



Soil physical properties and soil water dynamics under spotted knapweed and native grasses
by Tamara Dawn Sperber

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Rehabilitation

Montana State University

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Abstract:

Spotted knapweed (*Centaurea maculosa* Lam.) is an introduced perennial forb that has invaded disturbed and undisturbed semiarid grasslands in the western United States. In the past, success in controlling spotted knapweed and restoring invaded areas has been limited. I hypothesized that the persistence of spotted knapweed in semiarid rangelands might reflect an ability to alter site conditions or a superior ability to take up soil water. The objective of this study was to compare soil physical properties and soil water dynamics under spotted knapweed-dominated areas and native perennial grass-dominated areas on semiarid rangeland. I used six field sites in western Montana with blocks containing almost adjacent plots dominated by spotted knapweed and native perennial grasses. I estimated basal cover and measured plant density and leaf area index (LAI) in each vegetation type at three sites in 1999 and 2000. Basic soil physical properties including particle size fractions, bulk density, and organic carbon content of near-surface soil samples were measured for each vegetation type. I measured soil hydraulic properties in each vegetation type using tension disk infiltrometers. I measured thermal conductivity and calculated volumetric heat capacity and apparent thermal diffusivity of near-surface soils. Near-surface soil temperature regime in each vegetation type at three sites was characterized using buried thermocouples. Soil water dynamics were monitored using a neutron moisture meter at one site and time domain reflectometry at three sites. Total basal cover for spotted knapweed plots was similar to native grass plots at two sites, but basal cover was higher for spotted knapweed plots at one site. LAI was consistently greater in spotted knapweed plots than in native grass plots. Soil physical properties were highly variable and differences between vegetation types were inconsistent within and among sites. At my study sites, soils were not degraded in areas invaded by spotted knapweed. Spotted knapweed plots had lower net precipitation than native grass plots late in the growing season, likely the result of differences in rainfall interception of the two growth forms and litter. Spotted knapweed used more soil water at deeper depths and later in the growing season than native grasses. Soil water was reduced to lower absolute levels at some depths under spotted knapweed compared with native grasses. During this study, greater water use by spotted knapweed for longer periods of time resulted in less soil water for the subsequent growing season. Altering near-surface soil characteristics does not appear to be a mechanism for spotted knapweed's persistence. Rather, spotted knapweed may invade and persist in semiarid rangelands by taking up soil water unavailable to native grasses because of apparent differences in rooting characteristics and phenology and potentially leaving less soil water for native species during subsequent growing seasons.

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by

Tamara Dawn Sperber

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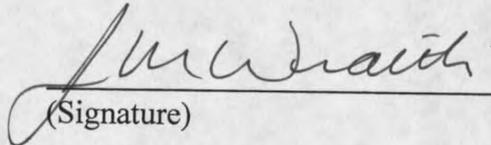
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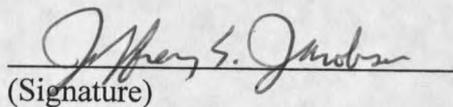
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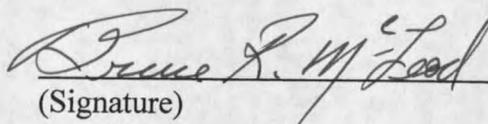
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ABSTRACT

Spotted knapweed (*Centaurea maculosa* Lam.) is an introduced perennial forb that has invaded disturbed and undisturbed semiarid grasslands in the western United States. In the past, success in controlling spotted knapweed and restoring invaded areas has been limited. I hypothesized that the persistence of spotted knapweed in semiarid rangelands might reflect an ability to alter site conditions or a superior ability to take up soil water. The objective of this study was to compare soil physical properties and soil water dynamics under spotted knapweed-dominated areas and native perennial grass-dominated areas on semiarid rangeland. I used six field sites in western Montana with blocks containing almost adjacent plots dominated by spotted knapweed and native perennial grasses. I estimated basal cover and measured plant density and leaf area index (LAI) in each vegetation type at three sites in 1999 and 2000. Basic soil physical properties including particle size fractions, bulk density, and organic carbon content of near-surface soil samples were measured for each vegetation type. I measured soil hydraulic properties in each vegetation type using tension disk infiltrometers. I measured thermal conductivity and calculated volumetric heat capacity and apparent thermal diffusivity of near-surface soils. Near-surface soil temperature regime in each vegetation type at three sites was characterized using buried thermocouples. Soil water dynamics were monitored using a neutron moisture meter at one site and time domain reflectometry at three sites. Total basal cover for spotted knapweed plots was similar to native grass plots at two sites, but basal cover was higher for spotted knapweed plots at one site. LAI was consistently greater in spotted knapweed plots than in native grass plots. Soil physical properties were highly variable and differences between vegetation types were inconsistent within and among sites. At my study sites, soils were not degraded in areas invaded by spotted knapweed. Spotted knapweed plots had lower net precipitation than native grass plots late in the growing season, likely the result of differences in rainfall interception of the two growth forms and litter. Spotted knapweed used more soil water at deeper depths and later in the growing season than native grasses. Soil water was reduced to lower absolute levels at some depths under spotted knapweed compared with native grasses. During this study, greater water use by spotted knapweed for longer periods of time resulted in less soil water for the subsequent growing season. Altering near-surface soil characteristics does not appear to be a mechanism for spotted knapweed's persistence. Rather, spotted knapweed may invade and persist in semiarid rangelands by taking up soil water unavailable to native grasses because of apparent differences in rooting characteristics and phenology and potentially leaving less soil water for native species during subsequent growing seasons.

