DISSERTATION

MAPPING AND MODELING LEAFY SPURGE SPREAD IN THEODORE ROOSEVELT NATIONAL PARK, NORTH DAKOTA USING SPATIAL INFORMATION AND SPATIAL STATISTICS

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY KARL BROWN ENTITLED MAPPING AND MODELING LEAFY SPURGE SPREAD IN THEODORE ROOSEVELT NATIONAL PARK, NORTH DAKOTA USING SPATIAL INFORMATION AND SPATIAL STATISTICS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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ABSTRACT OF DISSERTATION

MAPPING AND MODELING LEAFY SPURGE SPREAD IN THEODORE ROOSEVELT NATIONAL PARK, NORTH DAKOTA USING SPATIAL INFORMATION AND SPATIAL STATISTICS

Leafy spurge, an exotic species, is a durable, troublesome invasive weed with significant economic and social costs. The economic results in the northern Great Plains have made the study and control of leafy spurge a current and important research topic. Leafy spurge was first reported in Theodore Roosevelt National Park (THRO) in the late 1960's. In 1970, it was estimated that 13 ha of the park was infested. The latest 1998 estimate was 1,198 ha of the 18,680 ha 'South (Management) Unit.'

The primary objectives of this research were to define the relationships between various physical factors and the presence of leafy spurge on the landscape at THRO, develop a ranked probability map of occurrence, and to estimate the rate of spread. Spatial statistical analysis was used to develop a binary regression tree classifications for mapping leafy spurge, to evaluate spatial autocorrelation and cross correlation statistics between leafy spurge and physical environmental variables, and to develop the Ordinary Least Squares (OLS) based on stepwise regression analysis and examining residual characteristics using kriging based on semi-variogram models.

The traditional classification for presence and absence of leafy spurge had a 62% overall mapping accuracy, and the binary regression classification trees had a 74%

overall mapping accuracy. The criteria for selecting all the spatial statistical models were the lowest values of standard errors, Akaike's Information Criteria (AICC) statistics, and high R^2. The trend surface predictive probability model and the presence and absence (suitable vs. non-suitable habitat) predictive model accounted for ~35% of the variability of leafy spurge on the landscape, using the OLS procedure. All variables used to predict these two models were significant at $\alpha < 0.05$ level. To capture the fine-scale variability for both models, semi-variogram models, based on Exponential (probability model) and Gaussian (presence and absence) models were used to krig the residuals of both surfaces. The R^2 values were 42.5% (probability) and 39.9% (presence and absence).

The combined predictive spatial model indicated high probability areas in the drainages and midslope swales in the northwest wilderness area of the South Unit of THRO. Additional moderate probability zones were identified in most of the drainage basins. Spread rates averaged 5 to 10-meters per year at THRO. This study concluded that the OLS and kriged model of leafy spurge probability was superior over the OLS alone in performance, and that the slope, aspect, and zone (slope position) exhibited significant cross-correlation with elevation in the presence of spurge on the landscape. The study approach provided useful technical tools to forecast landscape-scale for invasive species (plants or animals) for improved management activities within ecosystems of the landscape at different scale levels.

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DEDICATION

This dissertation is dedicated to my wife Amy and to my parents, Donald and Jeanette Brown, whose tireless support was instrumental in the success of this effort. My father provided the love of natural resources and the basis of a land ethic. My mother provided the love of learning and a subtle hint of the importance of giving back to society. Finally, my wife Amy provided both her steady support and able assistance to make the journey possible.

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CHAPTER I

I. INTRODUCTION AND OBJECTIVES

1.1 Overview

Leafy spurge, an exotic species, is a durable, troublesome invasive weed with significant economic and social costs. Leafy spurge is a dicotyledonous, herbaceous perennial (Lym, 1998). Messersmith, Lym, and Galitz (1985) provide an extensive review of the biology of this plant. Methods to control this plant involve a sizable research effort, and the general conclusions of chemical, cultural, and biological controls research support an integrated weed management strategy for the control of this plant (TEAM Leafy Spurge, 2000). Cox (1998) summarized the lessons in detection and management from leafy spurge and yellow starthistle. In the northern great plains region, state based economic impacts currently total over $140 million per year (Anderson, 2001). These impacts were detailed earlier by Messersmith and Lym (1983) for distribution and economic impacts of leafy spurge in North Dakota, and by Bangsund et al. (1993) for the social and economic impact of leafy spurge in Montana, South Dakota and Wyoming. The loss of range productivity and the economic results to the rural economies in the northern Great Plains have made the study and control methods for leafy spurge a current and important research topic.

Citing Anderson et al (1996), leafy spurge (*Euphorbia esula* L.) is a perennial weed with erect stems 40 to 80 cm tall (Stevens, 1963). The weed reproduces by both vegetative buds and the production of large quantities of seeds. Leafy spurge produces yellow bracts in late May or early June that give the plant a conspicuous yellow-green appearance (Lacey et al. 1985b). A native of Eurasia, leafy spurge was first reported in the state of Massachusetts in the surprisingly early year of 1827 (Noble et al. 1979). Leafy spurge now occurs abundantly on the Northern Great Plains of the United States and the Prairie Provinces of Canada where it often forms stands dense enough to displace native plants and restrict cattle grazing (Rees and Spencer, 1991). The yellow-green color of the bracts, high plant density, and latex-like sap are shown in Figure 1.1.

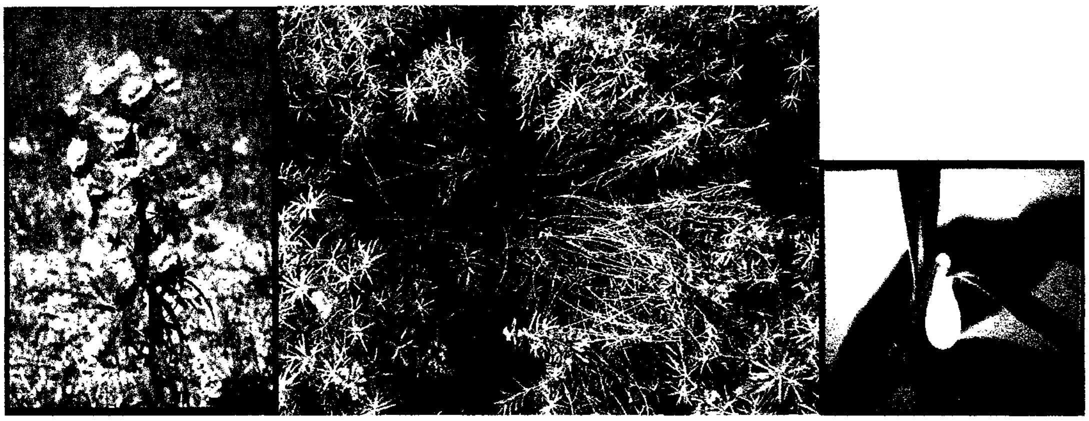


Figure 1.1 Leafy spurge bracts, dense clumps, and latex-like sap.

1.2 Inventory and Management Efforts at Theodore Roosevelt NP

Leafy spurge was first reported in Theodore Roosevelt National Park (THRO)in the late 1960's. The point of origin for introduction of spurge to the park was the Knutson Creek drainage that flows from the western boundary of the South Unit to the Little Missouri River. The Paddock Creek drainage forms the other major drainage, and flows east to west, joining the Little Missouri River downriver of the Knudson Creek confluence. In 1970, it was estimated that 13 ha of the park was infested. Between 1975 and 1983, the park estimated the spread to have increased to 162 ha. The spread was estimated at 283 ha in 1986. By 1993, an estimated 702 ha of the 18,680 ha park were infested by leafy spurge (Anderson et al. 1996). Despite earlier control efforts, and a revised 1993 estimate of 591 ha, the infestation almost doubled by 1998 to 1,198 ha (Anderson et al. 1999). Also during 1993, the park commissioned a leafy spurge management plan through a study panel (Carlson et al. 1994). The park is currently involved in an active leafy spurge control program, including herbicides, grazing management, and biological control. The park staff has historical records of these control efforts, including digital Geographic Information System (GIS) coverage and attribute data for the most recent biological control releases (Hager, 2001 personal communication).

Due to color and timing of the yellow bracts in late May or early June, many survey efforts to detect this troublesome plant have concentrated on the color. The utility of remote sensing data to aid in surveys for rangeland assessment is well established (Tueller 1982; Carneggie et al. 1983). Remote sensing provides rapid acquisition of data at lower costs than ground surveys (Tueller, 1982; Everitt et al. 1992). However, the possibility of misclassification error is higher (Kalkhan et al. 1998).

1.3 Background and collaboration for this study at Theodore Roosevelt NP

This study focuses on spread analysis involving flooding and moisture availability, derived from geospatial data sets and surface digital elevation models (DEMs). Hosted by the U.S. Department of Agriculture, TEAM Leafy Spurge (2000) combines research and technical assistance to landowners, and provided collaborative funding from 2000 to 2002 to the U.S. Geological Survey for this study. This collaboration, as part of the seven-member team, included this study and multiple related efforts researching hyperspectral imagery and Advanced Land Imager (Speciale, 2002) analysis and identification of leafy spurge listed in Table 1.2.

Table 1.2 A list of sensors used in researching hyperspectral imagery utility for analysis and identification of leafy spurge in Theodore Roosevelt National Park.

Sensor (Nickname)	Full Name	Platform / elevation	Ground Sample Distance (pixel)/ swath
CASI	Compact Airborne Spectrographic Imager	Civil Aircraft / 330 m (10,000 feet) AGL	3-4 meters / 1 km
AVIRIS	Airborne Visible Infrared Imaging Spectrometer (AVIRIS)	U-2; ER-2 NASA Research Aircraft / 20 km (80K feet)	17 meters / 11 km
EO-1 Hyperion & ALI	Earth Observer 1; Hyperion & the Advanced Land Imager	Spacecraft / 705 km flies next to Landsat 7; 1 minute behind	30 meters / ¼ swath of Landsat 7 @ 185 km; pointable ~ 50 km

The broader effort used three different types of airborne remote sensor data (aerial photography from 1993 and 1998, Airborne Visible Infrared Imaging Spectrometer (AVIRIS) from 2000, and Compact Airborne Spectrographic Imager (CASI), from 2000) augmented by ground surveys with the Global Positioning System (GPS) to assess the spatial extent of leafy spurge and its' change over time. The AVIRIS sensor provided a 17-meter image for potential leafy spurge mapping.

The contribution of this study is to extend the moisture and stream channel proximity-based prediction model described by Anderson et al (1996) by including two new factors, the soil texture class, and a slope position factor. The elements that were unique to this research effort were that the predictive spatial model included soil texture data and the slope position as surrogates or aggregate indicators of available plant moisture.

Spatial models of leafy spurge probability and presence / absence assists National Park Service resource management decisions. Difficult budgetary choices involve expected returns on weed control efforts. A predictive spatial model can refine high probability targets to prioritize funding and control efforts. Alternatively, low probability areas can reduce the search efforts, although a reduced effort in monitoring should still be invested to assess low and medium risk areas (after Carlson et al. 1994). As model capability grows, smaller and more juvenile infestations may be found through a combination of improved spectral or spatial resolution tools or platforms.

1.4 Models and Predictive Tools for Management

The desired management tools of the future include predictive spatial models using remote sensing, GIS, and spatial information, among others, to aid in decision-making. Two current types of predictive models either estimate spread or describe population dynamics, growth, and life stages. The population dynamics models do not contain a spatial component, but identify terrain factors that have known influence on the phases of population development (Anderson, 2001; Rinella, 2001). The few spatial models employed have used general buffering or distance from streams and proximity analysis to correlate spread potentials, with high correlation results (Anderson et al 1996, 1999). No models have yet incorporated soil type and slope position with the terrain factors that influence soil moisture and incoming solar radiation (Anderson, personal communication). The spread rate for leafy spurge at THRO can be determined by the change from 1993 to 1998 polygons. Spread rates with spread estimates derived from multiple year studies have been studied in Alberta and Colorado. Theodore Roosevelt has different latitude and soils, so the current effort gives insight into this geographical area. The development and testing of the additional terrain modeling factors and spread measurements will be unique for this Great Plains environment.

1.5 Field Data Modeling versus Mapping Classification

The traditional use of mapping technologies based on remote sensing imagery have dominated the characterization and mapping of landscapes for many years (Jensen, 1996). Common evaluations of quality have centered upon components of thematic classification accuracy against reference data. Percentage overall accuracy, users and producers accuracy, and the Kappa statistic have traditionally been used to quantify and clarify the quality of the thematic map (Jensen, 1996; Congalton, 1991). Caution must be exercised in how the reference data points are selected, as it is possible to control or bias the resulting accuracy to meet a desired percentage level (Jensen, 1996). Alternative approaches involve the use of field data and spatial statistics to design and refine spatial models to predict and interpolate the landscape. These trend surface models, or binary regression classification tree models have quantified variances, known errors of uncertainty, and explicit measures of spatial autocorrelation, cross-correlation, and measures of how the variance changes with distance between measurements (Kalkhan, personal communication). The model development proceeds from field reference measurements, utilizing generalized predictive spatial statistical models derived from aerial photography derived leafy spurge polygons, Geographic Information Systems (GIS), and field data. This expresses a fundamental difference between field data modeling and mapping classification.

To support the objective of a predictive surface of leafy spurge at THRO, this study utilized a modified field measurement based model development approach. The field data polygons were delineated by aerial photography, with many of the polygons verified by GPS ground reference. The derived physical variables involved slope and elevation traits. The remaining soil variable was ground reference based. Together, these variables were tested for spatial correlation and cross-correlation, with the development of a spatial surface as the desired product (Kalkhan et al. 2000; 2001; 2003). Unlike an imagery derived thematic classification, this surface model contained all the statistical strengths described above. In addition to the percentage accuracy and Kappa statistic, this surface has estimates of confidence, standard errors, and variance over distance. The predicted surface draws validation from the spatial statistics information. This method enables a spatial interpolation of the landscape with respect to distance; however, traditional thematic classification maps lack that capability.

For trend surface models, coarse and fine-scale landscape variances are represented by Ordinary Least Squares and kriging models, respectively. The binary regression tree model results in a presence and absence (suitable vs. non-suitable habitat) surface, with the tree branching chosen by minimizing the deviance, or variability with distance errors (Kalkhan et al. 2003). Binary regression tree-based models are exploratory and can uncover structure in data as an alternative to linear and additive regression models (Mathsoft, Inc. 1999). The regression tree is a non-parametric approach to regression that uses a binary partitioning algorithm to maximize the dissimilarities among groups by comparing all possible splits of independent, continuous variables. The algorithm recursively splits the data in each group until the subset is homogenous or there are fewer than 5 observations in the subset (Mathsoft, Inc. 1999).

1.6 Objectives

This study has two primary objectives. The first is to define the relationships between various physical factors that contribute to soil moisture and the presence of leafy spurge on the landscape at Theodore Roosevelt National Park (THRO) North Dakota. The second primary objective is to estimate the rate of spread using leafy spurge polygons interpreted from aerial photography.

The physical landscape parameters of slope and slope position, aspect, elevation, and soil type contribute to aggregate soil moisture on the landscape where leafy spurge exists. The information on the predictive value of these five physical characteristics of the spurge locations will be important for both National Park Service management and the design of future control efforts and spatial models. The specific sub-objectives of this research are:

1. To develop a thematic mapping estimate of the presence of leafy spurge using remotely sensed data based on the traditional classification approach. This landscape scale technique would be most frequently used by natural resource agencies attempting broad scale mapping.
2. To develop a new thematic approach using binary regression classification tree that utilizes only environmental factors (elevation, slope, aspect, slope position, and soil type) to predict the potential presence and absence (suitable vs. non-suitable habitat) of leafy spurge, and to compare the output with the traditional thematic classification developed in the first objective.
3. To examine the spatial relationships between leafy spurge presence and the topographic factors of elevation, slope, aspect, slope position, and abiotic soil type using Pearson linear correlation, spatial autocorrelation using Moran *I*, and spatial cross-correlation using Bi-Moran *I* statistics.

4. To develop a predictive spatial model of leafy spurge that captures both coarse-scale and fine-scale spatial variability, resulting in a presence and absence (suitable vs. non-suitable habitat) trend surface of leafy spurge.
5. To sample the boundary changes between the 1993 and 1998 polygons interpreted from the 1:10,000 scale aerial photography to estimate patch size change rates on the landscape occupied by the leafy spurge.

CHAPTER II

II. LITERATURE REVIEW

An unconstrained search of the literature for leafy spurge yields a tremendous amount of material because of the many socioeconomic and biological factors involved. Rapid growth in academic research and political attention given to invasive plants has resulted from both economic and biodiversity concerns. This literature review focuses on the factors influencing available soil moisture and the spread of leafy spurge, and a summary of the detection and modeling efforts to date that are relevant to the Theodore Roosevelt National Park (THRO) badlands environment. An additional literature review addresses selected related topics that influence management, but are beyond the primary scope of this study, so have been included in Appendix three. The following section describes the general status of our knowledge of the detection, mapping, and modeling of leafy spurge in the northern Great Plains, and a summary of invasive plants terminology.

2.1 General Status of our Knowledge of Leafy Spurge Detection, Mapping, and Modeling in the Northern Great Plains

2.1.1 Leafy Spurge Detection and Control

From introductions over 175 years ago, a survey of the U.S. found leafy spurge in 458 counties in 26 states from coast to coast (Dunn, 1979). Of the approximately one million hectares (2.5 million acres) infested with leafy spurge, more than half are in North Dakota and Montana (Carlson et al. 1994). Community detection efforts have involved many forms of citizen education and surveillance. Where possible, small infestations are targeted for eradication. Large infestations have the economies of scale for herbicide application or integrated weed management efforts. The moderate sized infestations are the most challenging, and may involve edge treatment to keep them from growing and provide time to return when the larger infestations have been treated. In all cases the minimum annual treatment should be to treat, if possible, the edges along the infestation. This will limit the spread of leafy spurge into non-infested land (Carlson et al. 1994).

2.1.2 Weed Lists and Invasive Plants Terminology and Definitions

A current challenge in the weed management at all levels of government involves the nomination and assembly of weed lists. No formal evaluation or definition guides the assembly of a city or county weed list, and weed districts are free to list any troublesome plant that they deem worthy (Beck, 2001 personal communication). The states compile the county lists into the state lists and in some cases have conflicting candidate plants. International confusion results from differing terminology and translation. Plants may be called weeds, invaders, aliens, and naturalized, depending on the history and lineage of the plant material (Richardson et al. 2000). “Invasive plant” may be linked to one with an aggressive growth habit, while “noxious” may be a title for a plant that is difficult and costly to control (Cronk and Fuller, 1995; Mack, 1997). Political recognition of categories can influence funding for control, and a wealth of non-defined terms adds to the confusion. This study will call an undesirable plant a “weed” and one with an aggressive and dominating growth habit “invasive.”

Various terminologies across national and international forums center upon the traits of invasive plants, but generally do not agree on definitions. Some efforts to define terms have been made, as in Richardson et al (2000). Richardson and others discuss the concepts of ecosystem invasibility, and the definitions and contrasts between invasive and naturalized plants. The considerations of what makes a plant invasive can help direct the title and category of the plant of concern. This can influence management choices regarding ecosystem risk and control strategies, because funding and enforcement typically follow the listed plants of concern.

Invasion Ecology as a new discipline had a clear starting point with Elton's (1958) classic book on invasions. The discipline suffered from his lack of definition of 'invasion' or 'invader', and the interchanging of these terms without the context of impact. This terminology was consistent with the other ecologists of the time, including the definition by Clements (1949; pg. 284) given as: 'Invasion – the movement of plants from one area to another, and their colonization in the latter', and the original definition by Goeze (1882; p. 109). This definition of invasion is consistent with the way the term is used today by most ecologists, and how it appears in texts in reference to "alien" or non-native species defined later in this section (Richardson et al. 2000).

The Executive Order on 'invasive species' issued by the President of the USA on 3 February 1999 defines invasive species as 'alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health.' This has a connotation of control measures needed, and conforms to some authors who define invasive plants as those that cause obvious ecological and/or economic damage (Cronk and Fuller, 1995; Mack, 1997).

Early and current efforts to define and describe a plant as naturalized or invasive have suffered from a lack of common definition, confusion involving non-English language interpretation and classification translation, and the coining of related socio-political and effects-based terms. A current discussion and summary of these terms and issues can be found in Richardson et al (2000), summarized in Table 2.1. Richardson et al propose the use of “invasive” without any constraint to environmental or economic impact, and prefer the terms ‘pests’ or ‘weeds’ for the 50-80% of invaders with harmful effects. For the 10% of invaders that modify character, condition, form, or nature of ecosystems they attach the term “transformer.” One challenge to interpretation involves the widespread use of the term ‘naturalized’ as a synonym for ‘invasive’, which combines two overlapping but dissimilar phases of the process. Of twelve authoritative dictionaries and encyclopedias of ecology, floras, and other volumes, divergence centered upon three factors. First, the role of man in assisting the alien plant; second, the assumption that natural vegetation must be invaded for an alien to be ‘naturalized’; and third, an imprecise accounting of the degree of alien establishment with reproduction and self-sustainment (Richardson et al. 2000). These variations are summarized in Table 2.2, with fifteen percent (15%) of the papers not categorized due to insufficient details of the intended meaning of the authors.

Table 2.1. Definitions of terms used to describe plant movement, status, and ecological significance relevant to invasive behavior. (from Richardson et al. 2000).

Plant relocation term	Definition relevant to invasive behavior
Introduction	The plant or propagule transported by humans across a major geographical barrier.
Casual Alien plants	Presence due to accidental or intentional introduction (alien) that may flourish or reproduce in an area without forming self-replacing populations.
Naturalization	Starts when abiotic or biotic survival barriers are broken and various barriers to regular reproduction are overcome.
Invasion	Introduced plants produce reproductive offspring at some distance from sites of introduction, using the following metrics: Seeds and other propagules: >100 m over < 50 years; By roots, rhizomes, stolons, or creeping stems: >6m in <3 yrs.
Transformer	10% of Invasives that modify character, condition, form, or nature of ecosystems. Proposed by Wells et al (1986)
Pests and Weeds	50-80% of invaders with harmful effects.

Table 2.2. Four primary categories of interpretations for 'naturalized' and 'naturalization' result from 157 papers reviewed. (from Richardson et al. 2000).

1. Naturalized	23%	Conventional meaning of alien sustainment without human intervention. Conforms to 'established' in Williamson (1996; pg. 37) and Vitousek et al (1997).
2. Naturalized in 'natural' or 'semi-natural' vegetation	8%	Same as 1, but only if outside human-dominated systems. Coincides with 'established' as defined by Kloot (1987).
3. Naturalized as a synonym for 'alien'	25%	Synonym for 'alien' [non-native], with typical examples in Holub and Jirasek (1967) and Sachse (1995).
4. Naturalized as a synonym for 'invasive'	29%	Most common usage. A typical example: 'this paper studies the ...which spread and naturalized in .... Information is usually qualitative e.g. decreasing / increasing (Esler, 1987); established vs. non-established (Knops et al. 1995).

Plant ecologists also employ invasive terminology in a different context to denote 'colonization'. Local vegetative succession, sometimes termed encroachment (Hodgkin, 1984) also appears in discussions of 'invasion' of loblolly pine in old fields (Golley et al. 1994), and 'shrub invasion of grassland' (Brown and Archer, 1999).

Stohlgren et al (1998) also separate the invasion and naturalization processes, and recommend they be studied in separate but integrated ways using methods to evaluate both far- and close-distance spatial variability. The context of distance dependent environmental fluctuation to invasiveness has general support (Sax and Brown, 2000; Davis et al. 2000; Lonsdale, 1999). Quantitative methods are developing rapidly, contributing to understanding of community assembly and potential utility for risk assessment of nonindigenous species (Kolar and Lodge, 2001). The focus of invasion prediction literature currently involves the introduction and steps, or transitions, and the factors affecting survival success as quantifiable entities for model development. Lonsdale states that "Successful invasion of a natural community requires dispersal, establishment, and survival" (Hobbs, 1989), with the species richness balanced between immigration and extinction (Lonsdale, 1999). Most invading species fail to establish (Williamson, 1996). Table 2.3 summarizes these terms and steps or transitions.

No general theory of community invasibility has emerged, because results from field studies have been inconsistent (Lonsdale, 1999; Williamson 1999). Invasion potential, by contrast, relies on traits of the invading species only (SPE in Table 2.3) (Lonsdale, 1999). The factors implicated in the invasion (Table 2.3) include: EP – ecosystem properties; SPN – native species properties; SPE – exotic species properties; or PP – propagule pressure (after Lonsdale, 1999).

Table 2.3. Invasive terms and steps, defined by Kolar and Lodge, 2001; Lonsdale, 1999; Williamson, 1996; and Hobbs (1989). (from Lonsdale, 1999)

Established	Self-sustaining population outside its range; 'alien' from Richardson et al. 2000.	Factor: SPE
Indigenous species	species found within its native range	Factor: SPN
Nonindigenous species	introduced to areas beyond its native range by human activity	Factor: SPE
Invasive species	Nonindigenous species that spreads from the point of introduction and becomes abundant	Factor: SPE
noninvasive species	Nonindigenous species that remains localized within its new environment	Factor: SPE
Transition	one step in the invasion sequence (e.g. transportation, release, and establishment)	Factor: EP, SPE
Transport	entrained in transport pathway (e.g. flooding)	Factor: EP
Release or introduction	Survives transport and introduction, may fail or become established (above)	Factor: EP, SPE, SPN
Spread (f(time))	A function of time, not always known; leads to non-invasive or invasive status	Factor: EP, SPE
Propagule pressure	Number of propagules arriving at a site (Williamson, 1996: 45)	Factor: PP

2.1.3 Population Based Modeling Approaches

Based on population dynamics and laboratory observations, North Dakota State University developed a proposed model of crown and root bud regulation (Galitz, 1994). That model and others (Maxwell et al. 1988, 1987) provides potential weak points in the life history stages of leafy spurge to suggest control strategies that concentrate on those weaknesses. Many other population-based models have been developed, and the recent decision support system effort by Rinella (2001) exemplifies this category of models.

A review of model-focused literature found that many authors were concentrating on population dynamics without a spatial component. To determine susceptible phases that may offer control options, many focus on plant stage transitions, and sensitivity analysis to evaluate the most promising paths of predicted 'valves' or process choke points of vulnerability in population growth. A current Ph.D. effort at the Sheley plant research lab in Bozeman by Matt Rinella has this focus, yet also recognizes the need for a spatial component to add to the growth model component (Rinella, 2001; personal communication). Maxwell et al. (1988, 1987) employ a population modeling approach for evaluating leafy spurge development and control (1988) and the use of a leafy spurge population simulation model to identify hypotheses and develop control strategies (1987). Four environmental factors identified in these models coincide with three of the proposed components of this study: water availability, light availability, and temperature. The soil moisture factors of elevation, slope, and aspect provide surrogates for these factors. Nutrient availability as the fourth factor can be partially inferred from the soil texture factor of this study.

Another focus of research involves the description of patch dynamics, including seedling establishment and vegetative spread. Selbo-Sarena, and Carmichael (1999) and Messersmith, et al. (1985) examine the reproductive biology of leafy spurge. Smith, et al. (1999) address the implications of variable or constant expansion rates in invasive weed infestations. Stroh, et al. (1990) address leafy spurge patch expansion, finding an annual average spread rate of 0.61 m per year and density of ~ 100 stems per square meter. This is much higher than the 0.64 m over 7 years and densities of 59 stems per square meter found by Selleck et al. (1962) in Saskatchewan. This study and others (Anderson et al. 1999) found zonal spread rates > 10 m in 3 years and patch sizes doubling in 5 years in THRO. Relevant to THRO, the density will increase with top kill by herbicides (Stroh et al. (1990) and density > 100 stems per square meter stunts the new stems to ~ 7.5 cm, with density rarely exceeding 200 stems per square meter.

2.1.4 Spread Direction and Terrain Patterns

Spread predictions have involved laboratory studies, field plots, and temporal observations. Rates vary from 0.61 m per year (Stroh et al. 1990) to 3-5 m in diameter (radial spread of 1.5 to 2.5 m) per year (Selleck et al. 1962 ;Galitz, 1994). Anderson et al (1999) reported a doubling in area coverage in 5 years in THRO, and zonal spread rates > 10 m in 3 years. Change detection and spread rates measured at THRO in the 5-year span from 1993 to 1998 showed a doubling of size of the leafy spurge infestation. Citing Anderson et al. 1999:

> "Most infestations were restricted to drainage channels, creek bottoms, and river bottoms. The extent of leafy spurge increased across all aspects and slopes, however, the rate of increase was slower on south facing aspects and flatter slopes. The faster rate of increase on slopes ranging from 6% to 20% indicate that leafy spurge is slowly moving out of the relatively flat drainage channels and butte tops onto steeper slopes. The difference in the rate of increase between the north and south facing aspects combined with the slope and proximity to drainage channel data indicate that water is likely the driving variable for leafy spurge establishment in the Badlands."

Small patches (< 8 m) expand at rates up to 500 times faster than larger patches, which highlights the need to regularly survey and control small patches as they appear (Lym, 1998; Selleck et al. 1962). Carlson et al (1994) provides a linear expansion formula for leafy spurge at THRO shown in Figure 2.1 with a graph of ages 5-15.

