



Geographical analysis of the distribution and spread of invasive plants in the Gardiner Basin, Montana
by Emily Nicole Rens

A thesis submitted in partial fulfillment of the requirements for the degree of Masters of Science in
Fish and Wildlife Management
Montana State University
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Abstract:

There is concern over weed invasion of native plant communities in the Gardiner Basin, Montana. The Gardiner Basin makes up the northwest portion of the Northern Yellowstone Winter Range (NYWR) and is a crucial destination for wintering ungulates such as elk (*Cervus elaphus*), mule deer (*Odocoileus hemionus*) and bighorn sheep (*Ovis canadensis*). Invasive plant species that replace native forage in this area are a threat to these wintering ungulates. I had 4 objectives in this study 1) to use GIS and logistic regression analyses to determine important spread vectors of 4 weed species, cheatgrass (*Bromus tectorum*), hound's-tongue (*Cynoglossum officinale*), spotted knapweed (*Centaurea maculosa*), and Dalmatian toadflax (*Linea dalmatica*), 2) to create spread probability maps for each weed species based on important spread vectors; 3) to determine the area of ungulate winter range currently invaded by weeds and the area at risk to future invasions; and 4) to determine if there was a relationship between current weed distribution and prescribed sagebrush burning. Important cheatgrass spread vectors and habitat variables in the Gardiner Basin were distances to rivers, streams, and mining, and cover type. Distances to grazing allotments, streams, and highways, and cover type were included in the most parsimonious model for hound's-tongue distribution. Spotted knapweed was best modeled by distances to streams and rivers, and cover type. The variables used in the top Dalmatian toadflax model were cover type, and distances to mining activity and rivers. Although current distribution, of weeds on ungulate winter ranges are limited, the area of ungulate winter range predicted to be at risk to future invasions varied extensively among ungulate species, weed species, and spread models. Areas that had been burned in prescribed fire programs currently had very few weeds. However, a test of error ranges indicated that there was significantly more cheatgrass on burned areas than on unburned areas. Dalmatian toadflax, which had the highest total percent of cover in the Gardiner Basin, was found more on burned than unburned areas. Spotted knapweed was found more on unburned than burned land, and there was no difference between hound's-tongue distribution on burned and unburned areas.

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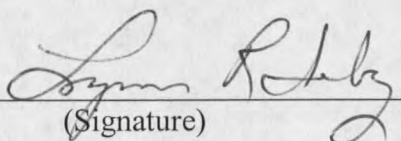
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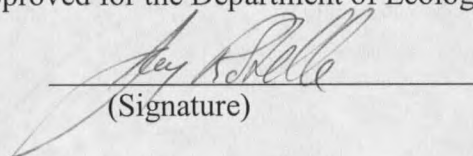
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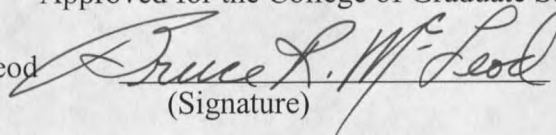
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ABSTRACT

There is concern over weed invasion of native plant communities in the Gardiner Basin, Montana. The Gardiner Basin makes up the northwest portion of the Northern Yellowstone Winter Range (NYWR) and is a crucial destination for wintering ungulates such as elk (*Cervus elaphus*), mule deer (*Odocoileus hemionus*) and bighorn sheep (*Ovis canadensis*). Invasive plant species that replace native forage in this area are a threat to these wintering ungulates. I had 4 objectives in this study 1) to use GIS and logistic regression analyses to determine important spread vectors of 4 weed species, cheatgrass (*Bromus tectorum*), hound's-tongue (*Cynoglossum officinale*), spotted knapweed (*Centaurea maculosa*), and Dalmatian toadflax (*Linea dalmatica*); 2) to create spread probability maps for each weed species based on important spread vectors; 3) to determine the area of ungulate winter range currently invaded by weeds and the area at risk to future invasions; and 4) to determine if there was a relationship between current weed distribution and prescribed sagebrush burning. Important cheatgrass spread vectors and habitat variables in the Gardiner Basin were distances to rivers, streams, and mining, and cover type. Distances to grazing allotments, streams, and highways, and cover type were included in the most parsimonious model for hound's-tongue distribution. Spotted knapweed was best modeled by distances to streams and rivers, and cover type. The variables used in the top Dalmatian toadflax model were cover type, and distances to mining activity and rivers. Although current distribution of weeds on ungulate winter ranges are limited, the area of ungulate winter range predicted to be at risk to future invasions varied extensively among ungulate species, weed species, and spread models. Areas that had been burned in prescribed fire programs currently had very few weeds. However, a test of error ranges indicated that there was significantly more cheatgrass on burned areas than on unburned areas. Dalmatian toadflax, which had the highest total percent of cover in the Gardiner Basin, was found more on burned than unburned areas. Spotted knapweed was found more on unburned than burned land, and there was no difference between hound's-tongue distribution on burned and unburned areas.

INTRODUCTION

Exotic plants threaten native wildlife in the west. This threat has not been fully appreciated nor evaluated. Invasive exotic plants can compete with and replace essential native plants from millions of hectares of wildlife habitat thereby impacting indigenous animal species ranging from insects to keystone carnivores (Trammel and Butler 1995, Belcher and Wilson 1989, Bedunah 1992, Sheley et al. 1999). Many animal species cannot adapt quickly enough to rapid weed invasions that replace essential native forage (Olson 1999). In the west, weeds have already reduced grazing capacity in some areas by 75% (Sheley et al. 1999, Bedunah 1992, U.S. Forest Service 1936). In western Canada and Montana, graminoid production declined 90% on some knapweed (*Centaurea spp.*) infested rangelands (Harris and Cranston 1979, Strang et al. 1979, Bucher 1984, Bedunah 1988).

The most economical and ecologically effective method for managing noxious weeds is to prevent their initial invasion (Sheley et al. 1999). By preventing invasions, land and wildlife managers can preserve native flora and fauna. Prevention plans require, in part, an understanding of the factors governing plant invasions.

Weeds are commonly introduced to new sites by wind, water-flow, and transportation routes, but wildlife may also serve as a mechanism to introduce weeds into new areas by transporting seeds internally (digestive tract) or externally (seeds caught in fur or feathers) (DeClerke-Floate 1997, Sheley et al. 1999, Wallander et al. 1995). However, the importance of wildlife as weed spread vectors is unknown in most ecosystems.

Disturbance is a significant factor in invasive plant spread (Bedunah 1992).

Various disturbance types facilitate weed invasions and are even considered a necessity for some species (Forcella and Harvey 1983, Kurtz 1999). Disturbance creates available space for competitive non-native species. After disturbance, native plants often cannot recover as quickly as non-native plants because many noxious weeds are early successional species that colonize recently disturbed sites (Baker 1986). When exotic early successional species compete directly with native plants that are trying to re-establish, native plants are often eliminated. Wildlife and livestock may disturb plant communities by over-grazing, hoof action, trail creation, and excavation (Tyser and Worley 1992).

One approach to determining the importance of wildlife as a weed-spread vector is to compare weed distributions with the distribution of wildlife and other potential vectors including those associated with human activity (Forcella and Harvey 1983, Kurtz 1999). Kummerow (1991) and Benninger-Traux (1992) found that trails were often avenues of weed infestations. Cole (1989) and Benninger-Traux (1992) found that human camping areas had high incidences of weed infestations. The prevalence of weeds was also related to climatic variables in studies by Forcella and Harvey (1983), Baker (1986), Mack (1986) and Weaver and Woods (1986). Wildlife were found to be weed-spread vectors by Robocker (1970) and Tyser and Key (1988).

My study had 4 objectives; 1) to determine the importance of habitat variables and spread vectors in weed spread, 2) to model current and future potential weed distribution in the Gardiner Basin, 3) to estimate the area of wildlife winter range at risk

to weed invasion, and 4) to determine if there was a relationship between prescribed burns and current weed distribution.

By comparing Geographic Information System (GIS) data layers of factors, such as burned areas, trails, cattle allotments, mined areas, roads, and wildlife distributions, with weed distribution layers, I determined spatial and temporal patterns that indicated the importance of specific vectors in the spread of weeds. I also identified areas where land managers should focus weed prevention efforts.

I chose the Gardiner Basin as a study area because of the availability of GIS layers and its importance to wintering ungulates in the Yellowstone Ecosystem. Native plant communities in the Gardiner Basin are essential to ungulates including bighorn sheep (*Ovis canadensis*), Rocky Mountain elk (*Cervus elaphus*), mule deer (*Odocoileus hemionus*), and pronghorn antelope (*Antilocapra americana*) and are experiencing increased pressure from human development of the area. Exotic plant species are present in the Gardiner Basin and could exacerbate habitat loss associated with housing and commercial development. I focused on the 4 most common non-native plant species in the Gardiner Basin: cheatgrass (*Bromus tectorum*), hound's-tongue (*Cynoglossum officinale*), spotted knapweed (*Centaurea maculosa*), and Dalmatian toadflax (*Linea dalmatica*). These plants are identified as aggressive rangeland invaders and are locally abundant in the study area.

Weed Taxa History and Biology

Cheatgrass

Cheatgrass (downy brome) is a winter annual grass originally from southwestern Asia. It is thought to have come to the United States in the mid-1800s in contaminated soil in the ballasts of ships arriving from Eurasia (Mosley et al. 1999). Cheatgrass is widely distributed in the United States and is a major range weed (Young et al. 1987) that limits establishment of native perennials via competition for moisture. Cheatgrass seedlings develop an efficient root system that gives them a competitive advantage in the spring when temperatures are adequate for shoot growth. Roots from fall-germinating plants of cheatgrass can continue to grow in the winter while the aerial portion of the plant remains dormant (Young et al. 1987). Cheatgrass establishment has dramatically increased fire frequency in areas where wildfires were once rare or non-existent (Billings 1990). After burning, sagebrush/bunchgrass dominated grasslands become fire-prone annual grasslands with cheatgrass as the dominant species. Preferred native bunchgrass species are out competed and, therefore, unavailable to wildlife when cheatgrass is dominant. Native wildlife species generally eat little cheatgrass.

Hound's-tongue

Hound's-tongue is a deep taprooted perennial from Europe that spreads via its barbed, Velcro-like nuttlets or burrs. Each plant can produce 1-8 flower stalks, which in turn can produce several hundred burrs (DeClerke-Floate 1997). Hound's-tongue is toxic, containing pyrrolizidine alkaloids which cause liver cells to stop reproducing in wildlife and domestic animals (Knight et al. 1984, Baker et al. 1989). Although livestock avoid

eating hound's-tongue, their hair serves as an effective vector for spread; and, therefore, this weed is frequently found in areas used by cattle. It is often all that remains in pastures after more palatable and desirable species are grazed. The success of hound's-tongue is likely due to extensive disturbance caused by logging and other human-related activities in conjunction with the abundance of dispersal agents such as cattle and indigenous ungulate species (DeClerke-Floate 1997).

Spotted Knapweed

Spotted knapweed was introduced from Eurasia and is currently found in 14 western states and in Canada. It was introduced in the late 1880s as an alfalfa contaminant (Sheley et al. 1999). It has deep taproots, forms rosettes, and can produce seeds annually. Competing with native plants, it reduces livestock and wildlife forage, increases soil erosion, and reduces bio-diversity (Sheley et al. 1999). Spotted knapweed can invade a wide range of elevations (500-3,050 meters), annual precipitation zones (20-200 cm), and soil types. It can produce 5,000 - 40,000 seeds/m² annually and can be spread by wind, water, animals, hay, and vehicles.

Dalmatian Toadflax

Dalmatian toadflax, a short-lived perennial native to the Mediterranean region, has become well established in the Northwest United States and Canada. Its introduction to North America in 1874 was intentional. It was used to make fabric dye and as an ornamental in gardens. It has since escaped the confines of home gardens and has become a successful weed in rangelands and agricultural areas. Dalmatian toadflax can flourish in

diverse environmental conditions and has high genetic variability that allows it to undergo local adaptations. This makes control efforts and management plans difficult. Also it is highly competitive, producing up to 500,000 seeds each year (Robocker 1970), reproducing vegetatively through buds on the rootstock, and emerging earlier in the spring than most desirable species. Dalmatian toadflax is not considered a forage source for wildlife or livestock and can decrease available forage by replacing native species in many plant communities.

STUDY AREA

Location

The Gardiner Basin is located in the northwest portion of the Northern Yellowstone Winter Range (NYWR) in southwestern Montana (Fig. 1). Although land ownership in the Gardiner Basin is divided among the Forest Service, National Park Service (NPS), Montana Department of Fish, Wildlife, & Parks (MDFWP), and private ownership, only Forest Service land was mapped for weeds. The Gardiner Basin runs north/south encompassing 10 different drainages from the Gallatin Range to the west and the Absaroka-Beartooth Mountains on the east. The Yellowstone River flows north out of Yellowstone National Park and runs through the valley floor of the basin. Foothills rise steeply from the floodplains to rolling benchlands with 50-60 degree slopes (McNeal 1984). Most land on the river terrace is in private ownership.

History

Plant and animal communities in the Gardiner Basin have been relatively stable since the ice sheets retreated in the Pleistocene. Human activity in the area was limited to hunter-gatherer societies until the late 1800s when the northern Rocky Mountains were settled by Europeans, who introduced large herds of cattle (Olson 1999, Bedunah 1992). Species composition in climax plant communities has remained relatively unchanged

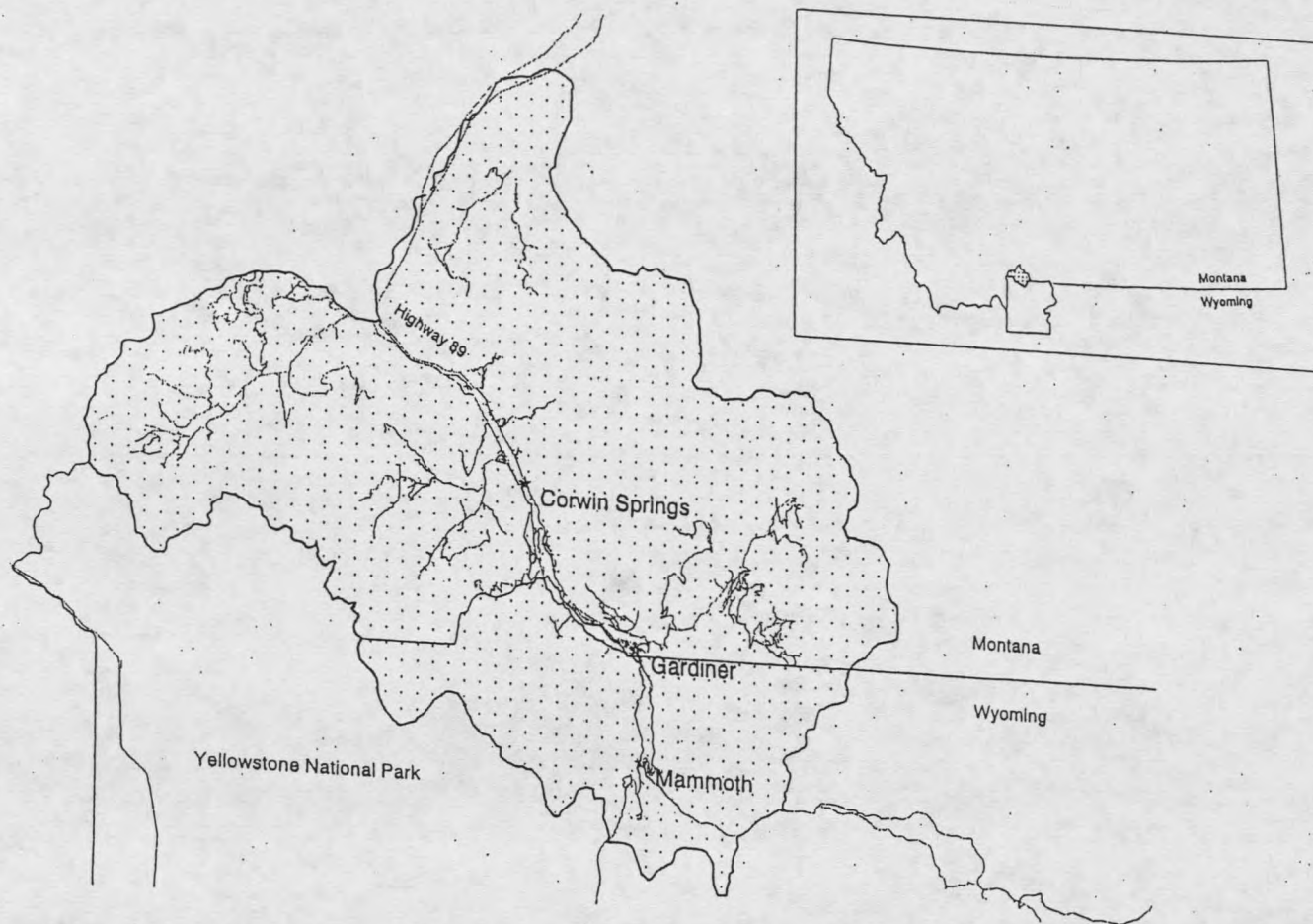


Figure 1. Gardiner Basin study area.

following European settlement. Natural disturbances such as fire, drought, and insect outbreaks undoubtedly have occurred throughout the Basin's history; however, native climax communities presumably are adapted to these disturbances. Introductions of non-indigenous plant species which have occurred over the past 100 years have the potential to produce major changes in species composition. At least 9 species of non-native weeds have been recorded in the Gardiner Basin. The 4 species I examined in this study are currently the most abundant of the nine.

Cheatgrass was seen in the Gardiner Basin area as early as the 1950s around the town of Gardiner and appears to be most abundant in areas where human activity is high (D. Tyers and P. Hoppe, US Forest Service, personal communication). Hound's-tongue was first recorded in Tom Miner Basin in the mid-1960s along private and Forest Service trails and was also found along drainages in Beatie Gulch (Fig. 2). Increases in hound's-tongue were noted in the 1980s (D. Tyers and P. Hoppe, US Forest Service, personal communication). Spotted knapweed was first found along Highway 89 in Yankee Jim Canyon in the late 1960s and on Deckard Flats in the 1970s. The first record of Dalmatian toadflax in the Basin was in the early 1970s along Eagle Creek, a popular recreation area.

