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PREDICTING SPOTTED KNAPWEED (*Centaurea maculosa*) RANGE EXPANSION NEAR MISSOULA MONTANA USING LOCALIZED CLIMATE AND ELEVATION DATA

By

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Abstract

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Predicting spotted knapweed (*Centaurea maculosa*) range expansion near Missoula, Montana using localized climate and elevation data

Chairperson: Anna E. Klene

Since the 1920s spotted knapweed (*Centaurea maculosa)* has adapted to a variety of habitats, including pastureland, rangeland, hay land, open forests, road sides, and ditches. In 2003 this plant species dominated more than five million acres in Montana, half of the total infestation of noxious weeds in the state.

This project demonstrates the utility of using downscaled Parameter-elevation Regressions on Independent Slopes Model (PRISM) data for predicting vegetation movement within a 2°×2° geographical area surrounding Missoula County, Montana. This localized climate change data was correlated against current knapweed range using validation data from the Volunteer for Wilderness Program at the Wilderness Institute at The University of Montana and the County of Missoula Weed District to examine optimal climatic conditions within the area. Parameters for precipitation and temperature were determined from current locations of spotted knapweed. These relationships were then used, with existing future climate scenarios from the Intergovernmental Panel on Climate Change (IPCC) and the United States Global-change Research Program (USGCRP), to predict the extent of knapweed based on its environmental tolerance ranges.

The potential expansion of suitable habitat for spotted knapweed within the study area was significant with minimal increases in temperature and precipitation, but the long-term effects of possible increases of 4.5°C and up to 10 cm of precipitation would cause a contraction of suitable habitat for spotted knapweed. Further studies on tolerance ranges would increase the understanding of potential invasive species movement and climate change.

Acknowledgements

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“Otsukare sama desu”

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If we are in our imaginations to give one species an advantage in the struggle for
existence probably in no one case would we know what to do.
Darwin, 1859

Chapter 1

INTRODUCTION

An invading species is “a foreign taxon that enters an established ecosystem and contaminates it” (Hirsch and Leitch, 2003). These species are not native to and tend to spread widely in a habitat or environment. Invasive species often have few natural predators or other biological controls in their new environment. Although not always considered harmful to an environment, invasive species can become agricultural or ecological pests and can displace native species from their habitats. If contamination means that the invader seriously disrupts the balance in that ecosystem and becomes harmful to native species, then the species becomes undesirable or “noxious” (Hirsch and Leitch, 2003). Noxious weeds displace native species; which may be endemic; change plant community structure; reduce forage for livestock and native wildlife; degrade and sometimes even eliminate suitable habitat for native wildlife and plant life (Duncan et al., 2001). Many such species have no natural enemies present to limit their reproduction and spread. Invasive species typically have high reproductive rates, fast growth rates, and effective dispersal mechanisms. Thomas Muzik (1970) compared humans to weeds by saying,

> …man, too, thrives best in disturbed habitat. The success of particular cultures or civilizations is measured by their ability to modify the natural environment in the direction necessary to ensure their own well-being. On the other hand, the population explosion may lead to man being considered undesirable. Some individuals such as thieves and other criminals, or even the modern-day “hippie”, may be considered weedy.

The increase in greenhouse gases, along with other anthropogenic changes, is producing conditions that are outside of the range of recent climate variation (Vitousek, 1992). These conditions will alter seasonal precipitation patterns (United States Global-change Research Program (USGCRP), 2000), and increases in mean global temperatures could reduce freezing winter temperatures in many regions of the world (Intergovernmental Panel on Climate Change (IPCC), 2001). The new plant communities that result from shifts of climatic zones are likely to be different from current vegetation assemblages because individual species will migrate at different rates and have different degrees of success in establishing themselves in new territories. This would be beneficial to some species, but would also cause certain species’ ranges to be expanded, including many native, nonnative, and potentially invasive plants (Stohlgren, 2005; Rosenzweig, 2003).

Between 1920 and 2000 (Rice, 2007) spotted knapweed (*Centaurea maculosa)* has become well adapted to a variety of habitats including pastureland, rangeland, hay land, open forests, road sides, and ditches (Duncan et al., 2001). Spotted knapweed threatens the long-term productivity of Montana’s croplands, grazing lands, and forests by reducing biological diversity and promoting soil erosion (Duncan et al., 2001). In 2003, this plant species dominated more than five million acres in Montana alone (Beck, 2003). That is half of the total infestation of noxious weeds in the state. The impact of this infestation on otherwise productive lands has been devastating (LeJeune and Seastedt, 2001). Identification of uninfested areas susceptible to invasion by spotted knapweed would permit land managers to implement preventive weed control methods. It is critical to protect the remaining, extensively managed rangeland from weed invasion.

Successful plant establishment is governed by climatic characteristics such as temperature and precipitation (Watson and Renney, 1974), as well as other factors such as soil chemistry and moisture and physiological and competitive factors. With these changes comes the possible contraction of suitable habitat of many native and non-native plant species, which could cause the extinction of species unable to adapt to these changes. Many attempts have been made to use climatic parameters to predict whether weedy species will become important in a region (Franklin, 1998; Welk, 2002; Kriticos et al., 2003; Rouget et al., 2004). Studies are needed to determine the effects of climate change upon the susceptibility of individual ecosystems to invasion and the responses that specific invasives will have to climate change. These studies would improve predictions of the potential ranges of invasive species under differing scenarios of global climate change and aid in finding ways to reduce their impacts.

Chapter 2

BACKGROUND

Global-change

The rise in temperature and alteration of precipitation associated with increasing greenhouse gases are expected to cause major changes in the location, extent, and species composition of many habitats (Wagner, 2003). The change in land-use and disturbance regimes in conjunction with global-change would cause a reduction in the ability of many species to colonize new habitat created by climatic change (Peters, 1991). With these changes comes the alteration in suitable habitat for all species. The ability of plant species to adapt to, and move with, these changes may cause extinctions in certain plant species, but would also create openings in vegetated areas for potentially invasive species to colonize.

Greenhouse Gases

Greenhouse gases are the leading cause of climate change. The concentration of carbon dioxide has risen approximately 30% since the late 1800s, (Vitousek, 1994; United States Global-change Research Program; USGCRP 2000). According to results from the European Project for Ice Coring in Antarctica (EPICA, 2004) ice core, obtained at the Concordia Station at Dome C Antarctica, this is an unprecidented increase, at least within the past 430,000 years. This has been caused by the burning of coal, oil, and natural gas, and the destruction of forests around the globe (USGCRP, 2000; IPCC, 2001).

As can be observed in Figure 1, atmospheric carbon dioxide (CO_2) is rising rapidly, and options for slowing the CO_2 rise are politically controversial as they largely require reductions in industrial CO_2 emissions from developed nations or sequestration through massive revegetation programs. The Mauna Loa record shows a 19.4% increase in the mean annual concentration of CO_2, (315.98 to 377.38 ppm from 1959 to 2004) with the 1997-98 increase of 2.87 ppm being the largest single year change since the record began (Keeling and Whorf, 2005).

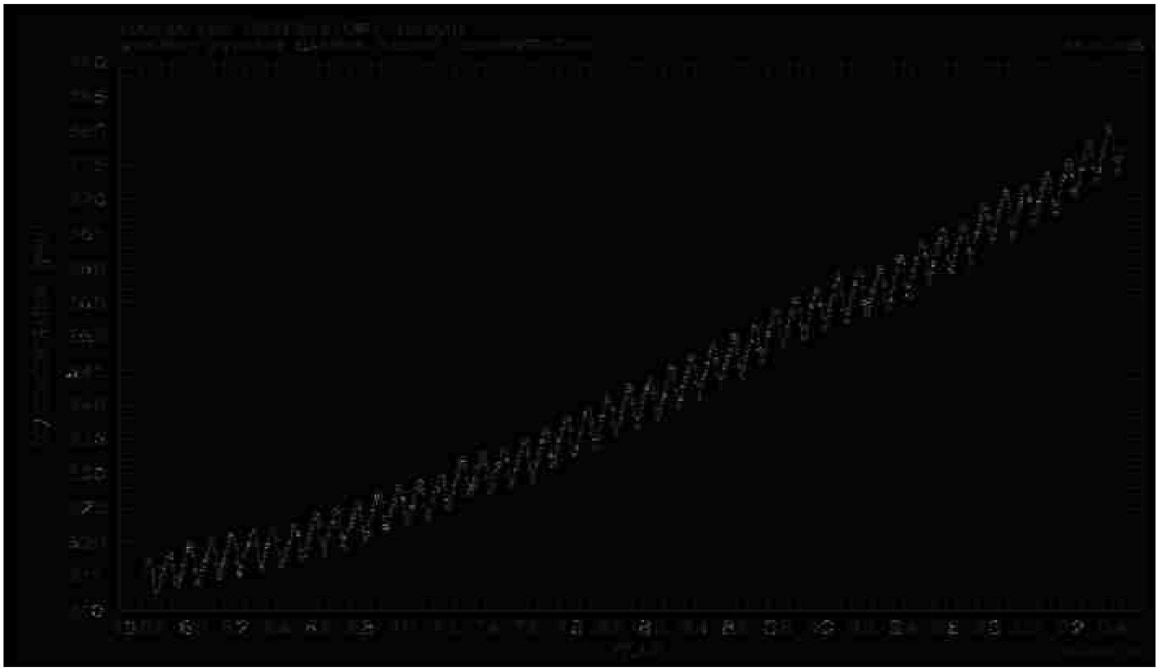


Figure 1. Mauna Loa Observatory CO_2 concentrations for the years 1958-2004 (Keeling and Whorf, 2005).

Global projections of population growth and assumptions about energy use indicate that the CO_2 concentration will continue to rise, likely reaching between two and three times the pre-industrial level by the year 2100 (USGCRP, 2000). About half of this rise has occurred since the 1970s. To add to this, methane concentrations have more than doubled since 1750 owing to agricultural and industrial activities (Green, 2000).

Rising Temperature

According to the Intergovernmental Panel on Climate Change (IPCC, 2001), temperatures recorded at ground-based stations reveal a mean annual warming trend ranging from 0.3-0.6°C since about 1850, with 0.2 to 0.3°C of this occurring since the middle 1970s (Green, 2000). Seventeen of the eighteen warmest years in the 20th century occurred after 1980 (USGCRP, 2000), and nine of the ten warmest years on record have occurred since 1995, with 2005 being "statistically indistinguishable" from the record set in 1998 (National Oceanic and Atmospheric Administration (NOAA), 2006). As the 20th century closed, the warming sped up, with mean global temperatures jumping by 0.5°C in the last 25 years. This would be the equivalent of 2°C per century. However the amount of change to which ecosystems can adapt is estimated at a maximum of 1°C over a century (Godrej, 2001), although regional changes have differed.

Model scenarios produced by the USGCRP 2000, projected regional warming in the Pacific Northwest of the United States in the 21st century to be much greater than observed during the 20th century, with mean warming over the region of approximately 1.5°C by the 2030s and 3°C by the 2050s. By the 2090s, mean summer temperatures are expected to have risen by 4-4.5°C (USGCRP, 2000).

Altered Precipitation

Increasing global surface temperatures are likely to cause changes in precipitation and atmospheric moisture owing to changes in atmospheric circulation, a more active hydrological cycle, and an increase in the water holding capacity of the atmosphere (Dore, 2005). Overall, global land precipitation has increased by about 2% since the beginning of the 20th century. Over this time, the annual zonal mean precipitation has increased by between 7 and 12% for the latitudes between 30 and 80° N (Dore, 2005). Precipitation over the U.S. has increased since 1900 by between 5 and 10%, since 1900 (Dore, 2005). Although this region may experience higher precipitation levels, rates of evaporation and transpiration are also likely to increase. Specifically in the northwestern U.S., mean precipitation is projected to increase through 2050, although some locations have small decreases (USGCRP, 2000).

Changing Land-Use and Disturbance Regimes

The general consensus is that land-use change is now, and will probably remain, the most influential aspect of global-change on ecological systems (Vitousek, 1994). It is estimated that about half of the ice-free terrestrial surface of the Earth has been transformed, managed, or utilized by human activity (Vitousek, 1994). Vitousek et al. (1986) estimated that nearly 40% of global net primary productivity (NPP) of the Earth is used or dominated by human activities. In the 19th century, land-use change contributed the largest concentration of CO_2 to the atmosphere and, through burning of fossil fuels, still makes an impact today (Vitousek, 1994). Fires associated with land-use change add nitric oxide and carbon monoxide to the atmosphere (Logan, 1985), altering its reactive chemistry and bringing occurrences of urban-like oxidant air pollution to the tropics (Vitousek, 1994). In the context of global-change, disturbance regimes are predicted to shift systematically. Within western North America, suppression of fire has altered natural disturbance regimes and landscape patterns at a regional scale (Laurance, 1998).

Invasive Plant Species Responses to Global-change

There is growing evidence that the Earth’s climate is being altered by anthropogenic causes (Houghton et al., 1996). Sessile organisms, such as plants, are susceptible to rapid global-change because they can only move from one place to another during dispersal. If the rate of change is too rapid, plants will not be able to adjust and become extinct in some or all of their range. Areas of suitable habitat which species could colonize would depend on many factors: a) the new habitat must exhibit suitable bioclimatic conditions, b) other species in the area must show a reaction to the change in climate which make the area more favorable to the new species, c) the dispersal rate of the new species must be effective enough to move into new areas, d) the substrate of the new habitat must exhibit favorable conditions for the new species, and e) the frequency of disturbances in the new habitat must facilitate the establishment of the new species (Dale, 1997).

With the potential increase in temperature and alteration of precipitation through climate change the potential changes in competition and facilitation will also change. Primary productivity generally decreases along gradients of increasing stress. Grime (1979) hypothesized that competition intensifies along an increasing gradient of primary productivity. Severe physical conditions that exist at the higher end of an elevational gradient may restrict the ability of plants to acquire needed resources such as light, water, and nutrients. Other experiments suggest that competitive effects are stronger under wet, cool conditions and more facilitative effects are prevalent when conditions are drier and warmer (Callaway and Walker, 1997). Therefore, the apparent interaction between species varies with the abiotic changes throughout the elevational gradient. As plants move from lower to higher elevations the way they interact changes from more competitive to more facilitative (Bertness and Callaway, 1994; Callaway, 1997; Choler et al., 2001). This represents the varying conditions that would exist from lower to higher elevations in the Missoula area with an increase in temperature and altered precipitation. Spotted knapweeds movement from the Pacific Coast to the higher elevation interior of the Pacific Northwest only emphasizes the need to study the effects of climate on the control of spotted knapweed invasion.

Projected climate changes are very likely to alter the biodiversity of the northwestern United States (Wagner, 2003). The composition of species that could arise in response to these changing climatic conditions could be detrimental to native species, which rely upon specific environmental parameters to survive (Mooney and Dukes, 1999). Invasive species have a history of exploiting habitats left vacant by native species. As climate changes, the indirect effects of weeds and pests seem likely to bring surprising challenges. Some native species are unlikely to be able to adapt fast enough to the changing climate regimes, resulting in a lowered competitive edge and weakened resistance of ecosystems to infestations by invasive plants and animals (Walther et al., 2002). Potential impacts include shifts in the relative abundance and distribution of native species, significant changes in species richness and communities, and local extinctions of native species (Walther et al., 2002). Increased mean temperature and annual precipitation in the northwestern United States could make it possible for invasive plants, such as Kudzu (*Pueraria* lobata) and Johnson grass (*Sorghum halepense*), now found in the south, to migrate northward (Mooney and Dukes, 1999). Additional land-use pressure on these native systems will occur if agricultural practices extend into these areas as a result of more favorable climatic conditions or increased demand for agricultural products.

It is now recognized that invasive species in general are an important element of global-change (Mooney and Dukes, 1999). Indeed, other changes in the Earth system, such as a change in greenhouse-gas driven climate change and changing patterns of land-use that fragment habitats and alter disturbance regimes are all affecting species distributions and resource dynamics in terrestrial ecosystems, and invasive species distributions are often viewed as feedbacks to these other driving factors (Mooney and Dukes, 1999).

Understanding how these other fundamentals of global-change can affect invasive species is an intimidating task. Ecologists and global-change specialists are just now beginning to understand how species and ecosystems respond to just a single aspect of global-change, let alone the effects that these changes will have upon the composition and density of invasive species (Mooney and Dukes, 1999). This can only add to the uncertainty. Some of these changes are homogeneous throughout the world, yet others differ tremendously over short distances. The most daunting task is to determine which ecosystems will become more susceptible to invasions (Mooney and Dukes, 1999). The only real way to determine this is to use current studies that incorporate aspects from both studies of invasive species and global-change research.

In general, it is expected that most aspects of global-change will tend to favor invasions and will intensify the impacts of invasions on ecosystems (Mooney and Dukes, 1999). These impacts include competitive effects, whereby an invading species reduces resources available to other species, and ecosystem effects, whereby an invader alters primary properties of the ecosystem. Either type of effect can threaten native biodiversity, and some ecosystem effects feed back to elements of global-change (Mooney and Dukes, 1999).

Invasives benefit from disturbance and the resources in these new environments (Mack and D'Antonio, 1998). Factors that contribute to the success of these invasive plants are their rate of natural increase, reproductive and genetic characteristics, abundance and range in their native habitat, adaptation to the climate, and the presence of a vacant niche in the new environment (Williamson, 1996).

Increased CO_2 Levels

There have been many studies done on the response of woody and agricultural plant species to elevated CO_2 concentrations (Bazzaz, 1996; Davis, 1989; Rogers et al., 1986; Karnosky., 2003; Ziska et al., 2001). Many invasive plants have been shown to respond favorably to increased CO_2 levels (Mooney and Dukes, 1999). Examples of these are species that have invaded North America, such as Cheatgrass (*Bromus tectorum*), Kudzu, and Japanese honeysuckle (*Lonicera japonica*). Plant species respond less predictably to CO_2 enrichment when they are grown in diverse communities (Mooney and Dukes, 1999). It is very risky to predict which species will thrive or perish in high CO_2 conditions or in the absence of other species (Mooney and Dukes, 1999).

It is believed that the rising CO_2 levels have already given rise to plant invasions (Mooney and Dukes, 1999). Rising CO_2 levels might have contributed to an increase in the abundance of many varieties of mesquite, or maybe even played a role in the invasion of cheatgrass in the Intermountain West by contributing to the acceleration of fire regimes (which is a limiting factor of cheatgrass). Elevated CO_2 levels stimulate plant growth and consequently increase fuel loading (Smith et al., 1987). This increase in fuels can lead to more frequent and severe fires. Rising CO_2 levels may slow the process of succession in grasslands, which would increase the dominance of non-native species in many ecosystems. Complex interactions among CO_2 effects and factors such as climate change will affect competition among native and alien species in ways that cannot yet be predicted (Mooney and Dukes, 1999).

Rising Temperature

Temperature is probably the most significant climatic factor in biological terms as all metabolic processes (and most chemical reactions) are temperature dependent (Ford, 1982). It determines the time of year for germination, growth, and reproduction (Duke, 1985). The physiological processes of all plants proceed at a rate dependent upon ambient temperatures. In consequence, there are diurnal and day-to-day variations in metabolic rates, but the annual cycle of temperature is considered to be of greatest significance when considering the biological impact of climate and climate change (Ford, 1982). Climatic changes producing a small change in annual temperature may result in a significant expansion in the length of the metabolically active season. Such a change may affect the growth of an organism in a particular area if there is a longer length of time between spring and autumn for the completion of the processes of development, growth, and successful reproduction (Ford, 1982). These slight changes could also affect a species if the tolerance range of the species is exceeded with warmer temperatures.

Most physiological processes exhibit upper and lower temperatures thresholds, above and below which the processes will not occur. Temperature can influence plant growth through its effects on enzymes that catalyze limiting chemical reactions, by affecting the uptake of water by roots in cold soil through its influence on the physical properties of water, and can influence photosynthetic CO_2 use through both short and long-term effects (Duke, 1985).

Rising temperatures associated with climatic changes would affect all plant species. Species ranges move when climatic patterns change. Expected responses to projected global warming during the next 50-100 years include the disruption of natural communities, potential for invasive species dominance, and possibility of extinction of some populations and species (Peters, 1991).

Altered Precipitation

The importance of moisture to plants and animals manifests itself when one considers that all living things are composed of about 80% water and that protoplasm is only physiologically active when fully hydrated (Ford, 1982). Water stress reduces photosynthesis by affecting stomatal conductance in cells, chlorophyll synthesis in greening leaves, electron transport, and photophosphorylation. Perhaps the most sensitive process to water stress is the reduction in leaf area, which reduces the capacity for photosynthetic processes (Duke, 1985). In addition, water availability and temperature are the major factors limiting plant productivity (Duke, 1985). Reduced soil-water availability increases the level of stress experienced by plants, because stress develops when the transpirational loss of water from leaves exceeds the uptake by roots

(Duke, 1985). In contrast, increased precipitation which is predicted in the study area could allow native vegetation more able to compete with non-native species or modify the ranges of both into areas with more favorable conditions. With high moisture levels, invasives originally from humid regions will be more competitive, while conversely, plants native to arid regions would be competitive in drier areas owing to climate change (Duke, 1985).

Changing Land-Use and Disturbance Regimes

The impact that land-use change has on invasive species proliferation is immense. As forested areas are cut and urban areas expand, so do non-native species (Vitousek, 1994). As more and more barriers to these species are literally torn down, with increased transportation, and decreased security against invasive species, the spread and proliferation of non-native species will only increase.

Extensive reviews on the relative importance of disturbance and propagule availability in invasion success have occurred (Mack and D'Antonio, 1998; Levin, 2000). For many years invasions have been linked, exclusively, to human disturbance. However, there is an increasing consensus that natural disturbances can benefit invasions (Levin, 2000).

Invasive species not only benefit from disturbances, but their presence may alter former disturbance regimes. Mack and D'Antonio (1998) compiled a number of studies that show a clear relationship between invasive species and changes in disturbance regimes. These interactions between invasive species and disturbance may contribute to the exponential growth of invasive populations, but on the other hand, these interactions can sometimes depress the invasion. Alterations related to invasive species include fire enhancement, fire suppression, increased and decreased erosion, biotic disturbance, and changes in the susceptibility of the community to disturbances (Mack and D'Antonio, 1998).

Habitat fragmentation may favor high dispersal ability. In addition, the disruption of communities may well select for characteristics of opportunistic (invasive) species, including rapid growth, high fecundity, self-fertilization, or apoximis, and dispersal or dormancy (Gerber and Dawson, 1993). Climate change and extinction in the palaeobotanical record are followed by the appearance of taxa with "opportunistic" life histories, typical of early successional habitats. The extensive migration of species in response to climate change and the ensuing disruption of communities will result in some species and populations being invaders and others being subject to invasion. Therefore, a very important approach to learning about the evolutionary consequences of altered biotic environments on species evolution will come from the study of biological invasions (Gerber and Dawson, 1993).

GIS Approaches for Habitat Prediction

Scientists estimating future climatic changes have focused on broad models of the climate system, general circulation models (GCMs), that attempt to mathematically represent the complex physical interactions among the atmosphere, oceans, ice, biota, and land (Schneider, 1993). GCMs used for long-term global climate predictions typically work on a grid of cells, each several degrees on a side. Within each cell all of the vegetation is treated as one unit. All processes are computed based on the "mean" conditions within it. On the other hand, most ecological studies are performed on much smaller (m^2 to km^2) areas (Schneider, 1993). Thus, a fundamental problem relating large-scale ecological studies to small-scale GCM predictions is to understand how this information can be transferred across scales and remain informative. What is most needed to evaluate potential ecosystem effects of temperature and precipitation change is a regional projection, based upon the concepts that these GCMs have displayed, of climatic changes that can be applied to ecosystems locally (Schneider, 1993).

