PROJECT C: PLANT, SOIL, AND WATER INTERACTIONS

EFFECTS OF ALTERNATIVE AGRICULTURE IN WESTERN NEVADA ON PLANT, SOIL, AND WATER INTERACTIONS

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Once Upon A Time In The Arid West -- *there was a beautiful sub-alpine watershed whose pristine water was unparalleled throughout the land. From the sub-alpine tributaries to its lake terminus in the arid desert, the system was rich with plants, wildlife, and Native American heritage – and all was well.*

New visitors to the west also marveled at the abundance of water resource and envisioned many potential uses such as rangeland improvement, Municipal & Industrial, recreation, and agricultural based homesteads. But there was enough for everyone – and all was well.

It was soon apparent, however, that the once abundant resource was being rapidly depleted. It became necessary to consider water reallocation; both socially and environmentally. But who was to choose, and how? How is just compensation to the once indigenous users, or to those once encouraged to homestead and from whom the water must now be reallocated to be determined?

– and all is not well in the west.

INTRODUCTION

Alfalfa (*Medicago sativa* L.) has played a crucial role in the development of western agriculture and was once the most widely produced forage in the Great Basin area of the western US (Jensen et al. 1988). It is a perennial forage crop typically produced in regions characterized by hot dry summers and cold winters, and in arid regions such as northwestern Nevada optimum production can only be achieved through irrigation (Teare and Peet, 1983). Unfortunately, the varied demand for limited surface water often exceeds resource availability, thus forcing decisions for prioritized reallocations of water use. This, coupled with record high prices in 2007-2008 followed by record lows in 2008-2009 has highlighted the economic and environmental vulnerability of the alfalfa hay production model for sustainable agriculture (Putnam, 2009).

The state of Nevada experienced a 48 percent increase of irrigated lands at the start of the 20th century from 504,168 acres to a reported 746,653 acres in the 2002 agricultural census (Knight, 1918; USDA, 2004). By the early 1990s, more than 80 percent of water withdrawal in the state of Nevada was for agricultural use (NDWR, 1992). Between 1980 and 1990, however, Nevada also experienced a greater than 90 percent increase in the demand for public water consumption as a result of increased urban population (NDWR, 1992). At the same time environmental awareness identified new concerns pertinent to declining wetlands, endangered species and terminal lakes as a result of diminished water supply.

As a major water consumer, the search for salvageable water commonly focuses on irrigated agriculture. This scrutiny is based partly upon conveyance efficiencies, but to a large degree on a perceived crop water requirement (often used interchangeably with crop consumptive use) – i.e., the depth of water needed to meet the water loss through crop evapotranspiration (ET_{crop}) of a disease free crop, growing in large fields under non-restricting conditions including soil, water and fertility, and achieving full production potential under the given circumstances (Doorenbos and Kassam, 1979).

Over 50 years of research effort has been devoted towards delineating the crop water requirement for alfalfa production in northern Nevada. Much of this effort has become “blurred” or even lost over time, but the impending impact of water reallocation has stimulated renewed interest among the agricultural sector, not only in terms of alfalfa production but also with respect to alternative agriculture (e.g., biofuel crops and the production of low water use crops which currently are not being cultivated) and the restoration of abandoned agricultural lands. Of parallel concern is the response of existing ecosystems to future changes in water availability, allocation, and management. About 50,000 acres in Lyon County are currently devoted to irrigated alfalfa production (personal communication; Nevada Cooperative Extension, Yerington, NV. Conversion to alternative agriculture could have a significant effect on water resources, the local economies, and ecosystem stability.

The overall objective of this study is to determine likely responses by soils and vegetation to changes in water application and consumptive use, water table depth, and soil salinity in three key landscape circumstances: 1) currently irrigated and peripheral lands that may undergo lowering of water tables due to reduced irrigation; 2) the Walker River riparian zone that presumably would undergo an increase in water table levels and a change in the net direction of water movement with increased in-stream flows during the irrigation season; and 3) the Walker River delta which currently suffers from soil salinization and infestation from invasive species. This objective will be accomplished through the measurement of important soil characteristics and parameters, such as soil moisture depletion and evapotranspiration, susceptibility to wind erosion, salinization, nutrient fluxes, temperature, and organic matter content, as they relate to water treatment and vegetative cover.

Early Investigations of Water Requirements for Alfalfa Production in Northern Nevada

Central to the alternative agriculture issue is the actual amount of water needed to produce a given crop at a profitable yield level. Unfortunately, crops are often watered based on conveyance operation rather than actual watering needs (Neufeld and Davison, 1998). In the case of alfalfa, Houston (1950) initially applied an early version of the Blaney-Criddle (1952) model of ET estimation in northwestern Nevada and reported an estimated crop water requirement of about 22 inches (56 cm) over a 127-day growth period. Later, using both field measurement and tank lysimeter studies for water balance control, Houston (1955) reported a three-year seasonal average consumptive use of approximately 34 inches (86.4 cm) over the more traditional 180 to 190 day growing season with corresponding yields of 6-7 T/A (13.4-15.7 Mg ha^{-1}).

McCormick and Myers (1958) subsequently conducted field trials at the University of Nevada, Reno, Newlands Agricultural Field Station, to evaluate the water requirements for forage crop production in the Newlands Project. They reported that a water application of 38.7 inches (98.3 cm) resulted in the production of 9.5 T/A (21.3 Mg ha^{-1}) alfalfa (~12% moisture content) the first year following establishment; typically the highest harvest year. The amount of applied water was determined from Parshal flume measurements, but it was unclear as to whether the yields were derived from small or large scale harvests methods (Hill *et al.* 1983 has reported an estimated 20% lower yield may be expected under field harvest conditions). Tovey (1963) next studied weekly consumptive use and alfalfa yields on differing soil types, under different irrigation regimes, and with different levels of static water table over the period 1959 to 1961. Estimates of consumptive use ranged from 31.2 to 42.0 inches (79.2 to 106.7 cm) per season according to treatment. The corresponding yields ranged from 6.2 to 8.9 tons per acre (13.9 to 19.9 Mg ha^{-1}); higher production required more water. In a follow-up to his original publication (McCormick and Myers, 1958), McCormick (1966) subsequently proposed a series of management guidelines for deep-rooted alfalfa wherein he suggested that higher yields could be obtained by reducing the impacts of a fluctuating water table and promoting deeper rooting through less irrigation. By reducing the number of irrigations from 7 per season to only 4 (1 per cutting), McCormick (1966) reported he had obtained the highest yields in over 8 years of study at the Newlands location. Unfortunately, no actual data on per harvest or seasonal yield, crop consumptive use, or actual water application per irrigation was provided in the publication.

This information became paramount at a critical juncture in time. The Federal government in 1967 (US Dept. of Interior, 1967) developed an operating criteria and procedures (OCAP) for the Newlands Project in response to the impacts of irrigated agriculture water diversions on Pyramid Lake and other adjacent and downstream wetland ecosystems (numerous OCAP revisions were subsequently developed over the next 30 years). OCAP was developed to increase the use of water from the Carson River and minimize the use of water from the Truckee River while still satisfying Newlands Project water rights. Central to the 1988 revised OCAP was the stipulation of an applied water requirement for alfalfa production of 28.3 inches (71.9 cm). It is unclear as to how the Department of Interior arrived at this specific value, however, application of the early Blaney-Criddle model of estimation (Blaney and Criddle, 1952), the findings of Houston (1950, 1955) suggesting a consumptive use of 22.0 to 34.0 inches (ave. 28.0 inches) (56 to 86.4 cm), and the suggestion by McCormick (1966) that alfalfa yields could be maintained by reducing the applied water of 38.7 to 42.0 inches (98.3 to 106.7 cm) (McCormick and Meyer,1955; Tovey, 1963 and 1969, respectively) by approximately three-sevenths (i.e., 4 irrigations instead of 7), were clearly contributing factors.

Numerous quantitative studies over the next 30 years reported a much higher crop water requirement for alfalfa production in northwestern Nevada and the Newlands Project. Guitjens and Mahannah (1973, 1974, 1975) investigated water management by considering climatological data, changes in soil moisture, and applied water at the University of Nevada Newlands Agricultural Experiment Station, Fallon, NV. Using a neutron probe for soil moisture measurement, the average annual crop water use for alfalfa was estimated to be 42.8 inches (108.7 cm) in 1971 and 49.9 inches (126.7 cm) in 1972. Corresponding field yields were 5.36 and 5.38 T/A (12.0 and 12.1 Mg ha^{-1}), respectively. In August of 1972, three non-weighing lysimeters (A, B, and C) 10 ft (3 m) in diameter by 8 ft (2.4 m) deep were installed at the same location flush with the ground surface, backfilled with the excavated soil, and seeded to alfalfa. The purpose of the lysimeter tanks was to quantify essential elements of the water balance equation so that an exact solution for consumptive use could be determined. These lysimeters along with the surrounding fields served as a research tool for six consecutive studies over the next decade (Nevada Cooperative Extension, 1987) by Greil (1974), Tuteur (1976), Neyshabouri (1976), Wilcox (1978), Staubitz (1978) and Rashedi (1983). In each study, lysimeters were hand-harvested rather than windrowed and yields must therefore be considered approximately 20% higher than would normally be obtained from field harvests (Hill *et al.*, 1983).

Greil (1974) measured the overwinter consumptive use of alfalfa during the first year of establishment (late Sep 1972 through mid-May 1973). Consumptive use ranged from 9.5 to 14.0 inches (24.0 to 35.6 cm). The pertinence of this contribution was that it clearly demonstrated water use during winter months, contrary to the presumption that crop consumptive use occurred only during the traditionally defined growing season from May 20 to September 24. Tuteur (1976) used the three non-weighing lysimeters to measure annual consumptive use and reported a total of 38.9 inches (98.8 cm) in 1973 and 59.3 inches (150.6 cm) in 1974. Lysimeters A, B and C yielded 5.36, 6.56, and 5.98 T/A (12% moisture content) (12.0, 14.7, and 13.4 Mg ha^{-1}), respectively, in 1973 and 10.05, 7.67, and 9.44 T/A (23.5, 17.1, and 21.1 Mg ha^{-1}) in 1974.

Neyshabouri (1976) continued the study through 1975 and reported the annual crop water requirement to be 49.5, 45.4, and 48.0 inches (125.7, 115.3, and 121.9 cm) for lysimeters A, B, and C, respectively. Corresponding yields were 9.60, 9.80, and 10.30 T/A (21.5, 22.0, and 23.1 Mg ha^{-1}). Wilcox (1978) continued the overall study, but manipulated water applications for purposes of deficit irrigation. The reported annual water application for lysimeters A, B, and C was 24.50, 61.25, and 36.50 inches (62.2, 155.6, and 92.7 cm), respectively, with a corresponding measured consumptive use of 36.00, 42.13, and 41.85 inches (91.4, 107.0, and 106.3 cm) and yields of 5.33, 5.93, and 6.26 T/A (11.9, 13.3, and 14.0 Mg ha^{-1}). Staubitz (1978) took an alternative approach to deficit irrigation. Equal amounts of water were applied to each lysimeter up to a specified total. From then on lysimeters were irrigated differentially for purposes of drought simulation. Precipitation over the study period was 6.62 inches (16.8 cm). Total applied water for the 3 lysimeters was 24.0, 55.5, and 33.65 inches (61.0, 141.0, and 85.5 cm), respectively, with corresponding yields of 6.82, 9.9, and 8.66 T/A (15.3, 22.2, and 19.4 Mg ha^{-1}). Measured consumptive use was 30.38, 45.96, and 40.63 inches (77.2, 116.7, and 103.2 cm**)**, respectively. Low, medium, and high irrigation applications corresponded to low, medium and high yields and consumptive use.

Using the same database, Rashedi (1983) sought to develop site-specific crop coefficients for estimating crop evapotranspiration using the Food and Agriculture Organization of the United Nations (FAO) modified Class A Evaporation Pan method and the subsequent scheduling of irrigation (Doorenbos and Pruitt, 1977) where

$$ET_{crop} = (((E_{pan} + P) * K_{pan}) * K_{crop}) * I_{eff} \qquad (1)$$

and E_{pan} is the pan evaporation, P is precipitation, K_{pan} is the pan factor or a coefficient describing local effects on pan evaporation (*i.e.* wind and humidity), K_{crop} is the plant factor or a coefficient describing the effect of plant growth stage on water usage, I_{eff} is the irrigation system efficiency, and ET_{crop} is the evapotranspiration of the crop or water lost through plant uptake that needs to be replaced. Data were taken from the highest yielding lysimeter during the 1974, 1975, 1977, 1978, 1981, and 1982 irrigation seasons. Crop coefficients ranged from 0.31-0.42 and 1.22-1.25, respectively, for the first and last five weeks of a twelve-week seasonal study period. The seasonal model, a second order polynomial, predicted an average crop coefficient of 1.16 over the entire irrigation season. From this study, Rashedi (1983) concluded that the main reason for lower annual yields was the lack of sufficient water for meeting consumptive use demands. Guitjens et al. (1983) also applied the long-term database to assess yield and water use efficiency, and determined that annual and per cutting yields were statistically proportional to crop evapotranspiration, whereas annual water use efficiency was not (Mahannah et al., 1987; Guitjens and Jensen, 1988).

There are a variety of additional models for the estimation of crop water requirements in *lieu* of actual measurement (Stewart and Hagan, 1969; Grimes *et al*., 1969; Hanks *et al*., 1969; Shipley and Regier, 1975; Stewart *et al*., 1975; Doorenbos and Pruitt, 1977; Doorenbos and Kassam,1979; Sammis, 1981; Guitjens, 1982; Wright, 1982; Martin *et al*., 1984; Kagele, 1985). Pennington (1980) published a report on the evaluation of several empirical methods (Doorenbos and Kassam, 1977; Doorenbos and Pruitt, 1978) for selected sites in Nevada, including the

Newlands Project. Compared to reported measured crop evapotranspiration, the standard FAO methods over-estimated consumptive use by an average of 32%, whereas the modified FAO methods over-estimated by an average of only 13%. He concluded that with the inclusion of locally derived crop coefficients, the modified FAO methods could provide a more precise estimation of consumptive use for western Nevada (Pennington, 1980). Ten methods used for determining consumptive use were also compared throughout the western U.S. in cooperation with the Bureau of Reclamation (Hill et al., 1983): the USDA Modified Blaney-Criddle, FAO Modified Blaney-Criddle, Jensen-Haise, FAO Radiation, Hargreaves, Modified Penman, FAO Modified Penman, Class-A Evaporation Pan, and the FAO Evaporation Pan. Findings confirmed that no model of estimation was best for all sites, and that there was a great need for local calibration. From the various methods studied, seasonal estimates of consumptive use for alfalfa in the Newlands Project from the years 1973 to 1978 varied from a low of 31.56 inches (80.2 cm) to a high of 45.3 inches (115.1 cm) as determined by the various methods of estimation studied.

Nagging questions remained, however, particularly with respect to the contribution of shallow water table to the crop water requirement. Marston (1989) compared alfalfa yield and water table depths on data from designated bottomlands over the period 1982 through 1984. She performed an analysis of variance and a significant difference test among irrigation border means (three windrows east, middle, and west) and found shallow groundwater (approximately 3 to 5 ft (0.9 to 1.5 m) to water table) to have no significant influence on sustaining yield in the absence of irrigation. Marston (1989) thus reported a significant correlation between alfalfa yield and irrigation but no significant correlation between yield and water table depth. In other words, when stressed through deficit irrigation, alfalfa did not utilize enough shallow groundwater to meet the crop water requirement necessary to sustain yields.

A subsequent study reported similar findings (Auckly and Guitjens, 1995). This study consisted of three separate irrigation regimes during the growing season; irrigation over the first two growth cycles (i.e., harvests), the first three growth cycles, and irrigation over all four-growth cycles. The corresponding depth to water table was also measured for each irrigation regime. Yield was found dependent on the frequency of irrigation but not on the resulting water table depth, which ranged from 4.33 to 5.05 ft (1.3 to 1.5 m) over the season. Furthermore, non-irrigation of an adjacent area resulted in an 80% yield reduction.

