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Effect of Biocrust Development on Establishment of Native Plants in a Salt Desert System

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EFFECT OF BIOCRUST DEVELOPMENT ON ESTABLISHMENT OF NATIVE PLANTS IN A SALT DESERT SYSTEM

by

Merran Owen

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Ecology

Approved:

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UTAH STATE UNIVERSITY
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ABSTRACT

Effect of Biocrust Development on Establishment of Native Plants in a Salt Desert System

by

Merran Owen, Master of Science

Utah State University, 2020

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Department: Wildland Resources

In salt desert shrublands of the Great Basin, exotic annual plants are displacing native species. The low productivity and recruitment of these systems leaves them with limited resilience, and active revegetation efforts are often unsuccessful. Biological soil crusts, an important component of these communities, may provide favorable microsites for the reintroduction of native species with increased water and nutrient availability, while limiting competition from exotics. I tested how differing levels of biological soil crust development influence establishment and persistence of three native grasses, Indian ricegrass (*Achnatherum hymenoides* (Roem. & Schult.) Barkworth.), squirreltail (*Elymus elymoides* (Raf.) Swezey), basin wildrye (*Leymus cinereus* (Scribn. & Merr.) Á. Löve) and one native forb, gooseberryleaf globemallow (*Sphaeralcea grossulariifolia*, (Hook. & Arn.) Rydb.). I tested responses of these species with two establishment methods: broadcast seeding and transplanting of greenhouse-grown seedlings. Experiments were done in a degraded salt desert shrubland in southeastern Idaho, on salt-affected soils. I evaluated planting techniques in areas of both high and low crust development. Plant survival, size, and reproductive success were measured at different points in time for a year after planting. Broadcast seeding largely failed across all levels of crust development and species. Biological soil crust development had a significant effect on the ability of spring plantings in a dry year to survive through the first summer after planting. The survival of transplanted seedlings differed significantly by species. This study demonstrates the greater success of transplanting as a method of native species establishment, and the benefits of high soil crust development in the initial establishment of transplanted seedlings under dry conditions.

(141 pages)

PUBLIC ABSTRACT

Effect of Biocrust Development on Establishment of Native Plants in a Salt Desert System

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Salt desert shrublands are semiarid, shrub-dominated ecosystems that inhabit salt-affected soils. In Great Basin salt deserts, exotic annual plants are invading and displacing native plants. Low plant productivity and slow population growth of native plants in these ecosystems makes them vulnerable to invasion and limits their ability to compete with invasive plants and return to a natural state. Active revegetation efforts, such as planting and direct seeding of native plants, are often unsuccessful for the same reasons. Biological soil crusts (communities of cyanobacteria, lichen, moss, microfungi and other microorganisms that live on the surface layer of the soil) are an important component of salt deserts and commonly occur in the interspaces between plants. Biological soil crusts may provide favorable places to target revegetation practices, as they can provide increased water and nutrients to vascular plants. Additionally, exotic annual species are less able to invade and dominate biological soil crusts. I tested how differing levels of crust development (the amount of cyanobacteria and other organisms) influence the effectiveness of two methods of planting native species: broadcast seeding and transplanting of greenhouse-grown seedlings. Experiments were done in a degraded salt desert shrubland in southeastern Idaho, on salt-affected soils. I evaluated planting techniques in areas of both high and low crust development. Treatment combinations were applied to three native grasses, Indian ricegrass (*Achnatherum hymenoides* (Roem.

& Schult.) Barkworth.), squirreltail (*Elymus elymoides* (Raf.) Swezey), basin wildrye (*Leymus cinereus* (Scribn. & Merr.) Á. Löve) and one native forb, gooseberryleaf globemallow (*Sphaeralcea grossulariifolia*, (Hook. & Arn.) Rydb.). Plant survival, size and reproductive success were measured at different points in time for a year after planting. Broadcast seeding largely failed across all levels of crust development and species. Biological soil crusts improved the ability of spring-planted species, in a dry year, to survive through the first summer after planting. The survival of transplanted seedlings varied across species. This study demonstrates the greater success of transplanting as a method of native species establishment, and the benefits of high soil crust development in the initial establishment of transplanted seedlings during dry times.

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Merran Owen

CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

INTRODUCTION

The Great Basin is an ongoing experiment in the revegetation of arid rangelands. Hundreds of costly interventions, dating back to the early 1900's, have attempted to prevent damaged shrublands from transitioning to a new, stable state dominated by invasive annual grasses (Pilliod et al. 2017). Historically, Great Basin-Colorado Plateau sagebrush semi-desert communities have received the most rehabilitation (Jessop & Anderson 2007), while Intermountain salt-desert shrubland – an ecosystem with less precipitation, less productivity and less resilience (Chambers et al. 2014a; Chambers et al. 2014b; Roundy et al. 2018) – has frustrated the revegetation efforts of land managers (Bleak et al. 1965; Hull 1963; Plummer 1966).

Salt deserts are a widespread ecosystem in the western U.S. (Blaisdell & Holmgren 1984; Jonas et al. 2018). In the Great Basin, salt deserts are found in enclosed basins that catch the weathering products of surrounding ranges. Annual precipitation is typically below 250-350 mm and highly variable from year to year. The lack of drainage, low precipitation and high temperatures ensure that salts accumulate rather than leach from the soil profile. The plant species that dominate in this type of habitat are deeply-rooted, salt tolerant shrubs with low productivity. The result is infertile soils with shallow accumulations of salts, and slow-growing plant communities that have proven susceptible to disturbance (Blaisdell & Holmgren 1984; Jonas et al. 2018).

Widescale sampling of Great Basin sites seeded with native, perennial grasses determined that established grass cover correlates with elevation (Knutson) et al. 2014). In low elevation, arid valleys where salt desert occurs, little perennial cover was found in the decades post-seeding, and seedings are less likely to suppress the invasion of annual grasses (Knutson et al. 2014; Roundy et al. 2018). Natural patterns of post-disturbance succession in salt desert shrublands can take up to a century (Blaisdell & Holmgren 1984), and plant recruitment from seed in these rangelands is often slow, with periodic establishment events that occur under favorable weather (Allen 1995). There is very little research demonstrating how to successfully restore native plant communities in degraded salt desert environments (Grant-Hoffman et al. 2015; Humphrey & Schupp 2002; Jessop & Anderson 2007; Jonas et al. 2018).

Even in the early years of rehabilitation, Great Basin land managers were quick to realize that seeding success in areas with less than 200 mm of annual precipitation was prohibitively low. Prioritizing revegetation in areas of higher precipitation and simply limiting the use of salt desert areas was seen as a better strategy (Bleak et al 1965; Plummer 1966). The majority of success in establishing perennial plant cover in salt desert has come from the introduction of Eurasian bunchgrasses (Johnson 1986; Rogler & Lorenz 1983). These grasses were used for projects that prioritized erosion control, forage availability and weed suppression, all problems that had come to the forefront by the mid-1900's. Introduced grasses such as crested wheatgrass (*Agropyron cristatum* [L.] Gaertn.) were better than the native species at establishing in the degraded conditions now common in rangelands (Young & Evans 1986).

Though crested wheatgrass functions as a stabilizing force in damaged rangelands, it does not act as a "bridge" species or allow for a linear return to a native plant community, and now forms naturalized stands across thousands of hectares within the Great Basin (Gunnell et al. 2011; Fansler & Mangold 2011). In fact, crested wheatgrass may provide fewer ecosystem services than native plant species. As forage grasses are chosen for their aboveground productivity, research in the Northern Great Plains has shown crested wheatgrass to have less below-ground biomass and supply less nitrogen to the soil than native grasses. This potentially affects invertebrate animal populations, soil microbial activity and soil erosion (Lesica & DeLuca 1996; Wilsey & Polley 2006). In the Great Basin, crested wheatgrass is known to interfere with native species establishment and growth (Gunnell et al. 2010; Morris et al. 2019), thus negatively affecting biodiversity and wildlife habitat (McAdoo et al. 1989).

If native plant establishment is the goal, a viable revegetation strategy may be to target microhabitats that may be more likely to aid establishment, such as biological soil crust (Bowker 2007). In the past, this crust cover, composed of cyanobacteria, cyanolichens, moss and other organisms, dominated plant interspaces in the Great Basin, but has since been severely degraded by overgrazing, dry farming and soil erosion (Belnap 2003; Mack & Thompson 1982). Loss of crust cover due to these historical disturbances may have been a prominent factor limiting the natural resilience of the salt desert ecosystem (Bowker 2007). In sparsely populated plant communities, it is the many organisms in biological soil crust communities that provide ecosystem services such as soil stabilization, soil aggregation and the fixation of both carbon and nitrogen. As legumes are uncommon in cold deserts, soil crusts act as a primary source of nitrogen fixation in this ecosystem. The secretion of soil organic matter and nitrogen by cyanobacteria and lichen improves soil fertility and augments soil microbial communities and mycorrhizal fungi. Biological soil crust also improves water filtration, and the pigmentation produced by cyanobacteria darkens the soil and extends soil warmth during the shoulder growing seasons (Belnap 2003; Belnap & Harper 1995; Blaisdell & Holmgren 1984; Harper & Pendleton 1993; Harper & Belnap 2001; Pendleton et al. 2003). Several studies have illustrated the contributions of soil crust to vascular plant growth. Concentrations of nitrogen and phosphorus have been found to be higher in the tissues of plants grown in biological soil crust in both the wild and the greenhouse compared to bare soil. (Belnap & Harper 1995; Blaisdell & Holmgren 1984; Harper & Pendleton 1993; Harper & Belnap 2001; Pendleton et al. 2003). In lab studies, seedlings planted in crust have increased mycorrhizal relationships as well (Harper & Pendleton 1993).

Despite the contributions biological soil crust makes to the growth of established plants, its effect on seed germination is more complicated. In many studies, soil crust has been found to inhibit seed germination by preventing water uptake (McIlvanie 1942; Prasse & Bornkamm 2000; Serpe et al. 2006) or by acting as a physical barrier (Prasse & Bornkamm 2000; Zaady 1997). However, these results are not conclusive, and some studies suggest that the presence of biological crust is beneficial to seed germination. St. Clair et al. (1984) demonstrated that when the soil crust of a salt desert community is damaged in a way that mimics the effects of grazing, seed germination of native and introduced grasses is depressed. This relationship was reinforced by a laboratory experiment in which biological crust samples were collected, seeded with perennial grasses and watered weekly (St. Clair et al. 1984). Current speculation is that seed-crust interactions may be species-specific, both for the species of vascular plant and the dominant crust microorganism (Bowker 2007; Serpe et al. 2006). The way in which crust develops and how it reaches its particular species composition and microtopography influence its effects on vascular plants (Belnap et al. 2001; Belnap 2003).

Many of the benefits provided by biological soil crust vary by the level of crust development. Crust development most generally indicates the amount of cyanobacterial biomass and species diversity (Belnap et al. 2001; Belnap 2003). In biological crusts around the world, cyanobacteria such as the common *Microcoleus vaginatus* are the first to colonize a soil, and begin the development process by bonding soil particles together. After initial colonization, climate becomes a primary factor in determining how crusts develop and which species will be involved. In hot deserts, moss and lichen are less abundant, and because soils do not frost-heave, result in biological crusts dominated by cyanobacteria and with a smooth surface. In cold deserts, lichens and moss colonization follow cyanobacteria successionally. Moss and lichen are the dominant species in biological crusts of the Great Basin (a cold desert), and thus an abundance of mosses and lichens can indicate advanced crust development (Belnap et al. 2001; Belnap et al. 2008; Serpe et al. 2006). Moss and lichen restrict frost-heaving to a “rolling” surface with pinnacles of around 5 cm or less (Belnap et al. 2001; Belnap et al. 2003). The highest pinnacles are typically seen in cold deserts with coarser textured soils – moss and lichens have difficulty colonizing these biological crusts, thus allowing pinnacles to reach 15 cm in height (Belnap et al. 2001; Belnap et al. 2003).

In Great Basin crusts that have developed a cover of moss and lichens, mosses are capable of desiccating seeds and preventing them from germinating (Serpe et al. 2006). This inhibitory effect was seen in lichen-dominated crusts in southwestern Idaho (Serpe et al. 2008). However, the accompanying increase in microtopography in well-developed, cold desert crusts may increase the availability of moist, protected sites ideal for germination (Belnap 2003; Eckert et al. 1986), perhaps explaining the depressed seed germination seen by St. Clair et al. (1984). Soil moisture may increase with increasing level of biological crust development. In cold deserts with pinnacled crust, the level of development, estimated according to coloration and microtopography (Belnap et al. 2008), is a reliable indicator of hydrological processes such as water infiltration, runoff and erosion. Field trials show that crust pinnacles cause water to pool, and water infiltration significantly increases (Belnap et al. 2013). More developed crusts also have both nitrogen fixing and carbon fixing bacteria, produce more soil aggregates and provide more protection from erosion (Belnap et al. 2001; Belnap 2003). A synthesis of the positive effects of biological crust on adult vascular plants and the mixed effects on seed germination, concluded that the overall effect of biological crust on vascular plant establishment and survival was likely a net positive (Bowker 2007).

There is a certain amount of nuance involved in vascular plant/biological soil crust interactions. Effects may differ based on plant life stage (seed vs. established plant), plant species, or the development, i.e., microtopography and species composition, of the biological crust. These factors suggest that, in revegetation projects utilizing biological crust, success may differ not only based on the level of crust development but based on the method of plant reintroduction. Transplanting greenhouse-grown seedlings is an alternative to more established methods like large-scale direct seeding (Bean et al. 2004), but juvenile plants may be better suited to benefit from soil crust than seeds. Transplants will have access to the improved water retention and nutrient availability of biological crusts and bypass the potential downside of limitations on germination. There is also evidence that in semi-arid and arid ecosystems, transplants are more successful than seedings overall (Abella et al. 2012; Bean et al. 2004; Dettweiler-Robinson et al. 2013; McAdoo et al. 2013; Van Epps & McKell 1983), as they have survived the most limiting life stages (James et al. 2011) and are better able to mitigate unfavorable conditions in the field (Hardegree et al. 2013).

My experiment investigated the effect of level of biological soil crust development on the survival and establishment of native, herbaceous plants in a degraded salt desert ecosystem. I studied survival and establishment of plants at two life stages: broadcasted seeds and transplanted, greenhouse-grown seedlings. My questions included:

- Will species establishment increase with biological crust development?
- Will germination and establishment differ by plant species?
- Will high-input practices, such as planting greenhouse-grown seedlings, be more effective for establishment than low-input practices, such as broadcast seeding?

METHODS

Study site

Antelope pasture, located in the Black Pine Valley of Oneida County, Idaho (Lat/Long: 42° 0'50.05"N, 112°55'53.90"W), is a 1500-acre portion of the Curlew Grazing Allotment, managed by the Pocatello Field Office of the Bureau of Land Management (BLM). The site is a low elevation (4500 m) shrubland. Mean annual precipitation for the 1981-2010 time period was 303.5 mm and mean annual temperature was 8.72 ºC (PRISM Climate Group 2014). Total annual precipitation was 203 mm in 2018 and 386 mm in 2019 (PRISM Climate Group 2014).

Until 2015, the pasture was on a spring/fall, three-year rest-rotation grazing schedule (DOI 2015), but grazing has now been discontinued. The pasture is heavily invaded with exotic annuals such as cheatgrass, halogeton (*Halogeton glomeratus* [Bieb.] C.A. Mey.), and clasping pepperweed (*Lepidium perfoliatum* L.). Land-use history of the pasture includes livestock grazing, possible homesteading and cultivation of crested wheatgrass (Appendix A).

My plots were located in the northwest corner of the pasture. The area has intact biological soil crust across a range of development levels, meaning a range of cyanobacteria, lichen and moss abundance. Dominant shrubs are Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis*) and black greasewood (*Sarcobatus vermiculatus* [Hook.] Torr.); dominant grasses are squirreltail (*Elymus elymoides* [Raf.] Swezey) and Sandberg bluegrass (*Poa secunda* J. Presl). The vegetation and soils were inventoried and mapped in the summer of 2017 (Appendix A). The northwest corner has less foliar cover of cheatgrass, on average, than the pasture as a whole, and a higher cover of invasive annual forbs (Appendix A, Figures A.9- A.12). The negative correlation between cheatgrass and biological soil crusts found in this pasture has been seen in other Great Basin plant communities (Ponzetti el al. 2007, Root et al. 2020; Appendix A, Fig A.31). I classified soils within the study area (Appendix A; Figure A.22) as fine-silty, mixed, superactive, mesic Xeric Natrargids, meaning that the biological soil crusts live in a thin, pale surface horizon with little organic matter and a soil moisture regime characterized by prolonged summer drought. The surface horizon are loams or silt loams with a mildly alkaline pH. The soils in my study area are very deep silt loams or silty clay loams. A natric horizon, characterized by clay illuviation and high sodium content, is present in the soil subsurface (Appendix A). Natric horizons are sodium-affected at a level that negatively affects plant growth (Brady & Weil 2010; Soil Survey Staff 2014). The upper boundary of the natric horizon occurs within 40 cm of the soil surface (Appendix A).

Experimental design

To test the effects of planting technique and biological soil crust development, I used a factorial design that crossed two planting techniques (broadcast seeding vs. transplanting of greenhouse-grown seedlings) with two levels of biological soil crust development (high vs. low). Level of biological crust development was measured using the visible assessment scale developed in Belnap et al 2008. This scale is based on using coloration and topography to rank or categorize cyanobacterial, lichen and moss development into six different levels of biological crust development. This scale was developed and tested in the soil crust of five semi-arid, western US plant communities, including a Wyoming Big Sagebrush community in semi desert loam. As such, it is considered directly applicable to Great Basin crust communities (Belnap et al. 2008). Crust ranking from 1-3 was categorized as “low” and crust ranking from 4-6 was categorized as “high.” This experimental design was repeated for each of three native grasses and one native forb species, all present within the general area: basin wildrye (*Leymus cinereus* [Scribn. & Merr.] Á. Löve), wild-collected seed, origin Utah; squirreltail (*Elymus elymoides* (Raf.), Rattlesnake Germplasm; Indian ricegrass (*Achnatherum hymenoides* [Roem. & Schult.] Barkworth), “Rimrock”; and gooseberryleaf globemallow (*Sphaeralcea grossulariifolia* [Hook. & Arn.] Rydb.), wild-collected seed, origin California. The experimental design for each species was repeated twice, once to compare fall seeding with fall planting, and once to compare fall seeding with spring planting.

Small 50 cm x 50 cm plots (n = 160) were randomly established within an approximately 400 m x 200 m area characterized by varying crust development, moderate to absent exotic annual plant cover, and co-dominance by black greasewood and Wyoming big sagebrush shrubs. Plots were split evenly between high and low crust development, so that five plots were assigned to each of the four crust-planting treatment combinations for each of the four target species in each of two years (Table 1). To establish plots, I walked outwards in a circle from randomly generated points until a suitable plot location was found; plots were entirely composed of biological crust from one category of development (high or low), located at least 3 m from any other plot, had < 5% perennial plant cover, and were located in interspaces between shrub canopies.

Fall seeding occurred in December of 2017 and 2018. Plots were broadcast seeded with 150 seeds of the species assigned to that plot. The USDA recommended single species rate for drill seeding of squirreltail, basin wildrye, Indian ricegrass and globemallow is 22-24 Pure Live Seed per square foot (Majerus 2013), which translates to about 65 seeds per 0.25 m^2. When broadcast seeding, best practices are to use two to three times the drill seed rate (Hardegree et al. 2016), which I approximated with my rate of 150 seeds per 0.25 m^2. Species with a hard seed coat (Indian ricegrass and gooseberryleaf globemallow) were stratified via immersion in 90% sulfuric acid for 1 minute, then rinsed under water and left to dry (Jones 1990). Once seeds were sown, cheesecloth was loosely placed over the plot to prevent seeds from blowing away and anchored using landscape staples. Cheesecloth was removed in the following February of each year.

Seedlings were transplanted on April 9 (spring planting) and Oct 24 (fall planting), 2018. Seedlings were germinated and grown in 10-cm conetainers in a greenhouse located on the Utah State University campus prior to planting. Slower growing species (Indian ricegrass and gooseberryleaf globemallow) were started a month earlier so that they would have more time to grow, and seedlings planted in the fall were older (and larger) to increase chances of winter survival (Grossnickle 2005). Indian ricegrass and gooseberryleaf globemallow were 4 months old at spring planting and 7 months old at time of fall planting. Basin wildrye and squirreltail were 3 months old at spring planting and 6 months old at time of fall planting. Seedlings were transplanted using a dibble stick, and soil was moist for the full depth of the seedling for both the spring and fall plantings. Four transplants of a given species were planted in a plot.

Seedlings were spaced at the mid-point of each of the 50 cm sides of a plot. Transplants were watered once, two weeks after planting, to settle the soil and alleviate transplant shock (Grossnickle 2005). Watering of plantings occurred between the hours of 7-8:30 am; a hole was poked into the bottom of a 500 ml water bottle with a pin, the bottle was placed next to the plant and allowed to drain.

Data collection

All seeded and planted plots were monitored for plant survival, height, basal diameter (for grasses) or number of stems (for forbs) and reproductive status during the first week of April, May, June and Sept in 2018 and 2019. Plants with any green biomass were recorded as alive. Height was measured from the ground to the highest point, inflorescence included, and the plant was not stretched or manipulated in any way. Reproductive status was measured by counting the number of flowering stems. At each sampling, ocular estimates of cumulative invasive species canopy cover were taken for all invasive plant species rooted within each 50 x 50 cm plot (Table 2). I included all invasive plant species that had a mean canopy cover of 1% or greater, which included clasping pepperweed, burr buttercup (*Ranunculus testiculatus* Cranz.) and cheatgrass.

Analyses

Survival of seeded plants was too low for analysis, so analysis was performed on survival of transplanted seedlings alone. Numbers of surviving plants were too low to analyze height, basal width and stem count. Analysis of spring-planted and fall-planted seedling survival was done separately. I analyzed the number of surviving seedlings in species-crust treatment combinations at four time points, corresponding to the beginning and end of summer: June 2018, September 2018, June 2019 and September 2019. For each season of planting - time period combination, I used a binary logistic regression model with the number of successes (live plants out of 4) as the response variable. The main fixed effects were plant species (ACHY, ELEL, LECI, SPGR) and biological soil crust level of development ("LOD"; high vs. low), with cumulative invasive plant cover as a covariate. Invasive plant cover was centered on its overall mean for each analysis. Due to a limited number of degrees of freedom in the spring cohort dataset, I began with an additive model and then used Akaike information criterion (AIC) testing to determine which interactions to include (Arnold 2010). For fall cohort data, I used a full factorial model. Post-hoc, pairwise testing was done using estimated margin means and a Tukey adjustment familywise error rate. I ran ANOVA tests on plant height and number of flowering stems for fall transplants only, due to the low survival rate in spring transplants. Pairwise testing used a Tukey adjustment familywise error rate. I used an alpha of 0.01. Analysis was conducted in R (R Core Team, 2018), using the glm function, car package (Fox & Weisberg 2019) and emmeans package (Length 2019).

RESULTS

Broadcast seeding failed to establish seedlings across all levels of species and biological soil crust development. There were small amounts of seedling emergence each spring (Table 2), but seedlings failed to establish, and the final count for each plot was zero. I saw a trend of higher frequency of emergence in 2019, when precipitation following seeding was above average (Fig. 1), and a possible trend towards higher emergence in plots with low crust development. Squirreltail showed the highest rates of emergence (total number from both June samplings: 25 seedlings, out of 12,000 broadcast seeds). Indian ricegrass and basin wildrye had no recorded emergence (Table 2).

Spring and fall transplants were subjected to different levels of precipitation during their first spring growing season and summer drought (Fig. 1). Both cohorts experienced a dry summer season, but fall transplants underwent a wet winter and spring following planting, with precipitation (Dec through the end of May) 74 mm above 30-year normals. In contrast, the winter preceding spring transplanting was dry, with precipitation 56 mm below 30-year normals for the same time period. Mortality was highest for spring transplants in the summer following planting (58% of all seedlings planted died between Jun and Sept 2018), and in the winter following planting for the fall transplants (36% died between Oct 2018 and June 2019) (Fig. 1).

Survival of spring transplants in the fall following planting (Sept 2018, 5 months post-planting) was 28%, while survival of fall transplants in the fall following planting (Sept 2019, 11 months post-planting) was 61%.

Within the spring-planted cohort, higher levels of biological soil crust development increased survival through the first summer drought. Five months after planting (Sept 2018), high levels of biological crust development were associated with increased survival (LOD effect p = 0.001; Table 3), an effect that appeared to be driven by squirreltail and gooseberryleaf globemallow (Tables B.1-2, Fig. 2; borderline significant Level of Development (LOD)*species interaction of p = 0.08 in top interactive model, Appendix B). The level of crust development did not have a significant effect on survival for subsequent time periods (Jun 2019, p = 0.187; Sept 2019, p = 0.235; Table 3). There were no significant crust effects on the survival of fall-planted seedlings for any time periods, though a plant species*level of development interaction was borderline significant in the summer and fall sampling periods (Jun 2019, p = 0.052; Sept 2019, p = 0.032; Table 4), an effect driven by a positive effect of crust development on Indian ricegrass and negative effect on globemallow (Table 4, Fig. 3).

Plants of some species were significantly more likely to survive than others, and the most successful species showed different patterns between the spring and fall cohorts. For spring transplants, Indian ricegrass over-summer survival (measured in Sept 2018, five months after planting) was significantly higher than that of the other three species (Tables 3&5; Figure 1). A full year later, pairwise comparisons showed no significant differences between species, likely because of low overall survival (9.6% across species) (Tables 3&5, Fig. 1). For fall transplants, squirreltail and basin wildrye consistently had the highest rates of survival over multiple time periods (Tables 4&6; Fig. 1), with final numbers of 82.5% and 95%.

Survival of spring transplants was too low to analyze flowering or height, but fall transplants (measured in June 2019, 8 months after planting) showed a significant effect of species, but not of crust development. Squirreltail produced more flowering stems than other species, regardless of crust development (Tables 8&9). Level of biological crust development did not significantly affect the height of fall transplants, either in spring or in the fall (Tables 10&11).

The percentage cover of invasive species within a plot did not significantly affect the survival of seedlings, nor interact with level of biological crust development (Tables 3-4).

DISCUSSION

My results indicate that transplanted seedlings, particularly when planted during fall of a wet year, led to high survival rates of four native species in salt desert. In contrast, broadcast seeding, in both a dry and wet year, yielded no established plants. I also found that biological crusts increased early survival of spring-planted transplants during a drier year, and that survival varied across species. Together these results suggest that restoration of native species into salt desert environments – something that rarely has been done – may be feasible with transplants under certain precipitation and microsite conditions and with certain species.

Seeding

Broadcast seeding failed over both levels of biological crust development and over both years, despite precipitation in 2019 being >50% greater than 30 year normals (Mar-May 2019 =159 mm, compared to 102 mm for 30 year normals (PRISM Climate Group 2014)). I did not see a difference in emergence based on the level of biological crust development because my seed emergence rates were too low to analyze. I did see a trend towards higher emergence in 2019, suggesting that moisture may have been a limiting factor in germination, emergence and establishment. In my second year, when precipitation was greater, I saw a possible trend towards higher emergence in plots with low crust development. If that trend proved significant with a larger sample size, it could suggest that higher crust development was more likely to inhibit seed moisture than prove beneficial for germination (McIlvanie 1942), or that microsites conducive to germination were available, but not enough seeds were able to reach them (Eckhart et al. 1986; Sheldon 1974).

There are several factors that could explain a negative relationship between crust development and germination rates. Serpe et al. (2006) demonstrated that mosses common to Great Basin crust can effectively decrease water uptake by seeds by half. This is primarily a mechanical rather than a chemical effect – seeds placed on the surface of moss-dominated crust are often prevented from contacting the surface of the mineral soil (Whitcomb 2017; Serpe et al. 2006). Mechanical obstruction from the soil surface is also seen in crusts that are dominated by cyanobacteria and are correspondingly low in moss and lichen (Prasse & Bornkamm 2000; Zaady 1997). Studies in which biological crust is subjected to small-scale disturbances that create fissures, show an increase in emergence, indicating that while crust itself may act as a barrier to seed radicles, fissures may be facilitative to seed emergence (Prasse & Bornkamm 2000; Sylla 1987).

In my study area, higher levels of biological crust development were associated with a greater degree of cracking at the soil surface, which I theorize could provide moist microsites for seeds (Harper et al. 1965; Winkel et al. 1991). Eckhart et al. (1986), working in Nevadan Aridisols with precipitation regimes similar to my study site, found that cracks and fissures had a higher cover of vascular plants than the pinnacled soil surfaces between them. In my study, I used cheesecloth to prevent seeds from traveling out of the plot in the strong, seasonal winds present in my study area. Although seeds were broadcast evenly over my plots by hand, the cheesecloth may have also prevented natural movement and interfered with the ability of seeds to find microsites. Seeds that find moist, “safe” sites with increased humidity are often more likely to germinate, depending on the requirements of the species (Sheldon 1974). In squirreltail germination trials, Young and Evans (1977) found 45% emergence for seeds placed on bare, clay soil, but when seeds were lightly covered with litter, emergence rose to 81%.