When climate warms, species may shift upward in both latitude and elevation. Generally, a short climb in altitude corresponds to a larger shift in latitude: for 3°C of cooling, 500 m in elevation equals roughly 250 km in latitude (Peters, 1991). Because mountain peaks are smaller than bases, as species shift upward in response to warming, they typically occupy smaller and smaller areas, have smaller populations, and may thus become more vulnerable to genetic and environmental pressures. Examples of past extinctions attributed to upward shifting include alpine plants once living on mountaintops in Central and South America, where vegetation zones have shifted upward by 1,000-1,500m since the last glacial maximum (Peters, 1991).

Some organisms will be able to keep up with the changing climate with range shifts, while others will not. For invasive species and others with high dispersal capabilities, migration rates exceeding 1000 m/yr may become common (Malcolm et al., 2002). After the arrival of cheatgrass (*Bromus tectorum*) to the U.S. in about 1880, it expanded to nearly all of its potential range (200,000 km^2) within 40 years (Mack, 1986). Assuming a circular range expansion, cheatgrass migrated at a rate of 6300 m/yr.

Each species of plant has evolved particular tolerance limits to climatic conditions. Tolerance limits may be considered as defining the main parameters of the fundamental niche of an organism, although its realized niche is constrained by biological interactions, notably competition. The tolerance limits of an organism are generally determined by experimental manipulation. The natural limits of an organism may also be mapped and then matched with an appropriate climatic parameter, usually a minimum and maximum isotherm. In temperate regions with a seasonal climate, many species of plants die down or overwinter in an inert state. Consequently, summer temperatures are more important in determining distributional limits.

There is estimation that for 1°C of warming, climatic zones can shift 100 to 150 km poleward. Batie and Shugart (1989) states that the climatic zones containing Yellowstone National Park could be pushed into Canada and that the Arctic National Wildlife Refuge (ANWR) would completely "vanish" into the sea. Of course, such evaluations are themselves subject to considerable uncertainty and to assumptions about the nature and time scale of biotic responses to change (Batie and Shugart, 1989).

The threats to natural systems are serious for the following reasons. First, 3°C of warming would present natural systems with a warmer world than has been experienced in the past 100,000 years. A 4°C rise would make the earth the warmest since the Eocene, 40 million years ago (Peters, 1991). This warming would not only be large compared to recent natural fluctuations, but it would be very rapid, perhaps 15 to 40 times faster than past natural changes. Second, ecological stress would not be caused by temperature rise alone. Changes in global temperature patterns would trigger widespread alterations in rainfall patterns, and we know that for many species precipitation is a more important determinant of survival than temperature. Because of global warming, some regions would see dramatic increases in rainfall and others would lose their present vegetation because of drought.

In order to understand the impacts of future climate change, it is necessary to predict the current and future potential distributions of species (Beaumont, 2005). Predicting current and possible future distributions of species have been conducted using bioclimatic models that assume that climate ultimately restricts species distributions (Welk, 2002). These models take into account many different climatic variables within the known range of a species, thus generating a “bioclimatic envelope”. These models are then used to identify species current potential distribution and assess whether these areas will remain suitable under future climatic scenarios (Beaumont, 2005). These models can replace many other means of determining possible future locations of a species, such as costly field surveys, determinations made with little or no knowledge of ecology or biology of a species, and the very limited present-not present records available through local authorities and herbariums (Beaumont, 2005).

There have been a number of studies that have attempted to project potential vegetation response to a changing climate (Franklin, 1998; Welk, 2002; Kriticos et al., 2003; Rouget et al., 2004). Many of these have focused upon the continental and global scale (Nielson and Drapek, 1998). The problem with these broad scale patterns is that they are often at relatively coarse spatial resolutions, which limit their ability to resolve the regional problem of vegetation response to climate change. The need for these higher resolution analyses within mountainous regions, where steep topography can cause large changes in temperature and precipitation, and therefore vegetation, over relatively small distances, is where studies such as this one are needed.

Case Study: Spotted knapweed (*Centaurea maculosa*)

Characteristics of Spotted Knapweed

Knapweed is an example of a species that can seriously disrupt an ecosystem (Hirsch and Leitch, 2003; Heirro et al., 2005; Callaway et al. 2004). Originally an intruder of only disturbed rangelands (Morris and Bedunah, 1984), knapweed now exists in nearly every habitat type west of the Continental Divide; it ranges from the driest bitterbrush/bluebunch wheatgrass (*Purshia tridentate/Agropyron spicatum*) zone to the lush western hemlock/beadlily (*Tsuga heterophylla/Clintonia* uniflora) forest (Mooers, 1986). After establishment in an area, knapweed density often increases.

Originally introduced to North America in Victoria, British Columbia in 1893 (Maddox, 1982), spotted knapweed had spread to western Montana by the mid-1920s and proceeded to colonize much of the state by the early 1990s, increasing rapidly from 75 counties in 1988 to 163 counties in 1992 (Rice, 2007). According to the University of Montana Invaders Database System, in 1933, Missoula County was the sixth county to recognize spotted knapweed as an invasive species throughout the five state Northwestern United States, including Idaho, Montana, Oregon, Washington, and Wyoming (Rice, 2007). This weed was likely introduced to the continent through soil used as ballast for ships and to the United States through contaminated alfalfa seed (Maddox, 1982). Spotted knapweed is also thought to have been introduced by beekeepers due to its late summer flowering, which gives a longer season for honey production after most natives are dormant (Toney, 1998). Once seeds are present in an area, the weed can colonize soils with a wide range of chemical and physical properties. Environmental conditions in the Pacific Northwest are quite similar to the forest steppe zone in Europe where knapweed is adapted and most aggressive (Harris and Cranston, 1979; Callway et al., 2004). It is estimated that after completely removing knapweed from an area it would take 5-6 years, without any further seed production, before the natural seed reserves in the soils were exhausted (Chicoine, 1984).

Viability tests have shown that 77% of buried knapweed seeds were viable after 12.5 months (Chicoine, 1984). After remaining buried in soil for five years, 40% were viable if planted two inches or deeper, while approximately 20% remained viable when planted at one inch (Shirman, 1981). Therefore, even after many years of controlling knapweed on the same site, the soil may still store a viable reserve of seeds.

Spotted knapweed populations are extended through the peripheral enlargement of existing stands. Bracts of the seed heads open when dehydrated, two to three weeks after maturity, and movement of the stem by wind or passing animals can flick the loosely held achenes up to one meter from the parent plant. Seeds may remain near the parent plant, or be transported to another site (Lacey et al., 1995). Long distance transport occurs when achenes become attached to passing animals, dispersed by rodents or birds, or, more commonly now, transpersed by vehicles or hikers boots. Vehicles driven several feet through a knapweed site can pick up nearly two thousand seeds, 10 percent of which may still be attached to the vehicle after 10 miles of driving (Lacey et al., 1995). Off-road vehicles also damage existing vegetation and disturb the soil surface, making it easier for knapweed to invade. Spotted knapweed seeds are spread through rivers and along watercourses, and are transported in crop seed and hay. While a mean spotted knapweed plant produces about 1,000 seeds annually, up to 18,000 seeds can be produced (Lacey et al., 1995). This means that as few as 100 plants per acre can produce more than one million seeds.

Spotted knapweed threatens the long-term productivity of Montana rangelands by reducing forage quality and decreasing suitable habitat for livestock and wildlife (Lacey et al., 1995). Knapweed infestation affects air quality, wildlife habitat, and soil and water quality and conservation (Hirsch and Leitch, 2003). Spotted knapweed invasion onto bunchgrass rangelands is detrimental to the protection of soil and water resources (Lacey et al., 1995). Soil and water conservation is also an issue when discussing the infestation of knapweed.

On the basis of soil type, elevation, annual precipitation, evapotranspiration, frost-free season and maximum July temperature, about 50 percent of Montana (46.5 million acres) could support knapweed infestations as of 1995 (Lacey et al., 1995). The threat is greatest in range dominated by bluebunch wheatgrass (*Pseudoroegneria spicata*), needle-and-thread (*Hesperostipa* comata) or Idaho fescue (*Festuca idahoensis*), and in woodland dominated by Ponderosa pine (*Pinus ponderosa*) or Douglas fir (*Pseudotsuga menziesii*) (Lacey et al., 1995).

The success of knapweed on any site is the outcome of a multitude of factors. Soil texture, slope aspect, percent slope, competitive vigor of neighboring plants and inhibition from allelopathic toxins are all factors that could make critical differences when discussing the impacts that global-change will have upon the success of knapweed particularly in western Montana. However, the importance of each of these variables changes as the environment becomes more arid, which involves the increase in temperature and reduction in precipitation (Mooers, 1986). In wetter areas there is almost no bare soil open to invading plants prior to disturbance (Mooers, 1986). Since initial densities of biennial weed seedlings depend upon the percentage of bare ground and on the number of seeds sown, knapweed requires disturbance before it can establish itself in wet areas that have no natural bare soil component (Holt, 1972; Gross and Werner, 1982; and Mooers, 1986).

Seedling recruitment is correlated to moisture in the winter-early spring period, with the highest levels seen in wetter years and lower levels when it is dry. Therefore, successful invasion by spotted knapweed into areas experiencing climatic change may be tempered by the increase in the competitive ability of native plants, which are most aggressive with warmer wetter conditions (Paul Alaback, personal communication, 2007).

Knapweed Response to Increased Levels of CO_2

While there is very little data currently available detailing the responses of invasive species to past or future atmospheric CO_2, knapweed has been examined. In a study performed by Ziska (2003), spotted knapweed responded very well to increased CO_2 concentrations (Figure 2). These responses are considerably higher than previously reported for any plant species for this level of CO_2 increase (Ziska, 2003).

The values of 284, 380, and 719 μmol mol^{-1} CO_2 were used on the plants grown from seed until the onset of sexual reproduction (the vegetative period). The values correspond to the ones that existed at the beginning of the 20th century, those that exist today, and those which are predicted to exist at the end of the 21st century. The vegetative period seemed critical because early development is a key factor in determining crop/weed competition (Ziska, 2003).

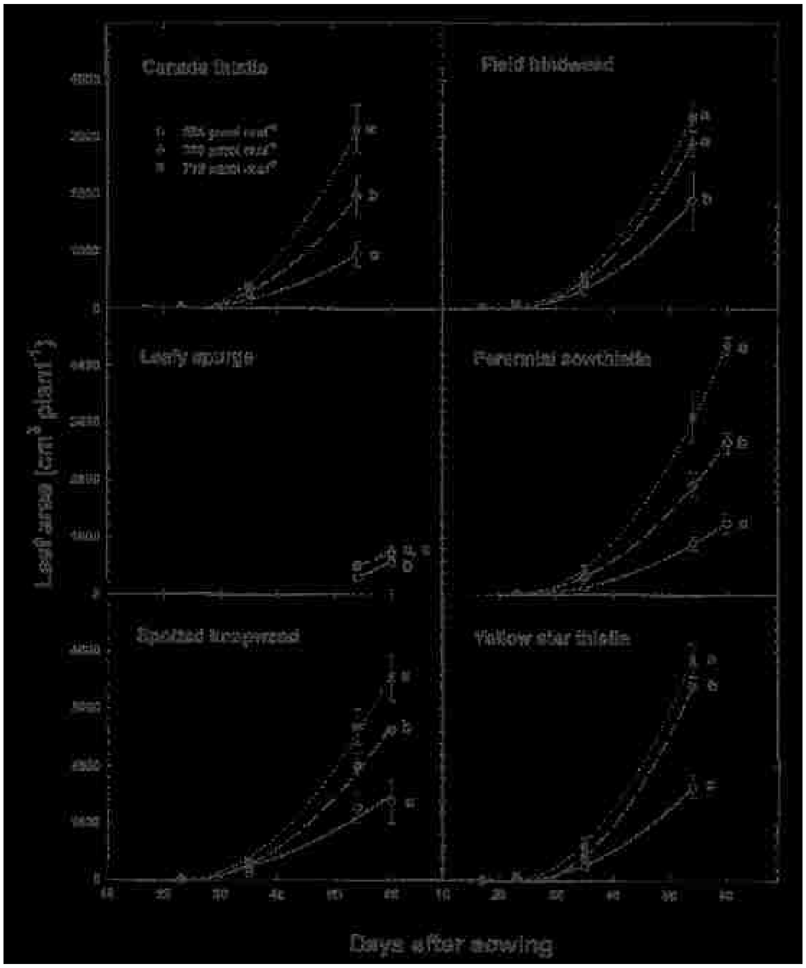


Figure 2. Leaf area for six invasive weedy species as a function of increased CO_2 (Ziska, 2003).

Knapweed Response to Temperature, Precipitation, and Disturbance

While knapweed seeds will germinate under a broad range of temperature from 7° to 34°C (Watson and Renney, 1974), there is a more narrow range in which it flourishes. A study conducted in 1985 by Timothy Chicoine revealed that on 116 infested sites in the

State of Montana, 92% of the test sites occurred in areas with 50 to 130 frost-free days, and the mean maximum July temperature at 72% of the test sites was 26.6 to 30.0° C (Chicoine et al., 1985).

Soil moisture requirements for germination are very specific. A study by Spears et al. (1980) reported a 90% germination rate when soil moisture was 65% or 70% by weight. However, at 75% soil moisture, only 73% of the seeds germinated, while at 55% soil moisture no seedlings emerged. Soil moisture appears to be a critical element governing the timing of germination, as well. In eastern Washington, Shirman (1984) observed that during a “wet” June about 70% of planted knapweed seeds emerged and survived. On the other hand, seeds planted during a “dry” June had a low emergence rate. Hence, timing of precipitation during a particular year impacts knapweed densities for several years into the future.

Precipitation influences the number of seeds that a plant will produce. Shirman (1981) observed that during a wet year, more flowers form on each knapweed stem and more seeds develop within each flower. Unlike many perennial grass plants (that require a year to recover vigor after a drought), knapweed responds immediately to moist, favorable conditions (Shirman 1981, 1984). Hence, knapweed seeds may invade bare soil left exposed after perennial forage plants have retreated during drought (Morris and Bedunah, 1984).

Surges in knapweed populations after drought could likely occur even if seed production did not increase during wet periods, since this opportunist also produces ample seeds under dry conditions. In British Columbia, Watson and Renney (1974) found that knapweed mean 436 seeds/plant under dry conditions, and up to 25,263 seeds per plant under irrigated conditions. Shirman (1981) reflected that even if only 0.1% of these seeds produced in a year germinated and flourished, then stand densities of this weed would remain constant.

Once established in wetter areas, knapweed does not seem able to out-compete native vegetation (Mooers, 1986). There are several reasons why knapweed may not be able to out-compete native vegetation in wetter sites. First, it could be that the allelopathic toxin, cincin, is leached from the soil before it has any adverse impact on neighboring plants (Locken, 1985). Second, native understory species probably out-compete knapweed because they have evolved advantages for this particular environment, unlike the opportunistic knapweed (Mooers, 1986). For example, these under-story species may retain more vigor under low light intensities than knapweed. Therefore, even though knapweed produces more seeds when moisture is not limiting, averaging 25,263 seeds per plant under irrigation as opposed to 436 seeds per plant on dry land (Watson and Renney, 1974), knapweed is less successful on wet sites (Mooers, 1986). In wetter habitats that were sampled, less vegetation probably grew on the better-drained, coarse-textured soils, so knapweed competed better there (Mooers, 1986).

The relationship between the amount of disturbance and moisture indicates that knapweed will only thrive in the wetter grand fir (*Abies grandis*), sub alpine fir (*Abies lasiocarpa*), western red cedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*) habitat series when the environment is greatly disturbed. In the drier habitat types such as bitterbrush/bluebunch wheatgrass, big sagebrush/bluebunch wheatgrass, Idaho fescue/bluebunch wheatgrass, bluebunch wheatgrass/Sandberg bluegrass, and rough fescue/bluebunch wheatgrass, knapweed can enter undisturbed climax rangelands whenever a seed source is present (Mooers, 1986). However, in a study performed by Stanley (2005), drought had large impacts upon knapweed growth rate; populations declined in dry years and increased in normal years.

If climate models are correct, the interior of the United States will continue to get hotter and drier, perhaps leading to reductions in knapweed infestations. As knapweed plants can live many years, a few years with moderate precipitation would produce a bumper crop of knapweed that could then survive 1-5 years of drought (Stanley, 2005). While knapweed can be found in almost every habitat type in western Montana, it probably will remain a non-dominant weed in wetter areas and exceptionally dry areas, except on very disturbed sites.

Summary

For nearly two hundred years, agriculture in western Montana has been reducing the habitat available to all species except for those few chosen by humans for cultivation or unintentionally assisted by such practices. This reduction has impacted the area available in which to maintain the species diversity. Meanwhile, human pressure has been accelerating extinction rates (Wilson, 1992) and introducing predatory and exotic species (Rosenzweig, 2003), while increasing global temperatures. The more habitat area reduced, the more likely that non-native invasive species will increase.

Weed management can and should be an important aspect of present-day forest management. In Montana, one of the most active states with regard to weed management, restoration efforts are focused upon biological controls, chemical spraying, thinning, and pulling (Lacey et al., 1995). Ironically, the susceptibility of an ecosystem to invasion can be increased when a restoration project is enacted due to the added amount of disturbance. Therefore, once a restoration project has begun, the effects of this project must be monitored and assessed for sustainability. Current forest restoration strategies can have multiple effects upon the spread of non-native species. First, there is the possibility of spread when new roads are built and logging is taking place. Seeds can cling to tires and skidders and create satellite populations miles and miles down the road (Harrod, 2001). The second effect is a positive one. The thinning and burning of forest will increase the diversity and productivity of native communities, which are likely to be more resistant to invasive species (Harrod, 2001).

The future of invasive-species research is a long and tenuous one. With global climatic conditions moving in the direction that favors non-native species proliferation, we can only predict that things will get worse. Many critical questions, such as whether the increased warming and alteration of precipitation patterns associated with an increase in greenhouse gases will increase the susceptibility of ecosystems to invasion, have yet to be addressed. The alteration of habitat and an increase in disturbance by human activity has decreased potential habitat for native vegetation and created new habitat for potentially invasive species.

Chapter 3

PROBLEM STATEMENT AND HYPOTHESES

This study used interpolated climate data to estimate current distribution and used several GCM-based scenarios of temperature and precipitation changes (IPCC, 2001; Giles, 2006) to predict the potential expansion or contraction of vegetation range. A bioclimatic envelope was defined to predict spotted knapweed population. Current locations of spotted knapweed were used with these scenarios to validate these bioclimatic thresholds. These conditions were then used to predict future knapweed distribution and range in the Missoula, Montana area.

Predictive vegetation mapping is defined as "predicting the vegetation composition across a landscape from mapped environmental variables" (Franklin, 1995). Essentially, this assumes that vegetation distribution can be predicted from the spatial distribution of environmental variables that correlate with or control plant distributions (Franklin, 1995). Predictions of potential ranges are often made for agricultural weeds (Baker et al., 2000; Pimental et al., 2006), but have, until recently, rarely been attempted for invasive species (Lindsay, 1953; Welk et al., 2002; Kritikos, 2003; Rouget et al., 2004). In most of these cases the potential distribution of the weed was much greater than the current distribution (Weber, 2001). Typically these species are tolerant of varying ranges of climate types.

In the discussion of climatic and ecosystem changes in the area surrounding Missoula, this paper will try to shed some light on the subject of climate change with regard to temperature and precipitation increases and the invasive species, spotted knapweed.

The hypotheses for this study are:

1) Temperature and precipitation parameters for spotted knapweed growth in the Missoula area are similar to the parameters determined by a 1974 study by Watson and Renney in southwest British Columbia based on geographical position.
2) Climatic conditions suitable for growth of spotted knapweed in the Missoula area have changed since the species' introduction in the 1920s. It should be noted that this hypothesis only looks at the potential range based on climatic conditions and does not study the effects of land-use change on the study area.
3) Potential climatic shifts in temperature and precipitation would cause a change in the range of suitable habitat for spotted knapweed in the Missoula area.

Chapter 4

METHODOLOGY

Study Area

The study area was defined as 2° latitude × 2° longitude, centered on Missoula County, Montana. The location was chosen because of the current extensive infestation and readily available data. The mean annual precipitation of the Missoula area between 1930 and 2004 was 34.25 cm, including 109.8 cm of mean snowfall. Approximately 17.2 cm of the annual precipitation comes during the growing-season months of April through August (NOAA, 2006). In this region, the greatest factor affecting the productivity of knapweed is the mean growing-season temperature from April through August (Mooers, 1986). Mean monthly temperature is -4.7°C for January and 19.4°C for July. The mean growing-season temperature is 14.4°C, with a mean high and low of 22.6°C and 6.16°C, respectively (NOAA, 2006). Elevation in the valley ranges from 3,200 to 7,200 ft., necessitating consideration of orographic precipitation and temperature lapse rates.

Missoula County vegetation was historically a diverse community of bunchgrasses, perennial wildflowers, and spring ephemerals (The University of Montana Natural Areas Integrated Plant Management Program (Marler, 2006), owing to the use of fire in landscape management by the Salish Tribe, as well as others. Unfortunately, the current infestations of invasive species, such as spotted knapweed (*Centaurea maculosa)*, Leafy spurge (*Euphorbia esula)*, and Dalmatian toadflax (*Linaria dalmatica)* have limited native communities abilities to reproduce and adapt through means such as improved resource utilization through deep taproots and, in the case of spotted knapweed, the presence of the allelopathic chemical cincin (Sheley et al., 1998).

Data Acquisition and Initial Processing

PRISM Data

In order to effectively predict future climatic conditions, past trends must be accurately portrayed. Mean monthly temperature and precipitation data from the Parameter-Elevation Regression on Independent Slopes Model (PRISM) project was obtained from the Oregon Climate Service for 1920-2004 (OCS, 2005). PRISM data are created using climate observations from weather stations in conjunction with digital terrain data and other environmental factors (Daly et al., 1997). The PRISM algorithm is based upon the assumption that elevation is among the most important factors controlling landscape patterns of temperature and precipitation, and uses linear regression to estimate climate spatially within local topographic orientations (Daly et al., 1997). The combined weight of a station is a function of elevation, coastal proximity, aspect, local relief, and vertical airmass layering. PRISM captures the influence of large water bodies, complex terrain, and atmospheric inversions in determining temperature and precipitation, including rain shadow effects (Daly et al., 1997).

To validate the use of this data, mean temperatures from the Missoula International Airport (3192 ft.) were obtained from the National Climatic Data Center in Asheville, NC (NOAA, 2006) and from the Stuart Peak (7400 ft.) SNOTEL station (SNOTEL, 2006), which is located in the Rattlesnake Wilderness Area northeast of the city, for the period 1995 to 2005. An annual mean environmental lapse rate of 3.5°F/1000 ft was calculated from the observations. An increase of 3.5°F/1000 ft also happens to be the standard environmental lapse rate used in climatological and environmental studies. This lapse rate was compared to the lapse rate seen in the PRISM data by reducting the map to sea level and then readjusting each pixel value using a digital elevation model (DEM). When this readjustment was compared to the original PRISM data, the two coverages were identical. These similarities should be expected. The PRISM data uses the same data as the validation. NCDC data as well as SNOTEL data are incorporated into the PRISM model (Taylor et al., 1993). Therefore, the 3.5°F/1000 ft. lapse rate seen in the Missoula area may not be the same with other areas. The PRISM model uses a DEM to estimate the elevations of precipitation stations. The similarity of these observations led to using the PRISM data with no alteration, except interpolation to 30 × 30 m resolution.