In a collaborative project the effects of irrigation regime on alfalfa yield were studied on sprinkler-irrigated benchland wherein there were no confounding effects from a shallow or fluctuating water table (Jensen et al., 1988; Kimbell et al. 1990). Irrigation treatments were again based on the crop water (or consumptive use) requirement as estimated from the FAO modified Pan Evaporation model (Doorenbos and Pruitt, 1977). The study consisted of both small plot (6 cultivars) and field scale (single variety) components. Treatment variables consisted of 50%, 75%, 100%, and 125% (I-IV, respectively) of the estimated crop water requirement. Irrigation applied water was determined from:

$$IAW = \frac{(ET_{crop} - ppt)(TV)}{Application\_Efficiency} \tag{2}$$

and

$$TAW = IAW + ppt \tag{3}$$

where IAW is the irrigation applied water, ppt is the effective rainfall precipitation, application efficiency is 0.75 , TV is the treatment variable, ET_{crop} is the estimated crop water requirement, and TAW is the total applied water. The total amount of water applied for treatments I-IV the first year following establishment (1984) was 29.5, 46.9, 61.0, 73.1 inches (74.9, 119.1, 154.9, and 185.7 cm), respectively. Precipitation was 5 inches (12.7 cm). The highest measured yields were characteristically obtained when irrigating at 100% of the estimated crop water requirement (i.e., 61 inches of total applied water). The total application of 29.5 inches (74.9 cm), similar to the 28.3 inches (71.9 cm) stipulated in the 1988 revised OCAP (US Dept. of Interior, 1994), resulted in a yield only slightly greater than 3 T/A (6.7 Mg ha^{-1}). Conversely, the production function projected yields of 5.9 to 7.6 T/A (13.2 to 17.0 Mg ha^{-1}) for irrigation at the decreed water supply of 4.5 AF/A (1.4 ha-m ha^{-1}) (Nevada Cooperative Extension, 1987).

A related component of the study considered the effects of the same four irrigation treatments on dry matter yield, applied water use efficiency (AWUE), and forage quality as determined from crude protein, acid detergent fiber, and total digestible nutrient content. The highest yields over a 2 yr period (1984-85) were found when irrigating at 100% (treatment III), and the best AWUE was found when irrigating on the basis of 75% of the estimated crop water requirement (treatment II). The amount of irrigation applied water (i.e., exclusive of rainfall precipitation) for treatments II and III was 39 inches and 51 inches (99.1 and 129.5 cm), respectively, with yields ranging from 7.7 to 8.8 T/A (17.2 to 19.7 Mg ha^{-1}). Interestingly, the highest forage quality was obtained when applied water was based on 50% of the estimated crop water requirement (Jensen et al. 1988). Although the overall forage quality was higher, the total digestible nutrient content and yields were so low that this did not represent an efficient use relative to dry matter yield per unit of applied water (Jensen et al. 1988).

Kimbell et al. (1990) in a summary paper (1984-1986), demonstrated a significant yield difference between water treatments I and II, and II and III, but not between III and IV. Consistent with the findings of Hill et al. (1983), field yields were 15 to 20% lower than those from the small plot harvested cultivars. Polynomial applied water production functions were developed and data over the 3 yr study period projected that an average yield of 7.6 T/A (17.0 Mg ha^{-1}) dictated a corresponding consumptive use of 46.0 inches (116.8 cm) which, in turn, required an average of 57.6 inches (146.3 cm) of applied irrigation water. Lower water applications clearly reduced yields. Reported alfalfa production in northern Nevada currently ranges from 4.5 to 7 T/A for 3 or 4 cuts, respectively (Curtis et al., 2005[a]; Curtis et al., 2005[b]; Breazeale and Curtis, 2006).

Another component the study focused on estimation of individual harvest as well as seasonal water use production functions. Long-term yields were projected to increase with increasing irrigation treatments I through III, but decrease for treatment IV. For individual harvests, the production function indicated that it would take an additional 12.11 inches (30.8 cm) of applied water to produce an additional ton of alfalfa for the first harvest, 30.25 inches (76.8 cm) for the second, 21.99 inches (55.9 cm) for the third, and only 8.33 inches (21.2 cm) of applied water for the fourth harvest. The findings clearly showed that water use efficiency changes throughout the growing season and that irrigation models must consider the use of locally derived production relationships for appropriate water allocations in accordance with profit maximization (Myer et al., 1991; and Myer et al., 1993). In water short years, it may be necessary to terminate irrigation at some point during the growing season. Whether water is reduced throughout the irrigation season or deficit irrigation is used and water is applied at normal rates until it runs out, yields are typically reduced (Guitjens, 1993; Hanson et al., 2007). Since each successive cut produces reduced yields with reduced irrigation, deficit irrigation is the preferred method in that by fully watering the larger first and second harvests an alfalfa producer can better ensure the best possible yields (Nevada Cooperative Extension, 1987; Guitjens and Jensen, 1988) in water short years.

Although the sale of alfalfa and forage in general was at an all time high in 2008 (Putnam, 2009), it was extremely short lived. Furthermore, increasing costs of establishment, overhead, and energy costs coupled with diminished purchasing power may soon reduce profits making current agricultural production management much less lucrative than it is today (Curtis et al., 2005a,b; Breazeale and Curtis, 2006; Hellwinkel, 2008). This scenario along with increasing trends for water reallocation will ultimately dictate the need for alternative agriculture and, in response, cause changes in plant/soil/water interactions.

Promising Opportunities for Alternative Agriculture

Alternative Grains

There may be a unique opportunity to secure productivity in the future with alternative grains of growing popularity. These are crops that have been produced for centuries in the international community and are just now gaining interest and support in the United States. They are proven sources of excellent nutrition for both human and animal consumption, and typically grow well in water stressed environments. Potential new crops include Teff (*Erograstis tef* (Zuccagni) Trotter), Buckwheat (*Fagopyrum esculentum* Moench), Amaranth (*Amaranth cruentus* L.), and Pearl Millet (*Pennisetum glaucum* (L.) R.Br.).

Teff is a cereal crop of great popularity in Ethiopia. It is a summer crop that does very well with limited irrigation. In fact, excess water and fertilizer actually decreases grain quality and does not increase yield (Norberg et al., 2005). Best yields appear to be obtained at about 13 inches of received water. Teff is very nutritious, gluten free, and can be used for either human consumption or as cattle feed.

Buckwheat, originally from Asia, is a pseudo-cereal grown internationally, as well as within the United States, for human consumption. It is sensitive to drought conditions, but has many other redeeming qualities. It can be used as a second crop, improves soil tilth, and grows so vigorously that the necessity for weed control is minimal (Meyers, 2002a). Buckwheat can be produced on a wide range of soil textures and, although it is a heavy consumer of available phosphorous, can be grown on soils of moderate fertility. It can be productive in water limiting environments due to its short growing season, as it will generally reach maturity by the time irrigation supply has been depleted in water short years. Buckwheat also has the benefit of attracting and supporting large bee populations (Berglund, 2003; Meyers, 2002a).

Grain amaranth actually originated as an American Indian food source. It provides an excellent source of nutrition with high lysine and protein content and is slowly making a reintroduction as a food staple (Baltensperger et al., 1991, Putnam et al., 1989). Amaranth can be used for either human or cattle consumption. It is well adapted to drought conditions and therefore should do well in the high temperature, low water conditions of the arid west (Putnam et al., 1989; Sullivan, 2003; Weber, 1987). It also requires little to no fertilizer which makes it a good alternative for reducing overhead costs (Baltensperger et al., 1991). A major down side of Amaranth production today is the lack of approved herbicides for use, thereby requiring hand weeding until well established and the need for a killing frost in order for it to properly desiccate for harvest.

Pearl Millet is a cereal crop native to Africa and India that has been grown for forage in the United States for quite some time. It has recently been gaining recognition as a better nutritive source for feed animals due to its high lysine and protein contents. Pearl Millet can be used as feed for cattle, but is especially beneficial to poultry and possibly swine, and can also be marketed as wild bird seed (Andrews et al., 1996). It is tolerant of sandy, acidic, or infertile soils making it well suited for the Great Basin region (Andrews et al., 1996; Lee et al., 2004; Meyers, 2002b; Sedivec and Schatz, 1991).

Biomass Production

Climate change, increasing oil prices, and decreased oil supply all set the stage for the rising interest in biomass production as an alternative fuel source. Biofuels are a renewable, biodegradable alternative to gasoline. Substituting biofuels for one gallon of gasoline can save up to 20 lbs of carbon dioxide emissions into the atmosphere because the carbon dioxide released is recycled rather than mined in the form of fossil fuels (U.S. D.O.E., 2001). Biomass crops not only have the potential to be used as biofuel, but also as thermal energy and for bioderived plastics (Karp and Shield, 2008; Ragauskas, 2006). The use of "biocrops" rather than petroleum could ultimately reduce our dependence on foreign oil. In response, lawmakers have begun to set standards for future energy usage. For example, the Energy Independence Act of 2007 requires fuel producers to increase biofuel usage nearly five-fold by the year 2022. This act will help to guarantee the growth of biomass crops as an industry in the United States.

Current biofuel production in the United States is primarily limited to corn (*Zea mays* L.) ethanol. As of 2001, the ethanol industry employed 200,000 people and saved $2 billion a year in oil imports (U.S. D.O.E., 2001). While ethanol production can boost the economy and increase energy security, as it stands, there is great concern for its sustainability. Today's ethanol production relies primarily on corn which may not be finite, but is still a limited source. The United States currently uses 25% of corn produced domestically to produce enough ethanol to meet only 3% of liquid transportation fuel requirements (Orts et al., 2008). Further increases in corn for ethanol could result in a rivalry between fuel and food, as demand skyrockets past supply. There is also concern regarding the effects of increased corn production on the environment. As the public outcry for alternative fuel sources rages with soaring oil prices, acreages in corn production will rise also. There is evidence that increasing corn production would negatively affect water quality by increasing nitrogen and phosphorous loads (Simpson et al., 2008) from fertilization. Although ethanol production from the fermentation of corn is a start in the effort to resolve our current energy dependence, it may not be the ultimate solution.

Current ethanol production takes simple carbohydrates, such as sugar and starch, and through fermentation creates combustible fuel (Karp and Shield, 2008). However, about 70% of plant mass is in the form of complex carbohydrates such as cellulose and hemicellulose (Dale, 2008). The cost of transforming these complex carbohydrates into fuel is currently too high to be cost effective. The key to being able to process complex carbohydrates in an economically viable way is to develop a pretreatment technology that opens cell walls to enzymatic breakdown and to provide a variety of inexpensive enzymes (Dale, 2008; Ragauskas, 2006). This current limitation has created frenzy in the field of microbiology and new methods for inexpensively producing ethanol from cellulosic feedstock are hopefully on the near horizon. Given the potential for technological development, biofuels from cellulosic feedstocks is considered a viable alternative to current ethanol production processes.

The use of cellulosic feedstocks for biofuels would open the door to using a much wider variety of crops for fuel (Orts et al., 2008; Karp and Shield, 2008). The conversion of cellulose into energy allows for perennial grasses, which are high in complex carbohydrate content and have high yield potential, to be in production for biofuel applications. The production of perennial crops offers many benefits. For example, they have less of an impact on the environment than annual crops. Once a perennial grass stand is establish, there is no need to till soil until the stand needs to be replaced; erosion potential is reduced, they require much less fertilization than annuals, and because they have few natural pests there is a reduced need for pesticides (Karp and Shield, 2008; Lewandowski et al., 2003; U.S. D.O.E., 2001). Perennials also have the potential to produce much greater quantities of dry matter per unit land (Karp and Shield, 2008). Production of perennial crops offers a better return on energy input and also has a greater potential to reduce greenhouse gases per energy unit produced than annual crops such as corn (Orts et al., 2008, Karp and Shield, 2008; Lewandowski et al., 2003). Current ethanol usage reduces greenhouse gas emissions by about 18% percent as compared to gasoline, while cellulosic ethanol has the potential to reduce greenhouse gas emissions by approximately 88 percent (Farrell et al., 2006).

The new challenge for biomass production will be to increase yields of perennial crops to keep up with growing energy needs (Ragauskus et al., 2006). Much work has been performed to maximize yields for traditional feed crops such as corn, but perennial crops have been relative untouched. There also is a need to determine the difference in biomass quality of various crops which can only be accomplished by growing them at the same sites (Lewandoski et al., 2003). Different agricultural practices such as watering, fertilization, and time of harvest can have an enormous effect on the plant cellulose content as well as the quality of ash produced when burned. Furthermore, long-term productivity trials are required to assess crop sustainability and long-term effects on the environment (Lewandoski et al., 2003). Problems with sustainability are best addressed in advance of mass production. While a monoculture can sometimes be easier to manage, a mixture of grasses is sometimes preferred. Mixing grasses can reduce the risk of total crop failure due to disease or pest infestation, creates biodiversity, and will optimize biomass supply by offering harvested biomass at various times during the year thereby reducing storage needs (Lewandowski et al., 2003). Studies are needed to determine which combinations of grasses are best for production in the dry Nevada climate.

Switchgrass (*Panicum virgatum* L.) has taken the lead as the perennial grass with the most potential as a biomass crop. It is a warm-season, perennial sod-forming grass and, as a native grass, is less controversial (Karp and Shield, 2008; Lewandowski et al., 2003). It can be produced in every state in the union under a variety of soil and drainage conditions, including those conditions generally associated with marginally productive lands (Karp and Shield, 2008; Simpson et al., 2008; USDA, NRCS, 2008). Switchgrass is tolerant of moderately saline or acidic soils (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008), and can be farmed similar to traditional forage thus reducing the need for additional farm equipment (Lewandowski et al., 2003). It is somewhat drought resistant, but does best with 16 to 18 inches of water received (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008).

Other crops potentially suited for biomass production include sand bluestem (*Andropogon hallii* Hack.), Indiangrass (*Sorgastrum nutans* (L.) Nash), prairie sandreed

(*Calamovilfa longifolia* (Hook.) Scribn), bluestem (old world) (*Bothrichloa ischaemum* (L.) Keng), tall wheatgrass (*Elytrigia elongate* (Podp.) Z.-W. Liu & R.-C. Wang), Basin wildrye (*Leymus cinereus* (Scribn. & Merr.) A. Löve), Mammoth wildrye (*Leymus racemosus* (Lam.) Tzvelev), and tall fescue (*Festuca arundinacea* Schreb.).

Sand bluestem is a native, long-lived, perennial, warm-season bunch grass. It occurs primarily in the west with adaptations to sandy and sandy loam soils and drought conditions (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008). Sand bluestem requires a minimum of 10 inches of received water. This species has weak seedling vigor and competition must be held in check during establishment (USDA, NRCS, 2008). A close seed source or a variety specifically suited for the planned production area would be an asset.

Indiangrass is a native, perennial, warm-season grass. It does well on deep, well-drained floodplain soils, but can be grown on poorly to excessively well-drained soils, in acid to alkaline conditions, and on any soil texture from sand to clay (USDA, NRCS, 2008). Indiangrass is moderately drought tolerant and requires a minimum of 12 inches of water annually. If well maintained, Indiangrass will produce a self-regenerating stand that does not need reseeding (USDA, NRCS, 2008).

Prairie sandreed is a native, sod-forming, warm-season grass. It does well on sandy soils in low precipitation zones (USDA, NRCS, 2008). Prairie sandreed is drought tolerant and adapted to an annual precipitation of 10 to 20 inches (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008). It is not, however, very salt tolerant. Seedling vigor is moderate, but stands are slow to establish.

Old world bluestem is a non-native, warm-season clumpgrass. It is highly tolerant of over-grazing and drought, and can be produced on virtually any soil with the exception of those that are excessively sandy in character (Dalrymple, 2001; Ohlenbusch and Kilgore, 2008).

Tall wheatgrass is a non-native, cool-season bunchgrass. It is highly adapted to a wide range of soils and exhibits high tolerance to saline and sodic soils (Pawnee Buttes Seed Inc., 2004). It performs best with at least 16” of water yearly so is likely to require irrigation in Nevada (Smoliak et al., 1969). Washington State University is currently studying various cultivars of tall wheatgrass to determine which is best for biofuels production in their area (Stannard, 2008).

Basin wildrye is a native, cool-season, perennial bunchgrass (USDA, NRCS, 2008). Its seedlings are slow to develop, but once established are long-lived. Basin wildrye is adapted to a broad range of soil textures. It is somewhat tolerant of saline and sodic soils and very tolerant of drought (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008). The Trailhead variety can be established in areas with as low as 5 inches of rainfall.

Mammoth wildrye is a cool-season, sod-forming grass. It does well on sandy soils, is highly tolerant of drought and can be moderately tolerant of saline and saline-sodic soils (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008). It performs best with a precipitation range of 8 to 16 inches annually.