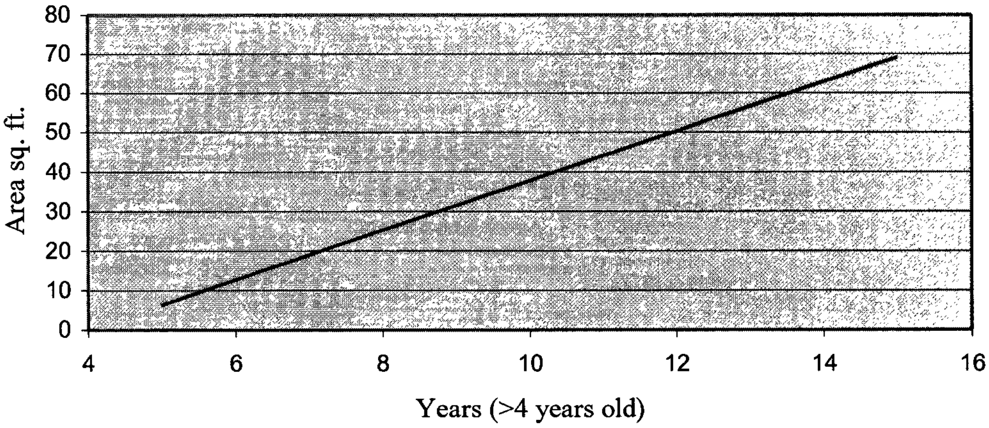


Figure 2.1. Patch expansion for THRO leafy spurge patches at least 4 years old (after Carlson et al. 1994).

Radial growth rate is related to circumference rather than area (Selleck, et al. 1962). Small patches will experience greater percentage increases in area than large patches, given a relatively equal increase in radii. Table 2.4 describes this relationship with examples of patch growth of 20 cm and 8 m patches, relative to similar 0.64 m per year radial spread. This demonstrates that circumference rather than area influences radial growth (adapted from Selleck, et al. 1962).

Table 2.4. Patch growth of 20 cm and 8 m patches, based on a similar 0.64 m per year radial spread over 5 years.

Patch diameter*	**Relative increase in size**
20 cm (6 inches)	500
8 m (25 feet)	1

*** (Radial spread of 0.64 m (2.09 feet) per year)**

Species richness, biodiversity, and landscape density and spread models have also been discussed by Chong et al. (2001); Chong (2002); Kalkhan et al. (2000; 2001; 2003);

and Williams and Hunt (2002). The studies by Chong and Kalkhan examined the species richness and biodiversity in Rocky Mountain National Park, and used spatial statistical modeling to successfully develop and describe the probabilities of invasive plants. Additional similar efforts by Kalkhan et al. at Cerro Grande fire site near Los Alamos, NM found the spatial statistical techniques useful for describing ecological and environmental characteristics of fire regimes, invasive plants, and hot spots of diversity of both native and non-native plants. The efforts by Williams and Hunt were conducted in the Devils Tower area of Wyoming, and examined the regression differences between draws and uplands for leafy spurge presence, and found a feasible method for estimating percent cover within broad cover classes using image filtering techniques. Based on these efforts, this study chose to apply a field data approach using the OLS and kriging techniques described by Chong et al. and Kalkhan et al. to develop the spatial models of the THRO landscape with both probability and leafy spurge presence and absence.

2.1.5 Weed Mapping and Geographic Information Systems

Weed mapping poses both educational and data collection challenges to state and local governments. Citizen involvement has long been sought to assist in the effort. Lacey et al (1985a) studied a successful bounty program in Montana. The bounty system in Montana provided a successful and cost effective detection and inventory effort (Lacey et al 1994). Availability of county control equipment leveraged the community effort, and increased the level of awareness and citizens' efforts to reduce the weed population. Stillwater County, Montana weed managers employed a weed bounty program as a citizen educational tool to promote awareness, detection, and control of spotted knapweed on rangeland. Thirty-four spotted knapweed infestations were located and recorded, and landowners and bounty hunters applied control measures to 20 of the infestations during 1984. County spray equipment and control information were provided to bounty hunters and landowners to aid their effort. By using a nominal $5.00 finders fee and the $50.00 control bounty, the total county expense of rewarding young people through the bounty program was $1170.00. The comparative costs were an estimated $5,670.00 to use county employees to locate and control the spotted knapweed infestations, resulting in a savings of $4500.00 to the county weed budget. Endorsement and adoption by other extension agents in Montana and surrounding states indicates the success of the program. Six additional counties implemented bounty programs in 1985 in Montana. Adoption of this program by other surrounding counties and states indicates that this has been a viable alternative to inventory and monitoring of rural lands (Beck, personal communication).

Larimer County, Colorado participates with a statewide effort to map weeds, and recent efforts include the use of GPS to delineate spot and area (polygon) infestations (Beck, 2001 personal communication). The challenge in mapping weeds and tabulating results focuses on the difference between a hectare (acre) of weeds, versus a hectare (acre) with weeds. Many simple presence and absence surveys are tabulated for county summaries, with crude estimates of the area affected based on the confusion of continuous or spotty densities (Beck, 2001 personal communication).

The use of geographic information systems has allowed easier representation of multiple factors related to spurge detection and mapping, and provided an excellent records system for spatial attribute data about leafy spurge control. Efforts to combine remote sensing data and videography have succeeded when combined with GPS data to georeference image collections and assist with location linkages for these media. Reasonable success in detecting leafy spurge has occurred using interpretation of aerial photography using < 1:24K true color and color infrared films (Anderson, 1994).

2.2 Biology of Leafy Spurge and Terrain Influences

To address the third objective, this study examined the spatial patterns and the published theories of why leafy spurge (termed an invasive plant and a difficult to control or "noxious" weed) occurs where it does. There have been a few early reviews of the biology of leafy spurge. The first to appear were the North Dakota Experiment Station (Hanson and Rudd, 1933) entitled Leafy Spurge, Life, History and Habits, and an Iowa Experiment Station bulletin, Leafy Spurge, *(Euphorbia esul*a) by Bakke, 1936. These presented what was known at the time regarding a basic description of the phenology and the biology of leafy spurge. Selleck, Coupland, and Frankton (1962) published an ecological monograph Leafy Spurge in Saskatchewan that reviewed the biology of leafy spurge and its adaptation to the environment of Saskatchewan, Canada. Galitz (1978) conducted a computer data base search of all the literature on the biology of leafy spurge and wrote a summary, which was published as a departmental report. Later, Galitz and Davis (1983) published Leafy Spurge Physiology and Anatomy, a brief review of some of the biological characteristics of leafy spurge. Messersmith, Lym and Galitz (1985) wrote The Biology of Leafy Spurge, a chapter included in "Leafy Spurge", a monograph published by the Weed Science Society of America.

Leafy spurge seedlings growing without competition develop roots that can penetrate to a meter (>3-foot) depth in four months and attain a lateral spread of 100 cm (40 inches) (Carlson et al. 1994). Barreto and Fay (1981) tested twelve native and introduced grass species grown in three soils to test for the presence of allelopathic compounds. The phenomenon of allelopathy involves the production of substances, called allelochems, by one plant that inhibit or reduce the germination and/or growth of another plant species (Galitz, 1994). It appears that allelopathy is not a major competition device for leafy spurge (Barreto and Fay, 1981). Galitz has also reported that a plant known as small everlasting, *(Antennaria microphyll*a), can grow adjacent to a leafy spurge patch but does not become invaded by the spurge. Experiments indicate that small everlasting produces allelochems that have biological activity, inhibiting the growth of spurge. Attempts to use this chemical as a control tool have not been successful (Beck, personal communication 2002).

2.2.1 Habitat and Nine Growth Habits of Leafy Spurge

Galitz (1994) summarizes the growth habitat as follows:

> "It has been noted that leafy spurge has been recorded to invade and become established in a wide variety of environments. It is especially quick to invade disturbed areas. It is readily found along roadsides and rail right-of-ways, open range, and wooded areas. Spurge can also be found in contrasting situations such as moist marshes as well as dry prairie, in open sunny areas or in the shaded understory of a floodplain, on northern slopes and on southern slopes. In addition to its westward migration since its introduction to the East Coast decades ago, spurge has also shown a gradual southerly migration. Fifteen years ago Nebraska was thought to be the southern limits for spurge. Today, there are reports of its occurrence as far south as Missouri and New Mexico. In the final analysis, there has not been a good ecological study conducted to determine the limiting parameters in the geographical distribution of leafy spurge in the United States."

The growth habit of leafy spurge has nine traits (TEAM Leafy Spurge, 2000).

Early shoot emergence may occur as soon as the ground thaws, which could be as early as mid April. Developing from dormant crown and root buds in August, these shoots remain beneath the soil debris in a cold hardened state. This offers leafy spurge an early competitive advantage over other plants. Rankness is defined as a luxuriant and vigorous growth trait. Although vigorous, spurge is not luxuriant due to the small leaf area yielding a diminished leaf area index. Root growth includes a long primary taproot even very early in development stages. Numerous secondary vertical roots and well developed lateral roots give leafy spurge an early dominant claim to soil moisture both near the surface and deep in the soil profile, typically beyond the root zone of the grasses. Apical bud dominance during the growth period suppresses the additional root buds on the horizontal roots. Additionally, Horvath found that possibly either leaves or stem buds produce enough auxin to prevent root bud growth (Horvath, 1998). These dormant buds begin to elongate because the auxins from the apical meristem decrease during senescence of the shoot during the end of the growing season. These dormant buds are cold tolerant and ready to emerge in early spring, reaching the surface of the soil by the end of the season. The roots are woody, having a durable structure, with numerous buds capable of producing new shoots at numerous points along any root segment (Lym, 1998). Roots are most abundant in the upper 12 cm of soil, but some roots can extend as deep as the water table (Hanson and Rudd 1933). The root system contains a large nutrient reserve capable of sustaining the plant for years (Lym and Messersmith 1987a). Colony expansion utilizes the complex network of horizontal roots that interconnect with the vertical root masses supporting the various stems. Galitz (1994) reports annual increases in radius of up to 3 meters in a good growing season for a 10-meter diameter colony. Approximately 1% of the seeds will germinate successfully and become established as vegetative seedlings (Bowes and Thomas 1978a). Roots of a single plant can spread to form a circle up to 5 m in diameter per year (Selleck, Coupland, and Frankton, 1962) and will inhabit 0.4 ha (1 acre) in 65 years with over 250,000 stems

(Stroh, Leitch, and Bangsund, 1990). Small patches (< 8 m) expand at rates up to 500 times faster than larger patches, which highlights the need to regularly survey and control small patches as they appear (Lym, 1998; Selleck, Coupland, and Frankton, 1962). Regrowth potential results from the apical dominance and lateral suppression provided by the colony shoots. As soon as grazing, mowing, fire, chemical burning, etc. disturb the dominant shoots, the reduction in auxin production releases the dormant root buds from shoot suppression, resulting in rapid regrowth. Population variability, which exists among collections from different sites, is called accessions. Some phenological differences result from environmental growing conditions; however, the variability between accessions is genetic (Galitz, 1994). The variability seen at THRO has been environmentally interpreted as variation in moisture, spurge green-up date, and late season curing (Hager, personal communication). The laticifer system involves a network of tubules containing large quantities of latex. This system is intermingled, but entirely separate from the vascular system. Latex can be found throughout the plant from root to shoot (Bakke 1936). Injury to any part of the plant will result in immediate flow of the white, sticky latex to seal the wound (Lym, 1998). Leafy spurge latex contains a highly irritating and inflammatory compound called ingenol (Seip and Hecker 1982; Upadhyay et al. 1978) that, when taken internally, is an irritant, emetic, and purgative to most species (Bakke 1936). Latex causes scours and weakness in cattle and may result in death (Selleck, Coupland, and Frankton, 1962). Factors for insect biocontrol may depend on some components of this latex compound. In previous studies, allelopathy has been considered as a dominant strategy for competitive control exerted by spurge, but has been dismissed after examination by Barreto and Fay (1981) and Beck (personal communication). Stress resistance is the ninth and final habit giving leafy spurge competitive advantage. Leafy spurge withstands considerable water stress by avoidance; the long tap root system serves to supply it from greater depths than other adjacent grassland plants. Under severe stress, tissue dormancy provides an additional mechanism for leafy spurge to resist stress.

2.2.2 Relationships Between the Physical Terrain Characteristics and Leafy Spurge Presence

In a previous 5-year study of leafy spurge spread at THRO, Anderson et al (1999) concluded that leafy spurge was moving out of the drainages and into the upper slopes. Earlier work by Anderson et al (1996) found that patch distance from streams influences the area of infestation. The relationship between area inhabited by leafy spurge and the distance of the stands from a drainage channel emphasizes the non-random distribution of leafy spurge within the park. The study by Anderson et al (1996) employed 10-meter zones to execute a proximity analysis, with terrain related summary sections quoted below:

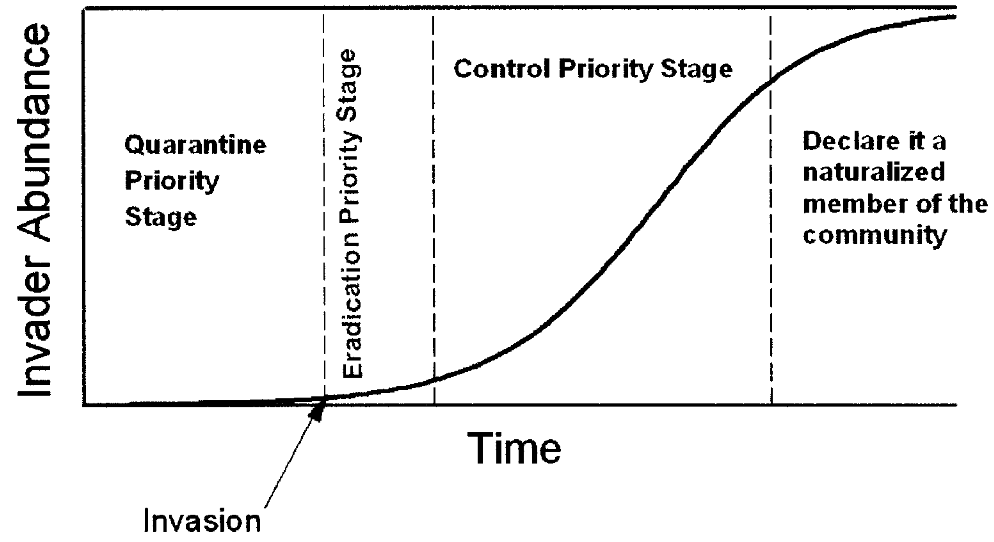
> “Most of the infestation appeared to be restricted to drainage channels, creek bottoms, and river bottoms. The curvilinear relationship:
>
> $$\text{Area} = 93.88e^{-1.013817821d}$$
>
> where area = the total area infested by leafy spurge and d = the distance from a drainage channel in 10 meter increments, accounts for 98 percent ($r^2 = 0.98$) of the variance found in the data. Leafy spurge was not closely associated with other topographic features. Spurge seemed to have a slight affinity for northeasterly aspects and gentler slopes.

> Leafy spurge was found in 15 of the 16 watershed basins. Sub-basins in the northwest portion of the park, contained 355 ha (over 50%) of the leafy spurge in the park and [a] sub-basin in the southeast portion of the park appeared to be free of leafy spurge. Qualitative assessment, however, indicated that not all leafy spurge in the park was detected. Leafy spurge was not detected under dense riparian forest canopies or woody draws. Interpreters also had difficulty-detecting spurge in deep stream channels and on steep slopes. Contributing factors included: limited visibility, shadows, reduced plant height in conjunction with sparse plant density, and limited bract production." (Anderson et al. 1996)

This is consistent with the findings of others (Carlson et al. 1994) and the general biology discussed earlier on the range of habitats of leafy spurge. Specific to THRO, the badlands geology and landforms offer small catchments and swales of higher moisture concentration, with a high apparent correlation to leafy spurge infestation and spread (Anderson et al 1999, 1996, 1994; Anderson, Root, and Brown, 2001).

2.3 Environmental Setting for Leafy Spurge in THRO

Relevant to this study area in Theodore Roosevelt National Park (THRO), exotic species spread within riparian zones is aided by contiguous, often linear or branching habitat where dispersal of seeds by water is common (Stohlgren et al. 1998). These may also serve as 'source' populations (Pulliam,1988) of exotic species, ready to invade the upland sites when local conditions are favorable. The corridor connectivity has profound negative impacts on the ecosystem; however, the positive aspects of migratory and habitat corridors are usually stressed (Primack, 1993). The National Park faces a balance of many competing needs, including native herbivore stocking to maintain the grassland ecosystem. Clearly, the migratory paths potentially serve as the vectors for exotic plant transport as well. Lonsdale (1999) found that in over 184 sites around the world, nature reserves had one-half of the relative exotic presence of sites outside reserves, and contrary to expectation, communities richer in native species had more, not fewer, exotics. This concurs with Stohlgren et al (1998). Of major relevance to the National Park Service, Lonsdale (1999) also noted that the number of exotic species in nature reserves increases with the number of visitors. Not only wildlife migration zones, but also human transportation vectors contribute to the spread of exotics in nature reserves. Figure 2.2 shows invader abundance relative to time and the control priorities and possible status changes. Transition from invader to status as a naturalized member of the community depends on the management regulatory climate (Hobbs and Humphries, 1994 citing Chippendale, 1991).



Adapted from Hobbs and Humphries (1994)

Figure 2.2 Invader Abundance relative to time since invasion.
(Adapted from Hobbs and Humphries, 1994 citing Chippendale, 1991).

To complete this section on invasive ecology, a review of soil moisture relations focuses the overwhelming importance of water in this ecosystem for plant community structure, diversity, and probable relevance in exotic spread prediction. Available soil moisture and the depth variations of that water will influence plant growth and vigor, the competitive advantage of different plants, and over time will control the resultant plant communities. Most THRO sites exhibit dry soils, which is the frequent state of soils in semiarid regions, interrupted by brief wet periods (Sala et al 1992). Both timing and amount of moisture influence the plant community. In general, adequacy of precipitation is the key variable for delineating ecological or agricultural sites (Bailey 1979). Skinner (1982) determined that soil texture, topographic position, and available water holding capacity were useful in stratifying large geographic areas to identify existing or potential leafy spurge populations near Devil's Tower, Wyoming.

The long-term depth distribution of available water will depend upon soil texture, temperature, and precipitation. Available water for plant growth can be defined as water in the soil held at a matric potential of 0 to –1.0 MPa, available during the growing season (Sala et al. 1992). Using available soil moisture as a prime target, the factors of precipitation delivery and concentration are defined by topographic and soil texture factors. Incoming solar energy described by aspect provides the plant stress and soil-drying component. Additionally, the inverse texture hypothesis of Noy Meir (1973) suggests that arid environments, with less than 50cm annual precipitation, will have an inverse relationship between soil texture and available soil moisture. The resulting grassland annual net primary productivity yields greater production on coarse textured soils with lower water-holding capacity because water penetration is deeper and less surface losses occur from bare soil evaporation. This is consistent with the findings of Carlson et al. (1994) for THRO where they suggest that leafy spurge grows in nearly all soil types, but appears to favor coarse textured soils. Conversely, in riparian and nearby upland zones, Stohlgren et al (1998) found a higher correlation between species richness and the presence of exotics with higher percentages of silt and clay. These observations are not contradictory, as the riparian zones have more moisture regardless of soil type, and the more arid uplands and plateaus have a drier moisture regime where the coarse textured soils will have higher available moisture by reduced surface losses.

Texturally, a clay loam ranges from 25-40% clay, 20-45% silt, and 20-45% sand. The loamy sand soils have the least clay and silt (>20% each), and the most sand (70-85%). This sandy texture will result in a lower field capacity than the clay loam texture that supports a higher field capacity. The available moisture decreases due to the lower field capacity of sand versus clay; however, the depth of penetration is deeper than the clay. As noted by Brye et al. (2000), the prairie residue layer also serves as an infiltration barrier, so the soil profile infiltration will be less than the precipitation delivered to the prairie ecosystem. Both evaporative losses from residue and bare soil evaporation will decrease available soil moisture.

2.4 Remote Sensing and Delineation

Geographic information system (GIS) and remote sensing methods, technology and classifications have been integrated for a variety of natural resource applications (Graetz et al. 1983; Eidenshink et al. 1988; Myhre, 1992; Richardson et al. 1993; Anderson et al. 1993b), including mapping the distribution of noxious weeds (Dewey et al. 1991; Anderson et al. 1993a; Everitt et al. 1994). To evaluate control measures on noxious plant populations, remote sensing data in geo-referenced formats help to evaluate the position and extent of infestations, and to develop management strategies.

Previous studies have also blended GIS with videography and aerial photography to develop spatial context. Elliston and Miller (1987) studied the mapping of leafy spurge with color video and micro-computer image processing, and Wilson et al. (1993) coupled GIS and models for weed control. Fourteen additional GIS and image processing articles that address imagery timing, spurge phenology, and plant to soil contrast are contained in the TEAM Leafy Spurge (2000) Purge Spurge compact disk. The timing and phenology of the plant are important. The leafy spurge near Medora, North Dakota peaks near the last week of June to the first week of July typically (Hager, personal communication). The spurge is most robust, and exhibits the full flush of flowering parts with the brightest yellow green reflectance at this time. The timing for the Advanced Land Imager collections for this study and the other related efforts using the AVIRIS and Hyperion EO-1 hyperspectral sensor data (Root et al, 2004 in press) matched this phonological timing, with a collection on July 6, 2001. Representative previous Theodore Roosevelt National Park (THRO) works with GIS and remote sensing on collection, effectiveness, cost utility, and spread and change detection include Everitt et al. (1995); Anderson (1995), Andrascik, (1994), Anderson et al. (1999) and Cogan and Butler (1999). As part of the TEAM Leafy Spurge study at THRO, a concurrent Ph.D. effort by Kay Dudek involves an AVIRIS sensor based change detection comparison between 2000-2001.

When comparing image analysis with ocular estimates, Birdsall et al (1997) concluded that photography based density estimates were comparable at high, medium, and low densities of leafy spurge, and the color prints provided a visual record of the coverage. That study used ground level 35mm photos at 1m height over the vegetation, in 9 by 13 cm color format, that were then gray scale scanned (eight bit) for digital analysis and comparison to ocular estimates in the field. Anderson et al. (1999) described the successful use of GIS and aerial photograph interpretation of leafy spurge from 1:10K true color and CIR in 1993 and 1998 respectively. That effort is described further in Chapter 3 and forms one dataset for this study. Alternatively, the efficiency and comparability of digital techniques could yield a cost benefit over larger study areas, compared to traditional photography (Jensen, 1996; Avery and Berlin, 1992).

Several unifying themes were present in the GIS and remote sensing topics. Those authors provided the following pertinent and relevant points for this THRO study. Several sensors (i.e. aerial photography, videography) gave appropriate spatial and spectral resolution for mapping leafy spurge and other invasive weeds (Everitt et al. 1995; Anderson, 1995). Myhre (1983) compared photo scales (1:16,000; 1:24,000; and 1:32,000), film types (color and color-IR), and seasons (peak flowering and fall coloration) to determine the combination(s) best suited for large area surveys. No spatial model type for spread prediction is currently present for a decision support system (Anderson, 2001; Rinella, 2001). The regional demand for a synoptic (landscape) evaluation of weeds will continue to require refinement of remote sensing data sets, as higher spatial and spectral resolution imagery becomes available

2.4.1 Spatial Resolution

In the broadest sense, spatial resolution of a map or any graphical visual product depends on the source data quality and accuracy. Generally, maps are derived from aerial photography or other remote sensing platforms, and each method has issues of resolution. Spatial resolution defines the capability of an imaging system to collect spatial detail. It also represents the smallest angular or linear separation between two objects that can be resolved by the sensor (Jensen, 1996). The resolving power of that system depends on the system capabilities, such as grain size and scale for photographic products. However, the resolution is inversely proportional to grain size because the larger the grains, the poorer the resolution and vice versa (Avery and Berlin, 1992) For digital scanning systems other than film, (e.g. Landsat TM @ 30 x 30m; CASI @ 4 x 4m), spatial resolution measurement is simply the dimension in meters of the ground projected instantaneous field of view (Jensen, 1996). The instantaneous field of view determines how much ground area a scanner 'sees' at any given instant in time; this ground area is called the 'ground resolution cell' (Avery and Berlin, 1992).

Hyperspectral sensors can detect leafy spurge from 3 m to 30 m pixel sizes (Anderson, 2001; Brown and Root, 2001). Depending on scale and drainage project size, aerial photography may be more cost effective than hyperspectral, due to higher collection and processing costs (~$75K AVIRIS flight costs) for hyperspectral sensor data. However, Everitt et al (1995) cautioned that even the spatial resolution of 0.3m on 1:10,000 scale aerial photography did not detect sparse stands or clumps of leafy spurge in THRO with less than 25% canopy cover and single plants less than 30cm in diameter. For THRO, the number of photos and analyst time required may only be cost effective for the finest detail searches for small starts. At large landscape scales, CASI (see Table 1.1) may be cost effective for detecting leafy spurge at 3-m resolution. The successful use of

Landsat TM at 30 m pixels has only found the excessively large, established patches, with a relatively simple supervised grassland classification (Anderson, 2001).

2.5 Prediction Maps and Spatial Statistics

Four-category maps of the 1993 infestation are presently available to THRO. The study by Anderson et al (1994) identified and grouped sub-basins of the park by the extent of area categorized as infested in 1993. In that study the general categories of leafy spurge infestation by watershed sub-basin were: heavy (>5%), moderate (1-<5%), light (>0 but 1<%), and none. The current Park leafy spurge prediction map is a simple constant-rate buffer applied to 1993 to 2001 mapped infestations.

Spatial statistical analysis involves a newer and less defined branch of statistical analysis. The study by Anderson et al (1996) developed the map products and statistics using software subroutines contained in the Geographical Resources Analysis Support System (GRASS)GIS (U.S. Army Corps of Engineers). Many modern GIS packages are equipped with statistical packages to assist in spatial analysis. GIS software are not purely designed as compared to common statistical packages, since the user does not have any idea about the statistical properties (Kalkhan, personal communication). More advanced functions than that contained in commercial GIS (e.g. autocorrelation) may require additional packages like S-plus (Mathsoft, Inc., 1995). Reich and Kalkhan (2000) summarize the application of autocorrelation measure and evaluation, kriging, and surface model development in natural resource applications. There are several studies discussing landscape variability and trend surface modeling (Gown et al. 1994; Reich et al. 1999). For accuracy assessment statistics, several studies on the Kappa statistic and proportional Kappa were reviewed (Bishop, 1975; Congalton, 1991; Kalkhan 1994;

Jensen, 1996; Kalkhan et al. 1997 and 1998). As stated by Jensen (1996) the Kappa statistic is a measure of agreement or accuracy. The Kappa incorporates the off diagonal elements in the error matrix, giving a product of the row and column marginals. By including these off diagonal omission and commission errors, this value tells more than the overall accuracy that uses only the major diagonal values. The value of the Kappa is to determine whether the results in the error matrix are significantly better that a random result.

Binary regression tree-based models are exploratory and can uncover structure in data as an alternative to linear and additive regression models (Mathsoft, Inc. 1999). The regression tree is a non-parametric approach to regression that uses a binary partitioning algorithm to maximize the dissimilarities among groups by comparing all possible splits of independent, continuous variables. The algorithm recursively splits the data in each group until the subset is homogenous or there are fewer than 5 observations in the subset (Mathsoft, Inc. 1999).

Hansen et al. (1996) describe binary regression classification trees:

> Classification trees use a set of independent variables to predict class memberships. A tree is constructed by recursively partitioning a data set into purer, more homogenous subsets. The method uses a deviance measure, the likelihood ratio statistic, to compare all possible splits of the data to find the one split that maximizes the dissimilarity among the resulting subsets. Possible splits of each independent variable are examined, and the particular split within a particular variable that produces the largest deviance measure is chosen to partition the dependent data. Once the tree partitions the data into new subsets, entirely different relationships using other predictor variables can be defined to split the new subsets. In addition, predictor variables which have already been used higher up in the tree may be reexamined and possibly reintroduced into the tree structure. In this manner, hierarchical, nonlinear relationships within the data are derived.

Pruning successively removes the least important splits, where the importance is determined by a cost-complexity measure that takes into account the deviance of the subtree, the number of terminal nodes of the subtree, and a cost complexity parameter (Mathsoft, Inc. 1999, p 385). Selecting the pruning level is accomplished by choosing the number of tree nodes having the lowest deviance with the lowest value (lowest error in classification) desired for the optimum pruning of the regression tree (Kalkhan, personal communication).

An excellent discussion of image classification and error analysis can be found in Jensen (1996). The classical estimates of omission and commission errors, kappa, and overall accuracy are frequently used to describe the quantity the quality of the effort (Jensen, 1996). Gown et al. (1994) stated that many spatial datasets suitable for coarse-scale ecological monitoring fall short in the precision required for more refined ecosystem resource models. Spatial statistics provide a means to develop spatial models to correlate coarse scale geographical data with field measurements of biotic variables (Kalkhan et al. 2000)

CHAPTER III

III. MATERIALS AND METHODS

3.1 Site Description and Overview

To allow broad examination and conclusions regarding the interactions among slope position, soils, and leafy spurge presence, this study included the interpolation of leafy spurge probability to the landscape-scale, utilizing generalized predictive spatial statistical models derived from aerial photography derived leafy spurge polygons, Geographic Information Systems (GIS), and field data.

