An Investigation of the Utilization of Soil Water and Nitrogen Among Diverse Forage Plant Species and Mixtures

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AN INVESTIGATION OF THE UTILIZATION OF SOIL WATER AND NITROGEN
AMONG DIVERSE FORAGE PLANT SPECIES AND MIXTURES

by

Sallee Reynolds

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

of

MASTER OF SCIENCE

in

Plant Science

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ABSTRACT

An Investigation of the Utilization of Soil Water and Nitrogen among Diverse Forage Plant Species and Mixtures

by

Sallee Reynolds Mathews, Master of Science

Utah State University, 2010

Major Professor: Dr. Jennifer W. MacAdam
Department: Plants, Soils and Climate

Species diversity achieved by adding novel functional groups (warm-season grasses and non-leguminous forbs) to pasture land, along with traditional grasses and legumes, could aid in the capture of nutrients and water in pasture systems by offering complementary rooting architecture to aid in water and nitrogen uptake and decrease nitrogen leaching. Because these species may differ from commonly used grasses and legumes in their seasonal pattern of productivity, they could also extend or enhance growing-season productivity. The goal of this project is to better understand the role of plant diversity in 1) nitrogen use and 2) distribution of rooting dynamics and forage production. On a larger scale, this project hopes to identify pasture mixtures with greater diversity and management practices that maintain desirable pasture composition and livestock productivity. Herbage dry mass (DM), root surface area (RSA), and \(^{15}\)N uptake of nine species grown individually in the greenhouse were measured in the first experiment. Species which performed well or which were of particular interest to our
study were used in mixtures in the second experiment, which contained varying numbers of functional groups. Individual species grown in monoculture varied in DM production over the course of the experiment, but there were no differences among mixtures, which all increased similarly in DM. Herbage DM of mixtures was 72 to 110% of that predicted by Experiment 1. The RSA of tap-rooted species was low and varied little with depth, while the RSA of cool-season grasses was higher closer to the soil surface. The RSA of mixtures decreased linearly with increased depth, and was between 150 and 350% higher than predicted from the RSA of individual species. Legumes, which have higher foliar protein content than grasses, accumulated more $^{15}$N in shoot DM than grasses, but mixtures did not differ from one another. It is concluded that the DM production advantage of mixtures is more consistent yield. Furthermore, increasing the diversity of simple grass-legume mixtures by adding non-leguminous forbs or other functional groups will likely improve water-use efficiency, thus reducing the risk of nitrate leaching compared with low-diversity grass-legume mixtures while fully exploiting biological nitrogen fixation.

(90 pages)
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Rising fuel and feed costs and uncertain availability of government land for grazing animals will require farmers in the Intermountain West to adapt their farming practices to remain economically viable. Converting land that is currently dedicated to mechanically-harvested feed for confinement production to pasture-based livestock production could be an important part of the change. It could also lower production costs and increase environmental sustainability.

In Utah, like much of the Intermountain West, the majority of agricultural receipts are from livestock production. In 2007, 74% of the state's agricultural receipts of $1.4 billion came from the combined total of all livestock and livestock products, including lamb, wool, beef, milk, poultry, eggs, and pork. Twenty-five percent of the state's cash receipts, $347 million, came from cattle sales alone. In the state, cattle production relies heavily on public rangeland (USDA, 2007a). Grazing occurs on about 80% of the 270 million acres of western public land administered by the Bureau of Land Management (BLM), Forest Service, and National Park Service (Bhattacharyya et al., 1996).

There is persistent pressure to reduce grazing on public land. The land that is currently dedicated to livestock production could be used for recreation, cultural preservation, wilderness areas, enhancement of biological diversity, protection of wildlife and their habitats, and protection of watersheds. (Bhattacharyya et al., 1996).

There is another side to the issue. Providing private ranchers with supplemental grazing land for livestock has historically been a major use of public land. Changing uses of public rangelands has the potential to directly and indirectly impact the income of ranchers who have relied on public land in the past. The repercussions of removing
private farmers from public land or increasing the fees to use public land would be felt in local economies and in the livestock industry of the western states (Bhattacharyya et al., 1996). The sustainability of grazing practices in Utah is therefore a particularly important economic and ecological issue.

As pressures to decrease grazing on public land become stronger, as fees are increased, or as less land is made available, ranchers may be forced to find ways to increase the efficiency of their private land to sustain production. They will need to optimize their use of resources and forage production throughout the whole season on irrigated private land so it can profitably be used for livestock production.

Small family farms, like those typical of Utah, are growing in value in public perception because of their inherent environmental and economic value. The World Food Programme report on food security states that the integrated practices like intercropping and crop and livestock rotation which are used on small farms throughout the world make them 200 to 1000 % more productive per unit area than their larger counterparts. Rosett (2000) suggests that these farms are able to produce with minimal use of expensive external inputs.

Though they are of great local value, small farms must still compete with the efficiencies of scale advantageous to large corporate farms and operations. The Kansas Farm Management Association, in a 10-year study examining the growth and size of farms in Kansas, found that farms that had an output of less than $150,000 were growing at an annual rate of 1.79% while those with production of more than $500,000 were growing at 3.82%. Larger farms only spent 14% of the value of their farm on production labor, while smaller farms spent about 43% of the value of their farm on production.
(Kastens and Dhuyvetter, 2005). Kumbhakar et al. (1989) found similar results in a study of Utah dairy farms. In their study of 116 dairies in Utah they found that large farms, those with more than 100 cows, were the most financially efficient.

With current changes in global politics and rising fuel costs, there is potential for an even greater discrepancy between the earnings of large and small farms. Since 1992, direct fuel and electricity expenses for US farms have averaged around 7% of total operating costs. That percentage is actually closer to 15% if indirect fuel and electricity costs are also included in the calculation. Increasing energy costs have the greatest potential to affect feed grain producers, and changes in energy prices will most affect producers in regions like the Intermountain West where irrigation is indispensable to crop production (Shoemaker et al., 2006)

Preliminary reports, like those of the World Food Programme and the USDA, suggest that plant diversity may play a critical role in the long-term economic sustainability and value of small farms. An analysis of the economic and environmental benefits of biodiversity (Pimentel et al., 1997) suggested that on the grand scale in the United States, the maintenance of biodiversity contributed an estimated $319 billion dollars or 5% of GDP and on a global scale it is estimated to contribute 11% of the world economy.

The environmental sustainability of small farms may also be aided by plant diversity. Before the Haber-Bosch N-fertilizer synthesis process was invented, the ancient Incan Empire used the native legume, lupine, to increase production of their fields. It is a process that is still used today in the Sacred Valley in Peru where the indigenous farmers cannot afford expensive production inputs (Morris, 1999). In the US, farmers can afford
to apply fertilizer at a high rate. As energy prices continue to increase worldwide, farmers in the developed world may find that commercially produced fertilizer is no longer a profitable input. As an alternative, species diversity and biological nitrogen fixation, as used in the developing world, can maintain yields while decreasing costs.

In 1970, Norman Borlaug was awarded the Nobel Peace Prize for his work with the "Green Revolution," which was hailed as bringing the world back from the brink of starvation. In the decades since the work and award, some questions have arisen about the practicality of implementing its practices for subsistence and near-subistence producers. Proponents of the Green Revolution tend to see the use of it in the developing world as desirable, arguing that the productivity improvements have outweighed any negative side effects. Opponents say that it has increased fossil fuel usage, exacerbated class inequality and differentiation, and accelerated rural emigration and urbanization (Buttel et al., 1985). The increased cost to farmers in the developing world may make the use of such advances impractical. Species or cropping diversity could provide much of the increased production benefits associated with Green Revolution production, while staying economically within reach of near-subistence farmers.

Species diversity may also play a vital role in protecting watersheds associated with pasture lands. Scherer-Lorenzen et al. (2003) noted that areas of intensive agriculture, like those common to large-scale cattle operations, disable the biotic watershed protection inherent in the relationship of plants, soils, and microorganisms, due to highly mobile nitrate ions leaching through the soil profile. To aid in decreasing the threat to groundwater quality, increased diversity in rooting system distribution and season of production could be used to increase soil profile exploration in a typical
pasture. More roots deeper in the soil could aid in nitrogen capture before it reaches the water table.

It has been shown that mixtures of plants can utilize nutrients and water more effectively than monocultures, and may be more productive (Tilman et al., 1996; Minns et al., 2001). In the semi-arid West, greater plant diversity is likely to increase the capture and utilization of nitrates that accumulate in the root zone during the growing season so they are not leached by winter precipitation, thereby protecting watersheds and adding to the environmental sustainability of production. As farmers switch from monocultures and simple mixtures that are mechanically harvested, to pastures used for grazing, diverse deep-rooted mixtures that include novel species and functional groups with complementary rooting architecture would be able to more fully capture the nutrients and water in these systems. Cool-season or C₃ grasses are most productive in the spring while warm-season or C₄ grasses are most productive during mid- and late-summer when high temperatures limit C₃ grass production. Novel species that differ in their seasonal patterns of productivity, replacement rate, lifespan, or demographics could alter or extend seasonal growth of pastures. Combining complementary traits of adapted forage species within an irrigated pasture may increase both livestock productivity and environmental sustainability.