Tall fescue is a long-lived, cool-season bunchgrass. It can be invasive in some situations due to good seedling vigor, rapid germination, and tolerance of abuse and low fertility (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008). Tall fescue is well adapted to most conditions. It is moderately adapted to drought conditions and can survive at 16 inches of water per annum although does much better in the 30 to 60 inch range (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008).

Considerations for Site Restoration: Water, Vegetation, Dust Control

As profits recede and water rights are transferred, fields previously irrigated and farmed become subject to abandonment. These areas then become susceptible to wind erosion and weed infestation due to dry out and the die off of previously irrigated vegetation (Perkins et al., 2008). Wind erosion from abandoned cropland can generate sources of fugitive dust which can cause a variety of respiratory health problems, reduce visibility on roadways, add nutrients and sediments to waterways, and damage property (NDEP, 2008). Factors that affect the level of wind erosion include climate, soil erodibility, field length, ridge roughness, and vegetation (Ferguson et al., 1999).

Two very pertinent historic examples exist. The classic example in the United States is the Dust Bowl in western Kansas, Oklahoma, and Texas, which is well documented in the literature. Well-established native grasslands had developed over the eons in response to limited summer precipitation. Since anthropogenic interests were more along the lines of production agriculture, native grasslands were destroyed in Kansas, Oklahoma and Texas in favor of what is now termed dry-land agriculture. In other words, a land use was adopted that was not suited to the climatic (hydrologic) conditions. Native vegetation was altered (biosphere), crop water requirements exceeded water availability (hydrosphere), continuous cropping and fallow degraded soil quality (lithosphere), with nothing to hold the soil there was a severe wind erosion hazard, and air borne particulate transport (atmosphere and air quality) caused devastating property damage and social consequences. A more recent example is that in the Owen’s Valley and Owen’s Lake of southern California, wherein surface and ground water were exported to serve the needs of a growing population elsewhere. Water exportation in Owen’s Valley and from Owen’s Lake has resulted in the lowering of water tables, changes in vegetation, the drying of Owen’s Lake, declining soil quality, and major dust derived air pollution. The problem has become so severe, that putting water back onto the land has become a viable mitigation strategy.

Specific to Nevada, initial water right acquisitions by the USFWS within the Truckee Division of the Newlands Project in the area of Swingle Bench (near Fernley < 50 miles from the Walker Basin Project) have created additional sources of fugitive dust, in part, due to the predominantly coarse textured nature of soils common to the Swingle Bench area (e.g. Appian, Tipperary, Swingler Series)(US Department of Agriculture NRCS, 2001). At this location it appears to take between two to four years from the termination of irrigation for sites with perennial vegetation to degrade to a barren state that is highly susceptible to wind erosion. This effect is much more rapid for agricultural production areas. Preliminary studies have shown sites with undisturbed native vegetation to be only slightly erosive; however, previously irrigated sites exhibit the least stability following water removal and are more subject to desiccation, invasive and other weed species establishment, and wind erosion. It was reported that dry, non-vegetated abandoned lands could produce as much as 50 times greater dust volumes than adjacent agricultural lands and four times as much as the surrounding native desert on an annual basis (Capitol Reporters, 2004).

Between the 1997 and 2002 agricultural censuses, Lyon County experienced a 10% reduction in irrigated farmland (USDA, 2004). Without water, unless converted to other uses these fields will soon become vacant of sustainable vegetation. A management plan that requires re-establishment of native vegetation prior to the total transfer of existing water rights could potentially return many of these lands to their previous natural landscape; or some facsimile thereof. Native vegetative cover would help promote wildlife populations, reduce weed propagation and invasive species, as well as reduce the movement and ultimate loss of valuable soil resources. Potential vegetation for restoration activities include Indian ricegrass (*Achnatherum hymenoides* (Roem. & Schult) Barkworth), Basin wildrye (*Leymus cinereus* (Scribn. & Merr.) A. Löve), Beardless wheatgrass (*Pseudoroegneira spicata* (Pursh) A. Löve), Western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Löve), and Inland saltgrass (*Distichlis spicata* (L.) Greene).

Indian ricegrass is a native, cool-season bunchgrass that is widely distributed among the intermountain west. It prefers sandy coarse textured soils but can be found on a variety of soil textures (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008). Indian ricegrass is a good revegetation species due to its palatable nature, its drought tolerance, salinity tolerance, and pleasurable appearance. It is, however, slow to establish and short-lived. Indian ricegrass can be produced in deserts with 6 to 16 inches of water per annum (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008).

Basin wildrye is a native, cool-season, perennial bunchgrass (USDA, NRCS, 2008). Its seedlings are slow to establish, but are long-lived. Basin wildrye is adapted to a broad range of soil textures, is somewhat tolerant of saline and sodic soils and very drought tolerant (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008). The Trailhead variety can be established in areas with as low as 5 inches of rainfall per year.

Beardless wheatgrass is a native, perennial, cool-season bunchgrass. It is common to the western intermountain regions. Beardless wheatgrass is long-lived, drought tolerant, has good seedling vigor, and establishes quickly (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008). It is also well adapted to slope stabilization, and performs well on medium to coarse textured soils. Beardless wheatgrass can reportedly survive the 8 to 12 inch zone of the Great Basin (Pawnee Buttes Seed Inc.).

Western wheatgrass is a perennial, cool-season grass. It does well in medium to fine textured soils. Western wheatgrass can withstand poor drainage, drought, and saline and sodic soils (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008). It is slow to establish due to poor germination, but is low maintenance thereafter. Annual water requirements fall in the 10 to 20 inch range (Pawnee Buttes Seed Inc., 2004; USDA, NRCS, 2008). Western wheatgrass is also considered good feed for domestic animals and wildlife.

Inland saltgrass is a native, perennial, warm-season grass common to the dry west. It is recommended for revegetation in the arid west as it is a drought and salt tolerant plant (USDA, NRCS, 2008). It remains green when most other grasses have dried out from water stress and is resistant to over-grazing. It can be planted as seed, but it is more easily propagated by rhizomes and requires adequate irrigation during the establishment year (USDA, NRCS, 2008). Saltgrass can become invasive under some conditions.

Salinization of Arid Croplands

Irrigation of cropland can result in the addition of large amounts of soluble salts to the soil, especially in arid environments such as are found in Nevada. Water pumped from groundwater or from rivers is more likely to have been exposed to large amounts of easily weatherable minerals as well as having been exposed to dry air and high evaporation rates, both leading to a high concentration of soluble salts. As large amounts of water are applied to parched croplands, these salts are deposited within upper layers of the soil and may or may not be subject to further leaching. Over time these salts accumulate and eventually lead to salinity and/or sodicity problems within the soil profile.

Soil salinity/sodicity can be detrimental to plant health. High salt levels reduce the osmotic potential, thereby making it difficult for plants to remove water from the soil. This can reduce growth in established plants and make germination next to impossible. High levels of specific ions can also become toxic. Extremely high levels of sodium ions can reduce the uptake of other essential nutrients, and can result in a reduction in overall soil quality as soil colloids breakdown, further inhibiting the movement of air and water throughout the soil profile.

Use of Fiber Optic Temperature Sensing for Distributed Soil Moisture Monitoring

Measurement of soil moisture content is a critical component in the development of efficient irrigation strategies. Unfortunately, few methods exist to monitor, at the field scale, the moisture content of the rooting zone at high spatial and temporal frequencies. While many "point" sensors are commercially available to measure moisture content, these are generally costly and have measurements support volumes of only a few cubic centimeters of soil. Remote sensing of soil moisture, typically performed with active microwave (Radar) can only resolve soil moistures in the upper few millimeters of the soil profile and cannot penetrate into the active rooting zone. Recent developments in Raman Spectra temperature sensing (frequently called Distributed Temperature Sensing, or DTS) now allow for the nearly continuous in time and space, measurement of temperatures in both soil and water mediums (Selker et al., 2007; Moffet et al., 2008, Tyler et al., 2008). In soils, the thermal response of a soil to solar heating is strongly controlled by the soil moisture content and therefore the time evolution of temperature in a soil profile can be used to infer soil moisture content.

The sensing system consists of a laser source, and Raman Scatter detector at the head of the fiber optic cable. The optical laser pulse which propagates down the light pipe induces Raman Scattering, and this signal is propagated back to the detector. The position of the temperature reading is determined by measuring the arrival time of the returned scattered pulse, and the temperature at that location is determined by the intensity of the backscattered light. This system is somewhat analogous to radar and is commonly used in atmospheric applications as LIDAR. For soil moisture applications, a fiber optic cable can be buried beneath the soil at a specified depth and monitored. Assuming a one-dimensional transport of heat in the soil profile, the governing equation for soil heat transport can be written as (Jury and Horton, 2004):

$$\delta T \frac{\partial T}{\partial t} = K_T \frac{\partial^2 T}{\partial^2 z} \qquad (4)$$

where T represents the soil temperature, z represents the depth below the soil surface and K_T represents the apparent soil thermal diffusivity, which includes the effects of both thermal conduction and latent heat flux. For many conditions, the apparent soil thermal diffusivity can be related to the soil moisture content. By applying appropriate boundary conditions, equation 1 can be solved to describe the propagation of thermal energy through the soil profile. Through measuring the rate of propagation of temperature in the soil, and using estimates of soil bulk density and mineral soil thermal conductivity and specific heat, it is possible to predict the vertically averaged soil moisture.

Effects of Alternative Crops on Soil Nutrients

Soil organic matter (SOM), which includes a variety of C compounds originating from plants, microbes, and other organisms, helps to maintain soil fertility by supplying essential nutrients for plants and it helps to increase moisture retention in soils. As a result, SOM is an important indicator of soil quality (Komatsuzaki and Ohta, 2007; Lemenih et al., 2005). Cultivation of soils often results in declines in soil organic C (SOC) as a result of increased decomposition (Grace and Oades, 1994; Golchin et al., 1995) but C losses can be partly mitigated through manuring, adequate fertilization, and crop rotation for maintaining agronomic productivity (Duff et al., 1995; Mitchell et al., 1996; Reeves, 1997). Upon decomposition of SOM, CO_2 is released into the atmosphere and nutrients such as N and P are released into the soil. Both C and N mineralization are affected by many environmental and soil properties including temperature, moisture, organic matter quality, soil texture, and microbial community structure, among numerous other factors (Cookson et al., 2006; Fierer and Schimel, 2002; Ford et al., 2007; Franzluebbers, 1999; Giardina et al., 2001; Hassink, 1994; Pare and Gregorich, 1999; McLauchlan, 2006).

Soil temperature can greatly influence microbial activity, and thus C and N mineralization when moisture is not limiting (Cookson et al., 2006; Cookson et al., 2002; Zogg et al., 1997. However, in semi-arid areas, soil moisture is most likely to be more important than temperature in regulating C and N fluxes especially under non-irrigated conditions (e.g., Cookson et al., 2006; Murphy et al., 1998a, b). Soil moisture affects microbial activity via O_2 availability for microbial metabolism and substrate diffusion through the soil matrix (Ford et al., 2007). When soil moisture is low, microbial activity is limited by lack of water whereas high moisture content can cause blocking of soil pores limiting O_2 availability (Bouma and Bryla, 2000). In addition, many arid systems are characterized by repeated wetting and drying cycles (Ford et al., 2007; Fierer and Schimel, 2002; Lundquist et al., 1999). Drying-rewetting events could result in moderate short-term changes in respiration rates, substantial reductions in long-term respiration rates, an increase in nitrifier activity, and an increase in the size of the microbial biomass C pool (Fierer and Schimel, 2002). Carbon and N mineralization can also be affected by soil texture. SOM can be protected from microbial decomposition especially in clay-rich soils causing C and N mineralization to be slower compared to sandy soils (Hassink, 1994; Franzluebbers, 1999; Pare and Gregorich, 1999). This protection by clay-sized particles has been ascribed to adsorption of organics onto clay and sesquioxide surfaces, encapsulation between clay particles, or entrapment in small pores in aggregates inaccessible to microbes (Hassink, 1994).

Plants have an important influence on C and N cycling in soils. Changes in plant productivity, particularly root biomass, are likely to strongly influence the soil microbial community by altering root exudation patterns and the supply of root C to soil through root turnover (Bardgett et al., 1999). In addition, organic matter decomposition and nutrient cycling can be affected by plants species through differences in plant tissue composition (Hooper and Vitousek, 1997; Wardle et al., 1997; Grime, 1998). Previous studies have shown that structurally and functionally distinct microbial communities develop under different plant species (Degens and Harris, 1997; Bossio et al., 1998; Marilley and Aragno, 1999) and plant species can significantly alter soil microbial communities within three months which in turn affected N concentrations, pH, and N mineralization in the soil (Kourtev et al., 2003).

For this study we focused on the effects of moisture and plant species on C and N transformations in soils in the Walker Basin. The goal was to assess if changes in irrigation regime and alternative agricultural crops affect C losses from the soil and N availability for plants. We measured C and N mineralization under controlled conditions using a series of laboratory incubations focusing on effects of moisture and vegetation. We conducted incubation of soils prior to planting and following one cropping cycle. These laboratory studies were augmented with field measurements of C and N status as well as soil CO_2 efflux over one growing season. Soil CO_2 efflux, or soil respiration, integrates all components of soil CO_2 production, including respiration of soil organisms and plant roots. As a result, soil respiration represents an important efflux of C from terrestrial ecosystems.

Riparian Zone Affect on Nutrient Flux

Riparian zones have long been valued and studied for their capacity to buffer and regulate nitrate contamination from surface inputs to ground and surface water resources (Haycock and Burt, 1993). Riparian zone sediments often contain the favorable reducing conditions necessary for the removal of nitrate via microbial denitrification (Puckett, 2004). Study of floodplain lithology is necessary to determine the location of deeper layers in which buried organic matter may increase denitrification at depth and flood deposited coarse material may create conduits for groundwater flow that bypass the riparian zone (Hill et al., 2003).

Riparian zone hydrology must be determined as flowpath influences both the extent of contact between nitrate (the electron acceptor) and organic matter (the electron donor) and the residence time of the nitrate plume in the carbon rich zone (Rassam et al., 2005). Past studies of riparian nitrate removal have tended to focus on sites with similar hydrogeologic setting where flow paths are shallow, often restricted by impermeable clay layers and flow direction is from upland areas to surface water (Hill, 1996). Burt et al. (1999) observed that although a riparian zone showed large potential for denitrification, nitrate still passed through the zone via springs and gravel lenses beneath the floodplain soil. There remains some uncertainty as to the effect of depth on riparian denitrification. Hill et al. (2000) suggested that unless a deeper flow path induces interaction with localized supplies of organic matter denitrification will be limited. Jacinthe et al. (2000) noted increased denitrification rates when depth to the water table decreased from 50 cm to 10 cm. A study of three Rhode Island riparian sites found no significant difference in denitrification by depth (Kellog et al., 2005). Seasonal effects on flow path and nitrate retention were found in the NICOLAS study of 13 riparian sites in Europe where in summer a reversed hydraulic gradient prevented buffering of upland subsurface runoff (Burt et al., 2002). Nitrate concentration and water flux were the major variables in nitrate retention (Pinay, 2001; executive summary at http://www.aopv55.dsl.pipex.com/nicolas/nicolas.htm). Riparian zones with a relatively flat topography resulting in a low hydraulic gradient and increased residence times enhance anaerobic conditions necessary for denitrification (Vidon and Hill, 2004).

There remains some uncertainty about whether or not riparian subsurface denitrification decreases with depth or is limited when water tables drop below shallow, carbon-rich soil layers. Burt et al. (1999) found an exponential decrease in potential denitrification activity with depth, little denitrification below 40 cm, and no evidence of deep denitrification (> 1 m). Bernal et al.

also reported higher denitrification potential for shallow (<30 cm) soils than for deeper soils (2007). Jacinthe et al. (2000) noted increased denitrification rates when depth to the water table decreased from 50 cm to 10 cm. A study of three Rhode Island riparian sites found no significant difference in denitrification by depth (Kellog 2005). In contrast, Domagalski et al. reported that denitrification in the saturated zone tended to increase with depth as dissolved oxygen decreased with depth (2008). Hill et al. (2000) suggested that unless a deeper flow path induces interaction with localized supplies of organic matter, denitrification will be limited.