Comparable greenhouse trials of seeds broadcast over samples of biological soil crust showed higher rates of emergence and/or seedling survival for squirreltail, Indian ricegrass and gooseberryleaf globemallow than my field trial (Sylla 1987; Whitcomb 2017), though protocols varied, and some included daily misting. I could not find comparable studies of aerial seeding in salt desert soils with biological soil crust, but my results compare to typical drill seeding projects in salt desert. Grant-Hoffman et al. (2015) counted individual seedlings in a western Colorado, *Atriplex* L. dominated salt desert with a mean annual precipitation (MAP) of 80-120 mm. After two years of sampling across 480 drill seeded rows, squirreltail varieties averaged 58 individual seedlings, Indian ricegrass 12, and basin wildrye and scarlet globemallow (*Sphaeralcea coccinea* (Nutt.) Rydb.) produced one seedling each. Similar to my experiment, emerged seedlings often did not survive from one sampling date to the next. Two post-fire studies, Jessop & Anderson (2007) and Humphrey & Schupp (2002), drill seeded mixes of basin wildrye, Indian ricegrass, squirreltail and others in western Utah salt desert sites with a MAP 220 mm or below. Both studies showed greater emergence than mine in the first year, but nearly all seedlings were dead three years post-planting. These results are further corroborated by broadscale resampling of revegetated salt desert sites. In the decades post seeding, there is typically an increase in the cover of seeded forage grasses (majority crested wheatgrass) but not of seeded, native bunchgrasses (Jonas et al. 2018).

Seeding failures in salt desert are often attributed to low precipitation, especially in the year post-seeding (Jessop & Anderson 2007). Basin wildrye, Indian ricegrass and other native bunchgrasses have shown higher germination and long-term establishment with supplemental irrigation in the first year (Porensky et al. 2014) or under simulated high rainfall (Bernstein et al. 2014). I hypothesize that the higher precipitation in 2019 might have acted as a "pulse event" for establishment (Allen 1995) in my second year of seeding, but it did not increase germination substantially or overcome the vulnerability of seedlings following germination (James et al. 2011).

Further reasons for seeding failure could include seed predation by rodents or birds (Archer and Pyke 1991; Nelson 1970). Seed predation is more of an issue when seeds are broadcast rather than drilled (Nelson 1970). This can be addressed by seeding in times and places where rodents are less common (Archer and Pyke 1991). For this reason, I seeded in early December.

In conclusion, though not statistically analyzed, my results showed possible inhibitory effects of biological soil crust on germination rather than a facilitative effect caused by surface cracking and topography. Precipitation was likely a limiting factor in emergence and establishment, as I saw a rise in germination in 2019, but even in those conditions, seedlings failed to survive the summer. Greenhouse trials that remove water limitations may be better able to isolate the effects of biological soil crust on germination. My results are not sufficient to recommend broadcast seeding as a revegetation technique in salt desert, biological soil crust-covered soils, even at above-average precipitation.

Transplants and biological soil crusts

Transplants overcome some of the key limiting steps of establishing plants from seed, such as high mortality rates as germinated seeds transition to emergence (James et al. 2011). Consequently, the high survival of fall transplants in my study may have been driven by higher precipitation, the larger seedling size at time of transplant, improved conditions associated with fall planting, or a combination thereof. In particular, fall transplants in a wet year showed high survival, 82.5% and 95%, respectively for squirreltail and basin wildrye, almost one year after planting. I also observed temporary effects of soil crust development on spring transplants, particularly for squirreltail and globemallow, that suggest the ability of biological soil crust to improve survival under drought stress.

The initial growing season for spring transplants had lower than average precipitation and many transplants died, but under these conditions, seedlings planted in crusts were more likely to survive through their first summer drought. Water stress is elevated in newly transplanted seedlings (Grossnickle 2005) and juvenile mortality is highest through summer in semiarid rangelands (James et al. 2011), as soil moisture in the upper horizons is quickly depleted (Ryel et al. 2010). Biological soil crust is capable of providing increased soil moisture to vascular plants (Belnap 2003), and recent research has linked the amount of crust development to water infiltration. In sandy loams on the Colorado Plateau, rainfall simulations demonstrate that more developed crusts (Belnap et al. 2008), have less runoff and greater infiltration than less-developed crusts. The depth of soil wetting increases with crust development as well and has been attributed to water slowing and pooling in the microtopography of a pinnacled crust (Belnap et al. 2013).

Soils with finer textures, like those in my study, will have higher runoff than a sandy loam, but less water loss due to infiltration and drainage (Noy-Meir 1973). Also, the Great Basin typically has rolling crusts with pinnacles 5 cm or less, due to the high lichen and moss cover (Belnap 2003).

My results suggest that highly developed soil crusts were advantageous for the 2018 dry year planting because they mitigated some of the drought stress for spring-planted seedlings during an initial summer drought. Water stored in the soil is of high importance in semiarid ecosystems with variable precipitation (Lampurlanés & Cantero-Martinez 2001). Precipitation in spring 2018 was lower and largely concentrated in March and May, while water would have been more continuously available to transplants in spring 2019 (PRISM Climate Group 2014). The increased infiltration of water in soil crusts could explain why I saw a positive effect of crust development in spring-planted 2018 seedlings, but not in fall-planted 2019 seedlings (despite higher rates of survival and a more powerful statistical model). This early advantage of biocrusts in spring 2018, however, was not enough to guarantee long-term survival. By the end of the experiment survival rates decreased, though squirreltail survival (15%) was nonetheless higher than the 5-10% recruitment typical to restoration seedings in sagebrush-steppe habitat (James et al. 2012; Lysne & Pellant 2004; Sheley et al. 2011; Williams et al. 2002), and minimal recruitment seen in salt desert systems (Grant-Hoffman et al. 2015; Humphrey & Schupp 2002; Jessop & Anderson 2007; Van Epps & McKell 1980).

Transplants – species differences

Differences in species survival suggested differing patterns of sensitivity to size at transplanting, season of planting or available moisture. Differences among species should be expected as some plants, such as squirreltail, are more aggressive at initial establishment (Booth et al. 2003; Hironaka & Tisdale 1972; Jones 1998). Squirreltail had among the highest survival rates for both cohorts (spring and fall planted), but while one-year survival of squirreltail was high for fall plantings, it was moderate for spring planting. Squirreltail may be better suited for fall planting. This species initiates root growth at cooler temperatures than many other native bunchgrasses, allowing it to more quickly elongate its roots in the fall and early spring (Booth et al. 2003; Hironaka & Tisdale 1972; Jones 1998). It can also respond to fall precipitation with growth comparable to that of spring (Coyne & Cook 1970). These traits would favor a fall planting season, as the fall could be effectively used to establish a root system. In a water-limited system with a summer drought, species able to elongate their roots at low temperatures are among the most competitive (Harris and Wilson 1970; Leger & Owen 2015). Squirreltail is known to enact this strategy in the wild through fall germination (Booth et al. 2003).

In contrast, Indian ricegrass results suggest less sensitivity to variation in size at transplanting, season of planting or available moisture. Final survival of Indian ricegrass in the fall of 2019 was 22% for spring transplants (17 months post-planting) and 35% for fall transplants (12 months post-planting). During my field sampling, I noted that among my four species, Indian ricegrass displayed a unique growth pattern – spring transplants died back to the ground early in the summer following planting, then resprouted the following spring with a wider basal diameter and increased number of shoots (MO, personal observation). Indian ricegrass is a deeply rooting bunchgrass with a larger root system than squirreltail (Jones 1990) and does not show the same positive aboveground growth response to fall precipitation (Coyne & Cook 1970). In the spring-planted cohort, Indian ricegrass had the most developed root system at the time of planting. Its larger root system may have allowed it to survive the initial summer drought, despite limited shoot growth. Whereas squirreltail may be able to capitalize on favorable conditions (Booth et al. 2003; Hironaka & Tisdale 1963) and benefit from increased biological crust development, Indian ricegrass would be a better choice for uncertain conditions and less developed soil crust.

The soil conditions at my study site may have favored certain species. Some studies in *Atriplex*-dominated salt deserts show a positive correlation between higher crust cover and finer textured soils and salinity (Anderson et al. 1982). Such growing conditions would favor squirreltail and basin wildrye, the more saline-adapted species, over Indian ricegrass, a species that favors sandy, well-drained soils (Jones 1990).

Transplants versus seeding

Though I could not statistically compare the success of my transplants to that of my broadcast seedings, transplanting was clearly more successful at establishing native forbs and grasses. There is limited research comparing transplants to direct seedings, especially for herbaceous species. In the Great Basin, transplanting is most commonly used in shrub revegetation, where long-term survival rates of 20-30% have been reported, with up to 300% improvement when herbicide is used to reduce competition from invasive plants (Dettweiler-Robinson et al. 2013; McAdoo et al. 2013; Van Epps & McKell 1983). My broadcast seeding trials, along with a swath of comparable results from salt desert drill seedings (Grant-Hoffman et al. 2015; Humphrey & Schupp 2002; Jessop & Anderson 2007; Van Epps & McKell 1980), show that while some germination can be expected, long-term survival is often minimal in salt desert direct seedings. In mesic systems, seedings may be effective enough to outperform transplants (Palmerlee & Young 2010), and perennial grass recruitment from direct seedings improves in the Great Basin as elevation and precipitation increase (Knutson et al. 2014; Roundy et al. 2018).

Meanwhile, in desert systems, transplants often perform better, as seen in several studies comparing seeding to greenhouse-grown transplants (Abella et al. 2012; Bean et al. 2004; Glenn et al. 2011). Abella et al. (2012), Bean et al. (2004) and Glenn et al. (2011) accomplished these results under supplemental irrigation, perhaps analogous to how transplants in my study continued to outperform seeding in 2019, a year of high precipitation. Microsite requirements for the survival of newly emerged seedlings are much more stringent than those of mature plants (Hardegree et al. 2013), and arid ecosystems have more temporal variability in temperature and precipitation (Noy-Meir 1973). Revegetation in salt desert continues to rely on direct seeding methods that work better in the more mesic regions of the Great Basin, when perhaps it should look towards the techniques of desert land managers, like irrigated transplants (Abella et al. 2012; Bean et al. 2004). My success with transplanted grasses and forbs shows that greenhouse-grown transplants merit further consideration for establishment of herbaceous species in unpredictable, salt desert ecosystems that have seen little success in direct seeding.

Season of planting

I hypothesize that the success of my fall transplants, though due in part to higher precipitation in 2019, shows the importance of root development in transplanted seedlings. In my study, fall transplants were larger than spring transplants and had more developed root systems, as well as a longer amount of time in the ground during fall and early spring, when soil moisture is often near field capacity (Ryel et al. 2010) and temperatures reach suitable levels for root growth (Hironaka & Tisdale 1972). Sufficient root growth and water stress are the primary issues facing transplants and may determine the ability of a new transplant to survive its first year (Grossnickle 2005). Root systems of newly planted seedlings have limited water and nutrient uptake until they grow sufficiently to access the available water in the soil (Grossnickle 2005). Cox et al. (1987) determined that grass seedlings transplanted at the initiation of the rainy season in the Sonoran Desert (summer) had higher 3-year survival rates than winter transplants; they attributed this to the longer availability of continuous soil moisture to transplants. Page & Bork (2005), working in a montane system in British Columbia, found the season of planting to interact with the grass species planted, underscoring the need to understand the autecology of individual species. Deformation of the taproot and lasting constraints on root expansion and biomass were observed with transplanted seedlings of woody species (Van Epps & McKell 1980; Young & Evans 2000), but these are from studies on woody species and but may be less applicable to fibrous rooted grasses.

CONCLUSION

My results show a potential for higher levels of biological soil crust development to improve survival in drought-stressed transplants and possible new planting techniques to increase success in salt desert revegetation. There is very little research on the suitability of biological soil crust as a target habitat for revegetation efforts, as well as on the potential for transplanting herbaceous species over direct seeding. Further research is needed to elucidate the specific drivers of success in transplant size, season of planting and precipitation, but I have shown the potential for high survival of native plant species in salt desert environments. Likewise, further monitoring of my plantings is necessary, but one-year survival results provide optimism that transplant establishment rates may be higher than the minimal recruitment seen in salt desert systems (Grant-Hoffman et al. 2015; Humphrey & Schupp 2002; Jessop & Anderson 2007; Van Epps & McKell 1980).

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TABLES AND FIGURES

Table 1. Eight treatment combinations replicated for each of four species: *Achnatherum hymenoides, Elymus elymoides, Leymus cinereus* and *Sphaeralcea grossulariifolia*.

	Year 1		Year 2	
	Fall 2017 seeding	Spring 2018 planting	Fall 2018 seeding	Fall 2018 planting
High crust	n = 5	n = 5	n = 5	n = 5
Low crust	n = 5	n = 5	n = 5	n = 5

Table 2. Mean percentage cover for invasive species with greater than 1% mean cover. Cover shown by two levels of biological crust development (LOD), and at four sampling dates. In 2018, n=40 for each LOD; in 2019, n=80.

		June 2018		Sept 2018		June 2019		Sept 2019	
	LOD	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Bromus tectorum	High	3.95%	0.26%	2.34%	0.13%	5.58%	0.10%	6.13%	0.15%
	Low	2.81%	0.19%	1.66%	0.11%	6.39%	0.13%	5.90%	0.15%
Lepidium perfoliatum	High	8.55%	0.23%	4.17%	0.09%	8.45%	0.08%	8.39%	0.08%
	Low	9.38%	0.19%	5.47%	0.12%	8.39%	0.10%	8.46%	0.96%
Ranunculus testiculatus	High	5.11%	0.08%	0.74%	0.02%	12.43%	0.07%	10.2%	0.08%
	Low	5.68%	0.13%	0.95%	0.03%	16.65%	0.10%	12.5%	0.08%

Table 3. Mean number of emerged plants per plot (n= 5 plots) at four sampling dates. Seeding dates are listed below species codes. Species codes are as follows: ACHHYM, *Achnatherum hymenoides*; ELYELY, *Elymus elymoides*; LEYCIN, *Leymus cinereus*; SPHGRO, *Sphaeralcea grossulariifolia*.

	Soil Crust Development	**June 2018**	**Sept 2018**	**June 2019**	**Sept 2019**
ACHHYM Dec 2017	High	0	0	0	0
	Low	0	0	0	0
ACHHYM Dec 2018	High			0	0
	Low			0	0
ELYELY Dec 2017	High	1.6	0	0.4	0
	Low	1.6	0	1.0	0
ELYELY Dec 2018	High			0	0
	Low			0.4	0
LEYCIN Dec 2017	High	0	0	0	0
	Low	0	0	0	0
LEYCIN Dec 2018	High			0	0
	Low			0	0
SPHGRO Dec 2017	High	0	0	0	0
	Low	0	0	0.4	0
SPHGRO Dec 2018	High	0	0	0.2	0
	Low			0.2	0

Table 4. Analysis of Deviance table results for binary logistic regression models on spring-cohort data with the number of successes (live plants out of 4) as response variable. Main fixed effects are plant species (ACHHYM, ELYELY, LEYCIN, SPHGRO) and biological soil crust level of development ("LOD"; high vs. low). Invasive plant species cover, centered on its mean, included as a covariate. Results significant at $\alpha = 0.01$ in bold. Invasive species cover was dropped from the Sept 2019 model due to outliers.

Analysis of Deviance Table (Type III Test)			
Spring-Planted Cohort			
Sample Date: June 2018	LR Chi Square	DF	P > ChiSq
Plant Species	2.766	3	0.429
Level of Crust Development	0.000	1	0.999
Invasive Species Cover	.460	1	0.500
Sample Date: Sept 2018	LR Chi Square	DF	P > ChiSq
Plant Species	44.697	3	**<0.001**
Level of Crust Development	10.502	1	**0.001**
Invasive Species Cover	3.776	1	0.052
Sample Date: June 2019	LR Chi Square	DF	P > ChiSq
Plant Species	40.259	3	**<0.001**
Level of Crust Development	1.745	1	0.187
Invasive Species Cover	0.529	1	0.467
Sample Date: Sept 2019	LR Chi Square	DF	P > ChiSq
Plant Species	17.260	3	**<0.001**
Level of Crust Development	1.409	1	0.235

Table 5. Analysis of Deviance table results for full factorial, binary logistic regression models on fall-cohort data with the number of successes (live plants out of 4) as response variable. Main fixed effects are plant species (ACHHYM, ELYELY, LEYCIN, SPHGRO) and biological soil crust level of development ("LOD"; high vs. low). Invasive plant species cover, centered on its mean, included as a covariate. Results significant at $\alpha = 0.01$ in bold.

Analysis of Deviance Table (Type III Test)			
Fall-Planted Cohort			
Sample Date: June 2019	LR Chi Square	DF	P > ChiSq
Plant Species	61.282	3	**<0.001**
Level of Crust Development	1.124	1	0.289
Invasive Species Cover	0.000	1	0.999
Species:LOD	7.746	3	0.052
Species:Inv	5.347	3	0.148
LOD:Inv	0.000	1	0.999
Species:LOD:Inv	0.519	3	0.915
Sample Date: Sept 2019	LR Chi Square	DF	P > ChiSq
Plant Species	59.712	3	**<0.001**
Level of Crust Development	1.769	1	0.183
Invasive Species Cover	0.691	1	0.406
Species:LOD	8.790	3	0.032
Species:Inv	6.726	3	0.081
LOD:Inv	3.600	1	0.058
Species:LOD:Inv	6.858	3	0.077

Table 6. Pairwise testing results of mean count for spring transplants in Sept 2018. Testing was done using estimated margin means and a Tukey adjustment familywise error rate. Degrees of freedom are infinite for each test, and tests were performed on the log odds ratio scale. Species codes are as follows: ACHHYM, *Achnatherum hymenoides*; ELYELY, *Elymus elymoides*; LEYCIN, *Leymus cinereus*; SPHGRO, *Sphaeralcea grossulariifolia*. Results significant at $\alpha = 0.01$ in bold.

Pairwise Testing of Estimated Margin Means				
Spring-Planted Cohort				
Sample Date: Sept 2018	Odds Ratio	Std Error	Z Ratio	P value
ACHHYM/ELYELY	9.376	6.026	3.483	**0.003**
ACHHYM / LEYCIN	135.882	155.276	4.298	**< 0.001**
ACHHYM/SPHGRO	12.589	8.267	3.857	**< 0.001**
ELYELY/LEYCIN	14.493	15.844	2.446	0.069
ELYELY/ SPHGRO	1.343	0.751	0.527	0.953
LEYCIN /SPHGRO	0.093	0.102	-2.171	0.131
Sample Date: Sept 2019	Odds Ratio	Std Error	Z Ratio	P value
ACHHYM/ELYELY	2.00e+00	1.00e+10	0.750	0.877
ACHHYM / LEYCIN	1.92e+08	4.81e+11	0.008	1.000
ACHHYM/SPHGRO	1.10e+01	1.20e+01	2.194	0.125
ELYELY/LEYCIN	1.22e+08	3.06e+11	0.007	1.000
ELYELY/SPHGRO	7.00e+00	8.00e+00	1.754	0.296
LEYCIN/SPHGRO	0.000	0.000	-0.007	1.000

Table 7. Pairwise testing results of mean count for fall transplants in Sept 2019. Testing was done using estimated margin means and a Tukey adjustment familywise error rate. Degrees of freedom are infinite for each test, and tests were performed on the log odds ratio scale. Species codes are as follows: ACHHYM, *Achnatherum hymenoides*; ELYELY, *Elymus elymoides*; LEYCIN, *Leymus cinereus*; SPHGRO, *Sphaeralcea grossulariifolia*. Results significant at $\alpha = 0.01$ in bold.

Pairwise Testing of Estimated Margin Means				
Fall-Planted Cohort				
Sample Date: Sept 2019	Odds Ratio	Std Error	Z Ratio	P value
ELYELY/ACHHYM	0.085	0.050	-4.187	**< 0.001**
ELYELY/SPHGRO	11.748	6.867	4.214	**< 0.001**
LEYCIN/ACHHYM	0.014	0.015	-3.982	**< 0.001**
LEYCIN/SPHGRO	70.095	75.047	3.969	**< 0.001**
ELYELY/LEYCIN	0.168	0.188	-1.590	0.3843
ACHHYM/SPHGRO	1.002	0.480	0.005	1.000

Table 8. Mean number of flowering stems for fall transplants (n= 5 plots) in June 2019. Species codes are as follows: ACHHYM, *Achnatherum hymenoides*; ELYELY, *Elymus elymoides*; LEYCIN, *Leymus cinereus*; SPHGRO, *Sphaeralcea grossulariifolia*.

Sample date: June 2019	**Soil Crust Development**	**Mean # Flowering Stems**	**SE**
ACHHYM	High	0.075	0.075
	Low	0	0
ELYELY	High	5	2.168
	Low	5.2	0.583
LEYCIN	High	0	0
	Low	0	0
SPHGRO	High	1.333	0.333
	Low	1	0.408

Table 9. Analysis of Variance table results for regression models on fall-cohort data in June 2019 with the number of flowering stems as response variable. Main fixed effects are plant species (ACHHYM, ELYELY, LEYCIN, SPHGRO) and biological soil crust level of development ("LOD"; high vs. low).

Analysis of Variance Table (Type III Test)					
Fall-Planted Cohort					
Sample Date: June 2019	Df	Sum Sq	Mean Sq	F Value	P > F
Plant Species	3	162.70	54.23	13.095	**<0.001**
Level of Crust Development	1	0.00	0.00	0.001	0.977
Plant Species* Level of Crust Development	3	0.29	0.10	0.024	0.995
Residuals	25	103.53	4.14		

Table 10. Mean height (cm) for fall transplants (n= 5 plots) in 2019. Species codes are as follows: ACHHYM, *Achnatherum hymenoides*; ELYELY, *Elymus elymoides*; LEYCIN, *Leymus cinereus*; SPHGRO, *Sphaeralcea grossulariifolia*.

	Soil Crust Development	**June 2019**		**Sept 2019**	
		Mean (cm)	SE	Mean (cm)	SE
ACHHYM	High	6.6	1.110	10.7	1.768
	Low	12.5	1.061	14.5	1.768
ELYELY	High	14.6	1.270	11.75	0.590
	Low	16.2	0.219	12.2	0.477
LEYCIN	High	14.4	0.672	15.6	0.593
	Low	15.2	1.337	18.2	0.953
SPHGRO	High	6	0.333	5.3	0.509
	Low	5	0.289	5.7	0.385

Table 11. Analysis of Variance table results for regression models on fall-cohort data in 2019 with height as response variable. Main fixed effects are the three grass species (ACHHYM, ELYELY, LEYCIN) and biological soil crust level of development (“LOD”; high vs. low).

Analysis of Variance Table (Type III Test)					
Fall-Planted Cohort					
Sample Date: June 2019	Df	Sum Sq	Mean Sq	F Value	P > F
Plant Species	2	242.6	121.29	4.920	0.0177
Level of Crust Development	1	32.4	32.38	1.314	0.2646
Plant Species* Level of Crust Development	2	25.3	12.67	0.514	0.6054
Residuals	21	517.7	24.65		
Sample Date: Sept 2019	Df	Sum Sq	Mean Sq	F Value	P > F
Plant Species	2	153.6	76.82	3.149	0.0647
Level of Crust Development	1	27.2	27.18	1.114	0.3038
Plant Species* Level of Crust Development	2	10.8	5.40	0.221	0.8033
Residuals	20	487.9	24.39		

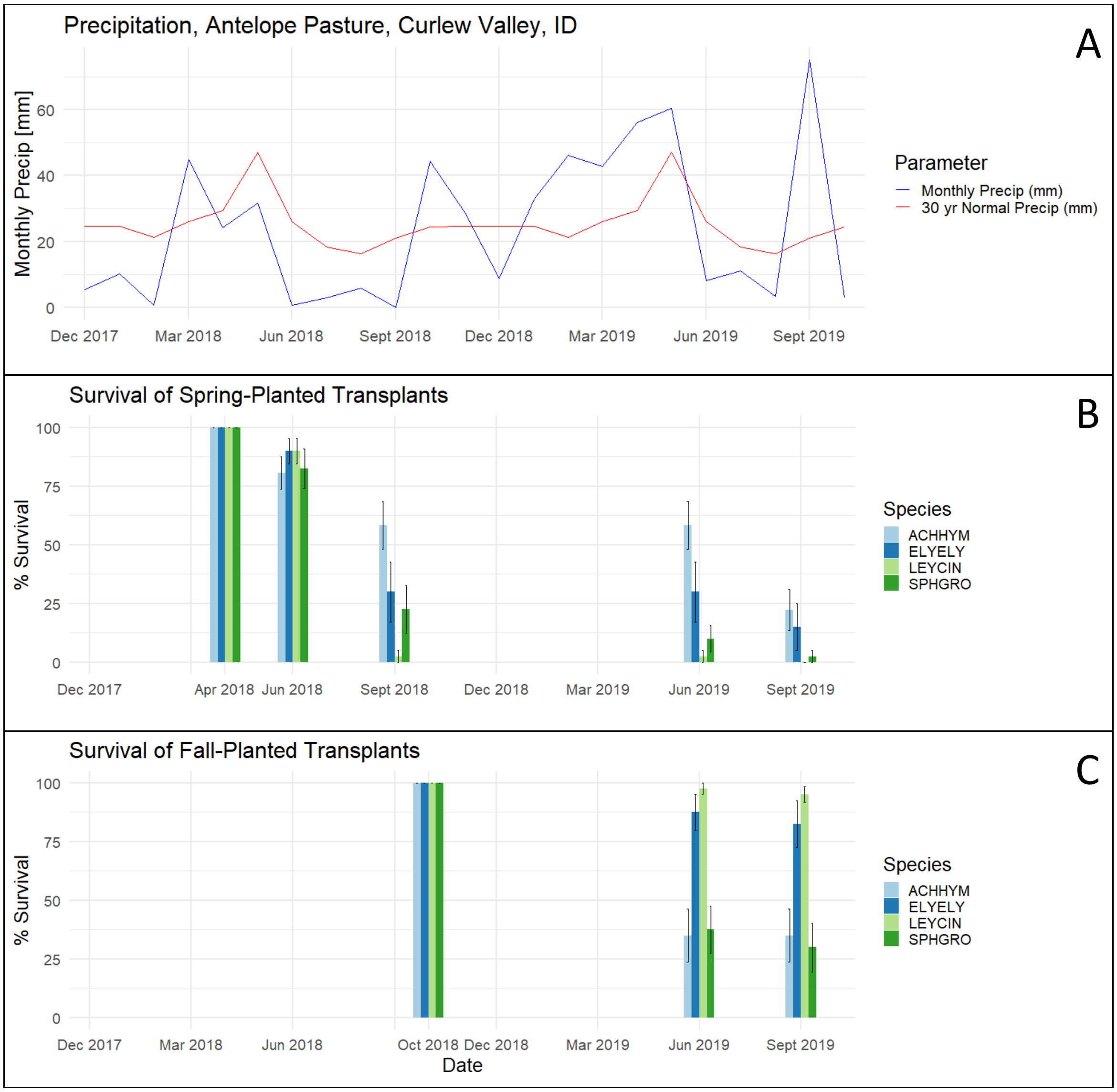

Figure 1. Precipitation data (panel A) and survival of transplanted seedlings in both spring (panel B) and fall (panel C) transplants. Bar graphs display mean and standard error bars. The spring cohort was planted in April 2018, and the fall cohort in Oct 2018, with four seedlings planted in each plot. Species codes are as follows: ACHHYM, *Achnatherum hymenoides*; ELYELY, *Elymus elymoides*; LEYCIN, *Leymus cinereus*; SPHGRO, *Sphaeralcea grossulariifolia*. Precipitation data is for 41°59'48.1"N 112°55'00.8"W, PRISM 2014.

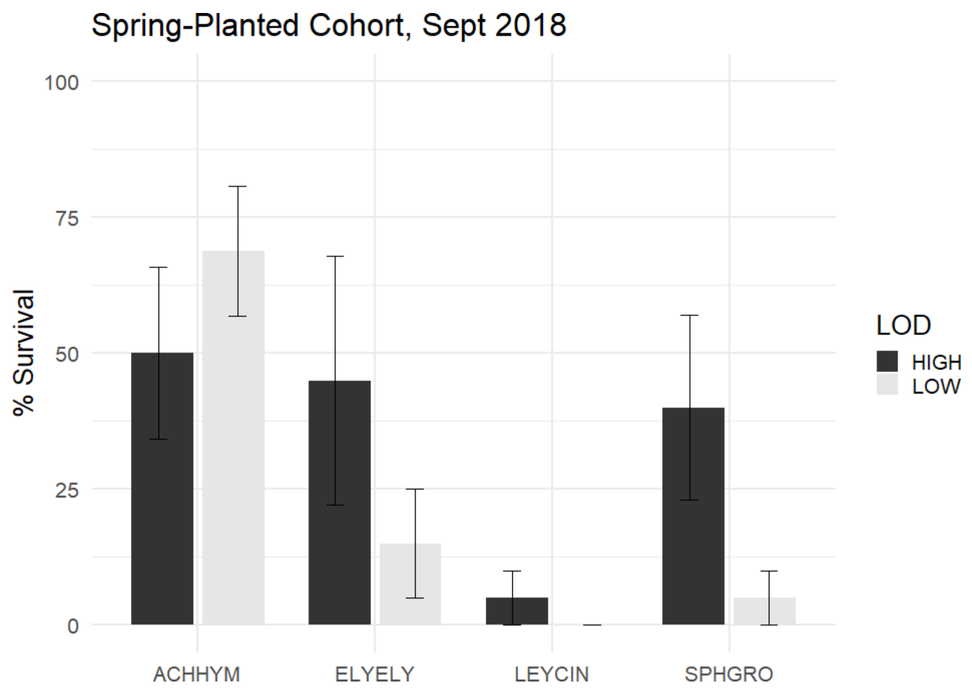

Figure 2. Mean (±1 SE) survival of spring transplants following the first summer after planting. Included are ACHHYM, *Achnatherum hymenoides*; ELYELY, *Elymus elymoides*; LEYCIN, *Leymus cinereus*; SPHGRO, *Sphaeralcea grossulariifolia*. LOD is the level of crust development. LOD is significant (p = 0.001); plant species significant (p = <0.001).