Diverse plant mixtures are beneficial to the health and robustness of the pasture as well. Monocultures may be capable of high productivity under a narrow set of conditions. Diverse mixtures of species that occupy a variety of niches across the landscape with varying seasonal distributions of productivity and complementary use of water and nutrients within the root zone, are more tolerant to environmental stresses and more
capable of maintaining productivity under a wide variety of conditions (Tilman et al., 1996; Minns et al., 2001, Scherer-Lorenzen et al., 2003).

Species diversity could directly affect pasture ecosystems, ecological, social, and economic sustainability. It has the potential to lower inputs and increase profitability for more stable livestock production. The goal of this project is to better understand the role of plant diversity in 1) distribution of rooting dynamics and forage production and 2) nitrogen and water use.

This research is part of a larger study that also includes grazing interactions within pastures. From the standpoint of animals, habitats that allow animals to select among alternatives enable individuals to better meet their nutrient needs and to better cope with toxins (Provenza et al., 2003). Individual herbivores can best manage their own need for nutrients and valuable plant secondary metabolites when they have a variety of foods to choose from. Grazing practices that allow producers to capitalize on plant diversity and the individuality of animals are likely to improve the performance of the whole herd as there can be marked variation in the need for nutrients and secondary metabolites among individual animals.

The ultimate goal of the work of which this experiment is one part is to develop robust pasture mixtures and management practices that maintain desirable pasture composition and livestock productivity. By designing a pasture system based on a better understanding of the abilities of well-adapted plant species to supply livestock requirements while making the best use of available water and nutrients, improvements in livestock productivity and environmental sustainability can be attained simultaneously.
INTRODUCTION

During the mid-20th century, an emphasis on increasing agricultural productivity in both western Europe and the U.S. was successful, but it resulted in many agricultural practices that have been shown to be environmentally unsustainable. For example, a large percentage of bird populations in the Great Plains prairies experienced a decline in numbers between the years 1966 and 1993, just as the condition of this land improved according to the traditional means of measurement, namely increased plant yield (Fuhlendorf and Engle, 2001). This suggests that the methods currently used to measure grassland quality are limited in scope. Traditional homogeneity-based approaches to rangeland management are not normally capable of incorporating alternative objectives like optimal biological diversity or high-quality habitat for wildlife.

Hobbs and Morton (1999) addressed the same discrepancy. They examined the ability of current ecological theory to serve as the basis for sustainable agricultural management and design. They suggested a new and more robust paradigm of rangeland quality evaluation that includes the flux of nature, the possibility of multiple stable states within an ecosystem, patchiness, and the realization that we, as humans, are an important ecosystem component. Using this paradigm, Revell and Sweeney (2004) proposed a new design for grassland management in South Australia. They found several sub-optimal features of traditional grassland systems and their management: (1) supply and quality of feed are affected by season, (2) reliance on feed supplements out of season, and (3) reliance on only a small number of species to make up pastures. They also found that water usage of pastures was sub-optimal in South Australia because pastures are unable to use all of the soil moisture in the wet season and are incapable of using out-of-season
precipitation. They concluded that the key criteria in the design of a mixed forage system in South Australia would be (1) to provide a mixture of plants that animals can use to compose a complete diet and (2) to broaden seasonal plant production by incorporating plants with peak growth later in the summer and fall.

Sanderson et al. (2004) pointed out that productivity is the primary focus for research because it is directly relevant to farmers and producers. They added that incorporating environmental and aesthetic benefits should be part of the greater scope of grassland management. The World Food Programme noted that the benefits of community involvement and a place for families to develop should also be part of the scope of farm management (Rossett, 2000).

Grassland is traditionally used for the production of beef cattle, sheep, and goats, while in the U.S., most dairy cattle production is concentrated in drylot systems, and most beef cattle are finished in feedlots. Grazing-based livestock production is a more environmentally sustainable alternative to confinement feeding. Confinement feeding requires more input of natural resources because high-input, mechanically harvested feeds are used, and waste products accumulate in a small area, while pasture-based systems allow waste products to be naturally distributed over the whole acreage from which nutrients were extracted. They are distributed reasonably well under rotational stocking management when large groups of cattle or sheep are moved frequently among small paddocks. Previous research (MacAdam, 2002; MacAdam et al., 2004; MacAdam et al., 2005) has shown that grass-legume mixtures are sufficiently high-yielding to support the transition from drylot to grazing-based production for farmers in Utah with a sufficient land base. Other studies at Utah State University have confirmed that milk,
beef, and lamb can be produced more profitably on irrigated pastures than in confinement or on rangeland (personal communication, D. L. Synder).

Pasture-based livestock production on lands that are currently dedicated to mechanically harvested feed for confinement milk and meat production is part of the solution to higher input costs and decreasing public land availability, and will allow small farmers to profitably produce and compete against larger operations. There is evidence that forage production can be maximized and be most environmentally sustainable if appropriate mixtures of plant species can be found that will offset the suboptimal features of grassland communities as discussed by Revell and Sweeney (2004), such as poor use of water and nutrients and poor seasonal distribution of growth.

In studies of seeded grasslands carried out at nine sites across western Europe, total plant biomass increased with species richness up to 32 species, the maximum number measured (Minns et al., 2001). The most productive of the grassland ecosystems were those that included all plant functional groups (annual and perennial grasses, legumes, and annual and perennial non-leguminous forbs). Mixtures that contained a legume produced more than mixtures that did not. Plant diversity and functional group diversity also affected nitrate leaching. Scherer-Lorenzen et al. (2003) found that the total annual loss of nitrate in mixed pasture was unaffected by the number of plant species or functional groups, but was highly dependent on the specific species composition of the communities. Plots with legumes lost significantly more nitrate than plots without them. The only plots in their study that leached nitrogen were those with no vegetation and those that contained legumes. In those plots that contained legumes, leaching decreased as the number of species added to the legume increased. They found that aboveground
biomass had no influence on nitrate loss, whereas leaching was negatively correlated with root biomass. In seeded replicated studies of native grassland species, Tilman et al. (1996) also found that productivity increased with species richness, while leaching potential of nitrate declined. It would seem that, while legumes are a necessary functional group for high shoot biomass production in the absence of nitrogen fertilization, some nitrate leaching is inevitable, even when the input is primarily from biologically fixed nitrogen. Optimization of the system will require determination of the best balance of legumes and other species or functional groups.
SPECIES SELECTION

The two objectives of this project were (1) to screen a number of species of forage plants, as potential components from each of four functional groups (perennial legumes, warm and cool-season grasses, and non-leguminous forbs), for development of productive mixtures for irrigated pastures with improved water and nitrogen utilization and (2) to test selected mixtures to determine if water and nitrogen use were improved in complex relative to simple mixtures.

Species were selected for this study based on several traits, including functional group association. Based on the evidence from the literature that complex pasture mixtures would not only be more productive and economically feasible but also more environmentally sustainable than simple mixtures, our goal was to identify forage plant mixtures relevant to irrigated, intensively grazed pastures for the Intermountain West. The functional groups and individual species used in this study are as follows:

Legumes

Birdsfoot trefoil (*Lotus corniculaus* L.) is a legume that is well-suited for use in grazed pastures. It is drought tolerant, persistent and high yielding under poor soil-drainage conditions, and is tolerant of flooding and saline soils (Frame et al., 1998). It is naturalized at high altitudes and can tolerate severe winters. It is a tap-rooted species, developing roots that penetrate the soil almost as deeply as those of alfalfa, but with greater lateral spread, especially in the upper 30 to 60 cm of soil. It has been reported to be slow to establish and have poor competitive ability (Frame et al., 1998). Birdsfoot trefoil flowers later in the season than do red clover and alfalfa, which makes it more
compatible with native tall prairie grasses like big bluestem. Its mature leaves remain highly nutritive, which makes it useful for stockpiling (Beuselinck and Grant, 1995). Birdsfoot trefoil has the ability to perform especially well on calcareous soil and has the potential to serve as an alternative to alfalfa, especially on poor soils. Perhaps its greatest advantage is that, unlike most other legumes such as alfalfa and the true clovers, which can cause bloat in ruminants, birdsfoot trefoil does not incite bloat because it contains condensed tannins that cause proteins to precipitate (MacAdam et al., 2006). Initially, alfalfa and clover species excreted more N into the soil from the root system than trefoil, but trefoil had the potential to contribute more N over time than the other two species due to the decomposition of dead root tissue and nodules (Ta and Feris, 1987). Birdsfoot trefoil was included in both the first and second experiments of this study because it performs well in the Intermountain West.