Previous studies of denitrification in riparian zones have often measured potential denitrification activity on soil cores in the lab (Hill, 1996). Microsites or "hotspots" of microbial denitrification result in denitrification being the most temporally and spatially variable of the N cycle processes (Mosier and Klemedtsson, 1994). *In-situ* methods are more capable of capturing microsite heterogeneity than soil core methods (Istok et al., 1997). Although *in-situ* methods are desirable for characterizing microbial metabolic activity, to date these methods have not been widely used and spatial relationships between microbial metabolic activities and in-situ water quality are lacking (Schroth et al., 1998).

Direct evidence of in-the-field denitrification below the saturated zone can be provided by conducting an *in-situ* "push-pull test" where groundwater amended with nitrate and a conservative tracer (bromide) is injected and subsequent changes in reactant and product concentrations are monitored during extraction (Trudell et al., 1986). Push-pull tests conducted in conjunction with the study of hydrogeologic setting can provide a more complete view of the nitrate removal capacity of riparian zones (Addy et al., 2001). Early studies employing the push-pull test method focused on the disappearance of nitrate (Istok et al., 1997; Trudell et al., 1986) or monitored the product formation of N_2O in the acetylene blocked partial denitrification reaction (Sánchez-Pérez et al., 2003; Schroth et al., 1998). Acetylene can be degraded both anaerobically and aerobically (Tiedje, 1982). Other limitations of the use of acetylene in the field include the inhibition of nitrification, incomplete diffusion of acetylene, and incomplete termination of the denitrification reaction at the N_2O step (Addy et al., 2001). The use of labeled $^{15}NO_3^-$ enables the researcher to allow the denitrification reaction to go to completion while also distinguishing the $^{15}N_2$ product from atmospheric nitrogen. Research has shown agreement between field push-pull methods and lab measurement methods of denitrification (Well et al., 2003).

Effects of Altered Water Use on Invasive Species in the Walker River Riparian Zone

Withdrawal of land from surface water irrigation in the Walker Basin may change the direction of groundwater flow and depth of the water table in the riparian zone particularly in the lower portion of the valleys where slopes are more gradual and water tables are higher. The change in water table depth may be the most critical factor in encouraging or discouraging the establishment and success of invasive plant species. Furthermore, the success or failure of invasive species with a high level of consumptive water use can have a dramatic effect on the ability of water to get into the Walker River and be delivered to the lake.

One invasive species that is of critical concern in the western United States and found in the Walker Basin is the invasive exotic crucifer *Lepidium latifolium* (Tall whitetop or Perennial pepperweed). *L. latifolium* is not only found in the Walker Basin, but it has also invaded thousands of acres of riparian lands in the Humboldt and Carson watersheds of Northern Nevada. The observations of the investigators in this study of the degree of infestation in the Truckee and

Caron River watersheds suggest that the Walker Basin is still in the early stages of invasion. This plant has had significant impacts on the ecology and economies of these areas, and it is expected to eventually spread throughout the entire state (Eiswerth et al., 2005).

Deep rooted invaders such as *Tamarix chinensis* (Saltcedar) use water from shallow water tables and gain a competitive advantage in disturbed riparian areas. These deep rooted invaders have also been reputed to have higher consumptive water use than native species and may negatively affect the availability of water in riparian ecosystems.

METHODS AND MATERIALS

Study Site Locations and Treatment Design

Walker Lake is a terminal lake within the Great Basin region. The bulk of the Walker River Basin is located in western Nevada with its headwaters in the Sierra Nevada along the eastern border of California. Elevations in the basin range from about 3,500 m in the upper reaches to about 1,200 m at the valley floor. Average annual precipitation ranges from approximately 32 inches at headwater locations within the upper watershed to as low as 4 to 6 inches at the lower elevations.

Study sites were located along the lower reaches of the Walker River in Mason Valley and included one riparian, one wildlife habitat, two sites under agricultural management, and one abandoned pasture (Figure 1). Two sites (wildlife habitat and flood irrigated pasture) were located within the Mason Valley Wildlife Management Area (WMA), and two were located at existing ranch sites (Valley Vista sprinkler irrigated alfalfa and 5C abandoned pasture). The basic study design consisted of planting alternative agriculture species for food, forage, and biofuels production, and a second component for land restoration. Differential water treatments were then super-imposed onto both components. Based on a total water allocation of 4 ft/year, four water treatments were planned for the alternative agriculture planted species: 0%, 50% (2 ft), 75% (3 ft), and 100% (4 ft). Planned water treatments for the restoration component were 0% and 25% (1 ft). The latter treatments were based on the common assumption that a 25% water allocation would be sufficient for the establishment of restoration vegetation. Different water treatments were reached by deficit irrigation. Plots within a water treatment were watered at full capacity until the water allotted to them for the season was used in full.

Vegetation treatments (Table 1) for the alternative agriculture included 14 crops of both annual and perennial varieties. Five alternative biofuel grain species were chosen as well as four cool season and five warm season grasses, for a total of nine potential biofuels. Five plant varieties were considered for the restoration component. Each vegetation and water treatment was replicated three times within each agricultural site. The alternative agriculture component was initially implemented at three of the four study locations (wildlife habitat, irrigated alfalfa, and abandoned pasture) and the method of water application was by sprinkler irrigation. The initial restoration component was implemented at all four study locations but the method of water application at the WMA irrigated pasture location remained under flood irrigation. Overall the general study design consisted of four locations, by two study components (alternative agriculture and restoration), 14 and 5 varieties respectively, 4 and 2 water treatments, and three replications. The two WMA sites were eliminated from consideration during the second year of study because of little or no germination during the establishment year. We believe this to have been due in part to alleopathy and fine soil texture at the wildlife habitat site, and high salinity/sodicity and fine soil texture at the flood irrigation site.

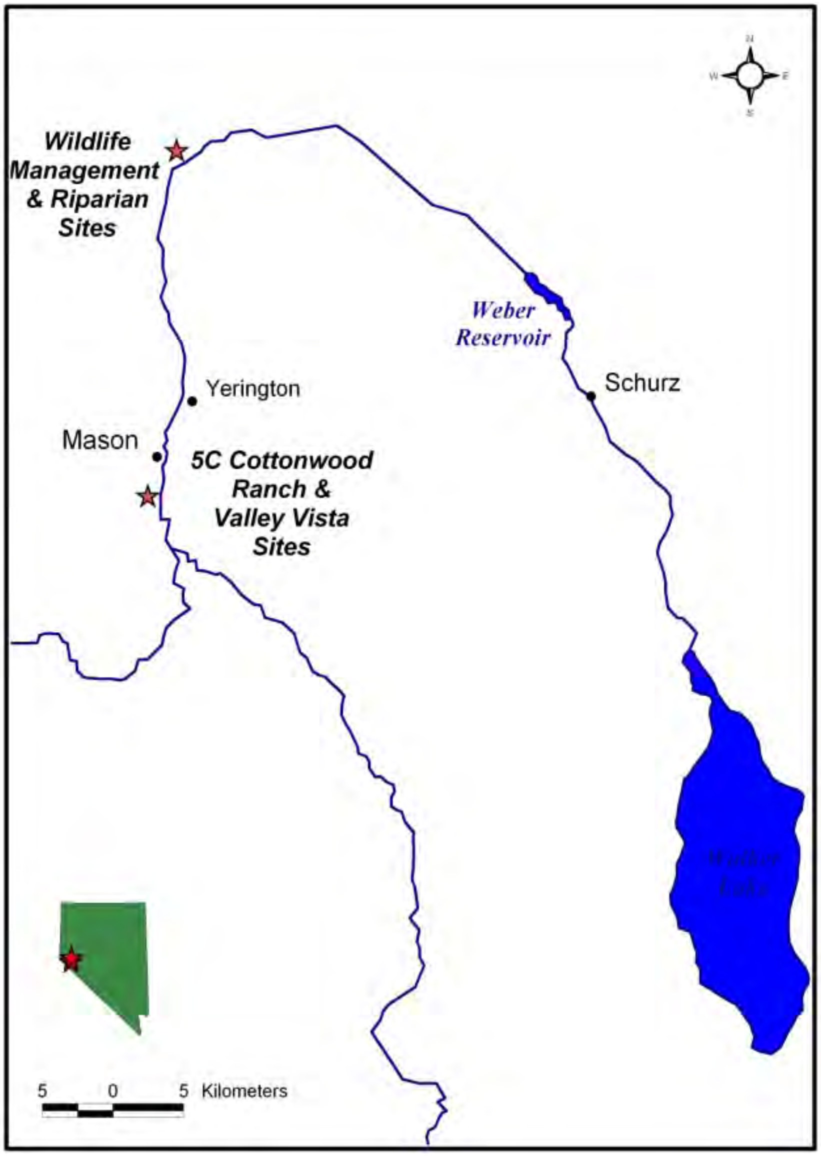

Figure 1. Map of agricultural and riparian site locations along the Walker River.

Table 1. Seeded plants for agricultural sites.

Common name	Scientific name	Variety
	Alternative crops	
Tef	*Eragrostis tef*	Brown
Tef	*Eragrostis tef*	Ivory
Buckwheat	*Fagopyrum esculentum*	Mancan
Amaranth	*Amaranth hybridus* x *hypochondriacus*	Plainsman
Pearl millet	*Pennisetum glaucum*	Tifgrain 102
Alfalfa	*Medicago sativa*	Mountaineer 2.0
	Warm season grasses	
Switchgrass	*Panicum virgatum*	Nebraska 28
Sand bluestem	*Andropogon hallii*	Woodward
Indian grass	*Sorghastrum nutans*	Cheyenne
Prairie sandreed	*Calamovilfa longifolia*	Goshen
Bluestem	*Bothrichloa ischaemum*	WW Iron Master
	Cool season grasses	
Tall wheatgrass	*Elytrigia elongata*	Alkar
Basin wild rye	*Leymus cinereus*	Trailhead
Mammoth wild rye	*Leymus racemosus*	Volga
Tall fescue	*Festuca arundinacea*	Fawn
	Revegetation species	
Indian ricegrass	*Achnatherum hymenoides*	Nezpar, Rimrock
Basin wild rye	*Leymus cinereus*	Trailhead
Beardless wheatgrass	*Pseudoregneria spicata*	Whitmar
Western wheatgrass	*Pascopyrum smithii*	Arriba, Rosana
Inland saltgrass	*Distichilis spicata*	VNS
Control	Nothing sown	

Study Site Descriptions

Valley Vista Ranch (VV)

The Valley View Ranch site location included both revegetation and alternative agriculture experiments (Figure 2B). This site was located on Malapais complex soils (60%), Tocan sandy loam 2 to 4% slopes (20%), and Tocan sandy loam 0 to 2% slopes (20%) (US Department of Agriculture, 1984). Since the site was still under alfalfa production, Round-up and Dicamba were sprayed to remove existing vegetation. The field was then ripped and disked prior to seeding. Cool season grasses were planted in December 2007, alternative food and forage crops and warm season grasses were planted in May 2008, and salt grass was planted in July 2007.

5C Cottonwood Ranch (5C)

The 5C Cottonwood Ranch site also included both alternative agriculture and revegetation treatments (Figure 2A). It was located on sandy textured Malapais complex 2 to 15% slopes soils (100%) (US Department of Agriculture, 1984). The site had not been in production for several years and was used primarily as grazing land for burros and llamas prior to project implementation. Soils were highly compacted and void of vegetation. Due to the lack of vegetation, the only preparation applied to this field was ripping and disking. Cool season grasses were then planted in December 2007, alternative agriculture crops and warm season grasses were planted in May 2008, and salt grass was planted in July 2007.

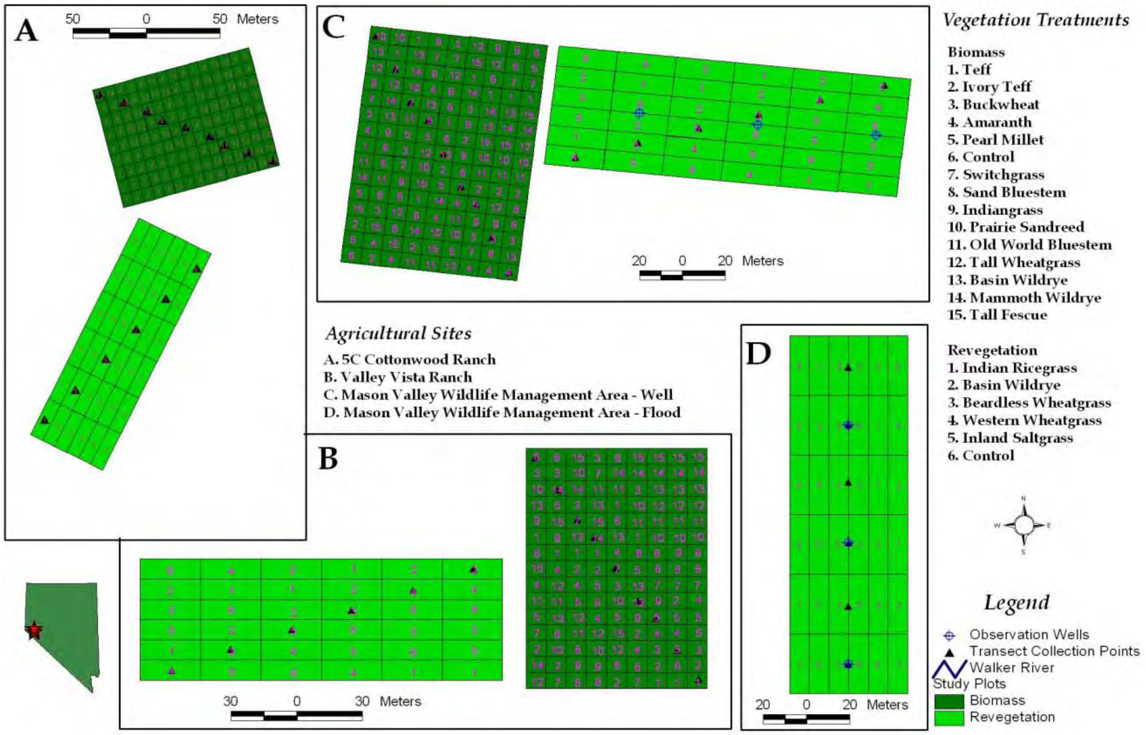

Figure 2. Site map of agricultural field sites with identification of transect locations and observation wells.

Mason Valley Wildlife Management Area Wildlife Habitat (WMW)

The wildlife habitat site at the Mason Valley Wildlife Management Area again included both alternative agriculture and revegetation experiments (Figure 2C). It was located on Dithod loam soils (75-80%) and Fallon fine sandy loam, saline alkali soils (15 to 20%) (US Department of Agriculture, 1984). The dominant existing vegetation at the wildlife habitat location was willows with intervening grasses. Willows were mechanically removed and Round-up and Dicamba were applied prior to planting. Cool season grasses were planted in November 2007, alternative agriculture crops and warm season grasses were planted in May 2008, and salt grass was planted in July 2007.

Mason Valley Wildlife Management Area Flood Irrigated Pasture (WMF)

The Mason Valley Wildlife Management Area flood site was used for only the revegetation portion of this study (Figure 2D). It was located on Dithod loam, saline-alkali soils (75%) and Eastfork clay loam, saline-alkali soils (25%) (US Department of Agriculture, 1984). Prior to clearing in the summer of 2007, existing vegetation consisted primarily of bunchgrasses.

This site was treated with Round-up and Dicamba, mowed, ripped, disked, and laser leveled. Cool season grasses were planted in November 2007, and saltgrass was planted in July 2008.

Walker River Riparian (WRR)

A riparian assessment site was also established along the Walker River within the Mason Valley Wildlife Management Area (Figure 3) for purposes of evaluating soil salinity and riparian zone nitrate buffering capacity. Land uses within the MVWMA include 1200 acres of farm land that is irrigated for grain and hay crops, in addition to native shrub and meadow lands. The soils at these two sites are classified as Fallon fine sandy loam, frequently flooded. Soil drainage class is listed as somewhat poorly drained and the area is arid receiving an annual mean precipitation of 10 – 18 cm (USGS, 2009). Elevation at the river is 1300.28 meters AMSL (Above Mean Sea Level) and the river flows north through the study site. The vegetation is composed of *Populus fremontii, Tamarix chinensis, Salix gooddingii, Distichlis spicata*, *L. latifolium,*and *Elymus trachycaulus.* Immediately north of these sites irrigation water is delivered to fields from surface water diversion ditches.

Figure 3. Aerial photograph of Walker River riparian site location.