Data manipulation was done in IDRISI (32, Kilimanjaro and Andes versions), ArcGIS 9.0, and ENVI 5.2. After the data were cropped to the study area, they were interpolated from a 4×4 km grid to a 30×30 m resolution (Figure 3) to increase the precision, using a common inverse-distance squared. This interpolation was limited to a 6-point search radius around each point.

The final manipulation of the data was to classify the data into the tolerance ranges of spotted knapweed in the area (Figure 4). Five categories were defined for both temperature and precipitation described as the following: Class 1) too cool or dry; Class 2) cool or dry; Class 3) optimal; Class 4) warm or wet; and Class 5) too warm or wet. The two layers were then summed and reclassed again into all observed combinations of tolerance classes to produce suitability classes for each five-year period (Figure 5). These classes are described further in later sections.

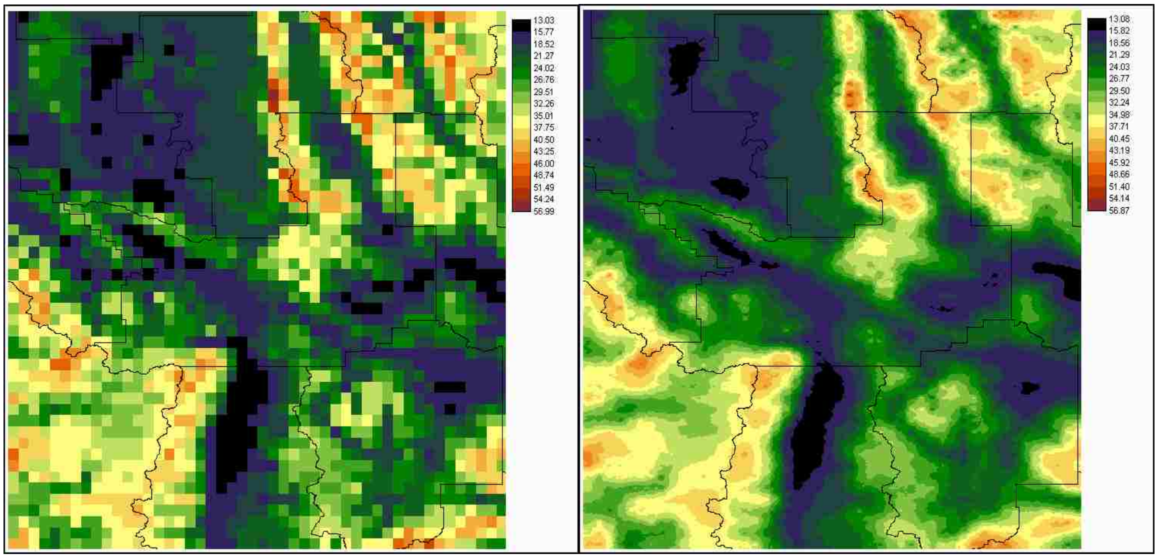


Figure 3. a) The study area (46-48°N, 113-115°W) at a pixel resolution of 4 × 4 km and b) after interpolation to a 30 × 30 m resolution.

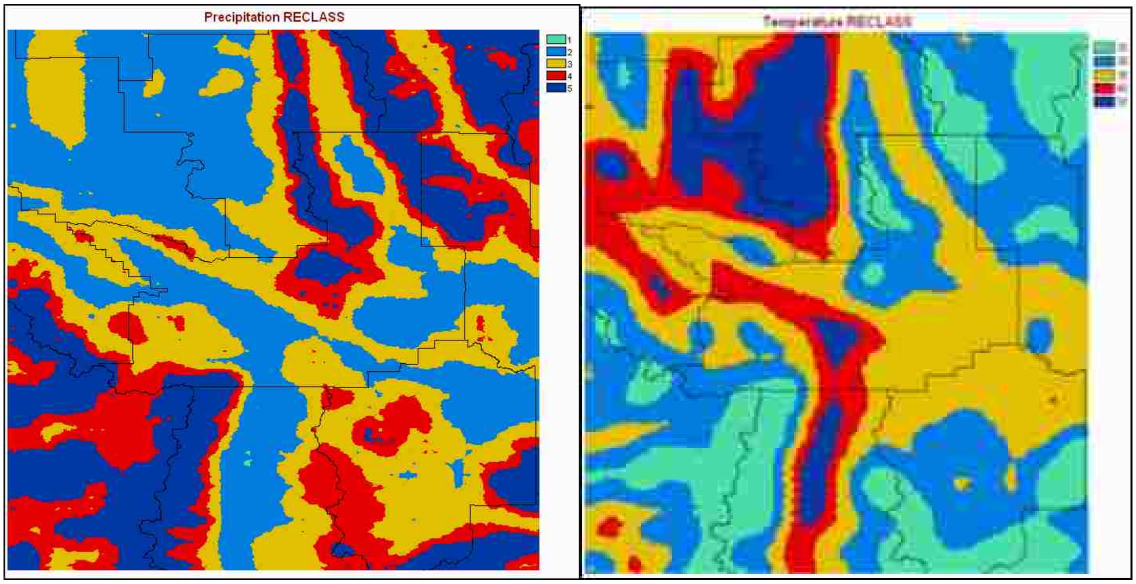


Figure 4. Reclassification of precipitation and temperature.

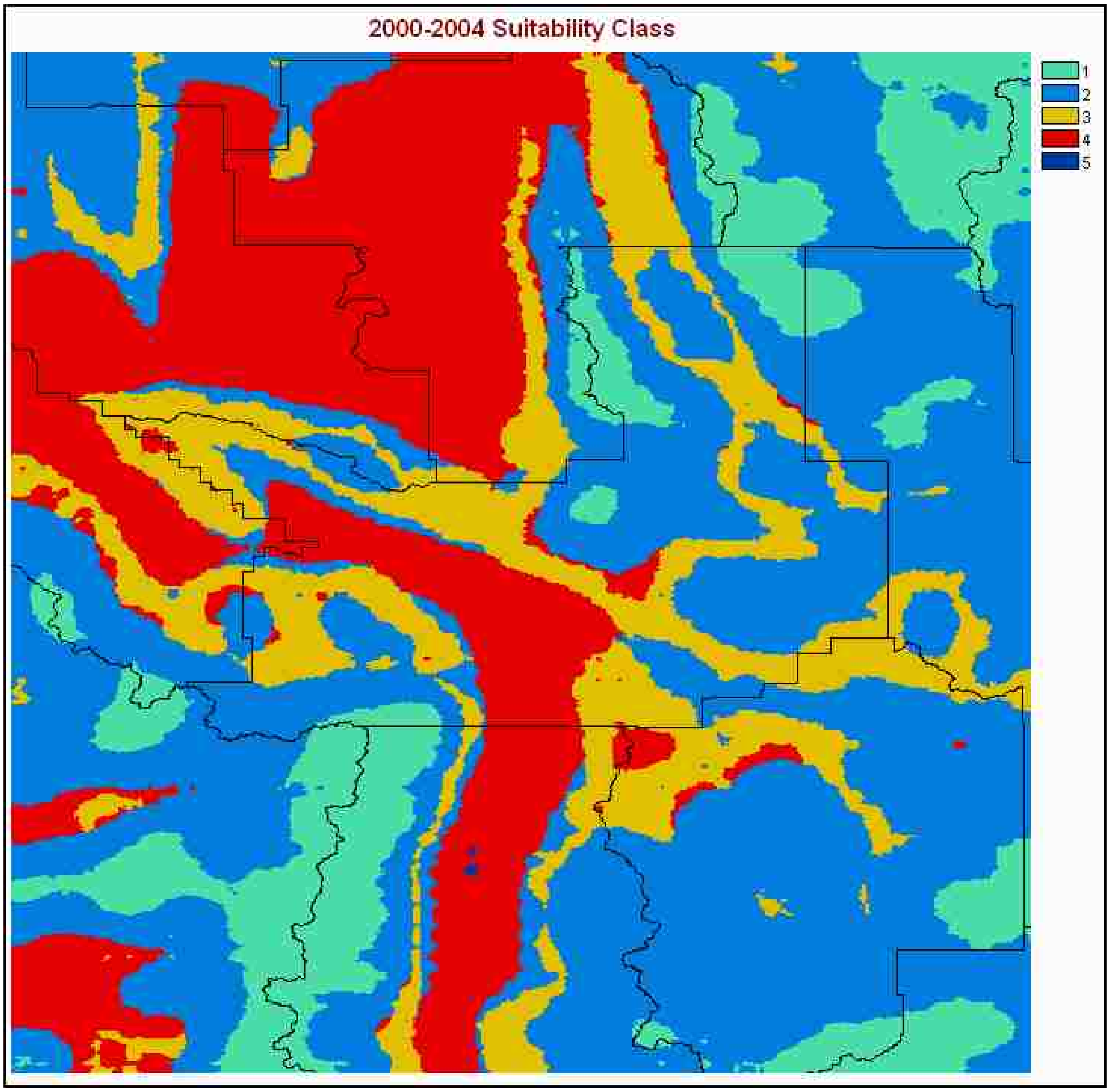


Figure 5. Precipitation and temperature combined and reclassed (Suitability Class).

Validation Data

Locations of knapweed infestations observed between 2002 and 2006 were obtained from Jed Little at the Missoula County Weed District as well as Laurie Ashley and Nathan Queener of the Wilderness Institute at The University of Montana-Missoula. This constituted all of the obtainable data in Missoula and the nine surrounding counties as of August, 2006. Surveyed regions include a mixture of Missoula open space, federal and county roads, and Wilderness and U.S. Forest Service designated areas. These occurences were all mapped within the past five years (Figure 6).

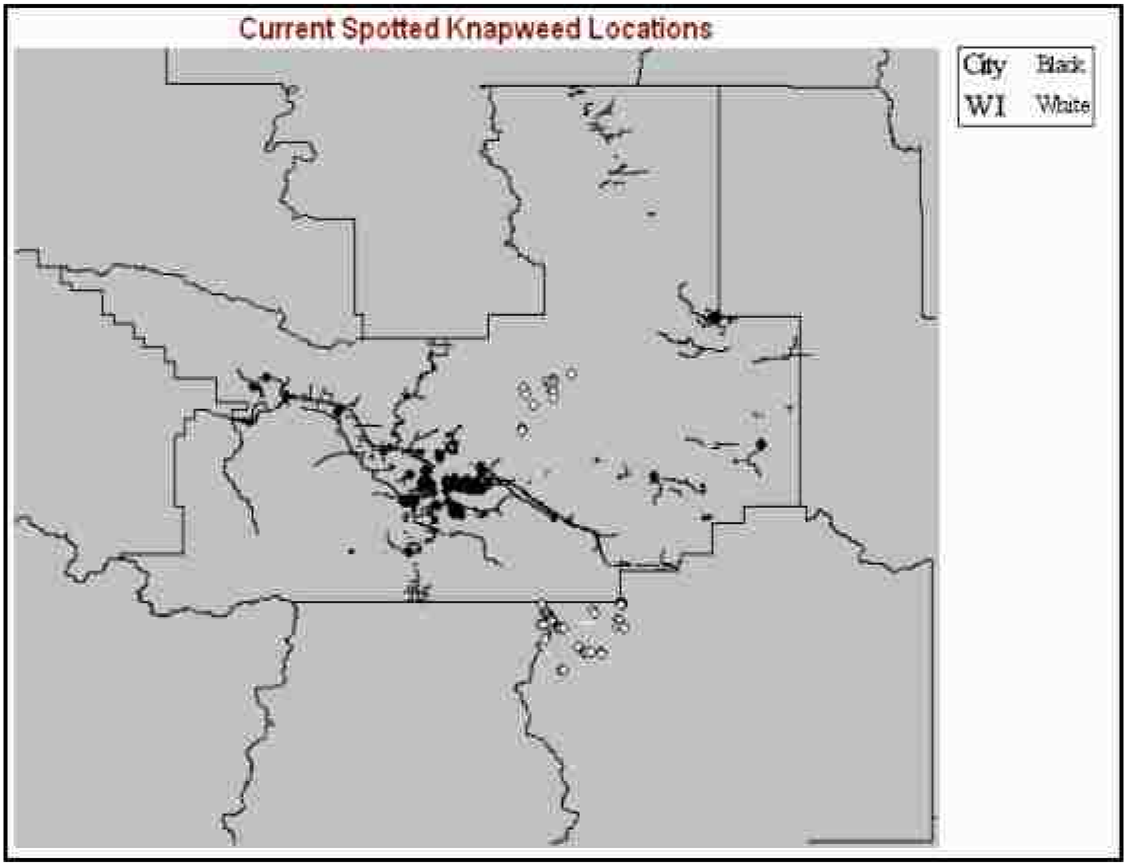


Figure 6. Validation points of spotted knapweed locations.

Climatic Limits

Initial Limits

In a 1974 study by Watson and Renney, environmental limitations for the growth of spotted knapweed were studied for the area of southwest British Columbia through field assessments of temperature and precipitation. This study resulted in general parameters for the survival of spotted knapweed in climatic conditions specific to British Columbia (Table 1).

These parameters were compared to the current range of spotted knapweed given by the locations determined by the Missoula County Weed District as well as the Wilderness Institute at the University of Montana. The study by Watson and Renney (1974) found that the mean annual temperature for southwest British Columbia was between 6.1°C and 7.8°C, whereas the growing-season temperature range was 9.7-21.0°C. The mean annual temperature at the Missoula International Airport reported by the NWS (NCDC, 2006) from 1931-2004 was 7.1°C (Table 1). Although the growing-season precipitation was stated by the 1974 study, the growing-season temperature was not. Therefore, the growing-season temperature of Kamloops, BC was determined and this was used (Environment Canada, 2006). These conditions were believed sufficiently similar enough to proceed with the study. The realized range for spotted knapweed within the Missoula area is represented by the growing-season temperatures and precipitation (Table 1).

Table 1. Climatic ranges of knapweed-infested areas in the southeastern interior of British Columbia (Watson and Renney, 1974) and revised parameters determined by current locations of spotted knapweed in the Missoula area.

	Watson and Renney (1974)	2000-2004 Missoula
Mean Annual Temp.	6.9°C	7.1°C*
Growing-season Temp. Range	9.7-21.0°C**	10.0-15.0°C
Annual Precip. Range	25.1-64.8 cm	13-57 cm*
Growing-season Precip. Range	14.7-24.9 cm	14.0-34.0 cm

* The mean annual temperature and precipitation ranges were determined from the Missoula International Airport NWS office (NCDC, 2006).

** The station that Watson and Renney used in the 1974 study was located in Kamloops, BC. Therefore, the growing-season temperature was determined from that station.

Revised Limits

Based upon the observation interval of the data used, the current study used the 2000-2004 period to calculate the new optimal growing conditions for spotted knapweed. The range of temperature during the 2000-2004 growing-seasons in the Missoula area was -1.5 to 24.2°C, and the range of precipitation was 13 to 57 cm, based upon all temperature and precipitation, illustrating the variability of climate in the region. These new parameters were determined by extracting the values of the pixel in which each observation was located on the temperature and precipitation maps for the mean 2000-2004 growing-season. These temperature and precipitation values were determined to be suitable areas for knapweed. This process disproves Hypothesis 1 for this study, therefore, the definition of these temperature and precipitation parameters came from the actual locations of spotted knapweed in the study area. Next, the ranges for potential growth of spotted knapweed were determined by reclassifying the optimal ranges of precipitation and temperature (Table 2) into five distinct categories.

Table 2. Ranges of growing-season temperature and precipitation used for reclassification.

	Temperature (°C)	Precipitation (cm)
Class 1	0-10.0	0-14.0
Class 2	10.0-11.67	14.0-20.67
Class 3	11.67-13.34	20.67-27.33
Class 4	13.34-15.0	27.33-34.0
Class 5	15.0-100	34.0-100

It was believed that the optimal growth conditions for spotted knapweed would be the center of this range (Figures 7 and 8). Therefore, the further away from the center of this range, the less suitable conditions would be. These numbers are very precise. This is owing to the uneven nature of the range. In order to have even classes, each class was broken into intervals of 6.33 cm for precipitation and 1.33°C for temperature. If whole numbers were used, then the classes would be unevenly distributed throughout the range of temperature and precipitation and not exhibit the same climatic conditions overall. These categories were next used to change the original map of the Missoula area into a five class raster map which displays the potential range of spotted knapweed along with the current locations (Figure 9). While the commonly discussed notion that spotted knapweed can grow "anywhere at anytime" is based upon some observations, it clearly does not grow in Tropical or Polar Regions. Therefore, limits must exist.

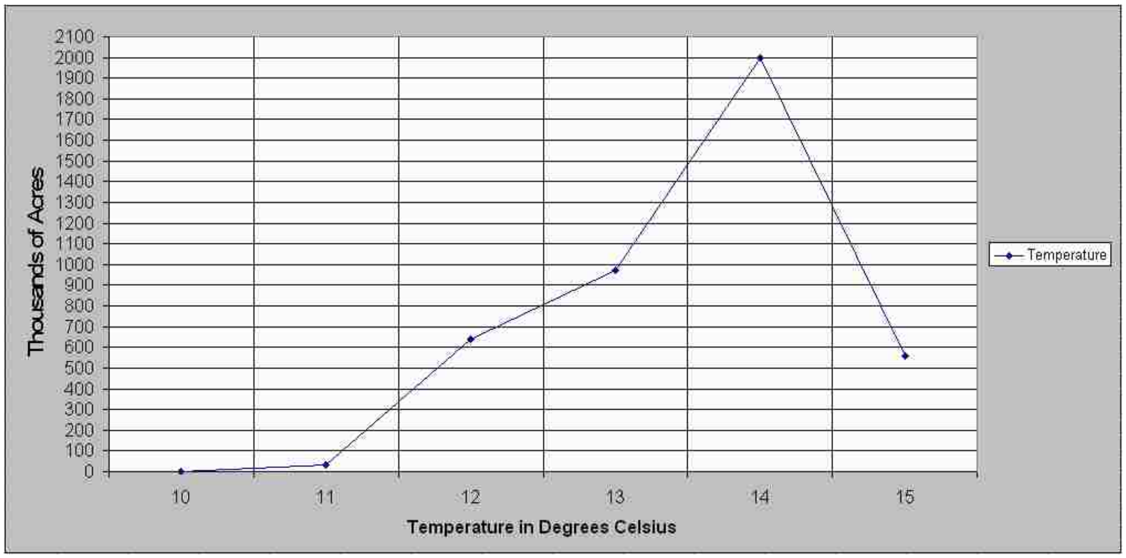


Figure 7. Distribution of observed growing-season temperature and precipitation at observed spotted knapweed locations.

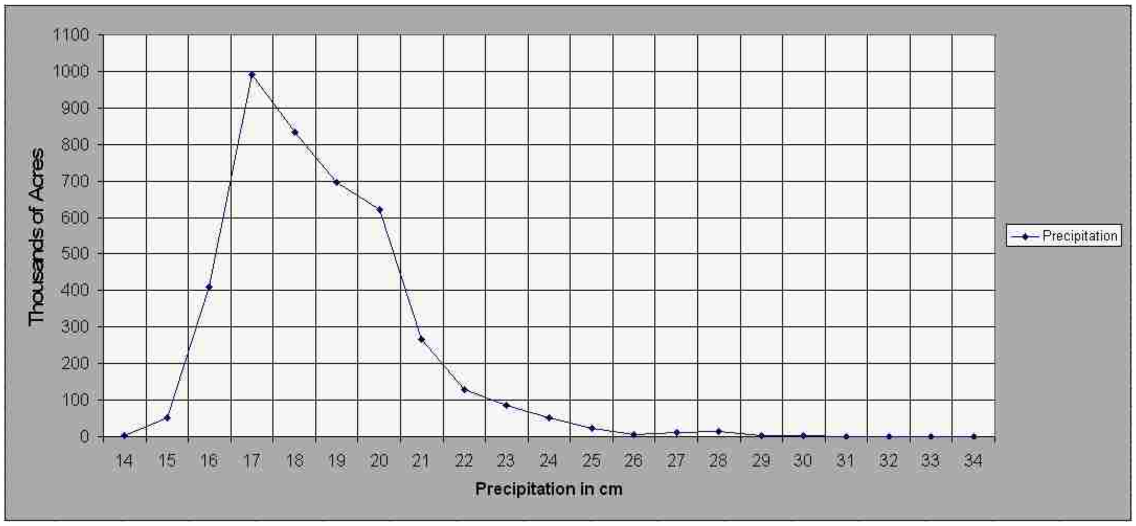


Figure 8. Distribution of observed growing-season precipitation at observed spotted knapweed locations.

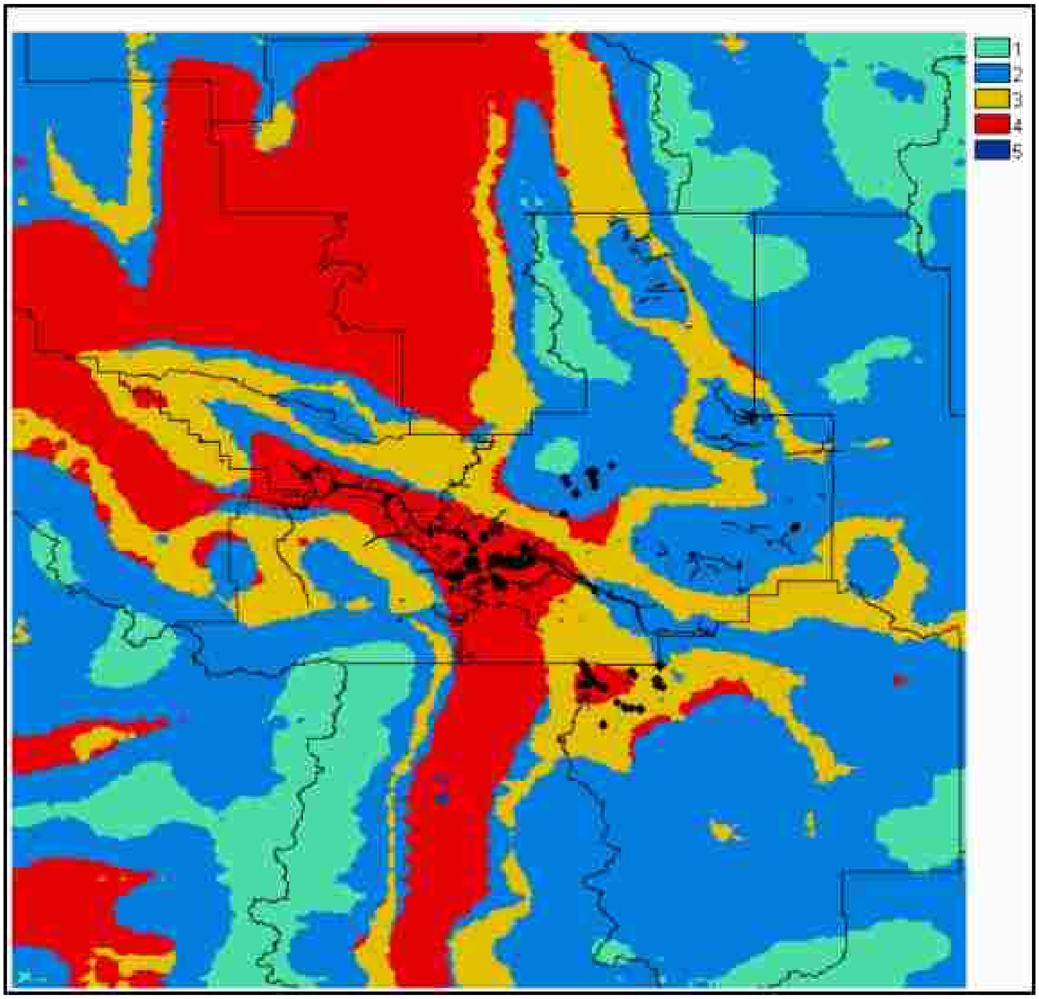


Figure 9. Validation of current plots of spotted knapweed based on 2000-2004 parameters. No observations fall within the categories of 1 or 5.