CHAPTER 1

INTRODUCTION

Invasion of native grasslands by exotic forbs has become a substantial threat to native ecosystems in the western United States. Grazing and human disturbance have greatly increased the spread of exotic species (DiTomaso, 2000; Mack, 1989; Watson and Renney, 1974). Initially only invading disturbed areas, many invasive species are spreading to undisturbed habitats (Mooers and Willard, 1989; Tyser and Key, 1988). Exotic species control has become very important in wildland management. Success in controlling invasive plants in the western United States, with herbicides, grazing, or biological agents, has been limited (Lacey et al., 1986). Invasive species' may persist by altering site conditions or by having greater ability to take up soil water or other limiting resources. Several plant species alter soil physical and chemical properties, favoring their own growth and reproduction (van Breemen and Finzi, 1998). Altering site conditions and/or preempting soil water or other resources may inhibit restoring native species in areas invaded by exotic forbs, because some effects may last long after the forbs are eradicated.

Centaurea species likely pose the greatest threat of all invasive plants to wildland management in the northern intermountain region of the United States (DiTomaso, 2000). On western Montana rangelands, spotted knapweed (*Centaurea maculosa* Lam.) is the number one problem weed (Whitson et al., 1996). Spotted knapweed has invaded 326

counties in the northwestern United States, including every county in Montana, Idaho, Washington, and Wyoming (Sheley et al., 1998). Its invasion has degraded wildlife habitat and cost millions of dollars in livestock forage (Hirsh and Leitch, 1996; Spoon et al., 1983; Watson and Renney 1974). This species invades grasslands and open woodlands in arid and semiarid regions, forming dense infestations that inhibit growth of other species (Fletcher and Renney, 1963; Kelsey and Bedunah, 1989; Tyser and Key, 1988; Watson and Renney, 1974). The limited success in controlling spotted knapweed may partially be due to prolific seed production and seed longevity (Davis et al., 1993; Lacey et al., 1990).

Spotted knapweed may alter hydrology by increasing surface runoff and erosion (French and Lacey, 1983; Lacey et al., 1989) and is thought to degrade wildland soils. However, evidence that this actually occurs is largely anecdotal. Only one study assessed the impact of spotted knapweed on erosion potential (Lacey et al., 1989). Rainfall simulation resulted in greater surface runoff and sediment yield in areas invaded by spotted knapweed compared with areas dominated by native grasses. However, these effects were not significant after the vegetation was removed by clipping, implying that the effects were a result of differences in plant structure and canopy cover rather than a result of altered soil conditions.

Perennial bunchgrasses, common in the semiarid climate of western Montana, have fibrous root systems which are most densely distributed in the upper 30 cm of the soil profile (Frank et al., 1996). Many large tussock grasses, such as bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Löve], have rooting depths that extend to

about 1.5 m (Dobrowolski et al., 1990; Weaver, 1919) under favorable conditions. Other common native grasses, such as Idaho fescue (*Festuca idahoensis* Elmer), have root systems concentrated in the upper 0.5 m of soil (Dobrowolski et al., 1990; Weaver, 1919). In general, most native grasses begin to grow in April or May (Dobrowolski et al., 1990; Stubbendieck et al., 1997). These native species mature and become quiescent in mid- to late summer (Stubbendieck et al., 1997). Regrowth in fall may occur if soil water and temperature conditions are favorable (Stubbendieck et al., 1997).

In comparison, spotted knapweed is a tap-rooted perennial (Watson and Renney, 1974). This forb generally remains a rosette its first year (Boggs and Story, 1987; Watson and Renney, 1974). Spotted knapweed seeds germinate in the fall and early spring (Watson and Renney, 1974). Rosettes form in early spring, tend to bolt in early May, and produce flower buds in early June, which bloom from July until as late as September (Sheley et al., 1998).

Mechanisms of spotted knapweed's persistence need to be determined for successful management and control of spotted knapweed and for sustainable restoration of invaded areas. Some near-surface soil properties and temporal and spatial soil water dynamics might be modified by spotted knapweed because rooting characteristics, basal and canopy cover, and phenology between this species and native grasses may differ. Infiltration of water may be reduced and surface runoff and erosion increased because of changes in near-surface soil characteristics as a result of lower basal and canopy cover in areas invaded by spotted knapweed compared with native grasses. Soil thermal properties might be altered by changes in soil water content, soil organic matter content,

or bulk density, which may result in more extreme temperature variations at the soil surface. This could be detrimental to seed germination of native species, seedling emergence and growth. Spotted knapweed might preempt soil water resources by taking up soil water at different times during the growing season than native grasses or by having access to soil water deeper in the soil profile via its taproot when surface soil is dry.