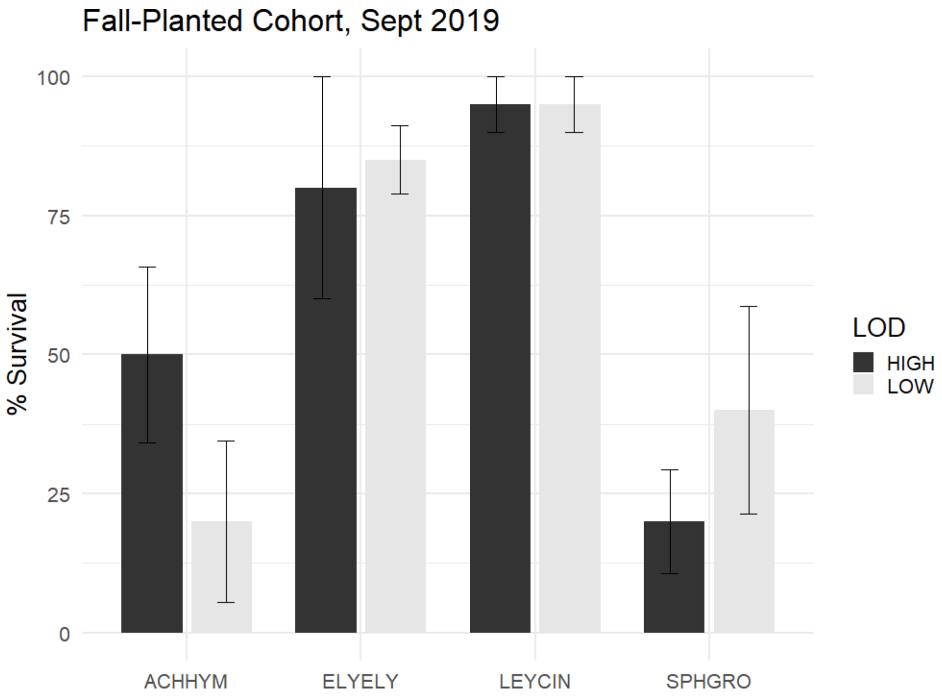

Figure 3. Mean (±1 SE) survival of fall transplants following the first summer after planting. Included are ACHHYM, *Achnatherum hymenoides*; ELYELY, *Elymus elymoides*; LEYCIN, *Leymus cinereus*; SPHGRO, *Sphaeralcea grossulariifolia*. LOD is the level of crust development. ANOVA tests indicated the following for significance: plant species (p = <0.001), LOD (p = 0.183), and species x LOD interaction (p = 0.032).

APPENDICES

APPENDIX A

SOIL AND VEGETATION SURVEY OF ANTELOPE PASTURE, CURLEW GRAZING ALLOTMENT, ONEIDA COUNTY, IDAHO

INTRODUCTION

Antelope pasture, located in the Black Pine Valley of Oneida County, Idaho, is a 1500-acre portion of the Curlew Grazing Allotment, managed by the Pocatello Field Office of the BLM (Fig. A.1). The pasture is heavily invaded with exotic annuals such as cheatgrass (*Bromus tectorum*), halogeton (*Halogeton glomeratus*), and clasping pepperweed (*Lepidium perfoliatum*), and grazing is temporarily discontinued. The history of the pasture includes such uses as livestock grazing, possible homesteading and cultivation of *Agropyron cristatum* (crested wheatgrass).

Land Use History

A patent search was conducted within the Bureau of Land Management (BLM) General Land Office Records for township sections within and around Antelope pasture (Fig. A.2) to determine land-use history. Two records were found for sections 27 and 23 (the pasture’s southern half and northeastern corner) (Dept of Interior 2018). Those patents reveal that the odd-numbered sections were once under the ownership of the Central Pacific Railroad and included in a 400,000 acre ranch managed by railroad baron Charles Crocker. In 1909, the ranch was purchased in its entirety by the Promontory-Curlew Land Company to be resold in small parcels (Bullen Jr 1966a; Francaviglia 2008). Advertisements produced in 1917 (Fig. A.3) indicate that neither the odd-numbered sections of Antelope Pasture nor any of the sections elsewhere in Black Pine Valley had sold by that time (Bullen Jr 1966b). Ultimately patent record show these sections were acquired by the federal government under the Bankhead Jones Act of 1937, which allowed the government to purchase degraded land for rehabilitation (Dept of Interior 2018).

No patents were found for sections 22 (the majority of the pasture's northern half) and 26 (the southeastern corner). If they were homesteaded, the settlers did not fulfill the requirements to "prove up," or file a claim. There is some visual evidence to suggest settlement in the northwest corner of Section 22-- artifacts such as pots and bed frames were found on the ground. The general area underwent a dry farming "boom and bust" in the early 1900's, due to the Enlarged Homestead Act of 1909 and the efforts of companies such as the Promontory-Curlew Land Co to sell land to wheat farmers. Many farms quickly failed and were abandoned by the 1920's (Morris et al. 2011).

Other than the possibility of a brief homestead, it is likely that the main land use history of Antelope Pasture was livestock grazing, from at least the time of Crocker's ownership and possibly earlier. Until the Taylor Grazing Act of 1937, public land was grazed on a first-come, first serve basis (Svejcar 2015), and Crocker's grazing of a checkerboard of odd-numbered sections would have ensured that cattle wandered freely across the neighboring sections if they were unfenced. In the Great Basin, extensive and unregulated grazing at the turn of the century is considered a main contributor to the invasion of cheatgrass and halogeton. Depletion of the native bunchgrasses and resulting soil erosion left the system open to invasion (Knapp 1996; Tisdale and Zappetini 1953). Great Basin valleys lowest in elevation and precipitation, such as the location of Antelope

Pasture, have been identified as among the most susceptible to degradation from novel disturbance (such as inappropriate grazing practices) and the least resilient. This is attributable to factors such as low and variable precipitation, low cover of native grasses, low productivity, and low or episodic plant recruitment (Chambers et al. 2007).

Once incorporated in the BLM, Antelope pasture was included in early attempts at controlling halogeton and soil erosion in alkali soils (Dept of Interior 1953; Dept of Interior 1960; Young 1988). In 1952, over 10,000 acres within Black Pine Valley were seeded with crested wheatgrass and *Melilotus officinalis* (yellow sweet clover). The project was described as a seeding of areas of "questionable rainfall," "heavily infested with jack rabbits" (Dept of Interior 1960) for the control of halogeton. Seedbed preparation involved chaining or light harrow dragging, plowing and fertilizer application (Dept of Interior 1953). Only the center swath of Antelope pasture was included in this seeding (Fig. A.4).

Grazing standards and pasture divisions set in 1997 for the Curlew Grazing Allotment put Antelope pasture on a fall/spring/rest rotation. A 2013 Land Health Assessment found that available forage in the pasture was far below allocated rates, and that the situation was similar for surrounding pastures in the 8-12" precipitation zone. Antelope pasture was determined to have failed Standard 5 (Seeding) and Standard 8 (Threatened and Endangered Plants and Animals) (Dept of Interior 2015a). In 2015, the Grazing Permit Renewal for the Curlew Allotment proposed that the stocking rate for Antelope pasture be reduced, that only fall grazing be allowed, or that the pasture be rested until a restoration plan could be developed (Dept of Interior 2015b).

Climate

Antelope pasture has a cold semi-arid climate. Monthly normals for the 30 year period of 1981-2010 were obtained from the PRISM Climate Group, Oregon State University (Fig. A.5). Mean annual precipitation for the 1981-2010 is 11.95 inches (303.5 mm), and mean annual temperature is 47.7 ºF (8.72 ºC) (PRISM Climate Group 2014). Precipitation is typically highest in May and then drops drastically as the temperature climbs during the summer months. The warmest months of July and August are also the driest, creating a short growing season and summer drought. The bulk of precipitation comes as spring rain or winter snowfall.

Geologic History

Black Pine Valley was covered by pluvial Lake Bonneville during the late Pleistocene epoch. At 4500-4400 ft (1372-1341 m) elevation, Antelope Pasture was inundated with fresh water during the Bonneville and Provo high stands. The geology of the surrounding ranges is predominantly sedimentary rocks and includes an abundance of Permian and Pennsylvanian limestone, a highly calcareous rock derived from marine sediment (Long and Link 2007). Lake Bonneville caught the weathering products of surrounding ranges transported in alluvial systems, and deposited them in deep layers of lacustrine sediment. As Lake Bonneville receded below the Provo high stand and dropped below its natural outlet at Red Rock Pass, solutes such as calcium and sodium concentrated as the lake evaporated. Concentrated salt deposits are a cause of saline soils in the low valleys of the Great Basin (Chronic 1990; Stokes 1986).

Aerial photography of the valley shows that as the lake receded, remnant shorelines left terraces ringing the valley. Two visible terraces pass through Antelope Pasture; one crosses the northern end and one runs through the middle (Fig. A.1&A.2).

Current USDA-NRCS Soil Classification and Ecological Site Descriptions

The United States Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) mapped the majority of Antelope Pasture as Mellor-Freedom complex, 0 to 2 percent slopes. According to the map unit description, 50% is Mellor series and similar soils, and 35% is Freedom series and similar soils; a complex is typically mapped when the main components of a map unit cannot be represented at 1:24,000 scale. A small area in the southeastern corner is mapped as Bayhook silt loam, 0 to 2 percent slopes (Fig. A.6). Soil classification changes at the Utah/Idaho border (the pasture's southern boundary). South of the pasture, soils have been classified as Thiokol silt loam, low rainfall, 0 to 1 percent slopes (Soil Survey Staff 2018c).

The Mellor series has been associated with two NRCS Ecological Site Descriptions -- Alkali Flat (Black Greasewood) R028AY004UT, and Semidesert Alkali Loam (Black Greasewood) R028AY202UT. The Alkali flat description is a greasewood/shadscale community with saline and sodium-affected soils. Halophytic plant species and warm-season grasses are present. The semidesert alkali loam description is an ecotone between greasewood/shadscale Wyoming big sagebrush communities. Soils are salt-affected with sodium as the dominant component (Soil Survey Staff, 2018a).

The Freedom and Bayhook series have been associated with the Semidesert Loam (Wyoming Big Sagebrush) R028AY220UT Ecological Site Description. This vegetation community is co-dominated by Wyoming big sagebrush and *Pseudoroegneria spicata* (bluebunch wheatgrass). (Soil Survey Staff, 2018a). Soils are neither saline nor sodic (Soil Survey Staff, 2018a).

Study Objectives

Although the existing information on Antelope Pasture outlined above provides general information about the soils and vegetation of the area, detailed site-specific information is required for successful management of the pasture. To that end, in 2017, the Pocatello BLM Office partnered with Utah State University to provide detailed soil and vegetation maps of Antelope Pasture, determine plant-soil relationships and incorporate these results into a series of experiments on revegetation approaches. This report’s focus is the soil and vegetation mapping and plant-soil relationships.

METHODS

A survey of the soil and vegetation of Antelope Pasture was conducted in the summer of 2017. Vegetation sampling took place in May and early June, and soil sampling in June and July. Vegetation sample points were distributed systematically along a grid, for a total of 282 points (Fig. A.7). A subset of 58 points, located 300 m apart (Fig. A.7), were designated for soil sample collection as well as vegetation measurements. In the westernmost column, sampling points were laid out 100 meters apart, but after this the grid was expanded to 150 meters for remainder of the survey. At each sample point, a 1x3 meter vegetation sampling plot (Fig. A.8) was set up to the east. Soil samples were taken from the center of the 1x3 meter plot.

Vegetation Mapping

Along both long sides of the 1 x 3 meter plot, plant and soil surface cover were measured using the line-point intercept method (Herrick et al. 2005), dropping a pin every 30 cm for a total of 10 points per transect and 20 points per plot. Any interception of live vegetation, dead vegetation attached to the root crown of a living plant, or standing dead annual species from the current growth year was recorded as an intercept of a live plant species. Interceptions of standing dead annual plant species from previous growth years were recorded as "dead herbaceous," to provide a measurement of the standing dead litter created by invasive annual plants. Detached litter was considered an intercept rather than a soil surface code. To obtain data on species of low or sporadic cover, presence of all additional species with canopy cover within the 1 x 3 meter plot, but not intercepting the 3-meter transects, was recorded. Together, these methods provided cover and frequency measurements and captured the presence of rarer species that would otherwise have been missed. Waypoints were taken for incidental sightings of species not found within any plots to provide additional data on rare species and facilitate future monitoring.

To depict cover of individual species and functional groups, maps were created in ArcMap 10.4.1 software (Environmental Systems Research Institute, Redlands, CA) using dot density symbology, which distributes dots randomly within a set polygon. This entailed creating a grid of 5.5-acre (300 x 300 meter) polygons across Antelope Pasture, centered on my vegetation sample points. Then, within each 300 x 300 m polygon, the cover value of a species or functional group (measured in the field at the sample point) was represented as a series of dots, with each dot representing 5% cover. Dots were randomly distributed throughout the 300 x 300m polygon, summing to the total % cover. For example, to represent 50% cover of a species in a given polygon, ten dots would have been randomly distributed throughout the polygon. This approach was used to display % cover of all plant species intercepted in the 2017 survey and introduced annual cover overlaid on presence/absence of shrubs and crested wheatgrass.

Spearman rank correlation tests were performed on vegetation cover data to analyze pairwise relationships. Pearson’s chi-square tests were performed on presence/absence data to test for independence between species or functional groups. To explore multivariate relationships among species, principal components analysis (PCA) was performed on vegetation cover data. After each PCA, variables that did not have a loading value of 0.3 or above for at least one of the first three principal components were eliminated, until a final solution was reached. To examine the effect of crested wheatgrass on invasive annual species, I subset cheatgrass and introduced annual forbs into populations with and without the presence of crested wheatgrass. Population distributions with and without crested wheatgrass were visualized with boxplots and compared using Wilcoxon rank sum tests. This same process was performed on population subsets of cheatgrass and introduced annual forbs with and without the presence of shrubs. Analyses were conducted in JMP v. 13. (SAS Institute Inc., Cary, NC) and R v. 3.4.2 (R Core Team, 2017).

Soil Mapping

At each sample point, soil was excavated to a depth of 150 cm with a bucket auger, laid out along a tarp according to depth, and broken into genetic horizons. For each horizon, I recorded color (dry and moist), texture, consistence, pH, effervescence, roots, and soil ped and void surface features. For surface horizons I also assessed soil structure and horizon boundary. I followed National Cooperative Soil Survey sampling protocols (Schoeneberger et al 2012; Soil Science Division Staff 2017; Soil Survey Staff 2012). Color measurements followed the Munsell Color System (Munsell Color Company 2012). Soil pH was measured using Phenol red and Thymol blue indicator solutions, and effervescence was measured using a 1M hydrochloric acid solution.

I classified soil samples to family following the USDA-NRCS Keys to Soil Taxonomy, 12th edition (Soil Survey Staff 2014). I prepared written descriptions of soil samples representative of the different families. A soil map of Antelope pasture, based on my classifications, was completed in ArcMap. Spatial patterns in topography, identified with the use of a Digital Elevation Model (USGS 10-meter DEM), as well as patterns in vegetation and soil morphology, were considered when delineating boundaries between soil types.

Soil pH was initially used as a proxy measurement for sodium during the classification process. Sodium content was confirmed by lab testing a subset of 12 soil samples. Soil horizons chosen for testing included a mix of strongly alkaline (pH 8.5 to 9.0) horizons with and without evidence of clay illuviation and one slightly alkaline (pH 7.4 to 7.8) horizon with evidence of clay illuviation. To provide enough soil for lab sampling, each sample consisted of two adjacent horizons from each pedon. Only horizons of similar clay content and pH were combined. The Utah State University Analytical Laboratories tested the selected samples for electrical conductivity and sodium adsorption ratio. Simple linear regression was performed to test for relationships between SAR, EC and pH in lab results.

Principal components analysis was used to examine relationships among a chosen set of soil variables. These variables included percent clay, pH, effervescence and depth of A1 horizons, pH and percent clay at 30 cm (a depth at which all but 3 natric horizons are intercepted), and maximum percent clay achieved within each pedon. Variables also included depth to, weighted average of and maximum amount of ped and void features: redoximorphic depletions and calcium carbonate, silica and redoximorphic concentrations. Amounts of concentrations and depletions are given as a percent of the visible soil surface area occupied within a horizon. Weighted average was calculated for the full 150 cm soil profile as follows: amounts for each horizon were multiplied by the horizon thickness (cm), summed and divided by 150. I created maps in ArcMap to show the spatial distribution, depth and amount of soil ped and void features for each pedon, using ArcMap multiple attribute symbology.

For PCA analysis, the soil variables described above were standardized by subtracting the mean and dividing by the standard deviation. During analysis, variables that did not have a loading value of 0.3 or above for at least one of the first three principal components were eliminated until a final solution was reached. In the final graph, if variables derived from the same soil attribute (such as maximum silica concentrations and weighted average of silica concentrations) covaried strongly, the one with the lesser eigenvector was eliminated. This process was repeated for the 12 pedons sampled for SAR and EC, with those two variables added and standardized. PCA analysis used the FactoMineR package (Le et al 2008).

Kruskal-Wallis rank sum tests were performed on the same set of soil variables to test for significant differences between soil families and subgroups. All analyses were conducted in R v. 3.4.2 (R Core Team, 2017).

Soil-Vegetation Relationships

Spearman rank correlation tests were performed to analyze one-to-one relationships between soil surface categories and dominant plants species and/or functional groups. Data from plots sampled for both soil and vegetation was subset based on soil family, subgroup, great group and hypothesized disturbance history (hypotheses included possible fire or plowing). Kruskal-Wallis rank sum tests were then performed on both soil and vegetation data to identify significant differences between categories. Constrained Correspondence Analysis (CCA) was performed on cover data for key species, using the set of soil variables described above. Plant species were chosen based on PCA analyses of vegetation data and CCA analyses were run on each explanatory variable separately, with an alpha of 0.05 set as criteria for inclusion in my final model (Draper and Smith 1981). All analyses were conducted in R v. 3.4.2 (R Core Development Team 2017). CCA analysis used the Vegan package (Oksanen et al 2013).

RESULTS AND DISCUSSION

Vegetation

I found a total of 42 plant species at Antelope Pasture, 26 of which are native to the region (Appendix Table 1-1). However, species of the highest cover and frequency were introduced annuals such as *Bromus tectorum* (cheatgrass), *Lepidium perfoliatum* (clasping pepperweed), *Descurainia pinnata* (flixweed) and *Ranunculus testiculatus* (burr buttercup), as well as the seeded perennial *Agropyron cristatum* (crested wheatgrass) (Tables A.5-A.8; Fig. A.9-A.14). Introduced annual forbs, as a functional group, had a lower mean cover value than cheatgrass (39% compared to 63%) but were similar in frequency (93% forbs, 94% cheatgrass). The dominant grasses were *Elymus elymoides* (bottlebrush squirreltail) and *Poa secunda* (Sandberg bluegrass) (Fig. A.13). Bottlebrush squirreltail was the most common native herbaceous species. Shrub cover was highest in the northwest corner of the pasture, where *Sarcobatus vermiculatus* (Greasewood) and *Artemisia tridentata* (sagebrush) were intermixed, and in the southeast corner, where sagebrush predominated (Fig. A.14).

Spearman rank correlation tests performed on vegetation cover data show weak correlations between species, especially those of native origin (Fig. A.19). Principal components analysis confirmed that invasive annual species drive the dominant relationships within the current vegetation (Fig A.20, Table A.1), consistent with displacement of native species and a lack of intact native communities. Native perennial grasses did show weak associations with shrubs, such as the positive correlation between squirreltail and sagebrush (Fig. A.19). As a functional group, native perennial grasses co-occurred with shrubs in 30% of plots, and shrub presence was significantly associated with native perennial grass presence ($X^2 = 52.18$, $p < 0.01$).

Cheatgrass tended to show negative relationships with other plant species and covaried with “dead herbaceous,” defined in my survey as standing dead herbaceous plant matter from previous growth years (Fig. A.19-A.20; Table A.1). From this I can infer that cheatgrass has reduced species diversity and has created a fuel load of standing dead litter. Open patches of cheatgrass, many greater than 1 acre in size, are distributed throughout much of the pasture (M. Owen, pers. observation). These patches can be identified by examining patterns of shrub cover (Fig. A.14); median cheatgrass cover was higher when shrubs were absent (Presence of shrubs = 62.5%, absence of shrubs= 90%; W=6371, p=<0.001; Fig. A.20), and shrubless patches are often located where cheatgrass cover is highest (Fig. A.10). Dense patches of cheatgrass are also visible in NAIP aerial imagery -- a comparison of field results in Fig. A.10 to imagery in Fig. A.2 shows that, in 2017, reddish or pinkish coloration in the aerial imagery coincide with field-mapped cheatgrass populations. The size and lack of biodiversity within these patches provide an opportunity for broadscale herbicide treatment and reseeding. The litter load should be taken into consideration during these treatments. Litter acts as a positive feedback for cheatgrass, not only by shortening the fire regime (Brooks et al 2004) but by promoting cheatgrass germination through moderated soil surface temperatures and lowered evapotranspiration (Young et al 1972). Experiments done in nearby Park Valley have shown that cheatgrass suppression is more effective and longer-lasting when treatments that remove litter, such as prescribed fire, are used (Hirsch-Schantz et al 2014).

Results also suggest that introduced annual forb species found during my survey (clasping pepperweed and burr buttercup) were more adept at invading shrub canopies than at competing with cheatgrass in open areas (Fig. A.17-A.18). Introduced annual forb cover was higher when shrubs were present (Presence of shrubs = 40%, absence of shrubs = 20%, W=12400, $p<0.001$; Fig. A.21). Introduced annual forbs tended to co-occur with specific shrub species (Fig. A.20, Table A.1). This pattern was most apparent in the northwest corner of the pasture, where clasping pepperweed and burr buttercup have invaded an intact canopy of greasewood and sagebrush but cheatgrass was limited or absent (Fig. A.9-A.12, A.16). The northwest corner of the pasture is distinctive due to its lack of cheatgrass, intact shrub community and other factors such as high biological soil crust development (Fig. A.14-A.15). I hypothesize that is due, in part, to a difference in disturbance history -- that while the portions of the pasture with fragmented shrub cover, open cheatgrass patches and low biological soil crust were mostly likely affected by fire or cultivation, this corner was not. Invasive annual forbs dominate the understory and perennial grasses are depleted but I believe this is more likely due to inappropriate grazing practices rather than fire or soil disturbance.

Crested wheatgrass was the dominant species over much of the area where it was was seeded in 1952 (Fig. A.4 & A.13). The central portion of the seeding appears to have been unsuccessful and has been invaded with cheatgrass (Fig. A.17). In plots where it was present, mean cover was 40% and median 45%, and plants were healthy and robust. Crested wheatgrass was found to have a suppressive effect on introduced annual species cover (Fig. A.17-A.18, A.21). Crested wheatgrass presence reduced median cheatgrass by 82% (Presence of CWG = 15%, absence of CWG= 85%; W=3667, $p=<0.001$). Although the 1952 seeding was largely successful and has continued to thrive and suppress populations of invasive annual plant species, vegetation cover data shows that these stands have also excluded native species and limited biodiversity.

Due to the degraded nature of the vegetation communities within the pasture, many species were rare and only encountered incidentally, outside of any sampling plots (Tables A.6-A.8). This was the case for the majority of native, perennial forbs, but also for many warm-season, introduced annuals. In particular, during my sampling period the distribution of the introduced annual *Halogeton glomeratus* (halogeton) was limited to ruderal zones or areas with soil disturbance, such as ditches and a few animal mounds near to the central two-track (M. Owen, personal observation). Halogeton populations were small enough to be feasibly controlled by spot-spray herbicide treatments along dirt roads, ditches running north/south in the northeast corner, and the prominent ditch beginning in the northwest corner and running diagonally through the pasture (M. Owen, pers. obs.). Other warm-season, introduced annuals such as *Atriplex rosea* (tumbling saltbush), *Salsola tragus* (Russian thistle) and *Kochia scoparia* (kochia) were either found incidentally or were limited in abundance, but were dispersed throughout the pasture (Fig. A.11). It is possible that these species have had a wider distribution in years when patterns in precipitation favored warm-season invasive annuals over cold-season. The diversity and number of introduced, annual forb species within the pasture creates the risk that cheatgrass control will result in dominance by a different invasive annual. The best way to mitigate this risk will be to plant competitive, perennial grasses subsequent to weed control.

In conclusion, the current vegetation of Antelope pasture is a mosaic of introduced annual species, seeded perennial species (crested wheatgrass) and remaining fragments of the original salt-desert shrub community. I conclude that due to the co-dominant and intermixed sagebrush and greasewood, the lack of bluebunch wheatgrass and the limited number of halophytic species or warm season grasses, the site is best described by the Semi-Desert Alkali Loam NRCS Ecological Site Description (Soil Survey Staff, 2018a). This ESD describes the reference state as a broad ecotone between Wyoming big sagebrush and greasewood/shadscale communities, with bottlebrush squirreltail, Sandberg bluegrass and Indian rice grass as the primary grasses. Shrubs are the dominant element, with cover in the reference state estimated at 50%. Grass and forb cover in the reference state are 35% and 10%, respectively. Current native species cover and diversity are well below these levels and are not likely to improve on their own. State and transition models developed for the Semi-Desert Alkali Loam ESD depict the Shrub-Dominated/Invasive Annual and Invasive Annual States as stable alternatives to the reference condition (Soil Survey Staff, 2018a). Without active restoration, transitions from shrub-dominated to annual-dominated communities are likely to continue.

Soils

In my 2017 survey, soils at Antelope Pasture were found to fall into four family classes: fine-silty, mixed, superactive, mesic Xeric Natrargids; fine-loamy, mixed, superactive, mesic Xeric Natrargids; fine-silty, mixed, superactive, mesic Xeric Calciargids; and fine-silty, mixed, superactive, mesic Sodic Xeric Haplocalcids. Figure A.22 shows these soil classes at their sampling locations and delineates the boundaries of these families within the pasture. The Digital Elevation Model is shown in Figure A.23. Written descriptions of individual pedons that best represent the different families follow this section. Official soil series and map unit descriptions for series mapped within Antelope pasture by the USDA-NRCS (Figure 21) can be found at <https://soilseries.sc.egov.usda.gov> and <https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx>, respectively.

I placed my soils within the Aridisol order, in agreement with the NRCS classification for the Idaho portion of the valley floor. At the time of sampling (July and August of 2017), soils were dry to the touch until approx 50-60 cm in depth. Soils had a thin, pale surface horizon (an ochric epipedon) indicative of low organic matter and fertility, matching the requirements for Aridisols (Soil Survey Staff 2014). Mean (and median) depth for A horizons was 8 cm. Fifteen percent of soils had an A2 horizon; including these horizons increased the median depth by 1 cm.

The primary diagnostic features for Antelope pasture soils were shallow accumulations of exchangeable sodium and calcium carbonates, resulting in natric and calcic horizons. All soil samples showed evidence of calcification (the accumulation of calcium carbonates), whether through the presence of finely disseminated carbonates, light coloration or effervescence in response to hydrochloric acid. Masses of secondary (i.e., translocated) calcium carbonates 2-20 mm in size were present in the subsurface horizons of all but a few samples (Fig. A.24). Illuvial horizons with non-cemented accumulations of calcium carbonates that meet set USDA-NRCS requirements were named as calcic. Soils with calcic horizons (and lacking natric horizons; discussed below) within 100 cm of the soil surface were classified into the Haplocalcids great group (Fig.

A.22 & A.25) (Soil Survey Staff 2014). There was no significant difference in depth, weighted average or maximum amount of calcium carbonate concentrations between soil families or subgroups.

I found 75% of soil samples to have a natric horizon -- these soils were classified into the Natrargids great group (Fig. A.22 & A.26). These horizons were often shallow -- median depth to the upper boundary was 10 cm, with a maximum depth of 61 cm. To qualify as natric, horizons must have a columnar or prismatic soil structure, contain a set amount of translocated clay, and show evidence that sodium caused the clay illuviation -- the sodium adsorption ratio much reach 13 or greater within 40 cm of the horizon upper boundary (Soil Survey Staff 2014).

I used pH as a proxy measurement for sodium when determining the presence of natric horizons. Soil pH has been shown to have a positive correlation with exchangeable sodium in aridic soils (Bhargava and Abrol 1978), and sodic soils will generally have a pH of 8.5 or greater. Lab results confirmed a positive relationship between SAR levels and soil pH ($F(1,9)=3.365$, $p=0.09$), with an r^2 of 0.191, though this relationship was not significant and had poor predictive value. Lab results (Table A.3) for soil pH were much lower than field results -- soil samples 53, 98, 158, 200, 260, 482 and 530 all showed a pH of 8.8 or above when tested with indicator solutions in the field. This suggests a high margin of measurement error, although all of these samples did show SAR values over 13 (the point at which soils are considered sodic).

Salinity ranged from normal to salic (soils with an EC greater than 4 dS/m are considered saline), while high ratios of sodium were found well within the rooting zone of perennial grasses, forbs and shrubs (soils with an SAR greater than 13 are considered sodic). Simple linear regression found a significant, positive relationship between SAR and EC (F(1,9)=142.4, $p<0.001$), with an r^2 of 0.933. EC increased 0.112 dS/m for a 1 unit increase in the sodium adsorption ratio.

Two pedons (416 and 418) contained horizons with a high amount of accumulated clay but maintained a pH of 8.4 or below. Illuvial clay was sufficient to meet the requirements for an argillic horizon, and as calcic horizons were also present, the soils were classified into the Calciargids great group (Soil Survey Staff 2014).

Silica masses and cementations (durinodes) 5-20 mm in size were found in nearly half of soil samples and in all families except for fine-loamy Xeric Natrargids (Fig. A.27). Despite this, soil samples did not meet the requirements for classification into duric subgroups (Soil Survey Staff 2014). Duric soils are common in arid or semi-arid soils and are distributed throughout the Great Basin (Bockheim 2014). Redoximorphic concentrations and depletions were found in nearly all soil samples (Fig. A.28-A.29). These features did not affect classification and are the result of reduction or oxidation of soil minerals. Reduction of iron oxides will typically happen when soils are saturated with water, however, these features can persist in soils for hundreds of years and may not reflect current conditions (James 2002; Shaw and West 2002). My soil survey, conducted in June/July of 2017, did not uncover any saturated soils. There were no significant differences in depth, weighted average or maximum amount of silica concentrations or redoximorphic features between soil families or subgroups.

