</th>
<th>MODEL 32</th>
<th>MODEL 23</th>
<th>MODEL 33</th>
</tr>
</thead>
<tbody>
<tr>
<td>1HR DEAD FUEL LOAD (kg/ha)</td>
<td>2500</td>
<td>3020</td>
<td>3061</td>
<td>4090</td>
<td>3512</td>
<td>4521</td>
</tr>
<tr>
<td>1HR S/V RATIO (cm³/cm³)</td>
<td>82.02</td>
<td>78.12</td>
<td>82.02</td>
<td>76.15</td>
<td>82.02</td>
<td>76.87</td>
</tr>
<tr>
<td>LIVE HERB. LOAD (kg/ha)</td>
<td>535</td>
<td>535</td>
<td>765</td>
<td>765</td>
<td>878</td>
<td>878</td>
</tr>
<tr>
<td>LIVE S/V RATIO (cm³/cm³)</td>
<td>82.02</td>
<td>82.02</td>
<td>82.02</td>
<td>82.02</td>
<td>82.02</td>
<td>82.02</td>
</tr>
<tr>
<td>FUEL BED DEPTH (cm)</td>
<td>1.8</td>
<td>6.1</td>
<td>2.7</td>
<td>8.5</td>
<td>3.6</td>
<td>10.4</td>
</tr>
<tr>
<td>HEAT CONTENT (kJ/kg)</td>
<td>18604</td>
<td>18604</td>
<td>18604</td>
<td>18604</td>
<td>18604</td>
<td>18604</td>
</tr>
<tr>
<td>DEAD FUEL MOISTURE OF EXTINCTION (%)</td>
<td>28</td>
<td>18</td>
<td>26</td>
<td>17</td>
<td>24</td>
<td>17</td>
</tr>
</tbody>
</table>
RESULTS

Fire behavior graphs produced using the second model for each burn were combined with the ones that resulted from the initial models and the observed values of fire behavior were marked on the combined graph. The graphs are shown in Figures 10-15.

![Graph](image)

**TEST BURN #1**

Figure 10. Predicted flame length for test burn #1.
Figure 11. Predicted rate of spread for test burn #1.
Figure 12. Predicted flame length for test burn #2.
Figure 13. Predicted rate of spread for test burn #2.
Figure 14. Predicted flame length for test burn #3.
Figure 15. Predicted rate of spread for test burn #3.
DISCUSSION

There was no attempt to statistically analyze the degree of agreement of the predicted with the observed fire behavior values. This comparison was avoided because the detail of the measurements in the test burns may exceed BEHAVE'S sensitivity and, most important, some of these measurements may reflect special fuel bed characteristics on a very small scale. On the other hand the graphs show some trends, which combined with personal observations during the burns, allow an explanation of the special characteristics of knapweed's fire behavior.

In marginal burning conditions, as dictated by dead fuel moisture content, slope and midflame windspeed, standing knapweed stems should not be included in the fuel loading because they usually do not burn. Fire behavior can be modeled using litter as fuel loading and its depth as fuel bed depth. When predicted flame length is longer than 35 cm fire behavior must be re-calculated including standing knapweed in the loading and changing fuel bed depth in accordance. There is a great deal of uncertainty when predicted flame lengths are between 20 and 35 cm where fire behavior can show the characteristics of either model depending on the particular fuel bed and the variability of the environmental conditions.
During the test burns fire tended to die out in some spots at moments that windspeed was very low. This seemingly disagrees with BEHAVE’s predictions for models 21, 22 and 23 which have very high dead moisture content of extinction. A closer look though at the flame length graphs (Figures 10, 12 and 14) shows that in general predicted flame lengths at windspeeds of less than 4 km/hour are less than 10 cm for these models. Small gaps of this magnitude are very common in a knapweed fuel bed. This is contrary to Rothermel’s continuous fuel bed assumption. It is not surprising that fire went out when it reached gaps that were large enough that fuel on the opposite side could not be effectively heated to ignition. Fireline intensity corresponding to 10 cm flame length is only 1.74 Kj/m/sec. Another observation that supports this explanation is that where fire did not go out it burned quite well as soon as a stronger wind started blowing and created a finger shaped burn. Patches between these fingers remained unburned because fire did not spread in directions other than the wind direction.