Assessing landscape-scale structure of forest and rangelands by the integration of spatial information (remote sensing data, GIS) and spatial statistics provides useful results for forecasting the condition and environment of the landscape at different scales and sample levels (Reich et al. 1999; Kalkhan et al. 2000, 2003; Chong et al. 2001). In addition, the generation of full-coverage maps depicting characteristics measured in the field is required to enable one to model the small-scale variability in landscape characteristics (Gown et al. 1994). Gown et al. (1994) point out the limits of spatial datasets, specifically that while many spatial datasets describing land characteristics have proven reliable for macro-scale ecological monitoring, these relatively coarse-scale data are wanting in providing the precision required by more refined ecosystem resource models. Reich et al. (1999) described a model to evaluate large-scale spatial variability based on the process using stepwise regression, trend surface analysis of geographical variables (e.g. elevation, slope, and aspect), and measures of local taxa. A modification of this model was used in this study.

A spatial model was chosen because previous work had identified distance from stream, slope, and aspect as important variables helping to explain leafy spurge occurrence (Anderson et al. 1996; 1999; Carlson et al. 1994). These earlier efforts identified leafy spurge spread near stream bottoms, but did not quantify 'where else' spread may be expected. Aspect, slope, and distance from stream were evaluated in previous work; however, a predictive spatial statistical model was not developed.

The integration of spatial information using spatial statistical models assists the investigation of spatial relationships among soils, slope position, and invasion by leafy spurge through the linkage of physical factors of topographic aspect, slope, and elevation (Kalkhan and Stohlgren, 2000). This technique provides two valuable products. First, the outputs yield useful information about the probability distribution of invasive plants. Second, the effort provides tools for describing ecological and environmental characteristics of leafy spurge invasive plant spread on the Theodore Roosevelt National Park, Medora, North Dakota.

3.1.1 Study Site and Theodore Roosevelt National Park Characteristics

Theodore Roosevelt National Park (THRO) is composed of two separate land units, and native mid-grass prairie occurs in both units. The Park units are each bisected by the Little Missouri River flowing north. The Little Missouri drainage has its headwaters near Devil's Tower in northeast Wyoming, shown in Figure 3.1. This study focused on the more visited south unit with an area of 18,680 ha. The park headquarters are in Medora, North Dakota, shown in Figure 3.1.

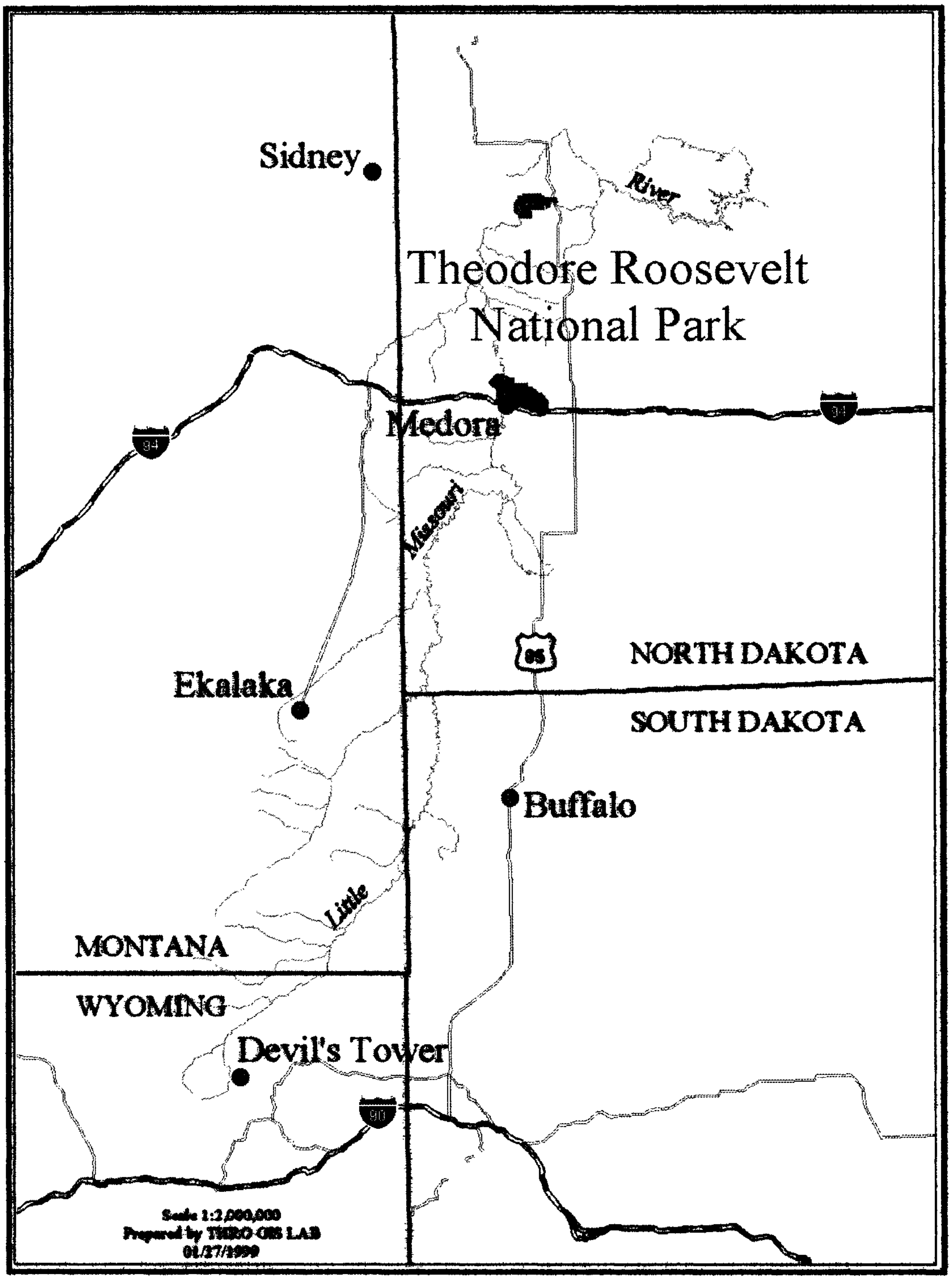


Figure 3.1 Vicinity map for THRO project area

The geology of the park includes clay and sandstone layers deposited in the Williston basin during the late Paleozoic period (Levin, 1978). The formation of the Black Hills uplifted the entire area, with subsequent erosion by glacial melt-waters released at the end of the last ice age. These geologic events and processes created the dissected clay buttes, shallow topsoil, and sedimentary outcroppings that characterize the North Dakota Badlands (Anderson et al. 1996).

The area receives an average precipitation of 380 mm distributed synchronously with the growing season, which is from April to September. Mean annual temperature equals 6° C, with a peak temperature in July of 22° C. Westerly airflow and general aridity dominate this climatic regime. These climatic factors, combined with fine textured soils, result in a mixed-grass dominated ecosystem which is juxtaposed between regions of the shortgrass steppe to the south and the tallgrass prairie further east (Lauenroth et al. 2000). The general climatic characteristics for the Medora, ND area are summarized in Table 3.1 below, based on 30 years of record (Weatherbase.com, 2001).

Table 3.1. 30-year Site and climate characteristics for THRO.

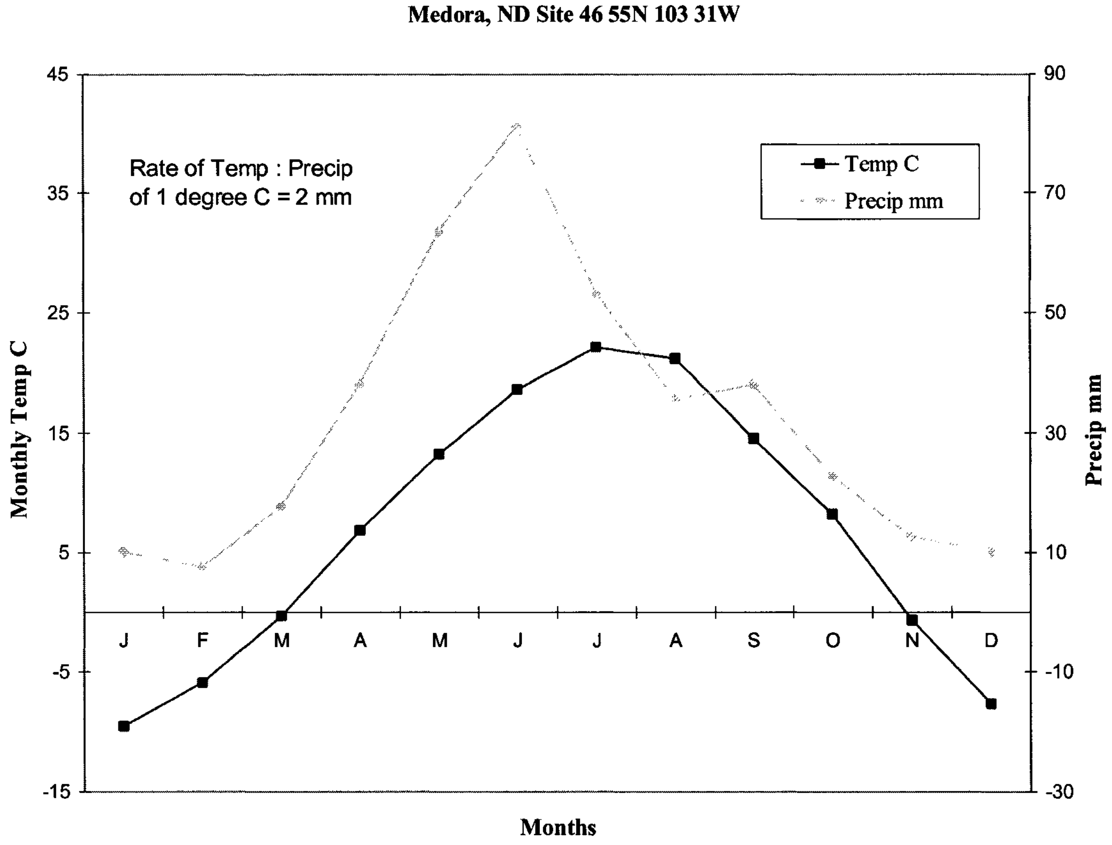
Medora, ND	Elevation	Latitude	Longitude
	697 m (2286 ft)	46° 55' N	103° 31' W
Average Temp	6°C (44.1°F)*/yr	High 14°C (58.7°F)	Low -1°C (29.5°F)
		Highest 22°C July	Lowest -8°C Jan.
Average Precipitation	38cm (15.3 in.)*/yr	High June 8cm (3.2 in.)	Low Feb <1cm (0.3 in.)

* Average for the year
Source: Weatherbase.com (2001): Historical Weather for Medora, North Dakota, USA. Years on record: 30.

The synchronous delivery of moisture with favorable growing temperatures is illustrated in Figure 3.2 below in a Walter and Lieth style climate diagram (Walter and

Lieth, 1960-1967; Walter et al. 1975; Lieth et al. 1999). The convention for this type of diagram sets the annual distribution axes at a rate of 1 degree C = 2 mm precipitation. (Walter et al. 1975; Lieth et al. 1999).

Figure 3.2 Walter and Lieth style annual climate diagram for THRO



3.2 Data Analysis

This study utilized both existing data sources and derived data. The primary leafy spurge data set used in this study was from the 1993 interpreted aerial photography. The previous leafy spurge mapping work and the advantages of that 1993 data set follows.

3.2.1 Previous Leafy Spurge Mapping at Theodore Roosevelt NP

Based on aerial photo interpretations, previous mapping efforts quantified the leafy spurge from 1993 to 1998, with film type and plant phenology described in the following section. The south unit had leafy spurge in a majority of the park drainages shown for 1993 in Figure 3.3. In 1993 the area of coverage was estimated at 702 then revised to 591 ha of the 18,680 ha south unit. (Anderson et al. 1996). Further, the previous leafy spurge work by Anderson et al. (1994; 1996) divided and classified the park's watershed sub-basins into the four infestation ratings shown in Figures 3.4 and 3.5.

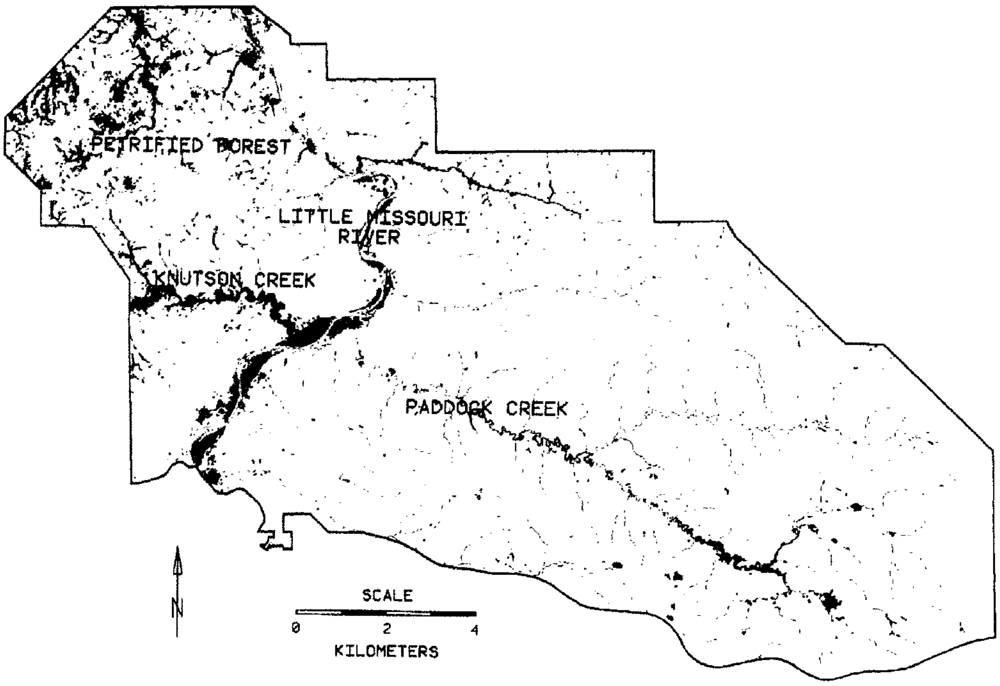


Figure 3.3 South Unit infestations (shown in green) in 1993 from Anderson et al. (1994)

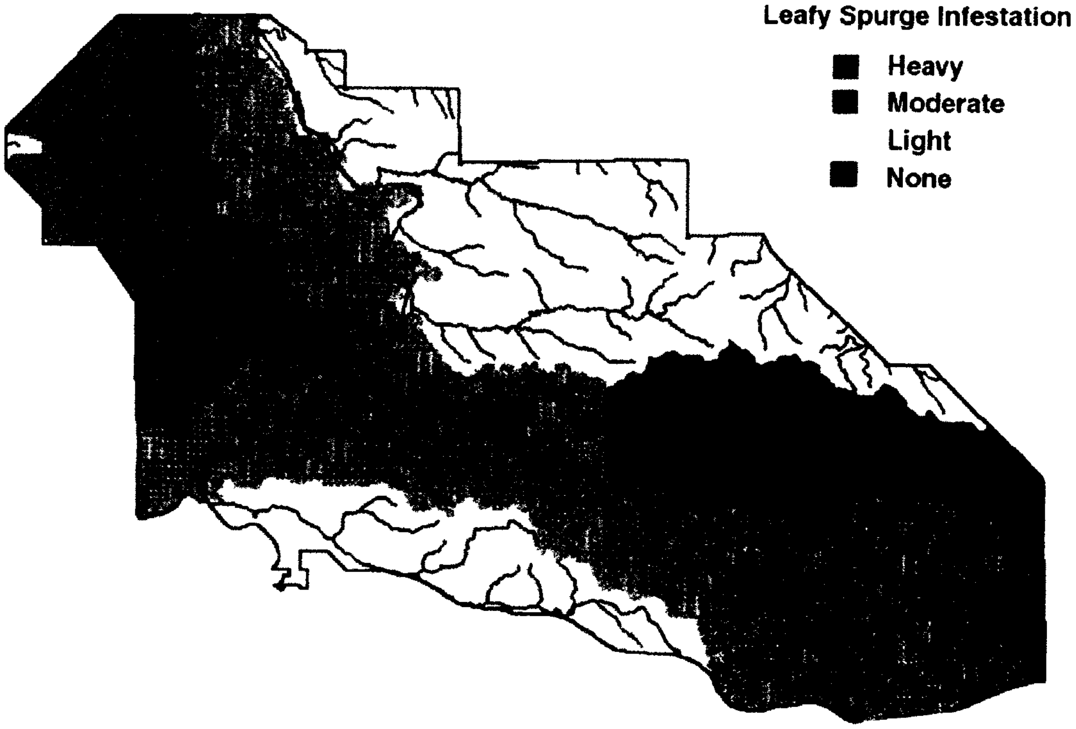


Figure 3.4 South Unit infestations by sub-basins from Anderson et al. (1994; 1996).

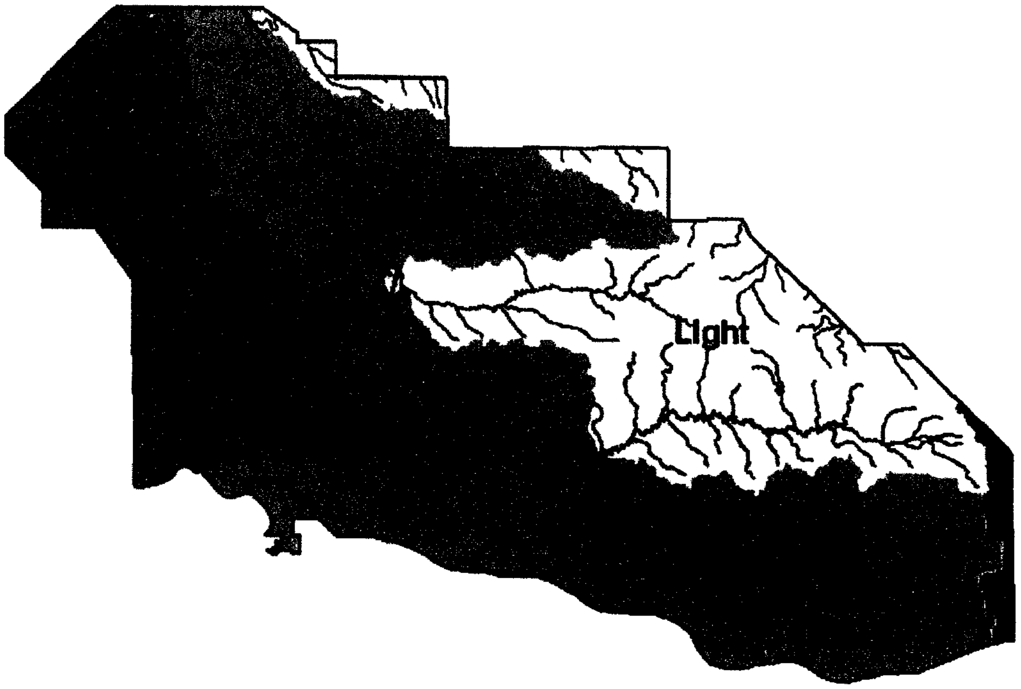


Figure 3.5 South Unit 1998 infestations by sub-basins from Anderson et al. (1999). Heavy (>5%, red), moderate (>1 but <=5%, orange), light (>0 but <= 1%, yellow), and none infested areas (green).

The previous figures 3.4 and 3.5 illustrate that between the 1993 and 1998 aerial photo evaluations, leafy spurge spread upstream into new sub-drainages, and expanded in density in the previous infestation areas (Anderson et al. 1999). Previous spurge mapping GIS data sets at THRO were used. Table 3.2 below summarizes the primary and associated data sets and their scale, date of collection, and availability that support leafy spurge mapping at THRO.

Table 3.2 A summary of the primary and associated data sets of the study, and their characteristics of scale, accuracy, date, and availability.

Data Sets (NAD83)	**Scale and Accuracy**	**Date**	**Availability**
Soils; reprojected vector data set	1:250K resampled to 1:24K tiled; meeting USGS National Map Accuracy Standards (see footnote1)	1994; digitized or raster scanned within 0.01 inches on 1:250K source (NAD27)	THRO GIS office; USGS-CBI[1] Denver
Digital Elevation Model (DEM); *raster data set*	10 meter tiled; meeting USGS National Map Accuracy Standards	USGS tiled and edge matched 2001	USGS-RMMC[2] Denver
1993, 1998 spurge polygons; base-line data; *vector data sets*	Many polygons GPS ground verified at ~2m (NAD83)	1993, 1998 1:10K photo interpretation by ARS / NPS	THRO GIS office; USGS-CBI[1] Denver
Hydrology; *vector data set*	1:24K tiled; meeting USGS National Map Accuracy Standards	USGS; unknown	THRO GIS office; USGS-CBI[1] Denver
Control Sites; *point, line, and polygon vector data sets*	GPS verified to sub-10m resolution. Use of PPS[3] and SPS[4] positioning methods	Continuous development at THRO since 1995	THRO GIS office; USGS-CBI[1] Denver
Field Surveys of Vegetation Type and biomass	32X32 meter grid cells; biomass on 550 plots, 3m x 5m in size	1999-2001	THRO GIS office; USGS-CBI[1] Denver

[1]USGS-CBI: Center for Biological Informatics, Denver
[2]USGS-RMMC: Rocky Mountain Mapping Center, Denver
[3]Precise Positioning Service, U.S. Dept. of Defense Navstar Global Positioning System
[4]Standard Positioning Service, U.S. Dept. of Defense Navstar Global Positioning System
ARS / NPS: Agricultural Research Service / National Park Service

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1 National map accuracy standard: 90% of the points will fall within 1/50th of an inch at the scale of use. On a 1:24,000 quad sheet this equates to ± 40 feet horizontally, and ½ the contour interval for height.

In 2001, detailed ground surveys by THRO staff were made of leafy spurge infestations to evaluate spatially the presence and density of spurge relative to the native vegetation. The 32 x 32 meter sample grids included the percent cover of up to 29 vegetation types (National Park Service, 2001). This data contributed to the verification of the point data for biocontrol evaluation. From 1999 to 2001 surveys were conducted by THRO cooperative researchers led by Dr. Diane Larson to monitor spurge response to chemical and biological control measures. Measures of biomass and crown cover of leafy spurge and native vegetation were collected on 550 plots located in a combination of known bio-control release areas, and stratified random samples from areas previously mapped as leafy spurge (Anderson et al. 1997). The 2001 spurge biomass data from this study was used in the quantitative accuracy assessment of the ALI traditional classification.

3.2.2 Theodore Roosevelt 1993, 1996, and 1998 Photo Interpretation

Three previous efforts to map leafy spurge at THRO employed both GPS (Global Positioning System) polygon data and reference aerial photos. The 1993 and 1998 photo missions were planned for summer acquisition to maximize the spurge flowering, and at a relatively fine (large) scale of 1:10,000 to aid in the interpretation. Figure 3.6 illustrates the change between 1993 and 1998 in the west side of the South Unit of THRO. In Figure 3.6, the original map scale of 1:50,000 has been reduced to fit the page. Between 1993 and 1998, leafy spurge expanded from 591 ha to 1,194 ha (Anderson, 1999). Based on personal involvement, the Park GIS specialist believes the 1998 interpretation by NPS staff overstated the extent on the aerial photography, but concurs with the general spread directions and patterns. (Hager, 2001 personal communication). The yellow lighter shaded polygons were digitized from 1993 1:10,000 scale true color air photos. The red darker shaded polygons, showing expansion, were from the 1998 1:10,000 scale color infrared (CIR) air photos. The Agricultural Research Service staff in Sidney, Montana interpreted the 1993 true color set, with review and concurrence of the THRO staff. Another effort from the USGS and National Park Service Vegetation Mapping Program utilized 1996 true color 1:8,000 aerial photography to characterize the vegetation associations, including leafy spurge vegetation. The National Park Service GIS staff at THRO interpreted the 1998 CIR photos. The Bureau of Reclamation GIS and Remote Sensing group, which was contracted for the vegetation mapping project, interpreted the 1996 photography and developed the GIS data layers and accuracy assessment for the vegetation map (USGS, 2003. Source URL: http://biology.usgs.gov/npsveg/). The minimum mapping unit was 0.5 ha, or ~70 square meters. The leafy spurge polygons from the 1996 effort were not as detailed as the 1993 set.

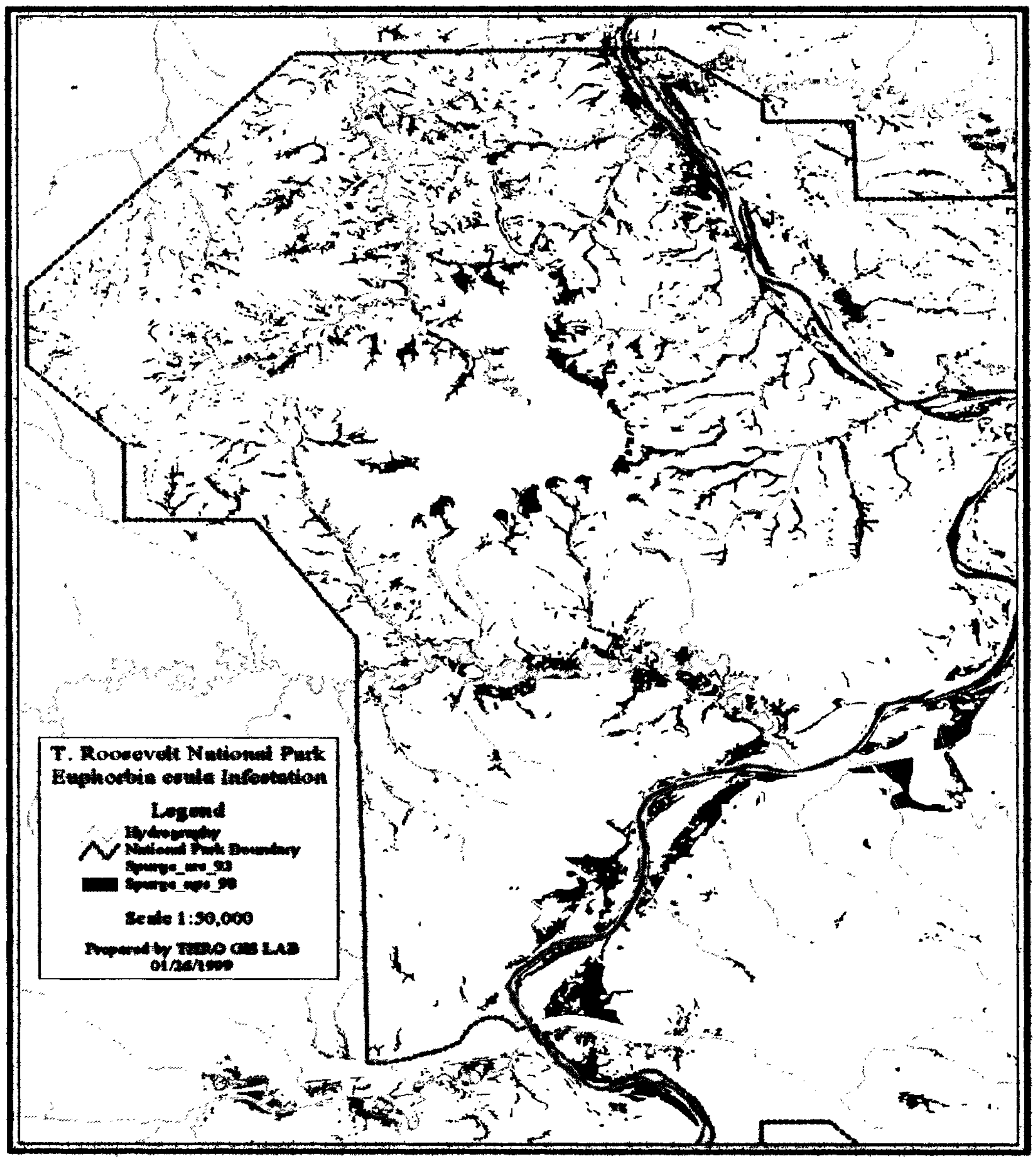

Figure 3.6 Aerial photography based maps of leafy spurge infestation in 1993 (591 ha) and 1998 (1,194 ha).
(Shown here at a scale of 1:61,540)

The relative ground reference confidences were as follows: Previous THRO spurge polygon data sets from 1993 and 1998 were collected and ground referenced with GPS prior to 2000, using a combination of Precise Positioning Service (PPS) and Standard Positioning Service (SPS) with differential correction to obtain the sub 10-meter accuracies needed for park management and for the larger research effort. The details of these GPS services are described in Appendix 3. The data sets from 1993 and 1998 shown in Figure 3.6 and the 1996 photography for the Vegetation Mapping Program (VMP) effort used the same sub-10 meter accuracy capabilities for geospatial rectification, or georeferencing. The 1996 VMP completed a formal accuracy assessment ≥ 80%. The THRO and Agricultural Research Service (ARS) photo interpreted polygons did not have a formal accuracy assessment. Subsequent fieldwork has verified the 10-meter georeferencing with high confidence at THRO. The Compact Airborne Spectrographic Imager (CASI) imagery was used for a qualitative ground reference only. It is described in Appendix 4.