Other non-native weed species, including leafy spurge (*Euphorbia esula*), oxeye-daisy (*Chrysanthemum leucanthemum*), diffuse knapweed (*Centaurea diffusa*), white-top (*Cardaria pubescens*) and mullein (*Verbascum thapsus*), are also found in the Gardiner Basin, but the abundance and distributions of these species are very limited at present.

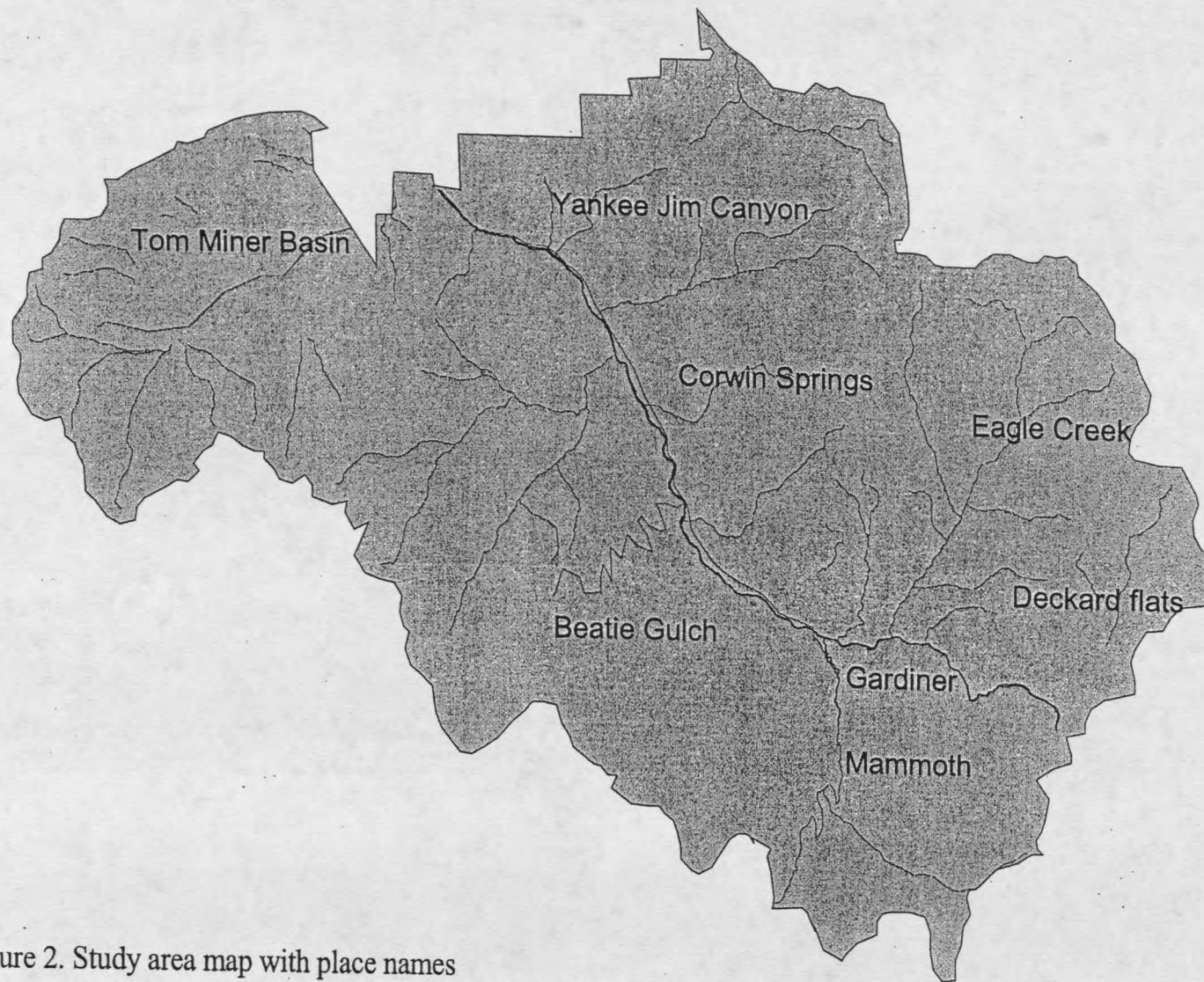


Figure 2. Study area map with place names

Climate

Due to a rain shadow created by the Gallatin Range, average annual precipitation at lower elevations of the Gardiner Basin (about 1,575 meters) is 305 mm. Precipitation increases with elevation. Benchlands receive an average of 406 mm, while the mountains may receive up to 760 mm (Farnes 1975). Roughly half of the overall moisture in higher elevations falls in the form of snow; therefore, late-summer soil water deficits are common. The highest amounts of rainfall occur in May and June. The growing season is generally from mid-April to mid-September but varies with the amount of snowfall, spring rain, and temperature. Mean annual temperature is 3.1°C. (NOAA 1994). The warmest month is July, with a mean temperature of 17.3°C. During my study, the area experienced unusually wet spring weather in 1999 and a dry growing season in 2000.

Soils

Soils in the Gardiner Basin are heavily influenced by scouring and deposition from 3 glacial advances that occurred during the Pleistocene (Blackwelder 1915). These glaciers formed steep and unstable valley walls (Good 1982) resulting in numerous slumps and landslides that extend from Yankee Jim Canyon to Cinnabar Mountain (Fig.2). Glacial parent materials include granites, basalt, breccias, and limestone. Soil depths in the Gardiner Basin range from over 1.5 m in depositional areas to only a few centimeters where glacial scouring occurred.

The dominant soil orders in the study area are Mollisols. In forested areas, Alfisols are present, and Inceptisols may be found near outcrops of basalt and bedrock

(McNeal 1984). There is a wide range of soil textures found within the study area. Loams and sandy loams are most common (Lane 1990), with coarse fragments ranging from gravel to boulders.

Vegetation.

In undisturbed habitat, bluebunch wheatgrass (*Agropyron spicatum*), Idaho fescue (*Festuca idahoensis*), black sagebrush (*Artemisia nova*) and big sagebrush (*Artemisia tridentata*) dominate the lower elevations of the Gardiner Basin. Other common native grasses and shrubs include needle-and-thread grass (*Stipa comata*), prairie junegrass (*Koeleria macrantha*), Indian rice grass (*Oryzopsis hymenoides*), and green and rubber rabbitbrush (*Chrysothamnus viscidiflorus* and *C. nauseosus*). Several forest habitat types occur at higher elevations and northern aspects throughout the study area. Limber pine (*Pinus flexilis*) and juniper (*Juniperus scopulorum*) are present at lower elevations, and Douglas fir (*Pseudotsuga menziesii*) is a dominant tree species found at mid-elevations and on north facing slopes. High elevation species are subalpine fir (*Abies lasiocarpa*), and whitebark pine (*Pinus albicaulis*). Sedges (*Carex* spp.), willow (*Salix* spp.), and quaking aspen (*Populus tremuloides*) often occur near streams, springs, and other moist areas.

Native Ungulates

The Gardiner Basin is part of the NYWR and is used by a wide variety of wildlife species. It is a critical wintering area for migratory ungulates due to relatively low snow

cover in lower elevation grass/shrub steppe communities (Houston 1982). The Gardiner Basin provides winter range for one of the largest extant herds of Rocky Mountain elk (Houston 1982). Thousands of elk and mule deer, and several hundred bighorn sheep and pronghorn antelope also escape the harsher winter environments of the surrounding high country in YNP and the Gallatin National Forest and occupy this portion of the NYWR during winter and spring. In the most severe winters, Mammoth and the Gardiner Basin may be the only portions of the northern winter range that remain open and available for ungulates (Turner et al. 1994).

Management of the migratory Yellowstone elk herd has been varied and controversial throughout the history of Yellowstone National Park (McNeal 1984). The NPS actively reduced elk herds by transplanting or intensive harvesting for 35 years until they adopted a natural regulation philosophy in 1968. The elk population subsequently increased from less than 4,000 animals to more than 23,000 by 1988. (Coughenour and Singer 1996). Following extensive fires in 1988, the severe winter of 1988-1989 reduced the herd by 40%, but the population was estimated at 25,000 animals in 1993 (Lemke 1996). From 1995 to 2000, elk numbers increased in and north of the study area (Tyers 2000). The 2001-2002 survey counted 5,104 elk north of YNP, slightly less than the average (5,211). Depending on winter conditions, 3,000 to 9,000 elk may use the study area sometime during November-April.

Resident mule deer in the study area are joined by migrants during the winter. During summer, they occur throughout the study area, as well as in YNP and nearby mountains. They migrate to lower elevations around the beginning of October and may

remain through June. Depending on winter severity, mule deer become increasingly restricted to areas of the Gardiner Basin with less snow cover and greater forage availability. In late winter/spring of 2000, the population of mule deer in the study area was estimated at > 1,800 animals, including both resident and migratory individuals. Mule deer population estimates have remained stable over the past 14-15 years, at about 2,000 animals. The 2001-2002 survey counted 1,934 mule deer, 8% lower than 2000-2001, and 4% lower than the 15-year average.

Bighorn sheep in the study area occur in 8, or more, small bands (Ostovar 1998) that also inhabit YNP seasonally. Bighorn sheep numbers on the entire NYWR as counted in fixed-wing aerial surveys, have ranged from 487 in 1981 to 134 in 1988. Ground surveys yielded counts of 31-265 animals during 1979 - 2002. During the winter of 1981-1982, an outbreak of infectious keratoconjunctivitis (pink-eye) reduced the northern range population by 60%. Although sheep outside the park were never seen with pink-eye, the population outside of the park declined by 80% between the mid-1980s and mid-1990s (Keating 1982, Meagher et al. 1992, Legg 1996, Ostovar 1998). In 2000, 40 sheep were observed during a ground count in the study area, 10 fewer than were counted in 1999. The 2001-2002 ground survey counted only 31 bighorns in the Gardiner Basin (White, 2002).

Two additional ungulate species, moose (*Alces alces*) and mountain goats (*Oreamnos americanus*), use the upper margins of the Gardiner Basin. There were no sightings of either species in the study area during 1999 or 2000. Bison (*Bison bison*), and pronghorn antelope (*Antilocapra americana*) range overlap elk and mule deer range,

however, overlap occurs mostly in YNP and not in my study area. Ungulates in the Gardiner Basin are preyed on by grizzly bears (*Ursus arctos horribilis*), mountain lions (*Felis concolor*), black bears (*Ursus americanus*), gray wolves (*Canis lupus*), coyotes (*Canis latrans*) and golden eagles (*Aquila chrysaetos*).

Livestock Grazing

Livestock graze 5 allotments on Forest Service land in the Gardiner Basin. Gallatin National Forest allotments are leased for cattle grazing from late June until October. Most cattle allotments are in mountain meadows ranging in elevation from 1,800 – 2,500 m and average approximately 700 ha. The allotment system began in the 1920s. From the mid-1800s to 1920, intensity of cattle grazing on USFS land was much greater than after the 1920s. Between 1920 and 2000, the Forest Service added abandoned homestead land to the National Forest system, decreased Animal Unit Months (AUMs) on some allotments, and eliminated other allotments to increase forage and cover for wildlife.

Mining Activity

Many small surface and subsurface mines occur throughout the Gardiner Basin. Most mines began around the turn of the century but are now dormant. One of the few active mines is a 36-ha travertine quarry operation. This mine has been active on a fairly regular basis since 1932, making it a continuous source of soil disturbance in the area. It

is situated on a bench 200-300 m above the Yellowstone River and about 3 km from Gardiner.

Gallatin National Forest has allowed travertine mining on a little over 4 ha of public land. The remaining 32 ha of land is privately owned and inter-mixed with forest service property. Quarries have face depths ranging from 10-20 m, although thousands of tons of surface stone and soil have been removed to expose rock. Soil disturbance has facilitated non-native weed invasion, especially spotted knapweed and Dalmatian toadflax, in the quarries and on access roads.

Transportation and Recreation

Montana Highway 89 bisects the Gardiner Basin. This is the primary road from Livingston, Montana to Gardiner. Agricultural operations and private homes are located along this road corridor, mostly on the floodplain and river terraces. Several county roads parallel the Yellowstone River and provide access to public land.

Ten National Forest Service trailheads are located within the Gardiner Basin, 4 of which are directly off of Highway 89. Six others are accessible from county roads. These trailheads provide access for hikers, horseback riders, and hunters to the Absaroka-Beartooth Wilderness, National Park and Forest Service lands.

Three developed fishing access and boat entry areas on Highway 89 provide access to the Yellowstone River. Also, there are 3 "Watchable Wildlife" pull-outs and 2 family picnic areas along Highway 89. Some of these sites have restrooms, parking areas, and visitor-created trails to the Yellowstone River or surrounding areas. There is only 1

National Forest campground directly on Highway 89, but 4 others can be accessed from county roads in the Gardiner Basin. These sites are used by visitors to National Forest lands and to Yellowstone National Park.

Prescribed Burning

During 1977-1982, the U.S. Forest Service burned more than 809 ha of sagebrush/grassland in the Gardiner Basin in an effort to improve wildlife winter range and domestic livestock grazing (D. Tyers, U.S. Forest Service, personal communication). Various wildlife winter range units and livestock allotments were burned, with sizes of burns ranging from spot burns to more than 20 ha. A goal of the prescribed burning was to increase forage on public lands to lessen impacts of wintering wildlife on private land.

METHODS

Weed Mapping

In 1999, Gardiner Ranger District of the Gallatin National Forest, in cooperation with the MDFWP, began mapping the distribution and cover of 4 weed species on federal and state land in the Gardiner Basin. Mapping was limited to the Gardiner Basin, a common study boundary for numerous Forest Service studies (D. Tyers, US Forest Service, personal communication). Weed mapping techniques were based on the *Montana Noxious Weed Survey and Mapping System* published by the Department of Plant, Soil, and Environmental Sciences at Montana State University (Cooksey and Sheley 1998). Weed distribution maps were created during the summer of 1999 and summer/fall of 2000. Infestation boundaries were identified and hand-drawn on mylar-covered aerial photographs and on 1:24,000 topographic maps. Geographic Positioning Systems (GPSs) were used to record Universal Transverse Mercator (UTM) coordinates for weed infestations. Weed species distributions were recorded for the 4 most prevalent species in the study area: cheatgrass, hound's-tongue, spotted knapweed, and Dalmatian toadflax.

Cover class (percent of ground infested) for each infestation was estimated as Trace (0-1%), Low (1-5%), Moderate (5-25%), or High (25-100%). Each area of infestation was also classified as a point, polygon or line. Polygons were drawn to surround large infestations of weeds (> 10 meter radius). Lines indicated a linear weed infestation, and the width of the line was recorded. Points were recorded for small

disjunct weed patches. Weed distribution maps were transferred to digital orthophotos using ArcView (ESRI 1998) GIS (Cooksey and Sheley 1998). A data layer was created for each weed species and included cover class and patch size attributes.

Accuracy Assessment of Weed Map

In the fall of 2000, the reliability of the weed distribution maps was assessed. My goal was to attain moderate to high accuracy and detail. According to Cooksey and Sheley (1998), a high level of accuracy requires intensive mapping techniques using survey methods often based on grid patterns; 80-100% accuracy is expected when mapping at this level. The moderate level of accuracy needs less intensive mapping techniques and is expected to result in a 60-80% accuracy level. Due to the large study area, I was willing to accept an accuracy level of 60-80%.

Accuracy was assessed by selecting random point locations from the weed distribution map. According to Van Genderen (1977), Tortora (1978), and Hay (1979), 50 point locations per weed species is sufficient to determine map accuracy. A total of 250 random points were generated from the study area; 50 points were drawn for each of the 4 weed species, and 50 points for areas mapped as weed free. Each weed or no-weed point was at least 10 m from any other point to minimize overlap in the 7-8 m circle examined to verify presence or absence of weeds.

UTM coordinates were obtained for each random point from the ArcView program *Animal Movement Extension to Arcview* (Hooze & Eichenlaub 1997). All random points were located on the ground using the same GPS units used in initial

mapping efforts. At each random point visited, weed presence or absence, cover type (Mattson and Despain 1985), disturbance type, burn evidence, and percent of bare ground were recorded. These data were compared with digitized weed map values in an error matrix (Story and Congalton 1986) indicating the user's, producer's, and overall accuracy. The producer's accuracy indicates the probability that a mapped weed infestation is classified correctly. The producer's accuracy is calculated by dividing the number of correctly classified points for each weed species by the total number of actual weed points seen on the ground, then multiplying by 100. The user's accuracy indicates the reliability of the weed map, or how well the map represents what is really on the ground. This accuracy is calculated by dividing the number of correctly predicted weed points by the total number of weed points predicted (50), and multiplying by 100. Overall accuracy is the total number of correctly predicted weed locations for all species, divided by the total number of points (250), and multiplied by 100. The overall accuracy gives a general accuracy estimate (Congalton 1991).

Wildlife Location Data Layers

Radio telemetry locations of elk (1970s-2000), mule deer (1986-2000) and bighorn sheep (1979-2000) have been collected in several studies in the Gardiner Basin: The Fish and Wildlife Management Program at Montana State University, U.S. Geological Survey (USGS) Northern Rocky Mountain Science Center, NPS, USFS, and MDFWP have collaborated in data collection. All wildlife telemetry locations have been digitized to create a GIS distribution layer (made up of data points) for each species. Each

GIS data point represents a single animal or a group location. Individual species data layers have an attribute table with the number of animals in each group, and, in most cases, the age group and sex composition. For this study, each point location represents the presence of the species. A 30m buffer was created around each of these locations. In an accuracy assessment conducted on mule deer locations from 1994 - 1997, 78% of locations were within 30 m of the UTM points (Olexa 2000). I assumed the same level of accuracy for elk and sheep layers.

Physiographic and Cultural Data Layers

The GIS data layers used in this study were based on a 1:24,000 mapping scale. All data layers were verified using site visits. Data sets were available in raster or vector format for ArcInfo and ArcView. Data sets were used with permission from the Gallatin National Forest's GIS Library (Appendix A for detailed descriptions). Geographic and environmental data layers used as potential explanatory variables to describe weed distribution include: elevation, cover type, and distances to highways, roads, recreation sites, river, streams, grazing allotments, mining quarry, trails, and sagebrush burns (Table 1).