Altered site conditions by spotted knapweed could limit success in restoring native species by possibly inhibiting seed germination or growth of native species. Spotted knapweed could potentially have a greater ability to utilize soil resources, affecting native species growth and survival. Together or separately, these factors might allow spotted knapweed to persist on semiarid grasslands. Ultimately, to restore invaded areas it is necessary to understand the ecological role of spotted knapweed rather than merely eradicating the invasive forb (Hester, 1991).

Thesis Objective

The objective of this study was to determine if soil physical properties and temporal and spatial soil water dynamics differ under spotted knapweed and native grasses in semiarid grasslands. The potential effects of spotted knapweed on site conditions and soil water dynamics need to be understood to improve weed and land management. Whether simply eradicating spotted knapweed is enough to restore native species, or whether site conditions and/or soil water dynamics differ sufficiently to inhibit restoration in invaded areas needs to be determined.

In this study, I used six field sites to determine whether near-surface soil physical properties differed in areas dominated by spotted knapweed compared with areas dominated by native grasses. Near-surface soil properties included particle size fractions, bulk density, organic carbon content, soil hydraulic properties, and soil thermal properties. Potential differences in selected soil properties were assessed by sampling near-surface soils, measuring infiltration with tension infiltrometers to determine soil hydraulic properties, estimating thermal conductivity with a line-source heat sensor, calculating volumetric heat capacity and thermal diffusivity, and monitoring soil thermal regime with thermocouples. Soil water dynamics under spotted knapweed were compared with native grasses at three field sites. Temporal and spatial soil water dynamics and soil water storage under spotted knapweed and native grasses were monitored using a neutron moisture meter and automated time domain reflectometry (TDR). Soil water retention of near-surface soils collected from spotted knapweed and native grass plots at three sites was measured in the laboratory using a pressure chamber apparatus.

Spotted Knapweed

Spotted knapweed, an invasive forb, was introduced from Europe into the U.S. Pacific Northwest around 1900 (Boggs and Story, 1987; Chicoine et al., 1985; Fletcher and Renney, 1963). Using climate and soils maps, Chicoine et al. (1985) estimated that almost 40% (15 million ha) of Montana is at risk for possible invasion by spotted knapweed. Almost 3 million ha in the Pacific Northwest, with more than 1.9 million ha

in Montana, had been infested by spotted knapweed as of 1989 (Lacey, 1989). Spotted knapweed has now invaded at least 326 counties in the northwestern United States, including every county in Montana, Idaho, Washington, and Wyoming (Sheley et al., 1998).

Spotted knapweed alters plant community composition by reducing species richness and species frequency (Tyser and Key, 1988). It also reduces wildlife habitat and costs millions of dollars in livestock forage (Hirsh and Leitch, 1996; Spoon et al., 1983; Watson and Renney 1974). Bluebunch wheatgrass (*P. spicata*)-rough fescue (*Festuca scabrella*) production was decreased by almost 88% in areas invaded by knapweed (Watson and Renney, 1974). The impacts of spotted knapweed in Montana have cost the livestock industry an estimated \$11 million annually (Hirsh and Leitch, 1996).

Spotted knapweed is a tap-rooted perennial that can live as long as 5 to 9 years (Boggs and Story, 1987). Its seeds (up to 40,000 m⁻²) germinate in early spring or fall (Watson and Renney, 1974). Spotted knapweed seeds may be viable for up to 8 years in soil (Davis et al., 1993). Spotted knapweed may over-winter as rosettes or seeds and can regenerate from old crowns for several years (Watson and Renney, 1974). Root growth is thought to be greatest when in the rosette form (Watson and Renney, 1974). Spotted knapweed infestations usually expand along boundaries of existing stands since seedfall usually occurs within 1 m of the parent plant (Tyser and Key, 1988; Watson and Renney, 1974). The plant contains the growth inhibitor cnicin and is considered to be allelopathic (Fletcher and Renney, 1963; Kelsey and Bedunah, 1989; Kelsey and Locken, 1987).

However, Kelsey and Bedunah (1989) did not consider cnicin's effects to be significant in most habitats.

Invasive Species

As the ecological effects of many plant invasions are becoming evident, more and more studies are being conducted on invasive species and their impact on the environment (Pyšek, 1995). However, research on ecosystem-level impacts of plant invasions has been limited (Ramakrishnan and Vitousek, 1989).

An invasive species can be defined as an exotic species which, regardless of the habitat, is increasing in abundance or distribution (Pyšek, 1995). Many invasive species pose threats to native ecosystems including replacing diverse communities with monotypic stands, threatening native fauna, leading to the extinction of other plant species, altering biogeochemical, geomorphological, or hydrologic processes, or altering disturbance regimes (Cronk and Fuller, 1995; Gordon, 1998). Invasions could change species composition, richness, and diversity, community physical structure, phenology, resource competition, or the trajectory of succession (Gordon, 1998, Walker and Smith, 1997; Woods, 1997). Effects on ecosystem properties are likely to be more substantial when the invading species differs in growth form or resource acquisition, or alters the pattern or frequency of disturbance events (Vitousek, 1986; Vitousek, 1990). However, one of the main catalysts of plant invasions is disturbance, thereby making it difficult to separate the disturbance effects from invasive species effects on an ecosystem (Ramakrishnan and Vitousek, 1989; Vitousek, 1986; Woods, 1997).