I classified my soils into three subgroups: Xeric Calciargids, Sodic Xeric Haplocalcids and Xeric Natrargids. The Xeric subgrouping denotes that while soils have an aridic soil moisture regime, they border on a xeric. In a normal year, aridic soils will be dry for a longer cumulative period of time than xeric soils (Soil Survey Staff 2014).

As expected from NRCS soil maps (Fig. A.6), the majority of soils fell into the Xeric Natrargids subgroup and were similar in description to the Mellor soil series. The greatest discrepancies came from differences in texture -- the Mellor series is in the fine-silty family texture class and has a clay loam to silty clay loam natric horizon. Textures within my natric horizons ran from silty clay loams to silt loams, and two pedons fell into the fine-loamy family texture class. The texture of my natric horizons ranged from silty clay loams to silt loams. I found Sodic Xeric Haplocalcids to be much more extensive across the pasture than expected. NRCS soil maps depict a Mellor-Freedom complex running through the center of Black Pine Valley, with the Bayhook series and other Sodic Xeric Haplocalcids encircling it (Fig. A.6). The Freedom series is a Xeric Haplocalcid and is not salt-affected, while my Haplocalcids classified into Sodic subgroups based on soil pH and the high sodium adsorption ratios. I would consider these pedons more similar to the Bayhook soil series, though again, there are differences in the family texture class -- Bayhook is classified as coarse-silty rather than fine-silty. As I could not test all pedons for exchangeable sodium, it is possible that some are in fact more similar to the non-salt affected Freedom series.

Principal components analysis found calcium carbonate and silica concentrations to be prominent sources of variation within the data (Fig. A.30, Table A.4). Silica concentrations and redoximorphic features varied independently of clay content, while solutes -- calcium carbonates, exchangeable sodium and other salts -- displayed strong relationships to soil texture.

Family classifications assumed all pedons to have mixed mineralogy, superactive cation-exchange activity (a ratio of cation exchange capacity to percent clay of 0.6 or greater) and a soil temperature class of mesic (mean annual soil temp of 8º C/47º F to 15º C/59º F) based on USDA-NRCS classifications in the area. I placed my soils into two particle-size classes: fine-silty and fine-loamy (Soil Survey Staff 2014), based on the texture within a soil control section of 25-100 cm from the soil surface.

In conclusion, the soils of Antelope pasture are made up of fine-grained, lacustrine sediment and are primarily characterized by alluvial deposits of calcium and sodium now accumulated in the subsurface horizons. The primary differences between pedons were the presence or absence of natric horizons or silica masses. Sodium adsorption ratios were higher than expected from USDA-NRCS classifications, leading us to classify a greater proportion of pedons into sodic subgroups.

Written Descriptions of Representative Soil Samples

The following seven pedon descriptions were prepared by Merran Owen and are based on data collected during my summer 2017 soil survey. These pedons were determined to best represent the four soil families classified within Antelope pasture in 2017. Their location within the pasture can be viewed in Fig. A.22. Pedons have been broken into genetic horizons and labeled according to qualitative features. Horizon definitions follow the National Cooperative Soil Survey (Schoeneberger et al 2012; Soil Science Division Staff 2017).

Master horizons are designated by capital letters and are defined as follows: A horizons form at the soil surface and consist of mineral soil mixed with accumulations of organic matter. They may have properties resulting from cultivation or pasturing. B horizons are subsurface, mineral horizons that show evidence of pedogensis such as the accumulation of silicate clay, iron, carbonates, sesquioxides, etc. C horizons are mineral soil or soft bedrock that have been little affected by pedogensis. A designation such as AB or BC indicates a horizon with characteristics of both master horizons but dominated by that which is listed first. Horizon suffixes are lowercase letters that indicate specific characteristics: “t” indicates an accumulation of silicate clay; “k” an accumulation of secondary carbonates; “n” an accumulation of exchangeable sodium and “q” indicates the accumulation of secondary silica (Schoeneberger et al 2012).

Soil Sample #47

This pedon is a very deep, well drained soil formed in fine grained lacustrine sediments derived from sedimentary rocks. The pedon is on a flat surface at an elevation of 1378 m. Slopes are 0-1 percent. Mean annual precipitation is 203-254 mm and mean annual air temperature is 8.3° C. Current vegetation is *Artemisia tridentata* ssp. *wyomingensis* (Sagebrush) and *Bromus tectorum* (Cheatgrass). Native vegetation is presumed to be sagebrush, perennial grasses and forbs.

TAXONOMIC CLASS: Fine-loamy, mixed, superactive, mesic Xeric Natrargids

TYPICAL PEDON: This pedon is in Antelope Pasture, Curlew Grazing Allotment, Oneida County, ID. Exact coordinates are 42◦1’30.7” N, 112◦55’54.4” W. (Colors are for dry soil unless otherwise noted. When described on July 12, 2017, soil was dry to slightly moist.)

A1--0 to 9 cm; light gray (10YR 7/2) loam, brown (10YR 4/3) moist; moderate medium granular structure; soft, very friable, slightly sticky and slightly plastic; many very fine and common fine roots; slightly effervescent, slightly alkaline (pH 7.8); clear smooth boundary.

A2--9 to 25 cm; light gray (10YR 7/2) silt loam, brown (10YR 5/3) moist; moderate fine subangular blocky structure; soft, very friable, moderately sticky and moderately plastic; many very fine roots; 3% fine gravel; slightly effervescent, strongly alkaline (pH 8.8); clear smooth boundary.

Btn--25 to 42 cm; light gray (2.5Y 7/2) silt loam, grayish brown (2.5Y 5/2) moist; moderately sticky and moderately plastic; 1% gravel; violently effervescent, strongly alkaline (pH 9.0).

Bn--42 to 75 cm; pale brown (2.5Y 8/2) loam, pale brown (2.5Y 7/3) moist; slightly sticky and slightly plastic; few medium prominent iron masses; few medium prominent iron depletions; 1% gravel; violently effervescent, strongly alkaline (pH 9.0).

Bk--75 to 114 cm; light gray (2.5Y 7/2) loam, light yellowish brown (2.5Y 6/3) moist; slightly sticky and slightly plastic; few coarse carbonate masses; few medium prominent iron masses; few medium prominent iron depletions; 5% gravel; violently effervescent, strongly alkaline (pH 8.6).

C--114 to 121 cm; light gray (2.5Y 7/2) loam, light yellowish brown (2.5Y 6/3) moist; slightly sticky and slightly plastic; few coarse carbonate masses; few medium prominent iron masses; 35% coarse gravel; violently effervescent, moderately alkaline (pH 8.2). This pedon was gravel-limited at 121 cm.

Soil Sample #92

This pedon is a very deep, well drained soil formed in fine grained lacustrine sediments derived from sedimentary rocks. The pedon is on a flat surface at an elevation of 1381 m. Slopes are 0-1 percent. Mean annual precipitation is 203-254 mm and mean annual air temperature is 8.3° C. Current vegetation is *Artemisia tridentata* ssp. *wyomingensis* (Sagebrush) and *Bromus tectorum* (Cheatgrass). Native vegetation is presumed to be sagebrush, perennial grasses and forbs.

TAXONOMIC CLASS: Fine-silty, mixed, superactive, mesic Xeric Natrargids

TYPICAL PEDON: This pedon is in Antelope Pasture, Curlew Grazing Allotment, Oneida County, ID. Exact coordinates are 42°1’20.5” N, 112°56’20.18” W. (Colors are for dry soil unless otherwise noted. When described on June 20, 2017, soil was dry to slightly moist.)

A--0 to 5 cm; light gray (2.5Y 7/2) silt loam, grayish brown (2.5Y 5/2) moist; moderate medium platy structure; slightly hard, friable, slightly sticky and slightly plastic; many very fine and many fine roots; noneffervescent, slightly alkaline (pH 7.6); clear smooth boundary.

Bt--5 to 20 cm; light gray (2.5Y 7/2) silty clay loam, grayish brown (2.5Y 5/2) moist; moderate very fine granular structure; slightly hard, friable, moderately sticky and moderately plastic; many very fine and many fine and few coarse roots; slightly effervescent, slightly alkaline (pH 7.8); clear smooth boundary.

Btk--20 to 33 cm; light gray (2.5Y 7/2) silty clay loam, light brownish gray (2.5Y 6/2) moist; moderately sticky and moderately plastic; common medium carbonate masses; strongly effervescent, slightly alkaline (pH 7.8).

Bkn1--33 to 52 cm; white (2.5Y 8/1) silt loam, light brownish gray (2.5Y 6/2) moist; moderately sticky and moderately plastic; common medium carbonate masses; violently effervescent, very strongly alkaline (pH 9.4).

Bkqn--52 to 75 cm; white (2.5Y 8/1) silt loam, light gray (2.5Y 7/2) moist; slightly sticky and slightly plastic; common coarse silica masses; few medium carbonate masses; violently effervescent, strongly alkaline (pH 9.2).

BC--75 to 120 cm; light gray (2.5Y 7/2) silt loam, light brownish gray (2.5Y 6/2) moist; slightly sticky and slightly plastic; few medium carbonate masses; few medium prominent iron masses; few medium prominent iron depletions; violently effervescent, strongly alkaline (pH 8.6).

C--120 to 153 cm; light gray (2.5Y 7/2) silt loam, light brownish gray (2.5Y 6/2) moist; slightly sticky and slightly plastic; few coarse carbonate masses; common medium prominent iron masses; few medium prominent iron depletions; violently effervescent, moderately alkaline (pH 8.4).

Soil Sample # 101

This pedon is a very deep, well drained soil formed in fine grained lacustrine sediments derived from sedimentary rocks. The pedon is on a flat surface at an elevation of 1383 m. Slopes are 0-1 percent. Mean annual precipitation is 203-254 mm and mean annual air temperature is 8.3° C. Current vegetation is *Artemisia tridentata* ssp. *wyomingensis* (Sagebrush) and *Bromus tectorum* (Cheatgrass). Native vegetation is presumed to be sagebrush, perennial grasses and forbs.

TAXONOMIC CLASS: Coarse-silty, mixed, superactive, mesic Xeric Natrargids

TYPICAL PEDON: This pedon is in Antelope Pasture, Curlew Grazing Allotment, Oneida County, ID. Exact coordinates are 42◦1’20.96” N, 112◦55’54.08” W. (Colors are for dry soil unless otherwise noted. When described on July 12, 2017, soil was dry to slightly moist.)

A--0 to 7 cm; light gray (10YR 7/2) silt loam, dark grayish brown (10YR 4/2) moist; moderate medium platy structure; slightly hard, friable, slightly sticky and slightly plastic; many very fine roots and few fine roots; very slight effervescent, slightly alkaline (pH 7.6); clear smooth boundary.

Btn—7 to 28 cm; light gray (10YR 7/2) silt loam, brown (10YR 5/3) moist; moderate fine subangular blocky structure; slightly hard, friable, slightly sticky and slightly plastic; common very fine and few coarse roots; strongly effervescent, strongly alkaline (pH 9.0); clear smooth boundary.

Bt1--28 to 58 cm; light gray (2.5Y 7/2) silt loam, light yellowish brown (2.5Y 6/3) moist; slightly sticky and slightly plastic; few fine roots; few medium prominent iron masses; violently effervescent, strongly alkaline (pH 8.8).

Bt2--58 to 78 cm; light gray (2.5Y 7/2) silt loam, light brownish gray (2.5Y 6/2) moist; slightly sticky and slightly plastic; few medium prominent iron masses; violently effervescent, strongly alkaline (pH 8.6).

B1--78 to 99 cm; light gray (2.5Y 7/2) silt loam, light brownish gray (2.5Y 6/2) moist; slightly sticky and slightly plastic; few medium prominent iron masses; few medium prominent iron depletions; violently effervescent, moderately alkaline (pH 8.2).

BCk--99 to 136 cm; white (2.5Y 8/1) silt loam, light brownish gray (2.5Y 6/2) moist; slightly sticky and slightly plastic; few medium carbonate masses; few medium prominent iron masses; few medium prominent iron depletions; violently effervescent, moderately alkaline (pH 8.0).

C—136 to 157 cm; white (2.5Y 8/1) silt loam, light brownish gray (2.5Y 6/2) moist slightly sticky and slightly plastic; few coarse carbonate masses; few medium prominent iron masses; few medium prominent iron depletions; violently effervescent, moderately alkaline (pH 8.0).

Soil Sample #260

This pedon is a very deep, well drained soil formed in fine grained lacustrine sediments derived from sedimentary rocks. The pedon is on a flat surface at an elevation of 1370 m. Slopes are 0-1 percent. Mean annual precipitation is 203-254 mm and mean annual air temperature is 8.3° C. Current vegetation is *Sarcobatus vermiculatus* (Greasewood) and *Bromus tectorum* (Cheatgrass). Native vegetation is presumed to be greasewood, perennial grasses and forbs.

TAXONOMIC CLASS: Fine-silty, mixed, superactive, mesic Xeric Natrargids

TYPICAL PEDON: This pedon is in Antelope Pasture, Curlew Grazing Allotment, Oneida County, ID. Exact coordinates are 42°0’51.55” N, 112°56’6.25” W . (Colors are for dry soil unless otherwise noted. When described on July 17, 2017, soil was dry to slightly moist.)

A--0 to 8 cm; light gray (10YR 7/2) loam, grayish brown (10YR 5/2) moist; strong medium platy structure; slightly hard, friable, slightly sticky and slightly plastic; many very fine roots; slightly effervescent, strongly alkaline (pH 8.6); clear smooth boundary.

Btn1—8 to 22 cm; white (2.5Y 8/1) silty clay loam, light brownish gray (2.5Y 6/2) moist; moderate medium subangular blocky structure; slightly hard, friable, moderately sticky and moderately plastic; common very fine and few fine and coarse roots; violently effervescent, strongly alkaline (pH 9.0); clear smooth boundary.

Btn2--22 to 49 cm; white (2.5Y 8/1) silt loam, light yellowish brown (2.5Y 6/3) moist; moderately sticky and moderately plastic; few fine and coarse and very coarse roots; violently effervescent, strongly alkaline (pH 9.0).

Bk--49 to 80 cm; white (2.5Y 8/1) silt loam, light brownish gray (2.5Y 6/2) moist; slightly sticky and slightly plastic; few medium carbonate masses; violently effervescent, strongly alkaline (pH 8.4).

Btk1--80 to 112 cm; light gray (2.5Y 7/2) silt loam, light brownish gray (2.5Y 6/2) moist; moderately sticky and moderately plastic; few coarse carbonate masses; violently effervescent, moderately alkaline (pH 8.0).

Btk2--112 to 150 cm; light gray (2.5Y 7/2) silt loam, light brownish gray (2.5Y 6/2) moist; moderately sticky and moderately plastic; few coarse carbonate masses; violently effervescent, moderately alkaline (pH 8.0).

Soil Sample #308

This pedon is a very deep, well drained soil formed in fine grained lacustrine sediments derived from sedimentary rocks. The pedon is on a flat surface at an elevation of 1370 m. Slopes are 0-1 percent. Mean annual precipitation is 203-254 mm and mean annual air temperature is 8.3° C. Current vegetation is *Artemisia tridentata* ssp. *wyomingensis* (Sagebrush), *Sarcobatus vermiculatus* (Greasewood) and *Bromus tectorum*

(Cheatgrass). Native vegetation is presumed to be sagebrush, greasewood, perennial grasses and forbs.

TAXONOMIC CLASS: Fine-silty, mixed, superactive, mesic Sodic Xeric Haplocalcids

TYPICAL PEDON: This pedon is in Antelope Pasture, Curlew Grazing Allotment, Oneida County, ID. Exact coordinates are 42°0’41.4” N, 112°56’32.03” W. (Colors are for dry soil unless otherwise noted. When described on June 30, 2017, soil was dry to slightly moist.)

A1--0 to 8 cm; light brownish gray (2.5Y 6/2) loam, dark grayish brown (2.5Y 4/2) moist; moderate fine granular structure; soft, friable, slightly sticky and slightly plastic; many very fine and common fine roots; violently effervescent, moderately alkaline (pH 8.0); clear smooth boundary.

A2--8 to 22 cm; light gray (2.5Y 7/2) silt loam, grayish brown (2.5Y 5/2) moist; moderate fine granular structure; soft, friable, slightly sticky and slightly plastic; common very fine and few fine roots; violently effervescent, moderately alkaline (pH 8.0); clear smooth boundary.

AB--22 to 54 cm; white (2.5Y 8/1) silt loam, light brownish gray (2.5Y 6/2) moist; slightly sticky and slightly plastic; few fine and coarse and very coarse roots; finely disseminated carbonates; violently effervescent, strongly alkaline (pH 8.6).

Bk1--54 to 67 cm; white (2.5Y 8/1) silt loam, light brownish gray (2.5Y 6/2) moist; slightly sticky and slightly plastic; finely disseminated carbonates; few medium prominent iron masses; violently effervescent, strongly alkaline (pH 8.6).

Bk2--67 to 80 cm; white (2.5Y 8/1) silt loam, light brownish gray (2.5Y 6/2) moist; slightly sticky and slightly plastic; few medium carbonate masses; few medium prominent iron masses; violently effervescent, moderately alkaline (pH 8.4).

Bk3--81 to 96 cm; light gray (2.5Y 7/2) silt loam, light brownish gray (2.5Y 6/2) moist; slightly sticky and slightly plastic; few medium carbonate masses; few medium prominent iron masses; few medium prominent iron depletions; violently effervescent, moderately alkaline (pH 8.0).

BCk--96 to 133 cm; light gray (2.5Y 7/2) silt loam, grayish brown (2.5Y 5/2) moist; slightly sticky and slightly plastic; few medium carbonate masses; few medium prominent iron masses; few medium prominent iron depletions; violently effervescent, moderately alkaline (pH 8.0).

C--133 to 158 cm; light gray (2.5Y 7/2) silt loam, grayish brown (2.5Y 5/2) moist; slightly sticky and slightly plastic; common medium carbonate masses; few medium prominent iron masses; few medium prominent iron depletions; violently effervescent, moderately alkaline (pH 8.0).

Soil Sample # 377

This pedon is a very deep, well drained soil formed in fine grained lacustrine sediments derived from sedimentary rocks. The pedon is on a flat surface at an elevation of 1367 m. Slopes are 0-1 percent. Mean annual precipitation is 203-254 mm and mean annual air temperature is 8.3° C. Current vegetation is *Artemisia tridentata* ssp. *wyomingensis* (Sagebrush) and *Bromus tectorum* (Cheatgrass). Native vegetation is presumed to be sagebrush, perennial grasses and forbs.

TAXONOMIC CLASS: Coarse-silty, mixed, superactive, mesic Sodic Xeric Haplocalcids

TYPICAL PEDON: This pedon is in Antelope Pasture, Curlew Grazing Allotment, Oneida County, ID. Exact coordinates are 42°0’32.8” N, 112°55’26.54” W. (Colors are for dry soil unless otherwise noted. When described on July 4, 2017, soil was dry to slightly moist.)

A--0 to 8 cm; light brownish gray (10YR 6/2) loam, dark grayish brown (10YR 4/2) moist; moderate medium platy structure; slightly hard, friable, slightly sticky and slightly plastic; many very fine roots and few coarse roots; slightly effervescent, slightly alkaline (pH 7.8); clear smooth boundary.

AB—8 to 28 cm; light brownish gray (10YR 6/2) loam, dark grayish brown (10YR 4/2) moist; moderate fine subangular blocky structure; slightly hard, friable, moderately sticky and moderately plastic; common very fine and few fine and coarse roots; strongly effervescent, moderately alkaline (pH 8.2); clear smooth boundary.

Bn--28 to 55 cm; light gray (2.5Y 7/2) silt loam, light brownish gray (2.5Y 6/2) moist; slightly sticky and slightly plastic; few medium carbonate masses; violently effervescent, very strongly alkaline (pH 9.2).

Bkqn--55 to 89 cm; white (2.5Y 8/1) silt loam, light brownish gray (2.5Y 6/2) moist; slightly sticky and slightly plastic; few coarse silica masses; few medium carbonate masses; common medium prominent iron masses; violently effervescent, very strongly alkaline (pH 9.2).

Bk1--89 to 111 cm; light gray (2.5Y 7/2) silt loam, grayish brown (2.5Y 5/2) moist; slightly sticky and slightly plastic; few coarse carbonate masses; common medium prominent iron masses; common medium prominent iron depletions; violently effervescent, strongly alkaline (pH 8.8).

Bk2--111 to 150 cm; light gray (2.5Y 7/2) silt loam, grayish brown (2.5Y 5/2) moist; moderately sticky and moderately plastic; few coarse carbonate masses; few medium prominent iron masses; few medium prominent iron depletions; violently effervescent, moderately alkaline (pH 8.2).

Soil Sample #416

This pedon is a very deep, well drained soil formed in fine grained lacustrine sediments derived from sedimentary rocks. The pedon is on a flat surface at an elevation of 1365 m. Slopes are 0-1 percent. Mean annual precipitation is 203-254 mm and mean annual air temperature is 8.3° C. Current vegetation is *Sarcobatus vermiculatus* (Greasewood), *Bromus tectorum* (Cheatgrass) and *Lepidium perfoliatum* (Clasping Pepperweed). Native vegetation is presumed to be sagebrush, greasewood, perennial grasses and forbs.

TAXONOMIC CLASS: Fine-silty, mixed, superactive, mesic Xeric Calciargids

TYPICAL PEDON: This pedon is in Antelope Pasture, Curlew Grazing Allotment, Oneida County, ID. Exact coordinates are 42°0’21.96” N, 112°56’31.42” W. (Colors are for dry soil unless otherwise noted. When described on June 30, 2017, soil was dry to slightly moist.)

A1--0 to 6 cm; white (2.5Y 8/1) loam, grayish brown (2.5Y 5/2) moist; weak medium platy structure; soft, very friable, slightly sticky and slightly plastic; common very fine roots; very slight effervescence, moderately alkaline (pH 8.2); clear smooth boundary.

A2--6 to 20 cm; white (2.5Y 8/1) loam, grayish brown (2.5Y 5/2) moist; moderate fine granular structure; slightly hard, friable, slightly sticky and slightly plastic; slightly effervescent, moderately alkaline (pH 8.2); clear smooth boundary.

Bk1--20 to 36 cm; white (2.5Y 8/1) silt loam, light yellowish brown (2.5Y 6/3) moist; slightly sticky and slightly plastic; few medium carbonate masses; few medium prominent iron masses; strongly effervescent, moderately alkaline (pH 8.2).

Bkq--36 to 70 cm; white (2.5Y 8/1) silt loam, light yellowish brown (2.5Y 6/3) moist; moderately sticky and moderately plastic; common coarse silica masses; few medium carbonate masses; few medium prominent iron masses; violently effervescent, moderately alkaline (pH 8.2).

Bk2’--70 to 97 cm; light gray (2.5Y 7/1) silt loam, light brownish gray (2.5Y 6/2) moist; moderately sticky and moderately plastic; few medium carbonate masses; few medium prominent iron masses; few medium prominent iron depletions; violently effervescent, moderately alkaline (pH 8.0).

Bk3’--97 to 117 cm; light gray (2.5Y 7/2) silt loam, light brownish gray (2.5Y 6/2) moist; moderately sticky and moderately plastic; few medium carbonate masses; few medium prominent iron masses; few medium prominent iron depletions; violently effervescent, slightly alkaline (pH 7.6).

Bk4’--117 to 155 cm; light gray (2.5Y 7/2) silt loam, light brownish gray (2.5Y 6/2) moist; moderately sticky and moderately plastic; common medium carbonate masses; few medium prominent iron masses; violently effervescent, slightly alkaline (pH 7.6).

Soil/Vegetation Relationships

The strongest relationships between soil and vegetation were found in soil variables in proximity to or at the soil surface (Fig. A.31). Analyses did not uncover patterns in vegetation based on prominent subsurface features such as silica concentrations or redoximorphic features. Canonical correlation analysis showed weak patterns of covariance between vegetation and soil variables relating to texture, such as the depth of calcium carbonate concentrations and percent clay at a depth of 30 cm (Fig. A.32). Greasewood cover was correlated with higher pH values in surface horizons, due to its ability to concentrate sodium oxalates and other solutes in its leaves (Rickard 1965), which are then shed each year onto the soil surface.

Invasive annuals such as cheatgrass and clasping pepperweed were more strongly associated with cover values for soil surface variables. Spearman rank correlations between vegetation species and soil surface categories are shown in Fig. A.31. Native species were positively correlated with cover values for both moss and biological soil crust. Research in the Great Basin has previously identified a pattern of association between native vegetation and cryptogam-stabilized soils, and has suggested that these soils offer favorable microsites for plant establishment (Eckert Jr et al 1986; Belnap et al 2001). In contrast, cheatgrass displayed a negative correlation with biological soil crust. The abundance of cheatgrass within the pasture and resulting high propagule pressure suggests that crust is acting as a barrier to seed germination in this species. This pattern has also been identified in previous research within sagebrush ecosystems (Peterson 2013). Meanwhile, introduced annual forbs such as clasping pepperweed and *Ranunculus testiculatus* (burr buttercup) did not show the same difficulty germinating in pasture soils with cryptogam or moss cover. This pattern is most apparent in the pasture's northwest corner, where crust and introduced annual forb cover is high and cheatgrass is largely absent (Fig. A.9-A.12, A.15). Clasping pepperweed and burr buttercup are small-seeded species, and may be more adept at penetrating the physical barriers established by the presence of these organisms.

No significant difference was found in the cover of dominant plant species (*Artemisia tridentata, Sarcobatus vermiculatus, Bromus tectorum* and *Lepidium perfoliatum*) between soils with natric horizons and without. Natric horizons can act as root-restricting layers and often exhibit poor infiltration of water and air due to increased clay illuviation (Buol et al. 2011; Brady and Weil 2010). However, analyses did not show any significant effect of their presence on vegetation cover. Sodium adsorption ratio and electrical conductivity values (SAR and EC) did not show significant linear relationships with vegetation cover, and many species were present in abundance in soils with high SAR values. *Agropyron cristatum* (crested wheatgrass), for example, was present at 70% cover in plot 215, which had a sodium adsorption ratio of 26.5 at a depth of 11-44 cm below the soil surface.

I conclude that the strongest driving factor in relationships between pasture soils and vegetation identified through analyses was the presence or absence of a biological soil crust or moss cover. Because so few relationships were found between vegetation and soil variables, other factors, such as disturbance history, are more likely to be the central cause of variation in vegetation across the pasture.

PRODUCTS

Antelope Pasture Geodatabase

I created a geodatabase with the following feature classes. The geodatabase uses the North American 1983 Datum (NAD83).

- Vegetation Cover

This point file includes vegetation, non-living plant matter and soil surface cover data for all 282 plots. Attribute fields include plot number, X and Y coordinates in NAD83, sample date and cover (by plot) for all plant species, non-living plant matter and soil surface categories, labeled by species code (see Tables A.5-A.9 for species codes).

- Vegetation Presence

This point file includes vegetation presence data for all 282 plots. Species are listed as present if they were intercepted along transect lines or located within the 3m plot. Attribute table fields include plot number, X and Y coordinates in NAD83, sample date and presence (by plot) for all plant species, labeled by species code.

- Incidentals

This point file includes data on incidental sightings of plant species, i.e., species that were only found outside of plots. Attribute table fields include X and Y coordinates in NAD83 and species codes.

- Family Polygons

This polygon file delineates the extent of all soil families mapped within Antelope Pasture. Attribute table fields include family classification.

Soil Data

This point file includes soil data for all 58 soil samples. Attribute fields include plot number, X and Y coordinates in NAD83, date sampled, soil subgroup/great group, pH and percent clay for the surface horizon (A1) and at a depth of 20 cm, 50 cm and 100 cm. Attributes also include EC and SAR lab results and maximum value for calcium carbonate, silica and redoximorphic concentrations and redoximorphic depletions, given as a percent of the visible soil surface area occupied within a horizon.

Digital Images

I prepared a compilation of photos taken at each soil sampling point during the 2017 survey.

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TABLES AND FIGURES

Table A.1. Principal component analysis factor loading values for vegetation data analysis. Included are two shrub species (ARTTRI and SARVER), one introduced annual grass (BROTEC), two introduced annual forbs (DESSOP and LEPPER) and standing dead herbaceous (DH). The accompanying PCA biplot is shown in Figure A.20.

Species Code	Species Name	Factor Loading Values: PCA1	Factor Loading Values: PCA2	Factor Loading Values: PCA3
ARTTRI	*Artemisia tridentata*	-0.192	-0.154	**0.598**
BROTEC	*Bromus tectorum*	**0.512**	-0.156	-0.131
DESSOP	*Descurainia sophia*	-0.087	0.047	**0.432**
LEPPER	*Lepidium perfoliatum*	-0.204	**0.332**	-0.280
SARVER	*Sarcobatus vermiculatus*	-0.112	**0.994**	0.020
DH	Standing Dead Herbaceous	**0.984**	-0.054	-0.172

Table A.2. Principal component analysis factor loading values for soils data analysis. Values for concentrations and depletions were calculated as a percent of the visible soil surface area occupied within a soil horizon. The accompanying PCA biplot is shown in Figure A.30.

Code	Definition	Factor Loading Values: PCA1	Factor Loading Values: PCA2	Factor Loading Values: PCA3
CaCO3.depth	Depth (cm) to calcium carbonate concentrations	-0.328	**0.535**	0.013
CaCO3.max	Maximum value of calcium carbonate concentrations within a horizon	0.428	**-0.445**	-0.032
Clay.max	Maximum percent clay within a horizon	**0.464**	-0.188	0.046
F3M.depth	Depth (cm) to redoximorphic concentrations	-0.172	-0.163	**-0.366**
F3M.max	Maximum value of redoximorphic concentrations within a horizon	**0.389**	0.200	0.441
FED.max	Maximum value of redoximorphic depletions within a horizon	0.182	0.348	**0.519**
Silica.depth	Depth (cm) to silica concentrations	-0.346	-0.400	**0.455**
Silica.max	Maximum value of silica concentrations within a horizon	0.400	0.364	**-0.437**

Table A.3. Soil sample lab results for electrical conductivity (EC) and sodium adsorption ratio (SAR). Sample location within Antelope pasture is shown in Figure A.22. Soils with EC greater than 4 dS/m are considered saline, and soils with an SAR greater than 13 are considered sodic (Brady and Weil 2010). Soil horizons chosen for testing were subsurface horizons showing clay illuviation and/or high pH.