Table 1. Geographic and environmental GIS data layer descriptions.

Data layer	Description
Elevation	Derived from a 10-m digital elevation model (DEM)
Cover type	Mattson and Despain's cover type classifications (1985)
Highway	Linear coverage of highways on Gallatin National Forest (GNF)
Roads	Linear coverage of roads on the GNF
Recreation sites	Campgrounds, trailheads, fishing accesses, and picnic areas
River	Linear coverage of the Yellowstone River on the GNF
Streams	Linear coverage of streams throughout the GNF
Grazing allotments	Polygon coverage of grazing allotments on the GNF
Mining quarry	Polygon coverage of the travertine mine footprint on the GNF
Trails	Linear coverage of the GNF trail system
Sagebrush burns	Polygon coverage of prescribed and wildfires in sagebrush covertypes, 1960-1992

Cover Types

I modified the vegetation cover map for the Gardiner Basin using the map originally constructed for the grizzly bear Cumulative Effects Model (CEM) in the Greater Yellowstone Ecosystem (GYE) (Mattson and Despain 1985). I reclassified the CEM cover types into 10 simplified cover types: dry sagebrush/open juniper woodland (CT1), moist sagebrush (CT2), wet grasslands/forb meadows (CT3), sparsely vegetated soils/talus slope (CT4), riparian areas (CT5), low to mid-elevation conifer forests (CT6), mid to high-elevation conifer forests (CT7), aspen forests (CT8), human-disturbed land (CT9), and avalanche chutes/cliffs (CT10) (See Appendix B for detailed cover type descriptions).

Analysis Methods

Plant and animal distributions can be mapped and modeled in numerous ways (Aspinall, 1999). GIS is a useful tool for creating simple distribution maps, as well as spatially explicit models. (Chicoine et al. 1985, Kurtz 1999, Farris et al. 1999). This study used GIS for both mapping and preparation for statistical analysis.

The program *Animal Movement Extension to Arcview* (Hooge & Eichenlaub 1997) was used to randomly sample weed and non-weed areas within the study area boundary. Only Forest Service lands were sampled; all private lands were excluded from the sampling universe. ArcView and ArcInfo were then used to determine elevation and cover type for each random location and calculate nearest distances (in meters) from the random weed points to all the explanatory variables (Table 1). One thousand random points were drawn for each weed species. A random set of 1,000 non-cheatgrass, non-hound's-tongue, non-toadflax, and non-spotted knapweed points (referred to as non-weed points) and their distances to each predictor variable was also drawn for comparison to weed points.

For this analysis, I made 3 critical assumptions about the finished weed maps. One was that the weed maps and GIS data layers were 100% accurate. This assumption was necessary in order to continue with analyses although it increased uncertainty in the finished weed probability maps. The second assumption was that areas mapped using low intensity surveys (mainly areas at high elevations) were as well mapped as areas that were intensively surveyed. This assumption was tenable because most weed infestations in the Gardiner Basin were in low elevation areas. The third assumption was that if a

weed was not found in a certain cover type, than that cover type was considered non-habitat for that weed. These cover types were then assigned a value of zero (meaning 0% probability of invasion) for the probability maps. Jointly, these assumptions allowed me to analyze my data as a valid case-control study, with random points having a value of 0 (non-weed point) assumed to have no weeds and those random points with a value 1 assumed to actually have weeds.

Weed Distribution Analysis

I used maximum likelihood logistic regression (Afifi and Clark 1990, SYSTAT 1996) to model distributions of the 4 weed species. Logistic regression uses a binary response variable (weed presence = 1, absence = 0) with an array of explanatory variables to model the probability of a weed species being present (Agresti 1996). I developed models *a priori* based on literature and my observations while mapping weeds. Burnham and Anderson (1998) advocate deliberate development of a set of *a priori* models, as opposed to searching the data for meaningful relationships and then creating models based on those results. I used Akaike's Information Criterion, AIC, (Burnham and Anderson 1998) to objectively rank the models. The most parsimonious model was selected as the one with the lowest AIC score. This model was then used as the reference, and other models were ranked and compared based on relative difference in AIC (ΔAIC). When ΔAIC values were less than or equal to 2, models were considered competitive. Models with a ΔAIC of 4 to 7 were considered potentially equivalent models, and those with a ΔAIC score >10 were considered inferior.

I developed 31 *a priori* models of weed distribution in the Gardiner Basin following Burnham and Anderson's (1998) guidelines for model building and ranking. The resulting models were statistically reasonable but logically flawed. Failure of these models was largely due to the high degree of correlation found among the variables. To assess correlation among explanatory variables, I developed a correlation matrix for the variables for each weed species. I also ran univariate analyses to determine the explanatory value of each variable.

I first used univariate logistic regression to evaluate effects of each variable and eliminate those that were clearly unassociated with weed distributions. I used the McFadden's rho-square (ρ^2) value to determine which variables to eliminate. McFadden's ρ^2 is a transformation of the log-likelihood ratio statistic and is intended to mimic an *r*-square value. McFadden's ρ^2 value is always between 0 and 1 with values closer to 1 indicating more explanatory power.

After examining the *a priori* logistic regression models, intercorrelation among variables and univariate logistic regression models, I developed 2 simplified models for each weed species. One model used the 2 variables that I classified as "habitat components" of weed distribution (elevation and cover type). I ran this constrained model type to examine the "habitat" components of weed spread separately and to identify the kinds of habitats that are susceptible to weed invasion, regardless of the means of spread. Assuming that weeds can reach suitable habitat, these models identified areas in the Gardiner Basin that are at risk based on only the cover type and/or elevation at that site.

Preliminary analysis showed that some weed species were not found in certain cover types. Because logistic regression does not allow for all "zeros" in modeling, I eliminated cover types that were not represented by presence of weeds from the probability models. By eliminating all the records for the cover types that were not represented, the sample size decreased. This did not cause any problems in the analysis because of the large sample size (pixels on a digital map) I had available. The cover types that were left out were obviously valuable for predicting weed absence and were incorporated in predictive models by assigning them a value of 0 and attaching this as a multiplicative term to the logistic regression models.

There were several cover types, different for each species, that were not represented in my sample of weed points. I checked ArcView and the original hand-drawn maps to verify that no points for a weed species were assigned to these cover types.

Cheatgrass

None of the 1,000 random points drawn from cheatgrass infestations fell in to cover types 5, 8, and 10. However, when I went back to the weed maps in ArcView, I found a few incidences of cheatgrass infestations within cover types 5, 8, and 10. Overlap between cheatgrass and these cover types was very small, and it was most likely due to digitizing errors. For example, in a small cheatgrass polygon that bordered the Yellowstone River, the cheatgrass polygon intersected with the river. Biologically, cheatgrass cannot grow under water, so it is likely that when the cheatgrass data layer was digitized boundary errors occurred. I believe that most, if not all, cheatgrass locations

in cover types 5, 8, and 10 were due to mapping and digitizing errors; therefore, these cover types were not used in the analysis of cheatgrass distribution.

Hound's-tongue

Cover type 10 was not represented in the sample of hound's-tongue distribution. I did not find any houndstongue infestations in cover type 10 when I examined the ArcView map or during field reconnaissance.

Spotted Knapweed

I checked the 4 cover types not represented in the sample of spotted knapweed infestations (3, 7, 8, and 10) in ArcView and found no incidences of spotted knapweed. If knapweed were present, field teams did not observe it.

Dalmatian Toadflax

The sample of 1,000 toadflax points did not have points that were within cover types 7 and 10. When I examined infestation boundaries in ArcView for toadflax, I found 2 instances where the polygon boundary overlapped from open vegetation in a draw into adjacent mid-level conifer forest (cover type 7). I believe that the overlap represented an error in mapping or digitizing, not in sampling. I found no toadflax in cover type 10.

The second type of model sets I tested included logical combinations of habitat and weed-spread variables. I assumed that weeds will invade suitable habitats when introduced to that habitat (via spread vectors). The simplified models developed from these analyses were then tested using logistic regression. The same set of rules for ranking models applied to the *a priori* models was applied to the simplified models. By

looking at simplified versions of the *a priori* models, I was able to address more specific questions that were still useful to land and wildlife managers.

Predictive Maps

Using the most parsimonious habitat and habitat + spread vector models for each weed species, I created 2 predictive models for each weed species distribution in the Gardiner Basin. One model included only the habitat variables, and the other included habitat and weed spread vectors. The models were projected using the "Map Calculator" function in ArcView. The resulting probability maps were then over-layed with each weed species distribution map to determine map accuracy. They were also used to make predictions for future spread of weeds.

In a study that uses simple random sampling, samples are drawn from a study area in proportion to their true distribution. However, this project was a case-control study, where random samples of equal size (1,000 points) were chosen from two strata, weeds or non-weeds, regardless of their true proportions in the study area. This created a biased estimate (β_0) of the logistic regression intercept parameter (β_0) which needed to be corrected before creating probability maps. I was able to calculate the bias of β_0 using the sampling fraction from the study area:

$$E(\beta_0) = \beta_0 + \ln\left(\frac{P_u}{P_{un}}\right)$$

where: P_u and P_{un} are sampling proportions for the used and unused (weed and non-weed) locations, such that $P_u = \frac{n_1}{N_1}$ and $P_{un} = \frac{n_0}{N_0}$, and N_1 and N_0 are the total numbers of used and unused pixels in the study area. This step was necessary in order to obtain true probabilities when I projected the probability maps.

Weeds and Ungulate Winter Range

I used winter and early spring radio telemetry locations for mule deer, elk, and bighorn sheep to determine their winter range boundary. I digitized polygons around the outer edge of each cluster of locations, omitting outliers and points outside the study area. I then used the current weed map to estimate the proportion of ungulate winter ranges currently infested by weeds. I used ArcView to calculate the area of winter range infested by invasive species. I then used the predictive maps to estimate potential future impacts. I used the Geoprocessing extension of ArcView to calculate four probability categories for weed invasion for each winter range, 0-25%, 25-50%, 50-75% and greater than 75%. This was done for each of the 8 probability maps that were created.

Effects of Prescribed Sagebrush Burns

The Gardiner Ranger District was interested in impacts of prescribed burns on weed invasions. I used my weed maps and error matrix data to compare weed coverages in burned versus unburned sage communities. Rather than sub-sample and use a conventional test of proportions, I used all sagebrush pixels in burned and unburned areas and I calculated an error range for each weed species. It is important to note that this was

a descriptive, rather than inferential, method of studying the effects of prescribed burns on weed distribution. I determined the high end of the error range using the number of times a weed was found in an area that was mapped as having no weeds. I determined the low end of the error range by using the user's accuracy. These values, expressed as percentages, were multiplied by the percentage cover indicated on my weed maps and added (high end) or subtracted (low end) from the percentage estimates for each weed species. If error ranges from unburned and burned sites overlapped, I assumed there was no difference in distribution of the weed associated with prescribed burns. If the error ranges did not overlap, I assumed that burned and unburned sites differed in weed coverage.

RESULTS

Accuracy Assessment of Weed Map

For each weed species and for non-weed areas, 50 random points were drawn from the weed maps to determine map accuracies. All 250 random points were visited on the ground. Mapping accuracy ranged from 70 – 86% from the user's standpoint, and 60 – 97% from the producer's standpoint (Table 2). Overall accuracy of the weed map was 75%, a moderate level of accuracy according to the Montana Noxious Weed Survey and Mapping System's standards (Cooksey and Sheley 1998).

Cheatgrass was the most accurately mapped weed species, with a producer's accuracy of 60%. There were 2 locations where hound's-tongue was found in place of cheatgrass, and 5 where no weeds were present. User's accuracy for cheatgrass was 86%. Spotted knapweed had a user's accuracy of 72%, meaning the user of the map can be 72% confident that when the map indicates the presence of spotted knapweed, then spotted knapweed will actually be present. The producer's accuracy was 90%. The user's accuracy of hound's-tongue was 70%, and the producer's accuracy was 81%. Toadflax had the highest producer's accuracy of 97% and a user's accuracy of 72%. Points that were mapped weed free had user's and producer's accuracies of 76% and 66%, respectively.

Table 2. Error matrix from the accuracy assessment of the weed map.

	Mapped Points					Total	User's Accuracy	Producers's Accuracy	Overall Accuracy
	Cheatgrass	Knapweed	Hound's-tongue	Toadflax	No Weeds				
	Actual Points								
Cheatgrass	43	0	2	0	5	50	86%	60%	
Spotted Knapweed	7	36	0	0	7	50	72%	90%	
Houndstongue	11	1	35	1	2	50	70%	81%	
Dalmatian Toadflax	7	1	0	36	6	50	72%	97%	
No Weeds	4	2	6	0	38	50	76%	66%	
Total	72	40	43	37	58	250			75%

Unconstrained *A Priori* Models

None of the *a priori* models I developed had meaningful results due largely to the high degree of correlation among the variables. These models were superficially good, exhibiting low AIC values and high McFadden's ρ^2 values. On closer examination, the coefficients for the variables did not make biological sense. For example, in the cheatgrass global model (one including all of the variables), variables measuring distance to highways, roads, and recreation sites all had positive coefficients meaning that areas closer to roads, highways, and recreation sites had less cheatgrass than areas farther from these variables. These results contradict our knowledge of spread vectors. Coefficients for quantitative variables were also close to zero, suggesting that none of them had much effect compared to habitat (qualitative variables). In addition, almost all of the confidence intervals for the odds ratios of each variable encompassed 1, meaning that I could not be sure that these variables were explaining anything.

Constrained Models

Univariate Models

Attempts to model distributions of the 4 weed species using *a priori* models did not yield meaningful results I, therefore, adopted an approach based on simpler models, with emphasis on reducing multi-collinearity within a model. I created these models after examining the results of univariate analyses of the variables and a correlation matrix showing relationships among variables. I then chose variables for each model that were not highly correlated and that had moderate to good explanatory value.

Based on the correlation matrices (Tables 3, 4, 5, and 6) and a univariate analysis of each variable (Tables 7, 8, 9, and 10), I reduced the number of covariates eligible for inclusion in each model. Variables that were removed varied among weed species. For example, McFadden's $\rho^2 = 0.005$ for trails in the cheatgrass univariate models, so the trail variable was not used in any of the cheatgrass models. I removed trails ($\rho^2 = 0.04$), and mining ($\rho^2 = 0.009$) from the hound's-tongue analysis. Trails ($\rho^2 = 0.013$) and streams ($\rho^2 = 0.034$) were removed from the toadflax models. I eliminated trails ($\rho^2 = 0.004$) and mining ($\rho^2 = 0.02$) from the spotted knapweed models. Because of the high correlation between wildlife telemetry locations and most other variables, wildlife (bighorn sheep, elk, and deer) telemetry locations were excluded from all models.

Cover type was consistently the least correlated with the other variables for all weed species. It also had a high McFadden's ρ^2 , meaning that its explanatory value was very high.

Table 3. Correlation matrix of variables for cheatgrass models. Refer to Table 1 for definitions.

	SAGE	TRLS	RDS	RIVER	DEER	ELK	STMS	REC	HIGH	ALLOT	SHEEP	MINE	CT2	CT3	CT4	CT6	CT7	CT9	ELEV
SAGE	1.00																		
TRLS	0.05	1.00																	
RDS	0.60	-0.20	1.00																
RIVER	0.89	0.01	0.57	1.00															
DEER	0.68	0.26	0.35	0.62	1.00														
ELK	0.71	0.13	0.12	0.72	0.59	1.00													
STMS	0.17	0.30	0.19	0.21	0.15	0.13	1.00												
REC	0.44	0.13	0.61	0.57	0.23	0.31	0.26	1.00											
HIGH	0.74	-0.05	0.60	0.88	0.46	0.53	0.19	0.60	1.00										
ALLOT	-0.30	-0.22	0.00	-0.23	-0.37	-0.33	-0.15	-0.16	0.11	1.00									
SHEEP	0.80	-0.01	0.63	0.87	0.54	0.41	0.21	0.48	0.77	-0.27	1.00								
MINE	0.14	-0.05	0.21	0.14	0.17	-0.07	0.15	0.22	0.07	-0.68	0.30	1.00							
CT2	-0.11	-0.01	-0.09	-0.11	-0.10	-0.09	-0.01	-0.07	-0.10	0.05	-0.09	-0.05	1.00						
CT3	0.01	-0.01	0.03	0.03	-0.02	-0.03	0.04	0.03	0.03	0.00	0.06	0.03	-0.03	1.00					
CT4	0.22	0.03	0.21	0.22	0.17	0.12	0.08	0.22	0.22	-0.06	0.17	0.10	-0.04	-0.03	1.00				
CT6	0.22	0.05	0.15	0.29	0.11	0.10	0.13	0.18	0.31	-0.13	0.35	0.19	-0.10	-0.06	-0.10	1.00			
CT7	0.51	0.00	0.39	0.52	0.35	0.39	0.17	0.38	0.46	-0.14	0.43	0.13	-0.09	-0.05	-0.09	-0.20	1.00		
CT9	-0.10	0.00	-0.09	-0.11	-0.05	-0.06	-0.09	-0.08	-0.12	0.00	-0.10	-0.01	-0.04	-0.02	-0.04	-0.10	-0.08	1.00	
ELEV	0.71	0.021	0.68	0.829	0.452	0.43	0.372	0.63	0.825	-0.03	0.75	0.1	-0.08	0.05	0.27	0.29	0.52	-0.13	1.00

Table 4. Correlation matrix of variables for hound's-tongue models. Refer to Table 1 for definitions.