The GIS staff at THRO believes the 1993 interpretation, subsequent GPS verification, and the resulting GIS data set for 1993 to be the best representation of leafy spurge, and was the spurge data set selected for the model development of this study (Hager, 2001 personal communication). The 1993 data set was chosen over the 1996 vegetation mapping effort because of the generalization of the 1996 vegetation polygons to meet the 80% overall accuracy requirement.

3.2.3 Data Preparation

To develop the needed spatial parameters, the physical factors contributing to soil moisture were reviewed. Slope, aspect, and drainage position were three of the physical factors (e.g. others might be latitude, elevation, etc. or others) controlling both moisture delivery and incoming solar energy. The 10-meter DEM provided four of the needed 'derived' products: elevation, slope, aspect, and slope position. Elevation was used to the nearest meter. Slope was broken into four classes based on recommendations from Anderson et al. (1999) and personal communication (Anderson, 2001). Aspect was divided into the eight cardinal directions using the standard ArcInfo classes. Slope position was derived from the DEM into three zones to reflect height above the floodplain. Soils texture was another component controlling soil moisture relations. Because available soil moisture had been identified as an important factor in leafy spurge occurrence and spread (Anderson et al. 1996), eight soil types (textures) were identified from existing GIS soils layers and used in this study.

The spatial resolution of this study is 10-meters. The scale of the aerial photography used in this study is similar (~1:10,000) to previous studies at THRO (e.g. Anderson et al. 1996). Everitt et al. (1995) caution that even the fine spatial resolution of 0.3m on 1:10,000 aerial photographs did not detect sparse stands or clumps of leafy spurge with less than 25% canopy cover and single plants less than 30 cm in diameter at THRO. This study uses a variety of data sources with different effective resolutions, all of which have been resampled to a 10-meter common resolution. Although GIS mapping techniques may provide a map at virtually any scale, the supporting data quality and accuracy will be constrained by the resolution of the source data. Because we used a 10-meter DEM, all spatial information (GIS) datasets shown in Table 3.3 were resampled to 10-meter grids using the GRID module in ArcInfo (ESRI, 2000) to facilitate processing for the spatial model developments. The S-plus (Mathsoft, 2000) statistical package was used for all statistical analyses in this study.

Table 3.3 Summary of the model parameters of interest in predicting leafy spurge spread in THRO.

Parameter	**Data source or lineage**	**Comment**
X coordinate	Standard UTM geocoding	Avenue script sampled across landscape and spurge polygons[2]
Y coordinate	Standard UTM geocoding	Avenue script as above sampled across landscape
Slope	Derive from 10-m DEM[1], and resample to 4 classes	1: 0-5°; 2: 5-15°; 3: 15-30°; 4: 30°+
Elevation	Derive from 10-m DEM	To nearest meter
Aspect	Derive from 10-m DEM to evaluate solar energy; 8 cardinal classes	8 standard ArcInfo aspect classes
Slope Position[3] Zones 1 (lowest) Zone 2 (midslope) Zone 3 (ridgetop)	Stratify into 3 zones	1: Floodplain <= 5m elevation difference; and foot of slope (bank edges above floodplain) 5-8m elevation change; 2: Midslope 8 m above floodplain to <=5m from ridgeline: 3: Ridges 5m below ridgeline on both sides
Soil type (category) e.g. FSL=Fine sandy loam	Soils texture name attribute from NRCS soil survey	1: silt; 2 Unweathered Badlands; 3: silty clay loam; 4: loamy fine sand; 5: loam; 6: gravelly sandy loam; 7: fine sandy loam; 8: Cn loam

[1] 10-m DEM may not be available for many parks, so the resampled 30-m DEM may suffice, IF the resampling does not use nearest neighbor methods. A Cubic convolution or other method will ensure proper resampling as described in Maloy and Dean (2001).

[2] Multiple X, Y points were retrieved across the landscape in a random sample and normalized by subtracting the minimum value to maintain numerical stability (Isaaks and Srivastiva, 1989).

[3] The major processing steps for the slope position classes are contained in Appendix 2.

3.2.4 Spatial Data Analysis

To derive the spatial models, subtasks were completed, as follows. First, the five independent physical variables of elevation, slope, aspect, slope position, and soil type were derived at a 10-meter resolution. Second, a random sample of the entire THRO south unit landscape extracted 2,931 X and Y UTM coordinates for sample points. Third, each sample point was loaded to a spreadsheet along with the five variables extracted from the GRID datasets with a GET CELL VALUE routine in ArcView (ESRI, 2000). Before developing the model, dummy variables were developed to help understand the relationships of the variables within the data set, and to provide a robust evaluation of the potential interactions between the five variables of interest. The dummy variables were based on Zone and size of the area to receive more weight. The interactions with zone 1 (floodplain) were weighted more heavily than zones 2 or 3. The zone 1 floodplain was more representative of the spurge expansion zone, therefore given more weight. This effort was an investment to build a better model. Reading the data included preparing dummy variables for interactions with slope position, aspect, etc., completing cleaning for no data entries, and converting the data into categorical classes, with one exception. The only continuous variable employed was elevation.

During the spatial matrix development, singularity was encountered, meaning a dividing by zero in the matrix. Due to singularity, the minimum value of the X and Y UTM coordinates was subtracted from the random sample point coordinate values. This was necessary to provide stability (Isaaks and Srivastiva 1989) because the inverse distance calculation resulted in zero distance values due to the single meter offsets between some neighboring sample points, resulting in the apparent overlapping of adjacent random points.

This spreadsheet was then loaded to the S-plus (Mathsoft, 2001) statistical package to explore spatial dependencies, derive and cross validate the predicted surface, and evaluate the need for interpolation through kriging. A regression tree classification was also developed as a spatial thematic map. Figure 3.7 illustrates the set of random sample points that were extracted with an ArcView script. With the sample complete, the data was ready for modeling.

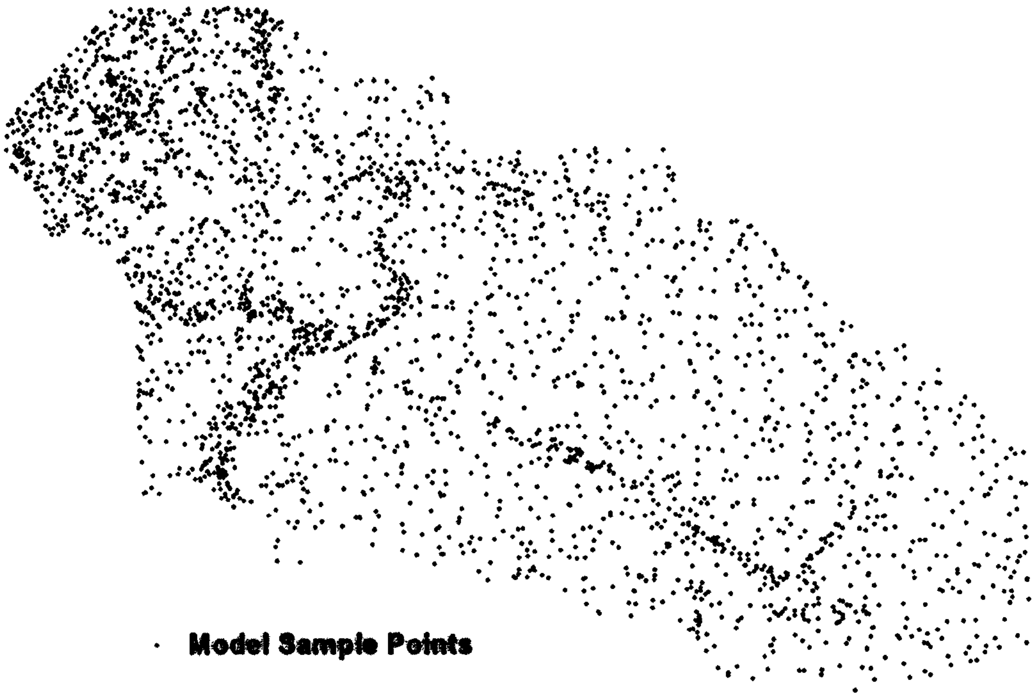

Figure 3.7 Sample points (2,931) in the South Unit of THRO.

The following sections describe the spread rate measurements, the mapping classifications using both a traditional supervised classification and a correlation regression tree classification, the evaluation of spatial autocorrelation and cross-correlation statistics, and the development of the spatial models using OLS and kriging.

3.3 Spread Rate Measurements

To address the second objective, spread rates were evaluated between the years of 1993 and 1998 using the vector coverages of the photo interpreted boundaries of the leafy spurge polygons. This was accomplished using the measurement tools in ArcView. In addition to the vector coverages, THRO also has a point coverage for biocontrol releases, and the dates and species applied for control efforts. These release points could influence spurge spread rates, and spread may be reduced due to biocontrol. To prepare for measurement, two subsets of the 'spurge_bugs' (insects) point coverage from THRO (Hager, 2001) were created. These were sorted into two new point shapefiles based on years of application relative to the two dates of aerial photography. The two shapefiles contained the release points before 1993 (1998 – 1992) and between 1993 and 1998, neither inclusive of the years 1993 or 1998. This accounted for patch response to biocontrol agents (*Aphthona. cyparissiae, A. nigriscutis and A. lacertosa, and Oberea erythrocephala*). For example, a biocontrol release in 1992 in a location that was interpreted from 1993 aerial photography would have an expected spread rate lower (or negative) than an uncontrolled patch of leafy spurge. This difference, if present, could provide a cursory evaluation of the efficacy of the releases. The rate changes observed could be due to biocontrol effects or other factors beyond the scope of this study.

Sampling was done by strips moving from the NW corner to the SE, with a total of five strips sampled across THRO. The sampling areas in each strip were also noted for presence or absence of biocontrol, so that summaries of each condition and average spread rate could be calculated. Each release point was identified by the ArcView record number (ID#), and the distance from the edge of the spurge polygon was recorded. In some cases, the point fell outside the 1993 mapped spurge polygons, and in some cases they fell inside the 1998 polygons. In either case, the distance to edge of the 1993 polygon was recorded. Then from that point, the edge expansion was measured in meters. Figure 3.8 displays a distance-sampling example.

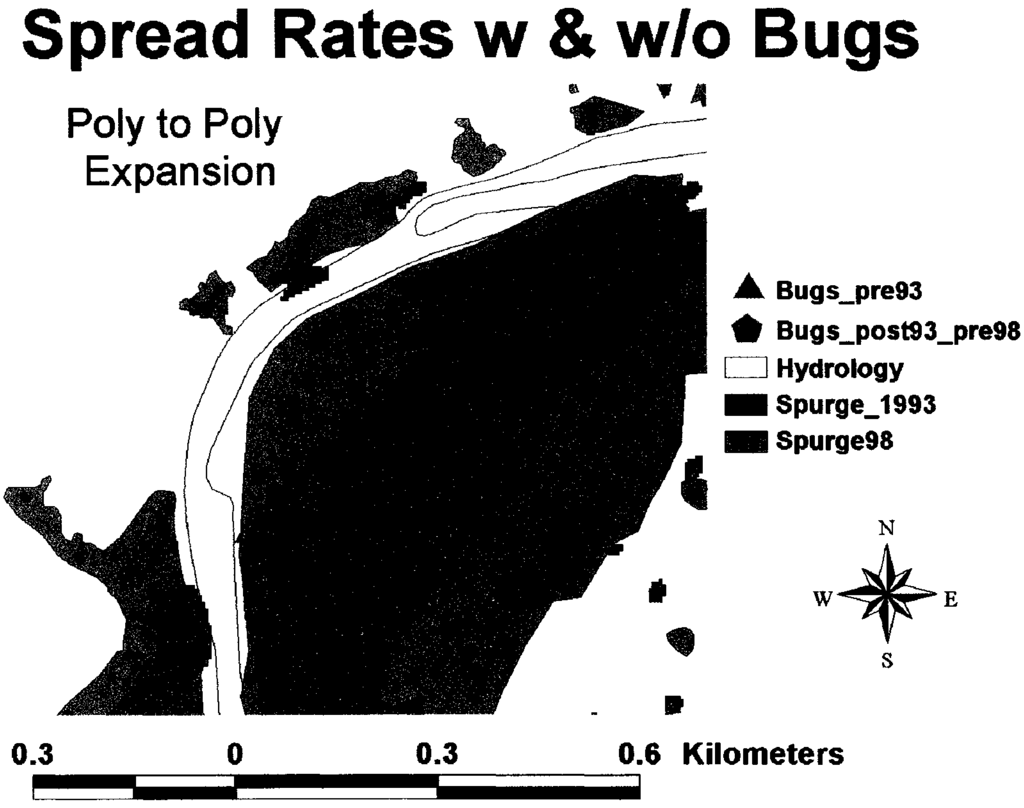

Figure 3.8 Spread Rate Distance Sampling Example

3.3.1 Spread Rates Without Biocontrol Effects

Because the patches without releases presented an unconfounded estimate of spread rates, 1993 polygons were also selected without biocontrol releases, and the spread along the long axis was recorded between 1993 and 1998. The downstream or upstream direction was noted as well for the measurement. For adjacent patches, the distance was halved because the fill-in between two patches could result from patch expansion in both directions (e.g. polygon to polygon expansion in Figure 3.8). Average annual spread rates were calculated for floodplain (flat), uphill, and downhill spread rates.

3.4 Mapping Accuracy (Two Procedures:Thematic Mapper and Spatial Model)

This study utilized two methods for classification and appropriate adjustments to the Kappa calculations (Kalkhan et al. 1997). The two classification methods were the traditional supervised method, and the binary regression classification tree method. To test the ranked prediction spatial map, this study evaluated spatial statistic model performance with cross-validation routines and AICC values. This cross-validation in S-plus included deleting one observation from the data set and predicting the deleted observation using the remaining observations (Reich et al. 1999). This was repeated for all observations in the data set, and the calculated accuracy was obtained. The same data was used in a non-parametric approach (data is not normally distributed) to produce a presence and absence thematic map of leafy spurge using a binary regression tree classification. The regression tree classification map was evaluated with classic errors of omission and commission with related Kappa statistics.

3.4.1 Alternative Kappa Accuracy Assessment Approach

The Kappa statistic (Cohen, 1960) gives a relative measure of agreement or accuracy (Rosenfeld and Fitzpatrick-Lins, 1986; Congalton, 1991). It may also be used to evaluate if the results in the error matrix are better than a random chance or result, or to compare two similar matrices (of identical catergories) to evaluate if they are significantly different (Jensen, 1996). This study used the topographic field data to develop a spatial binary map of zero and 1 to represent spurge presence (1) and absence

(0). Both an "unweighted" Kappa statistic and a "proportional area" Kappa (Bishop, 1975; Kalkhan et al. 1997, 1998) were calculated in the accuracy assessment. The equation for overall (unweighted) Kappa is shown below in Figure 3.9 (Bishop, 1975).

$$K = \frac{\sum_i P_{ii} - \sum_i P_{i+}P_{+i}}{1 - \sum_i P_{i+}P_{+i}} \qquad (1)$$

Where P_{ii} is the observation divided by the rows column total (correct classification);
P_{i+} is the row total divided by the rows column total;
P_{+i} is the observation column total divided by the rows column total

Figure 3.9 Kappa Calculation

The overall Kappa statistic (Cohen, 1960) assumes a multinomial distribution for large sample sizes (Bishop, 1975; Kalkhan, 1994, Kalkhan et al. 1998). The property of the Kappa statistic is not the same in multinomial distributions, so an alternative is to use a Kappa statistic that is suitable for stratified random sampling (Kalkhan, 1994; Kalkhan et al. 1997; 1998; Stehman, 1996). It is recommended to use exact Kappa for a specified sampling design, e.g. simple random, cluster, or double sampling (Kalkhan et al. 1997; 1998). Due to the need for a small sample size Kappa, Czaplewski (1993) derived an exact Kappa for each sampling design (e.g. stratified random). This specific Kappa design was important to maintain the statistical property of the variance (Kalkhan, personal communication). For a stratified sample, two ways may be employed: 1) proportional to area, or 2) derived Kappa for stratified random sampling (Kalkhan et al. 1998). This study used the proportional to area approach, by dividing the area of a specific cover type by the total area. This allowed the use of the Kappa statistic based on simple random sampling (Kalkhan et al. 1998). A new error matrix was developed based on the proportion of the size of the area for each cover type. Example A and B below in Table 3.4 show leafy spurge proportion to the total area of the South Unit of THRO. Then the Kappa for simple random sampling was applied. In the same fashion, this was applied to calculate the conditional Kappa.

Table 3.4 Proportional Areas for an Example A and B Error Matrix

Example A Error values

Spurge	Absent	Present	Totals
Absent	842	433	1275
Present	331	1325	1656
Totals	1173	1758	2931

Example B Error values adjusted by proportional area Spurge 42% present, 58% absent (determined by standard GRID commands, based on the total area of the park 18,680 ha).

Spurge	Absent (58%)	Present (42%)	Totals
Absent	488.36	181.86	670.22
Present	191.98	556.5	748.48
Totals	680.34	738.36	1418.7

Using the standard Kappa calculation shown in equation (1), the accuracy and Kappa values for the previous Example A error values are shown below in Table 3.5.

Table 3.5 Example accuracy and Kappa calculations for the Example A Error Matrix

Example A row total = 1275 for absent and 1656 for present;
Example A column totals = 1173 for absent and 1758 for present;
Where N = 2931 and the sum of the products of rows and columns = 4406823

Producers Accuracy	Omission Error	User's Accuracy	Commission Error
Absent = 842/1173 = 71.8%	28.2%	Absent = 842/1275 = 66%	34%
Present = 1325/1758 = 75.4%	24.6%	Present = 1325/1656 = 80%	20%
Kappa = (2931*2167- 4406823)/ (2931*2931- 4406823) = 0.46			

3.4.2 Proportional Area (Conditional) Kappa Calculation

The proportional area of the 0 and 1 spurge map in this study was determined to be 42% spurge and 58% non-spurge using standard GRID commands, based on the total area in the park (18,680 ha). The calculation for the conditional Kappa using the proportional area size gives a less biased evaluation of the accuracy (Bishop, 1975; Kalkhan et al. 1997; 1998; Stehman, 1996). This study calculated the accuracy as follows: calculate the proportion of area; weight the number of pixels to calculate Kappa. Accuracy assessment summary tables in the Chapter 4 results contain the proportional area Kappa calculation for the binary regression tree derived surface. Figure 3.10 shows the conditional Kappa calculation for a single class case type mapping (Bishop, 1975).

$$K_c = \frac{P_{ii} - P_{i+}P_{+i}}{P_{i+} - P_{i+}P_{+i}} \qquad (2)$$

Where P_{ii} is the observation divided by the rows column total;
P_{i+} is the row total divided by the rows column total;
P_{+i} is the observation column total divided by the rows column total

Figure 3.10 Conditional Kappa Calculation

3.4.3 Traditional Supervised Classification

To extend to a landscape view, a traditional supervised classification was run on the Advanced Land Imager (ALI) data from 2001 over THRO. Although at a 30-meter resolution, this imagery was more representative of the data available to a park manager. This comparison also illustrated the effect of remote sensing scale on management planning, and reinforced the value of large-scale (small distance) mapping to detect new leafy spurge infestations. The regression tree classification approach using S-plus provided a presence and absence map product for comparison in both spatial detail and accuracy. The accuracy assessments described overall accuracy, user and producer accuracies, and the Kappa coefficient in two forms using both an “unweighted” and “proportional area” or conditional Kappa (Bishop, 1975; Kalkhan et al. 1997, 1998).

The ALI data from 2001 was processed using the ENVI 3.4 software (RSI, Inc. 2001). An unsupervised ENVI Isodata classification was attempted using 100 classes, with the change threshold set at five, the maximum standard deviation set at one, and the minimum class distance at five. The unsupervised results did not separate the spurge favorably, so were not pursued. Consequently, a supervised classification was conducted using maximum likelihood with 16 regions of interest defined with the growth algorithm for the known broad landcover categories and cover types in the imagery. Additionally, the spectral angle mapper routine was utilized with several settings. The default of 0.1 radians was not narrow enough, so the final choice used was 0.025 radians, shown in the results of Chapter 4. The accuracy assessment for the ALI supervised classification used the Larson biocontrol data points as ground reference described earlier.

3.4.4 Binary Regression Classification Tree

A binary regression classification tree was employed to create a comparative model to see if the correlation would improve over the OLS and kriged residual model. The regression tree analysis was used to evaluate the candidate model parameters for their contribution potential to predicting leafy spurge on the landscape, and to compare accuracy performance with the traditional classification method. It also provided clues to the binary branching of the physical variables in the tree, yielding ecological insight and interpretive value in describing the trends of leafy spurge on the landscape.

3.5 Spatial Correlation Statistics

This study used the same approach by Kalkhan and Stohlgren (2000) by "using the cross-correlation statistic to test the null hypothesis of no spatial cross-correlation among all pairwise combinations of vegetation variables and topographic characteristics" (Kalkhan et al. 2003). In calculating the cross correlation-statistic (I_{YZ}), the inverse distance between sample points (the interaction of the zone1) was used as a weighting factor to give more weight to values in the lower slope position zones and less to those that were farthest away from the drainages (zones 2 and 3). When the P-value associated with the test statistic was less than 0.05, the null hypothesis of no spatial cross-correlation was rejected. *Moran's I* was used to calculate the spatial autocorrelation associated with each of the variables used in this study. *Moran's I* is a special case of the cross-correlation statistic I_{YZ} (Czaplewski and Reich 1993). Cliff and Ord (1981) showed that I_{YZ} ranges from –1 to +1, although it can exceed these limits with certain types of spatial matrices.

To identify the best linear combination of independent variables, a stepwise multiple regression analysis was used. This technique explores the variation in predicting spurge presence as a function of the slope, aspect, elevation, slope position, and soil texture type. To describe large-scale variability estimates, the selected independent variables were used in the Ordinary Lease Square (OLS) procedure. If the variable of interest had a linear relationship with the geographic coordinates of the sample points, the soils, and the topographic data, then OLS estimators were used to fit the model. Kalkhan et al. (2003 in press) reiterate two advantages. First, the least squares method fits a continuous, univariate response as a linear function of the predicted variable. Second, this trend surface model represents continuous first order spatial variation. A decision tool called Akaike's Information Criteria "AIC" (Brockwell and Davis 1991, Akaike 1997) was used as a guide in selecting the number of model parameters to include in the regression model where:

$$AIC = -2(\text{max log likelihood}) + 2(\text{number of parameters}) \qquad (3)$$

Applying this criterion, a model with a smaller AIC value demonstrated a better fit. Again, this study used the AICC, which is a modification model of AIC (Reich et al. 1999).

3.6 Predictive Spatial Modeling and Mapping

For the purpose of developing the spatial models and producing a spatial map, the following steps were needed to understand how the variables of interest contributed to the model development. The steps are listed as follows and shown in Figure 3.11.

1. Test for spatial autocorrelation, cross-correlation, and Pearson linear correlation between the variables of interest (elevation, slope, aspect, slope position = zone, soil texture, and the presence of leafy spurge)
2. Use a stepwise regression to screen the five independent variables
3. Compute Ordinary Least Squares (OLS) for the large scale variability
4. Examine the residuals to test for spatial autocorrelation
5. Utilize semi-variograms to evaluate small-scale variability, and select the model (variogram type gaussian, exponential, spherical) with the lowest Akaike's Information Criteria (AIC) and smallest variance. This study used AICC which is a modification model of AIC (Reich et al. 1999)

6. Apply kriging of the residuals to interpolate values for small-scale variability
7. Combine the OLS and kriged surfaces for the final trend surface grid

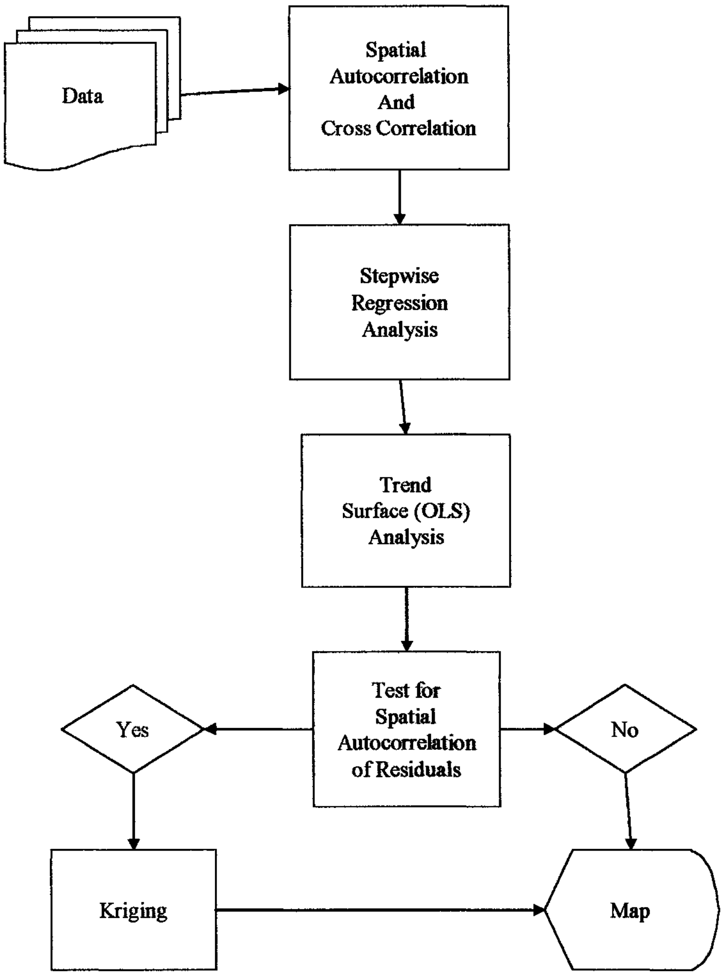

Figure 3.11 Flowchart of the data and statistical analysis steps.

3.6.1 Scale, Trend Surface, and Kriging Terminology

This study used modeling of large-scale and small-scale variability by integrating field data and spatial information (three derived slope position zones, soils, elevation, slope, aspect) and spatial statistics (after Kalkhan et al. 2003) to predict the distribution, presence, and patterns of invasive plant distribution. The mathematical and spatial statistical literature use the term "scale" differently than the remote sensing literature. In the non-remote sensing literature, "large scale" and "small scale" mean distance (and area) not ratio. For this discussion of the statistical models, large-scale variability will denote landscape level (large area) variation, and small-scale variability will denote close-in (small area) and near neighbor variability. Also, a surface derived from these variances (landscape and near-neighbor) is known as a 'trend surface.' Trend surface models that describe the large-scale spatial variability using stepwise multiple regressions based on the Ordinary Least Squares (OLS) method were used in this study. Models with small variance were selected. In addition, ordinary kriging (estimation) models of the residuals from the trend surface model based on the OLS estimates were utilized for modeling small-scale variability based on an exponential, spherical, or gaussian semi-variogram.

3.6.2 Trend Surface Residuals, Kriging, and the Final Map

Following the OLS surface development for large-scale variability, the residuals from the trend surface models were analyzed for spatial dependencies. This was accomplished using spatial autocorrelation statistics. A sample variogram was utilized to describe spatial continuity. With spatial data, generally the variation of the samples changes with distance. In other words, the variogram displays and measures how the variance changes with distance. Unlike Pearson's R for correlation, this technique captures the variability over the landscape (Kalkhan, personal communication). In this analysis, the variogram and cross-variogram models used were considered "basic" models, meaning they are simple and isotropic (Reich et al. 1999). The three types include gaussian, spherical, and exponential models (see Isaaks and Srivastiva, 1989). Prior to estimating the sample variogram and cross-variogram, the data were rescaled by subtracting the individual UTM variables by their respective minimum values (e.g. XUTM 611834 – 606223 = 5611 XUTM used). This was necessary to maintain numerical stability (Isaaks and Srivastiva 1989) by eliminating any differences in the magnitude of the variables without altering the solution.

A multi-stage effort was utilized to evaluate the best variables, fit a least squares regression, test the residuals for spatial relationships, and combine the multi-scale spatial model pieces together. The OLS represented the large-scale spatial variation, and the kriged residual surface represented the small-scale spatial variation. The combined surface yielded the probability surface for leafy spurge presence on the landscape:

Spurge (probability surface) = OLS + spurge-kriged

3.7 Figures displaying the variables of interest

The following figures display the data sets of the leafy spurge polygons from 1993 and the 1996 basin infestation ratings, and the five independent variables of slope, elevation, aspect, slope position, and soils. The figures display the independent variables in the context of moisture availability.