Alfalfa (Medicago sativa L.) is the highest-yielding of the temperate forage legumes, the most widely grown in warm temperate areas and is thought to have originated in Asia. It is grown primarily for hay in the Intermountain West. Alfalfa does not tolerate continuous stocking but is used in rotational grazing systems (Frame et al., 1998). Even though alfalfa is a deep-rooted legume that produces a taproot that can reach depths of more than 6 m, it is not unusual for the root system to be extremely branched. Sixty to seventy percent of the total root mass is in the upper 15 cm of the soil profile (Barnes and Sheaffer, 1995). Fibrous roots proliferate in the upper 20 cm of the profile and bear most of the nodules (Johnson et al., 1998; Barnes and Sheaffer, 1995). Ta and Feris (1987) in their study of mixed cropping systems, found that the inclusion of both alfalfa and birdsfoot trefoil improved the DM production of grasses; of the two, alfalfa
improved DM the most. Compared to N-fertilized grass-only pastures, alfalfa-based pastures without supplemental N can sustain animal productivity with only 28% of the external energy input (Chen et al., 2004). The germplasm used in the study reported here was a falcata-type alfalfa (*Medicago sativa* subspecies *falcata*) that is more adapted to grazing than sativa-types. A falcate alfalfa was included in the study as a means of comparison with birdsfoot trefoil, since the productivity of hay types is already well known in the Intermountain West.

The shallow-rooted white clover (*Trifolium repens* L.) was included because it is also used for grazing throughout temperate climates. White clover growth may be effectively supported by either taproot or adventitious root systems. Over 80% of white clover roots are usually located in the top 20 cm of soil (Pederson, 1995) because they become established from stolons. Clovers have also been shown to be very productive. In one mixed pasture study, not only did the inclusion of a legume impact DM production, but more specifically, the inclusion of red clover was found to significantly affect harvest DM more than other legumes (Minns et al., 2001). White clover responds well to grazing, and repeated defoliation causes rapid turnover of root and nodule tissue (Ta and Feris, 1987).

**Cool-Season Grasses (C₃)**

Orchardgrass (*Dactylis glomerata* L.) is a cool-season bunchgrass that is highly productive under irrigation (Jensen et al., 2001). It starts growth early in the spring, develops rapidly, and flowers during late May or early June with another lesser period of growth in the fall. Orchardgrass tillers almost continuously, allowing for rapid recovery
after cutting or grazing. The fibrous root system of orchardgrass is extensive and deep. And finally orchardgrass is easy to establish, survives for many years if properly managed, recovers rapidly after cutting or grazing, and produces good second- and third-harvest growth (Christie and McElroy, 1995).

Tall fescue \([\text{Schedonorus phoenix (Scop.) Holub}]\) is a perennial tufted bunchgrass that has a high nutritive value. It is taller, more drought and cold tolerant, denser, more competitive with weeds, and adapted to a wider range of soils than other fescue species. It is used extensively as the grass component of mixtures in irrigated pastures in the western Intermountain region of the United States and is considered to be the predominant cool-season grass species in the U.S. It is known to have a massive fibrous rooting system and its roots have been shown to decrease the bulk density of soil, improve soil structure, and reduce soil erosion (Sleper and Buckner, 1995). One study found that more than half of the total root length in the upper 40 cm of the soil profile was found between 0 and 20 cm (Beyrouty et al., 1990). Tall fescue demonstrates good shade and grazing tolerance (Duble, 2007). Typical of cool-season grasses, peak growth rate of tall fescue occurs in spring with a secondary peak of vegetative growth in autumn (Sleper and West, 1996). In a study of mixed pastures, Ta and Feris (1987) found that both orchardgrass and tall fescue benefited more than other grass species from their legume association.

Warm-Season Grasses \((C_4)\)

Big bluestem \((\text{Andropogon gerardii Vitman})\) is native to the Great Plains and has a root system that is very extensive, as deep as 2.0 to 2.5 m. Big bluestem often grows in
clumps, although most plants also have short rhizomes. It is desirable in pastures due to its ability to be productive during summer when cool-season grasses are relatively unproductive (Moser and Vogel, 1995). Though big bluestem produced more in the first experiment than blue grama [*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths] and is thought to be better adapted to drier environments, blue grama was chosen as the warm-season grass for the second experiment because big bluestem was highly susceptible to whitefly (*Trialeurodes vaporariorum*) in the greenhouse.

Blue grama is native to the Intermountain West. It is a bunchgrass that is well adapted to continuous stocking and is known to have excellent quality (Voigt and Sharp, 1995). Functional roots may reach depths of 60 cm, but 85% of the root mass is typically in the upper 20 cm of soil. Mature plants are well adapted to a scarce and highly variable water supply and to a precipitation patterns in which small rainfall events constitute a large portion of annual precipitation (Smith et al., 2004).

**Non-Leguminous Forbs**

Small burnet (*Sanguisorba minor* Scop.) is a hardy introduced perennial forb, has excellent forage quality and is not only useful for livestock, but is also well utilized by wildlife like elk, deer, antelope, and birds. Normally it is tap rooted but is also sometimes rhizomatous. Seedling vigor of small burnet is excellent but plants still establish slowly. Growth begins in early spring and flowering takes place in May and June (USDA, 2007c).

Lewis flax (*Linum lewisii* Pursh) has fair forage value for livestock and wildlife during spring and winter. It is native to a wide range of climates in the U.S. Both small
burnet and Lewis flax are very cold- and drought-tolerant and perform well on well-drained, infertile, and disturbed soils. They tolerate soils of neutral pH and are semi-tolerant of shade (USDA, 2007b).
MATERIALS AND METHODS

The first experiment in this study, directed to individual species, was initiated in the USU Research Greenhouses at Logan, UT in July 2005. Average day and night temperatures during this phase of the study were 25 and 20 °C, respectively. The relative humidity was approximately 40% at mid-day and 70% at night. Solar photosynthetic photon flux was supplemented using HPS lamps for an estimated total of 27 moles m$^{-2}$ day$^{-1}$. The experiment employed a randomized complete block design with four replications.

Individual plants of birdsfoot trefoil, white clover, falcata alfalfa, orchardgrass, tall fescue, big bluestem, blue grama, lewis flax, and small burnet, representing four functional groups (perennial legumes, warm- and cool-season grasses, and non-leguminous forbs), were grown in containers from seed. Seeds were planted in a calcareous Kidman sandy loam soil (coarse-loam, mixed, superactive, mesic Calcic Haploxerolls) in clear flexible plastic tubes with a diameter of 10 cm and a length of 1 m. The tubes were suspended in 10-cm-diameter PVC pipes for light exclusion and support (Bonos et al., 2004). Soil was tested for fertility at the USU Analytical Lab in Logan, Utah prior to planting and no phosphorus or potassium amendments were needed. Legume species were inoculated at planting. Replicate species were assigned to one of two rows 1 m apart, with approximately 5 cm between tubes within rows. When productivity calculations were made they were based on the soil surface area of the column and did not take into account the fact that many of the species grew outside their containers and even grew to interact with neighboring tubes.
The tubes were fitted with Soilmoisture® ceramic cups (Soilmoisture Equipment Corp., Goleta, CA) at their base, which facilitated the extraction of drainage water to prevent saturation. The pressure was kept at a constant -50 kPa for the duration of the experiment. During the study, soil moisture was measured with three Watermark® resistance block moisture sensors (Irrometer, Riverside, CA). Watermark sensors are granular matrix sensors, similar to gypsum blocks. They consist of two electrodes embedded in a matrix material surrounded by a synthetic membrane. They are then covered in stainless steel mesh and a rubber jacket for durability. Movement of water between the soil and sensor results in changes in electrical resistance, which can be converted to soil water potential. Watermark sensors can measure soil water potential from 0 (saturated) to -200 kPa (very dry) (http://www.specmeters.com/Soil_Moisture/).

The first sensor was placed at a depth of 10 to 20 cm from the soil surface, the second was placed at a depth of 40 to 50 cm and the third was placed at a depth of 70 to 80 cm from the soil surface in two replications of each species in the study. Columns were brought to field capacity with Logan City water before planting. For the first 15 days after planting, the soil surface of the columns was misted with water daily to ensure seedling survival. After 15 days, species were watered to field capacity, which was initially calculated using a soil characteristic curve. All replicates of any given species were watered using drip irrigation each time any of the three sensors located in either replicate containing sensors registered below -50 kPa, per manufacturer’s instructions, but no more often than once a week. Drainage was removed by suction via ceramic cups.