	SAGE	TRLS	RDS	RIVER	DEER	ELK	STMS	REC	HIGH	ALLOT	SHEEP	MINE	ELEV	CT2	CT3	CT4	CT5	CT6	CT7	CT8	CT9
SAGE	1.00																				
TRLS	-0.04	1.00																			
RDS	0.51	-0.18	1.00																		
RIVER	0.86	-0.10	0.55	1.00																	
DEER	0.49	0.26	0.30	0.47	1.00																
ELK	0.70	0.09	0.03	0.70	0.45	1.00															
STMS	0.11	0.16	0.26	0.12	-0.02	0.03	1.00														
REC	0.30	0.13	0.60	0.47	0.04	0.12	0.26	1.00													
HIGH	0.76	-0.11	0.57	0.92	0.38	0.53	0.11	0.50	1.00												
ALLOT	0.05	-0.23	0.15	0.09	-0.16	-0.19	0.00	-0.05	0.32	1.00											
SHEEP	0.66	-0.12	0.63	0.84	0.36	0.33	0.07	0.49	0.82	0.09	1.00										
MINE	-0.35	0.03	0.10	-0.19	0.08	-0.34	-0.07	0.11	-0.16	-0.51	0.06	1.00									
ELEV	0.60	-0.08	0.71	0.76	0.28	0.33	0.36	0.61	0.82	0.36	0.67	-0.19	1.00								
CT2	-0.16	0.01	-0.12	-0.16	-0.09	-0.08	-0.06	-0.10	-0.17	-0.02	-0.14	-0.01	-0.16	1.00							
CT3	0.06	-0.05	-0.01	0.08	0.01	0.06	-0.02	-0.02	0.06	-0.02	0.06	-0.02	0.03	-0.04	1.00						
CT4	0.17	0.02	0.24	0.18	0.11	0.08	0.06	0.27	0.19	0.02	0.13	0.03	0.26	-0.07	-0.03	1.00					
CT5	-0.01	0.01	-0.01	0.00	0.02	0.03	0.02	0.02	0.00	-0.04	-0.03	0.04	0.00	-0.01	0.00	-0.01	1.00				
CT6	0.06	0.01	0.01	0.11	0.02	0.03	0.05	-0.01	0.17	0.10	0.13	-0.03	0.10	-0.19	-0.07	-0.13	-0.02	1.00			
CT7	0.37	-0.03	0.36	0.38	0.18	0.21	0.13	0.32	0.38	0.09	0.30	-0.04	0.43	-0.12	-0.04	-0.08	-0.01	-0.23	1.00		
CT8	0.10	0.08	0.10	0.10	0.09	0.05	0.07	0.10	0.13	0.03	0.13	0.00	0.14	-0.06	-0.02	-0.04	-0.01	-0.11	-0.07	1.00	
CT9	-0.04	-0.01	-0.05	-0.05	-0.05	-0.02	-0.06	-0.01	-0.05	-0.04	-0.03	0.03	-0.07	-0.02	-0.01	-0.02	0.00	-0.05	-0.03	-0.01	1.00

Table 5. Correlation matrix of variables for spotted knapweed models. Refer to Table 1 for definitions.

	SAGE	TRLS	RDS	RIVER	DEER	ELK	STMS	REC	HIGH	ALLOT	SHEEP	MINE	ELEV	CT2	CT4	CT5	CT6	CT9
SAGE	1.00																	
TRLS	0.19	1.00																
RDS	0.71	-0.08	1.00															
RIVER	0.82	0.08	0.73	1.00														
DEER	0.46	0.34	0.19	0.34	1.00													
ELK	0.58	0.30	0.20	0.61	0.44	1.00												
STMS	0.23	0.30	0.34	0.37	-0.07	0.20	1.00											
REC	0.61	0.22	0.71	0.75	0.07	0.45	0.50	1.00										
HIGH	0.76	0.06	0.70	0.96	0.26	0.55	0.33	0.71	1.00									
ALLOT	0.04	-0.07	0.16	0.22	-0.29	-0.06	0.23	0.15	0.37	1.00								
SHEEP	0.71	0.00	0.72	0.87	0.29	0.27	0.29	0.60	0.83	0.15	1.00							
MINE	-0.08	-0.21	-0.01	-0.15	0.27	-0.16	-0.33	-0.20	-0.19	-0.75	0.00	1.00						
ELEV	0.68	0.11	0.76	0.88	0.16	0.42	0.54	0.77	0.89	0.40	0.75	-0.29	1.00					
CT2	-0.11	0.03	-0.05	-0.03	-0.12	-0.05	0.17	0.01	-0.03	0.18	-0.04	-0.21	0.04	1.00				
CT4	0.29	0.06	0.27	0.26	0.19	0.26	0.14	0.27	0.22	0.02	0.14	-0.05	0.30	-0.05	1.00			
CT5	0.00	-0.02	-0.02	-0.01	0.00	-0.02	-0.04	0.01	-0.01	-0.03	-0.01	0.03	-0.03	-0.01	-0.01	1.00		
CT6	0.30	0.04	0.30	0.42	-0.02	0.17	0.23	0.32	0.46	0.18	0.42	-0.09	0.45	-0.08	-0.10	-0.02	1.00	
CT9	-0.11	-0.20	-0.09	-0.13	-0.12	-0.10	-0.16	-0.16	-0.14	-0.09	-0.02	0.12	-0.16	-0.04	-0.05	-0.01	-0.08	1.00

Table 6. Correlation matrix of variables for toadflax models. Refer to Table 1 for definitions.

	SAGE	TRLS	RDS	RIVER	DEER	ELK	STMS	REC	HIGH	ALLOT	SHEEP	MINE	ELEV	CT2	CT3	CT4	CT5	CT6	CT8	CT9
SAGE	1																			
TRLS	0.13	1																		
RDS	0.67	-0.13	1																	
RIVER	0.88	0.08	0.6	1																
DEER	0.69	0.22	0.42	0.66	1															
ELK	0.65	0.27	0.13	0.67	0.56	1														
STMS	0.11	0.25	0.15	0.12	0.05	0.08	1													
REC	0.56	0.17	0.64	0.6	0.31	0.37	0.2	1												
HIGH	0.79	-0.01	0.58	0.91	0.52	0.56	0.04	0.55	1											
ALLOT	-0.46	-0.35	-0.27	-0.41	-0.44	-0.4	-0.27	-0.5	-0.1	1										
SHEEP	0.83	0.07	0.66	0.89	0.59	0.41	0.16	0.55	0.78	-0.48	1									
MINE	0.45	0.08	0.46	0.46	0.37	0.14	0.22	0.54	0.37	-0.74	0.59	1								
ELEV	0.75	0.09	0.66	0.84	0.51	0.44	0.28	0.63	0.83	-0.29	0.77	0.45	1							
CT2	-0.09	-0.01	-0.07	-0.08	-0.09	-0.05	0	-0	-0.1	0	-0.05	-0.03	-0.08	1						
CT3	0.09	-0.06	0.06	0.11	0.05	0.05	0.01	0.07	0.07	-0.11	0.11	0.13	0.09	-0.03	1					
CT4	0.25	0.02	0.22	0.25	0.24	0.23	0.09	0.27	0.24	-0.17	0.17	0.21	0.3	-0.06	-0	1				
CT5	-0.05	-0.02	-0.04	-0.06	-0.05	-0.04	0.01	-0	-0.1	0.05	-0.06	-0.05	-0.06	-0.02	-0	-0.03	1			
CT6	0.47	0.06	0.31	0.49	0.23	0.27	0.09	0.3	0.47	-0.31	0.53	0.4	0.47	-0.12	-0.1	-0.13	-0.1	1		
CT8	0.08	-0.01	0.1	0.07	0.03	0.03	0.05	0.1	0.07	-0.03	0.08	0.04	0.11	-0.05	-0	-0.05	-0	-0.1	1	
CT9	-0.03	-0.01	-0.04	-0.06	-0.03	-0.03	-0.04	-0.1	-0.1	0	-0.05	-0.01	-0.08	-0.02	-0	-0.02	-0	-0	-0.02	1

Table 7. Cheatgrass univariate models with McFadden's rho-square (ρ^2) and the estimated coefficient for each variable from logistic regression analysis.

Parameter	ρ^2	Coefficients	SE
Sageburn	0.40	-1.00	0.06
Trails	0.01	-0.16	0.05
River	0.53	-0.98	0.06
Roads	0.18	-0.94	0.06
Streams	0.10	-2.40	0.19
Recreation Sites	0.21	-0.69	0.04
Highways	0.36	-0.52	0.03
Allotments	0.07	0.11	0.01
Mining	0.08	-0.10	0.01
Elevation	0.51	-8.10	0.42
Sheep	0.48	-0.83	0.04
Deer	0.12	-1.00	0.08
Elk	0.18	-0.86	0.08

Table 8. Hound's-tongue univariate models with McFadden's rho-square (ρ^2) and the estimated coefficient for each variable from logistic regression analysis.

Parameter	ρ^2	Coefficients	SE
Sageburn	0.17	-0.40	0.03
Trails	0.01	-0.13	0.05
River	0.27	-0.42	0.02
Roads	0.20	-1.10	0.07
Streams	0.07	-2.00	0.17
Recreation Sites	0.16	-0.54	0.04
Highways	0.36	-0.52	0.03
Allotments	0.06	-0.13	0.01
Mining	0.01	0.03	0.01
Elevation	0.39	-6.35	0.33
Sheep	0.20	-0.38	0.02
Deer	0.04	-0.43	0.05
Elk	0.04	-0.17	0.02

Table 9. Spotted knapweed univariate models with McFadden's rho-square (ρ^2) and the estimated coefficient for each variable from logistic regression analysis.

Parameter	ρ^2	Coefficients	SE
Sageburn	0.23	-0.77	0.05
Trails	0.01	-0.16	0.05
River	0.74	-2.44	0.17
Roads	0.53	-4.75	0.32
Streams	0.20	-3.33	0.21
Recreation Sites	0.40	-1.15	0.06
Highways	0.65	-1.45	0.09
Allotments	0.05	-0.11	0.01
Mining	0.02	0.05	0.01
Elevation	0.73	-12.20	0.76
Sheep	0.53	-1.24	0.07
Deer	0.004	-0.15	0.06
Elk	0.07	-0.41	0.05

Table 10. Toadflax univariate models with McFadden's rho-square (ρ^2) and the estimated coefficient for each variable from logistic regression analysis.

Parameter	ρ^2	Coefficients	SE
Sageburn	0.58	-2.51	0.16
Trails	0.02	-0.38	0.07
River	0.46	-1.07	0.07
Roads	0.21	-1.45	0.10
Streams	0.04	-1.39	0.17
Recreation Sites	0.28	-1.02	0.06
Highways	0.26	-0.48	0.03
Allotments	0.39	-0.37	0.02
Mining	0.50	0.43	0.02
Elevation	0.44	-8.57	0.47
Sheep	0.67	-2.05	0.14
Deer	0.20	-2.26	0.17
Elk	0.19	-1.22	0.10

Results from the cheatgrass cover type model showed that the odds of cheatgrass being found in types other than dry sagebrush/open juniper woodlands were less than 1 for all cover types except the “human disturbance” type (Table 11). In this type, the odds of cheatgrass occurring were not significantly different from the dry sagebrush/open juniper woodland cover type (95% CI = 0.579 – 3.316). Low odds ratios for all types indicated that cheatgrass presence was most associated with dry sagebrush/open juniper woodland and human disturbed land types.

Table 11. Results of cheatgrass cover type model odds ratios, referenced to cover type 1 (CT 1, dry sagebrush/open juniper woodlands)

Parameter	Odds Ratio	95% CI	
		Lower	Upper
CT2 (Moist sagebrush)	0.253	0.149	0.430
CT3 (Wet meadows)	0.082	0.035	0.193
CT4 (Exposed bedrock)	0.020	0.009	0.048
CT6 (Low-mid conifer forest)	0.001	0.000	0.006
CT7 (Mid-high conifer forest)	0.003	0.001	0.009
CT9 (Human disturbed land)	1.386	0.579	3.316

Only the moist sagebrush cover type was significantly more likely to have hound's-tongue than the reference type, dry sagebrush/open juniper woodland (Table 12). Odds of occurrence in riparian and human disturbed areas were not significantly different from the reference type. All other types were less likely to have hound's-tongue than the reference type.

Table 12. Results of hound's-tongue cover type model odds ratios, referenced to cover type 1 (CT1, dry sagebrush/open juniper woodland)

Parameter	Odds Ratio	95% CI	
		Lower	Upper
CT2 (Moist sagebrush)	1.827	1.132	2.950
CT3 (Wet meadow)	0.181	0.072	0.456
CT4 (Exposed bedrock)	0.065	0.034	0.127
CT5 (Riparian areas)	0.362	0.023	5.824
CT6 (Low-mid conifer forest)	0.180	0.138	0.235
CT7 (Mid-high conifer forest)	0.023	0.013	0.043
CT8 (Aspen forest)	0.111	0.057	0.218
CT9 (Human disturbed land)	1.449	0.305	6.890

Human disturbed lands were much more likely to have spotted knapweed than was the reference type (Table 13). The reference type, dry sagebrush/open juniper woodlands, had the next highest odds of spotted knapweed infestation. Odds of occurrence in riparian areas were not significantly different from the reference type. Moist sagebrush shrublands, exposed bedrock/unvegetated soils, and low-mid elevation conifer forests had significantly lower odds of supporting spotted knapweed than dry sagebrush/open juniper woodlands.

No cover type had greater odds of supporting toadflax than the reference type (Table 14). Odds ratios for riparian areas and human disturbed lands were not significantly different from dry sagebrush/open juniper woodlands. All other types had lower odds of toadflax occurrence than the reference type.

Table 13. Results of spotted knapweed cover type model. Odds ratios referenced to cover type 1 (CT1, dry sagebrush/open juniper woodlands)

Parameter	Odds Ratio	95% C.I.	
		Lower	Upper
CT2 (Moist sagebrush)	0.429	0.240	0.769
CT4 (Exposed bedrock)	0.150	0.089	0.254
CT5 (Riparian Areas)	0.790	0.071	8.745
CT6 (Low-mid conifer forest)	0.006	0.002	0.020
CT9 (Human disturbed land)	17.770	2.438	129.500

Table 14. Results of toadflax cover type model. Odds ratios referenced to cover type 1 (CT1, dry sagebrush/open juniper woodland)

Parameter	Odds Ratio	95% C.I.	
		Lower	Upper
CT2 (Moist sagebrush)	0.280	0.170	0.467
CT3 (Wet Meadows)	0.019	0.004	0.083
CT4 (Expsed Bedrock)	0.059	0.033	0.104
CT5 (Riparian Areas)	2.950	0.386	22.650
CT6 (Low-mid conifer forest)	0.001	0.000	0.006
CT8 (Aspen forest)	0.181	0.108	0.304
CT9 (Human Disturbed land)	0.844	0.178	4.017

Multivariate Models

Habitat Models

When only habitat and elevation were included as possible variables, the most parsimonious model for all weed species included both (Table 15). Univariate models had lower AIC scores than models that included both variables.

Table 15. Results of constrained (cover type and elevation only) cheatgrass, hound's-tongue, spotted knapweed and toadflax habitat models. Models are ranked by ΔAIC value with the lowest being the most parsimonious. McFadden's rho-square (ρ^2) is the amount of variation explained by the model.

Model	ρ^2	AIC	ΔAIC
<u>Cheatgrass</u>			
Elevation+Cover type	0.64	774.60	0.00
Cover type	0.54	989.48	214.88
Elevation	0.51	1034.82	260.22
<u>Hound's-tongue</u>			
Elevation+Cover type	0.43	1276.38	0.00
Cover type	0.39	1334.32	57.94
Elevation	0.23	1702.08	425.70
<u>Spotted Knapweed</u>			
Elevation+Cover type	0.75	461.34	0.00
Cover type	0.73	489.42	28.08
Elevation	0.24	1382.54	921.20
<u>Toadflax</u>			
Elevation+Cover type	0.57	853.26	0.00
Cover type	0.44	1063.82	210.56
Elevation	0.42	1107.88	254.62

Habitat + Spread Vector Models

Comparing multivariate models in which variable type was unrestricted, I found that the best model for cheatgrass contained cover type and distances to rivers, streams, and mining (Table 16). McFadden's ρ^2 indicated that 71% of the variation in the model was explained by these variables. This model was not only the most parsimonious, but it

was much better than the second best model (cover type, elevation, and distance to mining areas; $\Delta AIC = 44.66$).

The best unrestricted model for hound's-tongue included cover type and distances to highways, allotments, and streams (Table 17). This model had the lowest AIC score (1179.54) and the highest McFadden's ρ^2 (0.47). The second best model (ΔAIC 23.78) included all the variables in the best model except for grazing allotments but had a ΔAIC of 23.78 (Table 17).

A model with cover type and distances to streams, and rivers was the best model of spotted knapweed distribution in the Gardiner Basin (Table 18). The second best model included only cover type and distance to river and differed by only 4 AIC points from the best model, suggesting that it was a potential viable alternative. Adding distance to streams to the model increased McFadden's ρ^2 by only 0.02.

The most parsimonious model of toadflax distribution in the Gardiner Basin included cover type and distances to mining and rivers (Table 19). Although this model was far superior to the other models considered and seemed to make sense biologically, the second and third ranked models contained the variable distance to sagebrush burn and

Table 16. Results of multivariate models for cheatgrass. Models are ranked by ΔAIC value with the lowest being the most parsimonious. McFadden's rho-square (ρ^2) is the amount of variation explained by the model.

Model	ρ^2	AIC	ΔAIC
River+Stms+Cover+Mine	0.71	635.02	0.00
Cover+Elev+Mine	0.69	679.68	44.66
Cover+River+Stms	0.69	680.48	45.46
Elev+Cover+Stms	0.66	738.46	103.44
Cover+ Sage+Stms	0.65	760.38	125.36
High+Cover+Stms	0.63	808.90	173.88
Sage+Rec+Cover	0.62	831.80	196.79
Rds+Stms+Cover	0.60	861.38	226.36

Table 17. Results of multivariate models for hound's-tongue. Models are ranked by ΔAIC value with the lowest being the most parsimonious. McFadden's rho-square (ρ^2) is the amount of variation explained by the model.

Model	ρ^2	AIC	ΔAIC
Cover+High+Allot+Stms	0.47	1179.54	0.00
Cover+High+Stms	0.46	1203.32	23.78
Cover+Elev+Allot+Stms	0.44	1250.30	70.76
Cover+Elev+Stms	0.44	1259.42	79.88
Stms+High	0.43	1262.54	83.30
Cover+River+Stms	0.39	1358.86	179.32

Table 18. Results of multivariate models for knapweed. Models are ranked by ΔAIC value with the lowest being the most parsimonious. McFadden's rho-square (ρ^2) is the amount of variation explained by the model.