Sample #	Sample Depth (cm)	pH	EC (dS/m)	SAR	Soil Family
50	23-67	8.5	4.28	32.0	Fine-silty Sodic Xeric Haplocalcids
53	10-44	8.7	2.42	15.7	Fine-silty Sodic Xeric Haplocalcids
92	6-33	7.5	0.81	2.20	Fine-silty Xeric Natrargids
98	7-50	8.6	6.00	46.1	Fine-silty Xeric Natrargids
158	10-57	8.3	3.14	24.9	Fine-silty Sodic Xeric Haplocalcids
200	10-56	8.6	1.86	14.3	Fine-silty Sodic Xeric Haplocalcids
215	11-44	7.6	9.06	26.5	Fine-silty Xeric Natrargids
260	9-49	8.5	4.79	44.7	Fine-silty Sodic Xeric Haplocalcids
308	22-67	8.6	2.43	21.5	Fine-silty Sodic Xeric Haplocalcids
377	29-89	8.6	2.56	21.8	Fine-silty Sodic Xeric Haplocalcids
482	7-39	8.2	1.91	17.4	Fine-silty Xeric Natrargids
530	7-58	8.4	2.91	27.0	Fine-silty Xeric Natrargids

Table A.4. Canonical correspondence analysis factor loading values soil/vegetation data analysis. Included are two native shrub species (ARTRI and SARVER), one introduced annual grass (BROTEC), two introduced annual forbs (DESSOP and LEPPER) and four soil variables. Explanatory soil variables are shown in blue, and plant response variables in red. For all, p-value <0.05. The accompanying CCA biplot is shown in Figure A.32.

Code	Species Name	Factor Loading Values: CCA1	Factor Loading Values: CCA2	Factor Loading Values: CCA3
Response Variables				
ARTTRI	*Artemisia tridentata*	-0.060	**-0.818**	-0.182
BROTEC	*Bromus tectorum*	**-0.240**	0.060	0.013
DESSOP	*Descurainia sophia*	0.498	**-0.585**	0.517
LEPPER	*Lepidium perfoliatum*	**0.349**	**0.021**	-0.031
SARVER	*Sarcobatus vermiculatus*	**0.957**	0.361	-0.047
Explanatory Variables				
A.depth	Thickness of A horizon	-0.613	0.181	**0.766**
A.pH	A horizon pH	0.381	**0.662**	-0.064
Clay.30	% Clay at 30 cm from soil surface	**0.823**	-0.543	0.132
CaCO3.depth	Depth to calcium carbonate concentrations	**-0.677**	-0.519	-0.203

Table A.5. Plant species identified at Antelope pasture in 2017. Taxonomy and nativity follow the Integrated Taxonomic Information System (ITIS). Functional groups follow the Natural Resources Conservation Service (USDA) Plant Database.

Family	Species Code	Scientific Name	Common Name	Functional Group	Introduced
Apiaceae	CYMPUR	*Cymopterus purpurascens*	Widewing Spring Parsley	Perennial Forb	
Amaranthaceae	ATRCAN	*Atriplex canescens*	Fourwing Saltbush	Shrub	
	ATRCON	*Atriplex confertifolia*	Shadscale	Shrub	
	ATRROS	*Atriplex rosea*	Tumbling Saltbush	Annual Forb	X
	HALGLO	*Halogeton glomeratus*	Halogeton	Annual Forb	X
	KOCAME	*Kochia americana*	Greenmolly	Subshrub	
	KOCSCO	*Kochia scoparia*	Kochia	Annual Forb	X
	SALTRA	*Salsola tragus*	Russian Thistle	Annual Forb	X
Amaryllidaceae	ALLNEV	*Allium nevadense*	Nevada Onion	Perennial Forb	
Asteraceae	ARTTRI	*Artemisia tridentata* subsp. *wyomingensis*	Wyoming Big Sagebrush	Shrub	
	CHRVIS	*Chrysothamnus viscidiflorus*	Yellow Rabbitbrush	Shrub	
	ERINAU	*Ericameria nauseosa*	Rubber Rabbitbrush	Shrub	
	LACSER	*Lactuca serriola*	Prickly Lettuce	Annual/Biennial Forb	X
	TRADUB	*Tragopogon dubius*	Yellow Salsify	Annual/Biennial Forb	X
Boraginaceae	CRYsp	*Cryptantha* species	Catseye	Annual Forb	
	LAPOCC	*Lappula occidentalis*	Stickseed	Annual/Biennial Forb	
Brassicaceae	ALYDES	*Alyssum desertorum*	Desert Alyssum	Annual Forb	X
	CHOTEN	*Chorispora tenella*	Purple Mustard	Annual Forb	X
	DESPIN	*Descurainia pinnata*	Tansymustard	Annual/Biennial/Perennial Forb	
	DESSOP	*Descurainia sophia*	Flixweed	Annual/Biennial Forb	X
	LEPPER	*Lepidium perfoliatum*	Clasping Pepperweed	Annual Forb	X

Table A.5 Continued. Plant species identified at Antelope pasture in 2017. Taxonomy and nativity follow the Integrated Taxonomic Information System (ITIS). Functional groups follow the Natural Resources Conservation Service (USDA) Plant Database.

Family	**Species Code**	**Scientific Name**	**Common Name**	**Functional Group**	**Introduced**
Brassicaceae	SISALT	*Sisymbrium altissimum*	Tumble Mustard	Annual/Biennial Forb	X
	SISLIN	*Sisymbrium linifolium*	Flaxleaf Plainsmustard	Perennial Forb	
Cactaceae	OPUPOL	*Opuntia polyacantha*	Plains Pricklypear	Shrub	
Fabaceae	ASTLEN	*Astragalus lentiginosus*	Freckled Milkvetch	Perennial Forb	
	ASTPUR	*Astragalus purshii*	Woollypod Milkvetch	Perennial Forb	
Poaceae	ACHHYM	*Achnatherum hymenoides*	Indian Rice Grass	Perennial Grass	
	AGRCRI	*Agropyron cristatum*	Crested Wheatgrass	Perennial Grass	X
	ARIPUR	*Aristida purpurea*	Purple Threeawn	Perennial Grass	
	BROTEC	*Bromus tectorum*	Cheatgrass	Annual Grass	X
	ELYELY	*Elymus elymoides*	Bottlebrush Squirreltail	Perennial Grass	
	ERETRI	*Eremopyrum triticeum*	Annual Wheatgrass	Annual Grass	X
	LEYCIN	*Leymus cinereus*	Basin Wildrye	Perennial Grass	
	PASSMI	*Pascopyrum smithii*	Western Wheatgrass	Perennial Grass	
	POABUL	*Poa bulbosa*	Bulbous Bluegrass	Perennial Grass	X
	POASEC	*Poa secunda*	Sandberg Bluegrass	Perennial Grass	
	VULOCT	*Vulpia octoflora*	Sixweeks Fescue	Annual Grass	
Polemoniaceae	LINPUN	*Linanthus pungens*	Prickly Phlox	Perennial Forb	
	PHLHOO	*Phlox hoodii*	Hood's Phlox	Perennial Forb	
	PHLLON	*Phlox longifolia*	Longleaf Phlox	Perennial Forb	
Ranunculaceae	RANTES	*Ranunculus testiculatus*	Burr Buttercup	Annual Forb	X
Sarcobataceae	SARVER	*Sarcobatus vermiculatus*	Greasewood	Shrub	

Table A.6. Annual/biennial species cover and frequency (calculated as the percentage of plots with species present) by nativity. Species with no recorded cover were not intercepted along any transect line. Species with no recorded frequency were found incidentally, outside of sample plots. Group cover may exceed 100%, due to overlap.

Annual/Biennial Forbs, Native

Species Code	Species Name	Common Name	Mean Cover	SE	Frequency
CRYsp	*Cryptantha* species	Catseye	N/A	N/A	N/A
DESPIN	*Descurainia pinnata*	Tansymustard	0.57%	0.21%	6.74%
LAPOCC	*Lappula occidentalis*	Stickseed	0.07%	0.04%	3.19%
Group Total			0.64%	0.21%	9.57%

Annual/Biennial Forbs, Introduced

Species Code	Species Name	Common Name	Mean Cover	SE	Frequency
ALYDES	*Alyssum desertorum*	Desert Alyssum	0.07%	0.06%	1.06%
ATRROS	*Atriplex rosea*	Tumbling Saltbush	N/A	N/A	N/A
CHOTEN	*Chorispora tenella*	Purple Mustard	N/A	N/A	0.35%
DESSOP	*Descurainia sophia*	Flixweed	3.28%	0.49%	40.43%
HALGLO	*Halogeton glomeratus*	Halogeton	N/A	N/A	N/A
KOCSCO	*Kochia scoparia*	Kochia	0.11%	0.04%	4.26%
LACSER	*Lactuca serriola*	Prickly Lettuce	N/A	N/A	8.87%
LEPPER	*Lepidium perfoliatum*	Clasping Pepperweed	32.22%	1.83%	85.82%
RANTES	*Ranunculus testiculatus*	Burr Buttercup	3.39%	0.63%	27.66%
SALTRA	*Salsola tragus*	Russian Thistle	N/A	N/A	N/A
SISALT	*Sisymbrium altissimum*	Tumble Mustard	0.11%	0.06%	4.61%
TRADUB	*Tragopogon dubius*	Yellow Salsify	N/A	N/A	1.42%
Group Total			39.17%	2.12%	94.33%

Annual Grass, Native

Species Code	Species Name	Common Name	Mean Cover	SE	Frequency
VULOCT	*Vulpia octoflora*	Sixweeks Fescue	0.05%	0.05%	0.35%
Group Total			0.05%	0.05%	0.35%

Annual Grass, Introduced

Species Code	Species Name	Common Name	Mean Cover	SE	Frequency
BROTEC	*Bromus tectorum*	Cheatgrass	62.54%	2.15%	94.68%
ERETRI	*Eremopyrum triticeum*	Annual Wheatgrass	0.07%	0.07%	1.42%
Group Total			62.61%	2.15%	94.68%

Table A.7. Perennial species cover and frequency (calculated as the percentage of plots with species present) by nativity. No introduced, perennial forbs were found in the 2017 survey. Species with no recorded cover were not intercepted along any transect line. Species with no recorded frequency were found incidentally, outside of sample plots. Group cover may exceed 100%, due to overlap.

Perennial Forbs, Native					
Species Code	**Species Name**	**Common Name**	**Mean Cover**	**SE**	**Frequency**
ALLNEV	*Allium nevadense*	Nevada Onion	N/A	N/A	0.35%
ASTLEN	*Astragalus lentiginosus*	Freckled Milkvetch	N/A	N/A	N/A
ASTPUR	*Astragalus purshii*	Woollypod Milkvetch	N/A	N/A	N/A
CYMPUR	*Cymopterus purpurascens*	Widewing Spring Parsley	N/A	N/A	N/A
LINPUN	*Linanthus pungens*	Prickly Phlox	N/A	N/A	N/A
PHLHOO	*Phlox hoodii*	Hood's Phlox	N/A	N/A	0.35%
PHLLON	*Phlox longifolia*	Longleaf Phlox	N/A	N/A	2.13%
SISLIN	*Sisymbrium linifolium*	Flaxleaf Plainsmustard	0.02%	0.02%	0.35%
Group Total			0.02%	0.02%	3.19%
Perennial Grasses, Native					
Species Code	**Species Name**	**Common Name**	**Mean Cover**	**SE**	**Frequency**
ACHHYM	*Achnatherum hymenoides*	Indian Rice Grass	0.04%	0.04%	0.35%
ARIPUR	*Aristida purpurea*	Purple Threeawn	N/A	N/A	1.06%
ELYELY	*Elymus elymoides*	Bottlebrush Squirreltail	1.37%	0.24%	28.37%
LEYCIN	*Leymus cinereus*	Basin Wildrye	N/A	N/A	0.35%
PASSMI	*Pascopyrum smithii*	Western Wheatgrass	0.39%	0.20%	2.84%
POASEC	*Poa secunda*	Sandberg Bluegrass	0.33%	0.12%	6.38%
Group Total			2.11%	0.36%	35.11%
Perennial Grasses, Introduced					
Species Code	**Species Name**	**Common Name**	**Mean Cover**	**SE**	**Frequency**
AGRCRI	*Agropyron cristatum*	Crested Wheatgrass	8.48%	1.24%	26.95%
POABUL	*Poa bulbosa*	Bulbous Bluegrass	0.05%	0.04%	3.19%
Group Total			8.53%	1.24%	28.72%

Table A.8. Shrub cover and frequency (calculated as the percentage of plots with species present) by nativity. No introduced shrubs were found in the 2017 survey. Species with no recorded cover were not intercepted along any transect line. Species with no recorded frequency were found incidentally, outside of sample plots. Group cover may exceed 100%, due to overlap.

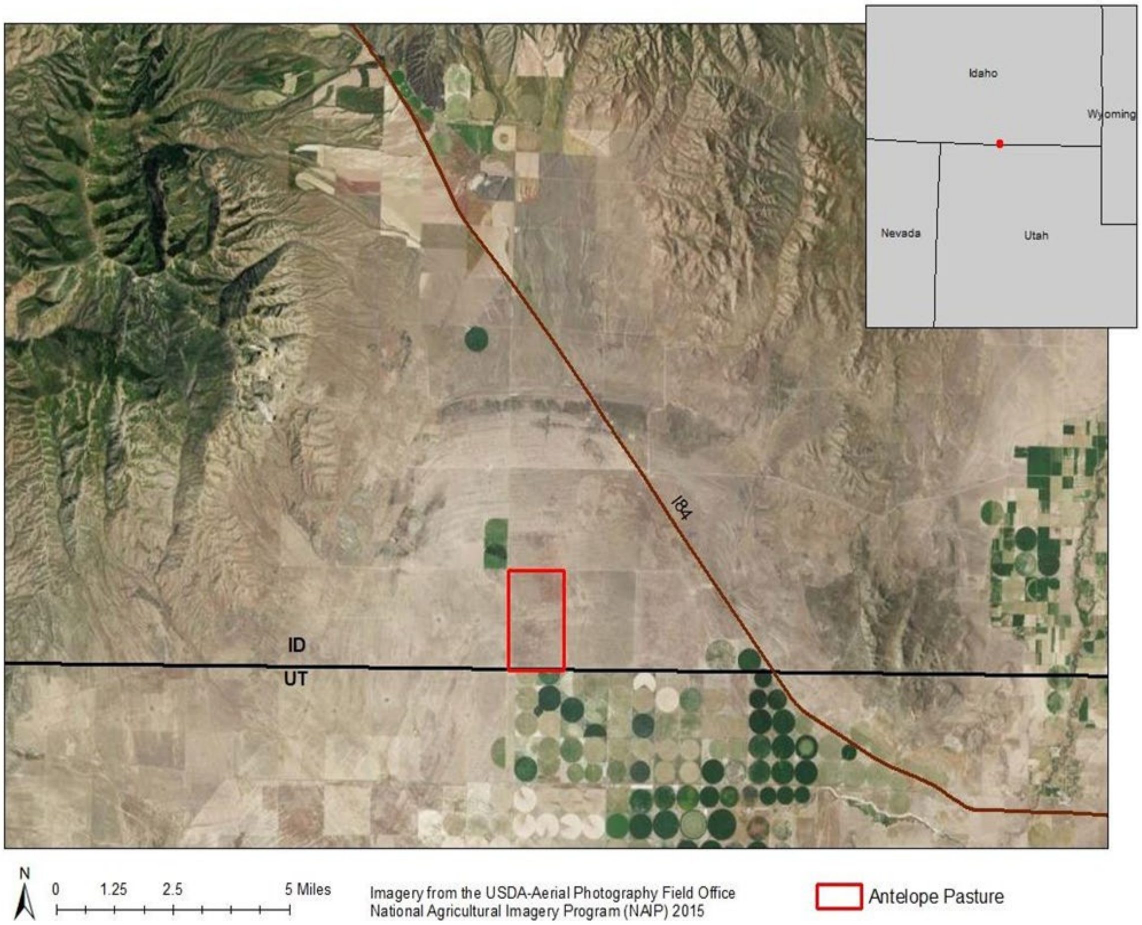
Shrubs, Native					
Species Code	**Species Name**	**Common Name**	**Mean Cover**	**SE**	**Frequency**
ARTTRI	*Artemisia tridentata* ssp. *wyomingensis*	Wyoming Big Sagebrush	6.13%	0.66%	40.78%
ATRCAN	*Atriplex canescens*	Fourwing Saltbush	N/A	N/A	N/A
ATRCON	*Atriplex confertifolia*	Shadscale	N/A	N/A	0.35%
CHRVIS	*Chrysothamnus viscidiflorus*	Yellow Rabbitbrush	0.46%	0.17%	7.80%
ERINAU	*Ericameria nauseosa*	Rubber Rabbitbrush	N/A	N/A	N/A
KOCAME	*Kochia americana*	Greenmolly	0.04%	0.03%	2.84%
OPUPOL	*Opuntia polyacantha*	Plains Pricklypear	N/A	N/A	0.71%
SARVER	*Sarcobatus vermiculatus*	Greasewood	3.51%	0.52%	21.63%
Group Total			10.14%	0.81%	57.45%

Table A.9. Cover of non-living plant matter.

Additional Intercepts				
Species Code	**Species Name**	**Definition**	**Mean Cover**	**SE**
DH	Dead Herbaceous	Standing dead herbaceous from previous growth years	33.07%	1.64 %
DS	Dead Shrub	Standing dead shrub	1.72%	0.27 %
LITT	Litter	Detached plant matter	42.91%	1.36 %
WD	Woody Debris	Detached, woody plant matter sized greater than 5 mm	2.22%	0.26 %

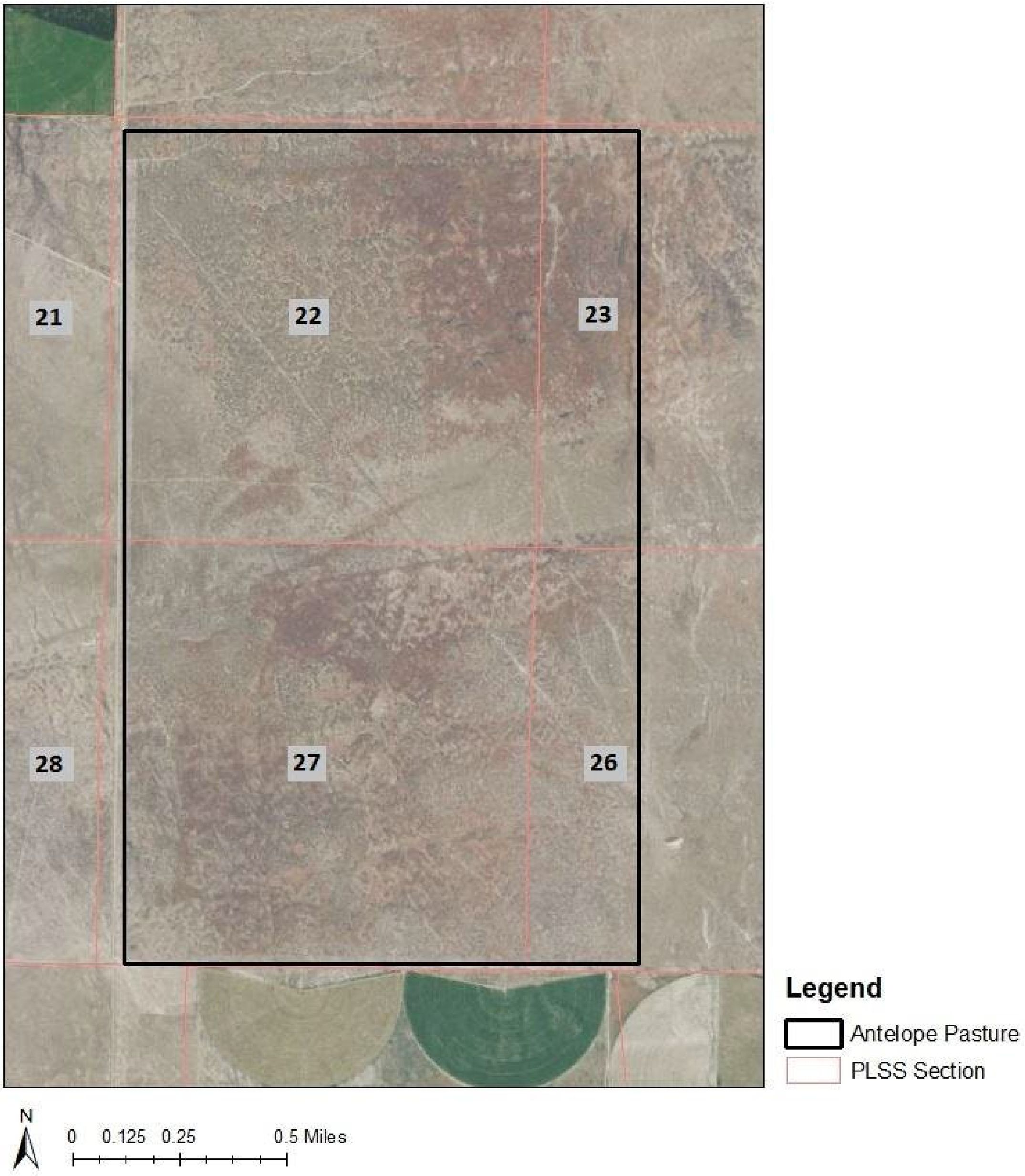
Table A.10. Cover of soil surface categories.

Soil Surface				
Species Code	**Species Name**	**Definition**	**Mean Cover**	**SE**
BSC	Biological Soil Crust	Living soil crust	19.57%	1.43 %
DUFF	Duff	Decomposed litter	2.25%	0.36 %
GRAV	Gravel	Rocky material sized 0.2 cm-7.6 cm	0.18%	0.06 %
LICH	Lichen	Lichen	0.39%	0.08 %
MOSS	Moss	Moss	14.36%	1.24 %
PB	Plant Base	Base of live plant	1.83%	0.28 %
ROCK	Rock	Rocky material sized greater than 7.6 cm	0.05%	0.03 %
SOIL	Soil	Bare soil	61.33%	1.93 %



Imagery from the USDA-Aerial Photography Field Office
National Agricultural Imagery Program (NAIP) 2015

Figure A.1. Location of Antelope pasture, Curlew Grazing Allotment



Imagery from the USDA-Aerial Photography Field Office
National Agricultural Imagery Program (NAIP) 2015

Township sections from the
BLM Public Land Survey System (PLSS)

Figure A.2. Township Sections of Antelope pasture. Township and range coordinates are 16 S 30 E.

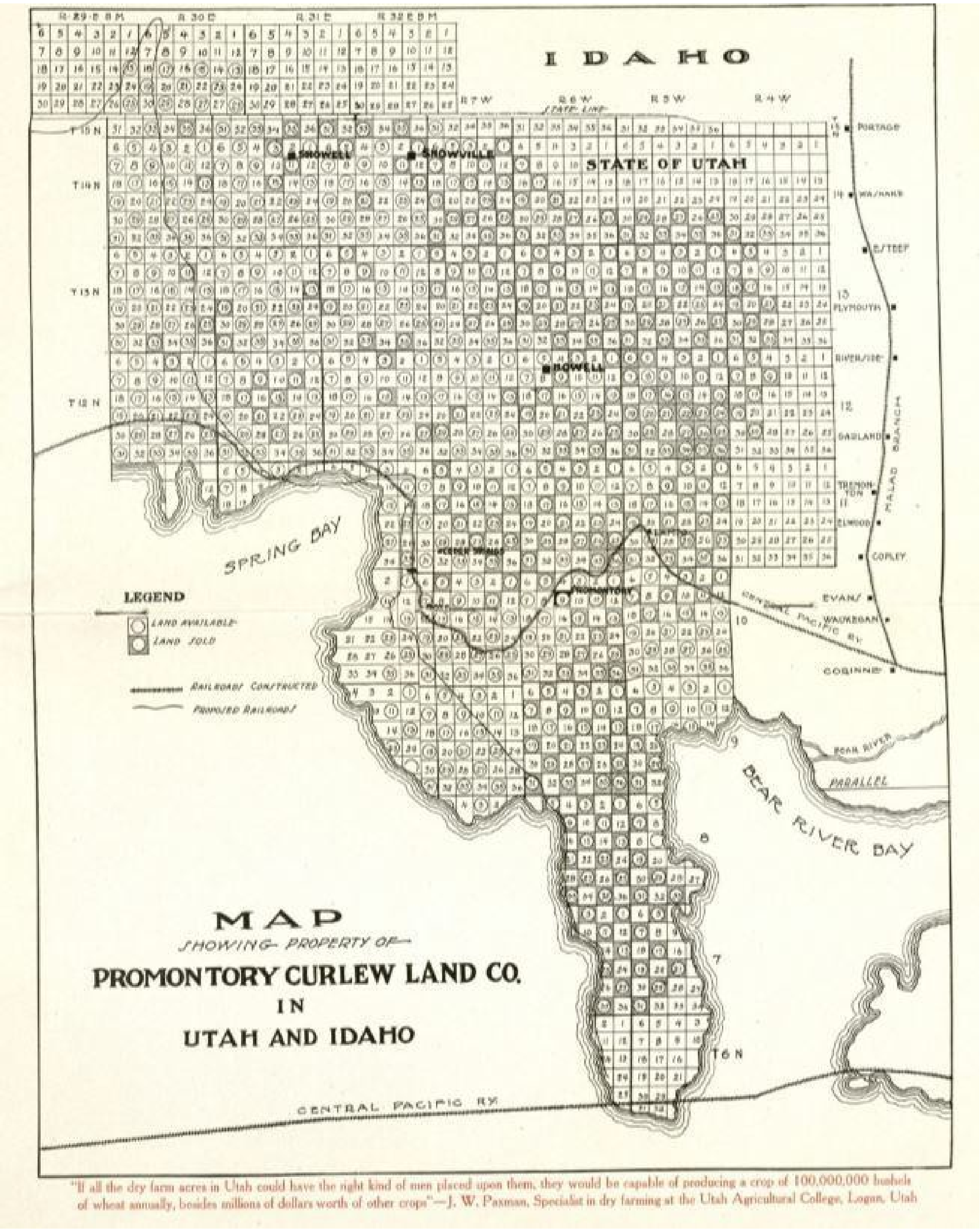
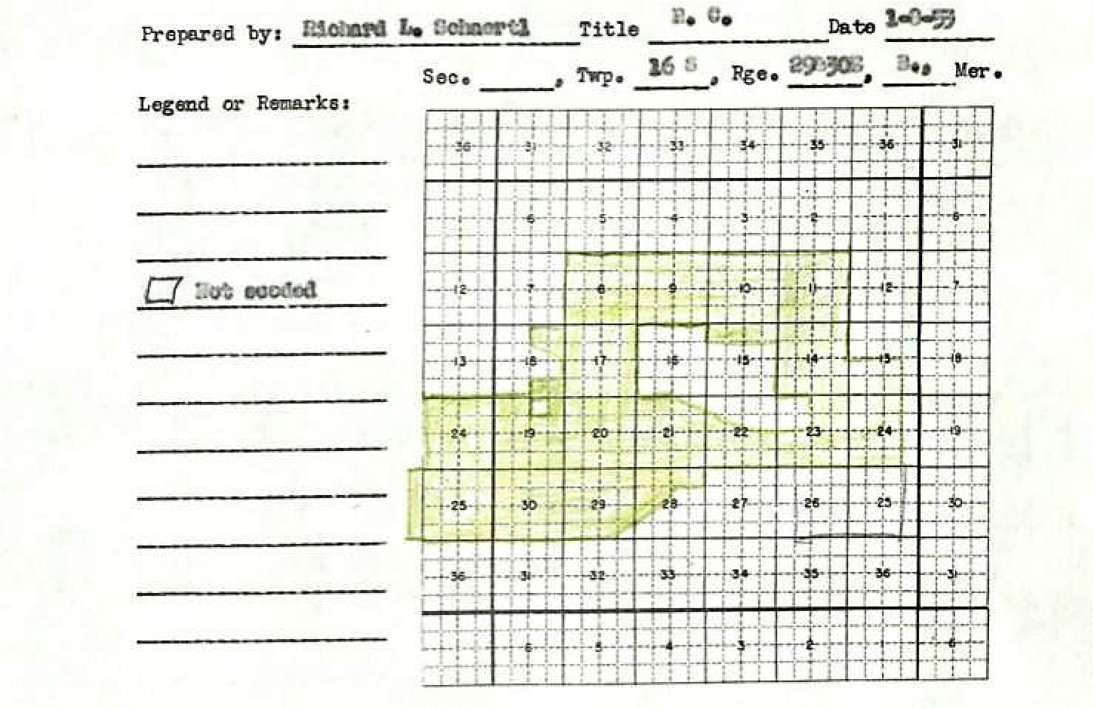


Figure A.3. Promontory-Curlew Land Company holdings, taken from the company's 1917 advertisement, "A Winning Combination" (Bullen Jr 1966b). Antelope pasture is located at the north end, on the Utah/Idaho border.



Prepared by: Richard L. Schnertl Title R. C. Date 1-3-53

Sec. _____, Twp. 16 S, Rge. 29-30E, B. Mer.