Soil Properties

Baseline soil analyses included infiltration, bulk density, and textural classification. A transect was established across each field. Along each transect one point was delineated in each water treatment, or row, totaling nine points for each alternative agriculture and six points for each revegetation component (Figure 2). At each of these sampling points two tests were performed. A bulk density sample was taken using a standard bulk density sampler to extract a core of known volume. The core was dried and weighed to determine the mass of soil per unit volume. An infiltration test was next performed using a disc permeameter. Philip’s equation was then applied to determine near saturation hydraulic conductivity at each location (Philip, 1957).

Soil texture was measured on the samples taken for chemical analysis using a Saturn Digisizer 5200 Laser Particle Size Analyzer.

Soil samples were collected within each water and vegetation sub-plot at each site. Baseline samples were collected June through September 2007 and post-harvest samples were taken in March/April of 2009 using a standard bucket auger (Figure 4). Control plots were sampled at six depths; 0 to 6”, 6 to 12”, 12 to 24”, 24 to 36”, 36 to 48”, and 48 to 60”. Non-control plots were sampled at two depths; 0 to 6” and 6 to 12”. Samples were taken from the center point of each sub-plot totaling approximately 1,300 samples each year. Control samples from 2007 were analyzed for soil electrical conductivity (EC), hydrogen ion activity (pH), and water soluble and exchangeable ions to characterize nutrient status. Sub-samples from each plot and depth from 2009 were analyzed to determine changes in nutrient status associated with differing crop types and water treatments.

Figure 4. Dr. Paul Verburg using bucket auger to collect soil samples at WMW site in the fall 2007.

Soil samples were hand ground and passed through a 2 mm sieve to break aggregates and remove coarse rock fragments and plant debris. Deionized water was added to develop a saturated paste according to methods outlined by Bower and Wilcox (1965). Soil solution was extracted using a vacuum system and Whatman no. 5 filters. The water extract was again filtered with a 0.45 μm nylon membrane filter to remove fine particulates. Filtered extracts were analyzed for water soluble anions (PO_4-P, SO_4^-, NO_3^--N, NO_2-N, Cl^-) (Dionex Corporation, 2003) and cations (NH_4^+, Na^+, Ca^{2+}, Mg^{2+}, and K^+) (Dionex Corporation, 2001) using a Dionex ICS-3000 ion chromatography system. Extracts were once again utilized to measure pH with a Hannah Instruments portable pH meter and electrical conductivity with an Oakton CON6/TDS 6 Hand-held Conductivity/TDS Meter. In a corresponding study, sub-samples consisting of 5 grams soil were equilibrated with 10 mL deionized water. Soil pH was measured and salinity was characterized by electric conductivity measurements of the soil/water slurry. Conductivity values (µS/cm) were converted to a salt concentration (mg/kg) according to the procedures followed by the Soil Characterization Laboratory at the Desert Research Institute.

Wind Erosion

Twenty-four dust collectors (Fryrear, 1986), were installed at the 5C and Valley Vista Ranch sites (Figure 5) in nests of 4 traps each. The traps on each nest were set to collect at heights of 10 cm, 35cm, 60 cm, and 100 cm above the soil surface. A mat was installed on the ground at the base of each nest to prevent rapid weed growth from interfering with the movement of the bottom trap. The dust collectors were established to capture the difference in soil erosion from varying water treatments within revegetation fields in comparison to control sites in neighboring fields.

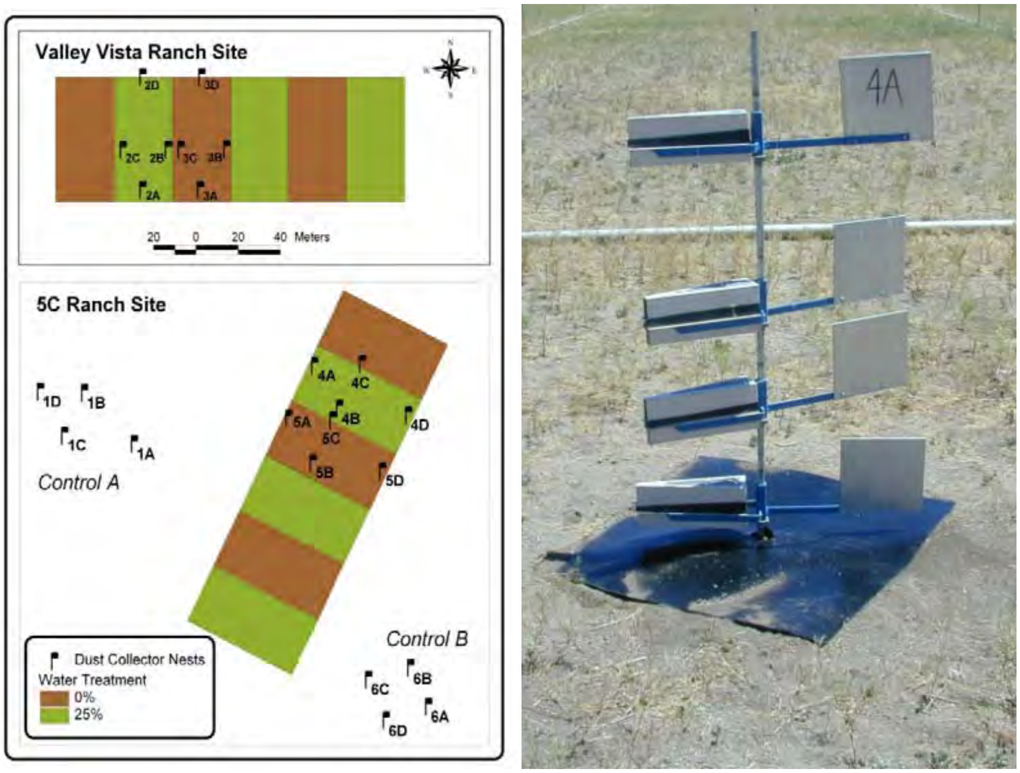

Figure 5. Dust collector locations as of spring 2009 and dust collector nest at 5C site (Fryrear, 1986).

After a number of preliminary measurements, a diamond shape layout was adopted and installed in the spring of 2009. This layout allowed us to best capture the dust entering and exiting each area from all boundaries and thereby determine what was being deposited and generated over the differing soil surfaces. Two control areas were selected to compare revegetated surfaces to those most representative of natural conditions in the area.

Control A, was located on similar soils west of the 5C revegetation plots. It has never been farmed, and was grazed at some point in its history but not within the previous 5 to 10 years. Comparatively it was not as compacted as was the Control B site.

Control B, located on similar soils just east of 5C revegetation plots. Like the revegetation plots, it had once been farmed and had been highly compacted by years of concentrated grazing until just before project planting. This area was not tilled for planting in 2007 and remained highly compacted.

Dust traps were emptied after each major wind event (sustained winds over 10 mph and gusts over 30 mph).

Agricultural Hydrology

A total of four rain gauges were installed at three of the four sites; one at WMW, one at WMR, and two on opposing corners of the site at 5C. Data collected from the rain gauges were added to irrigation values to determine the total water application to each site. Three observation wells were installed at each of the two Wildlife Management Area sites to monitor water table height (Figures 4 and 5). Wells were monitored before and after each irrigation, after rainfall events during the growing season, and monthly over the winter season. Soil moisture samples were taken weekly prior to irrigation and monthly during dormancy to isolate changes in the soil moisture profile. One point within each water treatment and replication along each transect were chosen for sampling at four depths; 0 to 6”, 6 to 12”, 12 to 24”, and 24 to 36”. Soil moisture data was also collected to correspond to soil temperature data. Corresponding soil moisture data was collected at 22 points along the cable path at the 6” depth pre- and post-irrigation (Figure 6).

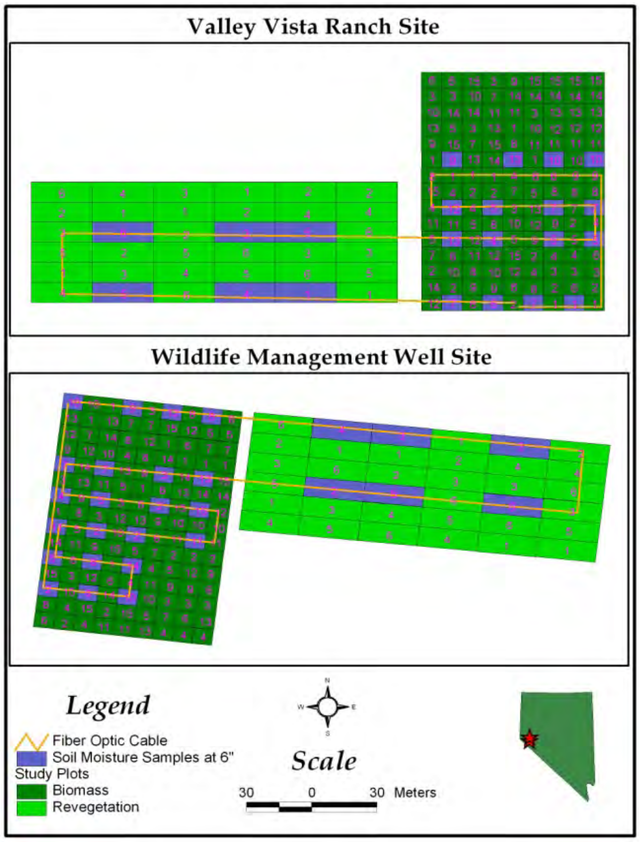

Figure 6. Location of fiber optic cable and soil moisture sampling points at VV and WMW sites.

Soil Temperature

A fiber optic cable was installed 15 cm beneath the soil surface using a plow system similar to that used to install subsurface drip irrigation tubing. Approximately 1,000 m of commercial fiber optic cable was buried at the WMW and VV sites (Figure 6). Figure 7 shows the installation of the fiber behind a small tractor. The fiber location was geo-referenced and mapped using GPS and was installed to generally cover the majority of alternative agriculture crops and all water treatments for the two sites. Temperatures were measured along the fiber optic cable using a Sensornet Sentinel and Sensornet Halo Raman spectra DTS system.

Figure 7. Installation of fiber optic cable at the Valley Vista ranch site in December 2007. Approximately 1,000 m of fiber was installed at both Alternative Agriculture sites.

In 2009, the WMW site was found to have poor quality control on the fiber burial depth. This was primarily a function of the heavy texture of the soil, as well as the moderate size of the installation plow system. A much heavier plow system, capable of burying up to 3 fibers has recently been constructed and tested, and will be used in subsequent studies. Furthermore, there was no germination of any plantings for any treatment at the WMW study site. Consequently, DTS temperature studies in 2009 focused on the VV site exclusively.

Soil Nutrient Availability

Laboratory Incubations

Two laboratory incubations under controlled conditions were conducted to assess potential C and N mineralization (Stanford and Smith, 1978). For the first laboratory incubation, soil samples from the Mason Valley Wildlife Management Area (WMW), the Valley Vista site (V V), and the Cottonwood Ranch (5C site were used. In this study four crops: Tef (*Erograstis tef)*, Amaranth (*Amaranth cruentus)*, Alfalfa (*Medicago sativa)* and Switchgrass (*Panicum virgatum)* were included. The samples for this incubation were taken in the fall of 2007 prior to planting between 0 and 15 cm depth. The alternative and revegetation fields from the Valley Vista and Cottonwood Ranch sites and the revegetation field from the wildlife habitat site were sampled. Five vegetation plots were randomly selected from each of the 5 fields for a total of 25 plots. Prior to incubation soils were air-dried and sieved over a 2 mm sieve. Each soil was incubated at three moisture levels 0.05, 0.15, and 0.30 g H_2O/g soil using three replicates for each sample resulting in a total of 75 samples. For each soil, 15 gram of air-dried soil was placed into a 250 mL glass jar equipped with a septum in the lid. Next, DI water was added to each soil according to its designated moisture level. After the water addition the lid was firmly screwed on to the jar and placed into a constant 25ºC temperature refrigerator for a period of 5 weeks. Periodically, air samples were taken from the headspace for CO_2 measurements using a 250 µL syringe through the septum in the lids of each jar. The CO_2 concentration in these samples was measured using a LI-COR 6251 CO_2 analyzer. The jars were opened periodically to allow for oxygen to enter the jars. Respiration was calculated as the increase in CO_2 concentration over time.

For the second (post-planting) incubation, only soil samples from the Valley Vista and Cottonwood alternative crop fields were used for reasons previously stated. Soils for this incubation were sampled at the end of August, 2008 following the first growing season. Within each field, soil samples were pooled by vegetation type and homogenized resulting in a total of eight samples (2 fields x 4 vegetation types) from which subsamples were taken. These samples were incubated at the same moisture level as used for the first incubation using three replicates for each field and moisture combination resulting in a total on 72 samples. The incubation procedures were the same as those used for the pre-planting incubation.

At the beginning and end of the incubation period, all soils were extracted using 2M KCl. Five grams of each soil were placed into a 50 mL plastic syringe equipped with a filter, 50mL of the KCl solution was added and allowed to soak into the soil for 30 minutes. After 30 minutes, the soils were extracted over a 30 minute time period with a SampleTek Vacuum Extractor. The extracts were frozen until analyzed. The extracts were analyzed for NH_4 and NO_3 using a Lachat autoanalyzer. Net mineralization was calculated as the change in total inorganic N concentrations between the end and beginning of the incubations. Subsamples of each soil were dried to obtain the moisture content at the end of the incubation and were used for total C and N analysis. Soil samples were analyzed for total C and N at the Soil Water and Forage Analytical Laboratory at Oklahoma State University using a Leco CHN analyzer. Bulk density cores were taken on October 23, 2008, using a 5.4 cm diameter, 3 cm tall ring. Particle size analysis of the all soils was conducted by sieving over a 2 mm mesh sieve followed by analysis of the <2 mm fraction using a Micrometrics Saturn DigiSizer 5200 Laser Particle Size Analyzer in the Soil Characterization Laboratory at the Desert Research Institute of Reno.

Field Measurements

Soil CO_2 efflux was measured during the first growing season in Valley Vista and Cottonwood alternative agriculture fields in four vegetation types. Initially, we selected plots to cover the three irrigation regimes. Due to a water year shortage only one irrigation regime was used. Respiration was measured at 7 times between June 6 and August 28, 2008 in 72 plots (4 vegetation types x 9 replicates x 2 fields) using a static chamber (0.48 L) equipped with a Vaisala GMT CO_2 analyzer. The static chamber was placed on a 15.24 cm diameter PVC ring, installed in each plot prior to the emergence of the crops. Soil respiration rates were calculated as the rate of increase in CO_2 concentrations inside the chamber. Each measurement lasted approximately one minute. All measurements were taken between 10:30 AM and 3:30 PM to limit changes in ambient temperature. Soil moisture was measured with a Delta-T HH1 Theta Meter for the first four trips and a Decagon ECH2O-5TE moisture and temperature probe for the last three sampling dates. Air temperature and relative humidity data were collected between June 6th and August 12th by a HOBO H8 Pro Temp/RH sensor (Onset Computer Corporation, Bourne MA) in the Valley Vista field. On the last three sampling dates, soil temperature was measured using the Decagon probe.

Vegetation samples were taken on August 20 and 21, 2008, to assess the total aboveground biomass in each plot at the end of the growing season. Aboveground vegetation was harvested inside a 1.36 m diameter circle surrounding the soil respiration collars. Biomass was separated into crops and weeds. All samples were dried at 70ºC until constant weight.

Statistical Methods

For the laboratory incubations effects of field, moisture and vegetation type and their interactions were tested using a 3-way Multiple Analysis of Variance (MANOVA). Student t-tests were used to determine differences between vegetation, field, and pre- and post planting incubations. The effects of moisture, texture, initial C/N, and initial percent organic N on C respiration rate constant, cumulative C production, net N mineralization were further examined using multiple linear regression analysis.

For the field measurements effects of vegetation type, field, and date and their interactions were tested using a MANOVA. Student t-tests were used to assess differences between vegetation types and fields. The effects of moisture, texture, vegetation biomass, percent N, percent C, fifteen minute air and soil temperature, and relative humidity on C respiration rate and net change in total inorganic N, NH_4 and NO_3 concentration were determined using linear multiple regression analysis. Multiple regression analyses run versus factors that were only measured at the end of the growing season (e.g. percent N and percent C in soil and biomass, and net change in inorganic-N) only included C respiration rates at the end of the growing season as well. Effects were considered significant if $p<0.05$. All statistical analyses were carried out using DataDesk version 6.1.