Model	ρ^2	AIC	ΔAIC
Cover+Stms+River	0.78	437.52	0.00
River+Cover	0.76	441.18	3.66
River+Streams	0.75	459.42	21.90
Stms+High	0.70	552.46	114.94
Sage+Cover+Stms	0.49	934.00	496.48

explained almost as much of the variation as the best model ($\rho^2 = 77$). I saw many toadflax infestations in previously burned sagebrush habitat while mapping suggesting that the best model may, in this case, have missed a potentially important variable. This failure was probably due to high correlation between the variable distance to sagebrush burn and distance to rivers.

Table 19. Results of multivariate models for toadflax. Models are ranked by ΔAIC value with the lowest being the most parsimonious. McFadden's rho-square (ρ^2) is the amount of variation explained by the model.

Model	ρ^2	AIC	ΔAIC
Mine+Cover+River	0.78	436.78	0.00
Cover+Sage+Allot	0.77	452.39	15.61
Sage+Mine+Cover	0.77	455.80	19.02
Allot+Rds+Cover	0.77	461.80	25.02
Mine+River	0.75	485.28	48.50
High+Cover+Mine	0.72	540.74	103.96
Sage+Mine	0.71	542.34	105.56
Sage+Allot	0.68	602.54	165.76

Predictive Models

Using the top habitat and habitat + spread vector models, I created 2 predictive models of weed distribution in the Gardiner Basin for each weed species. Tables (20 to 23) give the estimated coefficients for the variables in the top models, and the corrected estimate of the logistic regression intercept parameter. In the spotted knapweed and toadflax models, signs of coefficients for cover types changed between models. This was probably due to high correlation between individual cover types and variables in the model. For example, cover type 5 (riparian areas) had a negative coefficient in the spotted knapweed habitat model but a positive coefficient in the habitat + spread vector model.

Cover type 5 was more than likely highly correlated with river and streams in the habitat + spread vector model, which resulted in the sign change. Odds ratios for cover type 5 also greatly increased from 0.05 to 30.61; however, the confidence interval for the odds

Table 20. Estimated coefficients and 95% confidence intervals (CI) for variables used in habitat ($\rho^2 = 0.64$) and habitat + spread vector ($\rho^2 = 0.71$) predictive models of cheatgrass distribution in the Gardiner Basin.

Variable	Estimated coefficients	Odds ratio	95% C.I.	
			Lower	Upper
<u>Habitat model</u>				
Bias corrected constant	2.26			
Elevation	-5.62	0.003	0.001	0.01
CT2	-1.33	0.27	0.14	0.49
CT3	-1.50	0.22	0.08	0.63
CT4	-2.43	0.09	0.03	0.29
CT6	-5.33	0.005	0.001	0.02
CT7	-3.55	0.03	0.01	0.09
CT9	0.10	1.11	0.45	2.76
<u>Habitat + spread vector model</u>				
Bias corrected constant	3.54			
River	-0.68	0.51	0.44	0.58
Streams	-2.75	0.06	0.03	0.13
Mining	-0.11	0.90	0.87	0.93
CT2	-1.72	0.18	0.09	0.34
CT3	-1.47	0.23	0.06	0.84
CT4	-2.23	0.11	0.03	0.40
CT6	-4.93	0.01	0.002	0.03
CT7	-3.39	0.03	0.01	0.11
CT9	0.08	1.09	0.37	3.17

Table 21. Estimated coefficients and 95% confidence intervals for variables used in habitat ($\rho^2 = 0.43$) and habitat + spread vector ($\rho^2 = 0.47$) predictive models of hound's-tongue distribution in the Gardiner Basin.

Variable	Estimated coefficients	Odds ratio	<u>95% C.I.</u> Lower	Upper
<u>Habitat model</u>				
Bias corrected constant	0.94			
Elevation	-5.44	0.004	0.002	0.008
CT2	0.65	1.92	1.15	3.22
CT3	-0.92	0.39	0.13	1.18
CT4	-1.05	0.35	0.13	0.93
CT5	-0.33	0.72	0.001	439.19
CT6	-0.93	0.39	0.29	0.54
CT7	-1.92	0.15	0.07	0.30
CT8	-0.84	0.43	0.18	1.02
CT9	-0.23	0.79	0.15	4.27
<u>Habitat + spread vector model</u>				
Bias corrected constant	1.35			
Highways	-0.44	0.64	0.61	0.68
Allotments	-0.09	0.91	0.87	0.94
Streams	-2.49	0.08	0.05	0.13
CT2	0.67	1.96	1.14	3.37
CT3	-0.83	0.44	0.13	1.46
CT4	-1.23	0.29	0.11	0.72
CT5	-0.07	0.93	0.001	1476.79
CT6	-0.81	0.44	0.31	0.62
CT7	-2.23	0.10	0.05	0.22
CT8	-1.08	0.34	0.14	0.84
CT9	-0.29	0.74	0.13	4.35

ratio was very wide, indicating little confidence in the cover type being important in the habitat + spread vector model.

I used both model types to map probability of occurrence for the 4 weed species in the Gardiner Basin. I categorized maps into 4 probability zones: 0-25%, 25-50%, 50-75%, and 75%+. Some maps did not entirely include current weed distribution in the

Table 22. Estimated coefficients and 95% confidence intervals for variables used in habitat ($\rho^2 = 0.75$) and habitat + spread vector ($\rho^2 = 0.76$) predictive models of spotted

Variable	Estimated coefficients	Odds ratio	Lower	95% C.I.	Upper
<u>Habitat model</u>					
Bias corrected constant	1.79	4.56			
Elevation	-12.38	0.000	0.000		0.000
CT2	0.59	1.81	0.83		3.98
CT4	-0.37	0.69	0.23		2.06
CT5	-2.92	0.05	0.003		0.82
CT6	-3.84	0.02	0.004		0.11
CT9	-0.57	0.57	0.07		4.43
<u>Habitat + spread vector model</u>					
Bias corrected constant	1.30				
River	-2.15	0.12	0.08		0.17
Streams	-0.97	0.38	0.17		0.85
CT2	0.13	1.14	0.48		2.69
CT4	-0.46	0.63	0.20		1.90
CT5	3.42	30.61	0.00		123.18
CT6	-3.56	0.03	0.01		0.13
CT9	-0.08	0.92	0.12		7.09

predicted coverage. Models with only habitat variables more accurately predicted current distributions of all weed species than the habitat + spread vector models (Fig. 4, 6, 8, 10). The habitat + spread vector models varied in predictive capabilities among weed species (Fig. 3, 5, 7, 9).

The cheatgrass habitat + spread vector map captured almost all of the current cheatgrass polygons within the higher probability zones (50-75%, 75%+) (Fig. 3). There were a few places where cheatgrass existed in the low probability zone (0-25%). These

Table 23. Estimated coefficients and 95% confidence intervals for variables used in habitat ($\rho^2 = 0.57$) and habitat + spread vector ($\rho^2 = 0.78$) predictive models of toadflax distribution in the Gardiner Basin.

Variable	Estimated coefficients	Odds ratio	Lower	95% C.I.	Upper
<u>Habitat model</u>					
Bias corrected constant	2.72	4.30			
Elevation	-6.08	0.002	0.001		0.006
CT2	-1.29	0.27	0.15		0.49
CT3	-2.85	0.06	0.01		0.27
CT4	-1.50	0.22	0.10		0.51
CT5	0.82	2.27	0.28		18.15
CT6	-5.30	0.005	0.001		0.02
CT8	-0.63	0.53	0.27		1.05
CT9	-1.13	0.32	0.06		1.70
<u>Habitat + spread vector model</u>					
Bias corrected constant	4.50				
River	-1.01	0.37	0.28		0.47
Mining	-0.39	0.68	0.64		0.72
CT2	-1.94	0.14	0.06		0.32
CT3	-2.12	0.12	0.01		1.73
CT4	0.07	1.07	0.22		5.19
CT5	-0.03	0.97	0.11		8.51
CT6	-3.74	0.02	0.01		0.11
CT8	-0.72	0.48	0.17		1.40
CT9	0.01	1.00	0.06		15.76

sites were adjacent to private lands that could have had variables related to spread but were not included in the GIS layers I had available.

The hound's-tongue habitat + spread vector map did not predict current hound's-tongue distribution well (Fig. 5). Although many current infestations fell within higher probability zones, almost half fell in lower probability zones (0-25% and 25-50%).

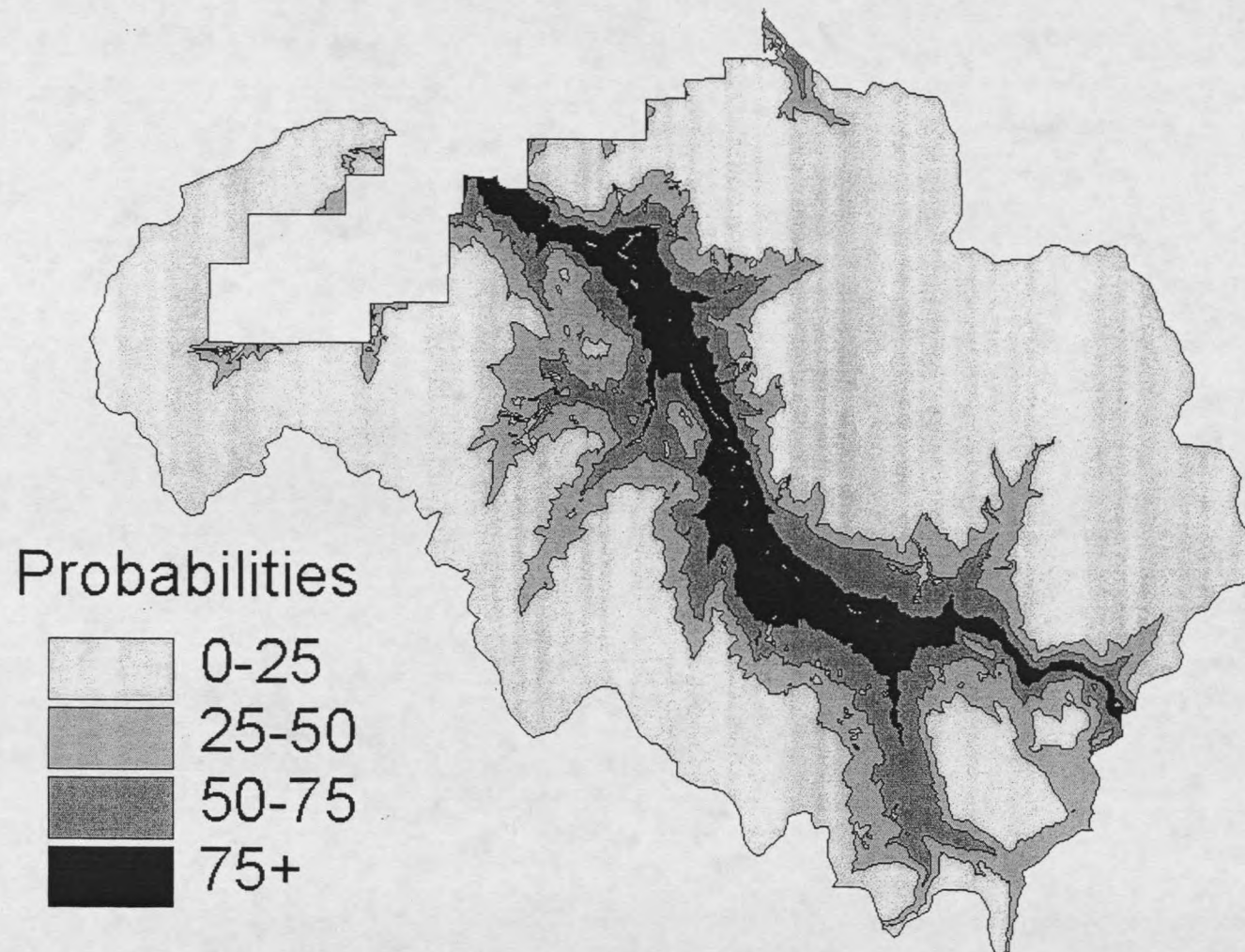


Figure 3. Cheatgrass habitat probability map.

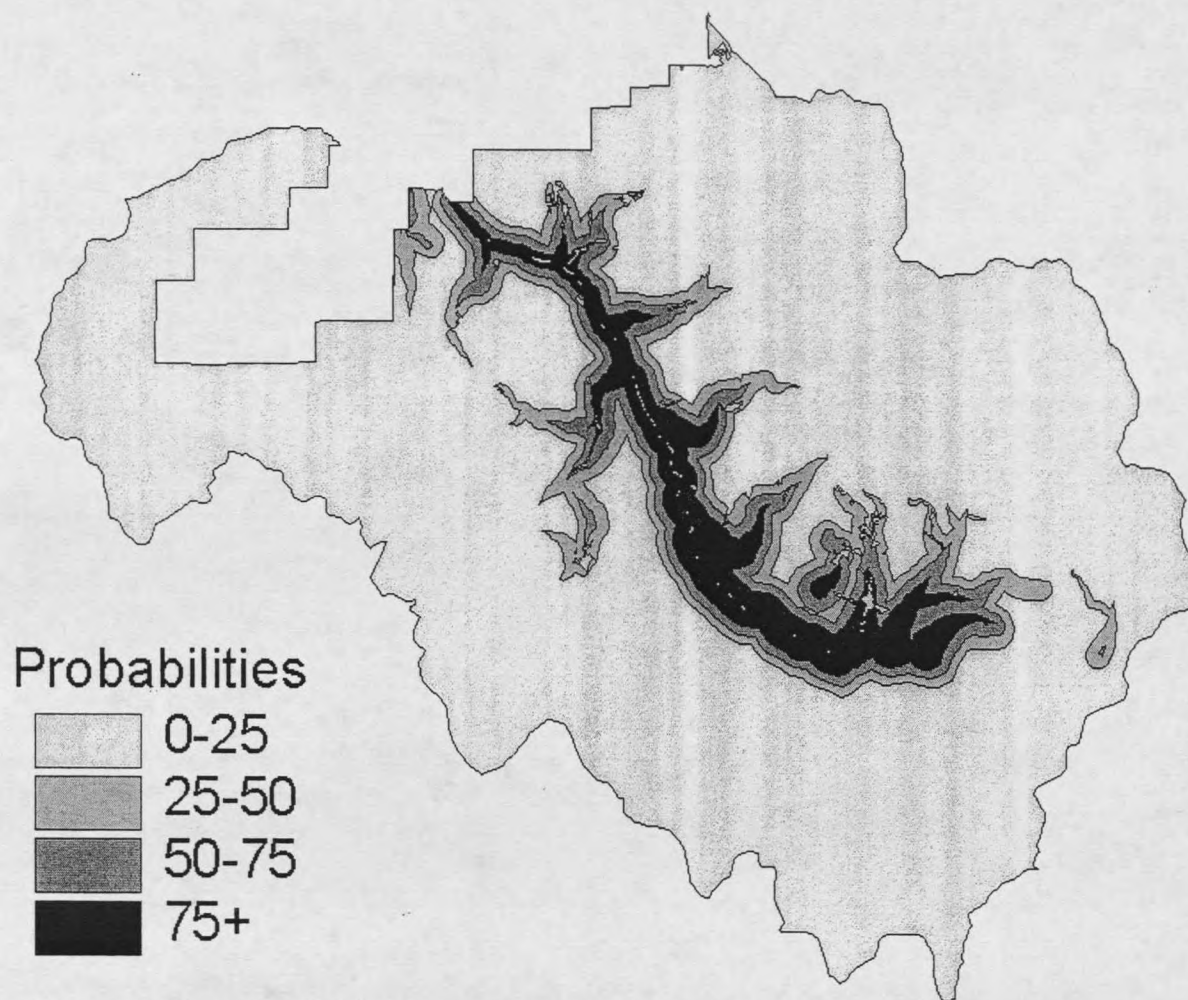


Figure 4. Cheatgrass habitat + spread vector probability map.



Figure 5. Hound's-tongue habitat probability map.

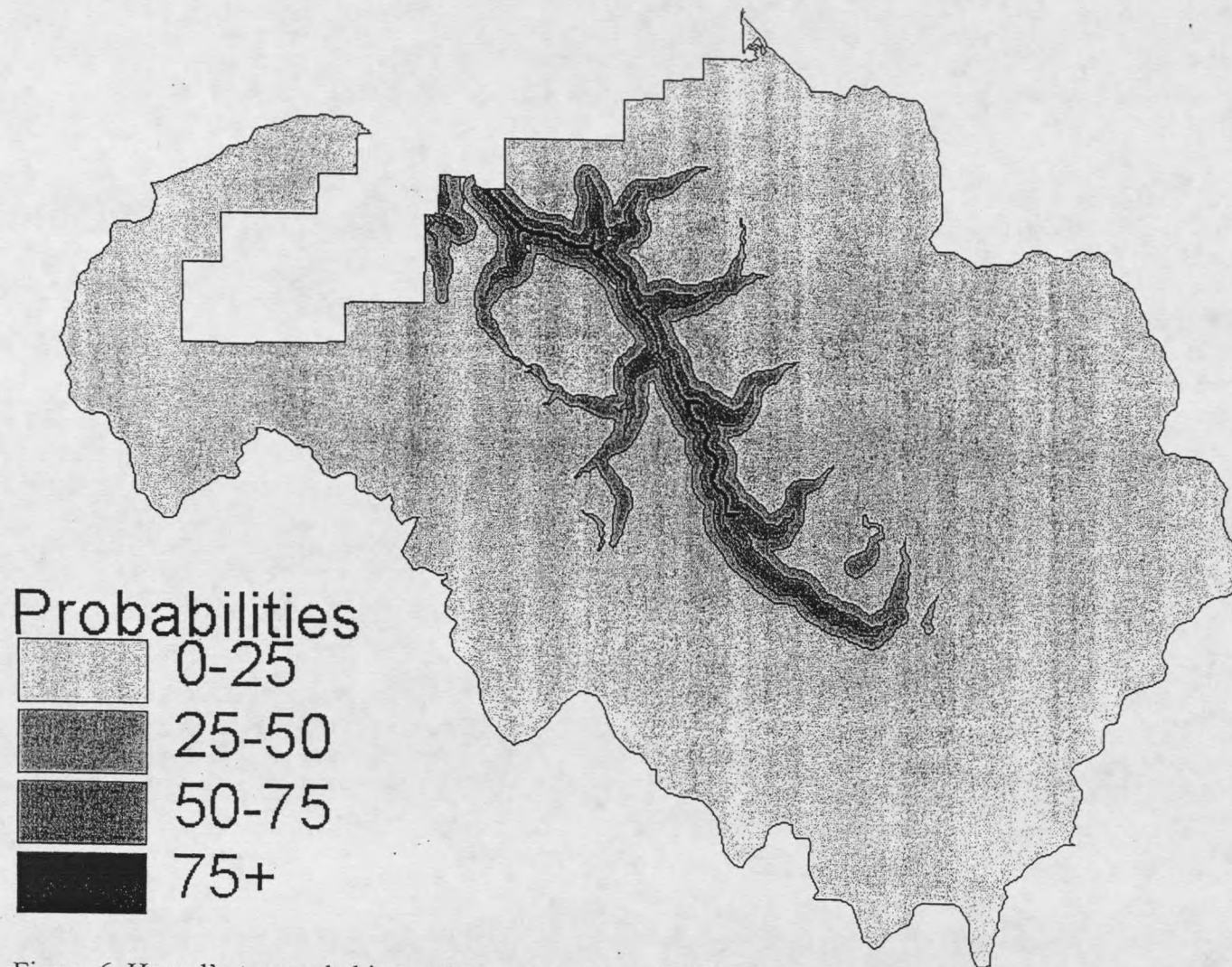


Figure 6. Hound's-tongue habitat and spread vector probability map.