These details of fire behavior should not be a problem when dealing with a wildfire situation since the "complete" knapweed model should be adequate under those circumstances. On the other hand when trying to burn knapweed for fire hazard reduction in spring these details
may offer an insight into the specifics of fire behavior and allow for the selection of environmental conditions under which fire will carry in the fuel bed without interruptions and without risk of escape. This approach means that the conditions should be as follows.

a. A flame length of at least 20 cm should be predicted using a fuel model that does not include standing knapweed.

b. A controllable flame length (less than 120 cm) should be predicted using the complete fuel model. This value depends on personnel training, width of previously created blackline, experience etc (Andrews and Rothermel 1982).

If these conditions can be met with a wide range of windspeed/dead fuel moisture content combinations, a low wind/low moisture one should be preferred because a more intense but still controllable fire will be created that will reduce fuel loading to a minimum. Completing a burn before cool season forbs and grasses start their growth is important because the burning prescription window may become very narrow.

A. Custom models for typical spotted knapweed infestations

Fire managers who are familiar with fire modeling concepts, have used BEHAVE and have access to it, should be
able to create their own site specific models for knapweed infestations they have to deal with, using the general knapweed fuel model as it is summarized in Table 7, and following the suggestions offered in the discussion of the test burn results.

Much of this modeling may be for fire fighting purposes in late summer when new knapweed dries. To facilitate fire managers in the inclusion of new knapweed in their models a series of measurements of live new knapweed moisture content were made in summer 1986. The samples were collected at the base of Mount Sentinel in Missoula which is a dry south facing slope.

Since the rate at which moisture content decreases differs considerably with the weather pattern during the summer, one should try to assign live knapweed fuel moisture values based on development characteristics as described next to fuel moisture values in Table 11, rather than on the date. The values in Table 11 agree with the guidelines offered in S-390 field guide (Table 3F).

On the other hand for those who try to burn knapweed for fire hazard reduction without access to BEHAVE, six stylized custom models for typical knapweed infestations were developed through procedure NEWMDL. They are based on the experience gained through the sampling process for this
study and they are followed by flame length, rate of spread and effective windspeed graphs which should be a useful guide of expected fire behavior to allow successful and safe burns (Figures 16 - 31 in appendix I).

Table 11. Summer progression of live spotted knapweed moisture content (%).

<table>
<thead>
<tr>
<th>Date</th>
<th>Average</th>
<th>Moisture Development characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/1/86</td>
<td>235</td>
<td>Flower heads in dough stage. Other grasses started drying.</td>
</tr>
<tr>
<td>7/9/86</td>
<td>210</td>
<td>Few flowers open. Other grasses drying.</td>
</tr>
<tr>
<td>7/15/86</td>
<td>170</td>
<td>Approximately 20% of the flowers open. Other grasses mostly dry.</td>
</tr>
<tr>
<td>8/1/86</td>
<td>120</td>
<td>80% of the flowers open. Few flowers (&lt;3%) lost petals and dried. Lower knapweed leaves turning yellow. Other grasses mostly cured.</td>
</tr>
<tr>
<td>8/6/86</td>
<td>93</td>
<td>All flowers open. 5-10% of flowers lost petals. Lower knapweed leaves mostly dry.</td>
</tr>
<tr>
<td>8/20/86</td>
<td>45</td>
<td>Knapweed plants look dry. Most leaves crumbly and yellow. Less than 10% of flowers retain petals.</td>
</tr>
<tr>
<td>8/27/86</td>
<td>30</td>
<td>Plants with any green leaves very rare. Less than 2% of flowers retain petals.</td>
</tr>
</tbody>
</table>

Such burns are generally attempted in early spring before new plants start their growth. Hence no live fuel was included in the models. If green grasses are present in significant amounts during a burn, fire behavior should be less intense than the one predicted by these models.