The potential of many invasive species to alter ecosystem properties is likely more widespread than initially imagined (Gordon, 1998). For example, at least half of the 31 most invasive, non-indigenous plants in Florida have the potential to alter ecosystem processes (Gordon, 1998). Sand dune formation is an example of a geomorphological effect of an invasive species (e.g., *Ammophila arenaria* L., *Casuarina equisetifolia* J.R. & G. Forst.; Macdonald et al., 1989). Biogeochemical processes, such as nutrient cycling, have been altered in areas invaded by the nitrogen-fixing species *Cytisus scoparius* L. in the Pacific Northwest (Vitousek, 1986), *Kochia scoparia* L. in Colorado (Vinton and Burke, 1995), and *Myrica faya* Ait. in Hawaii (Vitousek and Walker, 1989). These changes in nutrient cycling could potentially alter the trajectory of succession at invaded sites. In California, iceplant (*Mesembryanthemum crystallinum* L.) alters soil biogeochemistry by concentrating salt from the soil profile onto the soil surface (Vivrette and Muller, 1977). Hydrologic patterns have been altered by invasive species such as *Tamarix* spp. and *Andropogon virginicus* L. (Graf, 1978; Mueller-Dombois, 1973). In the southwestern United States and Australia, *Tamarix* spp. have dewatered streams and have altered streamflow and flooding regimes (Graf, 1978). In Hawaii, *A. virginicus* invasion has led to development of boggy areas because its phenology differs from native species (Mueller-Dombois, 1973).

Species Effects

Interest in the effects of individual species on ecosystem properties and processes has increased (Vitousek, 1986; Walker and Smith, 1997; Wardle et al., 1998). An

individual species could have an impact at the ecosystem level if it could alter biogeochemical and hydrological processes, disturbance regimes, or the trajectory of succession.

Wardle et al. (1998) studied 20 herbaceous species from the same functional group to determine if plant ecophysiological traits could be used to predict the impact of a species at the ecosystem-level scale. They assessed relationships between plant traits and litter decomposition, competition and herbivory, and effects of these plants on soil properties including microbial biomass, pH, nitrate concentration, and total nitrogen. They concluded that different plant species have substantially different effects on soil properties and that some plant traits, such as flowering and growth rates, were good predictors of these effects. Combinations of multiple traits could be used to determine a plant species' ecosystem-level effects on soil properties, nutrient dynamics, and the path of succession (Wardle et al., 1998).

Individual species' effects on site conditions and resources may alter successional processes, thus impeding or complicating restoration efforts. The trajectory of succession can be determined by initial and successive seral conditions (Allen, 1988). When the trajectory is altered by initial conditions, restoring the area to a predisturbance state may be impossible (Allen, 1988). Succession may be "suspended" in a state when a highly competitive species dominates (Allen, 1988). According to the traditional range condition model of succession on grasslands, when a community is disturbed it will always return to the "climax" community (Laycock, 1991; Westoby et al., 1989).

Changes in the plant community occur along a continuum and were considered reversible.

However, in the "state-and-transition" model, if a plant community is severely altered or disturbed to the extent that it crosses a "threshold," the system may not return to its original state without intervention (Friedel, 1988; Laycock, 1991; Westoby et al., 1989). Instead, the community will maintain a different stable state.

Exotic species are one of the main factors in North America that may "push" a stable community across a threshold to another stable state community dominated by exotic species (Laycock, 1991). An invasive forb that preempts soil water resources might prevent a plant community from returning to its initial state. If an area is severely infested by an exotic species that has altered site conditions, restoring native species may require additional intervention to remediate the site environment.

Soil Physical Properties

Soil conditions altered by exotic species could be detrimental to western wildlands. Exotic species effects on soil properties have rarely been studied (Macdonald et al., 1989). Most studies in the literature examine the effects of exotic species on soil processes such as nutrient cycling (Blicker, 2000; Vitousek and Walker, 1989; Vivrette and Muller, 1977). Studies on the effects of native or exotic plant species on soil physical properties have seldom been published. Research on the effects of different agricultural practices and crops on soil physical properties, and of soil physical properties influencing crop growth, crop production, root growth, and water use is relatively common. However, agricultural systems substantially differ from semiarid grasslands.

Because many nonindigenous species differ in physical structure, phenology, and function compared with native species, the potential for nonindigenous species to alter soil physical properties seems high. The ability of a soil to be an effective growth medium for plants depends on several physical properties including soil structure, texture, organic matter content, bulk density, and porosity. These same attributes strongly influence soil thermal and hydraulic properties. In semiarid grasslands, water and nutrients are often the most limiting resources (Fowler, 1986). Any changes in soil physical properties may potentially affect soil water and nutrient dynamics of these ecosystems.