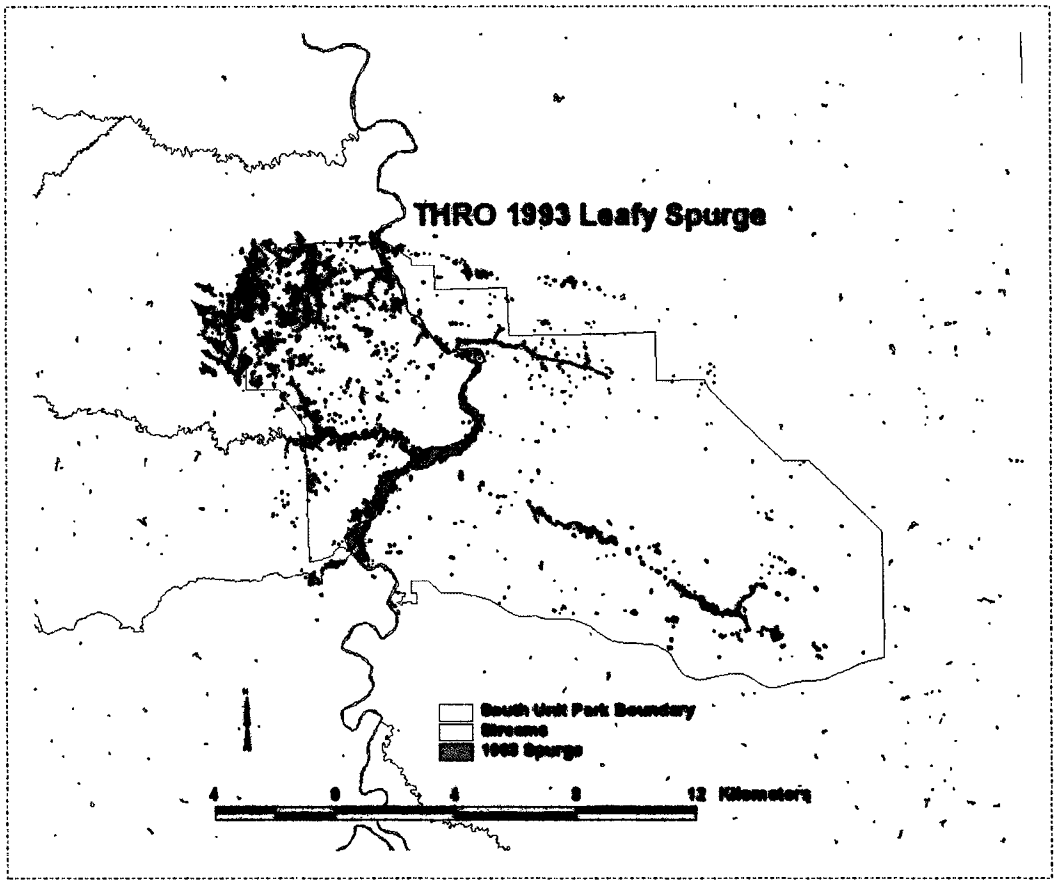

Figure 3.12 Leafy Spurge polygons from 1993 baseline data, interpreted from aerial photography and ground based inventory with GPS.

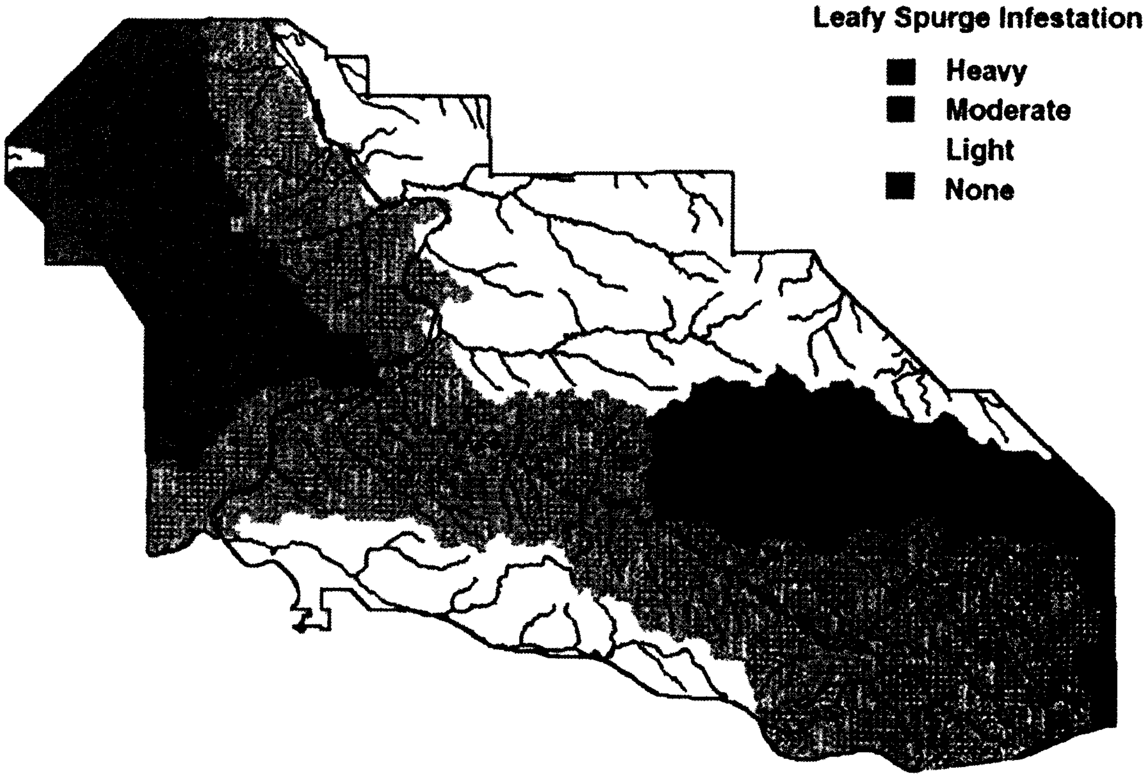

Figure 3.13. THRO 1994-96 basin infestation ratings (Anderson et al. 1996, 1999)

3.7.1 Components of moisture availability

The position in the drainage, and the slope position relative to the stream have been identified in previous studies (Carlson et al. 1994, Anderson et al. 1996; 2000) to influence leafy spurge spread. The following figures illustrate the five physical factors used in the study. Figure 3.14 show the drainage network as a lattice diagram of the south unit from 60 degrees and 10,000-foot perspective. The 1993 leafy spurge polygons are shown in red in the drainage bottoms (blue for hydrology) and plateaus of the northwest corner wilderness area.

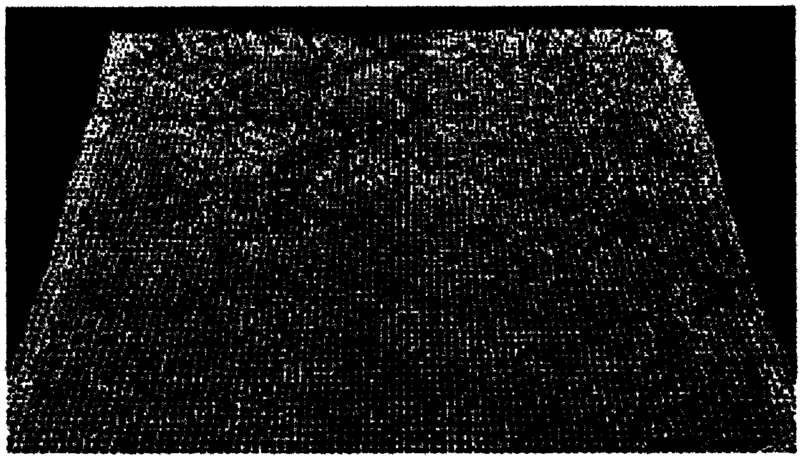

Figure 3.14. Moisture availability for spurge seen as a lattice diagram of the position in the drainage network, and spurge polygon proximity to the drainage bottom.

The next two figures show derived physical factors. Elevation and derived aspect were computed from the 10-meter DEM by the criteria in Table 3.3 and are shown below in Figure 3.15. A perspective view of derived slope is shown in Figure 3.16. A list of the 8 soil categories for THRO appears in Figure 3.17.

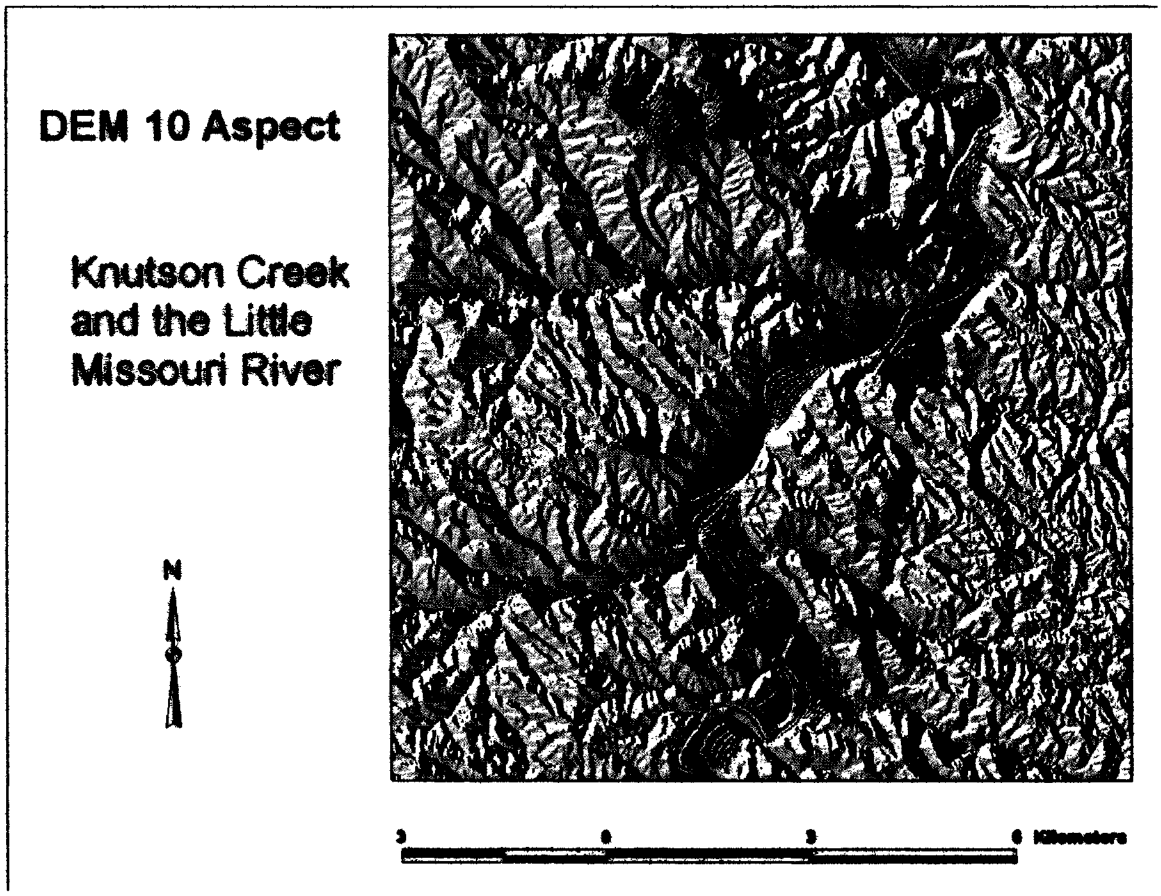

Figure 3.15. Moisture availability for spurge shown as a perspective view of elevation and derived aspect, as described in Table 3.3.

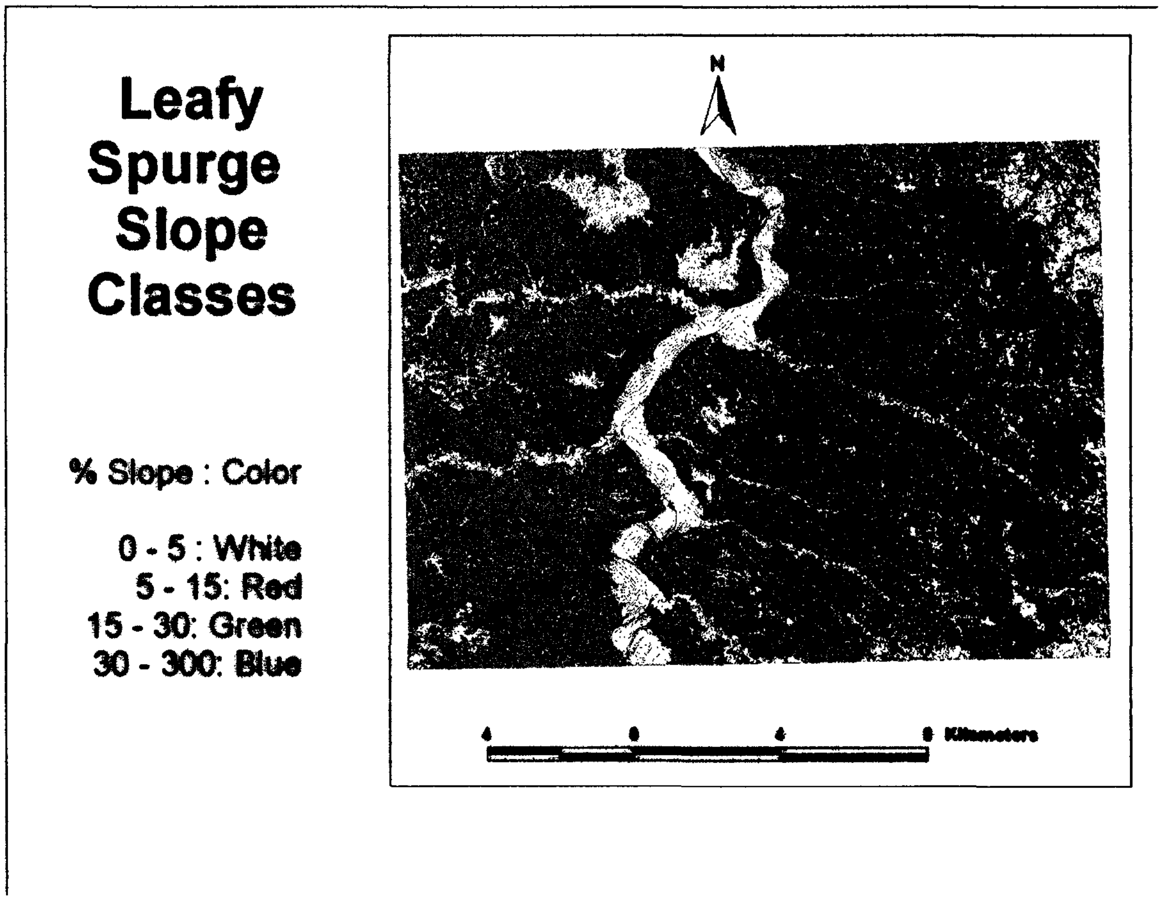

Figure 3.16 Moisture availability for spurge shown as a perspective view of derived slope in classes described in Table 3.3.

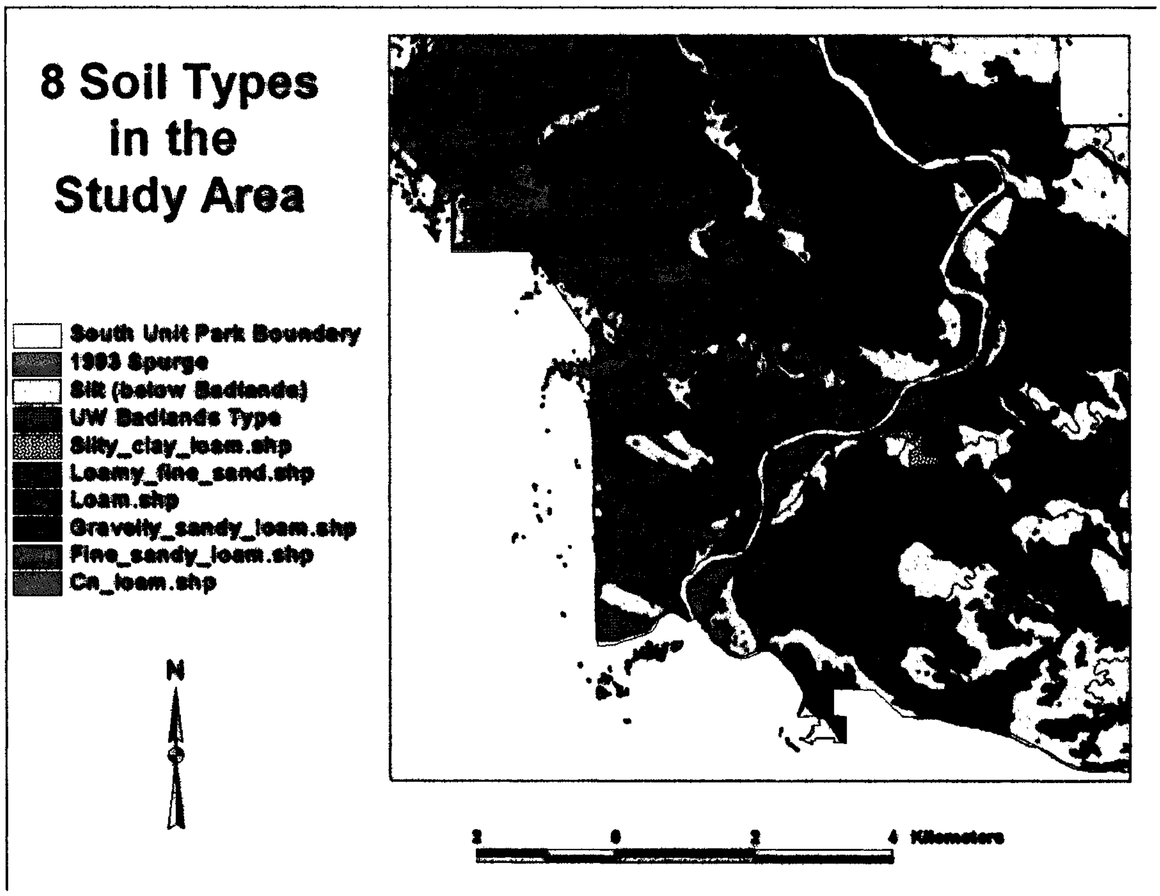

Figure 3.17 Soil texture as described in Table 3.3 as a soil moisture availability factor for spurge (same view as Figure 3.14)

CHAPTER IV

IV. RESULTS AND DISCUSSION

This study produced the three general results stated in the objectives. First, it developed a thematic map estimate of the leafy spurge with a comparison binary regression tree classification. It also developed an estimate of spread rates from the remote sensor data using spurge polygons interpreted from aerial photography. Second, it examined the relationships between the physical terrain characteristics and leafy spurge presence. Third, it developed and tested a ranked prediction map of potential spurge expansion at THRO that showed high, medium, and low probabilities of occurrence.

This study used *Moran I* (Moran 1948, Mantel 1967) and the bivariate cross correlation-statistic “l_{YZ}“(Czaplewski and Reich 1993, Bonhan et al. 1995) to test for spatial autocorrelation and cross-correlation with residuals. These statistics suggested that, at large-scales, the probabilities of presence and absence (suitable vs. non-suitable habitat) of leafy spurge were spatially dependent throughout the study site.

4.1 Map Classifications: Traditional and Regression Tree

4.1.1 Traditional Classification of the Advanced Land Imager

The Advanced Land Imager (ALI) data was collected on July 6, 2001 over THRO. The supervised and unsupervised methods generally result in similar accuracies, within 3-6% (Congalton, 1991). The classification was run in ENVI (RSI, Inc., 2001), using a supervised method.

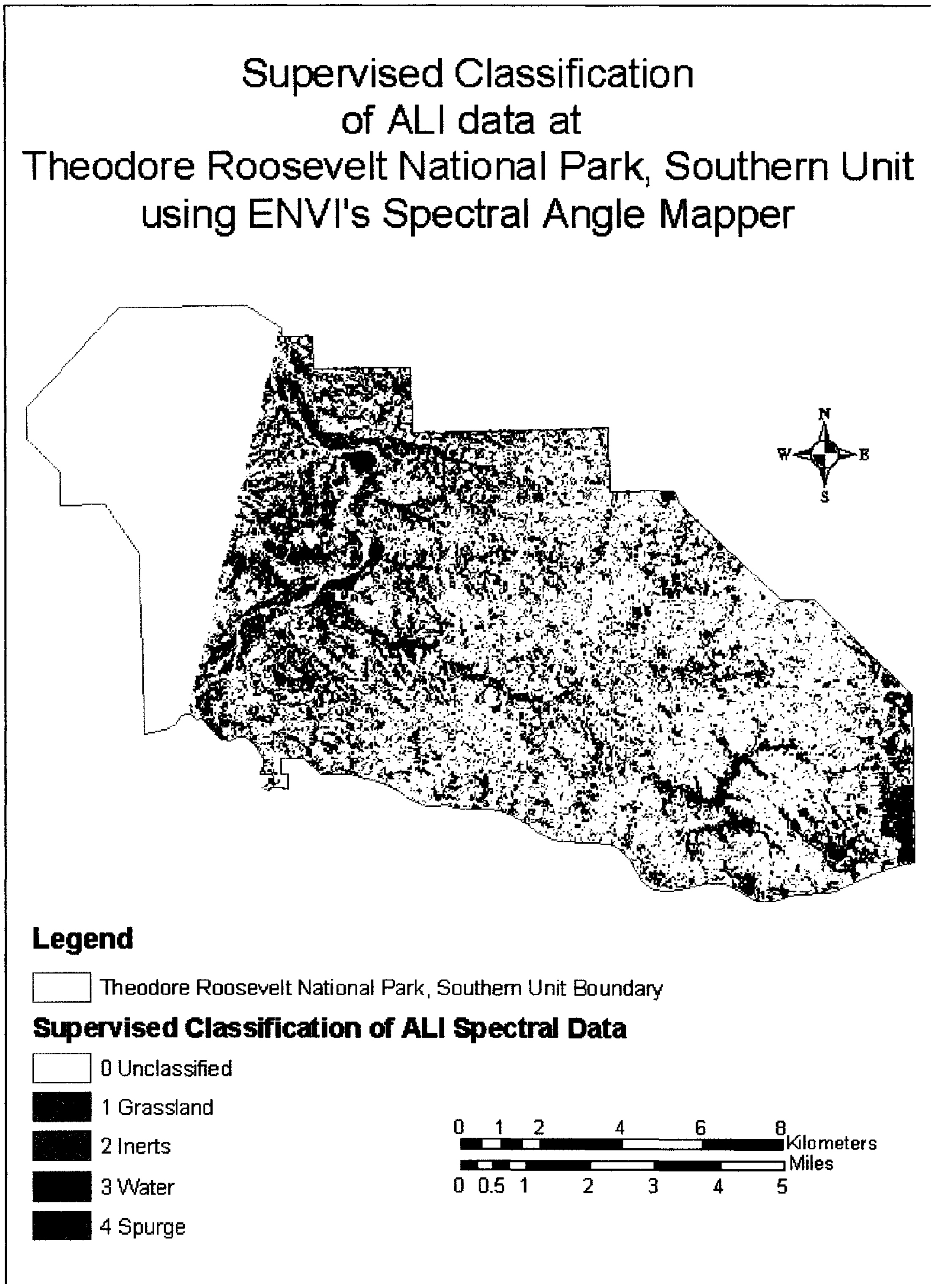

Figure 4.1 Supervised classification of the Advanced Land Imager (ALI) over THRO.

To prepare for classification, three image swaths were mosaiced and georeferenced based on a 1-meter resolution DOQQ. The mutispectral and panchromatic data were georeferenced separately. The georeferenced 30-meter multispectral image was resampled to 10-meter resolution using a nearest neighbor algorithm. It was combined with the 10-meter panchromatic data set, thus creating a 10-band, 10-meter data set.

The supervised method utilized 16 regions of interest (ROI) as training areas. These ROIs were selected from the cover types at THRO, representing grass and shrub, inert surfaces including highways and badland formations, water, and spurge. The file was classified with the ENVI Spectral Angle Mapper (SAM). The ENVI software describes the SAM method (citing Kruse et al. 1993) as follows:

> Use (SAM) to match image spectra to reference spectra in n-dimensions using a physically-based spectral classification method. The reference endmember spectra used by SAM can come from ASCII files, spectral libraries, statistics files, or can be extracted directly from the image (as ROI average spectra). SAM compares the angle between the endmember spectrum (considered as a n-dimensional vector, where n is the number of bands) and each pixel vector in n-dimensional space. Smaller angles represent closer matches to the reference spectrum. This technique, when used on calibrated data, is relatively insensitive to illumination and albedo effects.

The only parameter in the SAM routine is the angle between the end member spectrum and each pixel's vector, with smaller angles representing closer matches to the reference (ROI) spectrum. This parameter was set to 0.025 radians for this classification, so that only those pixels that very closely matched the spectrum of known leafy spurge locations would be classified as leafy spurge. The results are shown in Figure 4.1.

4.1.2 Advanced Land Imager Supervised Classification Accuracy

The classification was evaluated for the accuracy of leafy spurge distribution, as shown in Table 4.1. The ground reference data was derived from the biomass plot data collected between 1999 and 2001 by Dr. Diane Larson. Of the 550 sample points measured at THRO, 279 were located within the area of the ALI scene, and were used for the accuracy assessment of the ALI supervised classification. The ALI overall accuracy was 62% with a Kappa of 0.23. The User's Accuracy in the classification was 66.9% and 56.1% for absence (badlands) and presence of leafy spurge respectively. The Producer's Accuracy was 63.1% and 60.1% for absence and presence of leafy spurge respectively. When proportional to area weights were calculated for the ALI categories, the overall accuracy was nearly the same at 62.1% with an area weighted Kappa of 0.28.

Table 4.1 Accuracy Summary of the ALI Supervised Classification.

Overall Accuracy = (173/280) = 61.8%
Kappa Coefficient = 0.23 (unweighted, simple random sampling; need the proportional area weighted Kappa (k) to compare, see Equation 2 from Chapter 3)

Ground Truth (Pixels)				
Class	Non-spurge	Spurge	Total	User Accuracy
Unclassified	0	0	0	
Non-Spurge	99	49	148	66.89
Spurge	58	74	132	56.06
Total	157	123	280	
Producers Accuracy	63.06	60.16		

Ground Truth (Area Weighted)					
Class	Non-spurge Badland 61%	Spurge Spurge 39%	Total	Conditional Kappa (K_c)[1]	User Accuracy
Unclassified	0	0	0		
Non-Spurge	60.39	19.11	79.5	0.28	75.96
Spurge	35.38	28.86	64.24	0.17	44.93
Total	95.77	47.97	143.74		
Producers Accuracy	63.06	60.16			

Area Weighted Overall Accuracy = 89.25/143.74 = 62.1%

[1] Kappa statistic

4.1.3 Regression Classification Tree Results

Figures 4.2 and 4.3 show the deviance graph for choosing the optimum node selection, and the 39-nodes regression tree. No remote sensing was used in the binary regression tree, so this model provides data without the added cost for a large area. This modeling potential could be usable for landscape analysis (e.g. state of Colorado).

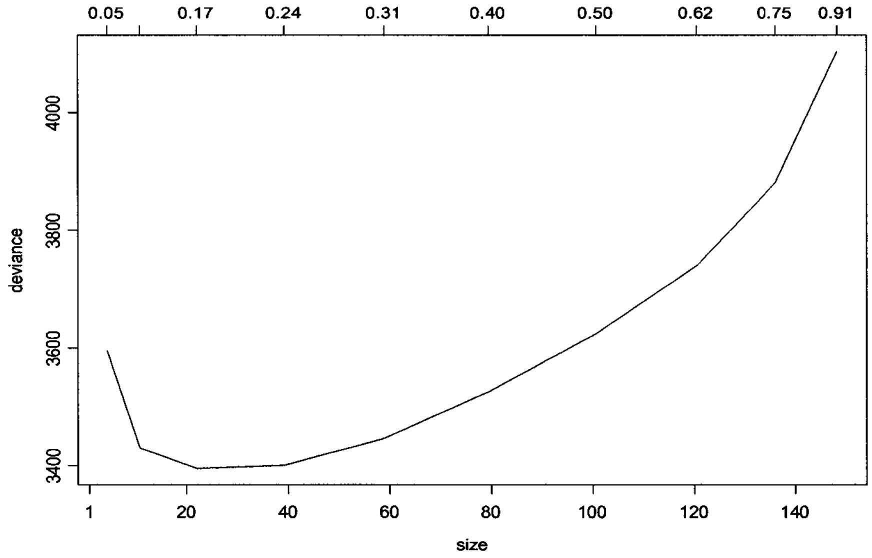

Figure 4.2 Regression tree deviance graph for selecting the optimum node value of 39 used to develop thematic mapping for leafy spurge.