Legend or Remarks:

☐ Not seeded

Figure A.4. Township sections included in the 1952 BLM seeding of crested wheatgrass and yellow sweet clover. Within Antelope pasture, sections 22 and 23 were partially seeded. Image taken from *Black Pine Reseeding #1; Project #12-0-372; Final Project Report*; BLM Form 4-120 (Dept of Interior 1953).

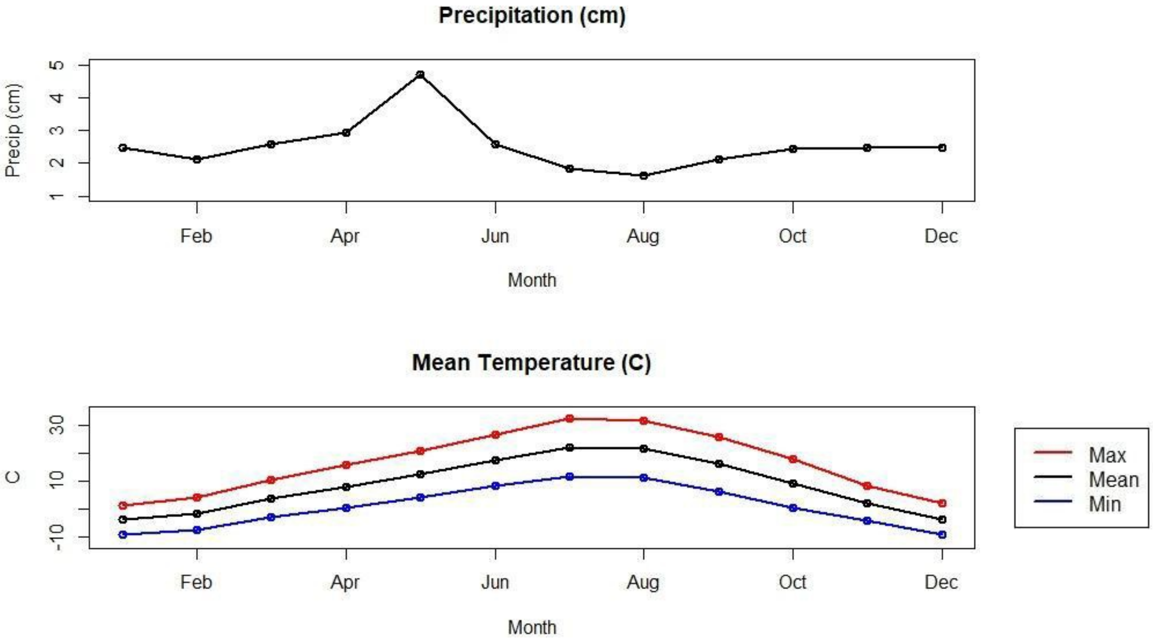
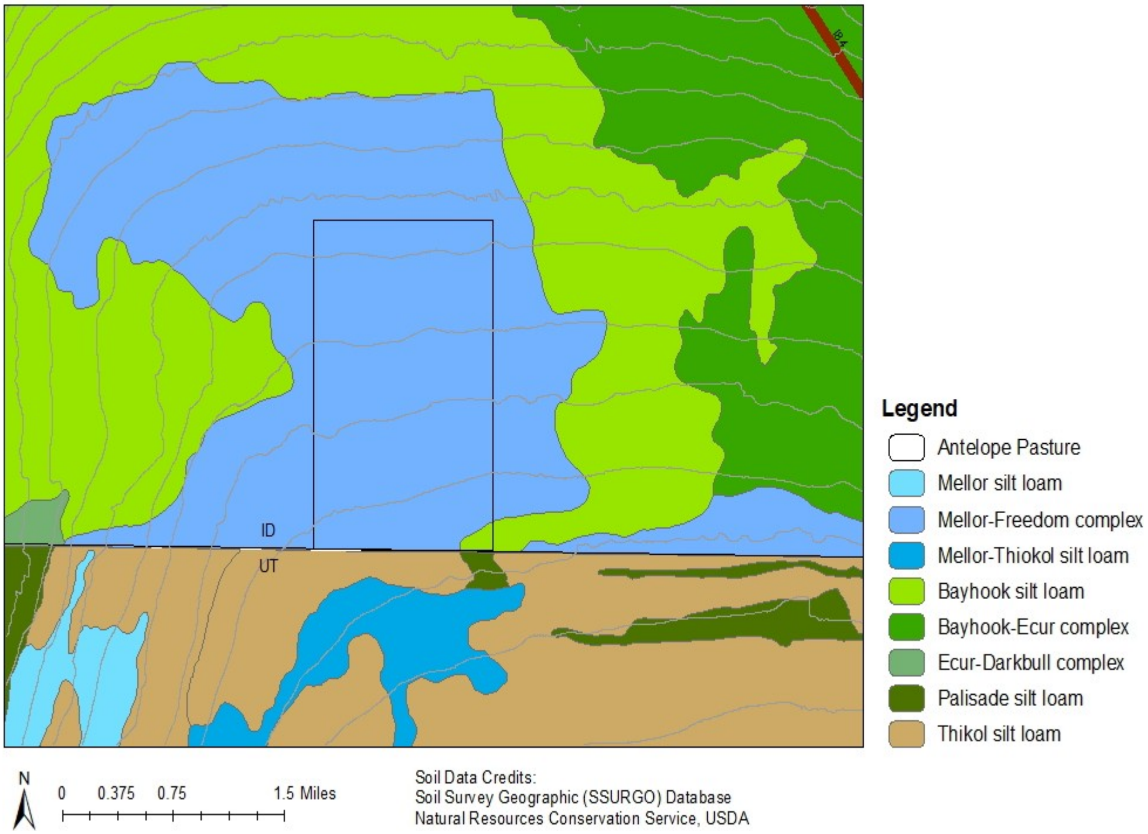
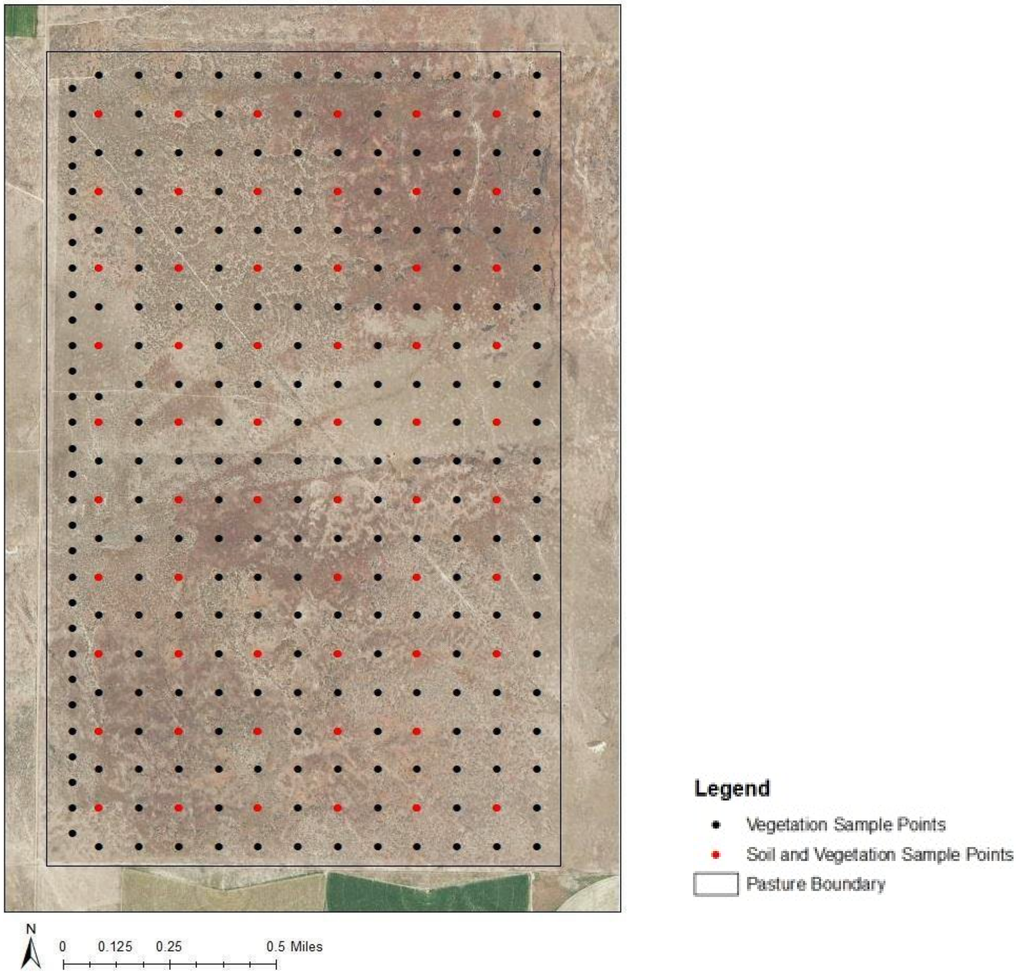


Figure A.5. Mean monthly precipitation and temperature for Antelope pasture. Data coordinates are 42º00’38.1600” N, -112º54’30.6000” W., elevation 1363 m. Data is monthly normals for the 30-year period of 1981-2010, sourced from the PRISM Climate Group, Oregon State University, downloaded April 2018.



Soil Data Credits:
Soil Survey Geographic (SSURGO) Database
Natural Resources Conservation Service, USDA

Figure A.6. Natural Resources Conservation Service (NRCS) soil classification of Antelope pasture and surrounding soils. Contour lines were created using a 10-meter DEM sourced from The National Map, USGS. Sodic Xeric Haplocalcids are shown in green. Soils or soil complexes with natric horizons present are shown in blue. Soil series descriptions and mapping unit descriptions for soils within Antelope Pasture can be found in Appendix 2.



Imagery from the USDA-Aerial Photography Field Office
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Figure A.7. Sampling layout. 282 plots were sampled for vegetation; out of those 58 were also sampled for soils.

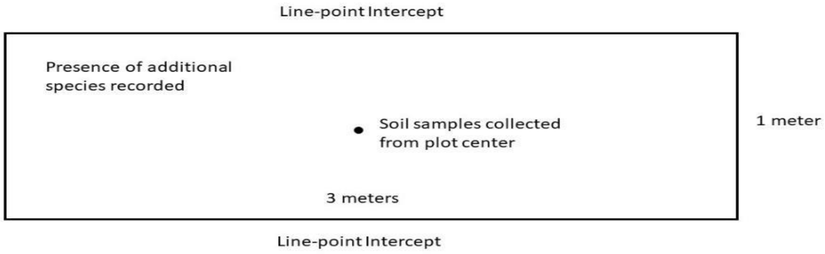
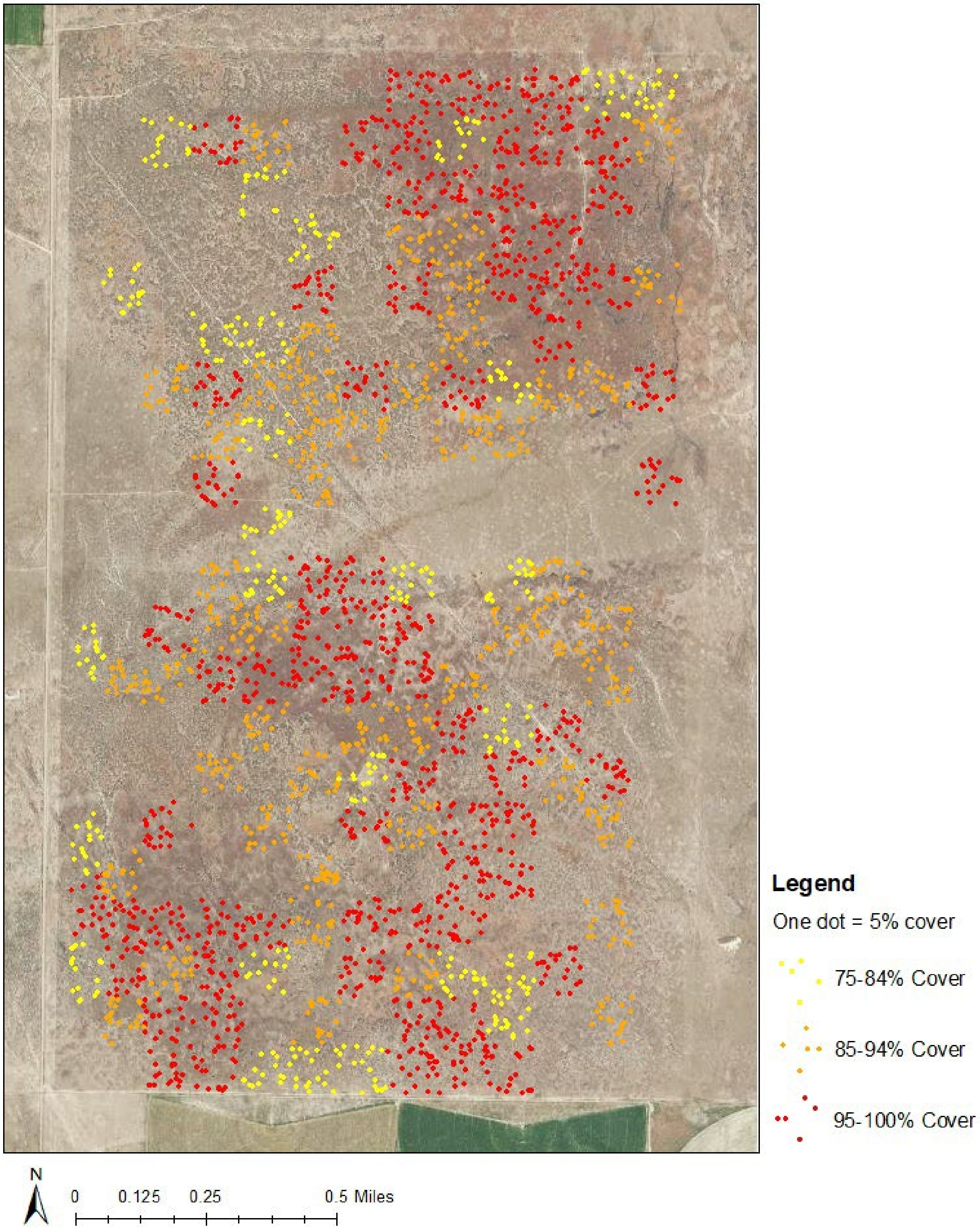


Figure A.8. Diagram of a sampling plot. Line-point intercepts were collected along both 3-meter sides, and the presence of additional species within the 1x3 m plot was recorded.

Imagery from the USDA-Aerial Photography Field Office
National Agricultural Imagery Program (NAIP) 2015

Figure A.9. Percentage cover of introduced, annual grasses. Map symbology displays cover as dot density distributed across a 5.5-acre grid of polygons.



Imagery from the USDA-Aerial Photography Field Office
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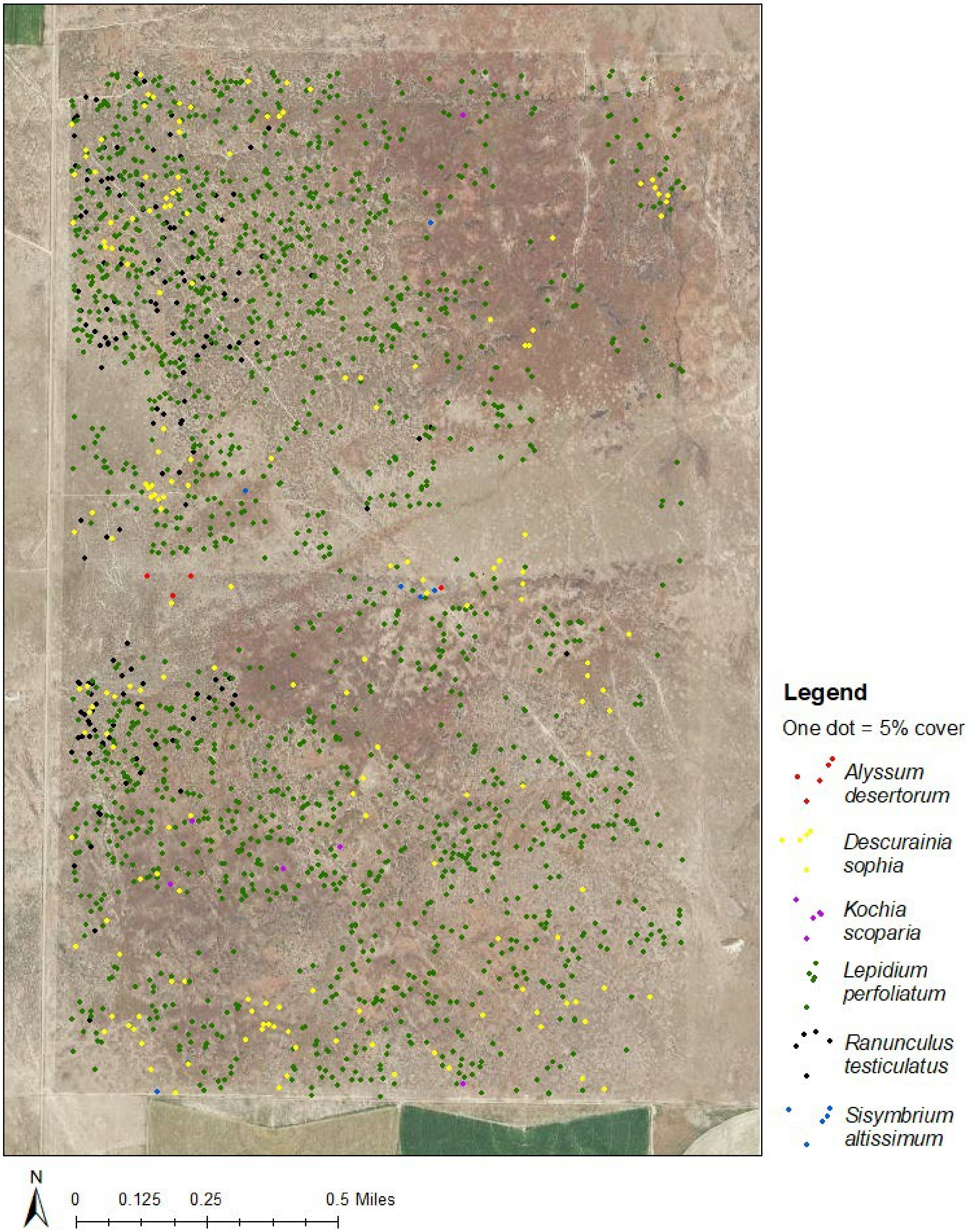
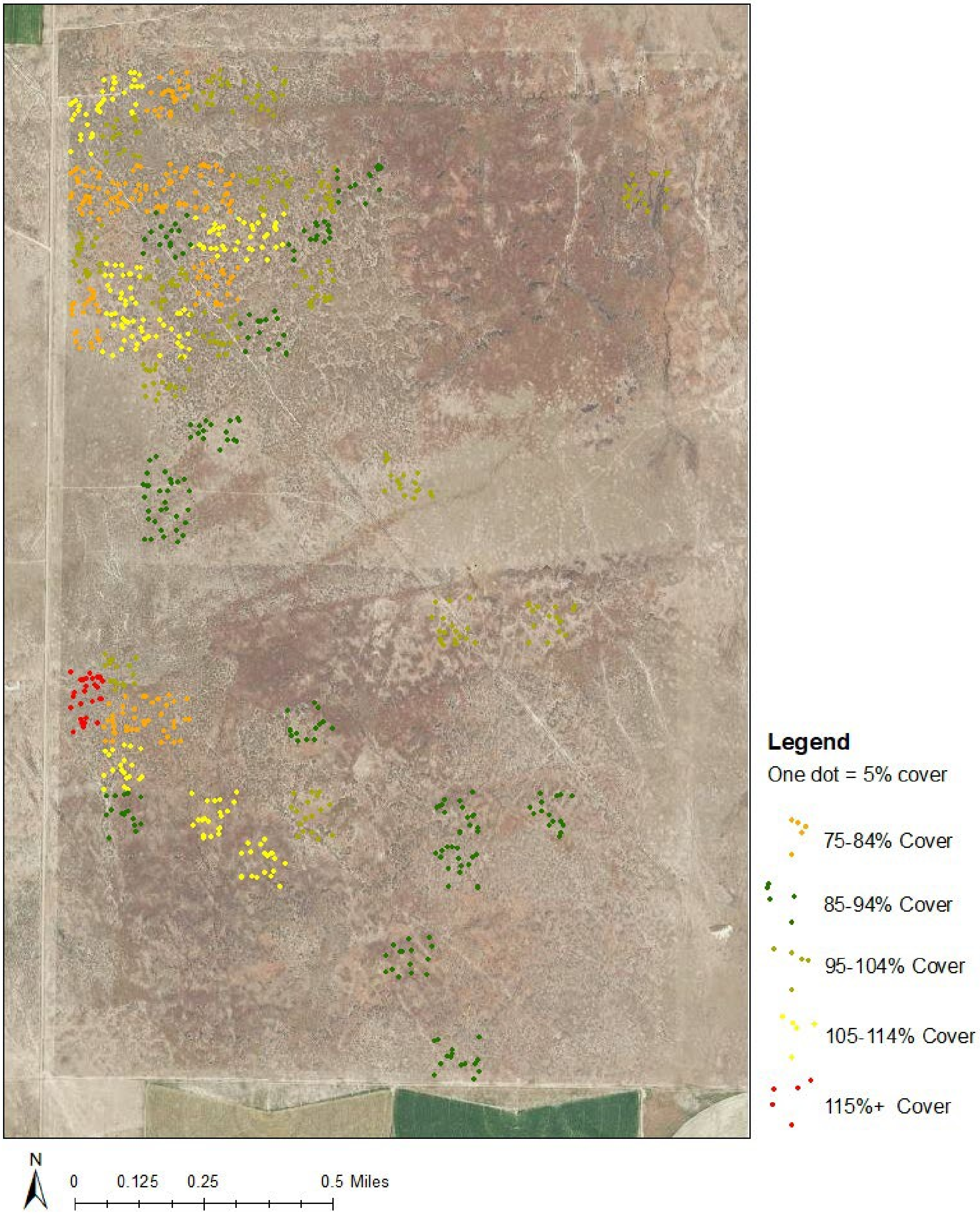
Figure A.10. Areas with 75% cover or greater of *Bromus tectorum* (Cheatgrass). Map symbology displays cover as dot density distributed across a 5.5-acre grid of polygons. Cover has been stratified into cover classes.



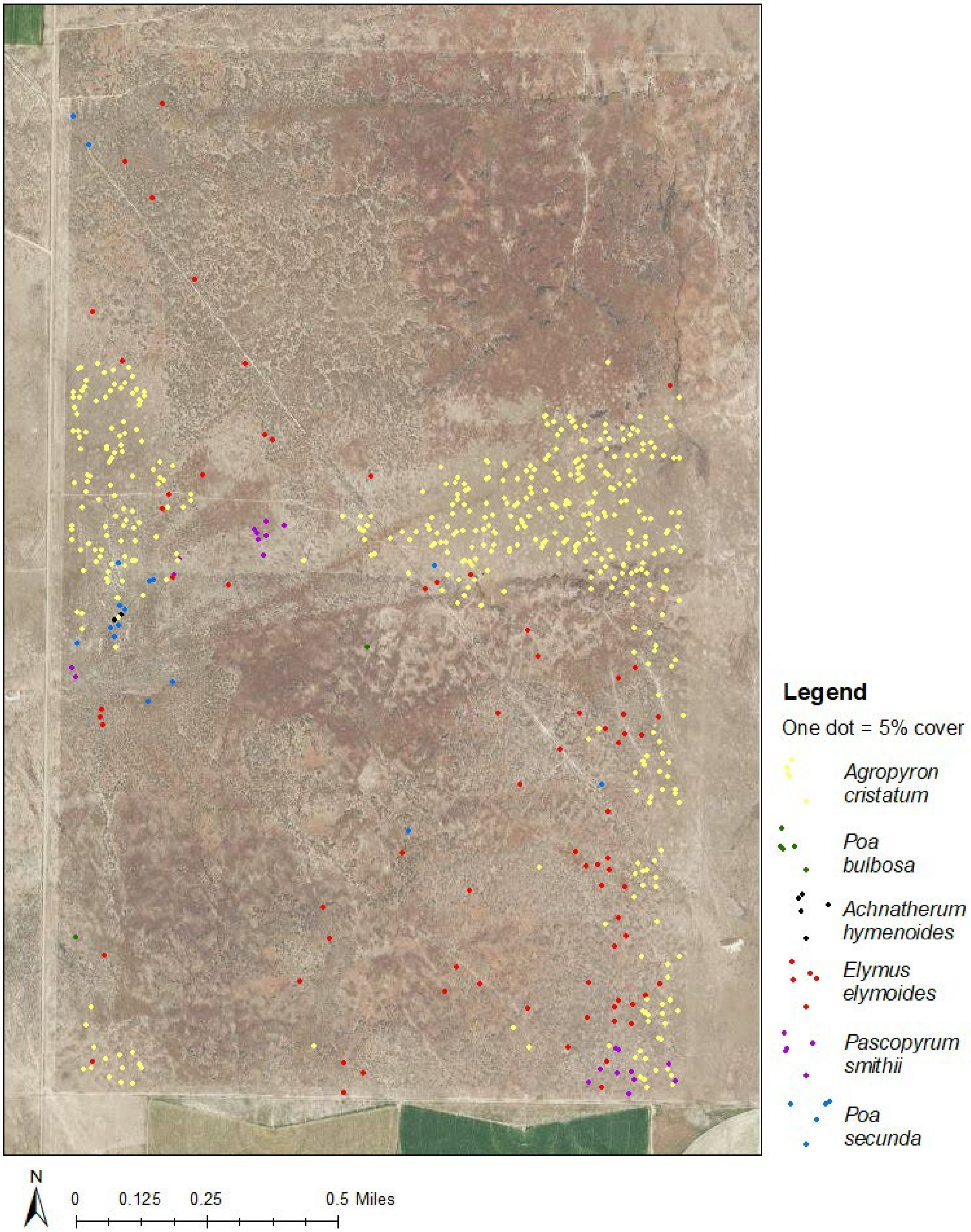
Imagery from the USDA-Aerial Photography Field Office
National Agricultural Imagery Program (NAIP) 2015

Figure A.11. Percentage cover of introduced, annual forbs. Map symbology displays cover as dot density distributed across a 5.5-acre grid of polygons.



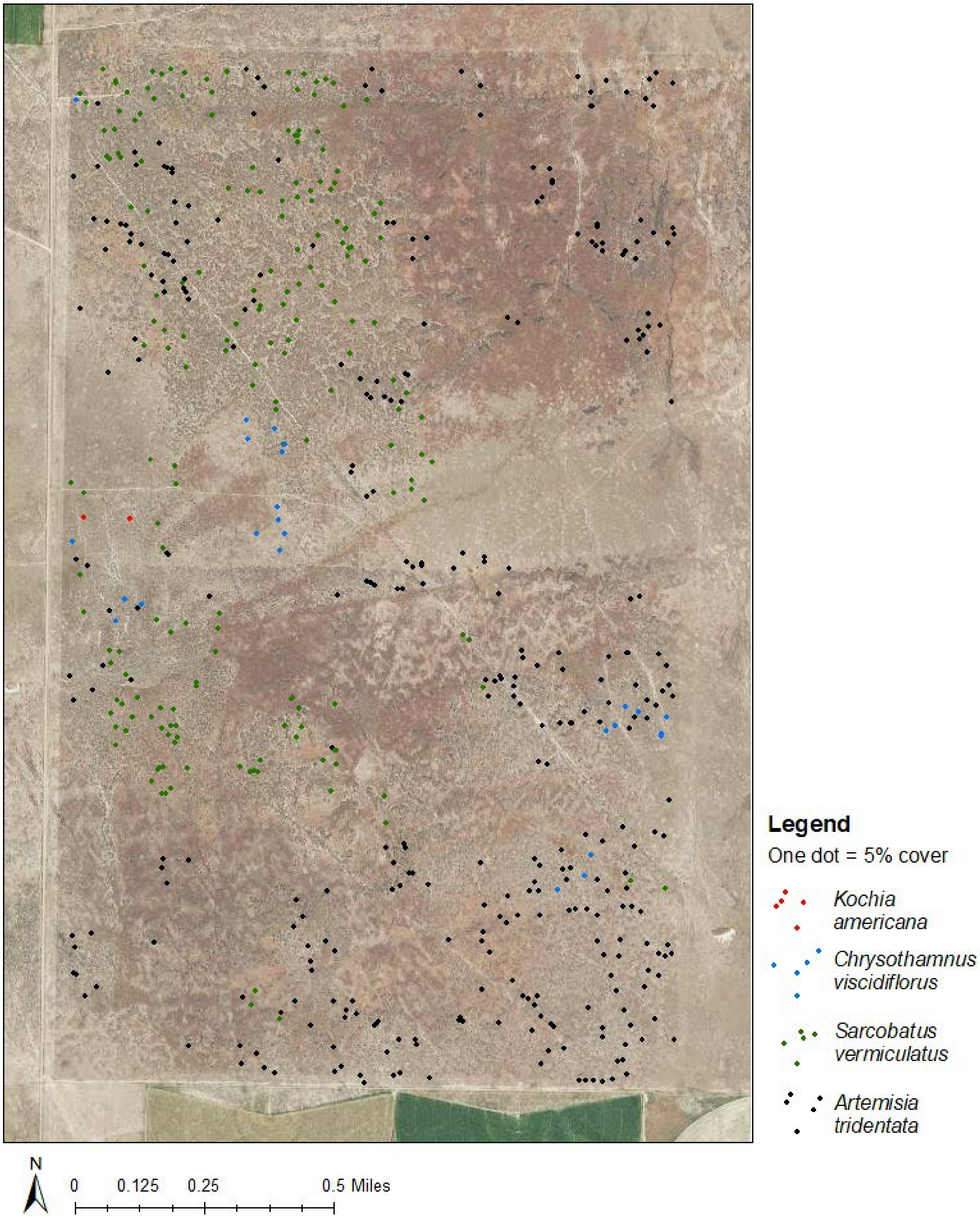
Imagery from the USDA-Aerial Photography Field Office
National Agricultural Imagery Program (NAIP) 2015

Figure A.12. Areas with 75% combined cover or greater of introduced, annual forbs. Map symbology displays cover as dot density distributed across a 5.5-acre grid of polygons. Cover has been stratified into groups and coded by color.