Initial harvest of species occurred between 55 and 90 days after planting depending on species development. Plants were harvested for the first time to a height of
5 cm when canopy light interception reached 90% for broadleaf species and 80% for grass species, as measured 1 cm in from the pot’s edge using a quantum sensor (model LEV, Apogee Instruments, Inc., Logan, UT). Plants were harvested and allowed to regrow two more times at 35-day intervals, and harvested material was dried for 48 h at 60 °C (Undersander et al., 1993). Flax did not recover quickly from harvesting and did not reach 80-90% coverage after the second harvest; consequently, flax was only harvested twice and was not part of the 15N portion of the experiment.

Each container was fertilized with urea 7 days after each harvest by applying 0.125 g, or the equivalent of 200 lbs N acre⁻¹ year⁻¹ before fertilization with 15N. Prior to a fourth, destructive harvest, mature plants were fertilized with urea containing 23% 15N stable isotope to track nitrogen uptake. Fourteen days after fertilization with the stable isotope, the plants were harvested to a height of 5 cm for the fourth time, dried for 48 hours at 60 °C and ground to pass a 40-mesh screen. A sub-sample of ground material was placed in tin capsules and analyzed for 15N at the USU Stable Isotope Lab.

Analytical precision was approximately 0.03% relative standard deviation, equivalent to approximately 0.0001 atom% 15N, evaluated at 0.37 atom% across the entire sample run. Background 15N atom % values in untreated samples were subtracted from labeled samples of the respective species to determine 15N atom % excess values. Pools of 15N in each species were calculated by multiplying shoot mass (g) and 15N atom % excess values (Hendon and Briske, 2002), and 15N atom % excess values for species were statistically analyzed.

At the destructive harvest, flexible plastic tubes were removed from PVC pipes and cut into six sections based on depth. The first five sections moving downward from
the soil surface were 17 cm deep by 10 cm diameter (1335 cm$^3$ per section) each, and the sixth section, which corresponded to the deepest portion of the column, varied in size and was not present in some cases due to soil compaction. Each section was placed in a root washer with a 2-mm screen. Extracted roots were then placed in 10% V:V isopropyl alcohol as a preservative and to settle organic matter. Roots were floated in a 20 cm by 30 cm dish, and digital images were acquired with a flatbed scanner at 300 dpi for root length and diameter using WinRHIZO Pro version 2005b (Regent Instrument Inc., Quebec, Canada).

The second experiment in the study was initiated in the USU Research Greenhouse in March 2006 at Logan, UT. Average day and night temperatures were 25/20 °C, respectively. The relative humidity was approximately 40% at mid-day and 70% at night. Solar photosynthetic photon flux estimated by the greenhouse manager was supplemented using HPS lamps for a total of 27 moles m$^{-2}$ day$^{-1}$. Experimental design was a randomized complete block design with four replications.

After the first experiment was completed, species that would make up the mixtures in the second experiment were selected based on visual observations and tap data. One cool-season grass (orchardgrass), one warm-season grass (blue grama), one deep-rooted legume (birdsfoot trefoil), one fibrous-rooted legume (clover) and one non-leguminous forb (small burnet) were picked to represent different functional groups as components of different mixtures. Mixtures were made up of two, three, or four different functional groups including either a fibrous or a tap-rooted legume. Plants were grown from seed in the USU Research Greenhouses for the second experiment. All mixtures
were comprised of four plants in rooting columns four times the surface area of the single-species columns.

One four-way mixture contained the deep-rooted legume birdsfoot trefoil, the C4 grass blue grama, the C3 grass orchardgrass, and the non-leguminous forb small burnet (BFT-4 Spp). The other four-way mixture contained the shallow-rooted legume white clover, blue grama, orchardgrass, and small burnet (WC-4 Spp). One two-functional-group mixture contained birdsfoot trefoil and orchardgrass (BFT-2 Spp), and the second contained white clover and orchardgrass (WC-2 Spp). The single three-functional group mixture contained birdsfoot trefoil, small burnet, and orchardgrass (BFT-3 Spp). All legume species were inoculated at planting.

Seeds were planted in a calcareous sandy loam soil in clear flexible tubes with a diameter of 20 cm and a length of 60 cm. The tubes were suspended in 20-cm-dia PVC pipes for light exclusion and support (Bonos et al., 2004). Soil tests (USU Analytical Lab in Logan, Utah) prior to planting indicated that no phosphorus or potassium amendments were needed. Each tube held four plants, and in all mixtures, legumes constituted 25% of the plants because it has been found that the higher the aboveground biomass of legumes, the smaller the root system of the whole community (Minns et al., 2001; Scherer-Lorenzen et al., 2003). In all mixtures that had fewer than four functional groups, more than one grass was planted to ensure that the percentage of legumes in the mixture remained at 25%. For example, the three-species mixture contained one plant each of birdsfoot trefoil and small burnet and two plants of orchardgrass. Each two-species mixture contained three plants of orchardgrass and one plant of the legume. Tubes containing mixture replicates were placed in two rows approximately one meter apart,
with 5 cm between tubes within rows. When productivity calculations were made they were based on the soil surface area of the column and did not take into account the fact that many of the species grew outside their containers and even grew to interact with neighboring tubes.

The tubes were fitted with Soilmoisture® ceramic cups at the base and water was constantly pulled off the columns and passed into individual containers at -50 kPa to prevent the base of the column from becoming saturated. Columns were brought to field capacity before plants were seeded. For the first 15 days after planting, the soil surface of columns was misted with water daily to ensure seedling survival. After 15 days, seedlings were thinned to four plants and the pots were put on an automatic drip timer and watered with 1 L of water weekly in four 5-minute time intervals 30 minutes apart to ensure water absorption. After the second harvest watering was increased to three 5-min intervals two times a week, for a total of 1.2 L per week to preclude drought stress.

Harvesting of the second experiment began 60 days after planting, an average number extrapolated from the first experiment, and regrowth was harvested at successive 28-day intervals. Initially it was planned for plants to follow the same procedure as the first experiment, but this was decreased from the first experiment because by 28 days, the majority of the mixtures had more than 90% canopy cover light interception. After the second harvest it was noted that many of the plants were experiencing water stress. In order to ensure that water stress did not compromise the DM results two additional harvests were added to the second experiment. One of the experimental units, which corresponded to the first replication of the birdsfoot trefoil four-functional group mixture, also had its drip tube slip from its housing and was left for more than nine days without
water. The small burnet, birdsfoot trefoil, and orchardgrass recovered, but the blue grama did not. The mixture was allowed to continue without replanting.

During Experiment 2, tubes were not fertilized so that the contribution of biologically fixed nitrogen from the legume component could be factored into the study. Seven days after the fifth harvest, plants were fertilized with urea containing 5% $^{15}$N stable isotope to track nitrogen uptake. This level was decreased from the first experiment due to $^{15}$N concentrations that were excessive for analysis. Seven days after the stable isotope fertilization, plants were destructively harvested to a height of 5 cm. Harvested biomass comprised of all species was dried for 48 hours at 60 °C and ground to pass a 40-mesh screen. A sub-sample of ground material was placed in tin capsules and analyzed for $^{15}$N at the USU Stable Isotope Lab. Analytical precision was approximately 0.03% relative standard deviation, equivalent to approximately 0.0001 atom% $^{15}$N evaluated at 0.37 atom% across the entire sample run. Background $^{15}$N atom % values from samples that had not been enriched were subtracted from labeled samples of the respective species to determine $^{15}$N atom % excess values. Pools of $^{15}$N were calculated by multiplying shoot mass (g) and $^{15}$N atom % excess values (Hendon and Briske, 2002), and $^{15}$N atom % excess values for mixtures were statistically analyzed.

At the destructive harvest, the plastic tubes were removed from PVC support tubes and cut into six sections from surface to base. The first five sections moving downward from the soil surface were each 10 cm deep by 20 cm in diameter (3142 cm$^3$ per section). The sixth section, which corresponded to the deepest portion of the column, varied in size and in some cases was not present due to soil compaction. The first, third, and fifth sections were placed in a root washer with a 2-mm screen. Extracted roots were
then placed in 10 % V:V isopropyl alcohol as a preservative and organic matter was allowed to settle. Roots were floated in a 20 by 30 cm dish and digital images were acquired with a flatbed scanner at 300 dpi for root length and diameter using WinRHIZO Pro version 2005b (Regent Instrument Inc., Quebec, Canada.)

In the first experiment the growing tubes were 1 meter deep and were cut into 5 sections of 17 cm (the extra length was variable due to compaction and was not counted). Due to the increased diameter of the tubes in the second experiment, the total length of the tubes had to be decreased to maintain a tube weight that would be manageable. When comparisons were made between the RSA data in Experiments 1 and 2 the data were first converted to cm$^2$/cm$^3$. Data from the first layer of the second experiment (0-10 cm below the soil surface) were compared to data from the first layer of the first experiment (0-17 cm below the soil surface). Data from the third layer of the second experiment (20-30 cm below the soil surface) were compared to data from the second layer of the first experiment (17-34 cm below the soil surface). Data from the fifth layer of the second experiment (40-50 cm below the soil surface) were compared to data from the third layer of the first experiment (34-51 cm below the soil surface).