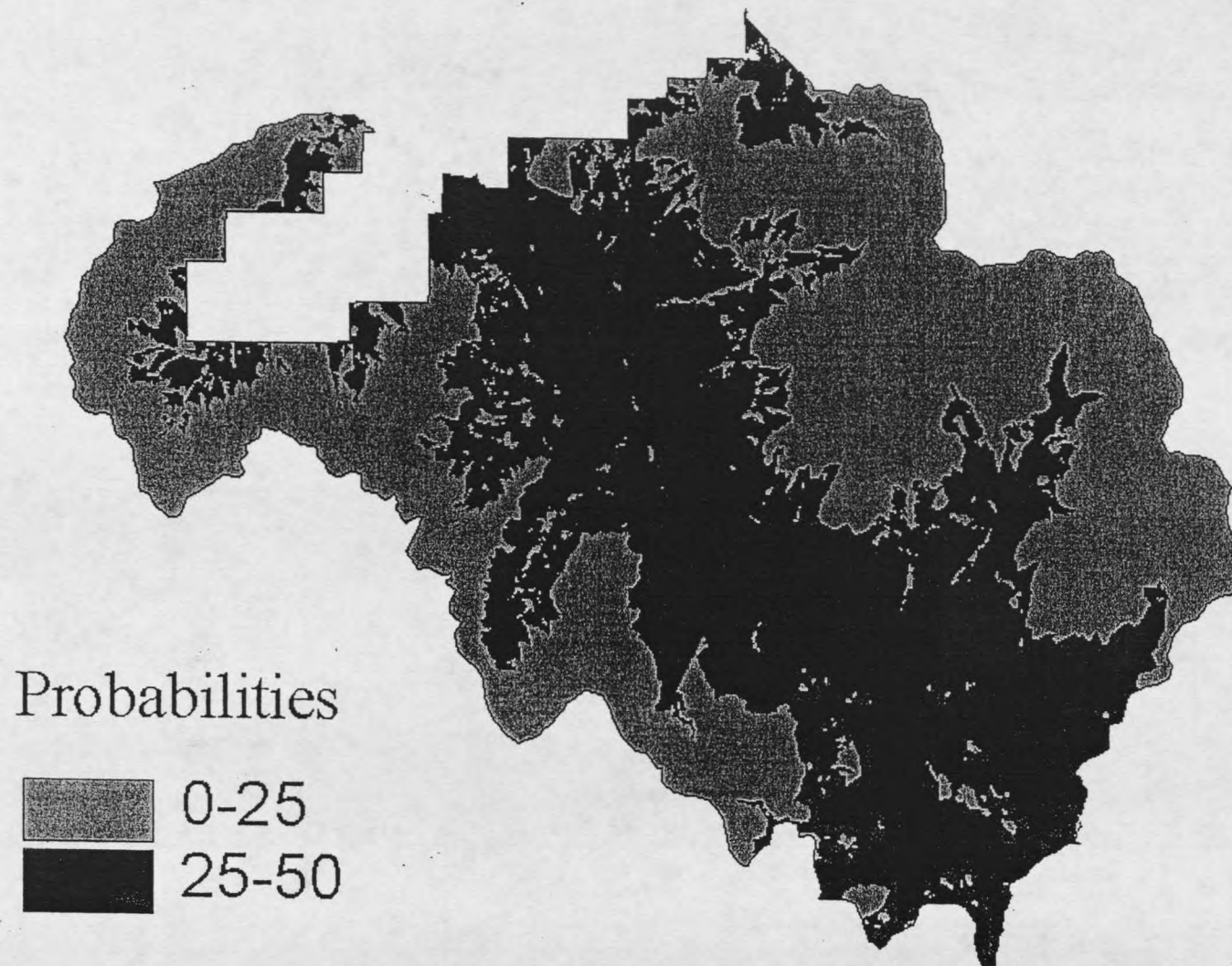


Figure 7. Spotted knapweed habitat probability map.

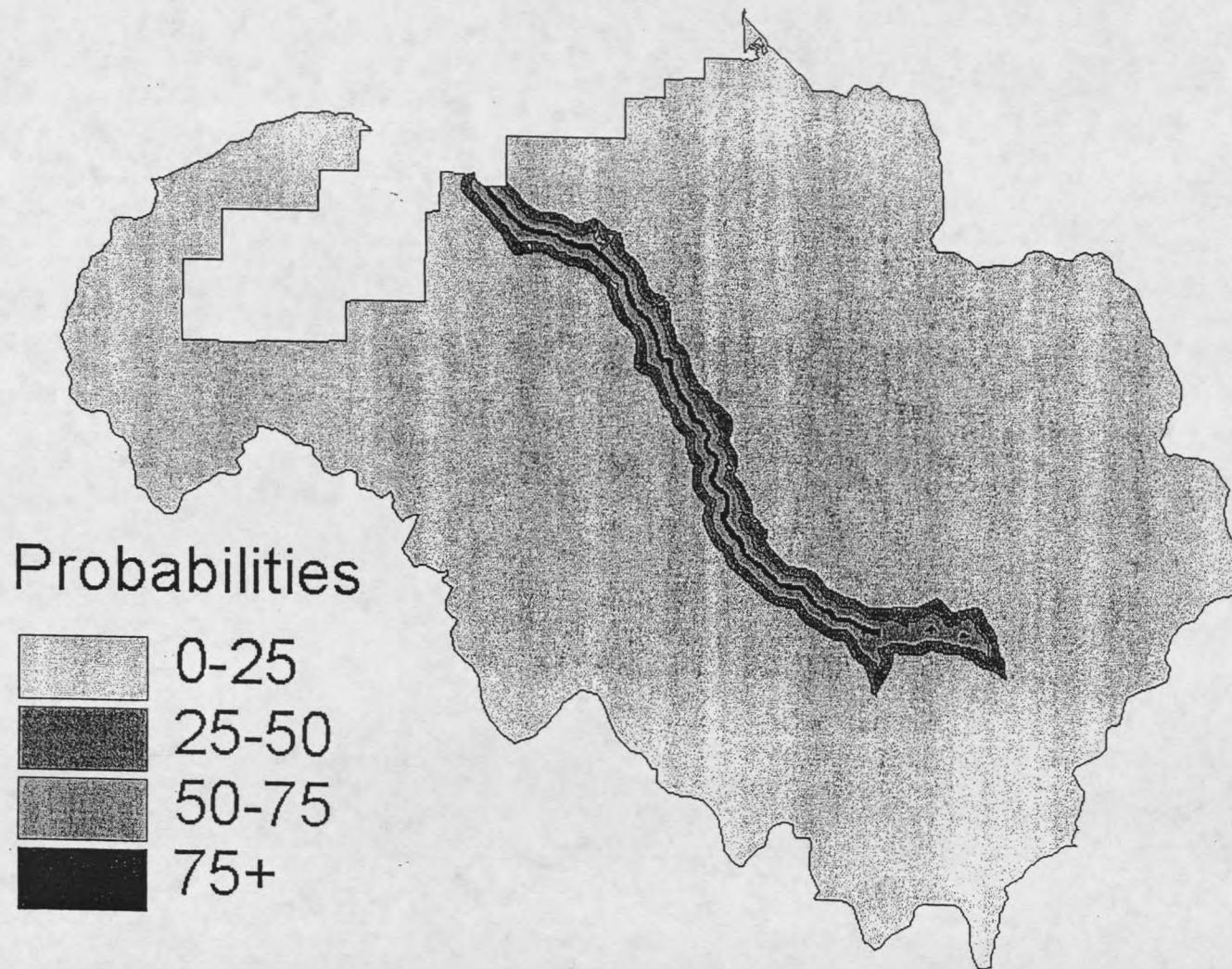


Figure 8. Spotted knapweed habitat and spread vector probability map.

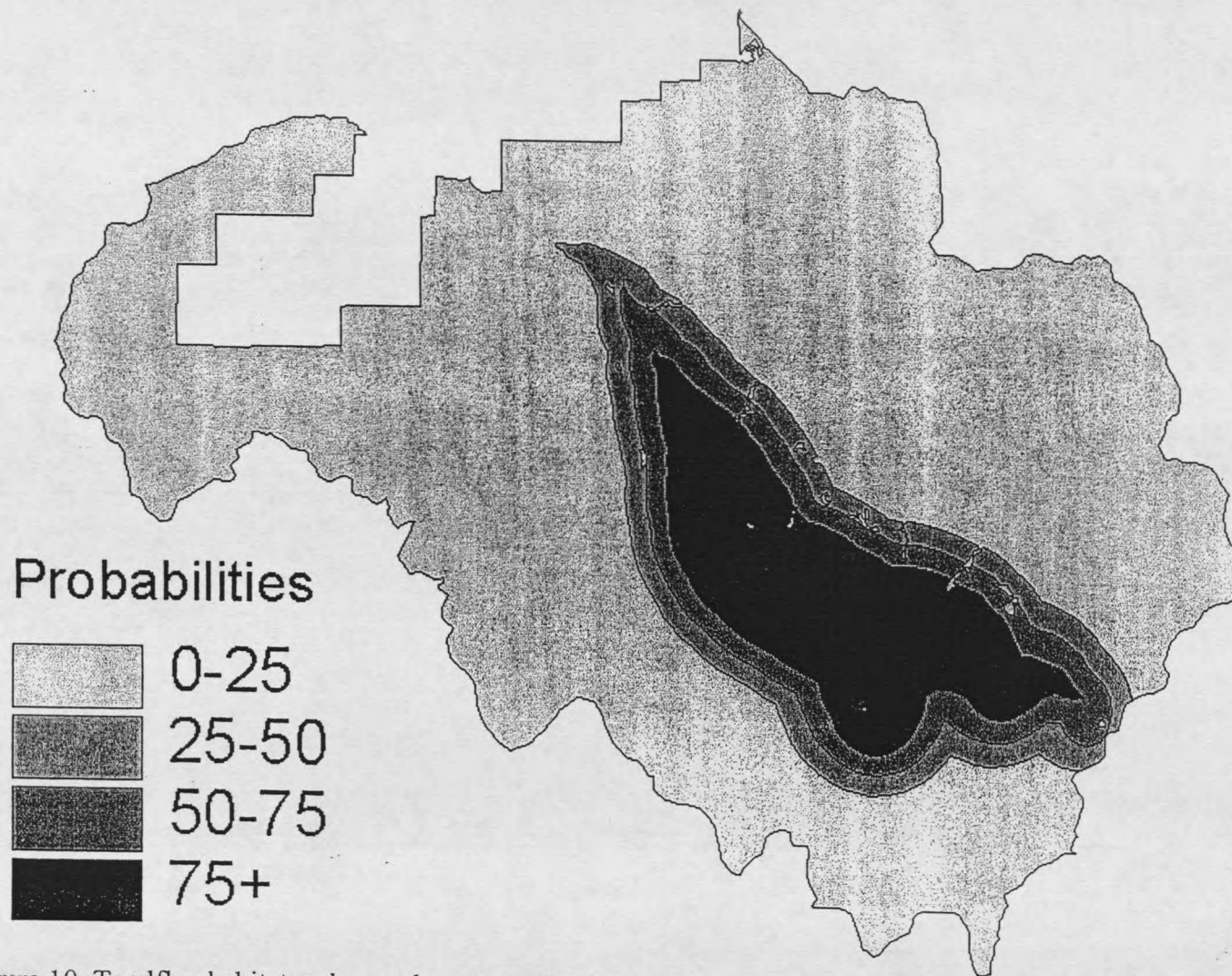


Figure 10. Toadflax habitat and spread vector probability map.

Despite this inaccuracy, this map may still be useful for predicting sites that are at risk of future invasions.

Most current knapweed infestations fell within the higher probability zones of the habitat + spread vector probability map (Fig. 7). Only a few points were located outside of these areas and most outliers were near high-probability areas.

When I overlaid toadflax distribution maps on the habitat + spread vector probability map, I found that most current locations were in high probability zones (Fig. 9). As with spotted knapweed, a few toadflax infestations were located within the low probability zones but near the outer edge of the higher probability zones.

Predicted Distribution of Weeds on Ungulate Winter Ranges

Estimated impacts from invasive plant species on ungulate winter range in the Gardiner Basin were based on a "worse case scenario" assumption that if a weed species can invade a site, it will (Tables 24-26). I estimated proportion of elk, mule deer and bighorn sheep winter ranges currently occupied by each weed species, and the proportion that might be at risk in the future under 2 assumptions: 1) weeds spread strictly by habitat features; and 2) weeds spread due to habitat and spread vectors. I looked at 4 separate categories of probabilities: 0-25%, 25-50%, 50-75% and greater than 75%.

Elk Winter Range

Currently, toadflax is the most wide spread weed on elk winter range (1.8 % of winter range pixels currently with toadflax present). Cheatgrass occupies 1.7% of pixels. The least common weed is hound's-tongue (0.27% of pixels). Both the habitat and habitat +

spread vector probability maps indicated that the majority of elk winter range (76% and 63%, respectively) had a 0-25% probability of being invaded by cheatgrass. In both models, the higher risk areas (50-75% and 75% +) were located at the lower elevations of the winter range near the Yellowstone River, roads, and highways.

My habitat model indicated that 99% of elk winter range fell within the 25-50% probability zone for hound's-tongue invasion, while the habitat + spread vector model indicated that 86% of elk winter range fell within the 0-25% probability range for hound's-tongue invasion. The habitat + spread vector model predicted a smaller impact from hound's-tongue. This was due to the absence of spread vectors (streams, allotments, and highways) in most of the elk range. The model may be overly optimistic for the long-term because all suitable habitats may eventually be invaded.

The habitat + spread vector model for spotted knapweed indicated that most of the elk winter range (95%) had low probability (0-25%) of knapweed invasion. As with hound's-tongue, the model based only on cover type and elevation included more elk range in the 25 – 50 % category.

Sixty percent of elk winter range was categorized as 0-25% at risk with the toadflax habitat + spread vector map, and 16% was in the 75%+ probability range. The toadflax habitat map showed almost the opposite with 81% of elk winter range at a risk 75% or higher.

Table 24. Distribution of pixels in elk winter range among 4 probability classes for 4 weed species. Elk winter range in the Gardiner Basin was estimated to cover 30,294 ha based on radio telemetry locations.

	Probabilities				
Weed/Map type	0-25%	25-50%	50-75%	75%+	Map range*
Cheatgrass					
Habitat	0.76	0.11	0.08	0.05	0-0.97
Habitat + spread vector	0.63	0.18	0.12	0.07	0-0.91
Hound's-tongue					
Habitat	0.01	0.99	0.00	0.00	0-0.37
Habitat + spread vector	0.86	0.08	0.03	0.03	0-0.79
Spotted knapweed					
Habitat	0.38	0.62	0.00	0.00	0-0.48
Habitat + spread vector	0.95	0.03	0.02	<0.01	0-0.79
Dalmatian toadflax					
Habitat	0.14	0.00	0.05	0.81	0-0.86
Habitat + spread vector	0.60	0.12	0.11	0.16	0-0.99

* Range of lowest rated pixel to highest rated pixel.

Mule Deer Winter Range

Toadflax was the most widely distributed weed (4.1% of pixels) on mule deer winter range. The least was spotted knapweed (0.1% of pixels). According to both the habitat and habitat + spread vector models, most deer winter range fell in the 0-25% and 25-50% risk categories for cheatgrass, hound's-tongue, and knapweed. The toadflax habitat model indicated that most deer winter range (89%) was in the highest risk category (75%+). The habitat + spread vector probability model indicated that most deer winter range (68%) fell in to the 0-25% category.

Table 25. Distribution of pixels in deer winter range among 4 probability classes for 4 weed species. Deer winter range in the Gardiner Basin was estimated to cover 31,219 ha based on radio telemetry locations.

	Probabilities				
Weed/Map type	0-25%	25-50%	50-75%	75%+	Map range*
Cheatgrass					
Habitat	0.71	0.13	0.09	0.08	0-0.97
Habitat + spread vector	0.57	0.22	0.15	0.06	0-0.91
Hound's-tongue					
Habitat	<0.01	0.99	0.00	0.00	0-0.37
Habitat + spread vector	0.86	0.11	0.04	<0.01	0-0.79
Spotted Knapweed					
Habitat	0.37	0.63	0.00	0.00	0-0.48
Habitat + spread vector	0.93	0.04	0.02	0.01	0-0.79
Toadflax					
Habitat	0.10	0.00	0.02	0.89	0-0.86
Habitat + spread vector	0.68	0.11	0.08	0.13	0-0.99

* Range of lowest rated pixel to highest rated pixel.