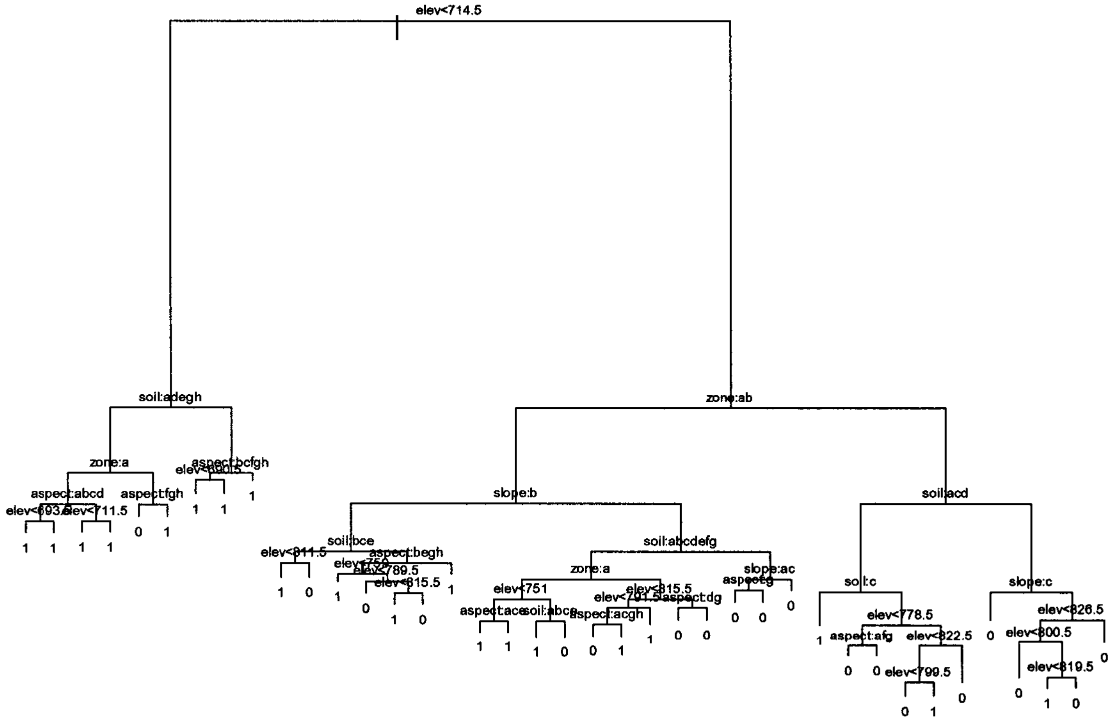

Figure 4.3 Regression tree with the optimum 39-nodes.

4.1.4 Regression Classification Tree Surface

The regression classification tree map had an overall accuracy of 74% and is shown in Figure 4.4, with light colored areas for leafy spurge presence.

The optimum tree model was evaluated by the deviance value, with the lowest value (lowest error in classification) desired for the optimum pruning of the regression tree. By moving from the original of 154 nodes with high error, this study chose the optimal node value with a low deviance, and the 39-node tree resulted in the smallest error.

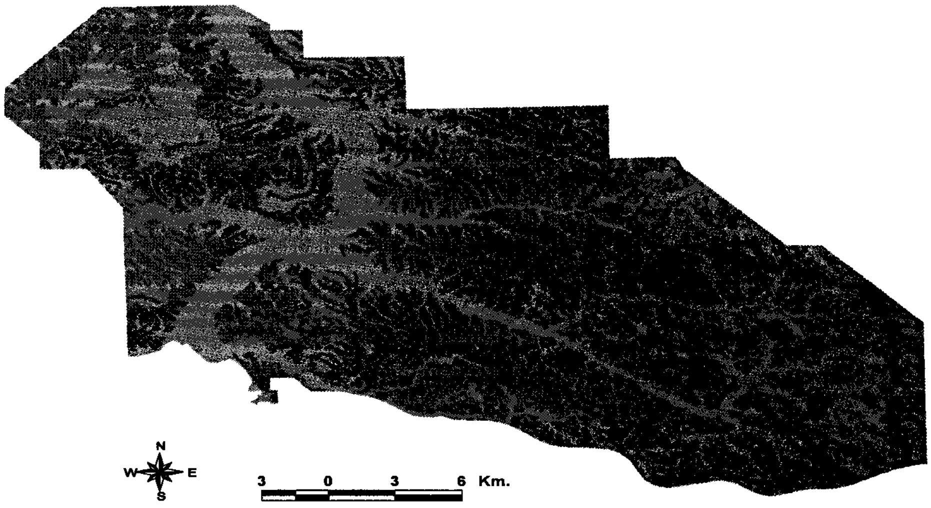

Figure 4.4 Regression Classification Tree surface developed from the 39-node optimum model for leafy spurge at THRO.

4.2 Mapping Accuracy (Two Procedures)

The overall accuracy using the traditional classification approach was ~ 62% with an area weighted Kappa of 0.28. The area-weighted method improved the user's accuracy of the non-spurge category, probably due to the higher 61% of the area in non-spurge classes. Secondly, this study used the binary regression tree classification as a comparison. The regression tree model achieved a modest (74%) overall accuracy improvement (using topographic physical factors without imagery) compared to both the traditional approach and the 34% accuracy of the OLS and kriged predictive model of leafy spurge probability. The S-plus software package contained an accuracy evaluation module called cross-validation (Mathsoft, Inc. 2000). The accuracy assessment tables for the 154 and 39 node regression tree classifications are shown in Tables 4.2 and 4.3. The decrease in accuracy was modest, with the 154-node model at 77% and the 39-node model at 74%. The 39-node model had the minimum deviance, with small variance or errors, so that was the selected pruning level of the regression tree. To calculate Kappa statistics based on the proportion of size of spurge and non-spurge in the areas, this study computed the percentage of each class at THRO as follows. The total area was 18,680 ha, and spurge was present in the 1993 coverage in 7,775 ha (42%) and absent in 10,905 ha (58%). In the traditional classification, spurge was present on 39% of the area and 61% absent.

4.2.1 Accuracy Assessment Results of the Regression Tree

The accuracy assessment tables for the 154 and 39 node regression tree classifications are shown in Tables 4.2 and 4.3. By using proportional area size, this study computed an exact Kappa statistic (Stehman, 1996; Kalkhan et al. 1997). All the results are cited in Table 4.2. The calculation is cited below the table.

Table 4.2 Accuracy values for the 154-node regression tree model

[Unweighted Error Matrix for Spurge]

Spurge	Absent	Present	Row Totals	User Accuracy	Conditional Kappa (K_c)[1]
Absent	892	383	1275	69.96	0.5034
Present	266	1390	1656	83.94	0.5934
Column totals	1158	1773	2931		
Producer Accuracy	77.03	78.39			

Overall Accuracy = 2282/2931 = 77.9%; Overall Kappa = 0.5447

[Area weighted Error Matrix for Spurge; 58% absent, 42% present]

Spurge	Absent (58%)	Present (42%)	Row Totals	User Accuracy	Conditional Kappa (K_c)[1]
Absent	517.36	160.86	678.22	76.28	0.5489
Present	154.28	583.8	738.08	79.09	0.5592
Column totals	671.64	744.66	1416.3		
Producer Accuracy	77.03	78.39			

Overall Accuracy = 1101.16/1416.3 = 77.7%; Overall Kappa = 0.5540

[1] Kappa statistic =

$$K_c = \frac{P_{ii} - P_{i+}P_{+i}}{P_{i+} - P_{i+}P_{+i}}$$

[1] Kappa (Area weighted) = $\frac{[(517.36/1416.3)-[(678.22/1416.3)*(671.64/1416.3)]]}{[(678.22/1416.3)-[(678.22/1416.3)*(671.64/1416.3)]]} =$

$\frac{0.138201}{0.251778} = \mathbf{0.5489}$

The primary result for the thematic map accuracy using the binary regression tree with 154 tree nodes had an overall accuracy of 77.9% and Kappa statistics of 0.54. The User Accuracy was 70% and 84% for absence and presence of leafy spurge respectively, while the Producer Accuracy was 77% and 78.4% for absence and presence of leafy spurge respectively. Using proportional to area sizes were calculated for the 154-nodes tree, and the overall accuracy was nearly the same at 77.7% with a proportional area Kappa of 0.35. The User Accuracy was 76.3% (higher) and 79.1% (lower) for absence and presence of leafy spurge respectively. The Producer Accuracy was the same at 77% and 78.4% for absence and presence of leafy spurge respectively.

Examining the values for deviance resulted in the reduction from 154 tree nodes, as the optimum node was 39. Using this smaller node model, the binary regression tree 39-node model had an overall accuracy of 73.9% (only 4% lower) with a Kappa statistic of 0.46. The User Accuracy was 66% and 80% for absence and presence of leafy spurge respectively, while the Producer Accuracy was 71.8% and 75.4% for absence and presence of leafy spurge respectively. When proportional to area size were calculated based on the 39-tree nodes, the overall accuracy was almost the same at 73.6% with an area weighted Kappa statistic of 0.48. The User Accuracy was 73% (higher) and 74% (lower) for absence and presence of leafy spurge respectively, while the Producer Accuracy was identical at 71.8% and 75.4% for absence and presence of leafy spurge respectively.

Table 4.3 Accuracy values for the 39-node regression tree model

Spurge	Absent	Present	Row Totals	User Accuracy	Conditional Kappa (K_c)[1]
Absent	842	433	1275	0.6604	0.26
Present	331	1325	1656	0.8001	-0.059
Column totals	1173	1758	2931		
Producer Accuracy	0.7178	0.7537			

Overall Accuracy = 2167/2931 = 73.9%; Overall Kappa = 0.465

$$\text{Kappa statistic} = \frac{[(2931*2167)-4406823]}{[(2931*2931)-4406823]} = \frac{1944654}{4183938} = \mathbf{0.465}$$

[Area weighted Error Matrix for Spurge]

Spurge	Absent (58%)	Present (42%)	Row Totals	User Accuracy	Conditional Kappa (K_c)[1]
Absent	488.36	181.86	670.22	0.7287	0.479
Present	191.98	556.5	748.48	0.7435	0.465
Column totals	680.34	738.36	1418.7		
Producer Accuracy	0.7178	0.7537			

Overall Accuracy = 1044.86/1418.7 = 73.6%; Overall Kappa = 0.472

[1] Kappa (Area weighted) = $\frac{[(488.36/1418.7)-[(680.34/1418.7)*(670.22/1418.7)]]}{[(680.34/1418.7)-[(680.34/1418.7)*(670.22/1418.7)]]} =$

$\frac{0.117682}{0.245869} = \mathbf{0.479}$

The results indicate that the model had slightly higher User and Producer Accuracy in the present category, representing 42% of the landscape area. Note how the user accuracy was more similar to each other by the use of the proportional weighting of the data in both the 154-node and 39-node models. Also notice the nominal (4%) reduction of overall accuracy with the major pruning of the tree from 154 to 39 nodes. Although this difference was not tested statistically, the simpler model has the advantage in both ease of computation, and in the ease of interpretation of model branches on the landscape.

4.3 Spatial Autocorrelation and Cross-correlation Statistics

Spatial dependencies in the five variables of elevation, slope, aspect, slope position, and soil type were evaluated. The spatial autocorrelations and cross-correlations are shown in Table 4.4. The cross-correlation coefficients (termed bi-*Moran I*) were used to evaluate the contributed strength of the variables. The stronger correlations were found with elevation and slope position zone 1 (drainages + 8M) and spurge occurrence. Based on spatial cross correlation, spurge has a negative spatial cross-correlation with the topographic, zone, and soil variables. Elevation was an important variable, as was slope position for the presence of leafy spurge. Leafy spurge was not random on the landscape, with slope, aspect and slope position having significant cross-correlation with elevation. All other linear correlations were weaker between variables. Although the Pearson linear correlation coefficient (red in Table 4.4) indicates that spurge was negatively correlated with all of the five variables of interest, the stepwise regression found that zone and interactions with aspect and soil type were the three strongest correlations found. The remaining variables of slope, aspect, and zone had no significant spatial cross correlation between members as shown in Table 4.4.

Table 4.4 Summary statistics for spatial correlation and linear correlation of leafy spurge, topographic, and soil types based on 2931 samples.

Spurge	Elev	Slope	Aspect	Zone	Soil	Variable
$\mathbf{0.131**}^{S}$ 1^{L}	$-0.037^{C, N}$ -0.286^{N}	-0.013^{N} -0.187^{N}	-0.013^{N} -0.125^{N}	-0.016^{N} -0.335^{N}	-0.037^{N} -0.222^{N}	Spurge
	$\mathbf{0.274**}$ 1	0.070* 0.282^{**}	0.068* 0.182^{**}	0.143** 0.626^{**}	0.044^{N} 0.182^{**}	Elevation
		$\mathbf{0.058}^{N}$ 1	0.034^{N} 0.211^{**}	0.051^{N} 0.258^{**}	0.020^{N} 0.197^{**}	Slope
			$\mathbf{0.036}^{N}$ 1	0.042^{N} 0.161^{**}	0.015^{N} 0.106^{**}	Aspect
				$\mathbf{0.092}^{**}$ 1	0.027^{N} 0.219^{**}	Zone
					$\mathbf{0.029}^{N}$ 1	Soil

^{S} Spatial autocorrelation statistic (first line) on the diagonal (bold).
^{C} Spatial cross-correlation statistic (bi-*Moran I*) on the off-diagonal = blue
* Autocorrelation statistics significant at $\alpha = 0.05$;
** Significant at $\alpha = 0.01$
^{L} Linear (Pearson's) correlation coefficient (second line); r = red
^{N} Not Significant

How do these variables contribute to the presence of leafy spurge? The ecological findings from the Table 4.4 results can be summarized by examining the spatial relationship among the five variables. **Slope** was significantly correlated with elevation and the interactions with 5-15% slope on northwest aspect and 0-5% slope on the midslope zones. **Elevation** was weakly correlated in OLS, major (first) regression tree decision point at 714.5 meters and many lower tree decisions. **Aspect** was significantly correlated with elevation and the interactions with 5-15% slope on northwest aspect and north aspects on the midslope zones. Of the nine interactions in the OLS, seven involved aspect, with the two strongest on south aspects with loam and gravelly sandy loam soils. **Zone** (slope position) was notable in the lowest floodplain region. Zone 1 (floodplain + 8m) was the strongest correlation of the OLS. Of the nine interactions in the OLS, four involved zone, with two on north midslope and 0-5% slope respectively. Weak negative correlations occurred on south floodplains and 5-15% floodplains. **Soil type** (texture) was the second regression tree decision point (not badlands or silty clay loam). All other types were affected by aspect and elevation. Six of the 17 OLS factors included soil texture. Of the nine interactions in the OLS, three involved soils, with the two strongest on south aspects with loam and gravelly sandy loam soils. Soils were not included in the previous work by Anderson; however, all the other findings are consistent with the previous work (Anderson et al. 1996, 1999).

4.4 Predictive Spatial Modeling and Mapping

The spatial modeling helped to explain the variables of interest by illuminating relationships in a variety of ways. The binary regression tree mapping approach discussed previously showed the importance of elevation, soils, and the interactions of aspect and slope on the influence on leafy spurge presence. The regression tree map shows the strong influence of the drainages on leafy spurge presence, as well as more subtle aspect and slope differences on the east/west tending drainages of Paddock and Knudsen Creeks. The other model maps using stepwise regression and kriging also reinforce the influence of the drainages. Topographic variable interactions, such as aspect and slope, are suggested by cross drainage differences in spurge presence in the presence and absence map (suitable and non-suitable habitat) and the probability trend surface map.

4.4.1 Significant Members in the Stepwise Regression and Noted Interactions

The stepwise regression screening of variables evaluated 184 potential interactions, and 17 showed significance. (P-value > 0.05). The 17 optimum model components represented the model with the smallest AICC score as discussed previously. The coefficients for both single independent variables and interactions are shown below in Tables 4.5 and 4.6. These 17 model coefficients were used to build the predicted surface map by combined conditional (con) statements in ArcInfo GRID.

Table 4.5 Description of the variables used to develop the models of probability and presence and absence (suitable vs. non-suitable habitat) of leafy spurge

Table A Significant Independent Variables and Interactions

Spurge OLS Coefficient	Description (Variables from Table 3.2)
Intercept	Model intercept value
Xutm	X value UTM coordinate
Yutm	Y value UTM coordinate
Elev	Elevation
A2	Aspect 2: Northeast
Z1	Zone 1 (floodplain + 8m)
So2	Soil type 2: Unweathered Badlands
So3	Soil type 3: silty clay loam

So8	Soil type 8: Cn loam
Z1s2	Zone1Xslope2: floodplain + 5-15%
Z2s1	Zone2Xslope1: midslope + 0-5%
Z1a5	Zone1Xaspect5: floodplain + south
Z2a1	Zone2Xaspect1: midslope, north
S2a3	Slope2Xaspect3: 5-15% + east
S2a7	Slope2Xaspect7: 5-15% + northwest
A4so7	Aspect4Xsoil7: southeast + fine sandy loam
A5so5	Aspect5Xsoil5: south + loam
A5so6	Aspect5Xsoil6: south + gravelly sandy loam

Table B Coefficients of the Significant Independent Variables.

	coef	**std.err**	**t.stat**	**p.value**
Intercept	-0.0389	0.1781	-0.2182	0.8273
xutm	0.0000	0.0000	-17.6212	0.0000
yutm	0.0000	0.0000	4.1634	0.0000
elev	0.0008	0.0002	3.5604	0.0004
a2	0.0443	0.0253	1.7554	0.0793
z1	0.3654	0.0243	15.0167	0.0000
so2	-0.0824	0.0548	-1.5042	0.1326
so3	0.1095	0.0427	2.5659	0.0103
so8	-0.1005	0.0228	-4.4006	0.0000
z1s2	-0.1068	0.0509	-2.0976	0.0360
z2s1	0.1529	0.0232	6.6040	0.0000
z1a5	-0.0751	0.0377	-1.9908	0.0466
z2a1	0.0973	0.0325	2.9900	0.0028
s2a3	-0.0937	0.0492	-1.9039	0.0570
s2a7	0.1812	0.1065	1.7020	0.0889
a4so7	0.0325	0.0201	1.6189	0.1056
a5so5	0.2874	0.0607	4.7345	0.0000
a5so6	0.2576	0.0812	3.1735	0.0015

Table 4.6 Results of the 0 and 1 (absence and presence) predictive spatial model

	coef	**std.err**	**t.stat**	**p.value**
Intercept	-8.6485	3.0559	-2.8301	0.0047
Xutm	-0.0006	0.0000	-17.4805	0.0000
yutm	0.0002	0.0000	4.1739	0.0000
elev	0.0133	0.0039	3.3847	0.0007
z1	6.2295	0.3976	15.6667	0.0000
z2s1	2.7502	0.3995	6.8849	0.0000
z1a5	-1.5207	0.6482	-2.3459	0.0190
z2a1	1.6779	0.5618	2.9865	0.0028
a4so3	1.8150	0.7343	2.4717	0.0135
a4so8	-1.8995	0.3750	-5.0656	0.0000
a5so5	3.5086	0.4578	7.6649	0.0000
a5so6	2.9779	1.0756	2.7686	0.0057

Combining the two models (the trend surface based on the OLS and the kriging surface of residuals) resulted in the final surfaces. The lowest values of standard errors, AICC statistics, and high R^2 served as the selection criteria for all models. The exponential model had the lowest AICC and lowest variance. For large-scale spatial variability models for predicting leafy spurge using the trend surface analysis based on the OLS procedure for modeling spatial probability, the R^2 value was 34.8 % and for predicting presence and absence (suitable vs. non-suitable habitat) of leafy spurge was 34.4% and all variables were significant at $\alpha < 0.05$ level. When adding the kriging and OLS models, R^2 values were 39.9 % for the Gaussian model, and 42.5% for the exponential model. The overall results, standard errors, and AICC values are shown in Table 4.7.

The spatial autocorrelation of residuals was evaluated with the LaGrange Multiplier as an indicator of spatial autocorrelation. The significance in the model prediction is indicated in the reduction of standard errors when the kriging was added to the OLS model alone. Accounting for the spatial autocorrelation, and employing the semi-variogram to evaluate how the variance changes over distance improved the model by adding the fine-scale variability to the coarse scale OLS model.

Table 4.7 Spatial model results and correlation values.

Summary statistics for large-scale and small-scale variability models for predicting leafy spurge within the Theodore Roosevelt National Park, Medora, ND.

Large-scale Variability (OLS Model)					Large-scale and small-scale Variability (OLS and Variogram Models)				
Variable/ Model Types	R^2 (%)	S.E.	AICC	P^3	Model	R^2 (%)	S.E.	AICC	P^3
Spurge Prob.	34.8	0.402	2987.0*	0	Exp.[1]	42.5	0.38	36.37	0
Spurge Presence /absence	34.4	6.98	19721	0	Gaus.[2]	39.9	6.67	146.7	0

Prob. = Probability
[1]Exp. = Exponential
[2]Gaus. = Gaussian
F- statistic = 91.4 (probability), and 138.9 (presence / absence or suitable / non-suitable)
* Spatial autocorrelation between residuals exists based on LaGrange Multiplier (form of Chi^2 test) = 1074.95

S.E. = Standard Errors
[3] P values using $\alpha < 0.05$ level.

Due to these spatial dependencies, the residuals of the Ordinary Least Squares (OLS) model were evaluated. A semi-variogram model describes how variance changes with distance. An exponential semi-variogram model was selected to model the residuals, and the kriged residuals were used to model the fine-scale variability on the landscape.

4.4.2 Kriging

Kriging has been used successfully in previous work with natural resources (e.g. soil textures) to interpolate the fine-scale variability on the landscape (Kalkhan et al.

2001, 2003). This study used kriging to interpolate the fine scale variability of the presence of spurge on the landscape. The need for kriging was confirmed by the presence of spatial autocorrelation of the residuals. The type of semi-variogram was determined by the lowest AICC and highest R^2 values, with the exponential model chosen in this study. The kriged surface was added to the OLS surface using standard GRID commands in ArcInfo for the final surface. In order to define the area to predict leafy spurge at the park, this study used a command to bound the geographic window for the variogram.

The evaluation of spatial autocorrelation with residuals utilized semi-variograms showing how the variance changes over distance. As this distance between points increases, the variogram will increase up to a plateau called the sill. The distance at which it reaches this plateau is called the range. The vertical jump at the origin is representative of the extremely small separation distances and is called the nugget effect. (Reich and Kalkhan, 2001). Figure 4.5 shows the nugget, sill, and range components of the variogram graph, and describes three different shapes of models. The summary of the components of the semi-variograms for the binary and probability models are shown in Table 4.8.

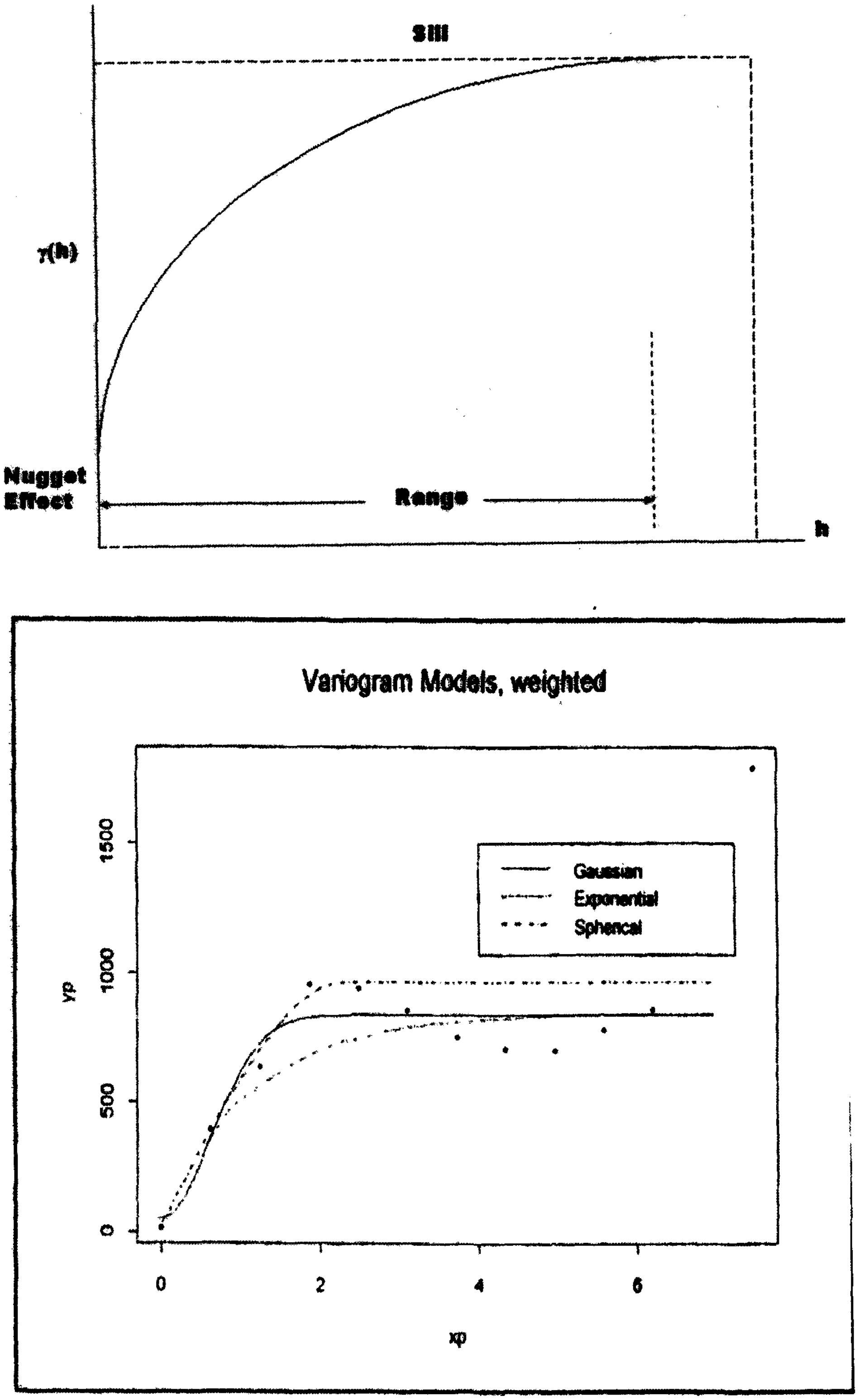

Figure 4.5 Nugget, Sill, and Range Components of Variogram Models

Table 4.8 Variogram Values for the Spatial Binary Model (0,1) and OLS Models.

Spurge variograms:	**Nugget**	**Sill**	**Range**	**alpha**	**Standard Error**
Binary 01: (0 = Absent; 1 = Present)					
Gaussian	11.99	41.81	159.36	0.287	6.47
Spherical	11.91	41.78	187.96	0.285	6.46
Exponential	Failed due to values less than 0				
Probability:					
Gaussian.	0.04	0.14	160.46	0.289	0.37
Spherical.	0.05	0.14	291.87	0.337	0.37
Exponential.	0.04	0.14	129.69	0.310	0.38

When modeling fine-scale variability, the desired alpha value was as low as possible, because as the alpha value approaches one, there are no spatial dependencies (no spatial autocorrelation) (Kalkhan, personal communication).

The regression tree provided two products. First, it provided a comparison to the surface model accuracy shown earlier. Second, the optimum node model was converted to a suitability surface of leafy spurge habitat with the intervening non-colored areas as uninhabitable. Based on this predicted habitat model, there is potential that leafy spurge will occupy the landscape based on favorable environmental factors (i.e. moisture availability, soils, drainage, slope position, aspect, and other factors). The habitat suitability map from the OLS trend surface is shown at the top of Figure 4.6 above the probability map. The probability map on the bottom of Figure 4.6 used the ratings of the likelihood of leafy spurge spread as:

Low – probabilities from 0 to 0.33

Medium – probabilities from 0.33 to 0.67

High – probabilities > 0.67

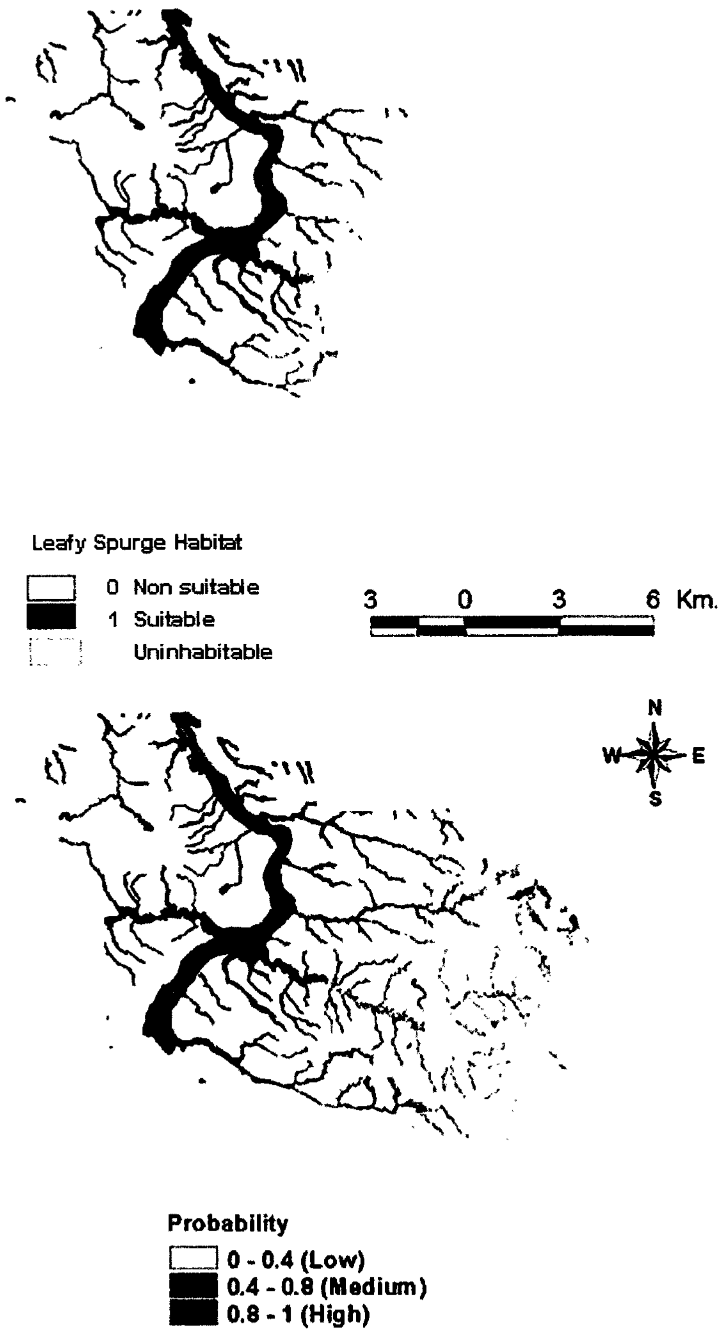

Figure 4.6 Suitability of Habitat and Probability Estimates for leafy spurge at THRO.