Two regression equations derived from the measurements made for this study were developed to allow the estimation of fuel loading - fuel bed depth pairs. They do not
include cover as an independent variable. The equation for old knapweed based on 117 measurements is:

\[ Y = 516.3 - (62.0432 \times X) + (1.7475 \times X^2) \]

where \( Y \) = old knapweed fuel loading (kg/ha)

\( X \) = old knapweed height (cm)

with adjusted \( R^2 = 0.75 \) and \( CV = 0.88 \)

and the equation for litter, with \( n = 102 \), is:

\[ D = -0.416 + (0.000813 \times L) \]

where \( D \) = litter depth (cm)

\( L \) = litter loading (kg/ha)

with adjusted \( r^2 = 0.69 \) and \( CV = 0.44 \)

The models were developed for knapweed heights of 30, 50 and 70 cm. Litter loadings based on personal observations of typical knapweed infestations were assumed for these knapweed loadings. The litter depth prediction equation allows for the estimation of a value to be included in the models as litter bed depth. The spring spotted knapweed models were given numbers for easier reference: 81, 82, 83, 91, 92, 93. They are described in Tables 12 and 13. Models 91, 92, 93, include both litter and knapweed loadings while the corresponding models 81, 82, 83 include only litter. A S/V ratio of 82.02 cm²/cm³ was assigned to litter and a heat content of 1860 kj/kg was used for all models the same used for the 13 NFFL
models.

Table 12. NEWMDL procedure inputs for stylized spotted knapweed fuel models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Fuel load</th>
<th>S/V depth</th>
<th>heat</th>
<th>cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>Litter</td>
<td>1500</td>
<td>82.02</td>
<td>18604</td>
</tr>
<tr>
<td></td>
<td>knapweed</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>91</td>
<td>Litter</td>
<td>1500</td>
<td>82.02</td>
<td>18604</td>
</tr>
<tr>
<td></td>
<td>knapweed</td>
<td>228</td>
<td>41.66</td>
<td>---</td>
</tr>
<tr>
<td>82</td>
<td>Litter</td>
<td>2500</td>
<td>82.02</td>
<td>18604</td>
</tr>
<tr>
<td></td>
<td>knapweed</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>92</td>
<td>Litter</td>
<td>2500</td>
<td>82.02</td>
<td>18604</td>
</tr>
<tr>
<td></td>
<td>knapweed</td>
<td>1783</td>
<td>41.66</td>
<td>50.0</td>
</tr>
<tr>
<td>83</td>
<td>Litter</td>
<td>3500</td>
<td>82.02</td>
<td>18604</td>
</tr>
<tr>
<td></td>
<td>knapweed</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>93</td>
<td>Litter</td>
<td>3500</td>
<td>82.02</td>
<td>18604</td>
</tr>
<tr>
<td></td>
<td>knapweed</td>
<td>4736</td>
<td>41.66</td>
<td>70.0</td>
</tr>
</tbody>
</table>

Load in kg/ha  S/V ratio in cm$^2$/cm$^3$
Fuel bed depth in cm  Heat content in kj/kg
Cover in percent

Table 13. Description of stylized spotted knapweed fuel models for spring burns.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>81</th>
<th>91</th>
<th>82</th>
<th>92</th>
<th>83</th>
<th>93</th>
</tr>
</thead>
<tbody>
<tr>
<td>1HR DEAD FUEL LOAD (kg/ha)</td>
<td>1500</td>
<td>1728</td>
<td>2500</td>
<td>4283</td>
<td>3500</td>
<td>8236</td>
</tr>
<tr>
<td>1HR S/V RATIO (cm$^2$/cm$^3$)</td>
<td>82.02</td>
<td>79.13</td>
<td>82.02</td>
<td>71.29</td>
<td>82.02</td>
<td>57.15</td>
</tr>
<tr>
<td>FUEL BED DEPTH (cm)</td>
<td>0.9</td>
<td>4.6</td>
<td>1.5</td>
<td>21.6</td>
<td>2.4</td>
<td>53.3</td>
</tr>
<tr>
<td>HEAT CONTENT (kj/kg)</td>
<td>18604</td>
<td>18604</td>
<td>18604</td>
<td>18604</td>
<td>18604</td>
<td>18604</td>
</tr>
<tr>
<td>DEAD FUEL MOISTURE OF EXTINCTION (%)</td>
<td>30</td>
<td>15</td>
<td>27</td>
<td>14</td>
<td>25</td>
<td>13</td>
</tr>
</tbody>
</table>

Effective windspeed graphs are based on S/V ratio and packing ratio of the fuels (Rothermel 1972). Packing ratio for models 81, 82, 83 is practically the same because
litter depth was derived from litter loading using a predictive equation and particle density has a constant value in BEHAVE. Since S/V ratio for litter did not change also for these three models, they share a common effective midflame windspeed graph (Figure 16).