Future Limits

The final conditions for the study are based upon reports from the IPCC (2001, 2007), the USGCRP (2000), and a more specific analysis of the northern and western Rocky Mountains, from a report completed at Utah State University for the USGCRP (Wagner 2003). In regard to the changes in temperature and precipitation in the northwestern U.S., these sources have similar predictions.

The time period for a doubling of CO_2 greatly influences the pace of temperature increase. Based upon IPCC estimates, the assumption is that there will be 70 years for CO_2 to double and then an additional 30 years for the temperature change to reach these estimated increased temperatures (IPCC 2001). The IPCC estimates for an increased global temperature were initially based on the combination of predictions from 7 modeling centers around the world. The latest estimates for an increase of 2 to 4.5°C, with an increase of 3°C becoming the standard projection (Giles, 2006).

Temperature Predictions

The USGCRP (2000) predicts a temperature increase of 1.5°C by the 2030s, 3°C by the 2050s, and 4-4.5°C by the 2090s (USGCRP, 2000). The predictions made by the IPCCs Third Assessment Report in 2001 follow similar patterns. These predictions indicated that the global mean surface temperature would increase by between 1.4 and 5.8°C by the year 2100 (IPCC, 2001). Most importantly, a report from Utah State University gives a regional report for the Northwest, particularly the Northern and Western Rocky Mountains. This study reports an increase in temperature ranging from 2.5-4°C (Wagner, 2003). The incremental increases of 1°C, 2°C, 3°C, and 4.5°C were determined through the division of the range of the increases in temperature predicted in the Utah State University study. These breaks evenly represent the predicted range of possibilities.

Precipitation Predictions

Localized changes in precipitation patterns based upon global climate change are very difficult to define owing to the large fluctuations in short-term climate. The Utah State Report (2003) predicts an increase in precipitation for the region of 0-0.3 cm per day for the growing-season. This would represent a change of 0 to 45.9 cm per growing-season for Missoula, which seemed extreme. Increments of 0.5 cm, 1 cm, 5 cm, and 10 cm were used for this study to illustrate a range of potential changes near Missoula. Obviously, if precipitation were to increase by 45.9 cm per growing-season, the area would experience many more potential problems than the expansion of non-native species, but for the range of estimates used will clearly affect spotted knapweed growth.

Climatic Scenarios

In order to portray areas of suitable habitat based upon possible climate scenarios, the map layers for the precipitation and temperature changes were summed and reclassed to give suitability predictions for a series of temperature/precipitation combinations (Table 4). Athough the use of potential evapotranspiration as a controlling agent for the distribution of vegetation might give a good addition to the interaction of energy (temperature and potential evapotranspiration) and water (precipitation) (Stephenson, 1990), the use of only temperature and precipitation for this study is based on the available data and the use of a raster mapping system for the prediction of vegetation range in a particular area. If the the precipitation range was classified as 1, 2, 3, 4, 5 from dry to wet (values of 14 - 34 cm), and the temperature range was categorized as 10, 20, 30, 40, 50 from cold to warm (representing values from 10 - 15°C), then the total of these two layers would range from 11-55, representing all possible combinations from “too cool or dry” to “too warm or wet” (Table 3). Thus every pixel can be easily evaluated based upon the first and second number (i.e. 11 would be the combination of 10 and 1, where 1 would be the driest (0 - 14 cm) and 10 the coldest (0 - 10°C) classification. As can be seen in Table 5, not all combinations are present. Categories 1 and 5 are considered to be too extreme for this study and serve as limits preventing current invasion. Classes 2 and 4 are considered to be marginal for productivity, while areas of ‘optimal’ conditions are represented by the number 3. If the category displayed only one 3 in the combination it was moved to either the category of 2 or 4, which is considered marginal for knapweed suitability.

The only combination that was considered ‘optimal’ was 33. This gives a very narrow area that is considered perfect for spotted knapweed growth, but the study is greatly enhanced by this precision. The areas that display these specific parameters will give a good indication of the sensitivity of the entire area to spotted knapweed invasion. The reasoning for deciding that the combination of 13, for example, was used to describe the dry/cool class was because the lower combinations had to deal with the lower end of the spectrum of climatic parameters. The combination of 10 (low temperature) and 3 (optimal precipitation) to create 13 might give a different classification, but for the purpose of this study the low temperature outweighs the optimal precipitiation. The only way that the combination would be considered ‘optimal’ was if it contained a 3 (optimal precipitation) and a 30 (optimal temperature).

Table 3. Classification Ranges for Suitability Areas for Spotted Knapweed

Condition	Dry/Cool	Dry/Cool	Optimal	Wet/Warm	Wet/Warm
Class	1	2	3	4	5
Combination	11*, 15	12-14, 21-32	33	34-45, 52-54	51, 55*

* No observations from the 2000-2004 sites are contained in the dry/cool (11) or wet/warm (55) environments.

The overall suitability of the area during the 2000-2004 time period shows that not all combinations were present. The coolest and driest combination of 11 was not present, nor was the warmest and wettest combination of 55. Table 4 shows the distribution of the number of acres within each category for the 2000-2004 period. Although these conditions were present during this time, there were no observations of spotted knapweed within these two categories. If the past conditions of the study area are analyzed it can be seen that these conditions have changed throughout the time period, as will be discussed in the results and discussion section.

Table 5 displays the overall dispersal of the suitability classes for the years 1920-2004. This shows the presence or absence of suitable areas for the growth of spotted knapweed in the study area. Not all classes have been represented throughout the time of spotted knapweed inhabitation. This table also shows that the two combinations of 54 and 55 have not been represented in the area throughout the time period. However, with the potential of climatic change, these areas are sure to develop and possibly hinder spotted knapweed growth and dominance. What are most interesting about this distribution are the changes since the 1920s. Most of the period shows no area representing higher temperature and precipitation (53, 54, 55), but during the last twenty years, these areas show more and more activity, most notibly the 53 combination. This increase shows the occurence of warmer and wetter conditions in the study area.

Table 4. Suitability class distribution for 2000-2004.

Category	Acres
11	0
12	0
13	21000
14	185640
15	563640
21	0
22	10920
23	452340
24	456120
25	347760
31	0
32	501060
33	656040
34	123900
35	17640
41	42
42	384300
43	86940
44	6720
45	0
51	840
52	341880
53	43260
54	0
55	0

Table 5. Suitability class distribution for 1920-2004. Each year represents the first of the five-year period. The absence is represented by the number 0 and presence by the number 1 and slight shading. Full detail of acreage per time period can be found in Appendix II.

		Combinations																								
		11	12	13	14	15	21	22	23	24	25	31	32	33	34	35	41	42	43	44	45	51	52	53	54	55
Year	2000	0	0	1	1	1	0	0	1	1	1	0	1	1	1	1	0	1	1	1	0	1	1	1	0	0
	1995	0	0	1	1	1	0	1	1	1	1	0	1	1	1	1	0	1	1	1	0	0	0	0	0	0
	1990	0	0	1	1	1	0	0	1	1	1	0	1	1	1	1	0	1	1	1	0	0	1	1	0	0
	1985	0	0	1	1	1	0	1	1	1	1	0	1	1	1	1	0	1	1	1	0	1	1	1	0	0
	1980	0	0	1	1	1	0	1	1	1	1	0	1	1	1	1	0	1	1	1	0	0	0	0	0	0
	1975	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
	1970	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0	0
	1965	0	1	1	1	1	0	1	1	1	1	0	1	1	1	1	0	1	1	0	0	0	1	0	0	0
	1960	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	0
	1955	0	0	1	1	1	0	1	1	1	1	0	1	1	1	1	0	1	1	0	0	0	0	0	0	0
	1950	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
	1945	0	0	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0
	1940	0	1	1	1	1	0	1	1	1	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0
	1935	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	0	0
	1930	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0	0
	1925	0	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	0	0	1	1	0	0	0
	1920	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0

Potential Errors

This study attempts to refute the notion that spotted knapweed can grow in any climate using the boundaries previously discussed for “optimal” growth. Using the available data, the current locations are used to determine limits of knapweed survival.

Including factors such as soil type, elevation, slope, aspect, and the influence of disturbance would presumably change the prediction of locations of knapweed. However, they were not used because the current study is focusing only upon climatic factors that affect the growth potential of spotted knapweed. Although the use of these additional factors may present a different picture for the future of spotted knapweed in the area, the use of temperature and precipitation data from the PRISM dataset, which takes into account the elevation and aspect parameters, will give a sufficient representation of how the area may change with regard to plant community alterations. At the present time, data pertaining to specific soil types within the study area is not available. The use of disturbance mapping was also not feasible for the study period. The use of slope and aspect for the current study was not added to the analysis because PRISM data incorporates these properties into its model.

Other errors could occur when utilizing the PRISM data. Poor predictions of climatic data for areas without adequate coverage by weather stations could result in poor estimates. The microclimates of small-scale features such as rivers and lakes are not captured. The area under forest canopies are often several degrees cooler during the day and warmer at night than the surrounding areas and the air temperature under a snow pack can be higher than the air above the pack. Consequently, how the environment of the particular plant of interest may vary within each pixel is expected (Wang et al., 2006).

Obvious problems are noticed when using the environmental parameters of the current locations for spotted knapweed as the basis for a model for vegetative movement prediction. First, the current locations would be enhanced by additional information. Owing to the expanse and history of knapweed infestation in western Montana, spotted knapweed studies must progress beyond than merely examining the locations of plants. Unfortunately, spotted knapweed has been in the area since the 1920s and has literally taken over, so much so that most county officials look only at presence and absence data for location analysis (Natural Resource Information System (NRIS), 2006). The use of only 33,560 points covering an area of 4.2 million acres only approximates the potential habitat of spotted knapweed. However, this dataset is much larger than what is available in most other counties of Montana. The use of climate data to predict the future locations of spotted knapweed is an important aspect that should be incorporated into local, state, and national-level studies.

Within the study area, many conditions exist that do not exist within the original Watson and Renney (1974) study. The current study area displays a slightly wider growing-season precipitation range and a narrower temperature range. This may reflect that spotted knapweed is able to grow in different precipitation and temperature ranges near Missoula than it had near Kamloops, B.C. These differences in growing-season temperature and precipitation indicate that these may be limiting factors in its success.

The potential for spotted knapweed to have adapted to the differing conditions between the two areas is not only based on climatic conditions, but the interaction between species as well. There are several hypotheses about the ability for species to invade new habitat (Hierro et al., 2005). The “natural enemies” hypothesis proposes that these invading species are free from natural enemies that restrict their population growth. The "evolution of invasiveness" hypothesis suggests that these new species may experience rapid genetic changes that are associated with new selection pressures in the new environment. The "empty niche" hypothesis suggests that these invading species may utilize available resources that are currently unused by the native species. The "novel weapons" hypothesis proposes that the new species may bring new ways of interacting biochemically with native species. The "disturbance" hypothesis suggests that the invading species are adapted to the disturbance type and intensity that are new to native species. The "species richness" hypothesis puts forth the idea that species-rich communities are more resistant to invasion that species-poor communities. Finally, the "propagule pressure" hypothesis proposes that the more invasive species that arrive in a community, the more variation in the level of invasion (Hierro et al., 2005). When discussing the potential of spotted knapweed to adapt fairly rapidly to changing climates, all of these hypotheses would provide new insight into further study of the potential invasiveness of knapweed in the Missoula area. Not only will knapweed respond to changing climate alone, but it will do so as a member of the whole community of plant species.

Finally, climate change will not affect every species in the same way. Vegetation does not respond to changes in climate immediately. It may take spotted knapweed many years or even decades to respond to the changes proposed in this study. Although it is a highly opportunistic species and can rapidly spread once introduced to a location, knapweed may find it difficult to cope with the stressors of rapid climate change in the context of all the other biotic factors discussed above.

Chapter 5

RESULTS AND DISCUSSION

The ranges of plants can be considered as optimum-response surfaces with highest abundances and population densities in the center of the range and decreasing density toward the range margins (Hengeveld and Haeck, 1982). If current trends in climate continue, the expansion of potential range may increase not only the abundance of plants, but the size and productivity of individuals as well. This increase may also be countered with the contraction of the species range in the marginal areas. Using the current distribution of spotted knapweed to determine climatic parameters for optimal growth and referring to the past suitability of the area, the future conditions within the study area can be inferred. The subsequent comparisons of varying temperature and precipitation changes based upon future climatic conditions will show that the potential expansion and contraction of spotted knapweed habitat is an important step towards a model that could be relevant to any type of vegetation in the Missoula area.

Current Distribution

As can be seen (Table 6), most of the habitat in the study area growth falls into the suitable categories of two through four (86.5%), which is the range considered optimal and marginal for the growth of spotted knapweed. Noticing the areas that are considered either too dry or cool (1) or too warm or wet (5) is the initial step to understanding the potential impacts of future climate change on the Missoula area.

Table 6. Distribution of suitability classes for spotted knapweed within the entire study area, 2000-2004.

2000-2004 Suitability Classes		
Class	**Acres**	**% Area**
1	563,640	13.4
2	1,974,840	47.0
3	656,040	15.6
4	1,004,640	23.9
5	840	0.01

Table 7 shows the current locations of spotted knapweed within the study area. As can be seen, all of the current locations of spotted knapweed fall within the categories of 2, 3, or 4. These represent the marginal and optimal conditions for spotted knapweed growth. Within the classification of 1, spotted knapweed would be limited by cooler and drier conditions. With an increase in temperature and precipitation the area would begin to display more suitable conditions for spotted knapweed. Passing through the optimal conditions class the area would display the narrow range of "optimal" climatic conditions. Moving into the fourth class the conditions become wetter or warmer than the previous class. Finally, the classification of 5 displays climatic conditions which are too warm or wet for spotted knapweed to sufficiently utilize the existing conditions and, therefore, it may have less opportunity to become invasive.

Table 7. Distribution of habitat suitability classes containing current locations of spotted knapweed, 2000-2004.

2000-2004 Spotted Knapweed Observations		
Class	**Acres**	**% Area**
1	0	0
2	1,203,432	28.6
3	419,749	10.0
4	2,576,817	61.4
5	0	0

Past Climate Trends

Observed climatic trends at the Missoula International Airport between 1930 and 2004 are shown in Fig. 10 and 11. The increase in temperature and precipitation since the 1960's is fairly consistent, although variability in precipitation appears to be increasing as well. A least-squares regression revealed a change from ~29.5 to ~37.5 cm/year between 1930 and 2004, with several of the highest mean annual precipitation years since observations began occurring within the last ten years. The annual temperature for the Missoula area is 7.1°C and the total annual precipitation is 33.5 cm, with a mean growing-season temperature of 14.4°C and precipitation of 17.3 cm (NCDC, 2006). Although the Missoula International Airport records only go back to the year 1930, PRISM data uses the total Missoula valley reacord, which includes all observations since the 1870s. This was done through a local kriging prediction method. PRISM accounts for the effects of elevation and aspect on the distribution of precipitation and temperature (Kittel et al., 1997).

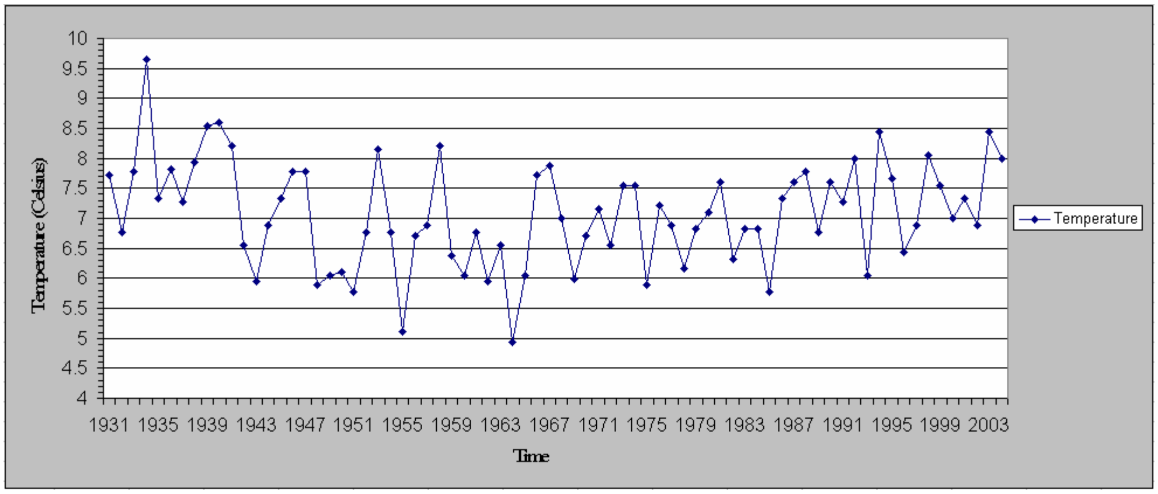


Figure 10. Mean annual temperature at Missoula International Airport, 1931-2004 (NCDC, 2006).

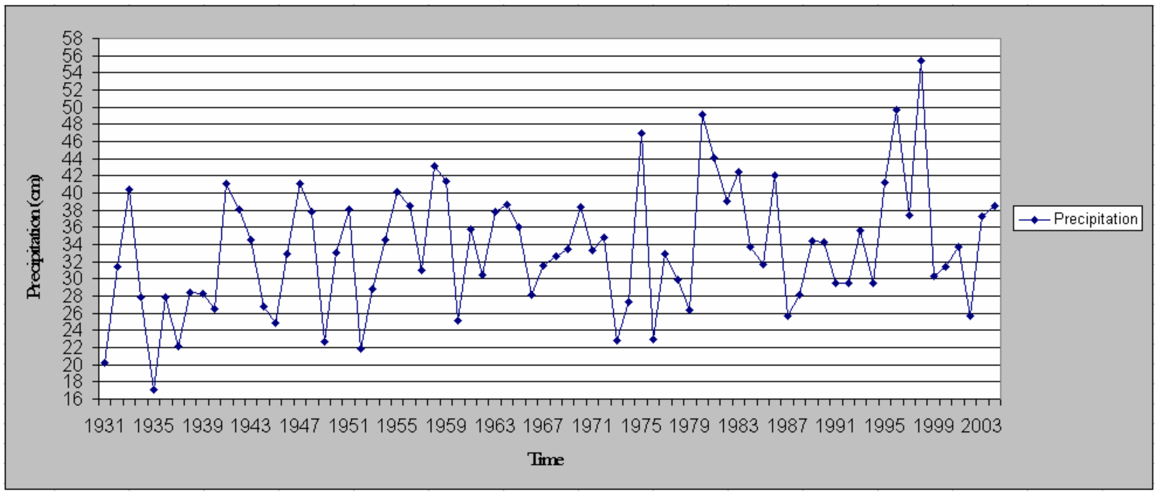


Figure 11. Annual precipitation at Missoula International Airport, 1931-2004 (NCDC, 2006).

Growing-season temperature is usually more useful than mean-annual temperature when predicting spotted knapweed growth (Watson and Renney, 1974). So, five-year historical mean growing-season temperatures were extracted from each pixel in which knapweed has been observed. For each five-year mean growing-season time slice, the maximum, mean, and minimum estimated temperature and precipitation was graphed in Fig. 12 and 13. This displays how temperature and precipitation have changed over the 1920-2004 time period, at the current location of spotted knapweed observations.

For the observed locations of spotted knapweed, the mean temperature for the growing-season is below the average at 12°C (Figure 12). The mean growing-season precipitation for the observation points is 25.5 cm (Figure 13). The 2.4°C and 8 cm differences are significant. These may be explained by the low elevation of the data points, but also imply something about the desirable conditions for the growth of spotted knapweed.

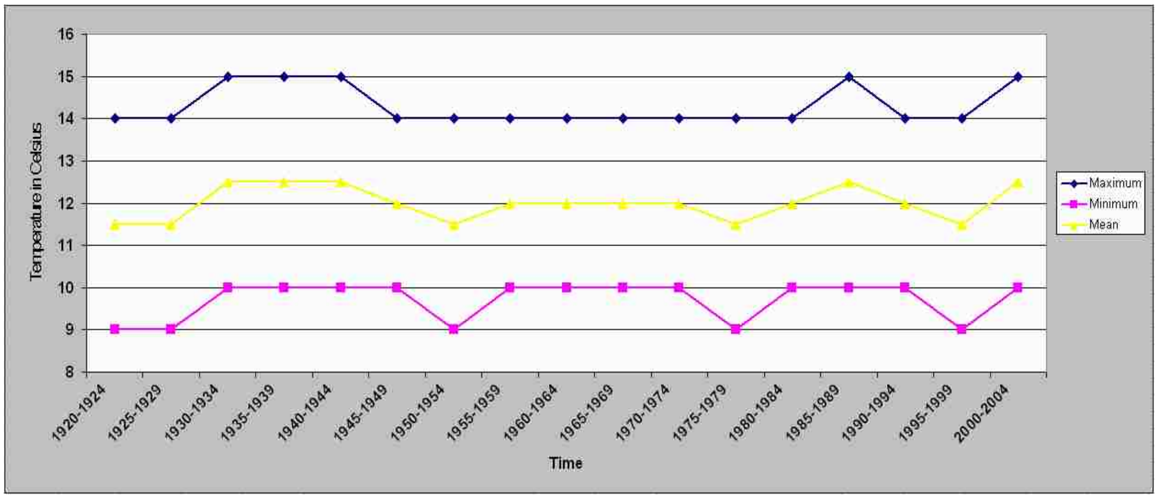


Figure 12. Maximum, mean, and minimum temperatures at locations of observed spotted knapweed,1920-2004. Values represented for maximum and minimum are in whole numbers.

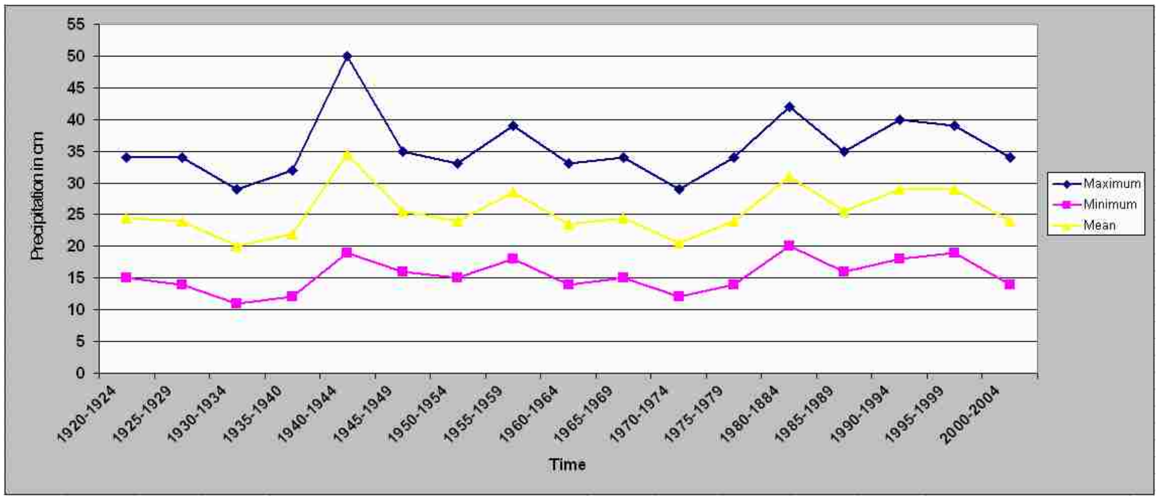


Figure 13. Precipitation change of observed spotted knapweed locations for the time period 1920-2004. Values represented for maximum and minimum are in whole numbers.