Riparian Zone Denitrifiction

A transect of 4 piezometers was installed and oriented perpendicular to the Walker River. Piezometers were constructed of 2 inch schedule 40 PVC pipe. Bore holes were constructed with 2 inch augers. During auguring, soil samples were collected at 1ft intervals and at any change in soil horizon characteristic. Lithology was determined based on visual inspection during augering. Piezometers were screened over the lower 2 ft. Maximum depth of piezometers (10 ft) was limited by the length of the auger extensions. Annular spaces were narrow and were backfilled with native sandy soil. The piezometers were vertically surveyed with an auto-leveling laser level with a factory specified precision of 2.4 mm at 30 m. Latitude/longitude was taken with GPS equipment. To supplement the piezometer transect, staff gages were installed in the river and in the drainage ditch. Staff gages were surveyed in the same way as the piezometers. A partial second transect with two additional piezometers was located 30 ft in the downstream direction (Figure 8).

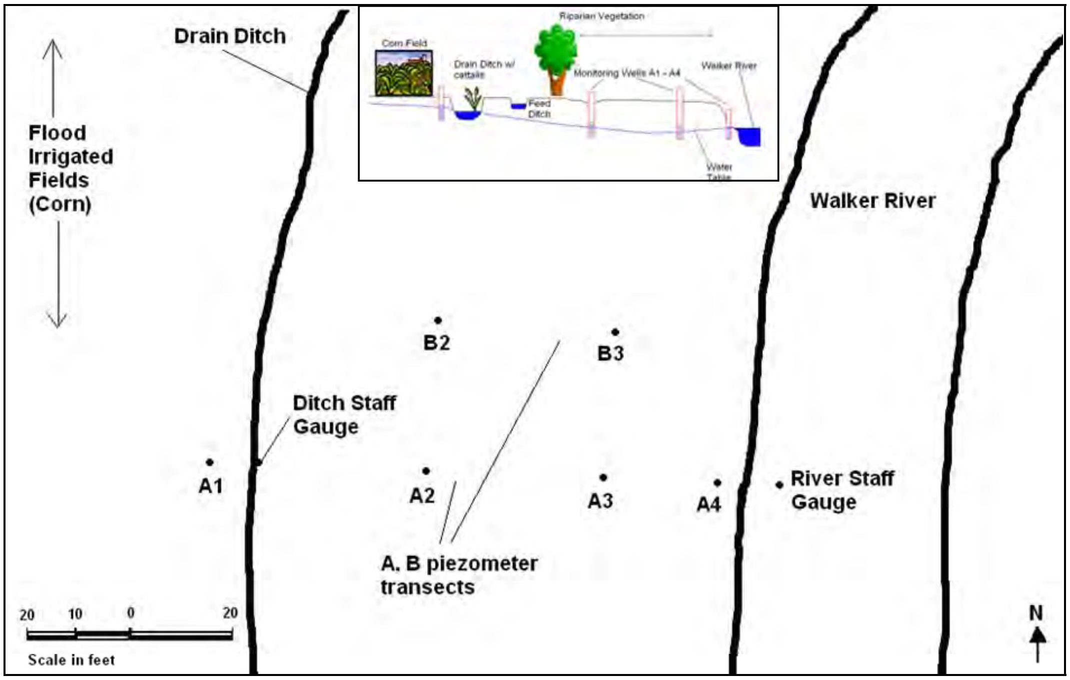

Figure 8. Piezometer transects at WRR site and site profile.

Depth to water measurements in the piezometers and stage levels in the river and ditch were taken monthly. Measurements in the piezometers were taken with a well sounder. Stage readings in the ditch and river were taken by sight reading off the previously installed staff gages. Slug tests were performed on 3 of the piezometers in order to characterize site hydrology and to target feasible sites to conduct the push-pull-tests. Water levels inside the well during the slug test were monitored with a pressure transducer/data logger. Slug testing followed the Bouwer and Rice method for partially penetrating wells as described by Kruseman and Ridder (1990).

Specific locations where “push-pull-tests” (PPTs) were conducted were chosen based on suitability of hydraulic conductivity, depth below water table, organic matter content, and distance along a transect perpendicular to the Walker River. Potential sites for PPTs were identified after conducting slug testing of piezometers, mapping the hydraulic gradient, and sampling soil horizons for combustible organic matter. Injection wells (Figure 9) for the PPTs were constructed of a retractable drive tip injection head attached to 3/16” ID tubing and two 5’ extensions. The injection wells were driven into the soil with a post pounder until just below the desired injection depth and the pulled up slightly to expose the screened section of the retractable tip. This enables the user to drive through clayey soil horizons without clogging the screens.

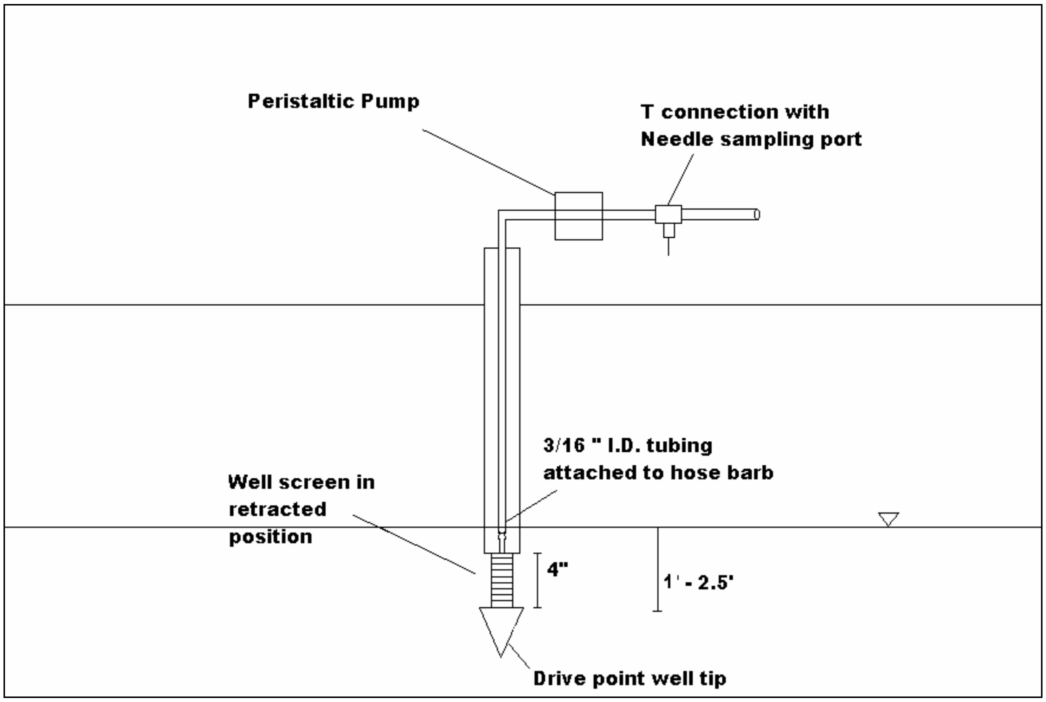

Figure 9. Injection well design as installed at WRR site.

Five "Push-Pull" tests (PPT) were performed in the Spring, Summer and Fall of 2008. Testing began on 5/04/08 with the first 24 hour PPT and was completed by 9/17/08 with the final PPT, also a 24 hour test. Only PPT 2 allowed for 48 hour incubation due to the lower hydraulic conductivity of soils at that site.

The use of a drive point style well prevents any annular space around the well. The use of narrow gauge tubing ensures that the minimum amount of injection solution will be left behind in the well. Both measures effectively ensure the maximum amount of injection solution will interact with in-situ soil microbes. Injection wells were developed by first extracting at least 5 L of groundwater. Groundwater samples were taken prior to injection and analyzed for bromide, nitrate, pH, temperature, dissolved oxygen (DO), and isotopic ratios of dissolved dinitrogen and nitrous oxide gas. DO, pH, and temperature were measured in the field using an Orion 5 star multiprobe (model # 1219000). Five L of ground water was then pumped and set aside in a carboy and amended with 10 mg/L 98% enriched KNO_3 and 100 mg/L KBr, a conservative tracer. The injection solution was then air sparged with high purity helium until DO reached background levels. Injection was accomplished with a peristaltic pump injecting at a slow rate (less than 500 ml/min) to minimize disturbance to the natural flow of groundwater. The injected solution was left to incubate for a period of 24 to 48 hours.

Following incubation, 1.5 times the injected volume was "pulled" from the injection well with a peristaltic pump. During the extraction phase dissolved oxygen was monitored with a polarographic DO probe (Orion, model # 083005MD). Water samples were taken at 1 L and 0.5

L intervals. Samples to be analyzed for dissolved nitrogen gas were taken via a “T” connection equipped with a non-coring needle directly into gas evacuated exetainers. Samples taken for solutes were collected via the HDPE tubing in 250 ml HDPE bottles and stored at 4 degrees C in a field cooler until being frozen for future analysis. Extraction rates were less than 500 ml/min.

Bromide concentrations were measured with a half cell bromide electrode (Orion, model #9435BN) and reference cell electrode (Accumet, model # 13-620-258) on an Accumet pH meter 900 in the mV setting. Millivolt readings were converted to mg/L by the equation derived from the linear relationship of the log of bromide to mV. A calibration curve of log bromide plotted against mV was developed with four data points ranging from 1 mg/L to 100 mg/L with a correlation coefficient of 0.998.

Nitrate concentrations were measured by flow injection analysis using a Lachat Quickchem 8000 autoanalzyer. Nitrate is quantitatively reduced to nitrite through a copperized cadmium column. A reaction with a sulfanilamide produces a reddish water soluble dye which is read at 513 nm. Calibration curves with 6 data points ranging from 0 to 1,600 micrograms/L nitrate produced correlation coefficients exceeding 0.999.

Gas samples were collected during the extraction phase of each push-pull test in order to analyze the concentrations of N gases produced in-situ. 98% labeled ^{15}N potassium nitrate was used for the injection solution so that gaseous products could be distinguished from natural background gases. Completely filled 12 mL exetainers were shipped to the UC Davis Stable Isotope Facility for analysis of dissolved N_2 and N_2O gas. Dissolved gas is sampled by head space equilibration where 6 ml of water is removed from the exetainer and replaced with helium under atmospheric conditions. Analytical equipment was a SerCon Cryoprep trace gas concentration system interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK). Data was reported as micromoles $^{15}N_{2,}$ - picomoles N_2O, total mass of N_2 and N_2O recovered, and percent enrichment.

Nitrate removal rates were calculated based on nitrate disappearance corrected for mechanical losses with bromide tracer data. Rates were assumed to be first-order. In a review paper by Heinen (2006), the majority of models evaluating denitrification were found to employ a first-order decay process. The $k_{\text{nitrate removal}}$ constants were calculated by determining the amount of nitrate remaining in the core of the injection plume after a known incubation period. Nitrate concentration values were corrected for mechanical losses by subtracting the ratio of nitrate in the sample divided by injected nitrate from the ratio of tracer in the sample divided by injected tracer. The first order equation was solved for $k_{\text{nitrate removal}}$ using the known initial concentration of nitrate and the tracer corrected nitrate concentration of a sample taken from the core of the plume during extraction.

$$k_{\text{denitrification}} = (\text{natural log } (\text{Nitrate}_{\text{at time t}} / \text{ Nitrate}_{\text{initial}}))/\text{incubation time} \quad (5)$$

The plume was considered to be the first sample volume interval where tracer recovery was the highest, unless dead volume was suspected in the injection apparatus, whereupon the following sample volume interval was used. Time was defined as the interval between the injection start time and the extraction end time. Since samples were collected at one time point, the first order decay equation was fit to two data points, tracer corrected initial nitrate concentration and tracer corrected nitrate concentration at time t.

Soil samples collected during piezometer installation were analyzed for combustible carbon. Samples were placed in tins and dried for 2 hours at 110ºC. Samples were then placed in a desiccator until room temperature was reached and then weighed. Samples were then baked for 4 hours at 450 degrees, allowed to come to room temperature in a desiccator and then reweighed. The difference in baked weight to dry weight divided by dry weight was reported as percent organic matter. Evidence was found of deeper buried carbon deposits, a phenomenon not uncommon in alluvial formations. SOM ranged from 0.5 – 3.7 %. SOM content of over 2% was found in 5 deeper samples (2 m and over). The data suggests some significant buried carbon deposits in the 2 - 3 m depth interval along the riparian transect at the B2, B3, and A3 bore hole sites.

In addition a simplified, field-scale model of nitrate attenuation that included hydrology was developed for the Walker River riparian area in which field measured nitrate removal rates and groundwater flow were taken into account. This provided a means to extrapolate nitrate removal rates based on measured soil properties. This was accomplished by building a 2-D grid nitrate removal and flux model based on "push-pull test" (PPT) results where available and extrapolated based on soil organic matter (SOM) for other grid cell locations. A MODFLOW groundwater flow model with the MT3D reactive transport module was used to solve for nitrate flux across the riparian zone. Two riparian subsurface flow scenarios were considered: a high gradient scenario where subsurface flow loss from a full drainage ditch traveled toward the Walker River, and a low gradient scenario where the ditch had just emptied and the hydraulic gradient was less severe but still toward the river.

Effects of Altered Water Use on Invasive Species in the Walker River Riparian Zone

Deep rooted invasive plants may gain a competitive advantage in anthropogenically disturbed riparian areas. Because deep rooting invaders have also been known to use water from shallow water tables and have higher consumptive water use than native species, these species may affect the availability of water for native plants in riparian and downstream areas. This portion of the study tested the hypothesis that *Lepidium latifolium* (Tall whitetop) gains a competitive advantage through a deep root system that has a substantial root mass which penetrates shallow saturated zones in riparian areas.

This study consisted of two complementary experiments: (a) a field study measuring the whether *Lepidium latifolium* is able to utilize groundwater from a relatively deep depth (1-2 m) in the riparian zone of the Walker River by comparing the isotopic signature of water taken up by the plant during the growing season to that of the groundwater and (b) competition experiments using the exotic invasive *L. latifolium* and the native perennial grass *Elymus trachycaulus* where the species were grown together in barrels subjected to various soil water conditions.

Isotopic Signature of Water Uptake

To compare root uptake of water as a function of depth samples of *L. latifolium* and associated soils were collected three times throughout the growing season. Xylem water was extracted from the *L. latifolium* plants and soil water was extracted from associated soil samples. The waters were then analyzed for stable isotopic ratios of ^{2}H and ^{1}H. The resulting ratios of ^{2}H to ^{1}H from the vegetation were then compared to those from the soil samples. Samples were collected from three sites that had stands of *L. latifolium* and were located within the riparian area of the Walker River.

Competition With Native Grass Under Different Soil Moisture Regimes

Competition experiments were conducted using the exotic invasive perennial dicot *L. latifolium* and the native perennial grass *Elymus trachycaulus* (Slender wheatgrass) where the species were grown together in barrels subjected to various soil water conditions. Competition experiments were carried out in triplicate at matric water potentials of either -10 kPa and -600 kPa, or -600 kPa with a water table that was maintained 1.1 m below the soil surface. The stomatal conductance rates of *L. latifolium* and *E. trachycaulus* were recorded to indicate whether the plants were able to maintain water uptake throughout the season. After harvest the above and below ground biomass of both plant species under the three moisture regimes. Belowground biomass was divided into 3 zones as a function of depth to determine which plants were able to reach the 1.1 m deep water table (Figure 10).

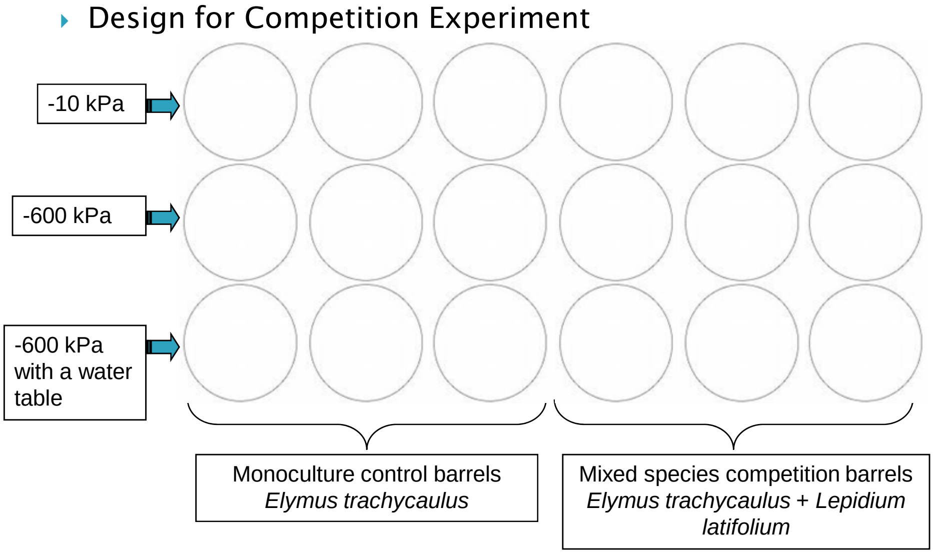

Figure 10. Experimental design for testing competition of *Lepidium. latifolium* and *Elymus trachycaulus*. Each circle represents a barrel in which either one or two species were grown. The designation of 3 moisture regimes is indicated by the labels on the left (e.g. -10 kPa) indicating the soil matric water potential at which the soil in the barrels was maintained.