Bighorn Sheep Winter Range

The most widely distributed weed on sheep winter range was cheatgrass (1.9% of pixels) and spotted knapweed and hound's-tongue were the least (0.1% for each). My models predicted that 79% and 28% (habitat and habitat + spread vector models, respectively) of winter range fell within the >50% probability range for toadflax invasion. These maps predicted very low cheatgrass, hound's-tongue, and spotted knapweed invasions on bighorn sheep winter range.

Table 26. Distribution of pixels in sheep winter range among 4 probability classes for 4 weed species. Sheep winter range in the Gardiner Basin was estimated to cover 20,174 based on radio telemetry locations.

	Probabilities				
Weed/Map type	0-25%	25-50%	50-75%	75%+	Map range*
Cheatgrass					
Habitat	0.77	0.06	0.06	0.10	0-0.97
Habitat + spread vector	0.54	0.16	0.16	0.13	0-0.91
Hound's-tongue					
Habitat	0.02	0.98	0.00	0.00	0-0.37
Habitat + spread vector	0.86	0.07	0.05	0.02	0-0.79
Spotted Knapweed					
Habitat	0.26	0.74	0.00	0.00	0-0.48
Habitat + spread vector	0.85	0.07	0.06	0.02	0-0.79
Toadflax					
Habitat	0.20	0.00	0.06	0.73	0-0.86
Habitat + spread vector	0.64	0.06	0.06	0.23	0-0.99

* Range of lowest rated pixel to highest rated pixel.

Prescribed Sagebrush Burns and Weed Invasion

The sagebrush cover type encompassed an estimated 27,159 ha in the Gardiner Basin. Of this, 12.6% was burned in prescribed fire programs. Burned sites had very few mapped weeds. Error ranges calculated from user's accuracy and occurrence of weeds in validation points for the "no weed" category (Table 27), varied from .039% to 13.5% of means for individual weed species.

Table 27. User's accuracy and weed points found in mapped no-weed points to determine the percent of underestimation for each weed species.

Species	User's Accuracy	Weeds in no-weed points (n = 50)	Percent underestimated
Cheatgrass	86%	4	8%
Hound's-tongue	70%	6	12%
Spotted knapweed	72%	2	4%
Toadflax	72%	0	0%

Maps of current weed distribution indicated that cheatgrass covered 6.4% of pixels in areas that had been burned (Table 28). Hound's-tongue covered only 0.75%. Spotted knapweed had the lowest coverage on burned areas, 0.04% of the total burned area. Toadflax had the highest coverage on burned areas (13.5%).

In unburned sagebrush areas, cheatgrass was mapped as present on 2.9% of pixels, and my test of map error ranges indicated that there was more cheatgrass on burned areas than on unburned areas. Hound's-tongue was found on 0.62% of unburned areas, and comparison of error ranges indicated that there was no real difference between hound's-tongue infestations on burned versus unburned areas. Spotted knapweed was found more often on unburned land (0.33%) than burned land (0.04%), and the error ranges did not overlap. Toadflax, which had the highest total percent of cover in the Gardiner Basin was found more on burned (13.5%) than unburned areas (3.7%).

Table 28. High, low, and total percentages of weed species pixels in the Gardiner Basin on burned and unburned areas.

Weed species	Burn status	% total pixels on map	High %	Low%
Cheatgrass	Burned	6.41	6.92	5.51
	Unburned	2.92	3.15	2.51
Hound's-tongue	Burned	0.76	0.85	0.53
	Unburned	0.62	0.70	0.43
Spotted knapweed	Burned	0.04	0.05	0.03
	Unburned	0.33	0.34	0.23
Toadflax	Burned	13.53	13.53	9.74
	Unburned	3.73	3.73	2.68

DISCUSSION

Weed Map Validation

The weed layer in the Gallatin Forest GIS library represents a tremendous input of labor and time for the Gardiner Ranger District. This was one of the largest scale weed mapping efforts attempted using ground-based mapping and verification on Forest Service lands in Montana. My evaluation indicated the accuracy of the weed map was 75%, high enough to inspire confidence in the analyses undertaken using this map. This accuracy would be classified as "moderate-high level" according to guidelines in the *Montana Noxious Weed Survey and Mapping System* (Cooksey and Sheley 1998). Obtaining this level of accuracy for highly variable vegetation over an area of 56,428 ha is an impressive feat that cannot be duplicated using today's remote sensing technology.

Although the weed map which I helped develop and validate is useful, it does have limitations. The Gardiner Basin study area has mixed ownership (private, state, FS and NPS), but only Forest Service lands were mapped. Because of this, the continuity of the map was lost. I may have found more significant relationships between certain spread vector variables and the presence or absence of weeds had private land been included in the final map.

Constraints in ground-based mapping may also have added to errors in the final map. Because crews had to physically cover the Gardiner Basin searching for weeds, all areas could not be covered simultaneously. Mapping took place over 2 years. In both years, crews were active during spring through early fall. Visibility and weed density

could have changed over the 2-year sampling period. Timing of sampling at individual sites could also compromise map accuracy. For example, dicotyledonous weeds in sites mapped in spring, before maturation and flowering, may have been underestimated compared to sites mapped in late summer. Other possible sources of error in the weed map were differences in skill or attention in personnel on the mapping crew. Mapping crews were trained together, but plant identification skills and GPS capabilities may have differed among individuals.

Changes in land ownership during and after mapping caused some problems in map coverage. The Forest Service acquired new land tracts through exchanges in land with private owners in the Basin. I attempted to map all Forest Service lands, including newly acquired parcels, but I did not have permission to map some privately owned parcels that were later transferred to the Forest Service. I was able to map other exchange parcels, but they were not Forest Service property when other GIS layers were mapped so I was unable to include them in many of my analyses.

Despite mapping errors and land ownership issues, the Gardiner Basin weed map has been and will continue to be useful. The map has a high user's accuracy rate for most weeds meaning that map users can be fairly confident that there will be weeds present at locations designated on the map. The existing map is in a format that can be easily updated to reflect changes in weed distributions. This creates an opportunity for future research on the spread of weeds in the Gardiner Basin.

Weed Distribution Prediction

Predicting weed distributions in the Gardiner Basin presented 2 major problems. The first, a conceptual problem, involved trying to develop a strategy for making predictions about distributions of plants that were actively expanding their range at the time data were collected. I resolved this problem by working with the data at hand. I cannot guarantee that models based on a map of present weed distribution on only Forest Service lands in the Gardiner Basin will predict future distribution. However, applying models developed in other areas (Chicoine et al. 1985, Kurtz 1999) to the Gardiner Basin likely has greater potential for false prediction.

The second problem related to analysis. The *a priori* approach recommended by Burnham and Anderson (1998) for developing explanatory models was not suitable for weed distributions in the Gardiner Basin. Their approach limits excessive data mining, but is vulnerable to multicollinearity among explanatory variables, a problem that frequently occurs on real landscapes. I avoided this problem by using a hybrid modeling approach that combined identification of inter-correlations among explanatory variables with a univariate analysis designed to identify the relationship between individual explanatory variables and the response variable (presence of a weed species).

Preliminary results indicated that 2 habitat characteristics, cover type and elevation, were significantly related to the presence or absence of the 4 weed species I mapped, as were several factors directly or indirectly influenced by human activities. This information allowed me to hypothesize 2 scenarios for predicting weed spread: 1) weeds would spread only to habitats with appropriate physical and biological growing

conditions, as indexed by cover type and elevation; and 2) weeds would spread to appropriate habitats but only when effective vectors allowed them to reach those habitats. I was unable to unambiguously identify the ultimate spread vectors because of the spatial correlation among vectors, but taking the vectors with the best fit for each weed provided me with a convenient analog for ultimate causes which could be used to develop predictive models.

Cheatgrass

In my best habitat-based model, cheatgrass was favored by low elevation dry sagebrush/open juniper habitats. Odds ratios indicated cheatgrass was significantly more likely to be found in this cover type than in other cover types where it occurred. I never located cheatgrass in riparian areas or aspen stands. Cheatgrass is known to be successful in the sagebrush steppe habitat type in other western areas (Young et al. 1987). However, the high genetic plasticity of cheatgrass allows it to thrive under a wide variety of site conditions; therefore, the potential for cheatgrass invasion is virtually unlimited (Mosely et al. 1998).

When I examined associations between individual spread vectors and cheatgrass distribution, the variable "distance to river" had the highest McFadden's ρ^2 (0.53). Elevation, distance to highways, and distance to sagebrush burns also had high McFadden's ρ^2 but these variables were highly inter-correlated. I could not separate effects of Highway 89, the Yellowstone River, recreation sites, and sagebrush burns because all occurred at low elevation primarily along the river corridor. The only variable

eliminated from consideration in cheatgrass models using univariate analysis was "distance to trails" (McFadden's $\rho^2 = 0.005$).

Distance to trails was eliminated from all weed models based on low McFadden's ρ^2 values in univariate analyses. This variable probably had little explanatory power because most weeds were found near or at the trailhead rather than declining linearly as distance from the trailhead increased. The variable "distance to trails" did not include trailheads but the variable "distance to recreation sites" did. I was not able to look at trailheads separately from the other recreation sites included in the variable.

The "trail" GIS layer for the Gardiner Basin contained only designated Forest Service trails. Game and cattle trails were not mapped. Therefore, although animals may be an important vector for spreading invasive plants (Zamora 1999), I was unable to investigate that possibility.

The variable "distance to recreation sites" included trailheads, boat accesses, picnic areas, and campgrounds. In the Gardiner Basin, cheatgrass was often locally abundant at these locations because they are highly disturbed areas. My results concur with those of Benninger-Traux (1992) who found that weed species richness was negatively correlated with distance from a trailhead.

Other variables eliminated from all weed models were the wildlife radio-telemetry locations. Elk, mule deer, and bighorn sheep locations were highly correlated with most other variables, however, the variable "bighorn sheep" had high McFadden's ρ^2 values in univariate models for spotted knapweed and toadflax ($\rho^2 = 0.53$ and $\rho^2 = 0.67$, respectively). I was unable to determine whether the high McFadden's ρ^2 values were due

to high correlation with variables such as roads, river, and highways, or because bighorn sheep were independently related to weed distribution. This determination may be possible using a study area, or multiple study areas, that have differing spread vector relationships.

The most parsimonious multivariate model that included both habitat and spread vectors indicated cover types and distances to river, mining, and streams were important in explaining cheatgrass distribution. Coefficients for all distance-based variables were negative, indicating more cheatgrass at closer distances. The dry sagebrush/open juniper woodland cover type had significantly higher odds ratios in this model than other types.

Although empirically reasonable, this model may overestimate the association between cheatgrass and the dry sagebrush/open juniper woodland cover type. Cheatgrass successfully invades areas that have been disturbed both by natural processes and human land use (Billings 1990). A disproportionate number of disturbed sites in the Gardiner Basin occur at low elevations, where soil and climatic conditions favor the dry sagebrush/open juniper woodland cover type. Human, natural, and wildlife disturbances along the Yellowstone River in the form of boating accesses, bridges, game trails, flood plains, county roads, and highways have created numerous sites suitable for cheatgrass establishment. Streams are also areas where disturbances occur because there are often wildlife and livestock trails, disturbed soil from overflow events, and in some cases Forest Service trailheads and trails that follow streams. Mining quarries are an obvious source of disturbed soil. Mined areas are typically highly disturbed sites resulting from digging equipment, access roads, and soil pilings from past mining activity. Cheatgrass

can be the first plant species to establish after a disturbance because it outcompetes native species for moisture (Young et al. 1987).

Hound's-tongue

The most parsimonious habitat-based model included elevation (with a negative coefficient) and cover type. Hound's-tongue most often occurred in the moist sagebrush cover type but was also common in some riparian areas. I was surprised at the low odds ratio for the low elevation conifer cover type because, while doing field mapping, I often found hound's-tongue under large Douglas fir trees where ungulates bedded. I also expected the "disturbed area" cover type to be important. I mapped several patches of hound's-tongue along roadsides where runoff from the crowned roads and highways provided slightly moister soil, but the "best" model indicated it had significantly lower odds ratios than moist sagebrush or the reference type, dry sagebrush/open juniper woodlands.

In univariate tests of spread vectors, the variables "elevation" and "distance to highways" had the highest McFadden's ρ^2 values. "Distance to roads" and "distance to river" also had high McFadden's ρ^2 values. Again, distances to roads, river and highways were all inter-correlated so it is not surprising that they all would have high McFadden's ρ^2 values.

In the best multivariate model including habitat and spread vector variables, cover type and distances to highways, grazing allotments, and streams were included. Distance to grazing allotments had a low McFadden's ρ^2 (0.06), but it was evidently important

enough to withstand the AIC penalty imposed by its inclusion. This model generally agreed with my field observations and the ecology of hound's-tongue reported in the literature (Kedzie-Webb 2002, DeClerke-Floate 1997). Hound's-tongue does well in moist sites so the relatively high association with moist sage is logical. The uneven association I found between this plant and riparian areas is presumably a result of infestations in riparian areas where seeds have been introduced and absence in areas in which seeds have not been introduced. Once seeds are introduced, hound's-tongue tends to increase in high disturbance areas used by humans and livestock. Areas where cattle congregate on forested grazing allotments routinely have high infestations of hound's-tongue because cattle easily pick up burrs of this species while grazing (DeClerck-Floate 1997). Because seeds stick to any mammal's fur, native ungulates can also serve as effective spread vectors (Zamora 1999).

Spotted Knapweed

As with the other weed species, cover type and elevation were included in the most parsimonious model based only on habitat variables. Spotted knapweed was most common at low elevations and in cover types associated with low elevation such as dry sagebrush/open juniper woodlands. It was also common at sites disturbed by humans.

Distance to river and elevation had the highest McFadden's ρ^2 values in the univariate analyses for knapweed. Distances to roads, recreation sites, and highways all had relatively high values, as well. These variables were all highly intercorrelated with correlation coefficients ranging from 0.69 to 0.93.

Of the models including both habitat and spread-vector variables, the most parsimonious spotted knapweed model included distances to streams and river, and cover type. This model accurately reflects what I saw in the study area. Spotted knapweed seeds spread in water, through wind, and via transport by humans and animals. This species can form dense stands in moist areas and on drier sites (Sheley et al. 1999). Seeds that are spread along watercourses can establish on banks and gravel bars, thus perpetuating the spread of seeds along streams and rivers. The best model did not have high odds ratios for riparian areas, probably because the introduction of this weed in the Gardiner Basin occurred relatively recently, and knapweed has not had time to spread widely from the introduction sites. Prevention plans for the Gardiner Basin should regularly monitor watercourses for new weed infestations, particularly spotted knapweed.

Dalmatian Toadflax

The most parsimonious of the habitat-based models included cover type and elevation. It was most frequently found in dry sagebrush/open juniper woodlands, and the odds ratio was significantly higher for this type than for the other 3 types, moist sagebrush, wet meadows, and bedrock.

Results of the univariate analysis for toadflax spread vectors indicated that distance to sagebrush burns, with a negative relationship, was the best single variable describing toadflax distribution. Distances to rivers, grazing allotments, and mining, were also important variables and had inverse relationships with toadflax presence. "Distance to sagebrush burns" was highly inter-correlated with distances to roads, recreation sites, and highways, and with elevation so "distance to a sagebrush burn" may have been

describing not only areas that were burned, but proximity to travel corridors, mining activity, and low elevation.

The most parsimonious model with both habitat and spread-vector variables included distances to river, and mining activity, and cover type. This model, with a few exceptions, was consistent with what I observed in the field. The importance of "distance to river" may have been due to inter-correlated variables as much as to the location of the river. Sites near the Yellowstone River were also near sagebrush burns, roads, recreation sites, and Highway 89 and were at low elevation. The high McFadden's ρ^2 I calculated in univariate analyses (0.58) and the inclusion of "distance to sagebrush burns" in the second best multivariate model (probably due to high inter-correlation among variables mentioned above) suggest that distances from the river were actually less important than distances from burned sagebrush. Both prescribed and wildfires on rangeland can increase the competitiveness of toadflax by removing desirable plant species (Lajeunesse 1999). Wambolt observed that toadflax was nearly absent from the Gardiner Basin until prescribed sagebrush burning occurred, shortly after, toadflax increased dramatically on burned sites (C. Wambolt, personal communication).

The variable "distance to mining" was likely included in the most parsimonious habitat + spread vector model because of the disturbance associated with the travertine mine in the Gardiner Basin. Mining areas have highly disturbed soil and offer an available niche to toadflax and other invasive species that compete with native plants for early spring moisture. The mining quarry in the Gardiner Basin is also surrounded by mule deer and bighorn sheep habitat. Deer and sheep will browse green Dalmatian

toadflax stems in the early spring and could be involved in spreading seeds in the fall and winter (Robocker 1970).

Toadflax is also highly competitive on disturbed areas such as roadsides, vacant lots, gravel pits, fields, and over stocked spring-grazing pastures (Lange 1958, Alex 1962, Robocker 1970, Lajuenesse 1999). Toadflax can invade rangeland in excellent condition on naturally disturbed sites or small openings. Due to its genetic plasticity, prolific seed production (up to 500,000 seeds per plant), and competitive vegetative growth, even rangeland in good condition can do little to slow the expansion of this species once it is established (Lajuenesse 1999).

Weed Distribution Probability Maps

Weed probability maps will be useful for land managers to identify areas at risk to weed invasion in the Gardiner Basin. They can also be useful when creating prevention plans, which are the most effect means of weed management (Sheley et al. 1999). A visual estimate of the accuracy of the probability maps was determined by placing current weed distribution data layers over the probability maps to see how well the models predicted current infestations.

In order to create the probability maps, I had to assume that the weed map and GIS spread vector data layers were 100% accurate. I also assumed cover types that were left out of the analysis (different for each weed species) were not suitable habitat and, therefore, were assigned a value of zero (probability of invasion) for the probability map. This was necessary for running the analysis, but the weed species I studied can invade

micro-sites within "unsuitable" habitat (Sheley et al. 1998). These assumptions increased the uncertainty in the final probability maps and the conclusions drawn from them.