Soil Structure

Soil structure, the arrangement of soil particles and pore spaces, plays a key role in soil water and nutrient dynamics (Angers and Caron, 1998). Although soil structure is influenced by climate, human activities, and other factors, vegetation has a substantial impact. Vegetative effects on soil structure and structural stability are related to root penetration, soil water extraction, organic carbon turnover rates, persistence of carbon in the soil, microbial activity, root exudates, and amount of protection provided against precipitation (Angers and Caron, 1998; Goss, 1991; Kay 1990).

Fine roots stabilize soil aggregates (soil particles strongly bound to each other) by enmeshment, by increasing microbial activity, and by releasing binding materials (Angers and Caron, 1998; Oades, 1984; Tisdall and Oades, 1982). Soil aggregate stability tends to increase in areas with perennial grasses because of higher root length density near the

soil surface (Kay, 1990). Roots penetrate the soil and enhance the formation of soil aggregates and pore sequences (Angers and Caron, 1998).

The arrangement of soil aggregates and pore spaces, integral components of soil structure, affect pore size distribution and pore continuity which are important to water flow and storage (Angers and Caron, 1998; Kay, 1990).

Particle Size Fractions

Soil particle size fractions, or texture, can influence soil properties such as bulk density, porosity, thermal properties, hydraulic properties, and water holding capacity. Surface soil in semiarid grasslands can be redistributed from openings between plants to areas surrounding individual plants (Hook et al., 1991). However, this contributes more to differences in soil organic matter content than to differences in soil texture.

Bulk Density

Bulk density of a soil, defined as mass of oven dry soil per unit bulk soil volume, is related to soil texture, soil structure, and the degree of soil compaction and affects soil aeration, root growth, microbial activity, and nutrient and water transport (Smith et al., 1987). Water holding capacity generally decreases with an increase in bulk density for a given soil texture. Although coarse-textured soils (e.g., sandy) have relatively larger pores, total porosity is lower and bulk density is higher than for finer soils or soils high in organic matter. Organic matter content, biological activity, and management practices also affect bulk density. Because the density of organic matter is about half that of soil minerals (Brutsaert, 1982), bulk density tends to increase with a decrease in organic

matter content (Smith et al., 1987). However, organic matter content is typically less than 3-4% percent (mass basis) in most soils of semiarid grasslands.

In general, plant growth is optimal in soils of intermediate bulk density (Passioura, 1991; Stirzaker et al., 1996). In soils with very high bulk density, penetration by roots can be inhibited and access to soil water and nutrients can be limited. In mineral soils with very low bulk density, likely as a result of cultural practices, root-soil contact may be low enough to restrict extraction of soil water and nutrients.

Organic Matter

Organic matter is one of the most important factors affecting soil structure (Hamblin, 1985; Kay, 1990; Smith et al., 1987). In agricultural soils organic matter content, commonly estimated from organic carbon measurements, is the most important indicator of soil quality and productivity (Reeves, 1997). The amount of organic matter in a soil affects soil physical properties such as structure, bulk density, water holding capacity, and heat capacity. Organic matter can increase infiltration by increasing the water holding capacity of near-surface soil, reducing crust formation, and increasing soil aggregation (Oades, 1984; Smith et al., 1987). Lack of organic matter in surface soils can lead to crusting which can decrease infiltration rates by orders of magnitude (Hamblin, 1985). Cultivated soils with lower organic matter contents have lower water holding capacities and are more susceptible to compaction compared with soils with higher organic matter contents (Hamblin, 1985).

In many ecosystems, roots are the most important source of carbon in the soil because a substantial portion of the carbon fixed by plants is allocated belowground (Angers and Caron, 1998). Plant traits such as growth form, biomass allocation, lifespan, and litter quality affect the quantity and quality of organic matter that accumulates under a plant (Burke et al., 1998). In general, grasses are the most efficient at improving soil structure because they allocate about 50% of their photosynthate belowground (Oades, 1984). In addition, there is some evidence that thin roots, which predominate in grasses, have higher turnover rates than thicker roots (Caldwell and Richards, 1986). Tap-rooted plants might contribute less organic matter to near-surface soil layers due to lower root density and slower root turnover rates compared with grasses.

Soil Thermal Properties

Soil temperature is affected by soil color, surface roughness, surface residue, soil water content (Singh and Sainju, 1998), and vegetation. Most literature evaluating the effects of vegetation on soil thermal properties reflects cultivated agricultural systems. Although these systems differ from semiarid grasslands, some general principles can be used to understand these plant-soil interactions.

Many biological processes such as seed germination, seedling emergence, plant production, root growth, microbial activity, and organic matter decomposition and mineralization are affected by soil temperature (Hillel, 1982; Hillel, 1998; Jury et al., 1991; Singh and Sainju, 1998). Most of these processes have an optimum temperature range, with a decrease in rate at temperatures above and below this range (Jury et al.,

1991; McMichael and Burke, 1998). Plant growth is affected by sub- and supra-optimal temperatures because they affect soil water and nutrient uptake (Jury et al., 1991). For example, soil water depletion increased with soil temperature for winter wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.; Wraith and Ferguson, 1994; Wraith and Hanks, 1992). Plants growing in warmer soils matured earlier than plants grown in cooler soils (Wraith and Hanks, 1992). Decomposition rates of organic matter are generally higher at higher temperatures and lower at lower temperatures (Hillel, 1998).