The previous basin ratings from Figure 3.4 earlier, shown below compare favorably with the predicted probabilities shown in Figure 4.6. The heavy infestations in the northwest area correspond well with the high probability surface, and the moderate infestations correspond well in the Little Missouri main stem and Paddock Creek confluence. In contrast, the moderate probability extends upstream further into the upper Paddock Creek drainage that includes light infestation areas from the basin studies earlier. The low probability also extends into the basin rated as none. The basin ratings are majority ratings by percentages, and the probability map is a 10 meter individual pixel rating, with no majority averaging.

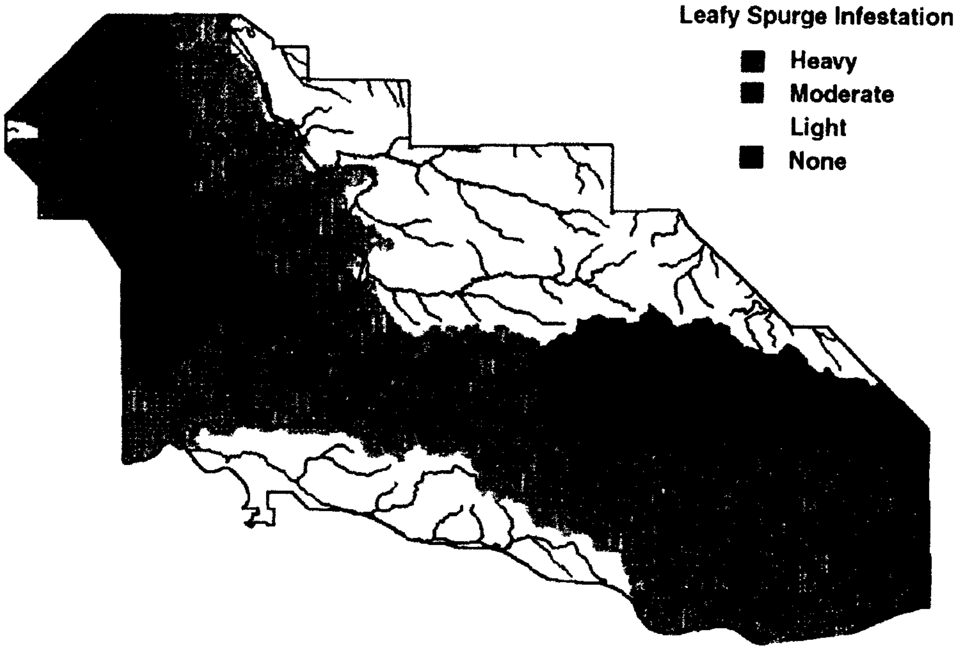

Figure 4.7 South Unit Infestations from Anderson et al. (1996).
Heavy (>5%, red), moderate (>1 but <=5%, blue), light (>0 but <= 1%, yellow), and none infested areas (green).

4.4.3 Predicted Surface Map for Theodore Roosevelt National Park

Figure 4.6 shows the predicted surface for leafy spurge at THRO and compares well with Figure 4.8 below of Zone 1 elevations (floodplain + 8 meters) that have the largest coefficient in the spatial models. In Figure 4.6, three categories of spread probability were created from the trend surface model. The model in this study generated a continuous surface of probabilities, and the categories were selected to reflect the ranges of probabilities associated with the spread severity. This study is consistent with the previous work by Anderson and others in describing the leafy spurge presence on the landscape at THRO. The Anderson et al. (1994, 1996, 1999) studies categorized the ratings as area extent values compared to the total area. Leafy spurge infestations by watershed sub-basin were: heavy (>5%), moderate (1-<5%), light (>0 but 1<%), and none in the 1994 paper, shown earlier in Figure 3.4. The category 'none' was barely present on the eastern edge in the upper headwaters of Paddock Creek by the 1999 paper, shown earlier in Figure 3.5.

Figure 4.8 Elevations for floodplain + 8 meters as Zone 1 at THRO
Lighter = lower floodplain, darker for higher elevation above floodplain

4.4.4 Ecological Interpretations

The results from cross-correlation values indicated a relationship between elevation and spurge occurrence. Additionally, slope position, slope, and aspect had significant cross-correlation to elevation. In the regression classification tree described later, elevation and soil type were the first and second decision points, respectively. This is consistent with the proposed moisture influence and distance from stream criteria of Anderson et al. (1998; 2001).

The three categories of spread probability represented the confidence in leafy spurge spread to those zones. The largest OLS coefficient for the model was slope position, or zone. The two next strongest coefficients included soil texture, in the south aspect loams and south aspect gravelly sandy loams. Spurge may be present on other landscape forms, regardless of whether it was detected during this study. For areas not showing a presence of spurge, it was possible that the spurge had not arrived yet, or had been arrested by the biological control efforts at THRO. The low probability areas were side slopes, soils types, and non-drainage areas that indicated a set of physical conditions not likely to support leafy spurge. As an example, by following the right branch of the regression tree diagram, Unweathered Badlands, silty clay loams (badland bases) and loams in the elevations 714.5< elevation < 811.5 meters within zones 1 and 2, slopes 5-15% were denoted as spurge absent.

4.5 Spread Estimation Results

As discussed in the previous Materials and Methods in Chapter 3, aerial photography interpreted polygons from 1993 and 1998 provided a measure of leafy spurge expansion. This sample between polygon boundaries addresses the last sub-objective of spread rate estimation. The spread rate results are summarized in Table 4.9 below.. This sample spanned the range of soil types, slopes, and elevations on the landscape. Spread rate estimates for both patches with biocontrol and patches without biocontrol were determined. Spread rates determined by 1993 to 1998 comparison paralleled the 5-year doubling found by Anderson et al. (1996; 1999) between the years 1993 and 1998.

Table 4.9 Spread rate results and comparison values.

Year Span	**Biocontrol dates**	**Sample Size**	**Average Spread**	**Comparison to Previous Studies**
1993-1998	1988-1992	40 Strip 1	4.8 m/yr	Consistent with Anderson at the low estimate range
1993-1998	1994-1997	54 Strip 1	14.3 m/yr	Consistent with Anderson at the upper estimate range
1993-1998	1994-1997	110 Strips 1-5	11.7 m/yr	Consistent with Anderson at the upper estimate range

4.5.1 Estimated Spread Rates

The westernmost Strip 1 estimate looked at polygons with the earlier 1988 through 1992 releases of biocontrol flea beetles. These polygons did not exhibit the scale of expansion measured in the release polygons from 1994 to 1997, or in the Strips 1-5 across THRO. The greatest expansion rates were found in the patches without any biocontrol releases. The spread rates for the areas that did not have any insect releases are shown in Table 4.10 below. These spread rates are higher than those reported by Anderson, but are generally consistent with the doubling of size discussed by Anderson (1999). The rates in the floodplain and uphill are slightly higher than downhill or the polygon to polygon spread rates. The long upstream expansions dominated the uphill category. The uphill spread rate could be an artifact of the sampling method, or there could be a biological effect. The shared spread rate between two polygons consistently lowered that estimated spread rate. Figure 4.9 shows the spread rate distribution for 1993 to 1998 for the biocontrol polygon samples for releases between 1994 and 1997.

Table 4.10 Spread Rates from 1993 to 1998 without biocontrol in meters per year

Sample Direction or area	Sample Size	Average spread in m/yr
Average for all directions	104	27 m/yr
Uphill direction of spread	49	37.3 m/yr
Downhill direction of spread	17	28.6 m/yr
Floodplain	5	29.9 m/yr
Poly to Poly spread	33	17.3 m/yr

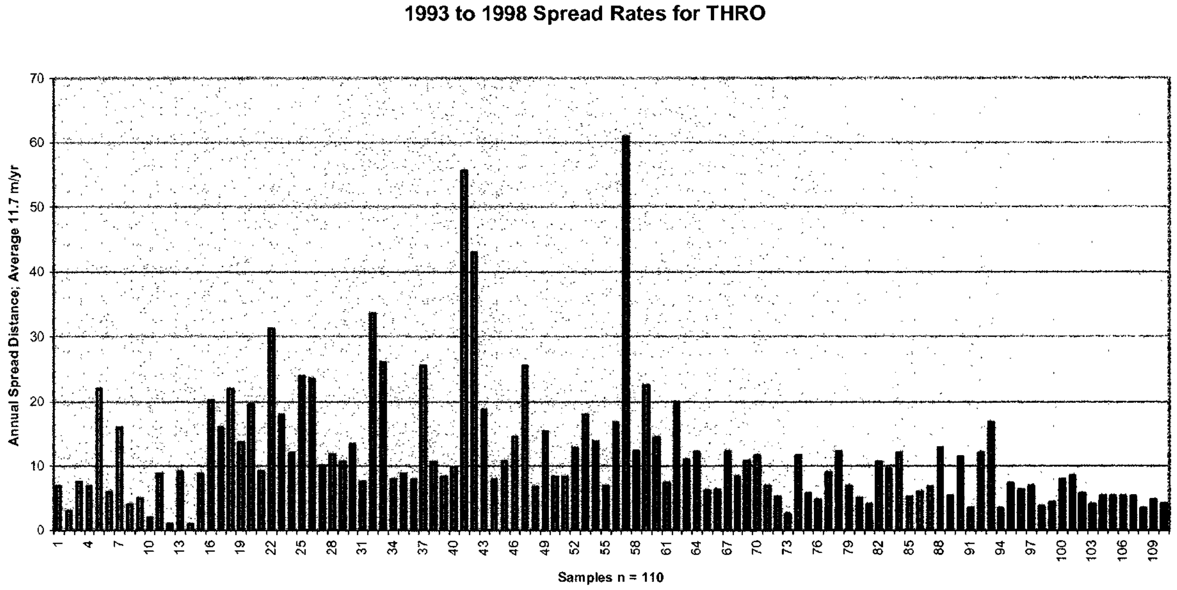

Figure 4.9 Spread Rate Distribution 1993 to 1998 with biocontrol effects

The average spread rate of 11.7 m/yr with biocontrol is one half to one third the rate of the patches without biocontrol. Variability of biocontrol success is evident in the range of patch expansion above 20 m/yr for 15% of the patches, and above 40 m/yr for 3% of the patches with biocontrol applied. Compared to the rates without biocontrol, these patch expansion rates indicate that biocontrol is having a positive effect for THRO.

4.6 Ecological Interpretation of the Landscape

Table 4.11 below summarizes the physical factors correlated to leafy spurge presence on the THRO landscape.

Table 4.11 Physical factors evaluated affecting spurge presence on the THRO landscape

Physical Factor	**Correlated Ecological Effects on Spurge Presence**	**Consistent with Anderson**[1]
Slope	Significantly correlated with elevation and the interactions with 5-15% slope on northwest aspect and 0-5% slope on the midslope zones	Yes, 0-5% slope
Elevation	Weakly correlated in OLS, major (first) regression tree decision point at 714.5 meters and many lower tree decisions	Yes
Aspect	Significantly correlated with elevation and the interactions with 5-15% slope on northwest aspect and north aspects on the midslope zones. Of the nine interactions in the OLS, seven involved aspect, with the two strongest on south aspects with loam and gravelly sandy loam soils.	Yes on South, mixed on North
Zone (slope Position)	Zone 1 (floodplain + 8m) was the strongest correlation of the OLS. Of the nine interactions in the OLS, four involved zone, with two on north midslope and 0-5% slope respectively. Weak negative correlations occurred on south floodplains and 5-15% floodplains.	Yes, with distance from stream as the major factor; plus 1998 movement onto the midslope
Soil Type	Second regression tree decision point (not badlands or silty clay loam) All other types affected by aspect and elevation. Six of the seventeen OLS factors included soil texture. Of the nine interactions in the OLS, three involved soils, with the two strongest on south aspects with loam and gravelly sandy loam soils.	Not included in Anderson

[1] Anderson et al. (1994, 1998).

The negatively correlated south floodplains (zone 1) and the 5-15% side slopes may be due to the native vegetation maintaining these ecological habitats due to sufficient water in the floodplain. However, spread continues in these areas due to both vegetative and seedling dispersal (Anderson, 1998). Several potential interactions may warrant further research in the development of better models of moisture availability in this geographical area. The northern cool aspects as well as the floodplain were reinforced as positive predictive factors as in previous studies. Midslope swales and midslope north aspects had positive predictive effects. The south loams and gravelly sandy loams showed positive predictive values. These soil types may exhibit the Noy Meir effect of soil texture, where coarser texture may contain more soil moisture due to deeper penetration and reduction of surface drying losses, compared to finer textured soils. The fine sandy loam (type 7) has an extremely similar landscape presence to the leafy spurge 1993 polygons. This soil type may warrant further research for leafy spurge presence in this geographical area.

These results, and the ecological interpretation of these results suggests that slope position, aspect, and soil type were helpful contributing variables for predicting leafy spurge presence, as studied earlier (Anderson et al. 1996; 1999).

4.7 Summary

The correlation values from the results indicated a relationship between slope position zone, soil type, aspect and slope interactions, and spurge occurrence. Additionally, slope percent and elevation contributed as indicators as well. This is both consistent with, and expands upon the proposed moisture influence and distance from stream criteria of Anderson et al. (2001). Both the regression tree classification and the OLS maps predicted leafy spurge presence at a 10-meter spatial resolution. The traditional classification in the ENVI Image Analysis software gave a more generalized product, using a 30-meter cell size. The accuracy assessment methods employed both traditional and proportional Kappa calculations. The conditional Kappa was used to account for the proportional area of leafy spurge on the landscape, and improved from 0.23 in the traditional classification to 0.48 in the regression tree classification.

CHAPTER V

V. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

Theodore Roosevelt National Park (THRO) is composed of two separate land units, and native mid-grass prairie occurs in both units. The control of leafy spurge is the top natural resource management priority for the park. This study focused on the more visited south unit with an area of 18,680 ha. The park headquarters are in the south unit at Medora, North Dakota.

Leafy spurge has spread on the landscape at THRO under the influence of moisture, topographic effects, biological control, and plant growth dynamics. To develop the needed spatial parameters, the physical factors contributing to soil moisture were reviewed. The variables used in this study included elevation, slope, aspect, slope position, and soil texture. The 10-meter DEM provided four of the needed 'derived' products: elevation, slope, aspect, and slope position. Elevation was used to the nearest meter. Slope was broken into four classes based on recommendations from Anderson et al. (1999) and personal communication (Anderson, 2001). Aspect was divided into the eight cardinal directions using the standard ArcInfo classes. Slope position was derived from the DEM into three zones to reflect height above the floodplain. Because available soil moisture had been identified as an important factor in leafy spurge occurrence and spread (Anderson et al. 1996), eight soil types (textures) were identified from existing GIS soils layers and used in this study.

This study has two primary objectives. The first is to define the relationships between various physical factors that contribute to soil moisture and the presence of leafy spurge on the landscape at THRO. The second primary objective is to estimate the rate of spread using leafy spurge polygons interpreted from aerial photography. To allow broad examination and conclusions regarding the interactions among slope position, soils, and leafy spurge presence, this study included the interpolation of leafy spurge probability to the landscape-scale, utilizing generalized predictive spatial statistical models derived from aerial photography derived leafy spurge polygons, Geographic Information Systems (GIS), and field data.

The data were analyzed to yield several products, including a traditional thematic classification, and binary regression tree classification, a binary spatial model of presence and absence, a predictive spatial model of leafy spurge presence, and an estimate of spread rates between 1993 and 1998. A traditional classification was completed in ENVI for 5 major cover types including spurge. The binary regression tree classification was completed on presence and absence of spurge. The accuracy assessment methods employed both traditional and proportional Kappa calculations. The conditional Kappa was used to account for the proportional area of leafy spurge on the landscape. This study completed six steps to derive the predictive and classification maps. The first step was to test for spatial autocorrelation, cross-correlation, and linear correlation between the variables of interest (elevation, slope, aspect, slope position and soil texture). A positive autocorrelation was found. The second step was to use a stepwise regression to screen the five independent variables. Their contributions were evaluated and relative strengths quantified. The third step was to compute Ordinary Least Squares (OLS) for the large scale variability using a spatial weight matrix for interactions. The fourth step was to examine the residuals to test for spatial autocorrelation and Chi square. Since autocorrelation was present, it was appropriate to utilize semi-variograms to evaluate small-scale variability, and select the model (variogram type gaussian, exponential, spherical) with the lowest Akaike's Information Criteria (AIC) and smallest variance. This study used AICC which is a modification model of AIC (Reich et al. 1999). The fifth step was to apply kriging of the residuals to interpolate values for fine-scale variability. The sixth step was to combine the OLS and Kriged surfaces for the final trend surface grid. The lowest values of standard errors, AICC statistics, and best R^2 served as the selection criteria for all models. The exponential model had the lowest AICC and lowest variance. The computational time for the spatial statistical runs varied widely. This study found that the Stepwise Regression and the Regression Tree modeling approach was much less computer intensive than the OLS spatial weighted matrix and the kriging approach (minutes vs. days for a single run). The spread rate estimates were completed by examining polygon boundary changes between 1993 and 1998.

5.2 Conclusions

The first primary objective generated four sub-objectives. They were designed to define the relationships between various physical factors that contribute to soil moisture and the presence of leafy spurge. They included a thematic mapping estimate of leafy spurge presence using traditional classification; a binary regression classification tree as a comparison; a spatial modeling approach using physical topographic factors and spatial statistics; and a predictive spatial model of leafy spurge that captures both coarse and fine scale variability. The conclusions regarding these sub-objectives follow:

- Both the OLS and regression tree classification maps effectively predicted leafy spurge presence at a 10-meter spatial resolution. The traditional classification in ENVI gave a more generalized product, using a 30-meter cell size.
- The binary regression tree classification was an improvement over the traditional classification, and was completed without remote sensing data as an alternative methodology.

  The traditional classification had an overall accuracy of 62%, and a Kappa of 0.23. By using a cross-validation routine in S-plus (Mathsoft, 2000) the overall accuracy of the binary regression tree classification was 74%, and a Kappa of 0.46.
- Using an area weighted Kappa and classification accuracy improved the performance.

  The area weighted overall accuracy was 76.3% with a Kappa of 0.45.
- The probability surface and the regression tree classification can provide areas of investigation for THRO to inventory, looking for new patches of leafy spurge.

The variables used in this study included elevation, slope, aspect, slope position, and soil texture. The conclusions regarding these physical variables are as follows:

- Evaluation of the effectiveness of these moisture indices showed that elevation and slope position were significant indicators for modeling leafy spurge spread. This study found that these five physical parameters and the juxtaposition to existing spurge patches were usable for developing spatial models.

An unexpected result was that the Pearson's linear correlation values from the cross correlation analysis did not support the use of the physical topographic factors, as they were weakly negatively correlated with spurge presence. However, the topographic factors and soils were strongly correlated to each other (significant at $\alpha < 0.01$ level). Using this test alone does not tell the story, as other ecological environmental factors may control the spread of leafy spurge.

- The regression classification tree found elevation to be the most important first branching variable, followed by soil type and zone; and slope and aspect third.
- The OLS modeling results indicated a relationship between slope position zone, soil type, aspect and slope interactions, and spurge occurrence. Additionally, slope percent and elevation contributed as indicators as well.

Overall, the model for probability had an R^2 of 42.5%, a standard error of 0.4, and an AICC value of 36.37. The regression tree presence and absence model had an R^2 of 34.4% a standard error of 6.98, and an AICC value of 19721. For large-scale spatial variability models using the trend surface analysis based on the OLS procedure for modeling spatial probability, the R^2 value was 34.8 % and for predicting presence and absence (suitable and non-suitable habitat) was 34.4% and all variables were significant at $\alpha < 0.05$ level. When adding the kriging of the residuals (to interpolate values for fine-scale variability) and OLS models, R^2 values were 39.9 % for the Gaussian model, and 42.5% for the exponential model. This is both consistent with, and expands upon the proposed moisture influence and distance from stream criteria of Anderson et al. (2001). Previous studies had shown that the distance from streams and slope percentage were significant indicators of leafy spurge spread at THRO. In this location, elevation effects may be equivalent to distance from (or to) permanent water; however, this may not be the case in other locations in the Western U.S. (Beck, personal communication).

- The computational time for the spatial statistical runs varied widely. This study found that the Stepwise Regression and the Regression Tree modeling approach was much less computer intensive than the OLS spatial weighted matrix and the kriging approach (minutes vs. days for a single run).

The second primary objective included an estimate of spread rates. The biological control data set was used in the spread rate estimates, which depended on the proximity to biological control releases. Areas with no releases provided the best-unconfounded estimates of spread rates in the study area. The spread rate conclusions are as follows:

- Biocontrol efforts have been effective in reducing the spread rates, but spread rates still exceed 5 to 12 m per year on average in the biocontrol areas, consistent with previous studies (Anderson et al. 1999).
- In the uncontrolled areas, spread rates are four to five times that rate, in excess of 20 m per year. Although outside the range previously reported, these rates are consistent with the doubling of patch sizes reported in previous work by Anderson et al. (1999).
- The control sites served as the epicenter of a ‘crater’ in the leafy spurge that expanded radially (Anderson et al. 2001; personal observation).
- Compared to the rates without biocontrol, measured patch expansion rates indicate that biocontrol is having a positive effect at THRO.

Variability of biocontrol success is evident in the range of patch expansion above 20 m/yr for 15% of the patches, and above 40 m/yr for 3% of the patches with biocontrol applied. The average spread rate of 11.7 m/yr with biocontrol is one half to one third the rate of the patches without biocontrol.

Confounding factors involve several physical and biological issues. The spatial modeling was not influenced, but the spread rate estimation was affected by biocontrol. Density of leafy spurge, efficacy of biocontrol agents, or some other factor at the biological control sites influenced the spread rates of leafy spurge. Temporal differences were expected, and provided the basis for evaluation of spread rates. Date stratification of the spread rate measurements incorporated the timing, presence and relevance of the biological control release sites. Flooding and seed transport were integrated into the spread prediction by the nature of the current infestation in the drainage bottoms.

- The observed leafy spurge spread patterns indicated the likely role of flooding for seed transport in the drainage, and this is consistent with the findings of others (Carlson et al. 1994, Anderson et al. 1996; 2000).
- Current biocontrol efforts have reduced spread rates, but spread still exceed 5 m per year on average in the biocontrol areas, consistent with previous studies (Anderson et al. 1999).
- In the uncontrolled areas, spread rates were consistent with patch doubling estimates of Anderson (1999), in excess of 20 m per year.

5.2 Ecology of the Landscape

Leafy spurge has spread on the landscape at THRO under the influence of moisture, topographic effects, biological control, and plant growth dynamics. Physical parameters describing the moisture availability for leafy spurge (elevation, slope, aspect, slope position, soil type) obtained for 2,931 random sample points were weakly negatively correlated with leafy spurge spread. However, the ecological relationships exhibit a pattern. All positive correlation coefficients were statistically significant at the $\alpha = 0.05$ level. The elevation and slope positions contribute to the predictive model, in addition to the aspect and slope discussed and demonstrated in previous studies by Anderson et al. (1996, 1999). These results make physical sense in the consideration of moisture availability. The predicted spatial map of leafy spurge probability, depicted high (>.6), medium (.3-.6), and low (<.3) spread potentials. The high probability spread areas show patch expansion between 1993 and 2000. New patch starts seen on the CASI imagery in the Appendix in Figure A.1 between 1993 and 2000 also appeared in high probability areas. Medium and low probability areas showed a reduced occurrence of new starts and patch expansion, seen in the spread rate measurements across the THRO landscape. The ecological conclusions are as follows:

- Among the five physical parameters tested, slope position (zone 1) showed the highest correlation (r = -0.335) with leafy spurge presence. Among the four other landform parameters, aspect and soil type interactions showed slightly weaker relationships with leafy spurge presence than slope position (r = -0.125 and –0.222 respectively).
- Soil types 2 and 8 were weakly negatively correlated, and represented Unweathered badlands and Cn Loam respectively.
- Highest leafy spurge presence was in the fine sandy loam soil type, which is typically found in the drainage bottoms and low swales on micro topography on hillsides.
- Lowest spread risk was on the unweathered badland soil type.

- The combined predictive surface indicated high probability areas in the drainages and midslope swales in the northwest wilderness area of the South Unit of THRO.
- Additional moderate probability zones were identified in most of the drainage basins.
- In the regression classification tree, elevation and soil type were the first and second decision points, respectively. This is consistent with the proposed moisture influence and distance from stream criteria of Anderson et al. (1998; 2001). The negatively correlated south floodplains (zone 1) and the 5-15% side slopes may be due to the native vegetation maintaining these ecological habitats due to sufficient water in the floodplain. However, spread continues in these areas due to both vegetative and seedling dispersal (Anderson, 1998).

5.3 Recommendations for Management

The integration of spatial information can improve management. Data considerations, management effects and future study improvements follow.

5.3.1 Spatial Data Considerations, Improvements and Future Capabilities

Two considerations should be applied in designing treatments and predictive models:

- The selection of data sets necessary to answer the questions posed depends upon the **scale and resolution** of the desired results.
- When developing a model, does the **timeframe** influence the results, and does the model depend on temporal change detection? For many reasons, possibly including detection resolution, what you are looking for may depend on the time frame.
- **Different spatial data needs** occur for management purposes (e.g. synoptic vs. drainage) for landscape trends of invasion versus small starts for potential eradication.

These three considerations are linked by resolution (spatial and temporal) of both the source data and the desired granularity of the answer to assist the management question being posed. Broad scale data (i.e. Landsat) may not be suitable for small patch detection, and the use of the higher resolution sensors may be more appropriate for fine-scale detection needs (Root, 2001 personal communication). A further discussion of these resolution and source data tradeoffs occurs below in section 5.3.3. The following efforts could assist the modeling and management of leafy spurge at THRO. These can be applied to the existing leafy spurge maps, or the predicted surface grid from this study:

- Use of **LIDAR and IFSAR** (aircraft platforms using laser [Light Detection and Ranging(LIDAR)] or interferometric synthetic aperture radar (IFSAR)) could generate a sub-meter digital elevation model (DEM), surface trends of both canopy and intermediate vegetation heights, and other products still in development.

A finer spatial resolution DEM skeleton would allow other efforts and datasets to be developed, modeled, and correlated. New scanning LIDAR / IFSAR platforms and software can process 5-returns per pulse to give improved detection of both canopy layers and structure, and virtual "bare" ground surfaces, and 1to2-meter DEMS. Although finer resolution DEMs were possible, desirable, and available, most public land mangers did not have access or funds for the acquisition of the source data (e.g. LIDAR or IFSAR). Additionally, a resampling of the more common 30-m DEMs could enable a manager to interpolate 10-m elevations; however, this may increase viewshed and surface modeling errors (Maloy and Dean, 2001). When preparing perspective plots and terrain visualizations, what is the best sampling of a 30-meter DEM to describe the terrain (e.g. cubic convolution)? Based on previous work by Maloy and Dean (2001), the nearest neighbor sampling is NOT recommended when resampling a 30-meter DEM.

To encourage further research and to assist in park management, below are some potential study topics that could improve management options for leafy spurge.

- When developing influence zones for flood spread or animal spread vectors, consider using **variable width buffers** along existing drainages or animal travel zones.

  The existing leafy spurge spread map at THRO is based on a simple buffer, so this technique could improve the existing spread map, and the results of this study if combined with animal travel route information.

- It is apparent from the spread rate differences that **insect interactions** with leafy spurge expansion are present and terrain influenced.

  Further study on the timing, distance from release, and terrain interactions would be helpful to evaluate the efficacy of the biological control program. From the spread rate measurements, it is evident that the control efforts have influenced the radial expansion rates. What the rate changes are, and under what insect combinations they occur, would assist in future management choices in the biocontrol program at THRO.

- The inclusion of **imagery D/N values** to model the presence of spurge would expand the predictive factors.

  It is noteworthy that the binary regression tree classification achieved 74% accuracy without imagery. The inclusion of imagery in the model should increase that overall accuracy, due to the addition of spectral information.

- Recommended further research could involve the **transportation and animal vectors** of spread at THRO.