Statistical Analysis

All statistical analysis was done using the SAS software. Experiments 1 and 2 both employed a randomized complete block design with four replications. Data for herbage dry matter, root surface area and 15N enrichment from both experiments were analyzed using the PROC ANOVA procedure of SAS (2010).
RESULTS AND DISCUSSION

Herbage Dry Matter

Mean herbage dry matter (DM) at each harvest of Experiment 1 is presented in Fig. 1 (see Appendix), and DM by species at each harvest is presented in Fig. 2. Mean herbage DM was greatest at the second harvest, followed by the third and first, with the fourth harvest being the smallest (p < 0.0001; Fig. 1). This pattern was driven by the most productive species, big bluestem and small burnet (Fig. 2; Table 1). The warm-season grass big bluestem had the highest mean DM of all the other species (p < 0.0001; Fig. 3). Blue grama and small burnet produced more DM than the lowest producing species, a falcate-type alfalfa and lewis flax (Fig. 3). Within the study, species such as orchardgrass, tall fescue, and white clover continued to increase in DM productivity through the third harvest (Fig. 4; Table 2). The species with the most consistent yields for the first three harvests were birdsfoot trefoil, tall fescue, and blue grama (Fig. 4).

In Experiment 2, mixtures were comprised of species from different functional groups and, based on Experiment 1, different patterns of production. Therefore, mean production within the first four harvests did not differ significantly. Harvest was a significant effect of the experiment (p < 0.0001), but only because the final harvest was extremely high (Fig. 5). The mixtures in the second experiment were visually noted to be experiencing water stress after the fourth harvest. After the fourth harvest watering was increased from once a week to once every 5 days. The increase in watering could be an explanation for the increase in the DM that was seen in the final harvest. Within harvests, the WC 4 Spp mixture was the only one that differed significantly and it only did so at
the final (fifth) harvest (Fig. 6; Table 3). There were no significant differences in productivity among mixtures (p = 0.0930), but the WC 4 Spp mixtures had the numerically highest mean DM production while the BFT 4 Spp mixture had the lowest (Fig. 7). The fifth harvest had the highest DM for all treatments, but within mixtures, the fourth harvest of the two-way mixture WC 2 Spp (white clover and orchardgrass) was also higher than the first three harvests (Fig. 8; Table 4).

This study demonstrates the buffering effect of mixtures, in which production is more balanced from the start and which continues to increase as individual plants find their niche. This is clearly advantageous compared with most of the monocultures. The data for production of mixtures with more and fewer species also suggest that as long as these well-adapted forage species are not resource-limited, yield is not strongly affected by the level of plant species diversity.

One of the other factors affecting DM yield in mixture studies could be that such studies often compare species with a well-documented history of success to new and untested species (Sanderson et al., 2005). For example, blue grama is a warm-season (C₄) species that is native to the Intermountain West, which could be a valuable component of mixtures, but it may not be as resilient under frequent defoliation as the cool-season grasses typically used in this area.

Although the two experiments were carried out eight months apart, the sum of individual species’ herbage DM from the first experiment, which was carried out in the same controlled environment, was compared with data for the first four harvests of the same plants grown in mixtures. The average number of days from seeding to final harvest for individual species in Experiment was 178, and the number of days from seeding to the
The fourth harvest of mixtures in Experiment 2 was 172. The soil surface area per plant (78.5 cm\(^2\)) was the same in both experiments. In this comparison, the mean of the sum of every mixture was between 72 and 110% of what would have been expected using the sum of DM data of the four individual components from the first experiment (Fig. 9). A statistical comparison among these values is not possible, of course, but one may speculate that the competition present when species are planted together as mixtures had no negative effect on total DM production.

While complex mixtures may not produce more herbage DM than simple mixtures under controlled conditions, complex mixtures have many other benefits including niche complementarity, improved ability to withstand environmental fluctuations (Minns et al., 2001), the ability to compensate for poorly performing species (Tilman et al., 1996), drought tolerance and less vulnerability to invasion of non-sown species (Sanderson et al., 2005).

Revell and Sweeney (2004) point out that our concept of ‘pasture improvement’ no longer simply means more production per hectare but is broadened to include resilience and sustainability. Some of the other specific outcomes desired in improving pasture land, such as improved animal nutrition, more sustainable management practices, more uniform growth across seasons, greater rooting depth, and improved wildlife habitat, may not support maximum DM production, but this study suggests diversity and the maintenance of dry matter production are compatible goals.

The mixtures used in this study contained species from different functional groups. The legume functional group contained both deep (BFT) and shallow-rooted (WC) species. In the harvests examined there were no differences in harvest DM whether
the mixture contained 2, 3 or 4 different functional groups or if the legume were deep or shallow-rooted. This complements the findings of Sanderson et al. (2005) who found that the identity of the functional groups and the individual species present in mixtures was more important than the number of functional groups in affecting productivity.

Root Surface Area

Experiment 1

Species and depth were significant effects (both at p < 0.0001) of root surface area (RSA). Mean species RSA decreased with depth (Fig. 10). The RSA of the species big bluestem, blue grama, lewis flax and orchardgrass decreased significantly with depth, contributing to this trend (Fig. 11; Table 5). Of these, big bluestem and orchardgrass concentrated much of their RSA in the upper 51 cm (20 inches) of the soil. For a second group of species that included alfalfa, birdsfoot trefoil, small burnet, tall fescue and white clover, RSA did not differ significantly with depth (Fig. 11; Table 5).

Among the species, orchardgrass, tall fescue, and big bluestem had the highest mean RSA (Fig. 12). Examined in detail (Fig. 13; Table 6), it is apparent that the strongly tap-rooted species (alfalfa, birdsfoot trefoil and small burnet) generally had the lowest RSA at every depth. Other species, such as lewis flax and blue grama, had relatively high RSA in the upper sections of soil columns but very little in the lower sections of the soil.

Experiment 2

In Experiment 2, mixture was not a significant main effect of RSA (P = 0.2289) although depth was (P < 0.0001). In all cases, mixtures decreased in RSA with depth
Within each of the three depths, mixtures did not differ from one another statistically (Table 8). In this experiment, mixtures either included birdsfoot trefoil or white clover as the legume functional group; birdsfoot trefoil has a tap root, while white clover develops fibrous roots along the stolons that branch from the seedling. Aside from the legume, the other species in the two-species mixtures (BFT-2SPP and WC-2SPP) and the four-species mixtures (BFT-4SPP and WC-4SPP) were the same. Even though there was no difference in RSA among mixtures, there was a difference in RSA distribution between the white clover and birdsfoot trefoil mixtures (Fig. 14 and Table 7): RSA in the upper soil section was higher than in the middle and lower soil sections for the two white clover-based mixtures, while RSA in the upper and middle soil sections was higher than RSA in the lower soil section for all three birdsfoot trefoil-based mixtures. This is likely to be an indirect effect of the nitrogen fixation and transfer of nutrients to non-leguminous species at greater depths for birdsfoot trefoil than for white clover mixtures.

For the sake of comparison, the mean RSA on a unit volume basis of the individual species from Experiment 1 used in each mixture was compared to unit volume RSA for the mixtures in Experiment 2 (Fig. 15). In Experiment 2, each of the mixtures had a much greater RSA at each level we compared, ranging from mixtures producing more than 350% of the expected RSA in the upper root zone to producing 150% of the expected RSA in the lower root zone. From these comparisons we can conclude that interspecies competition had no negative effect on root production at any rooting depths; in fact, the presence of the roots of more than one species increased shallow root production for all mixtures. The differential between expected and actual RSA in
mixtures decreased with depth similarly, regardless of the number of species included, the type of legume, or the functional groups present.

Our finding that there were more roots in mixtures than data for species grown alone predicted, which would indicate a positive root-growth interaction for species grown in diverse mixtures. Scherer-Lorenzen et al. (2003), in their mixed-pasture study, found that the size of the root system decreased significantly with decreasing diversity in mixtures containing legumes. Our findings are not supportive of this, but our range of diversity was also much smaller, and our data are from container studies while theirs are from field studies. They postulated from this finding, and that of nitrate leaching being negatively correlated with fine root biomass, that high-diversity conditions lead to better use of soil nitrate. The increased biomass of shallow roots in our mixtures compared with single species demonstrated in this study is indeed more likely to prevent nitrates from leaching deeper into the soil profile.