Imagery from the USDA-Aerial Photography Field Office
National Agricultural Imagery Program (NAIP) 2015

Figure A.13. Percentage cover of perennial grasses. Map symbology displays cover as dot density distributed across a 5.5-acre grid of polygons.

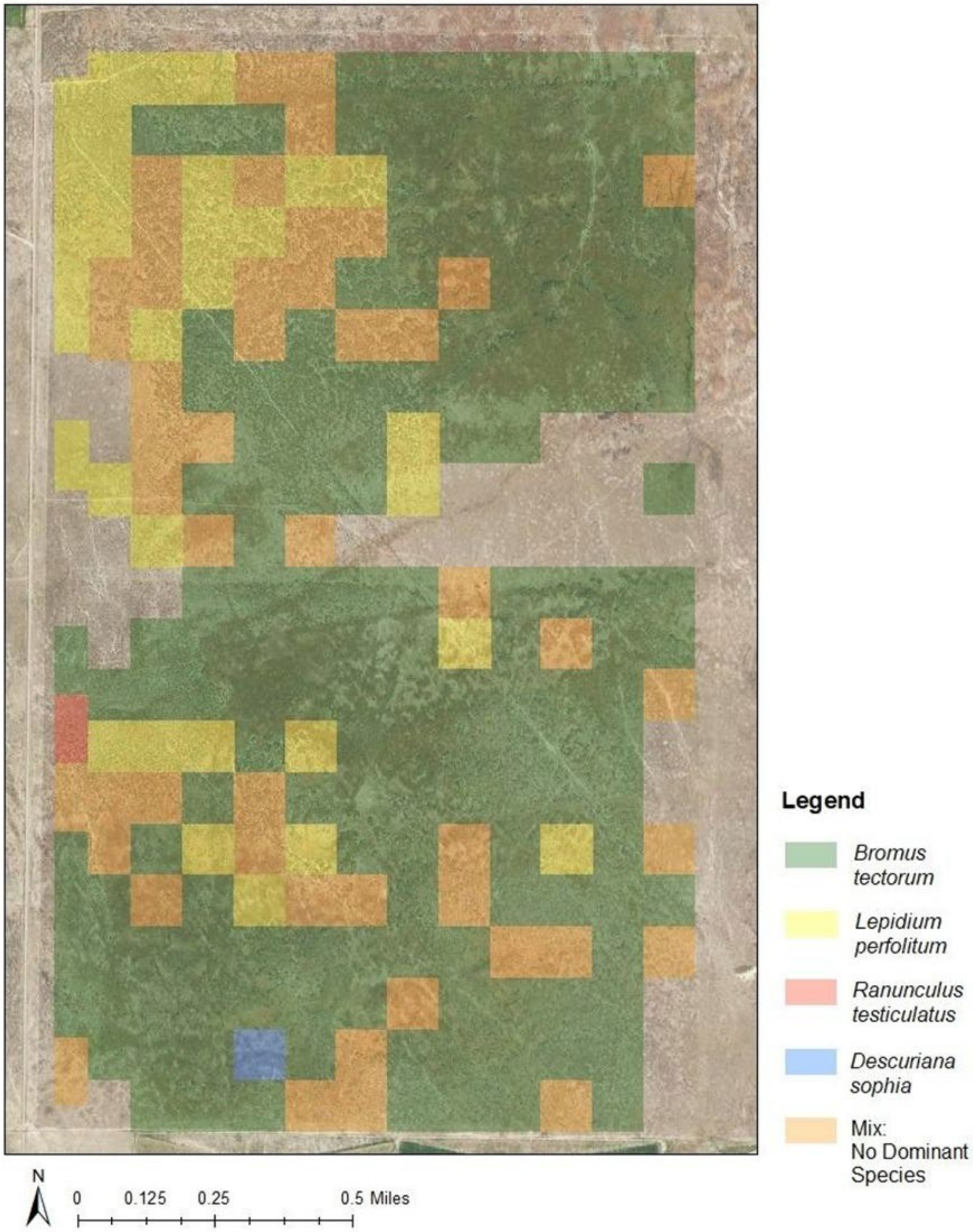


Imagery from the USDA-Aerial Photography Field Office
National Agricultural Imagery Program (NAIP) 2015

Figure A.14. Percentage cover of shrubs. Map symbology displays cover as dot density distributed across a 5.5-acre grid of polygons.

Imagery from the USDA-Aerial Photography Field Office
National Agricultural Imagery Program (NAIP) 2015

Figure A.15. Percentage cover of moss and biological soil crust. Map symbology displays cover as dot density distributed across a 5.5-acre grid of polygons.



Imagery from the USDA-Aerial Photography Field Office
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Figure A.16. Dominant introduced annual. Map symbology displays dominant species over a 5.5 acre grid of polygons. Species were considered dominant if percent cover was at least 25% greater than any other introduced, annual species within each grid polygon. Polygons with less than 25% combined cover of introduced annuals were not assigned a dominant species.

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Figure A.17. Percentage cover of *Bromus tectorum* (Cheatgrass) shown over shrub functional group and *Agropyron cristatum* (Crested Wheatgrass) presence. Map symbology displays cover as dot density distributed across a 5.5-acre grid of polygons. Polygons were shaded based on presence/absence data.

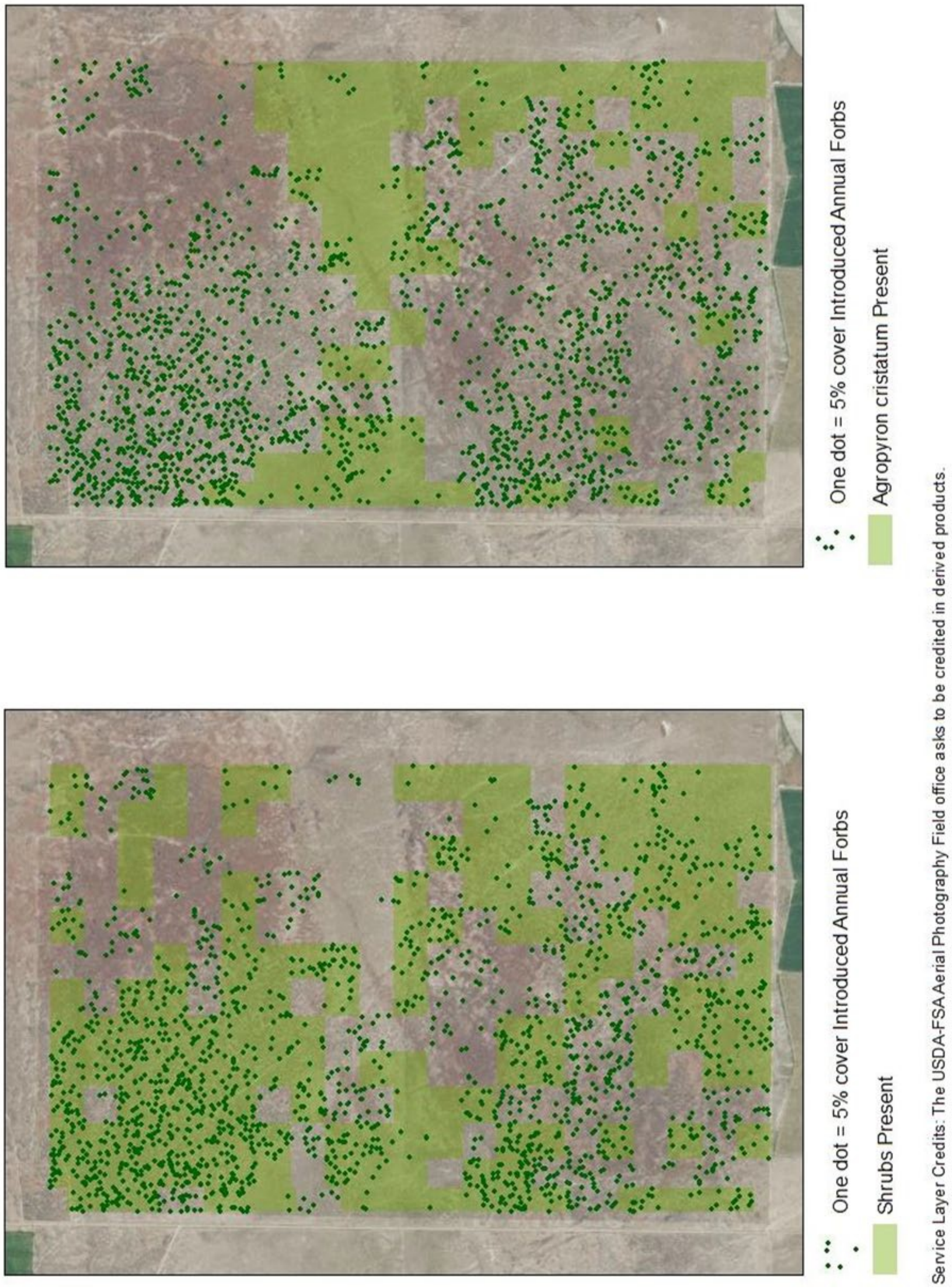

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Figure A.18. Combined percentage cover of introduced, annual forbs shown over shrub functional group and *Agropyron cristatum* (Crested Wheatgrass) presence. Map symbology displays cover as dot density distributed across a 5.5-acre grid of polygons. Polygons were shaded based on presence/absence data.

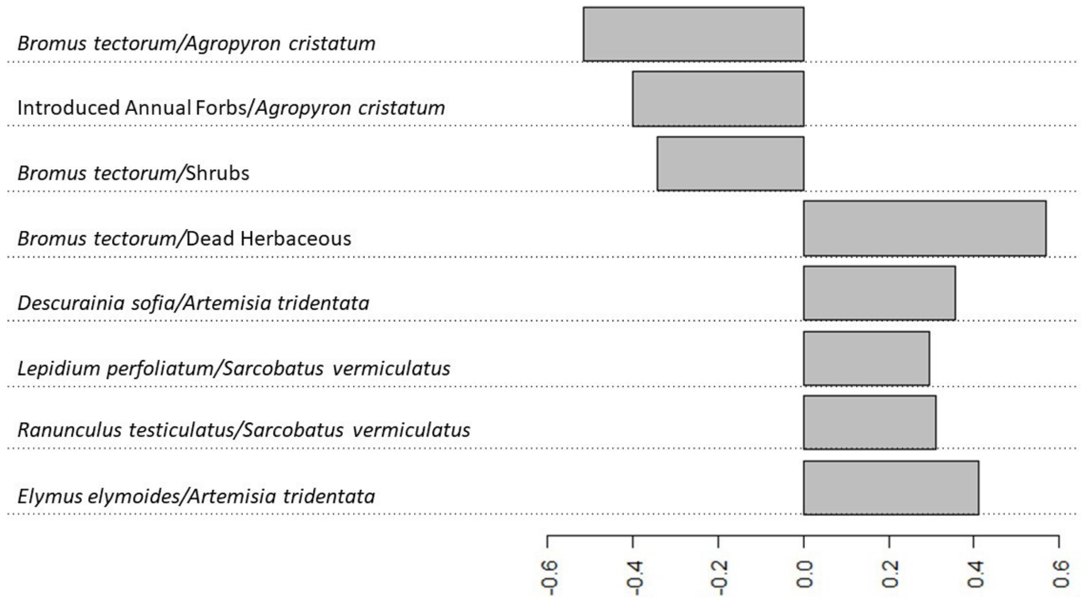


Figure A.19. Significant correlations between plant species of Antelope pasture. Spearman rank correlations with r > |0.2| and p-value <0.001 are shown above. Introduced annual forb species and shrubs were lumped into functional groups when individual correlations were in the same direction.

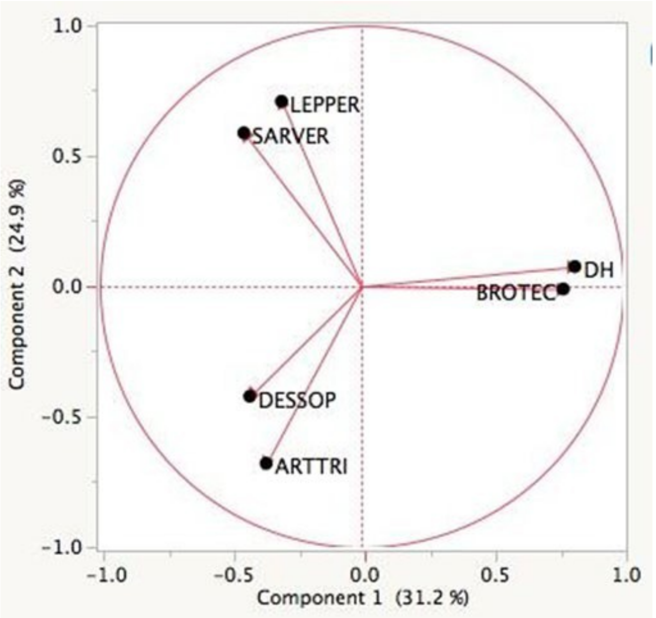
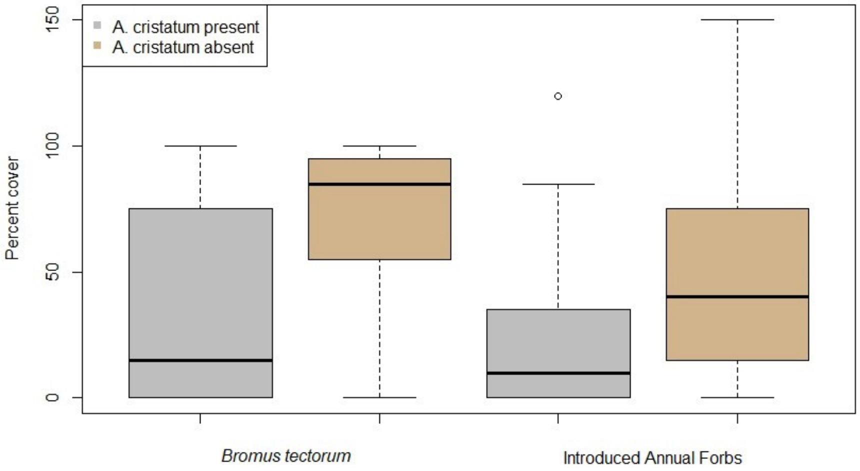


Figure A.20. Principal components analysis biplot. Axes are labeled by component and amount of variation explained. Plant species are labeled using 6-letter codes. Included are two native shrub species (ARTTRI/*Artemisia tridentata* and SARVER/*Sarcobatus vermiculatus*), one introduced annual grass (BROTEC/*Bromus tectorum*), two introduced annual forbs (DESSOP/*Descurainia sophia* and LEPPER/*Lepidium perfoliatum*) and standing dead herbaceous (DH). See Table 1 for loading values.



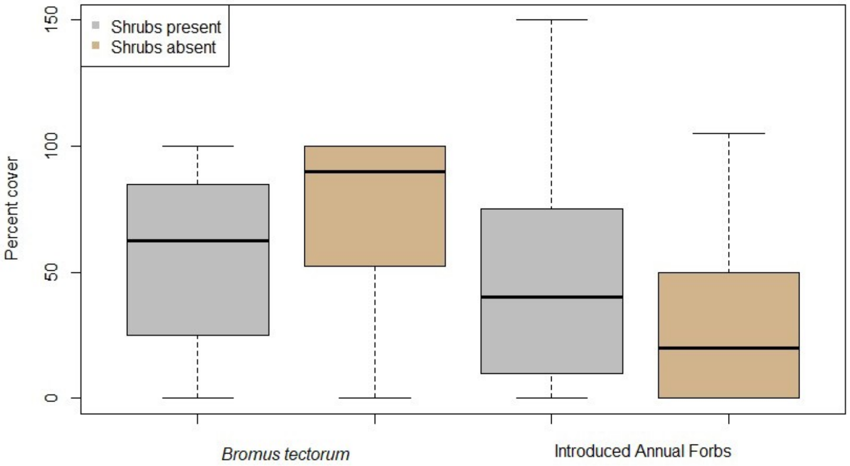


Figure A.21. Effect of *Agropyron cristatum* (crested wheatgrass) presence and shrub functional group presence on the percent cover of introduced annual species at Antelope Pasture. We subset cheatgrass and introduced annual forbs into populations with and without the presence of crested wheatgrass, and with and without the presence of shrubs. Cover for functional groups may exceed 100% due to overlapping species. Box-and-whisker plots display the median, interquartile range, maximum and minimum values.

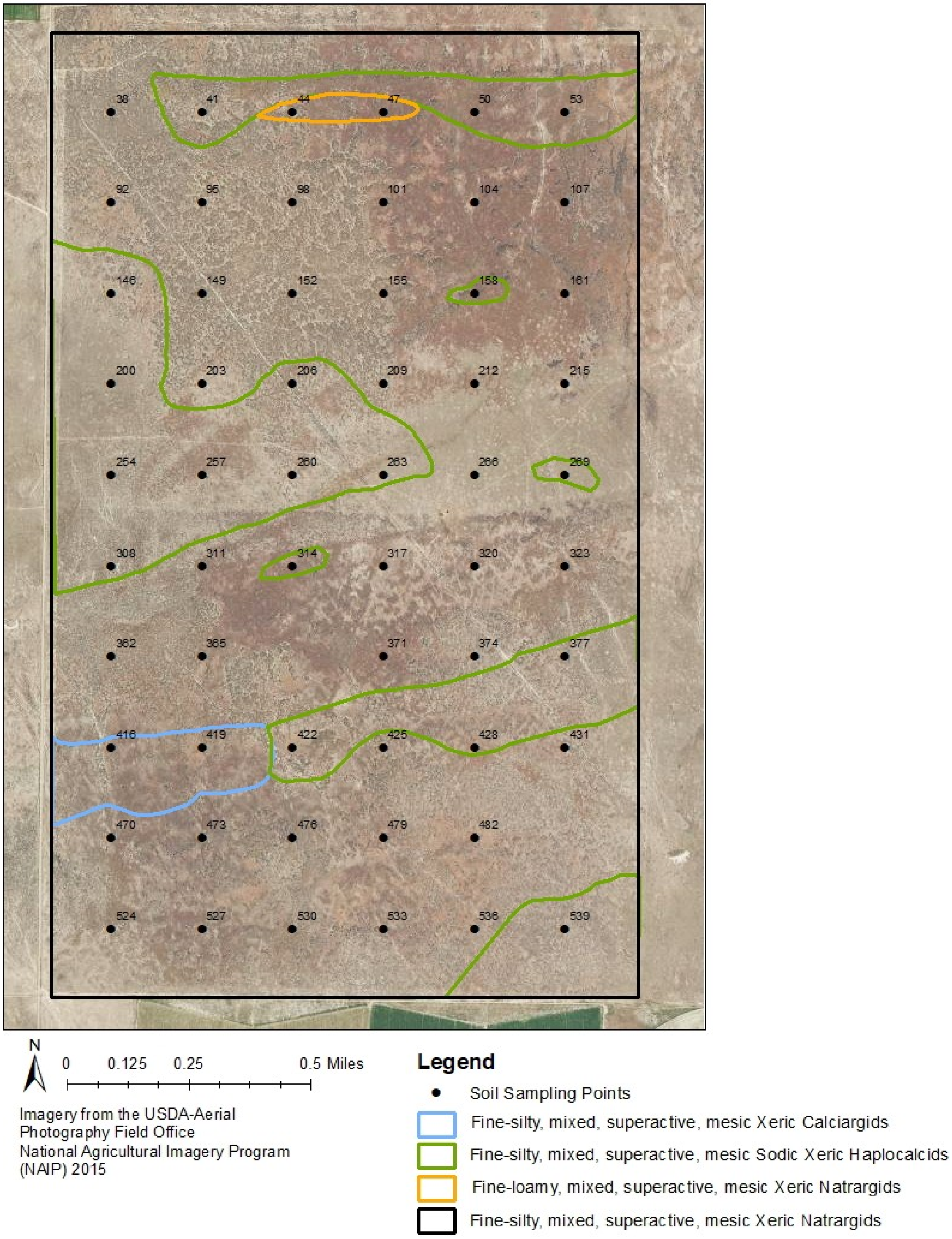
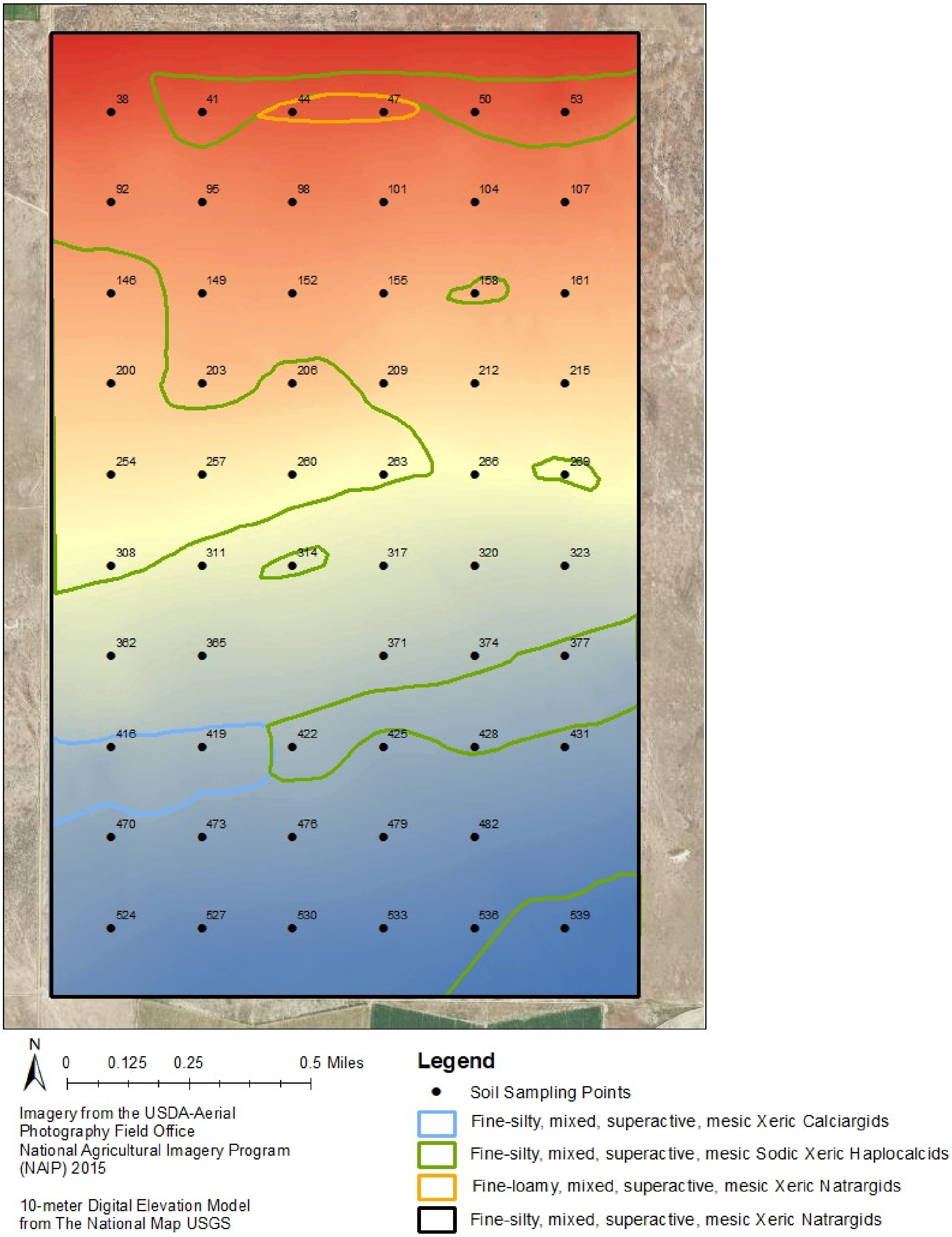


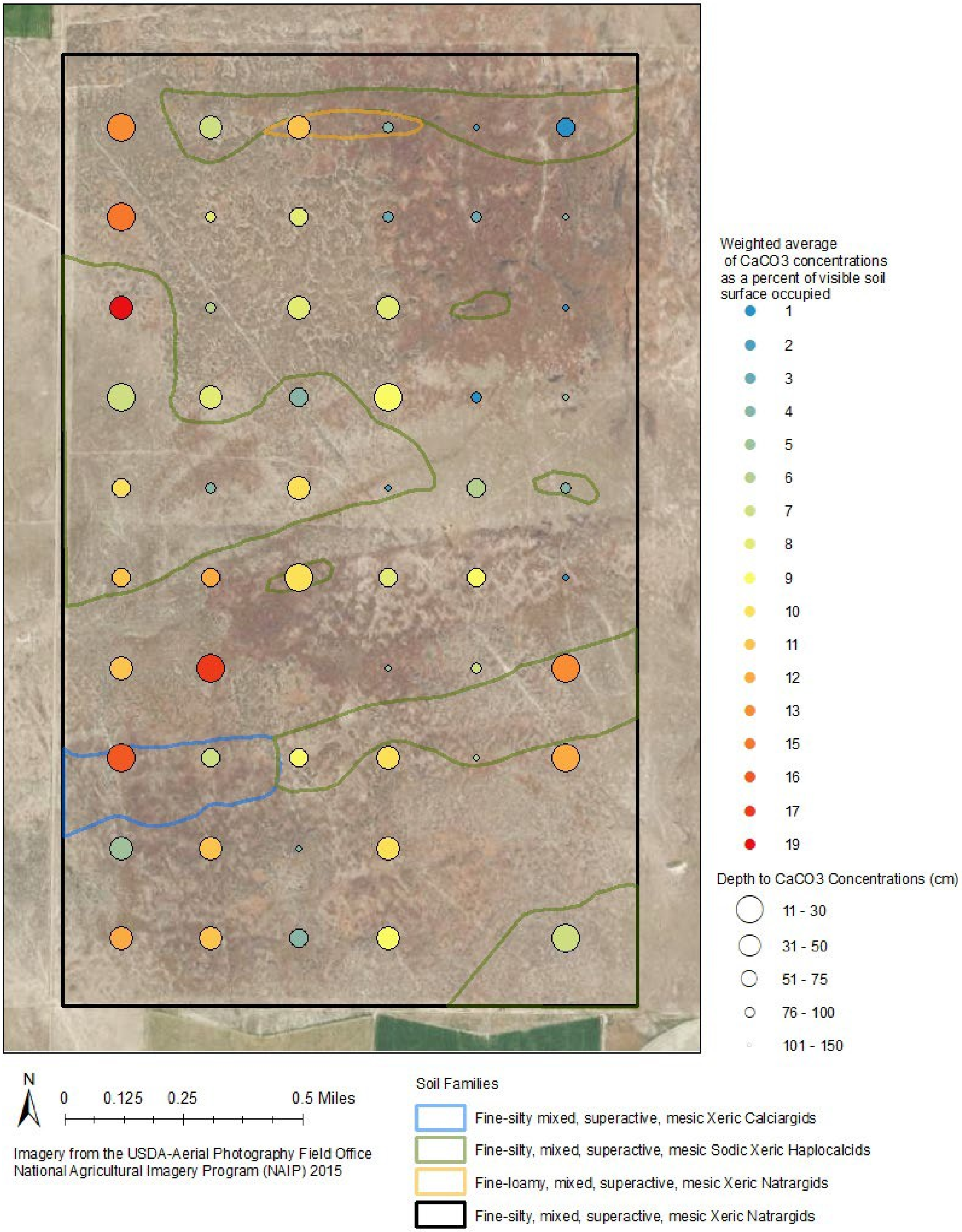
Figure A.22. Soil map of Antelope Pasture based on our 2017 survey. Soils are classified to family. Written soil descriptions for pedons 47, 92, 101, 260, 308, 377 and 416 are in Appendix 2. SAR and EC results for pedons 50, 53, 92, 98, 158, 200, 215, 260, 308, 377, 482 and 530 are in Table 3.



Imagery from the USDA-Aerial Photography Field Office
National Agricultural Imagery Program (NAIP) 2015

10-meter Digital Elevation Model from The National Map USGS

Figure A.23. Soil map of Antelope pasture laid over a 10-m Digital Elevation Model, sourced from The National Map, USGS



Imagery from the USDA-Aerial Photography Field Office
National Agricultural Imagery Program (NAIP) 2015

Figure A.24. Distribution, depth and amount of calcium carbonate concentrations. Map symbology uses size to depict depth (cm) to concentrations and color to depict weighted average (as a percent of visible soil surface occupied). Soil families are shown in the background. Soil pedons without calcium carbonate concentrations are not shown.