  These were not included due to a current lack of data. Animal vectors as avenues for spread were beyond the scope of this study. This recognized method of spread would have required additional resolution to detect, or needed to employ fine resolution GPS positioning to digitize the animal trails occurring along and headed out of the drainages. Animal tracking by collar or radio-telemetry may prove useful, and the use of data sets of animal routes would offer an additional research avenue to increase the quality of a future spread prediction model. Mapping the animal paths, to combine with the current park road and trail system would improve the estimate of vectors contributing to a spread model for THRO.

- **One to two-meter spatial resolution** products would enable the definition of game trails, animal movements, and other seed transport vectors.

  A rapid assessment system, like that employed for Rocky Mountain National Park and Grand Staircase-Escalante National Monument by Stohlgren et al. (1997, 2001) would utilize this vector network to assist in stratifying the assessment. The opportunities for fine spatial resolution data improve daily. The use of a finer DEM will be needed to model the small terrain features likely to contain early patches of leafy spurge on microsites and moisture pockets across the badlands topography. This DEM data set has the potential to emerge as a cost effective and usable tool to most National Parks. If appropriate, a mature GIS staff could then consider the investment of employing the collection and analysis of sub-3 meter hyperspectral imaging to detect the signature of these small patch starts.

5.3.2 Streamcourse Data and an Alternative Cost Model

The role of temporal differences and the disposition of missing data have been discussed earlier. Relevant to missing data, the determination of drainage bottoms might be considered not missing, but augmented, data. The drainage net shortcoming relates to the lack of the vector coverage extending to the headwaters. The line of the hydrology typically ends well before the ridge tops. This was overcome by modeling of the drainage bottoms with the DEM.

- A future improvement would involve the hillslope modeling of the **flow divergence and convergence** (Watts, in press).

The chosen model had the following traits and performance: spatial, non-physical, mathematical, deterministic, and dynamic. The predictive output depended on the deterministic and dynamic traits, with a spatial and mathematical basis.

- An alternative model considered was a **spread cost model** that used C programming. This study focused on the expected landscape relationships with leafy spurge and an autocorrelation component was needed due to the spatial relationships between moisture and the physical landscape traits identified in previous work. Although the spread cost model could potentially capture the direction and intensity of spread, it would not evaluate the effects of spatial autocorrelation.

5.3.3 Park Management Data Sources and Future Imagery

In design of a detection system, the public land manager must decide the size of change in conditions they are looking for. For invasive plants, early detection suggests finding the small patch starts. This requires the finest resolution, and the most expensive inventory methods. Discovery may also depend on time frame, because the size of the patch may not be apparent until several years have passed. Inventory crews may not be able to visit large expanses of lands regularly, giving favor to the use of remote sensing options. Balanced against the cost of detection, the size of patch recognition determines the spatial and spectral resolution of the methods used to sense the presence of the invasive plants. Using 30-m DEMs and Landsat-TM scale imagery, a manager will find relatively large patches, well past the beginning stages of infestation. Even 10-m DEMs and associated scale sensors do not define single or multiple plant expansions, until they grow either temporally or spatially to a detectable size. The economics of Park coverage in imagery, analysis, and manpower constrain the level of resolution a manager can request. Conventional aerial photography is not cheaper overall, due to the longer hours for analyst time and large number of images to interpret. As with many natural resource decisions, a matrix of pro and con issues present challenges in selecting measurement and inventory tools. Therefore the manager should select tools, scales, and resolutions appropriate to the level of detail required for the decision. This study utilized a 10-m resolution, but future efforts have the capability to use finer spatial resolution tools when they become available and affordable. Finer spatial resolution would allow the detection and probability modeling of smaller patches of leafy spurge.

- Insect interactions with **north slope considerations** may influence control, and the potential use of **animal control** of spurge may improve effectiveness.

  The north slopes contain the highest soil moisture content, but the lower temperature causes the lowest bio-control insect development. Conversely, south slope dryness is best for beetle production, but less favorable for spurge spread. This creates management implications of mixing control methods, and north slope conditions may require 3 other approaches. First, the development of beetle populations better suited to cool sites. Second, a mixture of integrated weed management tools on north slopes. Third, mechanical / cultural methods to reduce competitive advantage on north slopes.

Related to the north slope issues above, and dense leafy spurge stand heights in general, Harte and Shaw (1995) observed that altered soil temperature plays a direct role in shifting life-form dominance within a community. The native grasses evolved without an overtopping competitor. Leafy spurge gains competitive advantage by exploiting soil moisture deeper in the soil profile, earlier in the season, and by capturing sunlight above the native grass canopy (Beck, personal communication). This combination makes this invasive plant a staunch competitor.

- Are **goats or sheep** a prohibited option **on NPS lands**?

  If the issues of disease transmission and public perception can be addressed, they show great success west of the park on private lands. The recommendation of Carlson et al. (1994) identifies a zone along the Little Missouri and Knutson Creek drainages for the potential introduction of sheep or goats at three to four goats or sheep per 0.4 ha (acre) of leafy spurge. The concurrent use of biological agents, or a fall-applied herbicide should accompany grazing treatment.

- The use of **finer spatial resolution imagery** may improve detection and control.

  In comparison, one- to two-meter spatial resolution products will enable the future definition of game trails, animal movements, and other leafy spurge seed transport vectors because of the high contrast between those trails and vegetation. With sub-meter capabilities now offered with the launch of 'QuickBird' in 2001, the opportunities for fine spatial resolution satellite data has improved. These findings may be improved by working with a 10 meter or better sensor system. What can managers do with higher resolution data sets? Even though this (10-m DEM) data cannot model small starts (under 3 to 4 m in size), managers should pursue those data sets to answer that question.

A further research need involves the potential and limitations of 30-m resolution data sets for spread prediction mapping. This effort is underway with TEAM Leafy Spurge, and is beyond the scope of this study. A comparative evaluation of the advantages and disadvantages of spread predictions based on 30-m data sets could contrast with this study using 10-m data sets or higher resolution terrain and airborne remote sensor data.

- Expanded research and **future use of 2000 CASI imagery** may increase mapping and detection capability for THRO.

  Multiple flight lines of CASI data were collected in July 2000. The future use of the CASI data would require improved rectification. The westernmost flightline covered the Interstate 94 Interchange over the Little Missouri River called 'No

Man's Land', the Cottonwood Campground, and the confluence of the Little Missouri River and Knutson creek. For future research, these areas provide a full range of aspects and slope positions to develop and test a more robust spatial model. They do collect a modest range of elevations, but do not include the extreme topography to the east. Future flight line processing of the remaining three flightlines would allow a study of the Paddock Creek drainage that contains more topographic relief. Further spread rate research into the temporal changes between the 1993 baseline polygons and CASI data in 2000 could likely be due to patch size change. The CASI imagery detected the leafy spurge spectra in the polygons from 1993, with the exception of biological control zones (Brown and Root, 2000). Recommended future model efforts could focus on a predictive or descriptive paradigm, a temporal change inclusion, and sensitivity analysis to both spatial and spectral resolution. Much can be done with spectral library development keyed to plant phenology. There is not a single leafy spurge spectral signature; it depends on timing and plant phenology.

5.3.4 Future Research in Soils and Moisture Availability

Several potential interactions warrant further research in the development of better models of moisture availability in this geographical area. The northern cool aspects as well as the floodplain were reinforced as positive predictive factors as in previous studies. Midslope swales and midslope north aspects had positive predictive effects. The south loams and gravelly sandy loams showed positive predictive values. Crafted as a research question:

- Do these soil types (south loams and gravelly sandy loams) exhibit the Noy Meir effect of soil texture, where **coarser texture may contain more soil moisture** due to deeper penetration and reduction of surface drying losses, compared to finer textured soils?

The soil type categories contain complexes of soil associations. The within type variability might not exceed the between type variability; however, the finer spatial detail within the soil complex might provide usable predictive power in modeling. The optimum use and further refinement of the soil type inputs require further future study. The results of this study, and the ecological interpretation of these results suggests that slope position, aspect, and soil type were helpful contributing variables for predicting leafy spurge presence, as studied earlier (Anderson et al. 1996; 1996). The fine sandy loam (type 7) has an extremely similar landscape presence to the leafy spurge 1993 polygons. As a second research question regarding soils influence on leafy spurge:

- Does the fine sandy loam soil type **match or promote leafy spurge** presence in THRO and this geographical area of the northern great plains?

Further research on this topic of soil spatial distribution and correlation with leafy spurge would facilitate further understanding of the dynamics and ecological factors influencing the presence of leafy spurge in this geographical area.

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APPENDICES

A.1 Literature Search Parameters

The search parameters for the Literature Search and review were designed with the assistance of Kerri M. Skinner, Ph.D., Ecologist Research Associate, USDA-ARS-NPARL, 1500 N. Central Ave., Sidney, MT 59270:

Search parameters:

No.	Records	Request
1	1262	leafy
2	643	spurge*
3	366	leafy spurge*
4	2336	Euphorbia
5	390	esula
6	433	#3 or Euphorbia esula
7	46983	population
8	21163	dynamics
9	4913	dispersal
10	5594	spread
11	16791	population dynamics or dispersal or spread
12	11	#11 and #6
13	13324	movement
14	29634	predict*
15	94845	model*
16	1341	patch
17	21163	dynamics
18	1341	patch
19	4506	expansion
20	125466	movement or predict* or model* or patch dynamics or patch expansion
21	19	#20 and #6*
22	28	#21 or #12

A.2 Processing Steps for Slope Position Classes

Description of GIS analysis to produce Elevation Zone Grids from Theodore Roosevelt National Park - South Unit data

Grid Zone_1 = cells 0 to 8m above stream channels based on USGS 24K DLG Hydrography data

Major processing steps in GRID:

1. Calculate flowdirection from 10m DEM
2. Identify and fill sinks
3. Identify elevation zone cells within 100m of intermittent stream channels and within 800m of the Little Missouri River using Euclidean Allocation (eucallocation)
4. Identify cells 0 to 8m above intermittent stream channels and the Little Missouri River, assigning a cell value of 1
5. Assign elevation values to cells, multiplying the 10M DEM cell values by the grid cell value from step 4

Grid Zone_2 = cells having an elevation value greater than 8m above stream channels and less than 5m below ridgelines

Major processing steps in GRID:

1. Assign a value of zero to nodata cells from Zone_1 grid
2. Assign a value of zero to nodata cells from Zone_3 grid
3. Add Zone_1 grid and Zone_3 grid
4. Set all cell values greater than zero to nodata
5. Assign elevation values to cells, adding the 10M DEM cell values to the grid cell value from step 4

Zone_3 = cells 0 to 5m below ridgelines

Major processing steps in GRID:

1. Calculate flowaccumulation from 10m DEM
2. Identify ridgeline cells from the flowaccumulation grid (cell value 0 = ridge)
3. Eliminate outlier ridge cells using a majority filter with a 4 cell neighborhood
4. Eliminate small peaks in floodplains by creating an elevation mask less than 720m, adding the resulting grid to the majority filter grid

5 . Identify elevation zone cells within 50m of ridge cells using Euclidean Allocation (eucallocation)

6 . Identify cells 0 to 5m below ridgelines, assigning a cell value of 1

7 . Assign elevation values to cells, multiplying the 10M DEM cell values by the grid cell value from step 6

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A.3 Literature Review of Selected related studies pertinent to THRO

This Appendix of the Literature Review includes related studies that apply to National Park management issues, but are beyond the scope of this study.

Spread vectors

Spread vectors provided by animals, insects and humans are beyond the scope of this study, and may be found elsewhere. See Olson, Wallander, and Kott (1997) and Lacey, Wallander, and Olson (1992) for the recovery of viable seed from sheep and / or goats. See Blockstein, Maxwell, and Kay (1987) for dispersal of leafy spurge by mourning doves.

Population dynamics

See Watson, A.K. (1983) for population dynamics modeling using a Leslie matrix with a focus on transitions. Bowes and Thomas (1978) studied picloram herbicide control and leafy spurge life cycles, and recommend managers keep the seed at the soil surface with no cultivation for 8 years following the use of picloram for weed control.

Economic impacts

Relevant studies of economic impacts in the upper Great Plains region from 1992 to 1999 involved eight authors. Bangsund, Leistritz, and Leitch (1997, 1999) predicted future economic impacts and described methods of assessing economic impacts. Bangsund, Leitch, and Leistritz (1996) evaluated the economics of herbicide control, building from their earlier work on methods, models, and results in Leitch, Leistritz, and Bangsund (1994) and Leistritz, Thompson, and Leitch (1992) and Wallace, Leitch, and Leistritz (1992). A summary of the projected economic conditions in Leitch, Leistrich, & Bangsund (1997), states:

> "By 2025, biological control was estimated to recover 320,500 animal unit months of grazing on rangeland, which translated into $16.5 million annually of additional production expenditures and revenues from expanded beef herds in the four-state region [Montana, North Dakota, South Dakota, and Wyoming]. Revenues and expenditures from expanded beef herds were estimated to generate $36.3 million in secondary impacts to the regional economy. Total future annual economic benefits of the biological control of leafy spurge on rangeland were estimated to be $52.7 million (1997 dollars) in the four-state region."

Alternative models

The presence of alternative models helped refine this study, but an exhaustive comparison is beyond the scope of this effort. Structural Equation Modeling (SEM) is a generalized covariance analysis methodology that may include path models, and was developed in the early 1970s (Keesling 1972; Jöreskog 1973; Pugesek and Grace, 1988). Wrightian path analysis (Wright, 1918) was replaced long ago by SEM in the statistical literature, which contributes to the dearth of current literature on path analysis. Many authors interchange LISREL (Jöreskog & Sörbom 1996) modelling with SEM, and traditional path analysis can be performed by LISREL, causing greater confusion (Pugesek and Grace, 1988). Due to greater complexity, SEM was not employed in this study. Wilson, Inskeep, Rubright, Cooksey, Jacobsen, and Snyder (1993) employed a Chemical Movement through Layered Soils (CMLS) model to evaluate picloram weed control and groundwater effects in Teton County, Montana. They found that under normal precipitation, picloram does not move beyond the root zone of approximately 120cm. This model was not employed because the evaluation of layered soils is beyond the scope of this study. I selected the 'Moran's I' test and autocorrelation methods in S-plus (MathSoft, Inc., 1995) for this study (Reich and Kalkhan, 2000) because of the presence of autocorrelation in most spatial data, and the growing acceptance of this factor in affecting spatial model conclusions.

Biological control research

Biological control research spans the behavior, chemistry and genetics of both the agents and the targets. Christianson, Lym, and Messersmith (1998) studied flea beetle establishment and survival and movement along railroad right-of-ways. Harris et al. (1985) summarize the biological control of leafy spurge in North America, and multiple works are contained in the TEAM Leafy Spurge (2000) compact disk. Evans et al. (1991) conducted analytical pyrolysis and pattern recognition of leafy spurge extract. They concluded that the North American strains exhibited variable chemistry and susceptibility to biocontrol. Their study concurs with Harvey et al. (1988) on naming only one *E. esula* species for North America. Rowe et al. (1997) studied the genetic variation in North American leafy spurge using DNA markers, which suggests that either multiple introductions, or high within population variability within its native range accounts for the high variability, and is beyond the scope of this study.

Biological control also involves animals, although previous authors may have deemed animal control a cultural practice (Beck, 2001 personal conversation). Grazing with sheep *(Ovis* spp.) or goats *(Capra* spp.) may be the only cost-effective treatment option for controlling leafy spurge top growth in pasture and rangeland (Lym, 1998; Olson and Lacey 1994; Sedivec and Maine 1993) when leafy spurge infests large acreages.

Chemical and cultural control research

Lym (1998) reports that several grass species, including Rebound™ smooth brome, Rodan™ western wheatgrass, Pryor™ slender wheatgrass, and Manska™ pubescent wheatgrass, are competitive with leafy spurge. Cultivating twice each fall after harvest for 3 years in cropland completely controlled leafy spurge. A successful long-term management program should be designed for specific situations and should include combinations of herbicides, insects, grazing, and/or seeding competitive species (Lym, 1998). The key to controlling leafy spurge is early detection and treatment of the initial invasion of the plant. A persistent management program is needed to control top growth and to gradually deplete the nutrient reserves in the root system (Lym, 1998; Galitz, 1994).

Great Plains Grassland Stature Coevolved with Herbivory

Over a majority of the last 7 million years, a diverse group of large mammalian herbivores have grazed and coevolved with grassland vegetation (Brown and McDonald, 1995; Owen-Smith, 1988). Current global climate supports a warm interglacial temperature compared to the more frequent glacial periods over the past 2 million years. Mega-fauna extinction 10,000 to 11,000 years ago in the Western Hemisphere has occurred during the interglacials, as they have been long and extreme enough. (Tausch , Wigand, and Burkhardt, 1993). In addition, original native grasslands are associated with regional climatic shifts toward aridity (Singh, Lauenroth and Milchunas, 1983). As grasses increased specialization and adaptations to dry conditions, simultaneous development and spreading of large ungulate grazers occurred (Stebbins 1972, 1981). Grass species and genera on arid rangelands today have existed for hundreds of thousands if not millions of years, and their evolution was clearly influenced by a long history of megaherbivorous grazing (Owen-Smith, 1988). Specifically, the northern Great Plains experienced a long evolutionary history of herbivory (Milchunas, and Lauenroth, 1993).

Under this historic influence, the plants of these areas should exhibit basal meristems, small stature, high shoot density, deciduous shoots (high turnover), belowground nutrient reserves, and rapid growth to allow these grasses to evade or to tolerate semiarid conditions and grazing (Coughenour, 1985). Switching capabilities (of plant species and modes of competition) do not exist in semiarid grasslands with long evolutionary histories of grazing and convergent (drought and grazing) selection pressures (Milchunas et al. 1988). Cool season grasses using the C3 pathway (3 carbon sugars) and warm season C4 grasses (4 carbon sugars) share this geography with forbs and woody stemmed C3 shrubs and dwarf shrubs. Most grassland vegetation utilizes a root zone to about 30cm (Milchunas et al. 1988). Under these characteristics of climate and evolutionary development, the invasive forb leafy spurge exerts competitive advantage by growth habits that overtop the existing vegetation, and by utilizing moisture and nutrient reserves from a deeper root system described later (Lauenroth, 2001 personal communication).

Historic Climate and Aridity Influencing Leafy Spurge and Competition

The northern mixed prairie consists of grasses, forbs, and shrubs. This arid ecosystem is about 10,000 to 15,000 years old, with soils resulting during the last glacial cycle formed from alluvial outwash from melting mountain glaciers less than 15,000 years ago. The Holocene warming reached a maximum 5,000 to 7,000 years ago, and migration of more arid tolerant plants occurred (Singh et al. 1983).

Grasslands in arid environments depend on surface moisture, and leafy spurge can compete for water because of growth and rooting habits. Plants tolerant of arid conditions are adapted to minimize surface moisture losses. Grasses form dense root system in the top 30cm of soil, while adjacent shrubs use deeper root resources. The long evolutionary Great Plains history of mega-fauna and herbivory has resulted in vegetation that is grazing tolerant, concentrates belowground resources, and does not generally need to compete for light by structure or stature (Singh et al. 1983). Belowground processes involving nutrients, biomass development, and carbon cycling dominate grasslands with less than 500mm of annual precipitation, like those of THRO (Lauenroth and Coffin, 1992). These factors, compared to the growth habit of leafy spurge make this grassland community susceptible to invasion by any invasive plant that generally is not grazed or browsed and has growth habits that compete better for space, nutrients, or light.

Competitive Advantage of Leafy Spurge

The general consensus of many authors is that leafy spurge generally dominates areas as a dense forb monoculture and displaces native vegetation. Besides vegetative spread, seedling establishment can result from seed germination in cool moist conditions, with seed viability of 8 to 10 years in the soil (Galitz, 1994; Wicks and Derscheid 1964). Ten days after germination, while the shoot may be a few centimeters in length, the root may already by 10-cm long. This root to shoot ratio of at least 5/1 may continue to expand through vegetative maturity, making it a strong competitor for water and nutrients (Galitz, 1994). The following is an excellent summary of the competitive nature of leafy spurge:

> “It (leafy spurge) is an extremely competitive plant that can eliminate other species once it invades a plant community and becomes established. It is hardy, has a rank growth habit, is capable of growing vigorously in diverse environments, is a prolific producer of seeds with varying dormancy periods (which ensures a long lasting soil seed reserve), is able to reproduce vegetatively as well as sexually, is stress resistant and can, in mid to late summer, be revived with a second flush of growth and production of a second generation of seed. Lastly, because of its capacity to produce large quantities of latex, it is avoided by most livestock and wildlife as forage or browse.”(Galitz,1994)

Concepts of Invasibility

Concepts of invasibility described by Stohlgren et al (1998), David, Grime, and Thompson (2000), and Sax and Brown (2000) do not concur with Richardson et al (2000) on the requirement that successionally mature undisturbed communities involve a higher level of barriers to an alien plant. They hypothesize that normal disturbance resulting from natural resource availability shifts can produce openings for a plant that is alien to the ecosystem. In short, a plant community becomes more susceptible to invasion whenever an increase in the amount of unused resources occurs (Davis, Grime, and Thompson, 2000). Further, new plant species can become established in any plant community in the absence of human induced disturbances because the normal fluctuations in resource availability provide frequent opportunities caused by fluctuations in precipitation and natural disturbance. Opportunities arise from natural variations on the landscape. As long as propagule pressure > 0, and a portion of the propagules have appropriate adaptations, the site is invasible. Kolar and Lodge (2001) found the most frequent and strong result indicated that successful establishment was positively related to ‘propagule pressure’, and although intuitively obvious, it is difficult to quantify.

Sax and Brown (2000) agree with Williamson (1996) that most invasions fail; however, despite an opportunity to adapt to the local environment, invaders do establish, and sometimes dominate and replace native species. In addition to release from enemies and other well-established causes, they add four additional mechanisms to explain this success. First, the environmental variation over space concurs with others above. Second the role of dispersal in population dynamics. Third, the superior qualities for survival of 'colonists' from large species rich regions, and fourth, the historical contingency of evolution both provide additional mechanisms (Sax and Brown, 2000). Stohlgren et al (1998) found 85% of the exotic plant species they encountered could be found in riparian zones. They focus this issue for natural resource managers: (1) high-fertility or excessively disturbed upland sites may be equally invasible as some riparian areas; and (2) rapid assessments should target riparian zones and high fertility/ excessively disturbed sites (Stohlgren et al. 1997).

Integrated Pest and Weed Management

Integrated weed management should address cultural, biological, physical, and chemical options to decrease the competitive advantage of the plant. Integrated weed management represents an integrated system or synthesized strategy of several concerted actions employed to address the specific landscape conditions and plant types needing control. In choosing these actions, to "eventually reduce the intensity of a spurge infestation, it is absolutely essential to reduce the vigor of the root system and the development and growth of crown and root buds" (Galitz, 1994). The use of a mixture of weed management tools in concert with grazing management can reclaim infested rangelands and return some or all of the economic viability to those lands (Lym, 1998).

For an overview of the leafy spurge problem, several authors have assembled work on the integrated management of leafy spurge (Beck and Rittenhouse 2000; Lym, 1998; Sheley, 1995; Beck and Sebastian, 1993; Watson, 1985; and Noble, Dunn, and Andres, 1979). A summary compact disk of 'Purge Spurge' version 4.0 containing many articles on identification, control, and management recommendations is available from TEAM Leafy Spurge (2000). The nationwide problem of alien import was reviewed by Devine (1998) in Alien invasion: America's battle with non-native animals and plants. General noxious weed articles, with reference to leafy spurge include James, Evans, Ralphs, and Child (1991); Lym and Messersmith (1984); and Hester (1991) which describes the US National Park Service experience with exotic species. Multiple state fact sheets describe the leafy spurge problem and status for their area, and typically offer guidance on early detection and control (Davidson and Hackett, 1986 (NV); Huerd and Taylor, 1998 (IA); Van Der Puy 1986 (ND); Bultsma and Lym 1985 (ND); Mitich 1973 (ND); and Mass 1985 (MT and inland northwest)). The 'Purge Spurge' compact disk also contains articles on integrated (mixed) stock management. An example of economic feasibility of sheep grazing of leafy spurge in Montana can be found in Williams, Lacey, and Olson (1996). An integrated approach to sheep and flea beetles can be found in Beck and Rittenhouse (2000).

Biological, Chemical, and Cultural Control

Ten insect species for leafy spurge biocontrol have been released in North Dakota; the most successful have been the flea beetles, *Aphthona nigriscutis, A. czwalinae*, and *A. lacertosa*. The leafy spurge gall midge *(Spurgia esulae*) has been most successful near wooded areas (Lym, 1998). A combination of chemical treatments with biological or cultural control practices such as cultivation, cropping, and grazing is necessary to control and stop the spread of leafy spurge, especially when it infests large acreages (Lym, 1998; Alley et al 1984; Dersheid, Wrage and Arnold. 1985; Sedivec and Maine 1993). Lym (1998) summarizes that cultural control of leafy spurge includes properly timed cultivation and/or planting of competitive grass species. Cultural methods that control only leafy spurge top growth include mowing and fire. Grazing by sheep and goats, discussed below, provides a form of biological control that may be considered by some authors as a cultural practice. All cultural control methods are more successful when combined with herbicide treatments than when used alone (Lym, 1998).

Economics and Grazing

Agronomic losses are estimated at ~$140 million per year (Anderson, 2001). Citing Leitch, Leistrich, & Bangsund (1997), assuming 65 percent control of the future acreage of leafy spurge, the leafy spurge biological control program (LSBCP) should provide an economic benefit of nearly $60 million (1997 dollars) annually in the Upper Midwest. Success to date indicates that the LSBCP will be an economic success regardless of the precise amount of future control.

Although it displaces native vegetation, leafy spurge can provide usable forage value to selected herbivores, such as sheep and goats (Beck and Rittenhouse, 2000; Beck and Sebastian. 1993; Sedivec and Maine 1993). Hard figures for economic returns from sheep augmentation are not available, but models of returns look promising (Bangsund et al. 2000). Specific to THRO management, leafy spurge has no forage value to the large native ungulates in the Park and its presence is therefore reducing the carrying capacity of the area (Carlson et al. 1994).

Department of Defense (DoD) Navstar Global Positioning System (GPS)

The U.S. Department of Defense (DoD) Navstar system provides the GPS satellites (constellation), control segment, and user support. This all weather system of 24 dynamic orbiting satellites provides three products: position, velocity, and timing. Offered through two levels of service, both military and civilian users employ this system for georeferencing, navigation, and timing. To prevent abuse of the system signal, the Standard Positioning Service (SPS) was designed with a degraded signal to limit civilian access to data with accuracies $\geq$ 100 meters, 95% confidence. The U.S. Coast Guard Navigation Center in Alexandria, Virginia serves in a civilian navigation support role, by producing the Nationwide Differential GPS signal through a series of base stations across the continental U.S. Federal civilian agency access to the Precise Positioning Service (PPS) began in 1995 and 1996 for the Departments of Agriculture and Interior, respectively. The PPS signal allows a 3-10 meter solution, with 95% confidence. Access to this signal is provided by cryptographic keying, and requires a Memorandum of Agreement between a candidate U.S. Executive (Cabinet-level) Department and the DoD. In May of 2000, the DoD discontinued selective availability (S/A) on the Standard Positioning Service (SPS) Coarse Acquisition (C/A) code that previously limited civilian accuracy to 100 meters. After the ramp down of S/A, civilian GPS receivers typically receive signals that derive a 15-meter error ellipse, with 95% confidence.

A.4 CASI imagery qualitative ground reference

The CASI remote sensing data contains 3-4 meter picture elements (pixels) with digital number (D/N) values in raster [grid] format. The CASI data was limited to the western portion of the study area, so this study did not build the D/N values into the predictive model. Principal Components (PC) of the original CASI D/N values were displayed in a 3-band PC composite for detection and qualitative verification of model predictions. The CASI hyperspectral data collected in 2000 utilized on board differential GPS to georeference the 3-4m pixel imagery, and obtained similar sub10-meter accuracy. This study verified this relative accuracy by polygon matching. This study also determined a slight variable georeferencing error in the CASI data by noting the two to three pixel shifts compared to GPS polygon boundaries. A new tool called the 'thin plate spline' from ENVI (RSI, Inc. 2001) provided georeferencing improvements to the CASI imagery. This tool was reviewed at the USGS Rocky Mountain Mapping Center in Denver, and was used to improve georeferencing accuracy. Regardless of the known offset in the georeferencing, the CASI data set was spatially compatible (similar resolution) with the other data sets, and provided an imagery source in the sub 10-meter resolution range. Figure A.1 of July 2000 CASI imagery shows an overlay of selected 1999 check polygons. These check polygons in the I-94 Interchange and 'No Mans Land' study area provided ground spectral measurements of mixed species vegetation, as well as leafy spurge.

Evaluation of the Principal Components [Minimum Noise Fraction] of the CASI dataset used standard ENVI methodology. The inclusions of this imagery in either this evaluation or any previous method or leafy spurge spread detection was new. The Minimum Noise Fraction (MNF) classification product was a 'noise whitened' principal component product that may contribute significant detection power. Several other related study efforts at THRO examine change detection and atmospheric calibration of hyperspectral data. Those characterization efforts are beyond this study, and represent the efforts of other study team members.

Figure A.1 Leafy Spurge mixed vegetation detected July 2000 with CASI imagery.