The selection of a fuel model should be based mainly on height of knapweed if loading data are not available. One of the models 91-93 should be selected. A transect as used in the test burn plots, on a representative part of the field, can provide fuel loading data using the prediction equations of Table 7 and facilitate the selection of the appropriate stylized model especially in situations of strong spatial variation of knapweed height.

If time does not allow for measurements and an ocular estimation of height is used, it should be noted that this estimation usually corresponds to the maximum height. It was found from the initial random 90 plots that average height was approximately 70% of maximum height for each plot. This observation is supported by the guidelines offered for fuel bed depth estimation in the documentation of BEHAVE (Burgan and Rothermel 1984).

It should also be noted that knapweed height on the same site can vary considerably between years depending on rainfall. This variation was obvious between the spring
and early summer of 1985 that was very dry in the Missoula area and the 1986 season that was very wet. Knapweed grew more than 10 cm taller and was usually much denser in the same locations that had been sampled the previous year.

Once the fuel model is selected the flame length graph for its no-litter alternative should be examined and environmental conditions under which flame length can reach 20 cm should be noted. Using this range the user should examine the flame length graph for the corresponding complete model to select values that will permit a safe burn. Finally from the range of selected effective windspeeds the user can decide the range of midflame windspeeds that are acceptable for his specific site adjusting for the slope of the site with the help of the effective windspeed graph for his chosen model.
OVERALL DISCUSSION

It should be noted that trying to define prescription windows for spotted knapweed models results in very narrow ranges of acceptable conditions for effective but still safe burns. This fact reflects the difficulties that managers have had when trying to burn knapweed. The models for spring burns in spotted knapweed have been developed for sites with very low grass cover percentages as can be seen from the extremely low fuel bed depths of each model. As grass cover percentage increases fire will carry in the fuel bed more easily. If fine grass cover exceeds 40% one should use fuel model 1 from the 13 NFFL models rather than one of the knapweed models. Pastures left ungrazed for a year should burn more easily. In this respect fire behavior problems caused by discontinuous and nonuniform fuels are similar to the ones found in big sagebrush (Brown 1982). High fine grass cover is not common in cases of heavy tall knapweed infestations for which model 93 is built.

It should also be noted that these models are based on computer modeling, a few monitored test burns and personal observations during those and other knapweed burns. Potential users should be careful with these models until their predictions are verified in more tests and operational conditions.
APPENDIX I
Figure 16. Effective midflame windspeed graph for fuel models 81, 82, 83
Figure 17. Predicted flame length graph for fuel model 81.
Figure 18. Predicted rate of spread graph for fuel model 81.
Figure 19. Effective midflame windspeed graph for fuel model 91.
Figure 20. Predicted flame length graph for fuel model 91.
KNAPWEED MODEL 91

Figure 21. Predicted rate of spread graph for fuel model 91.
Figure 22. Predicted flame length graph for fuel model 82.
Knapweed Model 82

Figure 23. Predicted rate of spread graph for fuel model 82.
Figure 24. Effective midflame windspeed graph for fuel model 92.
Figure 25. Predicted flame length graph for fuel model 92.
Figure 26. Predicted rate of spread graph for fuel model 92.
Figure 27. Predicted flame length graph for fuel model 83.
Figure 28. Predicted rate of spread graph for fuel model 83.
Figure 29. Effective midflame windspeed graph for fuel model 93.
Figure 30. Predicted flame length graph for fuel model 93.
Figure 31. Predicted rate of spread graph for fuel model 93.
APPENDIX II
**SAMPLING FRAME DESCRIPTION**