Vegetation can affect the soil surface energy balance by changing the reflectance or albedo of the soil surface, shading the soil surface from solar radiation, altering the soil water regime, removing latent heat by evapotranspiration, and insulating the soil surface (Hillel, 1998; Jury et al., 1991). These effects reduce the amplitude of daily temperature fluctuations at the soil surface relative to bare soil conditions:

Heat is transported in soil mainly through conduction by soil particles, but also occurs by latent heat transfer. Substantial quantities of latent heat may be conducted through soils by evaporation and condensation of water, and by convection with moving water (Hillel, 1982; Shiozawa and Campbell, 1990). Extreme temperature changes may occur at the soil surface because it is the point of radiant energy exchange (Campbell and Norman, 1998). Diurnal and annual temperature regimes are affected by climate, vegetation, and soil thermal properties (Hillel, 1982). The amplitude of the soil temperature oscillations, which approximate a sinusoidal pattern around an average temperature, decreases with depth because heat is absorbed and released by the soil (Campbell and Norman, 1998; Hillel, 1982).

Soil thermal properties are characterized by volumetric heat capacity, thermal conductivity, and thermal diffusivity, which depend on soil composition including organic matter, bulk density, and soil water content (Hillel, 1982; Jury et al., 1991; Shiozawa and Campbell, 1990).

Volumetric heat capacity is the heat required to raise a unit soil volume one degree Celsius and is calculated using the volume fractions of soil constituents, their densities and specific heat capacities (Hillel, 1982; Jury et al., 1991).

Thermal conductivity is the amount of heat transferred through a unit area over a unit time across a unit temperature gradient (Hillel, 1982). Thermal conductivity depends on soil water content, soil aggregation, and soil structure (Hillel, 1982; Jury et al., 1991). The arrangement of soil particles affects the thermal contact between the particles through which heat flows. Thermal conductivity of air is much lower than for water or solids, therefore a soil with a lower water content, higher porosity, or lower bulk density will have lower thermal conductivity (Hillel, 1982; van Wijk and de Vries, 1966). The influence of soil water content on thermal conductivity is much greater in magnitude than the effect of bulk density (Jury et al., 1991).

Thermal diffusivity is the ratio of thermal conductivity to volumetric heat capacity and is the "change in temperature produced in a unit volume by the quantity of heat flowing through the volume in unit time under a unit temperature gradient" (Hillel, 1982).

The effects of plant-soil interactions on ecosystem processes are potentially very important. Considering the marked differences in plant structure, rooting characteristics, and phenology between spotted knapweed and native grasses, it is reasonable to

hypothesize that invasion by spotted knapweed may lead to differences in near-surface soil properties. Particle size fractions are not expected to differ under spotted knapweed and native grasses. In general, plants do not directly alter soil texture. However, different vegetation types could influence the manner in which water and wind redistribute soil particles. Changes in bulk density and organic matter content are possible because potential differences in plant canopy and basal cover, quality and quantity of plant litter, distribution of roots, and type of root structure. These possible changes could alter soil thermal properties and temperature regime, soil water holding capacity, and infiltration. Such changes in soil physical properties could persist after eradicating spotted knapweed and might limit the establishment and growth of native species.

Soil Water Infiltration and Dynamics

Several invasive species alter the hydrology or soil water dynamics of a plant community to the degree of inhibiting growth and survival of native species (Woods, 1997). Drastic effects include dewatering wetlands (*Iris pseudacorus*, *Mimosa pigra*; Woods, 1997), creating boggy areas (*A. virginicus*; Mueller-Dombois, 1973), and altering the hydrology of river systems (*Tamarix* spp.; Graf, 1978).

Invasive species can alter temporal and spatial soil water dynamics by several mechanisms. Invasive species can use more soil water than the native species (Walker and Smith, 1997), which would have a substantial impact in water-limited habitats such as semiarid grasslands. Invasive plants may differ in phenology and use water at different times in the growing season (Walker and Smith, 1997). Seasonal differences in

physiological activities associated with canopy formation, flowering, and dormancy could affect competitive relationships between invasive and native plants. Invasive species that remove soil water earlier or later in the growing season compared with native species could have a substantial impact by reducing the initial amount of water available at the beginning of the current or subsequent growing season. Invasive species may have access to soil water resources which are not utilized by the native community (Walker and Smith, 1997). For example, deep-rooted invasive species may have access to water deeper in the soil profile that is not available to shallower-rooted natives.

Invasive species that differ in growth form from native species could alter surface soil characteristics (Walker and Smith, 1997) or could intercept more or less rainfall. Both of these could affect the overall water balance of a site. Changes in surface soil characteristics could affect infiltration of water into the soil (Branson et al., 1981). An invasive species intercepting different amounts of rainfall than native species would affect the amount of water that reaches the soil surface.