It has been shown that trends in root growth do not always closely follow patterns of shoot growth (Beyrouty et al., 1990) so it was important to examine not only the DM production of the shoot, but also the root development of the individual species and mixtures. We were most interested in soil water use, and RSA corresponded more closely than root volume or root DM to water uptake. Since the mixture RSA resembled the sum rather than the mean of RSA for the individual species included in the mixture, we conclude that resources were not a limiting factor for these species under irrigation.
The water use of each species in the first experiment was tracked over time and can be seen in Figures 16-24. Statistical comparisons were made and results can be seen in tables 9 and 10. There was considerable day-to-day variation; data reported are the mean of these two reps. Average sensor readings for each species at three depths can be found in Figure 25. In all cases, more water was drawn from the upper than from the lower section of the soil profile. Grieu et al. (2001) found in their study of mixed legume/grass pasture that a plant’s ability to extract water from deep within the soil profile is more advantageous to plant growth than the development of a large root biomass or density.

Comparing the two tap-rooted legumes, alfalfa had lower shoot DM than birdsfoot trefoil and lower apparent water use, based on mean moisture sensor data (Fig. 25). The deepest sensor had a reading of less than -40 kPa only twice throughout the entire growing season for birdsfoot trefoil (Fig. 19) and three times for alfalfa (Fig. 16). White clover, reputedly a more shallow-rooted legume, appeared to use at least as much water as the tap-rooted legumes at all depths. When water use was compared with RSA, however, we see that the RSA of white clover was higher at all depths than the RSA of the two tap-rooted legumes. However, the lowest reading of the deepest sensor for white clover was not as low as the lowest readings for the deep-rooted legumes. It could be concluded that, while white clover more consistently used water from deeper in the soil profile than the two tap-rooted species, alfalfa and birdsfoot trefoil were capable of pulling greater amounts of water from deep in the profile, as shown by lowers sensor readings. Lucero et al. (2000) found in their study of white clover and ryegrass that plant
competition did not affect water use efficiency of either species. In another white clover-ryegrass study, Grieu et al. (2001) found that after three months of growth, white clover roots obtained water from a soil depth that was 30% greater than that of ryegrass.

The differential in water use between the two cool-season grasses (orchardgrass and tall fescue) had the same trend as their shoot DM production (Fig. 3). However, based on the statistically higher RSA of orchardgrass in the upper half of the rooting container (0 to 51 cm; Fig. 11), water use based on the orchardgrass Watermark sensor placed between 40 and 50 cm seemed surprisingly low (Fig. 21). Both tall fescue and orchardgrass had high RSA compared with other species, but only average water use. Cool-season grasses have been shown to produce nearly double the amount of adventitious roots (which typically begin formation at the seeding depth) as their warm-season counterparts (Newman and Moser 1988). This would explain the higher water extraction by these grasses observed in the shallowest section of the soil profile.

The two warm-season grasses, while having relatively high yield compared to other species, had water use at all depths that was similar to the tap-rooted legumes. Big bluestem appeared to be particularly efficient, with higher yield than blue grama but lower water use. The RSA of big bluestem and blue grama were similar near the surface of the container, but while the RSA of big bluestem in the middle of the container was similar to that closer to the surface, blue grama RSA declined linearly with rooting depth. The RSA differential of big bluestem and blue grama reflected the yield differential of these two species.

The two forbs (lewis flax and small burnet) appeared to be the least water-use-efficient plants. Small burnet had relatively high yield, but also the highest water use of
any species at all depths (Fig. 16). Both its pattern of water use and RSA were similar to the other two tap-rooted broadleaf species, alfalfa and birdsfoot trefoil. The pattern of RSA and water use of lewis flax were both very similar to big bluestem, but its yield was about one-quarter that of big bluestem. Species with high water use relative to yield have a strategy better-suited to survival in limited water availability environments than to high DM production in resource-rich environments.

There is clearly a different water use pattern in the tap-rooted species compared with both the cool-season and warm-season grasses. The ability to withdraw water from the lower two-thirds of the rooting container, as indicated by sensors in these parts of the rooting profile, was greater than suggested by their RSA. The forb, small burnet, which yielded well and used water from throughout the rooting depth, would be a good candidate species to protect the watershed from nitrate leaching without the addition of nitrogen to the system through biological fixation. This, along with its high yield and high nutritive value for livestock, make it a valuable addition to forage species mixtures for irrigated pastures in the Intermountain West.

$^{15}$N Uptake

$^{15}$N-labeled nitrogen was fed as urea prior to the final, destructive harvest to estimate nitrogen uptake both in individual species (Experiment 1) and in mixtures (Experiment 2). Background $^{15}$N levels were determined for each species and mixture, and were compared to values determined after enrichment. We have equated the difference in the two values with nitrogen uptake that occurred between enrichment and destructive sampling. Figure 26 shows the excess pool values for $^{15}$N in each of the
species used in Experiment 1. Blue grama had a higher excess pool than did alfalfa, tall fescue, big bluestem and small burnet; birdsfoot trefoil and orchardgrass were intermediate, and white clover took up less labeled N than blue grama, birdsfoot trefoil, and orchardgrass (p<.0001).

All plants used in Experiment 1, including the legumes, were fertilized with N following each harvest, so even though the legumes were capable of fixing their own N, biological N fixation should not have influenced uptake as much as root morphology and translocation of N to the shoot. The three species with the highest excess pools, blue grama, orchardgrass and birdsfoot trefoil, are each from different functional groups. White clover, which had the lowest uptake, is shallow-rooted, so it does not appear that shallow-rooted plants took up more labeled N than other plants. Since the species differed sufficiently and consistently enough for the means to separate statistically, this appears to be a real effect, but may be due to a combination of plant nitrogen status, shoot DM production, root morphology, and uptake ability that is not directly correlated with either herbage DM or RSA.

Figure 27 shows the excess pool value of $^{15}$N found in each of the mixtures in the second experiment. There were no statistical differences among any of the mixtures (p = 0.1957). An experiment by Minns et al. (2001) demonstrated that, given more nitrogen, mixed plant communities tended to hold a constant percentage of nitrogen in the vegetation, but produced more biomass. As there were no significant differences among the dry weights of our mixtures, different levels of $^{15}$N between mixtures would not be expected; N uptake by mixtures benefits from the diversity of root morphologies to scavenge effectively from the soil N pool.
Another cause of the lack of results seen within mixtures that contained different numbers of species and different types of legumes could be that our mixtures were only grown for one season. In a study of N transfer in mixed pastures by Ledgard (1991), most of the differences occurred more than 4 months after the experiment had begun, and the highest percentages of N transfer occurred at the end of the study, after the roots and nodules of legumes had time to decompose. Boller and Nosberger (1987) studied clover N transfer and found that annual yields of N derived from symbiosis went from 21-227 kg ha\(^{-1}\) in the first year to 165 to 373 kg ha\(^{-1}\) in the second year. The transfer of N increased with time, suggesting that decomposition was the main contributor to N transfer.
CONCLUSIONS

The two objectives of this project were (1) to screen a number of species of forage plants with representatives from four functional groups (perennial legumes, warm- and cool-season grasses, and non-leguminous forbs), for development of productive perennial mixtures for irrigated pastures with improved water and nitrogen utilization and (2) to test selected mixtures determine if water use efficiency might be higher in mixtures relative to individual species, and compare nitrogen uptake of species with complex and simple mixtures. We believe there are great advantages to mixed pastures and found that both small burnet and big bluestem had the potential to improve pasture production and water- and nitrogen uptake while increasing functional group diversity. Small burnet is recommended especially where there is a concern about nitrate leaching out of the root zone.

The two objectives of this project were (1) to screen a number of species of forage plants, from each of four functional groups (perennial legumes, warm and cool-season grasses, and non-leguminous forbs) as potential components of productive mixtures for irrigated pastures with improved water and nitrogen utilization and (2) to test mixtures composed of species identified by this screening to determine if water use efficiency was improved and nitrogen uptake was increased in complex relative to simple mixtures.

Three legumes were used in the study: birdsfoot trefoil, a falcata-type alfalfa, and white clover. When species were compared, birdsfoot trefoil was more productive at the first harvest, but this did not appear to benefit mixtures containing birdsfoot trefoil. In contrast, white clover productivity increased over time and white clover mixtures were more productive than birdsfoot trefoil mixtures, particularly at the final (fifth) harvest.
The falcata-type alfalfa was used because it has a deep spreading crown that is more resistant to grazing than sativa-type alfalfas. Its performance was very similar to birdsfoot trefoil, so birdsfoot trefoil was used in mixtures because it is not bloat-causing.

The advantage of adding a warm-season grass functional group to irrigated pastures includes a shift of herbage DM production to later in the season, away from spring when cool-season grasses are reproductive and produce excessive dry matter. The warm-season grasses are very deep-rooted (Moser and Vogel, 1995; Voight and Sharp, 1995), and could capture nitrates within the root zone to reduce leaching from the system. Two warm-season grasses were used in this study, big bluestem and blue grama. Big bluestem consistently produced more DM than other species at all harvests when species were grown in monoculture. Despite its outstanding performance in the first experiment it was not used in the second experiment due to its susceptibility to white-fly in the greenhouse. Big bluestem and blue grama both had lower RSA in the upper root zone than the two cool-season grasses, but big bluestem had comparable RSA to the cool-season grasses in the lower root zone. Blue grama had much less RSA deep in the root zone than big bluestem, being comparable to the tap-rooted legumes, but was as productive as the cool-season grasses.