RESULTS AND DISCUSSION

Infiltration, bulk density, sodicity and water soluble nutrient status for each study site are presented in the following tables and figures. Because this project component was focused on changes in soil solution chemistry, exchangeable and plant available nutrient extractions were not considered. Since the WMW and WMF sites were abandoned due to poor germination and establishment no post-project comparisons are presented for these locations.

Pre-Project Baseline Soil Characteristics

Valley Vista (VV) Ranch Site

Mean steady state infiltration rate, though notably higher at VV (7±2.4 in hr^{-1}; 2.7±1 cm hr^{-1}) study site, was generally similar to that at the 5C Cottonwood (4±1.9 in hr^{-1}; 1.6±0.7 cm hr^{-1}). This was attributed to the predominance of coarse textured surface soils at both sites and the long-term cultivation of alfalfa at the VV location (Table 2).

Soils at all depths were not found to be saline (Table 3). High variability in SAR at depths greater than 36 inches indicates that there may be hot spots of sodic soil (Table 4). The average pH at all depths fell within 8 to 8.5.

Higher concentrations of Ca and Mg near the surface and increasing Na with depth (Figures 11 and 12) suggest the application of agricultural gypsum sometime in the past. Consequently, the near surface Sodium Adsorption Ratio (SAR) is well within the normal range (Table 2). There also appears to be some historic evidence of NO_3 leaching. Water extractable solution concentrations of NH_4^+, Ca^{2+}, Mg^{2+}, and to some extent K^+ tended to decrease from east to west across the field site, whereas concentrations of Na^+, SO_4^-, NO_3^- /NO_2^- and PO_4^- tended to peak midway; albeit water extractable P was quite limited throughout the soil profile (Figure 12).

Table 2. Baseline infiltration and field bulk density for agricultural study sites.

Site	Steady State Infiltration Rate (in*hr^{-1})	Bulk Density (g*cm^{-3})
VV	7.0 ± 2.4	1.40 ± 0.12
5C	4.0 ± 1.9	1.34 ± 0.17
WMW	3.2 ± 1.5	1.07 ± 0.07
WMF	3.4 ± 1.4	1.18 ± 0.05

Table 3. Average Electrical Conductivity (dS*m^{-1}) for agricultural study sites. An electrical conductivity > 4 dS*m^{-1} is indicative of a saline soil.

Depth	VV	5C	WMW	WMF
0-6”	1.1 ± 1.9	1.0 ± 0.9	2.5 ± 1.5	**25.5 ± 34.8**
6-12”	0.6 ± 0.5	1.7 ± 4.4	2.1 ± 1.6	**15.9 ± 4.5**
12-24”	0.6 ± 0.4	1.0 ± 1.0	1.9 ± 1.3	**12.8 ± 4.5**
24-36”	0.7 ± 0.8	1.3 ± 1.5	1.0 ± 0.6	3.8 ± 2.4
36-48”	0.6 ± 0.6	1.3 ± 1.7	0.5 ± 0.3	2.3 ± 1.4
48-60”	1.0 ± 1.0	2.2 ± 3.7	0.3 ± 0.2	

Table 4. Average Sodium Adsorption Ratio (SAR) for agricultural study sites. An anomaly within the 5C site is represented in parenthesis and not included in averages. An SAR > 13 is indicative of a sodic soil.

Depth	VV	5C	WMW	WMF
0-6”	1.8 ± 0.2	1.3 ± 0.5 (**43.6**)	6.6 ± 3.9	**40.4 ± 12.6**
6-12”	1.7 ± 0.2	1.8 ± 0.5 (**67.0**)	9.8 ± 10.7	**58.5 ± 10.1**
12-24”	2.1 ± 1.1	1.8 ± 0.2 (**97.8**)	14.5 ± 14.7	**49.9 ± 14.0**
24-36”	4.5 ± 7.2	1.9 ± 0.2 (**47.2**)	11.0 ± 9.8	**19.0 ± 13.0**
36-48”	5.9 ± 7.4	2.0 ± 0.7 (**76.3**)	5.0 ± 4.5	11.1 ± 3.7
48-60”	10.5 ± 13.8	2.7 ± 1.8 (**77.4**)	2.9 ± 1.2	

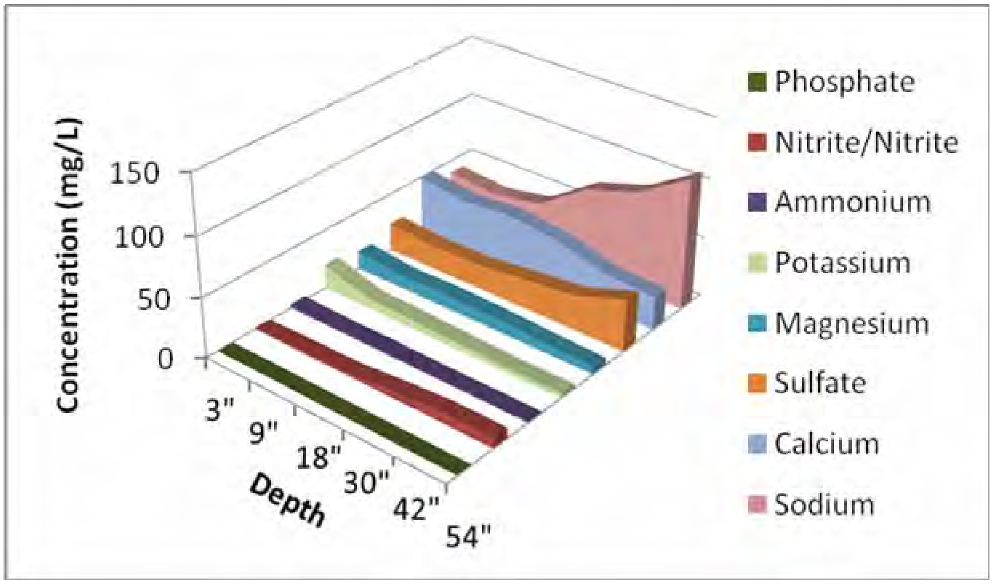

Figure 11. VV agricultural site soil nutrient profile in summer of 2007 – Average concentration of water extractable analytes by depth within the soil profile.

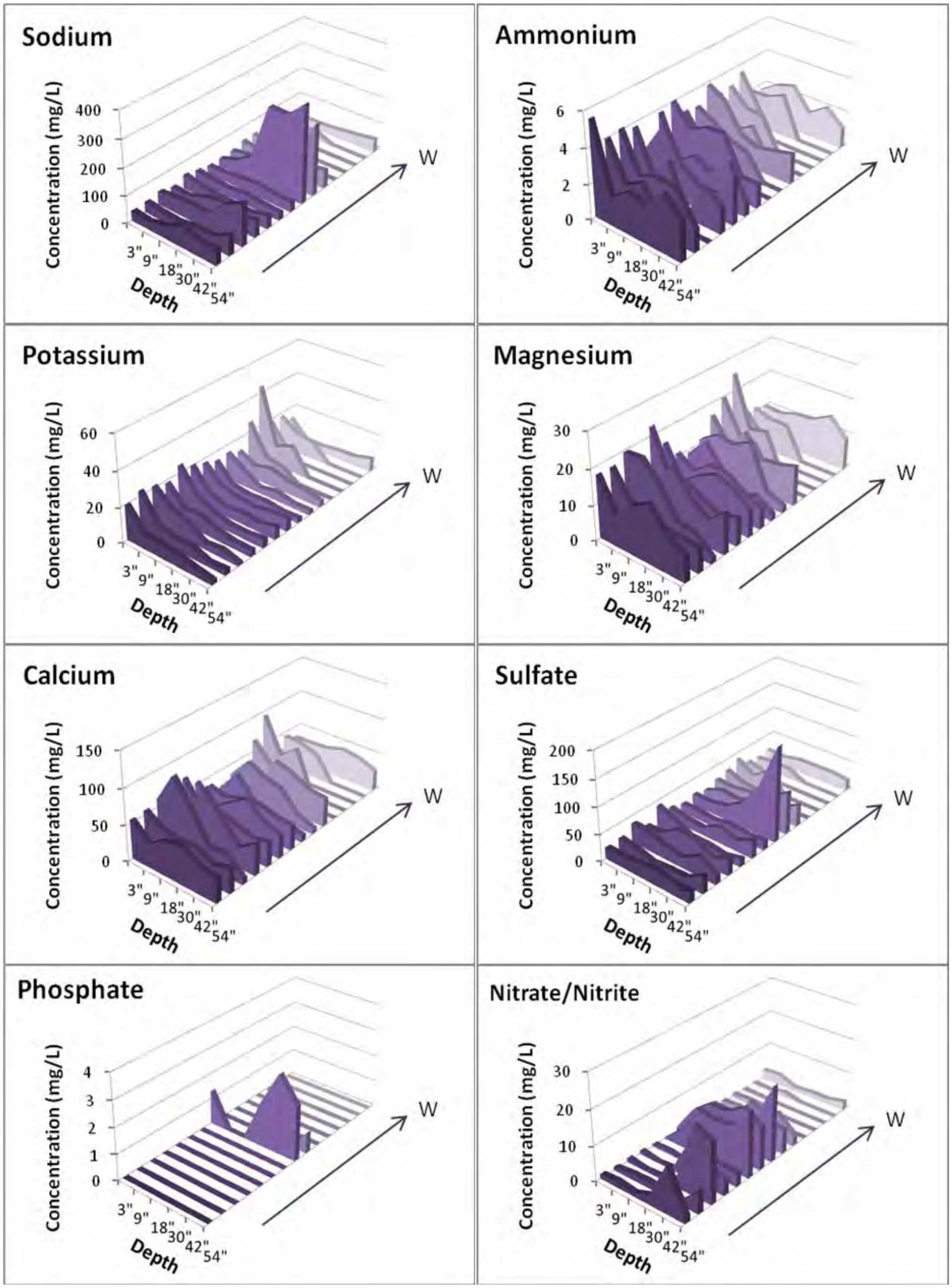

Figure 12. Individual analyte concentrations at VV agricultural site by depth within soil profile along the length of the field for summer 2007.

5C Cottonwood (5C) Ranch Site

Mean soil bulk density at the 5C was slightly lower than that of the VV study site (1.34±0.17 and 1.4±0.12 g cm^{-3}, respectively), but both were comparable to typical bulk densities found in coarse textured sandy loam soils (Table 2).

Variability in electrical conductivity in at depths greater than 48 inches indicates that soils at that depth could, on occasion, be saline (Table 3). Soils were not considered sodic with average SAR being less than 3 at all depths (Table 4). One sample location was considered an anomaly and not included in averages. Soil at this location was found to be sodic at all depths with extremely high average SAR of 40 to 100. The average pH at all depths fell within 8 to 8.5.

Water extractable concentrations of Ca^{2+} and Mg^{2+} at shallow depths did not suggest the historical application of agricultural gypsum (Figure 13) and although the SAR was more variable and somewhat higher than that found at VV, it remained within the normal range overall (Table 2). Concentrations of most nutrients were found to decrease from south to north and were typically higher near the surface decreasing with depth (Figures 13 and 14).

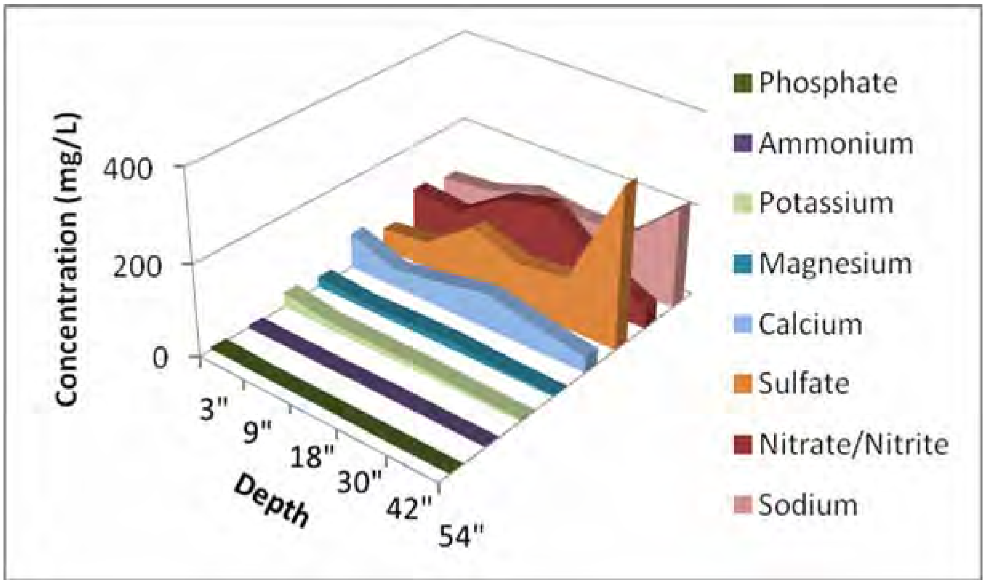

Figure 13. 5C agricultural site soil nutrient profile in summer of 2007 – Average concentration of water extractable analytes by depth within the soil profile.

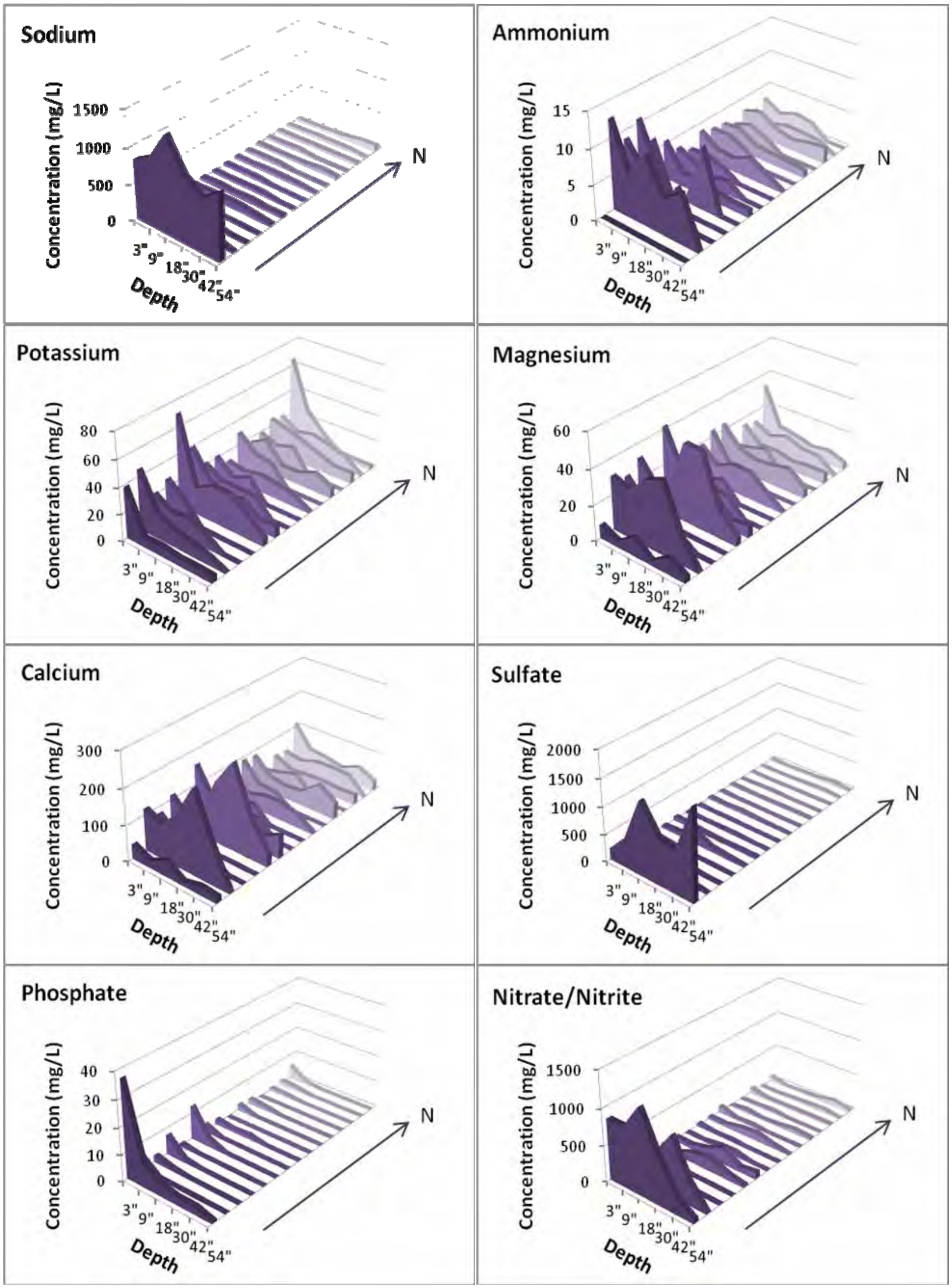

Figure 14. Individual water extractable analyte concentrations at 5C agricultural site by depth within soil profile along the length of the field for summer 2007.