Soil water is often the most limiting resource in semiarid ecosystems (Fowler, 1986). Plant characteristics such as rooting density and depth can greatly influence spatial and temporal water dynamics. The rate at which plants can take up water is a function of soil properties, climatic conditions, and plant traits (Hillel, 1982). The principle soil properties affecting plant water uptake are hydraulic conductivity, matric potential distribution, and soil water retention (Hillel, 1982). Small differences in soil water content can be biologically important because of the nonlinear relationship between soil water content and soil water potential. Soil matric potential is a major factor

affecting plant available water and is primarily affected (at a given soil wetness) by pore size distribution, soil texture, and soil structure (Hillel, 1982).

Soil properties that influence infiltration may affect the amount of water available to plants, in addition to the potential for surface runoff and erosion (Hillel, 1982).

Infiltration depends on several factors, including initial soil water content, soil hydraulic conductivity, and conditions of the soil surface (Hillel, 1982). Vegetative growth form, density, and spatial distribution are important factors that may influence erosion by adding organic matter, detaining particles transported by wind and water, and their impacts on soil faunal activity which will alter surface soil characteristics (Blackburn and Pierson, 1994). Infiltration rates are nearly three times greater near the stems of some desert plants than for areas between plants (Lyford and Qashu, 1969). Soils in areas under plant cover may also have lower bulk densities and higher organic matter contents than soils in open areas (Lyford and Qashu, 1969).

Plant basal and canopy cover, soil structure, soil texture, organic matter content, bulk density, and rainfall intensity affect erosion and runoff (Branson et al., 1981; Gutierrez and Hernandez, 1996; Wertz et al., 1998). Vegetative cover affects erosion by intercepting or dispersing raindrops as well as by obstructing and dispersing overland flow (Rogers and Schumm, 1991). This decreases the velocity of runoff water and its capacity for erosion. Plant and litter cover are among the most influential site factors and organic matter content is one of the most important soil factors influencing erosion (Meeuwig, 1970).

Other factors being similar, as the amount of bare soil increases, erosion rate usually increases (Gutierrez and Hernandez, 1996; Weltz et al., 1998). Erosion and runoff usually increase as grasses are replaced by forbs because of reduced basal and aerial cover (Gutierrez and Hernandez, 1996). In areas with lower basal and canopy cover, less precipitation is intercepted and more bare soil is exposed to the impact of raindrops. The impact of raindrops on bare soil causes the breakdown of soil aggregates (Dobrowolski et al., 1990; Hillel, 1982; Oades, 1984). This can result in a 'sealing' or crusting of the soil surface, decreasing hydraulic conductivity and infiltration, and possibly increasing erosion and surface runoff (Dobrowolski et al., 1990; Hillel, 1982; Oades, 1984). In addition, seedling emergence and survival can be reduced by surface crusting (Hillel, 1982).

About 50 to 70% grass cover is needed to control surface runoff during the growing and dormant seasons on semiarid rangelands of northern Mexico (Gutierrez and Hernandez, 1996). The presence of a fibrous-rooted species decreased runoff by about 250% compared with tap-rooted species by creating more root channels near the soil surface for preferential flow of water into the soil (Pearse and Woolley, 1936). Soil porosity surrounding roots is reduced as a result of compression and the production of organic materials in the rhizosphere (Kay, 1990). However, root channels are created because the soil adjacent to a root has greater strength and stability than the surrounding soil. After the roots die, these root channels are sites for preferential flow of soil water and new root growth (Kay, 1990).

Lacey et al. (1989) examined the effects of spotted knapweed on surface runoff and sediment yield. Using a rainfall simulator, they found that runoff and sediment yield from grass-dominated sites were significantly less than for spotted knapweed-dominated sites. However, there were no significant species effects on surface runoff and sediment yield after vegetation was clipped. This suggests that soil properties affecting surface runoff and sediment yield were not affected by any particular characteristic associated with spotted knapweed. The authors concluded that grasses protect the soil and enhance infiltration more than spotted knapweed.

Preempting soil water resources by using more water or using soil water earlier or later in the growing season may be a competitive mechanism of some invasive species. Semiarid regions characteristically have high potential evapotranspiration rates with most precipitation coming in small rainfall events (Sala et al., 1992). Therefore, the surface soils of these areas are usually dry. The upper layer of soil generally has the highest root density and is subject to extreme drying because of evaporation as well as water uptake by roots. The response times of plants to small rainfall events can influence which temporal and spatial water resources are available. Plants with quicker response times are more able to exploit small rainfall events than plants that have slower response times (Sala and Lauenroth, 1982; Wraith et al., 1995).

Root distribution also influences which soil water resources are available to plants (Sala et al., 1992). In general, root density decreases with depth (Singh and Sainju, 1998). Fibrous roots are relatively more dense near the soil surface than taproots which usually grow to deeper depths (Singh and Sainju, 1998). Plant species with deeper root

systems may escape competition at certain times by having access to water deep in the soil during prolonged periods when evaporative demands are high (Dobrowolski et al., 1990). The deeper penetration of taproots may allow access to soil water deeper in the soil profile when the surface soil may be dry (Sala et al., 1992). In the shortgrass region of the U.S. Great Plains, deep taproots of shrubs and forbs provide an advantage during or following wetter years when soil deeper in the profile has been recharged (Sala et al., 1992). Extensive fibrous root systems may have greater overall root length and surface area, which may facilitate rapid access to the volume of soil in which water is most often present. However, in a case where growth form, root distribution, and root biomass were similar between two tussock grasses, Eissenstat and Caldwell (1988) found that other differences in the root systems (root thickness and season of root growth) affected the ability to compete for soil water and nutrients.