Blue grama had the highest $^{15}$N atom % excess pool of all the species. In pastures this nitrogen uptake ability could protect against leaching near urine spots, still making the N available through later grazing. At the destructive harvest at the end of the second experiment, in many of the pots that contained all four functional groups, blue grama was suffering visually and seemed to be struggling, especially in the pots that contained small burnet. This suggests that blue grama is not well-suited to competition in resource-rich
environments and may perform better in monocultures than mixtures. Further research should be done with blue grama to determine if it has a niche in irrigated pastures, since it is so productive.

Two cool-season grasses were included in the study, orchardgrass and tall fescue, and orchardgrass was used as the cool-season grass component of mixtures. Dry-matter production of both cool-season grasses was comparable to the legumes and less than big bluestem, and RSA of both was high, especially in the upper soil profile. This was also reflected for both species in the moisture sensor data. The higher enrichment of orchardgrass compared to tall fescue may simply reflect the higher RSA and greater water uptake of this species (Sleper and Buckner, 1995; Jensen et al., 2001).

Lewis flax was one of the poorest producers of dry matter in the first experiment. Lewis flax has a history of being very hardy and competitive on dryland sites (USDA, 2007b), but it was relatively slow to recover from clipping. Small burnet produced more shoot dry matter than lewis flax in the first experiment and it was consequently chosen as a mixture component in the second experiment. While small burnet had a low RSA, it extracted more water from the middle and lower sections of the root zone than other species. Small burnet is a non-leguminous forb that showed potential for mixed pastures, where there is a concern about nitrate leaching out of the root zone.

The only difference in dry matter production among mixtures was in the last harvest, where the WC-4SPP mixture yielded more shoot dry matter than BFT-3SPP or BFT-2SPP. However, the RSA of this mixture was numerically the lowest, suggesting the root, rhizobium, and N turnover benefits a complex mixture more than a simple one (Ta and Feris, 1987). It was found that that species grown in mixtures produced more shallow
roots than predicted from the average of the RSA of the same species grown in monoculture. It has been found in other studies that soil nitrogen was utilized more completely when there was a greater diversity of species, leading to lower leaching loss of nitrogen (Tilman, 1996; Minns et al., 2001). In the Minns et al. study (2001), communities with four or fewer species were deemed to be “leaky” while communities composed of eight or more species were much more impermeable. Overall they found a negative correlation between root biomass and leaching—underlying the importance of well developed root systems which, our study has also shown, are produced when plants are grown as mixtures.
LITERATURE CITED


United States Department of Agriculture. 2007a. 2007 Utah Agriculture Statistics and Utah Department of Agriculture and Food Annual Report.


APPENDICES
Table 1. Statistical differences in herbage DM production among species within each harvest in Experiment 1 (see Fig. 2).

<table>
<thead>
<tr>
<th>Species</th>
<th>Harvest 1</th>
<th>Harvest 2</th>
<th>Harvest 3</th>
<th>Harvest 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>3.23(^b)</td>
<td>5.20(^{cd})</td>
<td>4.43(^{ab})</td>
<td>1.31(^{bcd})</td>
</tr>
<tr>
<td>Big bluestem</td>
<td>11.38(^a)</td>
<td>14.07(^a)</td>
<td>9.10(^a)</td>
<td>5.00(^a)</td>
</tr>
<tr>
<td>Birdsfoot trefoil</td>
<td>5.13(^b)</td>
<td>6.62(^{bcd})</td>
<td>6.07(^{ab})</td>
<td>1.09(^{cd})</td>
</tr>
<tr>
<td>Blue grama</td>
<td>7.90(^{ab})</td>
<td>8.64(^{bc})</td>
<td>7.42(^{ab})</td>
<td>3.60(^{abc})</td>
</tr>
<tr>
<td>Lewis flax</td>
<td>4.66(^b)</td>
<td>2.46(^d)</td>
<td>2.69(^b)</td>
<td></td>
</tr>
<tr>
<td>Orchardgrass</td>
<td>3.45(^b)</td>
<td>7.11(^{bcd})</td>
<td>7.14(^{ab})</td>
<td>4.09(^{ab})</td>
</tr>
<tr>
<td>Small burnet</td>
<td>5.30(^b)</td>
<td>11.44(^{ab})</td>
<td>6.56(^{ab})</td>
<td>3.96(^{ab})</td>
</tr>
<tr>
<td>Tall fescue</td>
<td>5.12(^b)</td>
<td>5.60(^{cd})</td>
<td>5.68(^{ab})</td>
<td>0.97(^{cd})</td>
</tr>
<tr>
<td>White clover</td>
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<td>5.37(^{cd})</td>
<td>7.14(^{ab})</td>
<td>4.82(^a)</td>
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Means within columns with unlike superscripts differ (P ≤ 0.05).
Table 2. Statistical differences in herbage DM production among harvests within each species in Experiment 1 (see Fig.4).

<table>
<thead>
<tr>
<th>Harvest</th>
<th>Species</th>
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<tr>
<td></td>
<td>Alfalfa</td>
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<td>5.19&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.43&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>14.07&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.10&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>6.62&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.07&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>8.64&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.42&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.60&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>2.46&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.69&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>7.14&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.09&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>4.82&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.670</td>
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Means within rows with unlike superscripts differ (P≤0.05).
Table 3. Statistical differences in herbage DM production among mixtures within each harvest in Experiment 2 (see Fig. 6).

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<th>4</th>
<th>5</th>
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<td>BFT-2 Spp</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>3.11&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>10.87&lt;sup&gt;ab&lt;/sup&gt;</td>
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</tr>
<tr>
<td>BFT-4 Spp</td>
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<td>4.05&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.26&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.88&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.54&lt;sup&gt;b&lt;/sup&gt;</td>
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</tr>
<tr>
<td>WC-2 Spp</td>
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<td>3.57&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.19&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.92&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.14&lt;sup&gt;b&lt;/sup&gt;</td>
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</tr>
<tr>
<td>WC-4 Spp</td>
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<td>3.05&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.38&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.33&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.08&lt;sup&gt;ab&lt;/sup&gt;</td>
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Means within columns with unlike superscripts differ (P≤0.05).
Table 4. Statistical differences in herbage DM production among harvests within each mixture in Experiment 2 (see fig. 8).

<table>
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<tr>
<th>Mixture</th>
<th>Harvest</th>
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<th>4</th>
<th>5</th>
<th>SE</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFT-2 Spp</td>
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<td>3.11&lt;sup&gt;b&lt;/sup&gt;</td>
<td>5.19&lt;sup&gt;b&lt;/sup&gt;</td>
<td>10.87&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>3.26&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>3.19&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4.92&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>6.14&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>2.38&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>4.34&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4.07&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>15.30&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.166</td>
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Means within rows with unlike superscripts differ (P≤0.05).
Table 5. Statistical differences in RSA among depths within species in Experiment 1 (see Fig. 11).

<table>
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<tr>
<th>Species</th>
<th>Depth 1</th>
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<th>Depth 5</th>
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<tr>
<td>Alfalfa</td>
<td>0.256</td>
<td>0.204</td>
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<td>0.166</td>
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<td>Big bluestem</td>
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<td>0.455</td>
<td>0.429</td>
<td>0.331</td>
<td>0.300</td>
<td>0.051</td>
<td>0.0016</td>
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<tr>
<td>Birdsfoot trefoil</td>
<td>0.238</td>
<td>0.241</td>
<td>0.224</td>
<td>0.192</td>
<td>0.145</td>
<td>0.087</td>
<td>0.5083</td>
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<tr>
<td>Blue grama</td>
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<td>0.355</td>
<td>0.256</td>
<td>0.163</td>
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<td>0.109</td>
<td>0.059</td>
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<td>0.541</td>
<td>0.382</td>
<td>0.221</td>
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<td>0.225</td>
<td>0.078</td>
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Means within rows with unlike superscripts differ (P ≤ 0.05).
6. Statistical differences in RSA among species with depths in Experiment 1 (see Fig. 13).