Maps of future knapweed distribution were estimated using predicted growing-season precipitation and temperature amounts from general trends in climatic conditions (IPCC 2001; USGCRP, 2000). This information was checked by using the future location maps that were generated and comparing them to the current coverage location maps provided by The Missoula County Weed District and The Wilderness Institute at The University of Montana.

Past Conditions

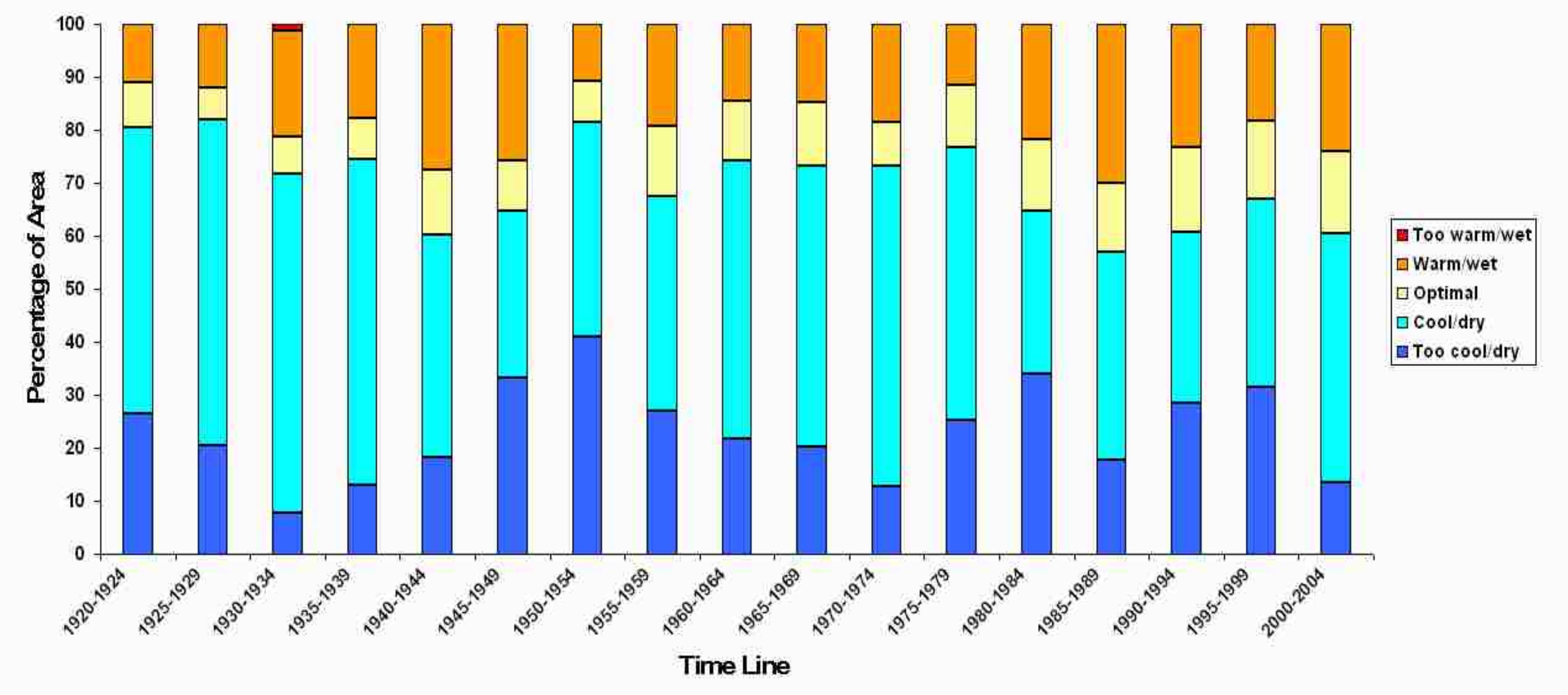
In order to effectively discuss future trends with regard to suitable habitat for spotted knapweed within the Missoula area, past suitability must be examined first. Figure 14 shows that suitable conditions for spotted knapweed have fluctuated over time, with high oscillations in the marginal and unfavorable areas. This is mainly owing to the fairly narrow "optimal" parameters used in this study. The analysis of the past conditions in the Missoula area support the second hypothesis of this study, which states that climatic conditions suitable for growth of spotted knapweed in the Missoula area have changed since the species' introduction in the 1920s.

The most interesting result from a study of past climate is the absence of conditions considered too wet or warm. With the possibility of warming and increased precipitation in the area, this category will see the most change. At the present time the study area exhibits a relatively cool and dry climate. With the prediction of a warmer, wetter climate, the areas that display suitable habitat for spotted knapweed growth will continue to increase, and only when these areas have been pushed out of the parameters for suitability within the area will populations begin to decrease. This, however, would be altered if other factors, such as competition, prevent or enhance spotted knapweeds ability to spread. This is evident when looking at the climatic conditions present in the southeastern United States where spotted knapweed does not pose a serious threat as an invasive species.

Three southern states (Tennessee, Kentucky, and Virginia) currently list spotted knapweed as a medium threat (Douce et al., 2006). This means that it has yet to dominate rangeland or pastureland, but is present. However, there do not seem to be any studies or specific management plans in place at the current time for spotted knapweed. The average growing-season temperature and precipitation of these three states are as follows: Nashville, TN: 21.3°C and 51.1 cm; Louisville, KY: 20.8°C and 51.4 cm; and Norfolk, VA: 21.3°C and 52.9 cm (NCDC, 2006). These are significantly above the ranges for Missoula, with 14.4°C and 17.2 cm. Tennessee, Kentucky, and Virginia serve as examples of climates which limit knapweed growth. Since the introduction of knapweed in the 1920s there has been ample time for the species to move into southern areas. The fact that it has not been a dominant plant in these areas may show spotted knapweeds inability to fully utilize these conditions.

These comparisons merely illustrate the effects of temperature and precipitation increases. They do not, however, indicate the existing competition for knapweed in these areas. Due to the increased biological diversity within these areas the potential for spotted knapweed to become invasive decreases.   Similar conditions exist within the state of Washington, where the extent of spotted knapweed is centered in the much drier eastern regions of the state (Roche and Roche, 1988). Therefore, it should be understood that the moisture regimes and diversity of individual plant communities may play a significant role in whether spotted knapweed becomes dominant or not.

Figure 14. Suitability Classes From 1920-2004**.**



Climatic changes that have occurred from 1920-2004 could be a sign of many problems. First, the past conditions reflect how spotted knapweed expansion noticed suitable conditions for expansion during this period, but this expansion was largely prior to modern control methods. Not only has knapweed spread through mechanical means (i.e. transportation by humans), but it has experienced more optimal growth conditions over time as well. The fluctuation in growing conditions shows the ability of spotted knapweed to persist in changing, and less than optimal, climates. Considering that the study area covers 4.2 million acres, even a small change in optimal conditions could account for hundreds to thousands of acres of potential infestation. The area has also changed dramatically since the early 1900s with regard to the assemblage of plants that have grown there.

Future Conditions

Figure 15 shows how optimal knapweed conditions in the Missoula area could change given potential climate change within the next 100 years. A warming of 1°C and an increase in precipitation of 0.50 cm from the 1975-2004 normals could show a 10% increase in suitable habitat (73.8% to 83.6%), or an additional 420,000 acres. Changes shown by an increase of 2°C and 0.50 cm would increase suitable habitat by nearly 20% to 93.1%. The central and most widely used climate scenario predicts increases in temperature of 3°C and precipitation by 0.50 cm, and gives a grim picture of suitable habitat for spotted knapweed--with nearly 98% of the area suitable knapweed. Interestingly, a warming of 4.5°C and 0.50 cm precipitation increase yields a suitability area of 94.7%, which is large, but less than the previous scenario.

The potential change in conditions with a warming of 1°C and an increase in precipitation of 1.0 cm is very similar to an increase of 1°C and 0.50 cm. With such a wide range of precipitation considered in the suitable habitats for spotted knapweed (14.0-34.0 cm), this is not surprising. The effects of warmings of 2°, 3°, and 4.5°C are not dissimilar to this, only decreasing by 0.1% for each, although this does represent 4200 acres.

While the area considered optimal actually decreases within each warming level as precipitation increases, an increase in overall suitable habitat are seen. The addition of as much as 5.0 cm of precipitation begins to limit suitable areas. A warming of 1°C and addition of 5.0 cm of precipitation decreases suitable habitat over 1°C and 1.0 cm by 2%. The change in suitable area increases to 92.3% when an increase of 2°C and 5.0 cm of precipitation are considered. This increases to 97.4% under a warming of 3°C and 5.0 cm of increase in precipitation. When a warming of 4.5°C and a precipitation increase of 5.0 cm is considered, contraction to 86.6% is predicted.

Further contraction of suitable habitat is realized with the addition of even more precipitation. By adding 10.0 cm of precipitation, the wide range of suitable habitat determined by precipitation begins to reach its estimated limit. When warming by 1°C, the addition of 10.0 cm of precipitation contracts the amount of area represented by suitable habitat to 80.7%, 1% less than adding 5.0 cm. A scenario of 3°C and 10.0 cm increased yields a decrease to 89.0%. With increases of 4.5°C and 10.0 cm, the contraction of suitable habitat is clear. The 15% decrease from the 4.5°C and 5.0 cm scenario (86.6% to 71.7%) illustrates how the conditions considered more suitable for spotted knapweed growth will change with projected climate change. The scenarios represented here show a nearly complete eradication of suitable habitat for spotted knapweed. The potential of a 49 cm increase in precipitation throughout the study area was not even considered in this study. This was considered after studying the effects of an increase of only 10 cm.

The changes in suitable habitat for spotted knapweed could mean several things for the Missoula area. First, the possibility within the next 30 years of minimal climatic changes (i.e. 1°C warming and 1.00 cm increase in precipitation) could actually show an expansion of suitable habitat for spotted knapweed. Although predictions for the next 100 years are considerably more than this, the rapid spread of spotted knapweed toward the edges of these potential habitats could help it invade new areas when climate changes. Alternatively, the widely agreed upon warming of 3°C and a possible increase of 5-10 cm of precipitation (IPCC 2001; USGCRP 2000), the Missoula area could experience an increase in suitable habitat and most likely further expansion of spotted knapweed. Finally, the possibility of a very large climatic shift (i.e. 4.5°C warming and up to 45 cm increase in precipitation [IPCC 2001; USGCRP 2000]) would cause a contraction of suitable habitat which would alter weed management, open up habitat for new potential invaders, and may help native species become dominant again. Although both of these conclusions indicate an increase in suitable habitat, they merely indicate the increase in area based on precipitation and temperature alone. The increased ability for certain native plants to successfully compete with spotted knapweed, especially at higher elevations, will alter the area suitable for spotted knapweed infestation and domination.

Figure 16 shows the distribution of suitable (Classes 2, 3, and 4) and not suitable (Classes 1 and 5) habitat for spotted knapweed with potential climate scenarios. As can be seen, the decline in suitable habitat becomes evident if the increases in temperature and precipitation are extreme. Increases of 1, 2, and 3°C show an increase in suitable habitat overall. This increase is seen throughout the scenarios until the temperature increases to 4.5°C, where the temperature and precipitation are pushed further away from the optimal conditions for spotted knapweed. These conclusions support the third hypothesis of this study, which states that potential climatic shifts in temperature and precipitation would cause a change in the range of suitable habitat for spotted knapweed in the Missoula area.

The preceeding conclusions discuss the predicted affects of temperature and precipitiation on the spread of spotted knapweed within the Missoula area. The limitations of using just these parameters may limit the usefulness of these conclusions. The competitive ability of spotted knapweed is based not solely on temperature and precipitation, but also level of disturbance (Duncan et al., 2003). With the increased mean temperature and precipitation levels, the potential increase in area left by species that are unsuited to these changes also changes. The tendancy for plants such as spotted knapweed to move quickly into these newly disturbed environs is thus a clear advantage with changing climate. As discussed earlier, the hypotheses that invasive species possess the ability to fill niches that are not utilized by native species, evolve more rapidly to new selection pressures, and are able to adapt to disturbances that are new to native species, give spotted knapweed an advantage at all levels of precipitation, temperature, and elevation.

Figure 15. Suitability area graph based on potential climate scenarios.

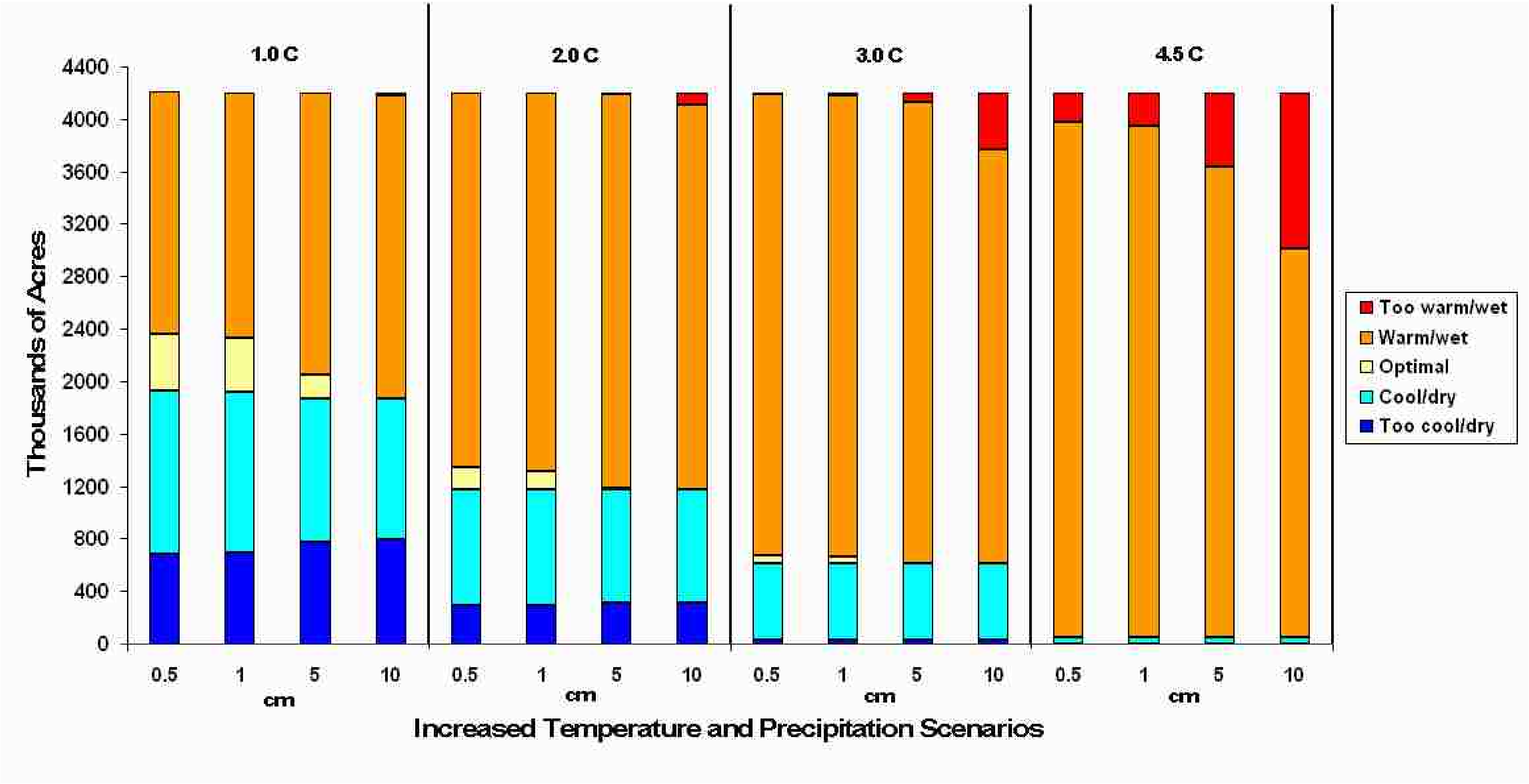
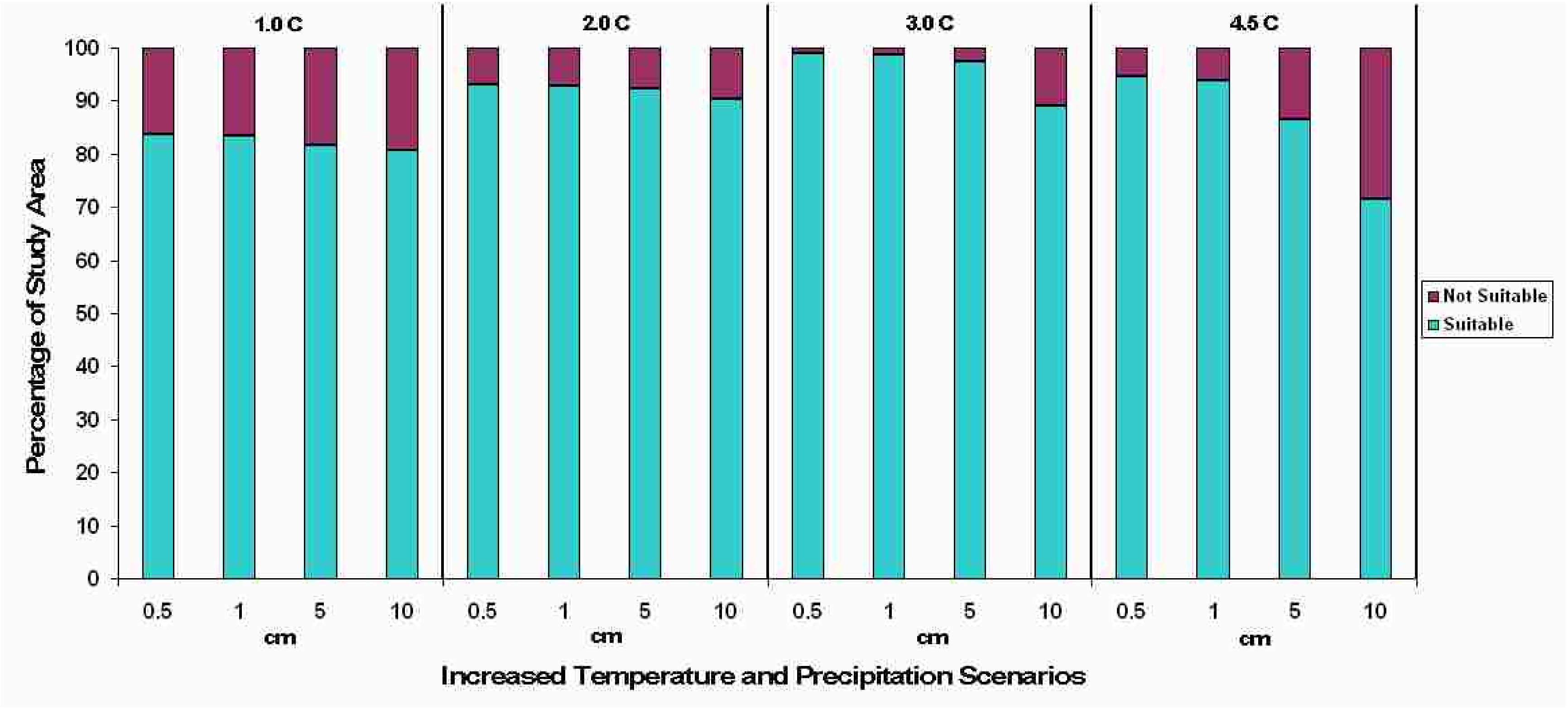


Figure 16. Percentage of suitable and not suitable areas based on potential climate scenarios.



Chapter 6

CONCLUSIONS AND FURTHER RESEARCH

This study assessed the potential distribution of areas vulnerable to invasion by spotted knapweed as a consequence of climate change unless adequate control measures prevent further spread. The area at risk of invasion by spotted knapweed under current climate conditions greatly exceeds the current distribution, with “marginal” to “optimal” habitat comprising over 55% of the study area. Predicted climate change (IPCC, 2001; Wagner, 2003; Giles, 2006) will most likely increase the area at risk to invasion. The large potential for futher invasion under both current and future climates justifies concerns that this plant is a weed of significance. A high priority should be placed upon the early identification and eradication of any outlying populations of spotted knapweed. Results from scenarios for warming and increased summer-time moisture in the area were used to provide a framework for considering knapweed response. With the acceptance of the hypotheses for this study, the goals of determining the current and potential future range for spotted knapweed in the Missoula area, based on temperature and precipitation parameters, were deemed successful, with definite need for future research and study.

Vegetation responses to climate change are generally predictable. A much warmer and wetter scenario might lead to expansion of forested zones upward into the alpine zones and downward into the grasslands (Wagner, 2003). These changes would hinder the expansion of spotted knapweed as shown in this study, whereas the contraction of suitable habitats through a very large climatic shift, (i.e. 4.5°C warming and up to 10 cm increase in precipitation) would hinder the growth and expansion of spotted knapweed populations (Figures 15 and 16).

Many studies have discussed the potential movement of plant species based on changing climatic conditions using bioclimatic variables (Overpeck et al., 1991; Sykes et al., 1996; Shafer et al., 2001). The use of variables such as mean annual precipitation, summer temperature, the mean temperature of the coldest month, sunshine percentage, growing degree days, and moisture index are similar to this study in that they use growing-season temperature and precipitation to predict the potential range for many tree and shrub species. The predicted potential range for plant species, however, only produces the potential niche, not the realized niche. The use of mean growing-season precipitiation and temperature to show past distribution of spotted knapweed within the study area and potential future distribution is much greater than that of what the realized niche of the species will be with potential climate change. The addition of potential species interaction and the use of potential evapotranspiration would greatly enhance this study as well as all studies using bioclimatic conditions to predict plant distributions based on climate change. However, modeling such interactions is very complex, and thus is not commonly done.

With the most widely agreed upon scenario of temperatures increased by 3°C (IPCC, 2001; Wagner, 2003) and precipitation by 1.0 cm, suitable habitat within the area would increase (Figures 15 and 16). Although this scenario could change areas from marginal conditions to more optimal ones or different marginal conditions, the changes would show how a warming and an increase in precipitation coincide. The ability of spotted knapweed to thrive within this area would only continue with these mean climatic changes. If increases occur by the year 2050, the ability of not only spotted knapweed, but native species as well, to react to these changes would dramatically strengthen the need for further studies, not just of climate, but also on the ability of vegetative to adapt to these changes.