Early spring growth and/or delayed dormancy in late summer or fall could make spotted knapweed relatively effective at utilizing limited soil water resources and this could result in less soil water being available for growth of native species. The taproot of spotted knapweed could allow access to water stored deeper in the soil profile, which is relatively inaccessible by native grasses. However, in many semiarid regions presence of substantial soil water at depths below native plant roots is probably not common.

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CHAPTER 2

SOIL PHYSICAL PROPERTIES AND PROCESSES UNDER
SPOTTED KNAPWEED AND NATIVE GRASSESIntroduction

In the western United States, native grassland ecosystems are being threatened by invasive plant species. Initially invading disturbed areas, many exotic species are spreading into undisturbed habitats (Lacey et al., 1990; Tyser and Key, 1988). Spotted knapweed (*Centaurea maculosa* Lam.), an invasive forb introduced from Europe (Boggs and Story, 1987; Chicoine et al., 1985), is an extensive noxious weed on western Montana rangelands (Whitson et al., 1996) and is a serious concern in the Pacific Northwest (Sheley et al., 1998) and Canada. Spotted knapweed invades grasslands and open woodlands in arid and semiarid regions, forming dense stands that inhibit the growth of other species (Fletcher and Renney, 1963; Tyser and Key, 1988; Watson and Renney, 1974). Wildlife habitat and millions of dollars in livestock forage have been lost as a result of its invasion (French and Lacey, 1983; Hirsh and Leitch, 1996).

Success in controlling spotted knapweed and restoring invaded areas to native species has been limited. Because of differences in plant and root structure, and phenology between spotted knapweed and native grasses, spotted knapweed may alter site conditions or may have a superior ability to utilize limited soil resources such as water or nutrients. Several plant species alter soil physical and chemical properties, favoring their

own growth and reproduction (van Breemen and Finzi, 1998). The potential for nonindigenous species to alter soil physical properties may be related to differences in plant growth form, phenology, and function compared with native species. Native grasses in semiarid grasslands have fibrous root systems that are densely distributed in the upper soil profile (Dobrowolski et al., 1990; Weaver, 1919). Spotted knapweed is a tap-rooted perennial (Watson and Renney, 1974). This forb generally spends its first year as a rosette and bolts during subsequent years (Watson and Renney, 1974).

Soil physical properties including texture, structure, bulk density, and organic matter content influence plant germination and growth as well as soil thermal and hydraulic properties and processes. Changes in plant community structure might alter near-surface soil properties, which could impact root growth, soil water and nutrient uptake (Hamblin, 1985), water holding capacity, infiltration characteristics, or heat capacity (Oades, 1984; Smith et al., 1987). Altering properties such as soil water content, organic matter content, or bulk density would alter soil thermal properties, which could influence seedling emergence and growth. Substantial changes in soil physical properties could sufficiently alter site conditions to inhibit native species' growth or limit the success of restoring desired plant communities. Such changes might persist long after eradicating the invasive plant community. If so, suitable revegetation with native species would require amending these altered soils.

In semiarid grasslands, soil water and nutrients are frequently limiting resources for plant growth (Fowler, 1986). Changes in soil physical properties might alter soil water and nutrient dynamics of these ecosystems. As bare soil area increases, erosion and

potential for surface runoff also generally increase (Gutierrez and Hernandez, 1996; Weltz et al., 1998). Areas dominated by species with fibrous root systems generally have less runoff than areas dominated by taproot species (Pearse and Woolley, 1936). Greater exposure to raindrop impact can cause surface soil crusting, reducing hydraulic conductivity and infiltration (Dobrowolski et al., 1990; Hillel, 1982; Oades, 1984). Surface crusting can also negatively affect seedling emergence and survival (Hillel, 1982).

Spotted knapweed might increase surface runoff and erosion (French and Lacey, 1983; Lacey et al., 1989) and is thought to degrade wildland soils, but evidence for this appears to be largely anecdotal. Only one study has assessed the impact of spotted knapweed on erosion potential (Lacey et al., 1989). Simulated rainfall resulted in greater surface runoff and sediment yield in areas dominated by spotted knapweed compared with areas dominated by native grasses. However, after clipping the vegetation and repeating the measurements, surface runoff and sediment yield were similar. This suggests the initial responses were a result of differences in plant structure and canopy cover rather than of altered soil properties. Therefore, if soil properties are not altered in spotted knapweed-dominated areas, to successfully restore these areas land managers would not need to physically ameliorate soils.

The objective of this study was to determine whether near-surface soil properties differed between adjacent areas dominated by spotted knapweed and native grasses. I measured selected soil physical properties including particle size fractions, bulk density,