<table>
<thead>
<tr>
<th>Species</th>
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<tr>
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<td>0.541&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.184&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.166&lt;sup&gt;abc&lt;/sup&gt;</td>
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<tr>
<td>Big bluestem</td>
<td>0.439&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>0.455&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.474&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.331&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>0.300&lt;sup&gt;ab&lt;/sup&gt;</td>
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<tr>
<td>Birdsfoot trefoil</td>
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<td>0.224&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.238&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.192&lt;sup&gt;bc&lt;/sup&gt;</td>
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<td>0.256&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.162&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>0.440&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>0.389&lt;sup&gt;abc&lt;/sup&gt;</td>
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<tr>
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<td>0.291&lt;sup&gt;bcd&lt;/sup&gt;</td>
<td>0.321&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.173&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.237&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>0.250&lt;sup&gt;abc&lt;/sup&gt;</td>
</tr>
<tr>
<td>Tall fescue</td>
<td>0.481&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.472&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.474&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.413&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.319&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>White clover</td>
<td>0.347&lt;sup&gt;abcd&lt;/sup&gt;</td>
<td>0.296&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.270&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.226&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>0.225&lt;sup&gt;abc&lt;/sup&gt;</td>
</tr>
<tr>
<td>SE</td>
<td>0.085</td>
<td>0.092</td>
<td>0.082</td>
<td>0.086</td>
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<tr>
<td>p-value</td>
<td>0.0003</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>0.0010</td>
<td>0.0017</td>
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</table>

Means within columns with unlike superscripts differ (P≤0.05).
Table 7. Statistical differences in RSA among depths within mixtures in Experiment 2 (see Fig. 14).

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Depth</th>
<th>SE</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFT 2 SPP</td>
<td>1.376&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.132&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.707&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>BFT 3 SPP</td>
<td>1.403&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.176&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.681&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>BFT 4 SPP</td>
<td>1.258&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.018&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.575&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>WC 2 SPP</td>
<td>1.439&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.043&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.694&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>WC 4 SPP</td>
<td>1.192&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.802&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.5393&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Means within rows with unlike superscripts differ (p ≤ 0.05)
Table 8. Statistical differences in rsa among mixtures within depths in Experiment 2 (see Fig. 14).

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Depth 1</th>
<th>Depth 3</th>
<th>Depth 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFT 2 SPP</td>
<td>1.376&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.132&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.707&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>BFT 3 SPP</td>
<td>1.403&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.176&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.681&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>BFT 4 SPP</td>
<td>1.258&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.018&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.575&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>WC 2 SPP</td>
<td>1.439&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.043&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.694&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
Table 9. Statistical differences in Watermark reading for each species in Experiment 1.

<table>
<thead>
<tr>
<th>Species</th>
<th>Watermark Placement</th>
<th>10-20 cm</th>
<th>40-50 cm</th>
<th>70-80 cm</th>
<th>P</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td></td>
<td>28.13&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.82&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.07&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.183</td>
<td>8.15</td>
</tr>
<tr>
<td>Big Bluestem</td>
<td></td>
<td>32.72&lt;sup&gt;a&lt;/sup&gt;</td>
<td>12.04&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.27&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.115</td>
<td>8.25</td>
</tr>
<tr>
<td>Birdsfoot</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trefoil</td>
<td></td>
<td>33.47&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.50&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7.45&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.014</td>
<td>5.19</td>
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<tr>
<td>Blue Grama</td>
<td></td>
<td>35.06&lt;sup&gt;a&lt;/sup&gt;</td>
<td>14.86&lt;sup&gt;a&lt;/sup&gt;</td>
<td>13.59&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.060</td>
<td>5.93</td>
</tr>
<tr>
<td>Lewis Flax</td>
<td></td>
<td>27.36&lt;sup&gt;a&lt;/sup&gt;</td>
<td>13.14&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.64&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.127</td>
<td>6.28</td>
</tr>
<tr>
<td>Orchardgrass</td>
<td></td>
<td>27.86&lt;sup&gt;a&lt;/sup&gt;</td>
<td>16.64&lt;sup&gt;b&lt;/sup&gt;</td>
<td>15.79&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.027</td>
<td>2.48</td>
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<tr>
<td>Small Burnet</td>
<td></td>
<td>35.93&lt;sup&gt;a&lt;/sup&gt;</td>
<td>18.04&lt;sup&gt;a&lt;/sup&gt;</td>
<td>17.48&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.063</td>
<td>5.27</td>
</tr>
<tr>
<td>Tall Fescue</td>
<td></td>
<td>28.47&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.52&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.93&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.008</td>
<td>3.12</td>
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<tr>
<td>White Clover</td>
<td></td>
<td>29.98&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.11&lt;sup&gt;b&lt;/sup&gt;</td>
<td>10.89&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.040</td>
<td>4.74</td>
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</tbody>
</table>

Means within columns with unlike superscripts differ (P≤0.05).
Table 10. Statistical differences in Watermark reading at each depth in Experiment 1.

<table>
<thead>
<tr>
<th>Species</th>
<th>Watermark Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10-20 cm</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>28.13\textsuperscript{a}</td>
</tr>
<tr>
<td>Big Bluestem</td>
<td>32.73\textsuperscript{a}</td>
</tr>
<tr>
<td>Birdsfoot Trefoil</td>
<td>33.48\textsuperscript{a}</td>
</tr>
<tr>
<td>Blue Grama</td>
<td>35.07\textsuperscript{a}</td>
</tr>
<tr>
<td>Lewis Flax</td>
<td>37.36\textsuperscript{a}</td>
</tr>
<tr>
<td>Orchardgrass</td>
<td>27.84\textsuperscript{a}</td>
</tr>
<tr>
<td>Small Burnet</td>
<td>35.93\textsuperscript{a}</td>
</tr>
<tr>
<td>Tall Fescue</td>
<td>28.48\textsuperscript{a}</td>
</tr>
<tr>
<td>White Clover</td>
<td>29.98\textsuperscript{a}</td>
</tr>
<tr>
<td>P</td>
<td>0.673</td>
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<tr>
<td>SE</td>
<td>5.55</td>
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</tbody>
</table>

Means within columns with unlike superscripts differ (P≤0.05).
APPENDIX B. FIGURES

Figure 1. Mean herbage dry matter at each harvest in Experiment 1. Means for depths within species with unlike letters differ (P≤0.05).
Figure 2. Herbage dry matter for each species within each harvest of Experiment 1. For statistical differences among species at each harvest, see Table 1.
Figure 3. Mean herbage dry matter production by species for Experiment 1. Means for depths within species with unlike letters differ (P≤0.05).
Figure 4. Herbage dry matter for each harvest within species for Experiment 1. For statistical differences among harvests within each species, see Table 2.
Figure 5. Mean herbage dry matter at each harvest in Experiment 2. Means for depths within species with unlike letters differ (P≤0.05).
Figure 6. Herbage dry matter for each mixture within each harvest of Experiment 2. For statistical differences among mixtures within each harvest, see Table 3.
Figure 7. Mean herbage dry matter by mixture for Experiment 2. Means for depths within species with unlike letters differ (P≤0.05).
Figure 8. Herbage dry matter for each harvest within each mixture for Experiment 2. For statistical differences among harvests within each species, see Table 4.
Figure 9. Ratio of percentage of total herbage dry matter production in Experiment 2 to herbage dry matter production predicted by Experiment 1.
Figure 10. Mean root surface area (cm$^2$ per cm$^3$ of soil) of all species at each depth in Experiment 1. Means for depths within species with unlike letters differ (P≤0.05).
Figure 11. Root surface area (cm² per cm³ of soil) at each depth for each species in Experiment 1. For statistical differences among depths within each species, see Table 5.
Figure 12. Mean root surface area (cm² per cm³ of soil) of each species at all depths in Experiment 1. Means for depths within species with unlike letters differ (P ≤ 0.05).
Figure 13. Root surface area (cm$^2$ per cm$^3$ of soil) of individual species at each depth in Experiment 1. For statistical differences among species within each depth, see Table 6.
Figure 14. Root surface area (cm$^2$ per cm$^3$ of soil) at an upper, middle and lower depth for each mixture in Experiment 2. For statistical differences among depths within each mixture, see Table 7. For statistical differences among mixtures within each depth, see Table 8.
Figure 15. Ratio of percentage root surface area in Experiment 2 with values of mixture components predicted from Experiment 1 at each depth.
Figure 16. Watermark data for alfalfa. Units are negative kPa.
Figure 17. Watermark data for big bluestem. Units are negative kPa.
Figure 18. Watermark data for blue grama. Units are negative kPa.
Figure 19. Watermark data for birdsfoot trefoil. Units are negative kPa.
Figure 20. Watermark data for lewis flax. Units are in negative kPa.
Figure 21. Watermark data for orchardgrass. Units are in negative kPa.
Figure 22. Watermark data for small burnet. Units are in negative kPa.
Figure 23. Watermark data for tall fescue. Units are in negative kPa.
Figure 24. Watermark data for white clover. Units are negative kPa.
Figure 25. Mean Watermark sensor data from three depths of all species. Means for depths within species with unlike letters differ ($P \leq 0.05$).
Figure 26. Percentage $^{15}$N excess over background of the species used in Experiment 1. Means for depths within species with unlike letters differ ($P \leq 0.05$).
Figure 27. Percentage $^{15}\text{N}$ excess over background of the mixtures used in Experiment 2. Means for depths within species with unlike letters differ ($P \leq 0.05$).