Under more extreme climate-change scenarios, potential contraction of knapweed range or its eradication from some areas may occur, which, unfortunately, means that other species could change their competitive status as well. Until recently, the specific location of spotted knapweed infestation in Missoula and across the United States has seen relatively little study. The University of Montana invaders database (Rice, 2007), as well as NRIS (The Natural Resources Information System) of Montana (NRIS, 2006), have shown the historical pattern of spotted knapweed invasion throughout the state, yet they show only presence/non presence by county.

Climate is already changing rapidly (Godrej, 2001) and biodiversity is showing the effects of these changes (Vitousek et al., 1996). Future invasions will occur based upon climate changes, such as increasing levels of CO_2, rising temperatures, precipitation increases, and land-use change. This will, consequently, change the opportunities for invasive species to spread across geographical areas. Predictions and documentation will ony be achieved through extensive observational and experimental studies. It is possible to design experiments that simultaneously address questions about the impact of global-change on specific alien species and general questions about invasion biology (Mooney and Dukes, 1999).

The main focus of future research should be integrated. The region of interest in this study is complex. The variations in elevation and latitudinal extent relate to variability in the ecosystem itself. Because of its use of elevation, slope, and aspect when describing precipitation and temperature conditions within a specific area, PRISM data provides a good source for these types of studies. The integration of PRISM data with known presence and absence data for specific plants was only touched upon with this study, but begs further studies of this kind. Modeling is needed and will play a role in spatial database management, analysis, and extrapolation (Wagner, 2003). The integration of these climatic prediction models into other studies of invasive species, such as the Weed Invasion Susceptibility Prediction (WISP), which uses not only precipitation, but also disturbance, pH, soil texture, and distance from water when determining future locations of a specific weed (Gillham et al., 2004) should be encouraged.

Invasive species are a growing problem for the Missoula area, both ecologically and economically. In response to the problem, governments are devoting increasing resources to control, prevention, and eradication of invasives. To enable efficient use of these resources, the scientific community needs to identify where invasives are likely to become a problem in the future. Missoula County is at the forefront of invasive-species studies and GIS technology research use was a major reason for this study to be conducted in the local area. Most counties within this study area, as well as most counties in the State of Montana, do not have the kind of information needed to conduct a study of this type at the moment. Further cooperation from the BLM, Forest Service, and other county GIS specialists would help show that the location of spotted knapweed in the area is determined by not only disturbance and land change, but the micro- and meso-climates within it. It is hoped that this study would demonstrate the need for more extensive studies dealing with climate change as a dominating factor influencing invasive species movement and proliferation.

Global circulation models indicate that warming will be greatest at high latitudes and that this increase will be most pronounced in winter and spring months (IPCC, 1995). The recognition that biological invasions are a component of global-change leads one to ask how the movement of species might interact with other changes taking place in the world. The scientific community far from understands the dynamics among all of these components, but the ultimate consequences are likely to be more complex than simple cumulative effects. We must recognize and attempt to understand all causes of global-change to begin to fully understand how invasive species will affect the world's ecosystems. Even though future climate and species ranges cannot be predicted with certainty, the results of this study suggest ways that ranges of spotted knapweed may change with time. The responses of spotted knapweed that have been shown here demonstrate the need for more studies on the expansion and contraction of vegetation to potential climatic change on a regional scale with more confidence in the future.

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Alaback, Paul. February 19, 2007. Written note, via email, concerning suggestions for thesis content clarification.

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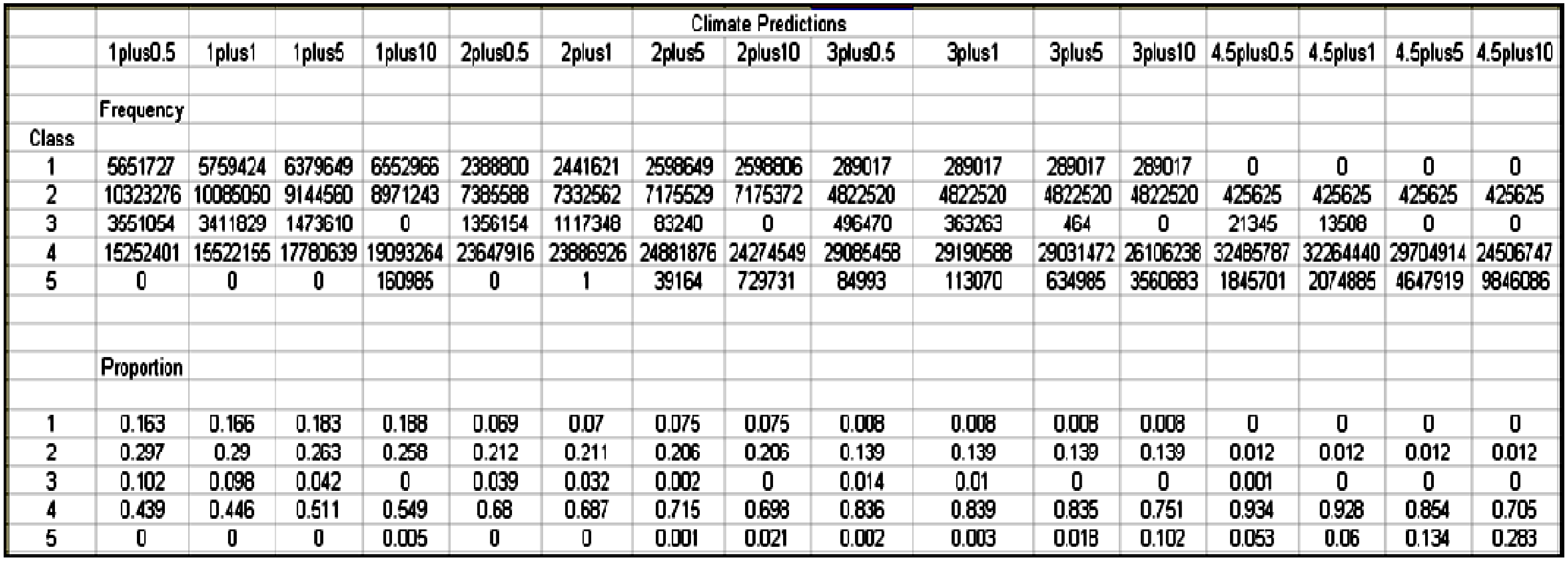
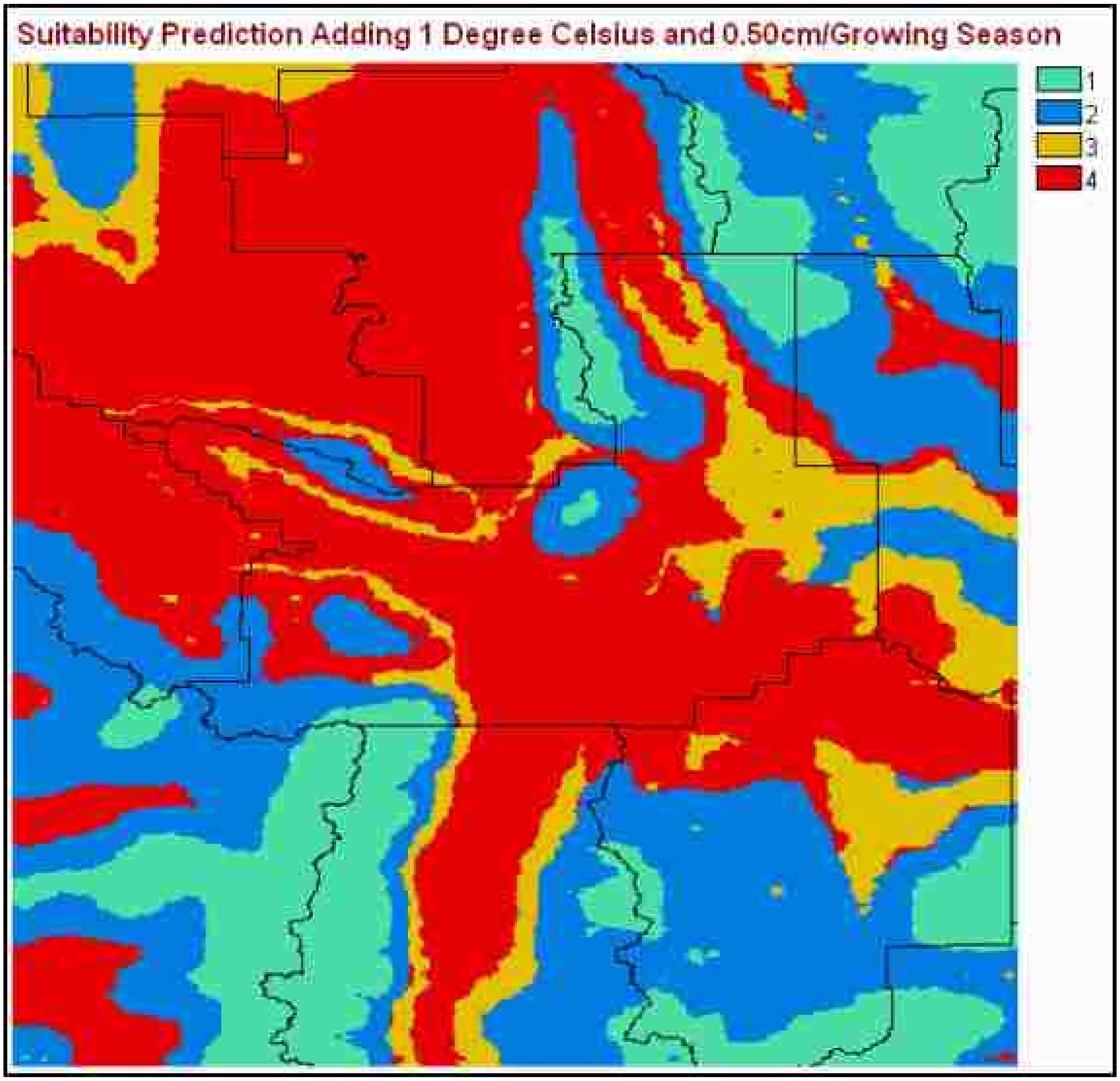
APPENDIX A
Total Suitability Predictions
Showing Warming and Precipitation Variations in Combination

A-1. Suitability areas based on potential climate change

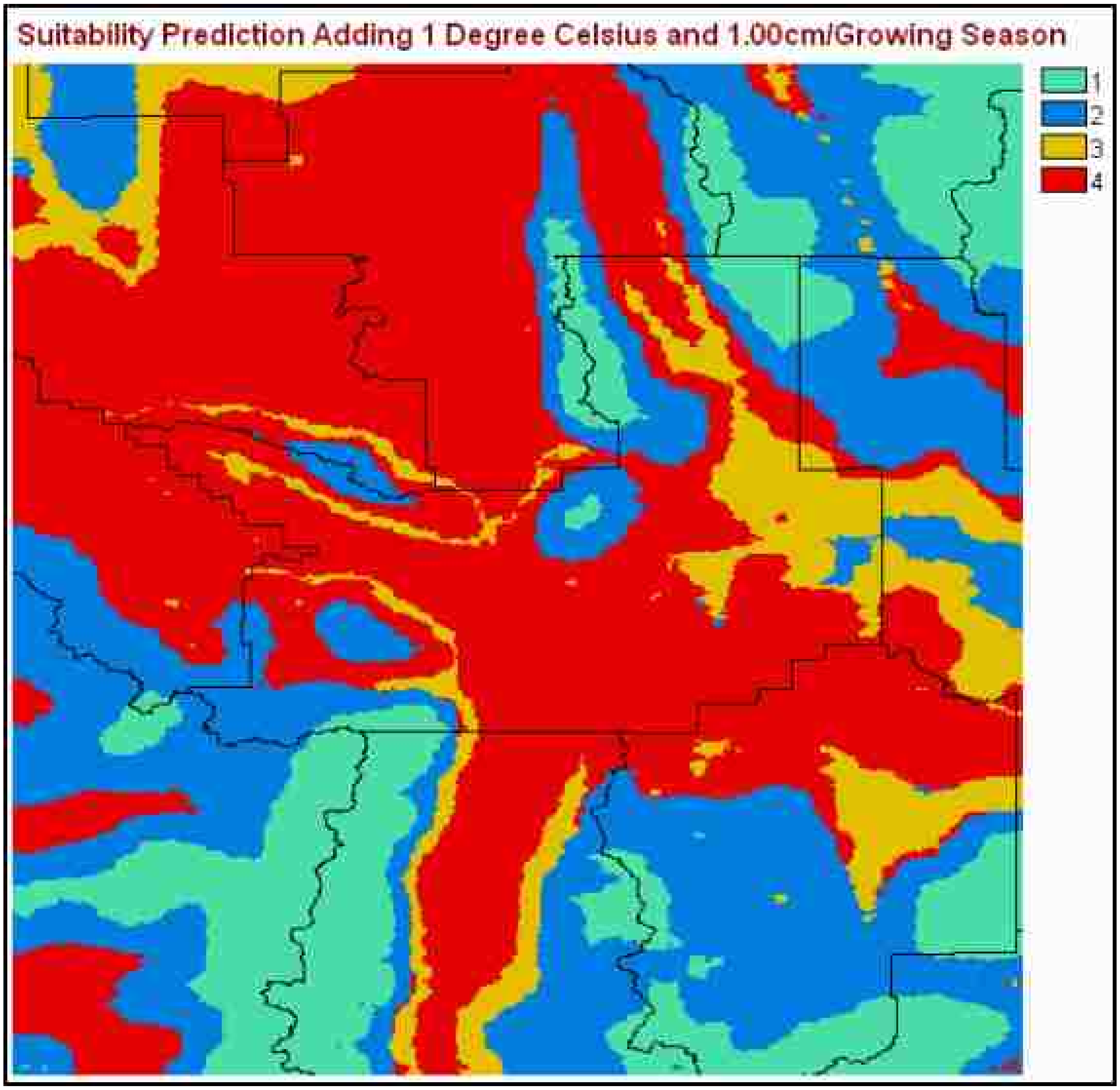


	Climate Predictions															
	1plus0.5	1plus1	1plus5	1plus10	2plus0.5	2plus1	2plus5	2plus10	3plus0.5	3plus1	3plus5	3plus10	4.5plus0.5	4.5plus1	4.5plus5	4.5plus10
	Frequency															
Class																
1	5651727	5759424	6379649	6552966	2388800	2441621	2598649	2598806	289017	289017	289017	289017	0	0	0	0
2	10323276	10085050	9144560	8971243	7385588	7332562	7175529	7175372	4822520	4822520	4822520	4822520	425625	425625	425625	425625
3	3551054	3411829	1473610	0	1356154	1117348	83240	0	496470	363263	464	0	21345	13508	0	0
4	15252401	15522155	17780639	19093264	23647916	23886926	24881876	24274549	29085458	29190588	29031472	26106238	32485787	32264440	29704914	24506747
5	0	0	0	160985	0	1	39164	729731	84993	113070	634985	3560683	1845701	2074885	4647919	9846086
	Proportion															
1	0.163	0.166	0.183	0.188	0.069	0.07	0.075	0.075	0.008	0.008	0.008	0.008	0	0	0	0
2	0.297	0.29	0.263	0.258	0.212	0.211	0.206	0.206	0.139	0.139	0.139	0.139	0.012	0.012	0.012	0.012
3	0.102	0.098	0.042	0	0.039	0.032	0.002	0	0.014	0.01	0	0	0.001	0	0	0
4	0.439	0.446	0.511	0.549	0.68	0.687	0.715	0.698	0.836	0.839	0.835	0.751	0.934	0.928	0.854	0.705
5	0	0	0	0.005	0	0	0.001	0.021	0.002	0.003	0.018	0.102	0.053	0.06	0.134	0.283

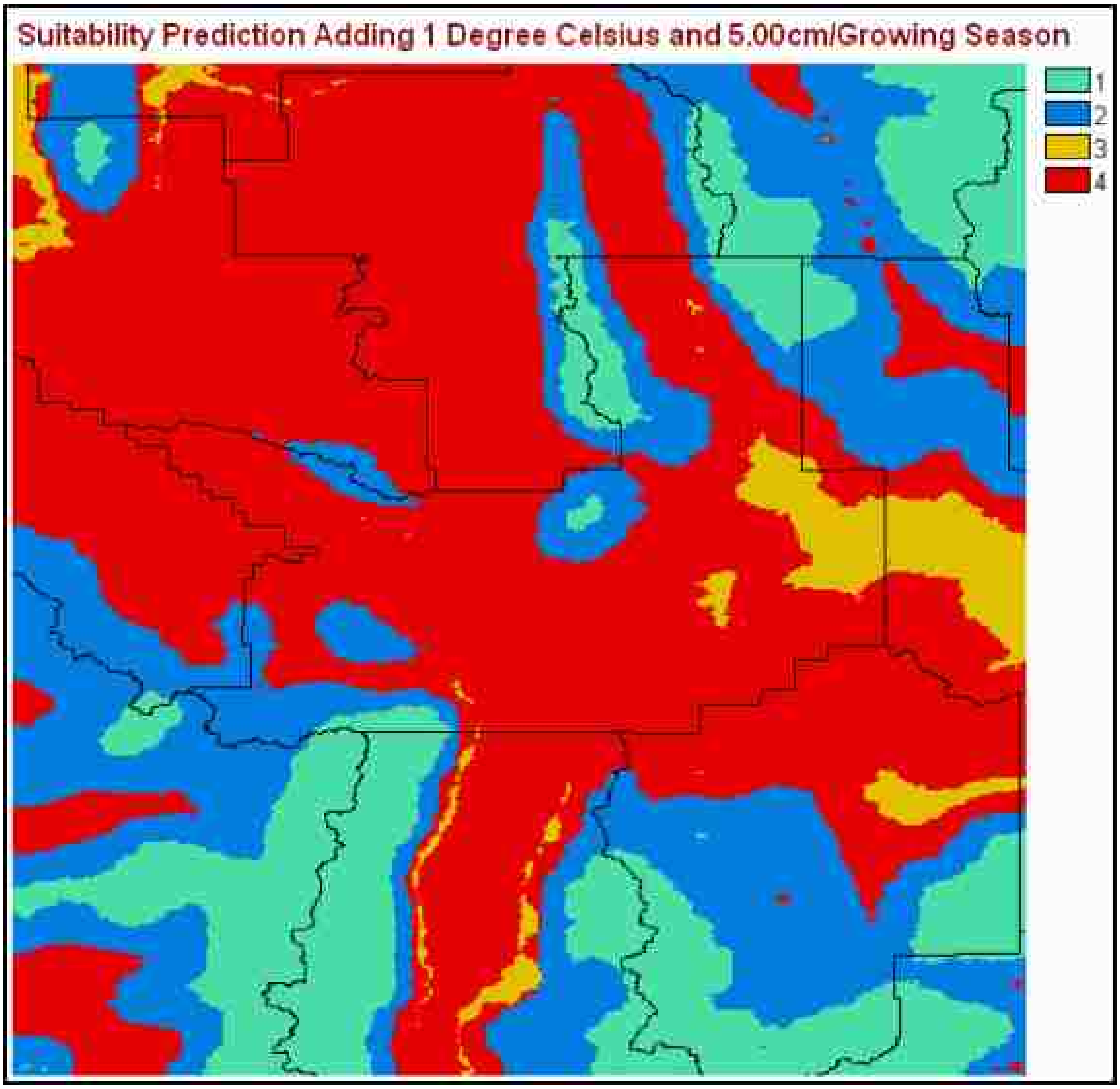
* Pixel frequency and proportion of each suitability class for all potential climate change scenarios



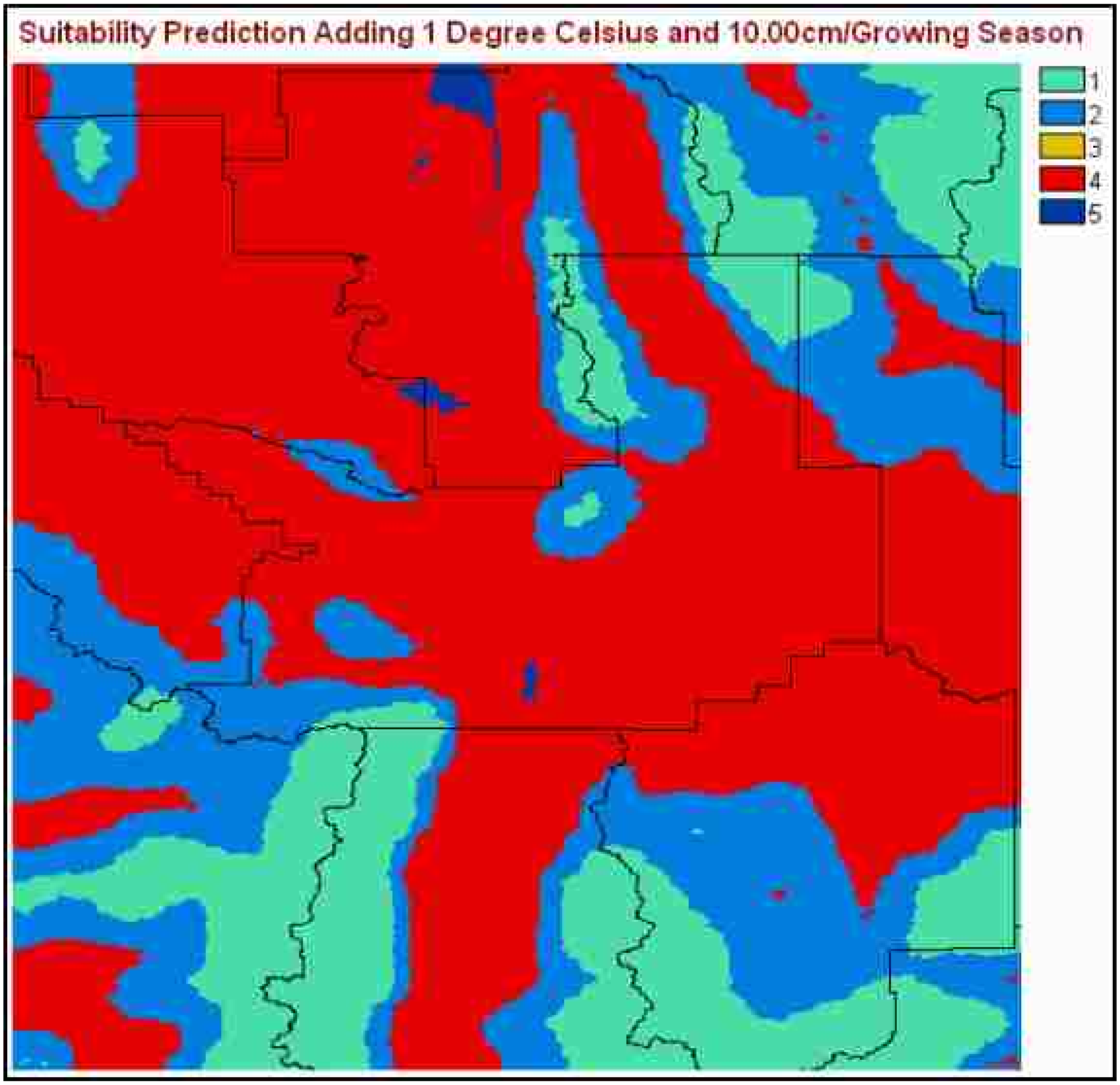
A-2. Suitability class prediction using the climate change scenario adding 1ºC and 0.50 cm per growing-season.