Rectangle 40 cm X 50 cm aluminum frame

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**Figure 32. Sampling frame description**
Figure 33. Data collection form.
10 PRINT "ENTER 1 TO USE METRIC UNITS, 2 OTHERWISE : ";
20 INPUT X
30 IF X<>1 GOTO 150
40 PRINT "*** METRIC SYSTEM UNITS INPUT SECTION CHOSEN ***"
50 PRINT "ENTER S/V RATIO (in sq.cm/cu.cm) : ";
60 INPUT SM
70 LET S = SM * 30.48
80 PRINT "ENTER 1-HR DEAD FUEL LOADING (in kg/ha) : ";
90 INPUT WIM
100 LET WI = WIM / 2238
110 PRINT "ENTER FUEL BED DEPTH (in cm) : ";
120 INPUT DM
130 LET D = DM / 30.48
140 GOTO 220
150 PRINT "*** ENGLISH SYSTEM UNITS INPUT SECTION CHOSEN ***"
160 PRINT "ENTER S/V RATIO (in sq.ft/cu.ft) : ";
170 INPUT S
180 PRINT "ENTER 1-HR DEAD FUEL LOADING (in tn/acre) : ";
190 INPUT WI
200 PRINT "ENTER FUEL BED DEPTH (in feet) : ";
210 INPUT D
220 LET W = WI / 21.78
230 LET PB = W / D
240 LET B = PB / 32
250 LET C = 7.47 * (EXP(-.139 * (S^.55)))
260 LET BI = .02526 * (S^.54)
270 LET E = .715 * (EXP(-3.59 * (.0001 * S)))
280 LET BOP = 3.348 * (S^(-.8189))
290 LET L = (B / BOP) ^ (-E)
300 OPEN "O", #1, "A:81M.PRN"
310 FOR U = 0 TO 30 STEP 5
320 LET UM = (U * 5280) / (60 * 1.6093)
330 LET FW = C * L * (UM^BI)
340 FOR F = 0 TO 120 STEP 5
350 LET FS = 5.275 * (B^(-.3)) * ((F / 100)^2)
360 LET FE = FW * FS
370 LET EW = ((FE / (L * C)) * (1 / BI)) * (60 / 5280)
380 LET EWM = EW * 1.6093
390 PRINT #1, USING" ####.#### "; U; F; EWM
400 NEXT F
410 NEXT U
420 CLOSE #1
430 END

Figure 34. GWBASIC program for effective windspeed calculation.
10 OPEN "O", #1, "21LBM.PRN"
20 LET H=8000
30 LET LFM=3
40 LET PR=32
50 LET ST=.0353
60 LET SE=.01
70 PRINT "ENTER 1 TO USE METRIC UNITS, 2 OTHERWISE: ";
80 INPUT X
90 IF X<>1 GOTO 300
100 PRINT "***METRIC SYSTEM UNITS INPUT SECTION CHOSEN***
110 PRINT "ENTER S/V RATIO FOR DEAD 1-HR FUELS (in sq.cm/cu.cm): ";
120 INPUT DSM
130 LET DS=DSM*30.48
140 PRINT "ENTER S/V RATIO FOR LIVE HERBACEOUS FUELS (in sq.cm/cu.cm): ";
150 INPUT LSM
160 LET LS=LSM*30.48
170 PRINT "ENTER WEIGHTED S/V RATIO FOR THIS MODEL (SIGMA) (in sq.cm/cu.cm): ";
180 INPUT SM
190 LET S=SM*30.48
200 PRINT "ENTER 1-HR DEAD FUEL LOADING (in kg/ha): ";
210 INPUT WIM
220 LET W=WIM/487601
230 PRINT "ENTER LIVE HERBACEOUS FUEL LOADING (in kg/ha): ";
240 INPUT LWIM
250 LET LW=LWIM/487601
260 PRINT "ENTER FUEL BED DEPTH (in cm): ";
270 INPUT DM
280 LET D=DM/30.48
290 GOTO 460
300 PRINT "***ENGLISH SYSTEM UNITS INPUT SECTION CHOSEN***
310 PRINT "NOTE: RESULTS WILL BE REPORTED IN METRIC SYSTEM UNITS"
320 PRINT "ENTER S/V RATIO FOR DEAD 1-HR FUELS (in sq.ft/cu.ft): ";
330 INPUT DS
340 PRINT "ENTER S/V RATIO FOR LIVE HERBACEOUS FUELS (in sq.ft/cu.ft): ";
350 INPUT LS
360 PRINT "ENTER WEIGHTED S/V RATIO FOR THIS MODEL (SIGMA) (in sq.ft/cu.ft): ";
370 INPUT S
380 PRINT "ENTER 1-HR DEAD FUEL LOADING (in tn/acre): ";
390 INPUT WI
400 LET W=WI/21.78
410 PRINT "ENTER LIVE HERBACEOUS FUEL LOADING (in tn/acre): ";
420 INPUT LWI
430 LET LW=LWI/21.78
440 PRINT "ENTER FUEL BED DEPTH (in feet): ";
450 INPUT D
460 PRINT "ENTER MOISTURE CONTENT OF EXTINCTION (percent): ";
470 INPUT MXI
480 PRINT "ENTER MOISTURE CONTENT OF DEAD FUELS (percent): ";
490 INPUT MFI
500 LET MX=MXI/100
510 LET TW=W-LW
520 LET PB=TW/D