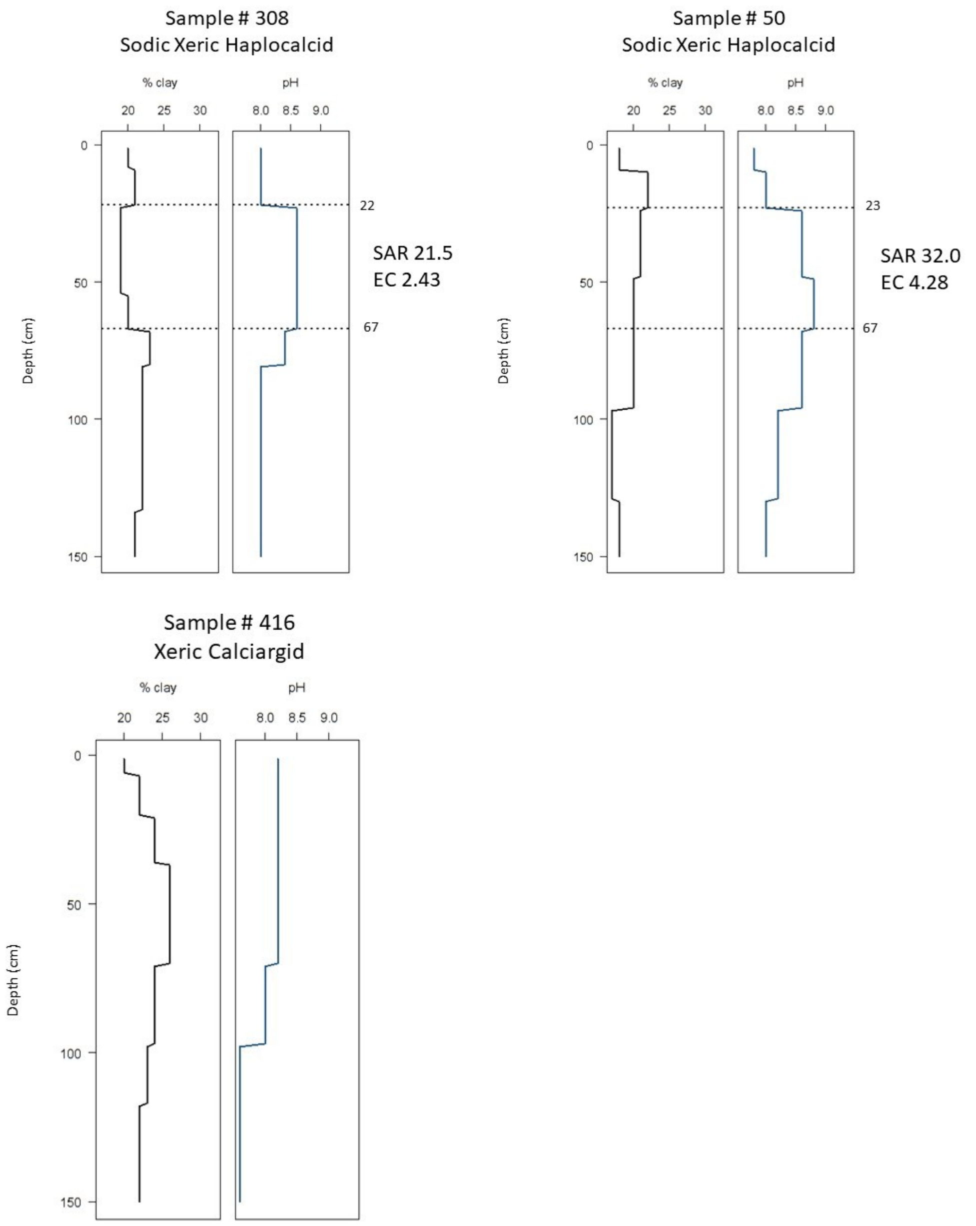


Figure A.25. Soil pH and percent clay for two representative Sodic Xeric Haplocalcids and one Xeric Calciargid: soil pedons 308, 50 and 416. Their location within the pasture can be seen in Figure 22. Percent clay and soil pH is shown for the full 150 cm depth sampled. The portion of each pedon tested for SAR and EC is located between the dotted lines, and results are shown to the right. Pedon 416 was not lab tested. Sodium adsorption ratios are above normal in pedons 50 and 308 but we do not see the necessary increase in illuvial clay to classify these soils into the Natrargids great group, although for pedon 50, the increase in clay from 9 to 23 cm comes very close to qualifying. Pedon 416 maintains a pH of 8.2 or below, indicating normal levels of exchangeable sodium, but the “clay bulge” from 20 to 97 cm qualifies as an argillic horizon.

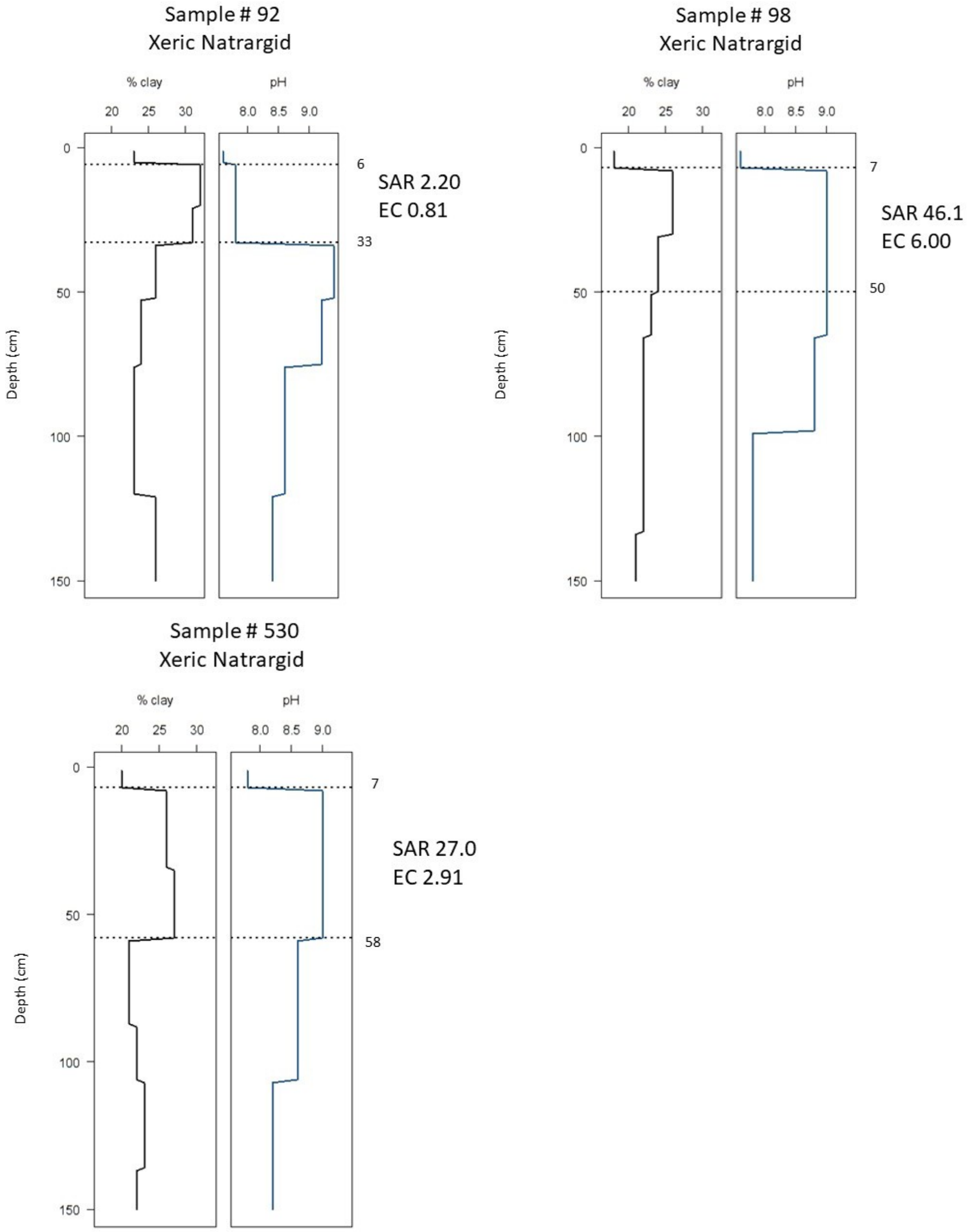
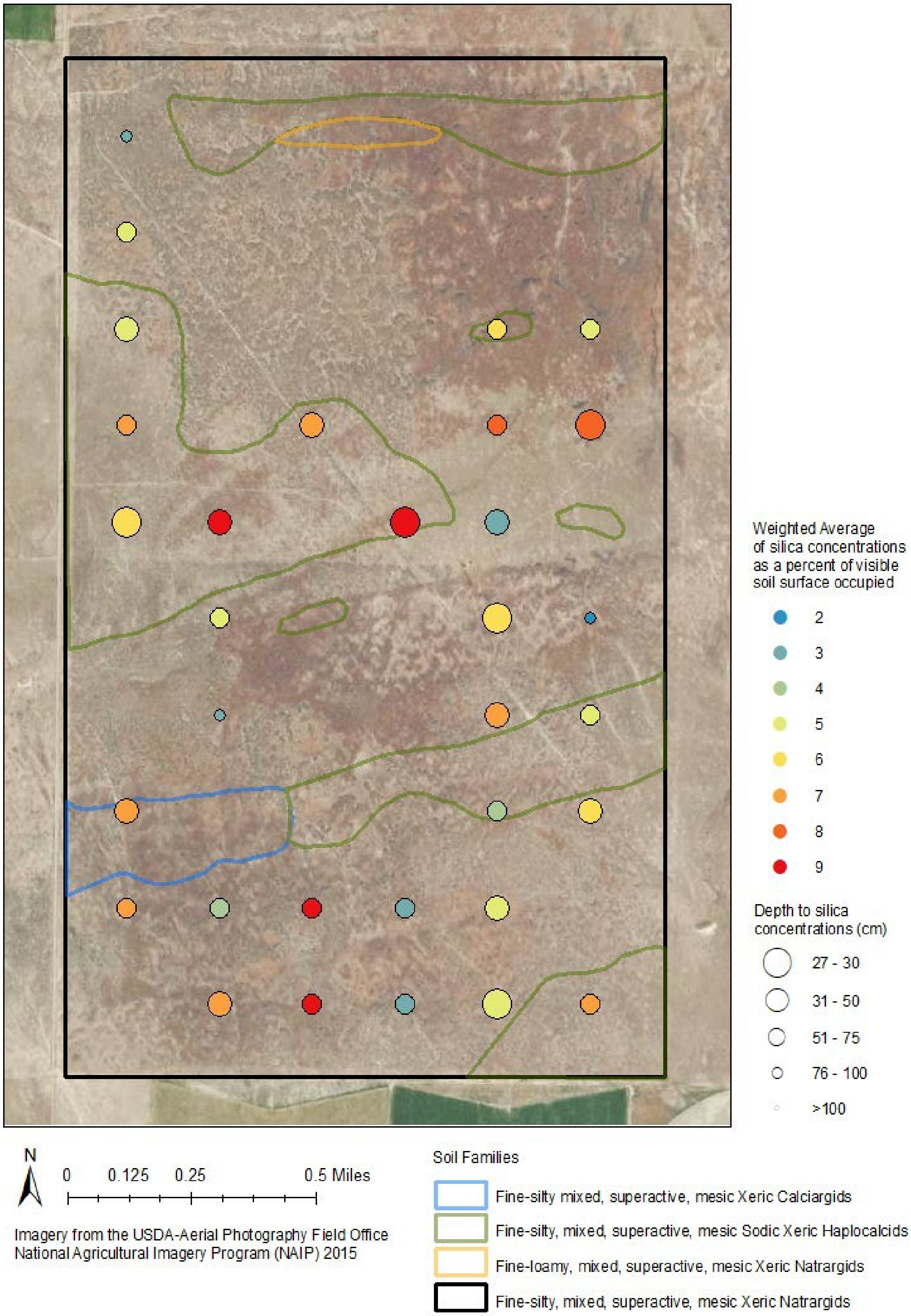
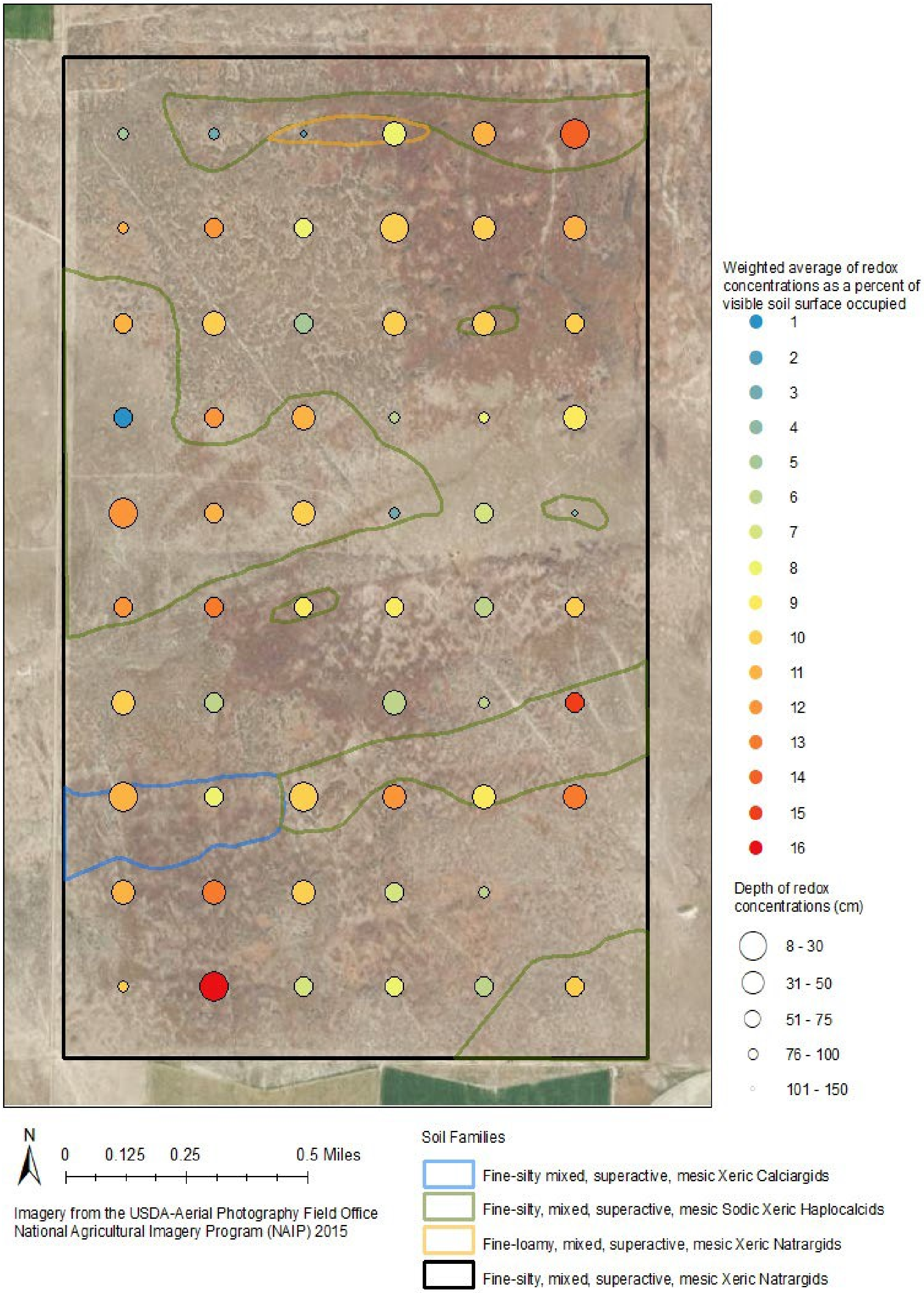


Figure A.26. Soil pH and percent clay for three representative Xeric Natrargids: soil pedons 92, 98 and 530. Their location within the pasture can be seen in Figure 22. Percent clay and soil pH is shown for the full 150 cm sampled. The portion of each pedon tested for SAR and EC is located between the dotted lines, and results are shown to the right. In pedons 92 and 530, the full natric horizon is also within the two dotted lines; for pedon 98, the natric horizon extends to 65 cm below the soil surface. For pedon 92, the increase in pH (and exchangeable sodium) is below the “clay bulge” of the natric horizon (6-33 cm), but still within 40 cm of the upper boundary. In pedons 98 and 539, the increase in clay content and pH are concurrent.



Imagery from the USDA-Aerial Photography Field Office National Agricultural Imagery Program (NAIP) 2015

Figure A.27. Distribution, depth and amount of silica concentrations. Map symbology uses size to depict depth depth (cm) to concentrations and color to depict weighted average (as a percent of visible soil surface occupied). Soil families are shown in the background. Soil pedons without silica concentrations are not shown.



Imagery from the USDA-Aerial Photography Field Office
National Agricultural Imagery Program (NAIP) 2015

Figure A.28. Distribution, depth and amount of redoximorphic concentrations. Map symbology uses size to depict depth (cm) to concentrations and color to depict weighted average (as a percent of visible soil surface occupied). Soil families are shown in the background. Soil pedons without redoximorphic concentrations are not shown.

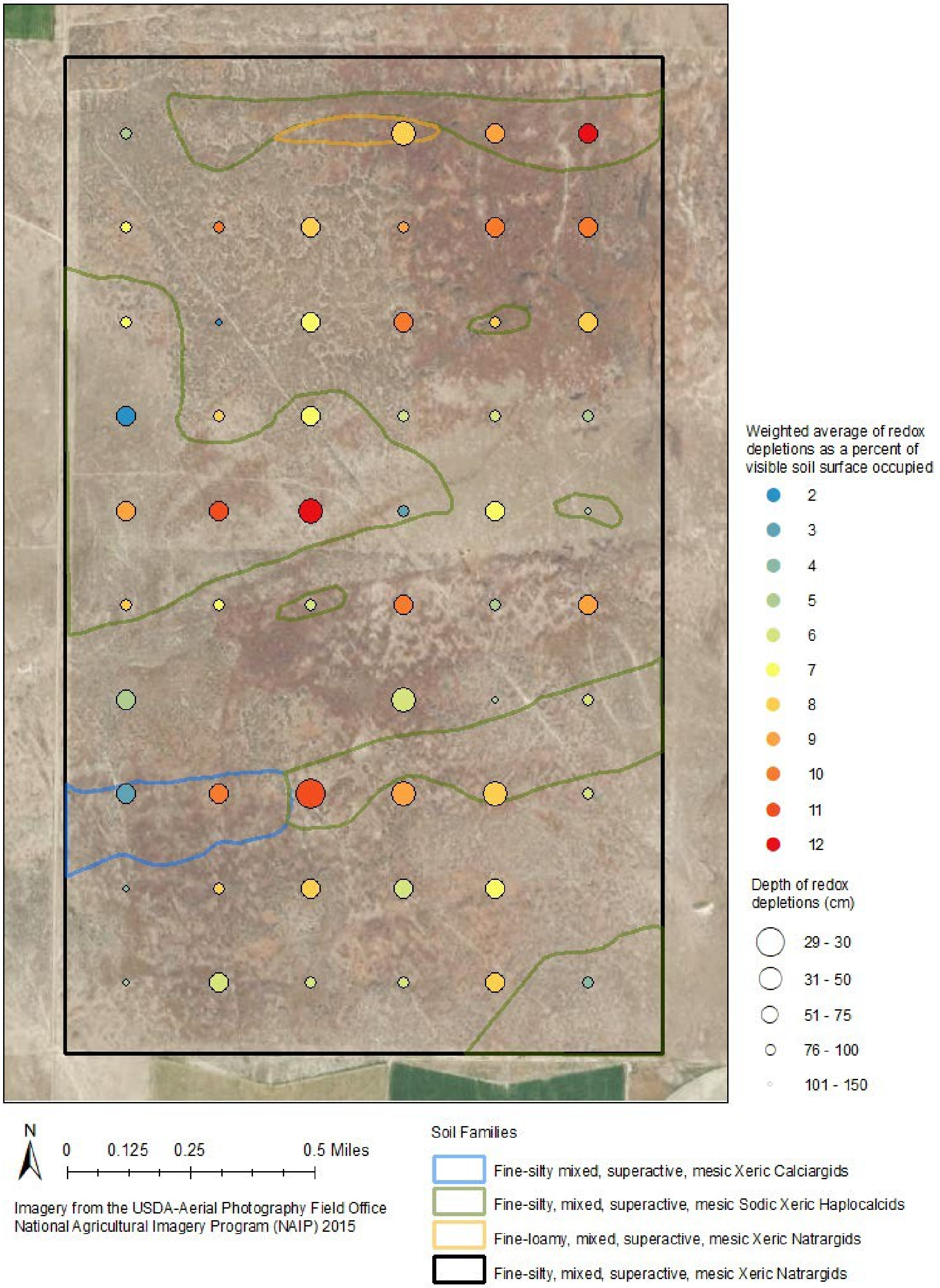


Figure A.29. Distribution, depth and amount of redoximorphic depletions. Map symbology uses size to depict depth (cm) to depletions and color to depict weighted average (as a percent of visible soil surface occupied). Soil families are shown in the background. Soil pedons without redoximorphic depletions are not shown.

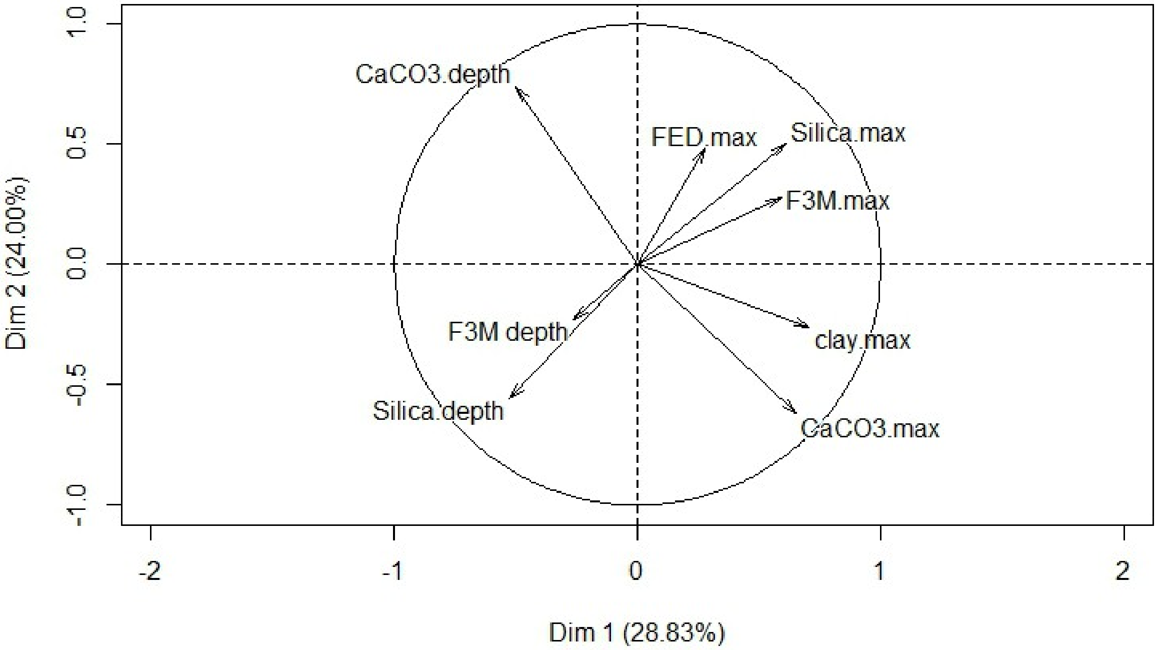


Figure A.30. Principal components analysis biplot for soil variables. Axes are labeled by component and amount of variation explained. Variables included are: CaCO3 depth (depth to calcium carbonate concentrations), FED.max (maximum value for redoximorphic depletions), Silica.max (maximum value for silica concentrations), F3M.max (maximum value for redoximorphic concentrations), clay.max (maximum value for percent clay within a horizon), CaCO3.max (maximum value for calcium carbonate concentrations), Silica.depth (depth to silica concentrations) and F3M.depth (depth to redoximorphic concentrations). Values for concentrations and depletions were calculated as a percent of the visible soil surface area occupied in a horizon. Loading values are given in Table 2.

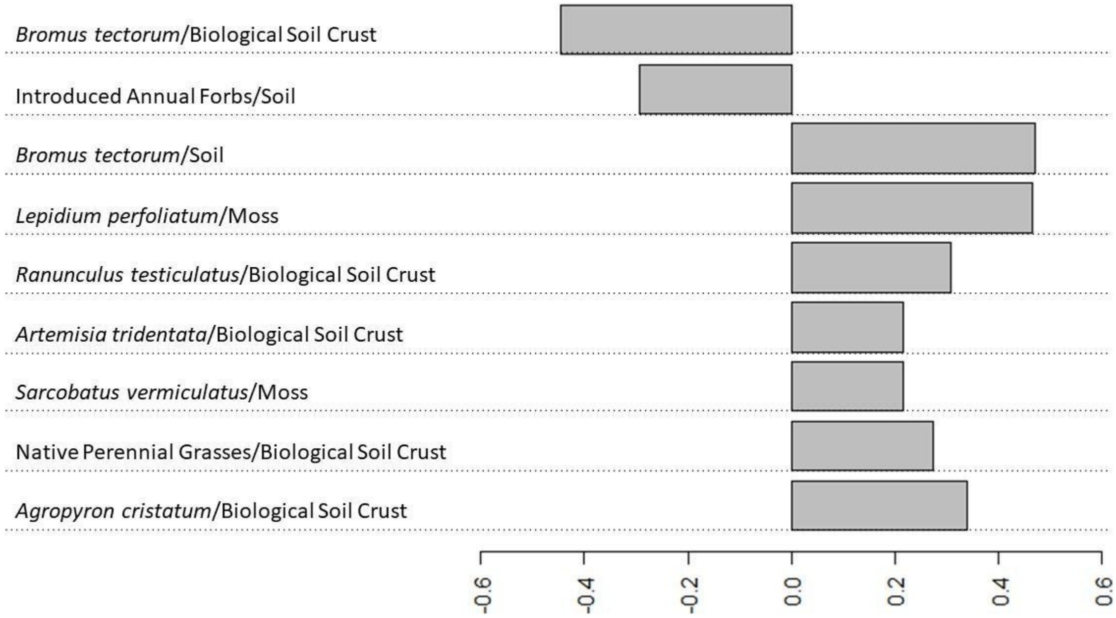


Figure A.31. Significant correlations between plant species and soil surface categories of Antelope Pasture. For all, p-value <0.001. Spearman rank correlations with r > |0.2| and p-value <0.001 are shown above. Introduced annual forb species and shrubs were lumped into functional groups when individual correlations were in the same direction.

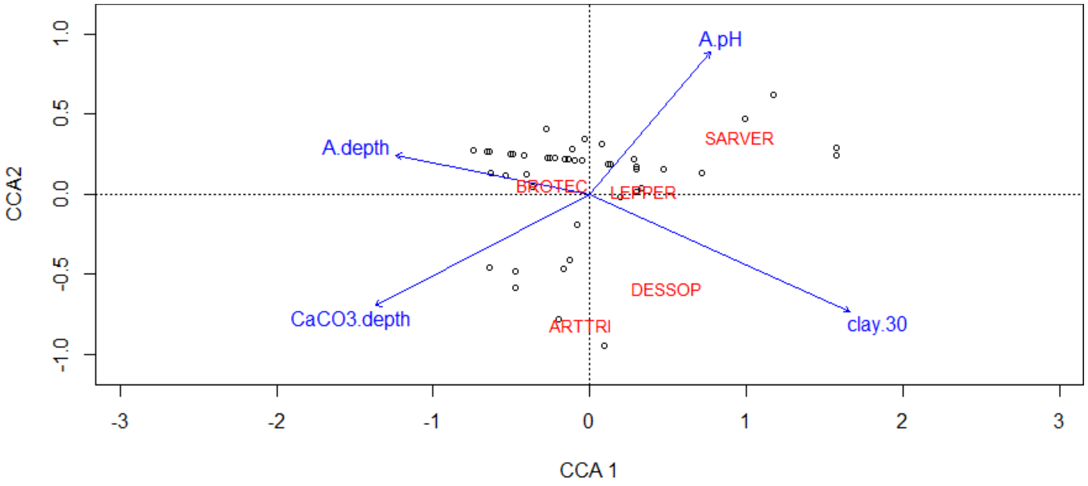


Figure A.32. Canonical correspondence analysis biplot. Graph displays data matrix and eigenvectors. Axes are labeled by component. Included are two native shrub species (ARTRI and SARVER), one introduced annual grass (BROTEC), two introduced annual forbs (DESSOP and LEPPER). Soil variables include A. depth (thickness of A horizon), A.pH (pH of surface horizon), CaCO3.depth (depth to calcium carbonate concentrations), and clay.30 (percent clay at a depth of 30cm). See Table 4 for loading values. Explanatory soil variables are shown in blue, and plant response variables in red. For all, p-value <0.05.

APPENDIX B

Table B.1. Akaike information criterion (AIC) scores for different models in analysis of spring transplants in Sept 2018. Models are binary logistic regression models with the number of successes (live plants out of 4) as response variable. Main fixed effects are plant species ("Species", ACHY, ELEL, LECI, SPGR) and biological soil crust level of development ("LOD"; high vs. low). Invasive plant species cover (Inv.c), centered on its mean, included as a covariate.

AIC Scores for all possible models		
Spring-Planted Cohort		
Sample Date: Sept 2018		
Model	df	AIC Score
Species + LOD + Inv.c	6	93.73
Species + LOD + Inv.c + Species:LOD	9	93.03
Species + LOD + Inv.c + Species:Inv.c	9	94.54
Species + LOD + Inv.c + LOD:Inv.c	7	93.32
Species + LOD + Inv.c + Species:LOD + LOD:Inv.c	10	94.59
Species + LOD + Inv.c + Species:LOD + Species:Inv.c	12	94.42
Species + LOD + Inv.c + Species:Inv.c + LOD:Inv.c	10	93.72
Species + LOD + Inv.c + Species:LOD + Species:Inv.c + LOD:Inv.c	13	93.73

Table B.2. Analysis of Deviance table results for borderline significant Level of Development (LOD)*species interaction, binary logistic regression model on spring-cohort data in Sept 2018. Number of successes (live plants out of 4) as response variable. Main fixed effects are plant species (ACHY, ELEL, LECI, SPGR) and biological soil crust level of development ("LOD"; high vs. low). Invasive plant species cover, centered on its mean, included as a covariate. Results significant at $\alpha = 0.01$ in bold.

Analysis of Deviance Table (Type III Test)			
Spring-Planted Cohort			
Sample Date: Sept 2018	LR Chi Square	DF	P > ChiSq
Plant Species	44.735	3	**< 0.001**
Level of Crust Development	7.602	1	**0.006**
Invasive Species Cover	2.572	1	0.109
Species:LOD	6.699	3	0.082