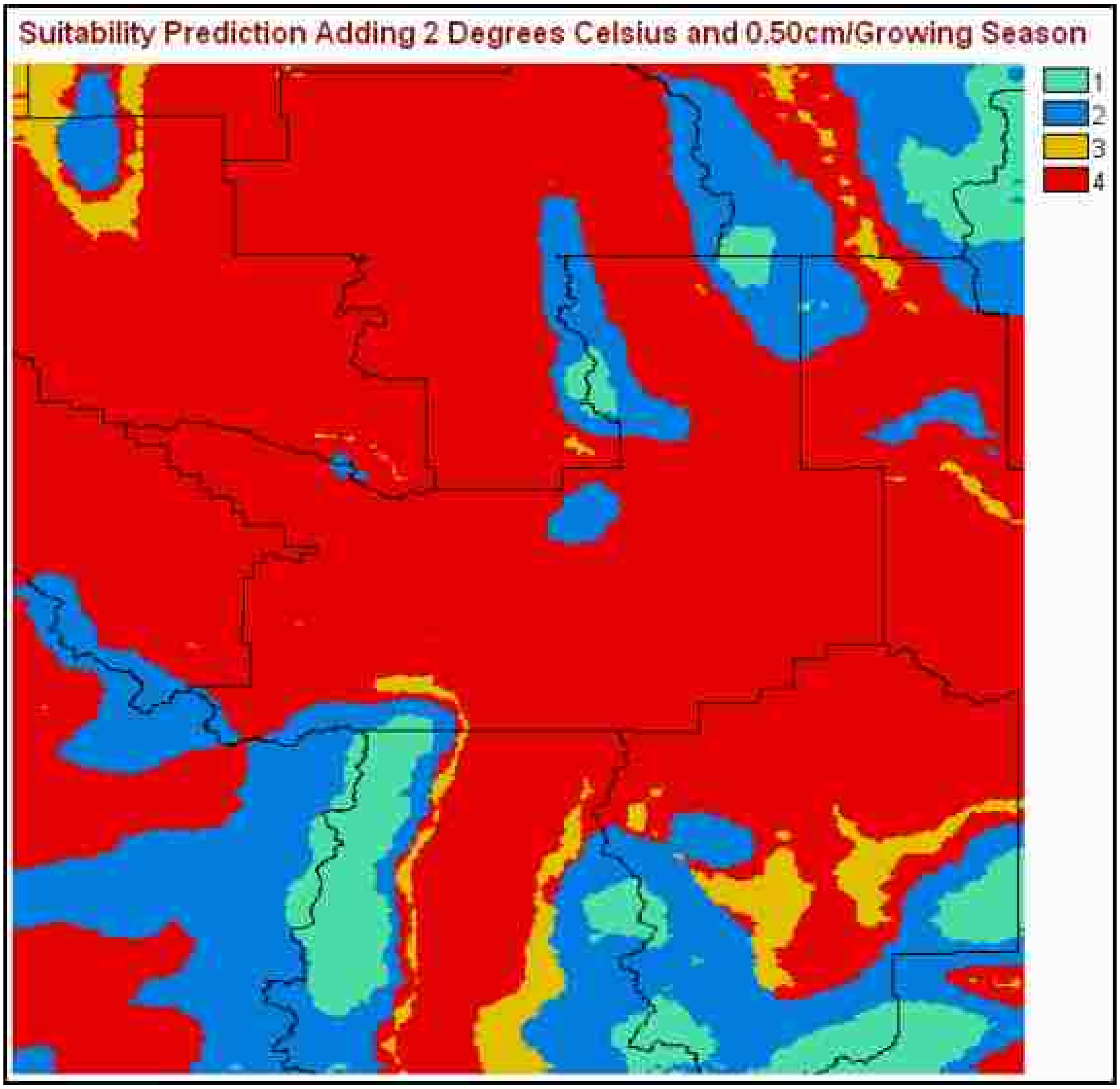
A-3. Suitability class prediction using the climate change scenario adding 1ºC and 1.00 cm per growing-season.



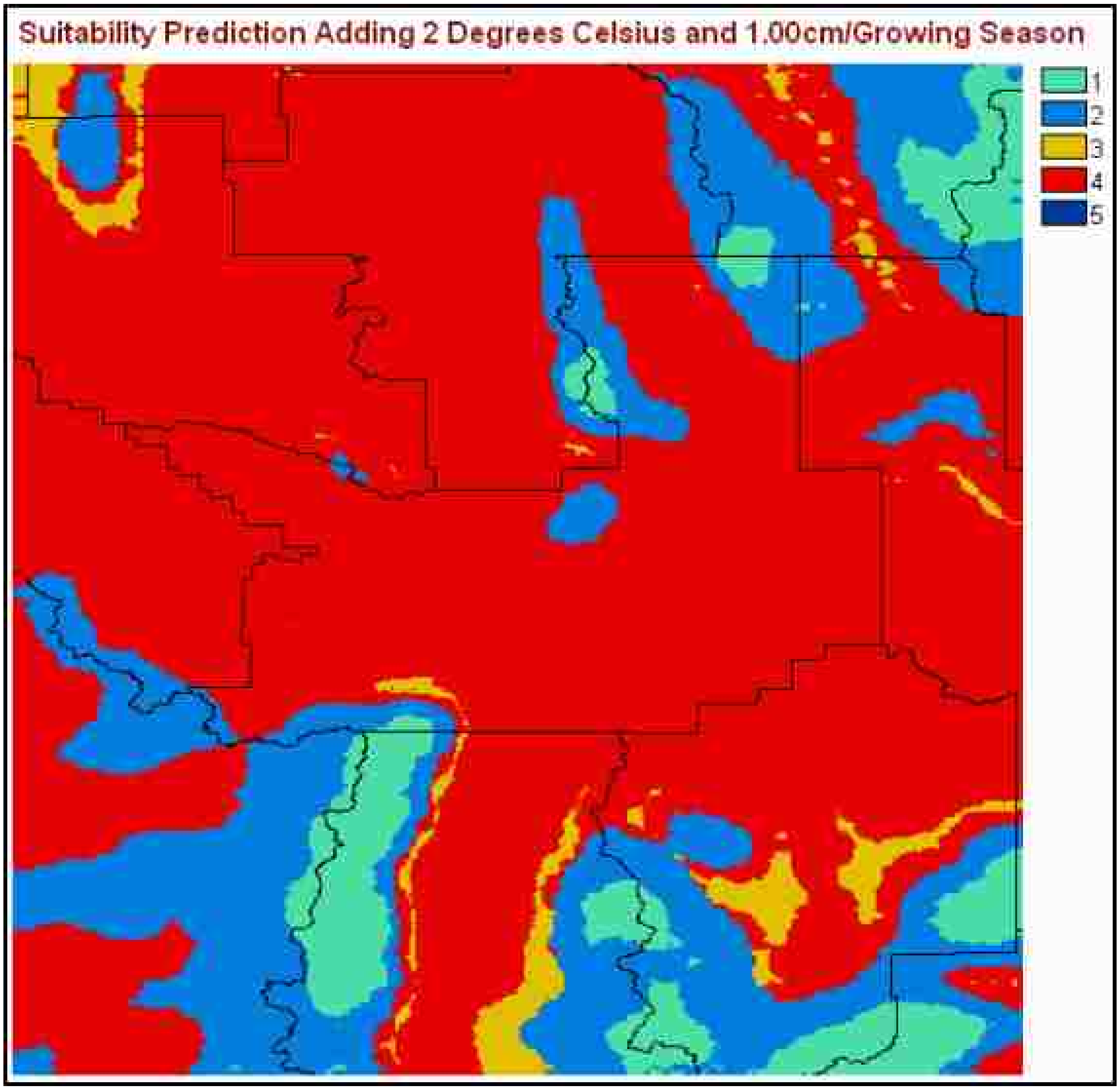
A-4. Suitability class prediction using the climate change scenario adding 1ºC and 5.00 cm per growing-season.



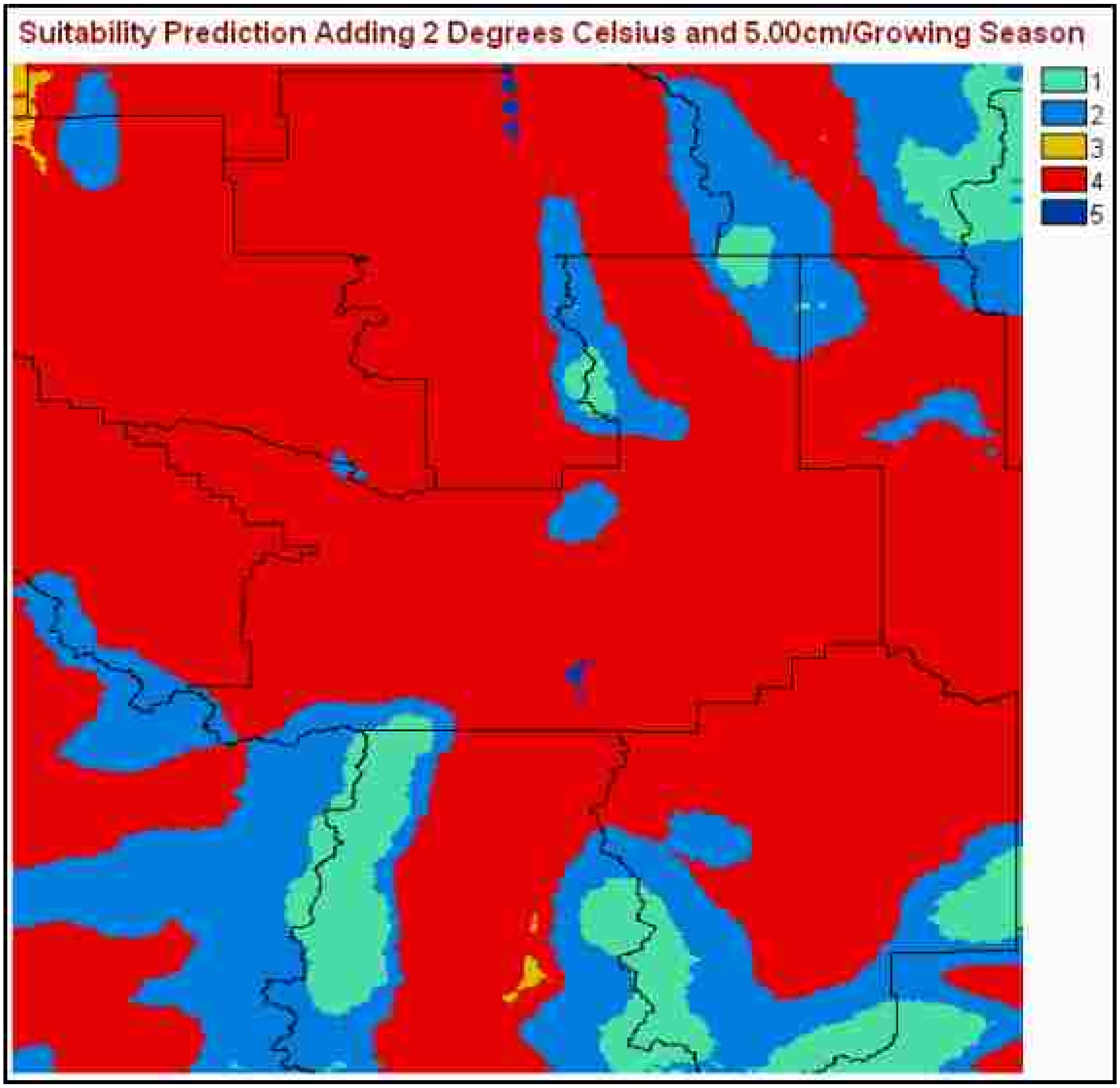
A-5. Suitability class prediction using the climate change scenario adding 1ºC and 10.00 cm per growing-season.



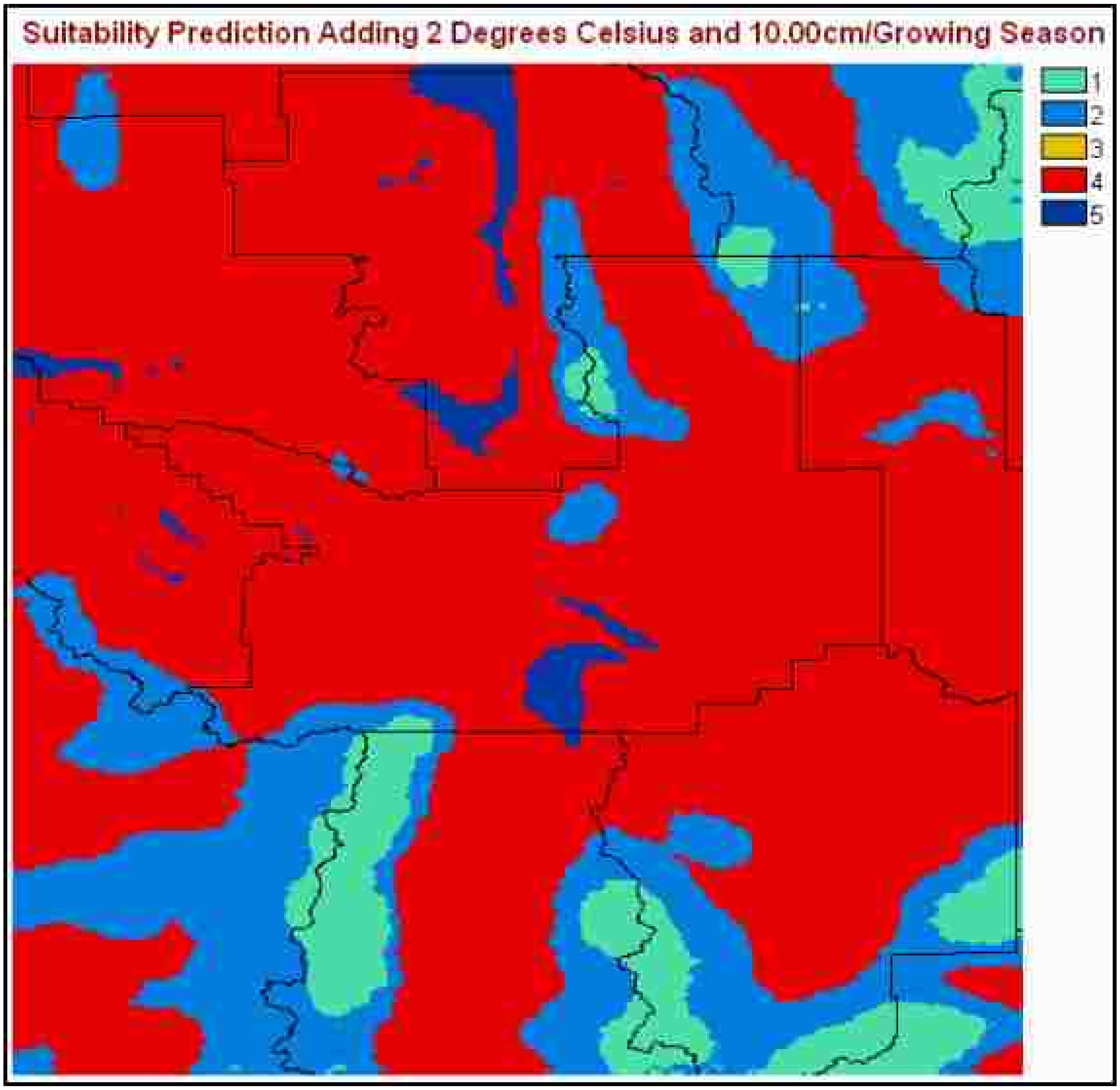
A-6. Suitability class prediction using the climate change scenario adding 2ºC and 0.50 cm per growing-season.



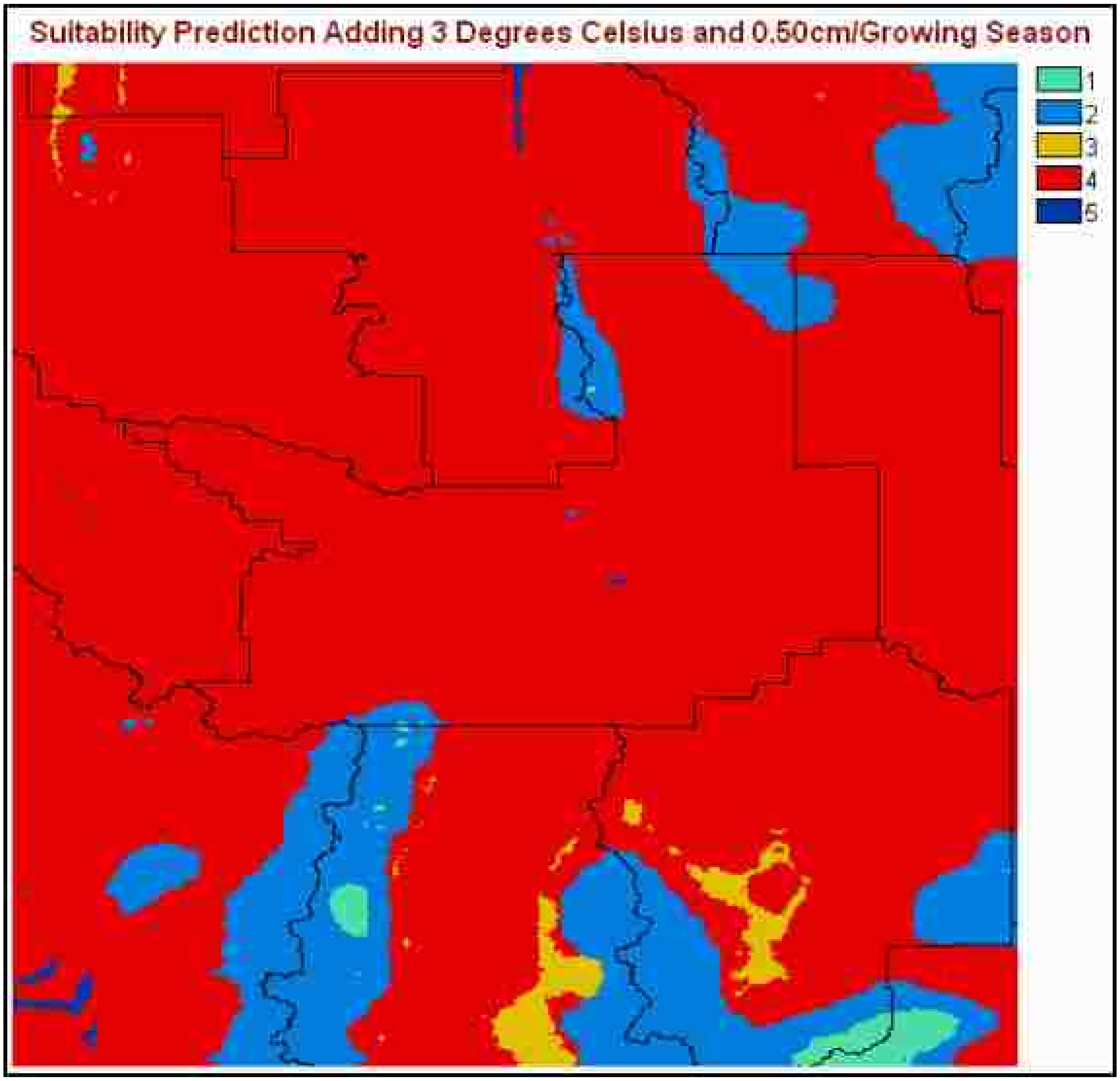
A-7. Suitability class prediction using the climate change scenario adding 2ºC and 1.00 cm per growing-season.



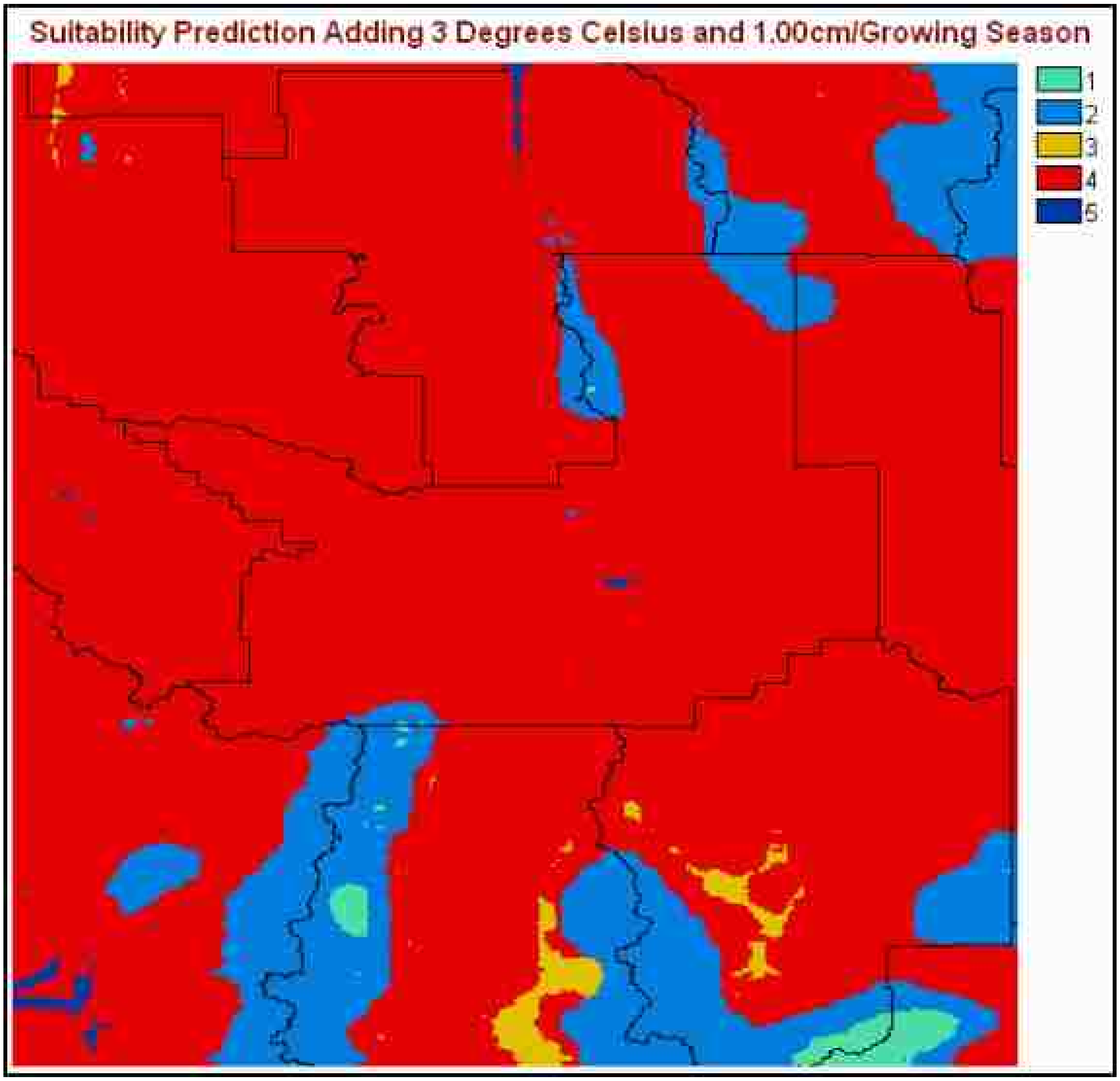
A-8. Suitability class prediction using the climate change scenario adding 2ºC and 5.00 cm per growing-season.