Figure 35. GWBASIC program for fire behavior calculations.
530 LET ALF=LW*LS/PR
540 LET ADF=W*DS/PR
550 LET TA=ALF+ADF
560 LET FID=ADF/TA
570 LET FIL=ALF/TA
580 LET WN=W*(1-ST)
590 LET LWN=LW*(1-ST)
600 LET WL=(W*(EXP(-138/DS)))/(LW*(EXP(-500/LS)))
610 LET B=PB/PR
620 LET C=7.47*(EXP(-1.13*(S^.55)))
630 LET BI=.02526*(S^.54)
640 LET E=.715*(EXP(-3.59*(.0001*S)))
650 LET BOP=.3.348*(S^(-.8189))
660 LET LI=B/BOP
670 LET L=LI^(-E)
680 LET MF=MFI/100
690 LET SUM3=FID*(EXP(-138/DS))*250*(1116*MF)*FIL*(EXP(-138/LS))*(250*1116*LFM)
700 LET LMX=2.9*WL*(1-MF/MX)-.226
710 IF LMX>MX THEN LMX=MX
720 LET GMAX=(S^1.5)*((195*0.0594*(S^1.5)))^(1)
730 LET A=133/(S^.7913)
740 LET G=GMAX*(LI^A)*(EXP(A*(1-LI)))
750 LET WN=W*(1-ST)
760 LET RM=MF/MX
770 LET LRM=LFM/LMX
780 LET HM=1-2.59*RM*.11*(RM^2)-3.52*(RM^3)
790 LET LHM=1-(2.59*LRM-.511*(LRM^2))-(3.52*(LRM^3))
800 LET HS=.174*(S^(-1.19))
810 LET LIR=LWN+LHM+HS
820 LET DIR=WN+HM+HS
830 LET IR=G*(LIR+DIR)
840 LET XI=((192*.2595*S)^(-1))*(EXP(.792*.681*(S^.5)))*(B+.1))
850 LET RATE0=IR+XI)/(PB*SUM3)
860 FOR U=0 TO 20 STEP 1
870 LET UX=(U*5280)/(60*1.6093)
880 LET FW=C*L*(UX^BI)
890 LET UX=.9*IR
900 IF UX<UX GOTO 920
910 LET FW=C*L*(UX^BI)
920 LET RATE=RATE0*(1-FW)
930 LET RTEM=RATE*.3048
940 LET TR=364/S
950 LET DF=RATE/TR
960 LET IB=(IR+DF)/60
970 LET FLAME=.45*(IB^.45)
980 LET FLAME=FLAME*.3048
990 PRINT USING "#####.## *",MFI;U;RATE;FLAME
1000 PRINT USING "#####.## *",MFI;U;RATE;FLAME
1010 NEXT U
1020 CLOSE #1
1030 END

Figure 35. (continued)
LITERATURE CITED


Carpenter, J. L. 1986. Personal communication. Univ. of Montana, School of Forestry, Missoula, MT.