One major limitation of my probability maps was that they lack a time factor. In general, habitat maps predicted a worse-case scenario, identifying all suitable habitats that may be invaded in the future. The habitat + spread maps may underestimate the long-term invasion potential of weeds because they indicated that areas near spread vectors were at higher risk to invasion than areas farther from spread vectors. Given time, weeds may invade areas far from spread vectors by other means of spread (wildlife, wind etc.). Because of the limitations in weed mapping and analyses, the probability maps should only be used as a "best approximation" of future weed invasion.

Habitat probability maps (using only the variables elevation and cover type) more accurately predicted current weed distributions in the Gardiner Basin than habitat + spread vector maps. This is probably because the DEM and CEM, from which elevation and cover type distributions were derived, included private and state lands and provided more complete coverage in GIS layers. The habitat probability maps were less restrictive than the spread vector maps in most cases. More area was designated in the higher risk zones (50-75% and 75%+) using maps based on habitat variables than on habitat + spread vector maps; and, therefore, more of the current weed infestations were captured correctly. This could also mean that more area that will not be invaded by weeds was included in the habitat maps than the habitat + spread vector maps.

In some areas, historic disturbance on private land not included in the spread vector GIS layers seriously reduced the reliability of maps based on spread vector and

habitat variables. An example is Beatie Gulch, an area in the west-central part of the study area which consistently had weed invasions that were not predicted by the habitat + spread vector probability maps. Coal mining, railroad construction and maintenance, and human settlements that occurred in the late 19th and early 20th centuries produced soil disturbances that persist today. This area is now in Forest Service ownership after being in private ownership for many years. Many GIS data layers have not been updated to include this area.

It is always a risk to extrapolate information from areas outside data collecting and data coverage areas. Data layers, such as roads, streams, and rivers, did not include Yellowstone National Park lands. Also, some data layers were not updated to reflect recent Forest Service land exchanges. Despite these coverage problems, the probability maps based on habitat and spread vectors may be better at indicating areas where weed prevention plans should focus than the maps based solely on habitat variables. It is evident that invasive plants species are capable of invading a variety of habitats, but they may require help in getting to them. Maps that include spread vectors, while far from perfect, do identify areas with both suitable habitat and features that can accelerate spread.

Habitat and spread vector variables have been used in predictive models in other studies in Montana (Chicoine 1985). Several studies successfully predicted weed infestations using elevation and vegetative cover types as predictor variables. A study by Chicoine (1985) found elevation, along with edaphic and climatic characteristics, to be useful in predicting weed migration. Forcella and Harvey (1983), and Weaver et al.

(2000) studied vegetation adjacent to weed infestations and determined that weed infestations were restricted to a vegetational gradient, depending on disturbances.

Weeds and Ungulate Winter Range

Invasive plant species can cause the degradation of native plant communities and local extinction of preferred plant species which could reduce the carrying capacity of the landscape for native wildlife (Trammel and Butler 1995). Bighorn sheep, elk, mule deer, and other ungulates in the Gardiner Basin depend on native plant communities on the Northern Yellowstone Winter Range for winter and early spring survival. Current weed infestations on ungulate winter range in the Gardiner Basin are low compared to other winter ranges in Montana and Idaho. For example, on the Lolo National Forest, Spoon et al. (1983) calculated that forage production lost to weed invasion on big game winter ranges they studied would result in a loss of forage equivalent to that required to support 220 elk through winter. Bedunah and Carpenter (1989) hypothesized that spotted knapweed infestations of bunchgrass sites on a study site in western Montana could result in a loss of 27 elk days/acre of elk winter forage. Spotted knapweed infestations on sites in western Montana and Alberta have reportedly reduced graminoid production by 90% (Harris and Cranston 1979, Bedunah 1988).

Current weed infestations on ungulate winter range in the Gardiner Basin have likely not dramatically affected winter range carrying capacity; however, my predictive weed maps show that large portions of the winter range for each ungulate species are at risk. On mule deer and bighorn sheep ranges, as defined by radio-telemetry locations, my

maps indicate that 91% and 79%, respectively, had a >50% probability of invasion by 1 or more weed species. Eighty-six percent of the winter range for elk, as defined by radio-telemetry locations, had a >50% probability of invasion by 1 or more weed species.

The spatial distribution of areas susceptible to weed invasion indicated that elevation and distances to roads and human activities were the most important factors in predicting which areas of winter range would be impacted by weeds. The 0-25% probability range for each weed probability map tended to include areas of ungulate winter range that were the farthest from the floor of the Gardiner Basin and, therefore, at higher elevations and further from human disturbances. Conversely, with the exception of the toadflax habitat probability model, the highest probability range for each map (75%+) were at lower elevations and closer to human disturbances.

Based on the current weed map and probability maps, the weed species most likely to cover the most area of winter range is Dalmatian toadflax. Habitat + spread vector maps indicated that for mule deer, bighorn sheep and elk winter ranges 13%, 23%, and 16% of the total area respectively, have a 75% or greater probability of toadflax invasion. The habitat probability model indicated a much greater amount (89%, 73%, and 81%, respectively) of ungulate winter ranges have a 75% or greater probability of toadflax invasion.

Many studies have examined the effects of spotted knapweed invasion on ungulate winter ranges, but few have looked at large scale toadflax invasion of winter ranges. Because toadflax is adaptable, highly competitive, and able to establish far from the centers of infestation (Lange 1958), there is a real risk to native plant communities on

ungulate winter range. Once a perennial weed invades a site, it seems to be able to move into healthy stands of native plants causing huge management problems (Harris 1991). Ungulates tend to use non-infested areas more than weed infested areas (Trammel and Butler 1995). Overgrazing can occur on the non-infested sites creating disturbed soil that encourages weed species to establish. This not only accelerates the depletion of native winter range, but it forces wild ungulates to move to more favorable habitat which is often private land (Bedunah and Carpenter 1989). Toadflax is known to cause loss of forage and to impact big game species, especially on winter ranges (Lajeunesse 1999). Although deer and sheep browse Dalmatian toadflax when it is green, it is not heavily used by any ungulate species (Robocker 1970).

Although my models suggest toadflax is the greatest threat in the Gardiner Basin, other weeds may also be a problem. The combination of spotted knapweed, cheatgrass, hound's-tongue, and toadflax invasion on winter range could influence habitat by displacing forage species, modifying habitat structure, or changing species interactions within the ecosystem (Belcher and Wilson 1989).

Sagebrush Burns and Weed Distribution

Results of the weed distribution analysis on sagebrush indicated that the sagebrush burns done in 1970s and 1980s have not produced dense stands of weeds in the Gardiner Basin. However, two of the 4 weed species, (cheatgrass and Dalmatian toadflax) were more common on burned than unburned sagebrush sites. This may indicate only a spatial association between burned sites and weed introduction points, or

it could indicate burns have been, and continue to, facilitate establishment and spread of some weeds in the basin. For example, toadflax was first recorded on prescribed burns in the Gardiner Basin immediately following burning, and increased dramatically on these areas (C. Wambolt, personal communication).

Fire is reported to increase cheatgrass distribution (Billings 1990). Fire opens up bare soil for cheatgrass seeds. Cheatgrass seeds will consolidate their gains across a sagebrush burn for many years, and, in summers following moist winters, cheatgrass will provide abundant tinder creating an environment that burns more frequently. This shortened fire cycle then replaces sagebrush shrublands with annual grasslands. Cheatgrass tends to burn uniformly so that islands of unburned areas do not remain as a seed source for native species (Mosely et al. 1999). This ecological repercussions of this process on ungulate winter range could be substantial. Sagebrush species that are an important diet component can be lost as cheatgrass, a less palatable and less nutritious plant, increases.

I thought cheatgrass would be more abundant on burned areas than the other weed species I mapped. However, I found toadflax occupied more area on burned sites than cheatgrass. Toadflax was proportionately >3 times more abundant on burned sites than unburned sites 25-30 years post burn. Toadflax is not considered a fire-dependant species, but burning can increase the competitiveness of toadflax by removing desirable plants (Lajeunesse 1999). There is no documentation of whether Dalmatian toadflax increases fire frequency as does cheatgrass (Olsen 1999).

My data suggest that manipulation of sagebrush habitat by burning areas where there is a seed source for invasive species may be detrimental, and the benefits of sagebrush burning for understory production may be forfeited to loss of biodiversity and ungulate winter forage as weeds replace native plant species. A study on the effects of sagebrush burning for wildlife habitat improvement in the Gardiner Basin indicated that sagebrush was nearly eliminated from the burned sites, and that even though some grasses and forb species initially increased, they became desiccated by winter and were lower in protein value than sagebrush (McNeal 1984). This study also found that Idaho fescue, an important winter forage for elk, was reduced on burned sites. When native bunchgrasses are reduced on burned areas, the open sites become vulnerable to weed invasion. Future fires may only exacerbate the problem because many weeds are more fire-tolerant than native species (D'Antonio and Vitousek 1992).

It will be important to monitor weed species on burned sites in the Gardiner Basin to determine if weed presence changes the normal fire cycle and to measure how rapidly weeds spread. Future burning of sagebrush habitat should be done with caution and careful planning to ensure that newly burned areas are weed-seed free. Any benefits of burning sagebrush to improve wildlife habitat in places where weed species are present can be easily out-weighed by loss of native forage and costs incurred in control of weeds.

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APPENDICES

APPENDIX A

DETAILS OF GIS DATA LAYERS

Distance to sagebrush burns

This data layer consists of a polygon coverage of prescribed and wildfires in sagebrush cover types between the 1960s and 1992. All burns were verified with ground reconnaissance. Attributes recorded included severity of burn (complete or partial), the taxonomic classification of sagebrush that was burned, and the area and shape of the burn. I used perimeter and area data to calculate distances from points to burns. For this study, only the perimeter and area of the burned areas was used in order to determine the distance from a weed or non-weed point to the closest burned area.

Cover type

Cover type of each random point was generated from a Cumulative Effects Model (CEM), in the USFS GIS library. This model includes habitat type, cover type, and other information. Cover types were designated using Mattson and Despain's cover type classification (1985) and forest habitat types defined in Pfister et al. (1977). I condensed the cover types in the CEM to form the 10 cover type groups I used in my analysis.

Distance to highways, roads and trails

These layers are in the USFS GIS library and consist of separate linear coverage for roads, highways, and designated forest service trails in the Gallatin National Forest. Roads, trails, and highways were mapped using 1:24,000 USGS quad maps and transferred to GIS. The "near" command in ArcInfo generated the distance from each point (random or points associated with weed/no-weed attributes) to the nearest road,

trail, and highway. Each category was treated separately to determine if there were differences between the 3 in the distribution and presence of weeds.

Distance to rivers and streams

These data layers consist of digitized linear maps of streams and rivers on the Gallatin National Forests. Rivers, and perennial and intermittent streams were mapped as separate layers using 1:24000 USGS quad maps. Because large watercourses may have different impacts on weed spread than small watercourses, I used "distance to rivers" and "distance to streams" as separate variables.

Distance to recreation areas

The recreation areas data layer consists of point data in ArcView GIS and is in the USFS GIS library. Recreation points were mapped and digitized from a 1:24,000 USGS quad map. Recreation areas included campgrounds, trailheads, picnic areas, watchable-wildlife stops, boat launches, and fishing access sites. Most picnic areas and watchable-wildlife areas are located along Highway 89, the major road from Livingston to Gardiner, Montana. Campsites and trailheads are found both along Highway 89 and along secondary roads. Boat and fishing access areas are mainly found along the Yellowstone River.

Distance to mining quarries

Travertine mining quarries are mapped on USGS 1:24,000 quad maps, and a record of changes is maintained at the Gardiner Ranger District office. I outlined the entire mining area and digitized a boundary around the mining quarries. The mining area has

roads, quarries, and other disturbance factors, so I did not separate individual mine-associated features. Distance from weed and non-weed points to the mining quarry data layer was determined with the use of the "near" command in ArcInfo.

Elevation

The elevation of each point used in analyses was obtained from a digital elevation model (DEM). The DEM was produced by the USGS and gives elevation, slope, and aspect on a 10 m pixel scale.

Grazing Allotments

Boundaries of grazing allotments on the Gallatin National Forest have been digitized as polygons in the GIS library. I used these data to obtain the distance from each point in my analyses to the nearest grazing allotment. There are 5 active grazing allotments in the Gardiner Basin area.

APPENDIX B

COVER TYPE DESCRIPTIONS

Cover Type 1 (Reference Type): Dry sagebrush/open juniper woodland

This cover type typically occurs on exposed south facing hillsides. Dominant shrub species include mountain and Wyoming sagebrush (*Artemisia t. vaseyana*, *A. t. wyomingensis*) and rabbit brush (*Chrysothamnus* spp.). Dominant grasses are Idaho fescue (*Festuca idahoensis*), bluebunch wheatgrass (*Agropyron spicatum*), and needle grass (*Stipa* spp.). In some sites, Rocky Mountain juniper (*Juniperus scopulorum*) dominates with an understory of bluebunch wheatgrass, Idaho fescue, and big sagebrush. This cover type is usually found at lower elevations (2,125 - 2,425 m). Bare ground is often evident, and soils tend to be somewhat shallow and rocky.

Cover Type 2: Moist sagebrush

This cover type is found mainly on moist benches, floodplains, and hillsides with north and east exposures. Mountain sagebrush is the characteristic dominant sagebrush taxon. Shrubby cinquefoil (*Potentilla fruticosa*) occasionally occurs as a co-dominant. Common herbaceous species include Idaho fescue, timothy (*Phleum* spp.), bearded wheatgrass (*Agropyron caninum*), and sedges (*Carex* spp.). Soils are medium textured and deep. Some areas contain a high percentage of fragmented rock.

Cover Type 3: Wet grasslands and forb meadows

This cover type usually occurs on north and east hillsides and benches, and occasionally in basin meadows. Herbaceous vegetation in this type is dense and moderately tall. Important species include sedges, timothy, cinquefoils (*Potentilla* spp.), wild geranium (*Geranium* spp.), bluebells (*Mertensia* spp.) and tufted hairgrass

(*Deschampsia cespitosa*). Soils are moist and are often wet through the growing season, especially when influenced by seeps. Most sites occur above 2,275 m.

Cover Type 4: Exposed bedrock/sparsely vegetated soils/talus slopes

These sites occur where predominately unfractured bedrock or unvegetated soils are exposed. Vegetation is sparse or restricted to margins of talus slopes. Loose fragmented rock is pervasive on gentle to steep slopes.

Cover Type 5: Riparian areas/stream channels

This cover type includes stream channels with flowing water for most of the year. Channels are usually unvegetated and consist of flowing water or dry beds of cobbles or boulders. Vegetation is generally limited to floodplains and streamsides. Tall willow species such as Geyer willow (*Salix geyeriana*), Booth willow (*S. boothii*), Bebb willow (*S. bebbiana*), and Drummond willow (*S. drummondii*) are the dominant shrub species. Alder (*Alnus tenuifolia*) and birch (*Betula* spp.) may be co-dominant. Dominant grasses and forbs include: bluegrass (*Poa pratensis*), reed grass (*Calamagrostis* spp.), sedges, avens (*Geum* spp.), and wild strawberry (*Fragaria virginiana*). Soils are often depositional or medium textured mineral alluvial. Sites usually occur below 2,275 m.

Cover Type 6: Low-mid elevation conifer forest

Low-mid elevation conifer forests include all stages (40 – 300 years post-fire) of lodgepole pine (*Pinus contorta*) and Douglas fir (*Pseudotsuga menziesii*) cover types. This cover type also includes forests dominated by mature limber pine (*Pinus flexilis*) and may contain considerable Engelmann spruce (*Picea engelmannii*) or lodgepole pine. This

cover type is associated with well-drained mountain slopes and extends from lower elevations to about 2,200 m. Soils are gravelly and acidic, and have noticeable bare soil and rock.

Cover Type 7: Mid-high elevation conifer forest

This cover type is made up of all successional stages of the spruce-fir (*Picea* spp.), whitebark pine (*Pinus albicaulis*), and mixed forest cover type series. I also included Krumholtz stands comprised of dwarfed, wind-shaped Engelmann spruce, whitebark pine, and subalpine fir stands close to timberline. These sites generally occur on moist and cool north facing slopes ranging in elevation from 1,800 to 2,100 m. This cover type has variable soil types and occurs on both calcareous and noncalcareous substrates. Bare soil and rock are rare at the lower elevations of this cover type but occur in the Krumholtz stands.

Cover Type 8: Aspen forests

The aspen forest cover type includes all successional stages of sites dominated by aspen (*Populus tremuloides*). Although conifer species may eventually dominate some sites where aspen occurs, the stands classified as "aspen forest" in the Gallatin National Forest GIS library typically include sapling to mature classes of aspens and very few conifers in the over story. This cover type tends to occur on moist slopes, forest openings, and edges of mountain lakes and meadows. Soils are typically moist. This cover type has been found at various elevations.

Cover Type 9: Human disturbed land

These sites include areas where human activities have modified the natural plant community. Changes include agricultural modification, such as hay meadows, seeded pasture, and cropland, where native vegetation has been eliminated or greatly reduced. Also included in this cover type are areas with significant surface disturbance by humans such as driveways, railroad yards, access roads to houses, and human residences. This human disturbed cover type includes sites where human disturbance is no longer present but native vegetation has not re-established. This category is spread over several soil types and terrain forms, but the majority of human disturbed sites were at low elevation on low to moderate slopes.

Cover Type 10: Avalanche chutes and cliffs

Areas with this cover type are typically highly disturbed and occupy the basal portion of avalanche chutes. These chutes occur at both high and low elevations, so vegetation varies. Forbs and/or graminoids form substantial cover in higher elevations, while berry producing shrubs, such as raspberry and blackberry (*Rubus* spp.) and mountain ash (*Sorbus* spp.) are often abundant in low elevation avalanche chutes. This cover type also includes the cliff component. Cliffs are vertical to near-vertical rock formations where vegetation is sparse or restricted to small areas within the cliff that have collected soil.

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