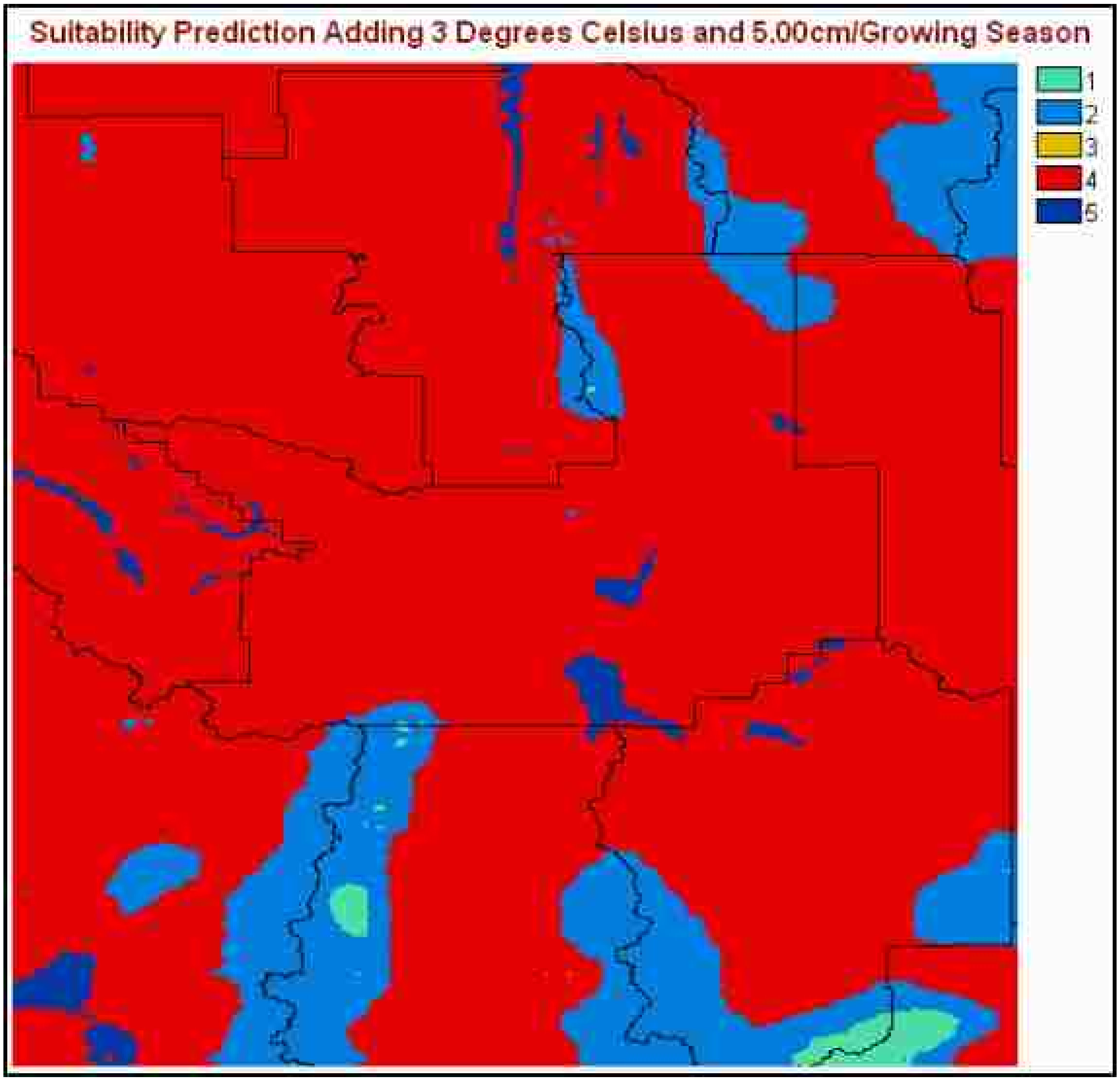
A-9. Suitability class prediction using the climate change scenario adding 2ºC and 10.00 cm per growing-season.



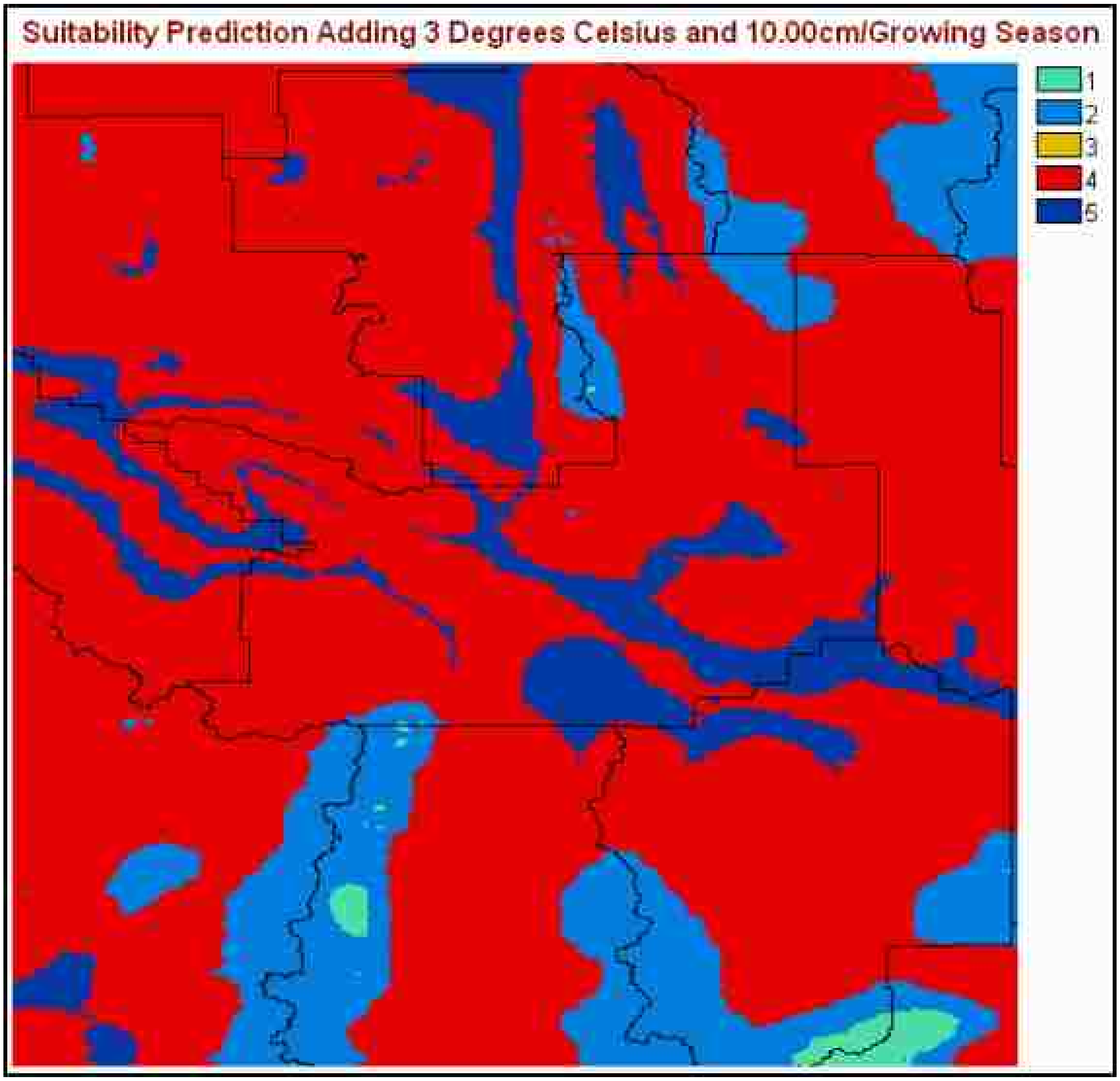
A-10. Suitability class prediction using the climate change scenario adding 3ºC and 0.50 cm per growing-season.



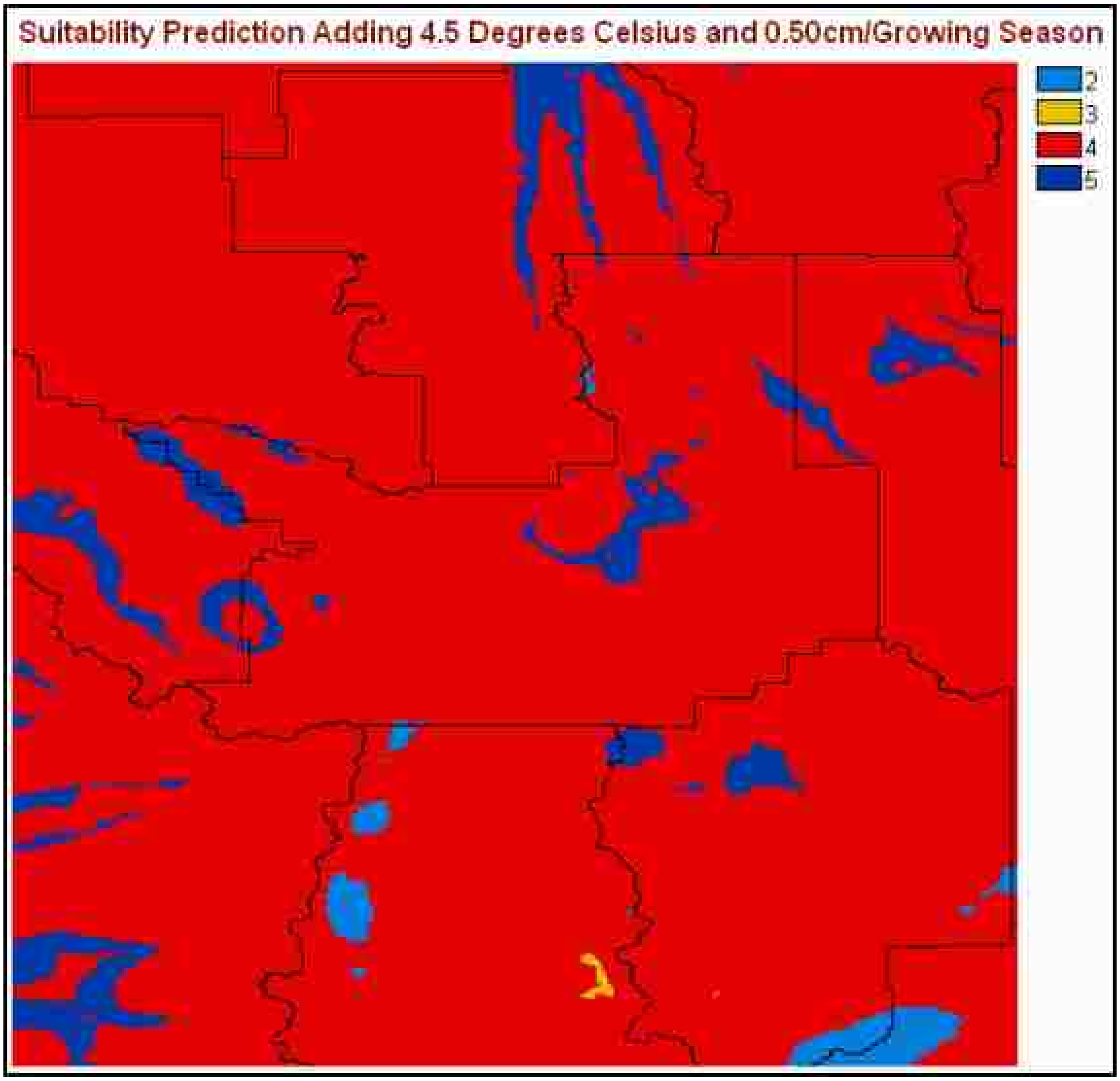
A-11. Suitability class prediction using the climate change scenario adding 3ºC and 1.00 cm per growing-season.



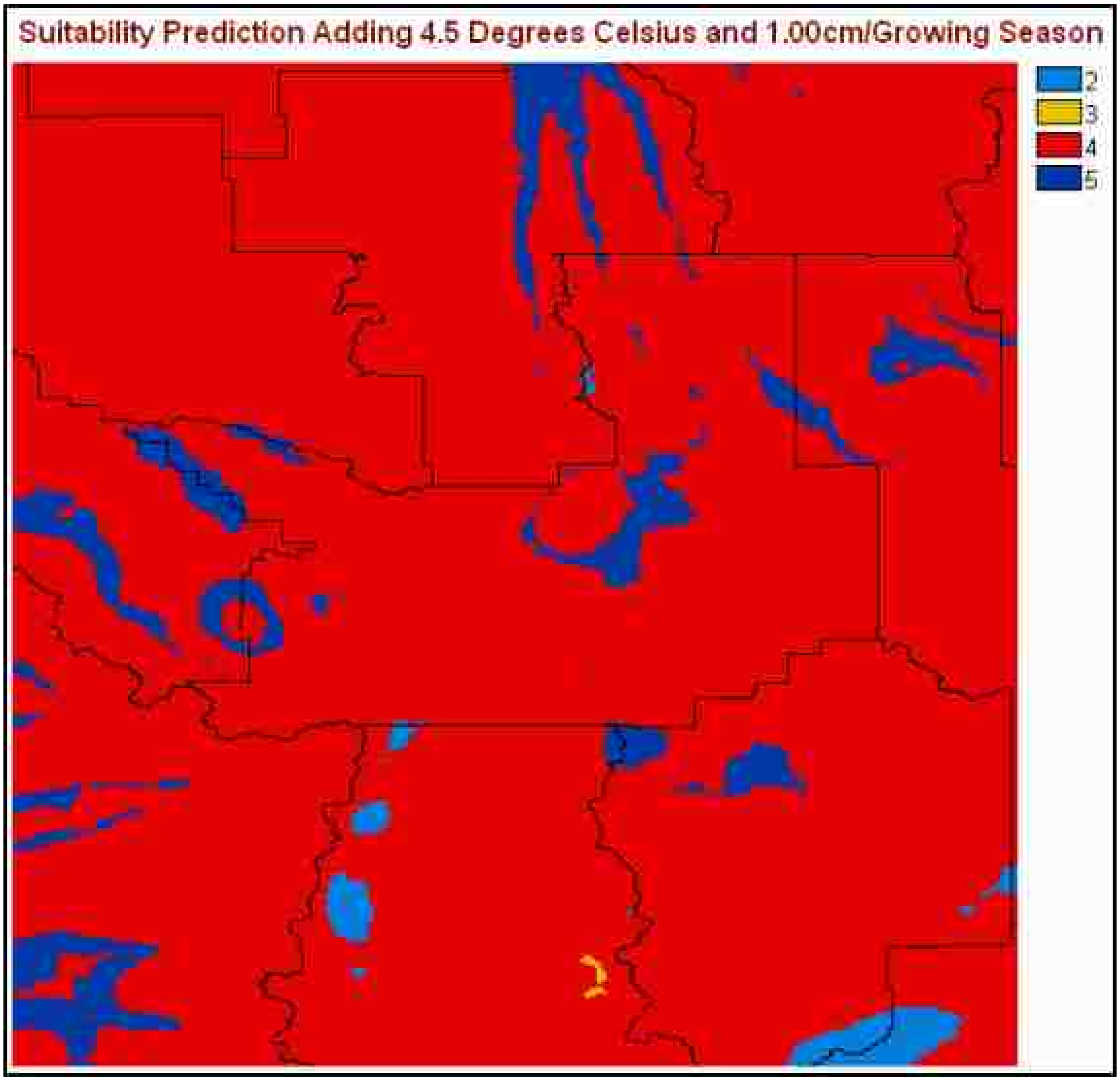
A-12. Suitability class prediction using the climate change scenario adding 3ºC and 5.00 cm per growing-season.



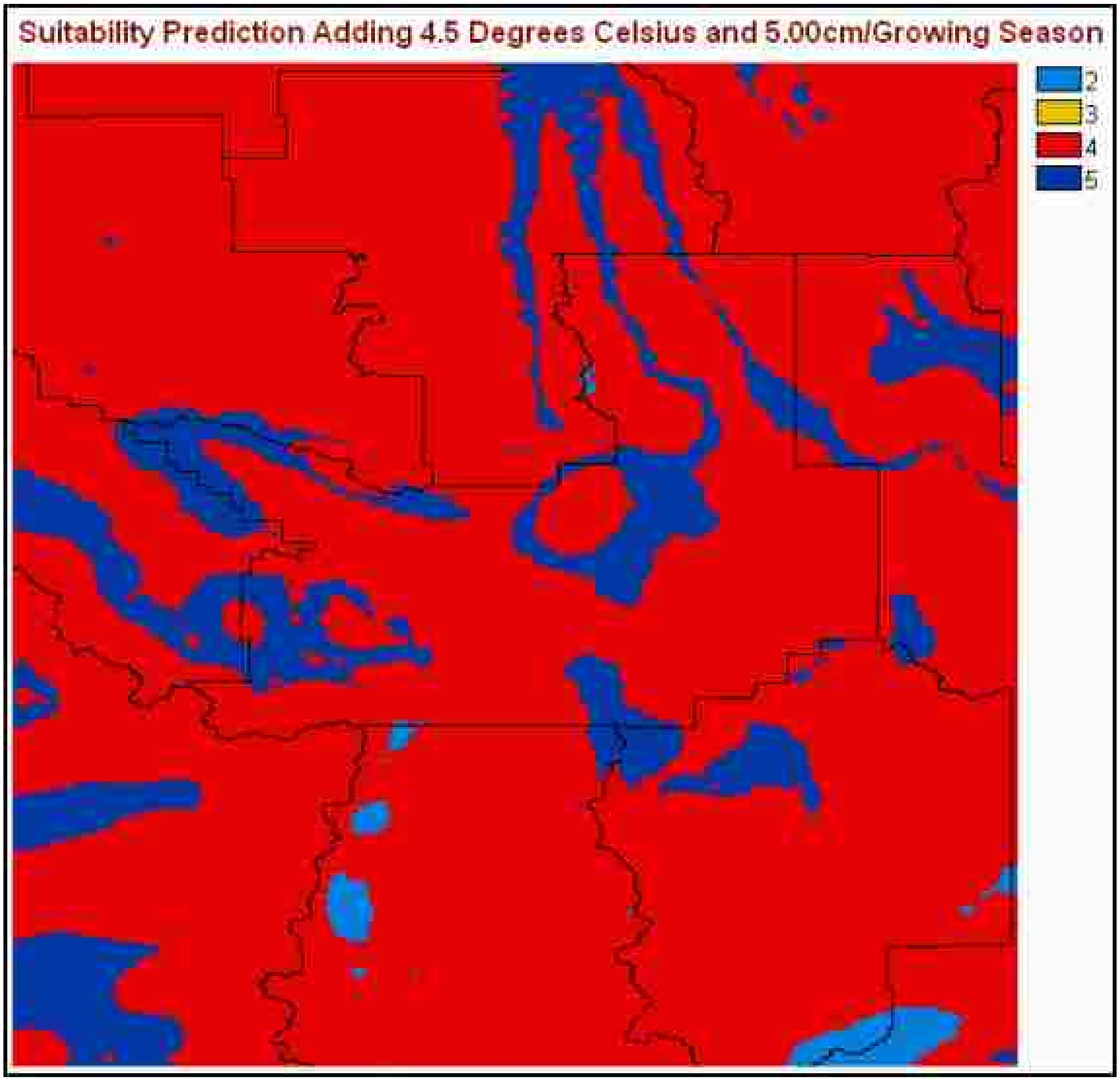
A-13. Suitability class prediction using the climate change scenario adding 3ºC and 10.00 cm per growing-season.



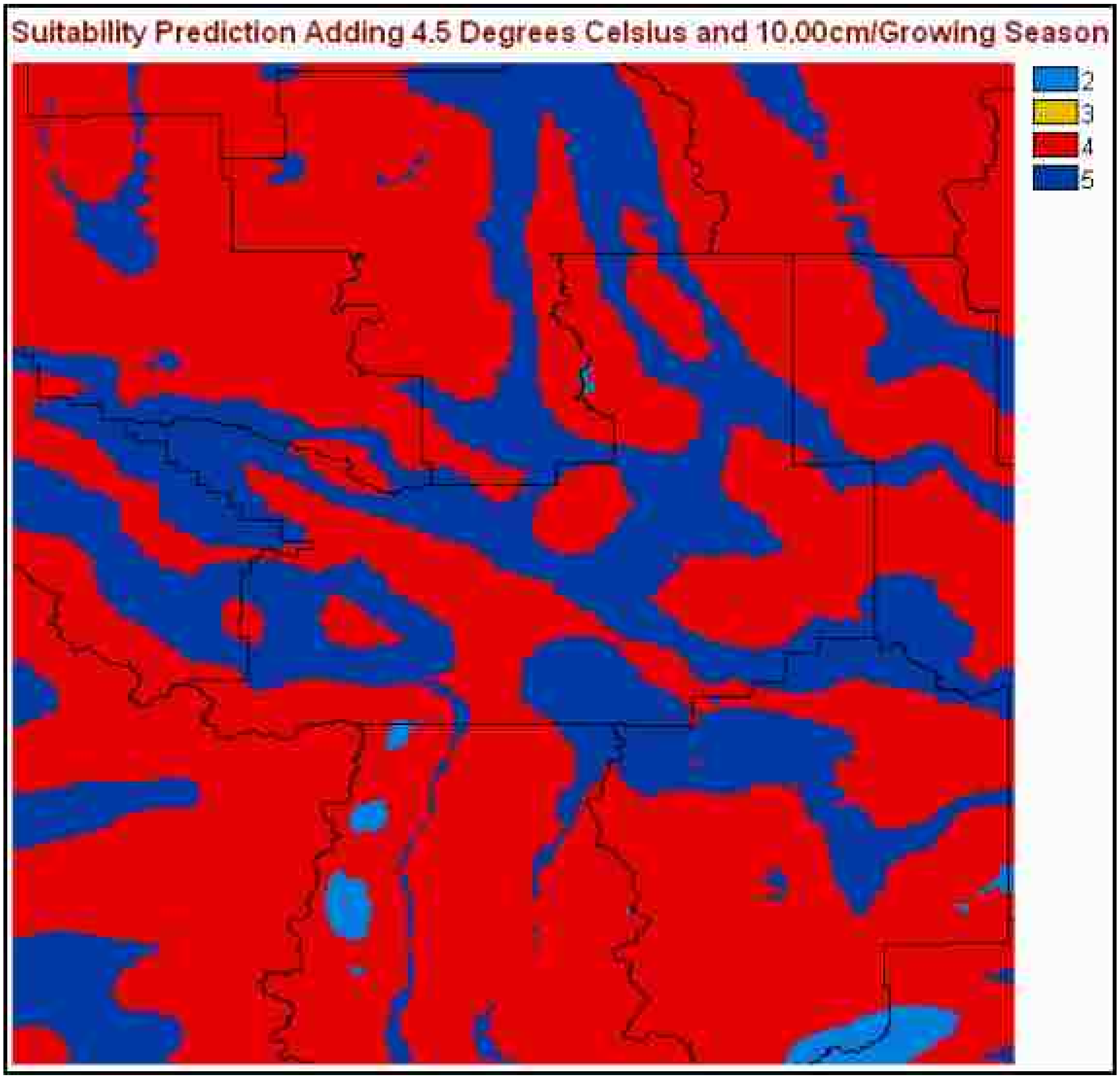
A-14. Suitability class prediction using the climate change scenario adding 4.5ºC and 0.50 cm per growing-season.



A-15. Suitability class prediction using the climate change scenario adding 4.5ºC and 1.00 cm per growing-season.



A-16. Suitability class prediction using the climate change scenario adding 4.5ºC and 5.00 cm per growing-season.



A-17. Suitability class prediction using the climate change scenario adding 4.5ºC and 10.00 cm per growing-season.

Appendix B

B-1. Suitability classes for the years 1920-2004 percent of area and number of acres represented.