Mason Valley Wildlife Management Area: Wildlife Habitat Site (WMW) and Wildlife Flood Irrigation Site (WMF)

Mean infiltration rates and mean soil bulk densities were similar at both wildlife management sites and were lower than those found at either the VV or the 5C study locations (Table 2).

Averages for electrical conductivity and SAR were found to be within normal ranges at all depth at the WMW site (Tables 3 and 4). A closer look at the variability within, however, reveals that there are most likely areas of saline soils at the surface above 6 inches and areas of sodic soils at depths greater than 36 inches. Soils at the WMF site were found to be saline-sodic at depths 0 to 24 inches. Soils at 24 to 48 inches, while on average were within normal ranges, had spots of salinity and sodicity. The average pH at both sites fell within 8 to 9, with higher pH being found in the surface soils.

Concentrations of water extractable phosphate were below detection at both sites indicating limited P solubility (Figures 15 and 16). Solution concentrations of sulfate and sodium were extremely high at the WMF site (Figure 16). Soils at the WMF location were clearly saline-sodic and higher concentrations of nutrient parameters (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, and SO_4^-) were typically found in the middle of the field (Figure 17) from south to north.

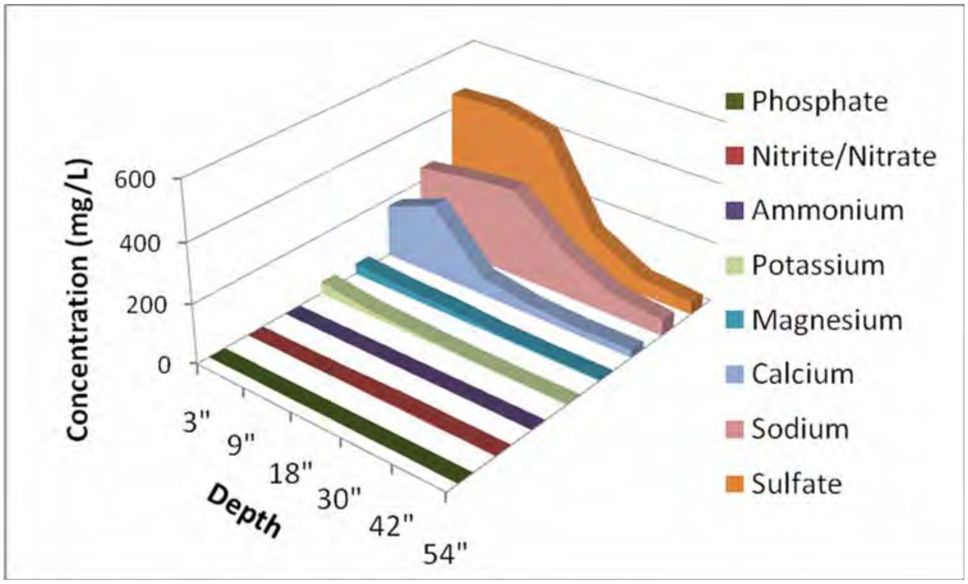

Figure 15. WMW agricultural site soil nutrient profile in fall of 2007 – Average concentration of water extractable analytes by depth within the soil profile.

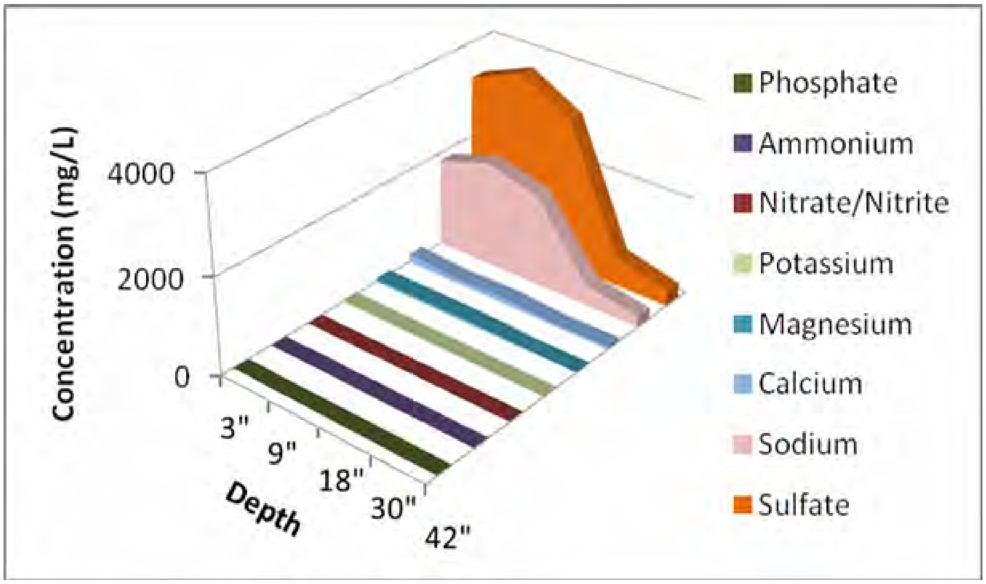

Figure 16. WMF agricultural site soil nutrient profile in summer of 2007 – Average concentration of water extractable analytes by depth within the soil profile.

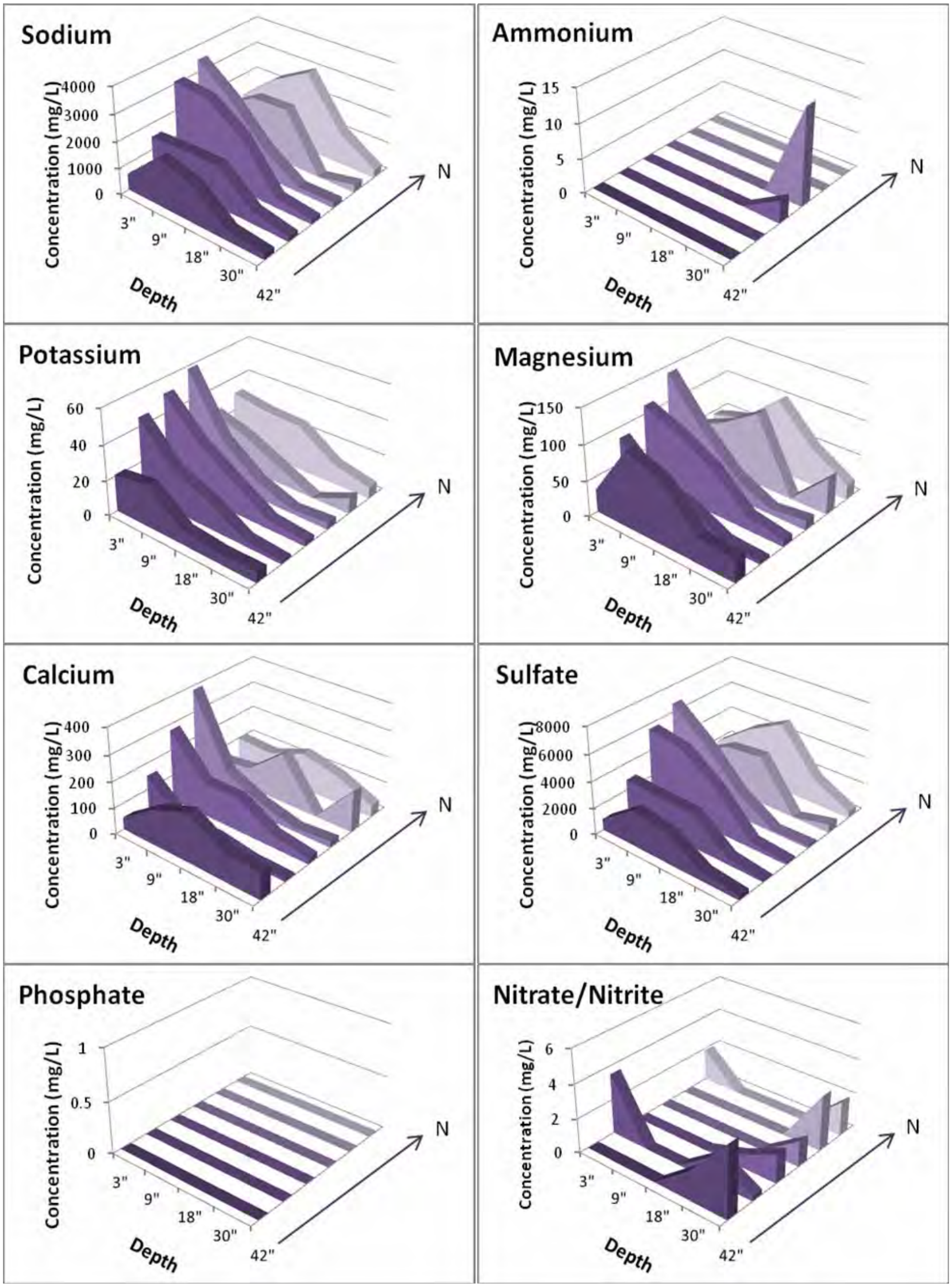

Figure 17. Individual water extractable analyte concentrations at WMF agricultural site by depth within soil profile along the length of the field for summer 2007.

Post-Harvest Nutrient Comparison

Valley Vista (VV) Ranch Site

Concentrations of water soluble calcium, magnesium and phosphate in control (non-treatment plots) were similar between pre- and post-project years (2007 and 2009, respectively) (Figure 18). Water extractable sodium and sulfate was greater in the 6 to 24” range post harvest suggesting some downward mobility consistent with the use of agricultural gypsum. Pre- and post-project potassium, ammonium, and nitrate/nitrite were significantly different throughout the soil profile. Solution concentrations of pre-project ammonium were higher whereas concentrations of nitrate/nitrite and potassium were higher post project. The difference in N species can largely be attributed to nitrification. Differences in soluble potassium between 2007 and 2009 may simply be the result of spatial variability.

Post-project soil nutrient analysis for individual water and vegetation treatments is currently in progress. Once available, data will allow further analysis of water treatment and vegetation type impacts on soil nutrient status at both the Valley Vista and 5C study sites.

Soil Moisture Profiles

The 2008 water year was extremely drought limited. Although enough water was available for all biomass and pseudograin treatments at the Valley Vista site (100%, 75%, and 50%), these study plots at the 5C Cottonwood site received a maximum of only 50% (2 AF/A) water allocation for the planned 75% and 100% treatments. The restoration plots at Valley Vista, 5C and Wildlife Flood sites received the planned water treatments of 0% and 25%, however rrigation at the Wildlife Well site was discontinued mid-season due to problems with the irrigation system, excessive weeds and the lack of plant variety establishment. Only the Valley Vista and 5C study sites were irrigated in 2009, and the available water supply was sufficient to meet the experimental treatments on all study plots (100%, 75%, and 25% for biomass and pseudograins; 0% and 25% for restoration).

Valley Vista (VV) Ranch Site 2008

An increase in soil moisture content relative to the control (0%) was observed to a depth of 2 to 3 ft following each irrigation, and a significant increase in soil moisture persisted for at least 24 hours after irrigation (Figure 19). Although the moisture profiles are similar for the 75% and 100% irrigation treatments (SMC 10-15%), soil moisture content was clearly diminished in the 25% restoration water treatment (SMC ~5%) and remained only slightly greater that the 0% treatment (SMC typically <5%).

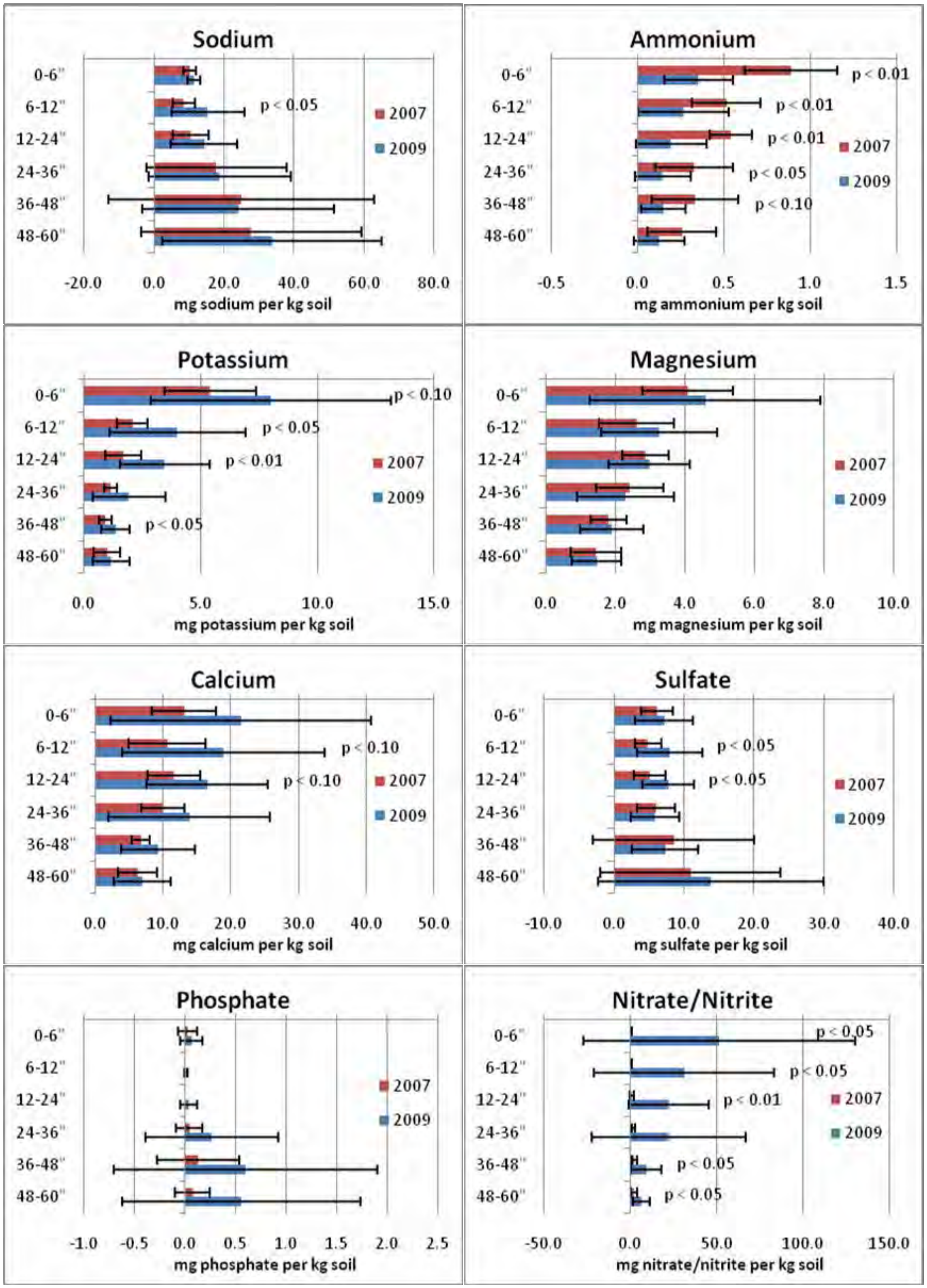

Figure 18. Comparison of summer 2007 water extractable nutrients to those of spring 2009 for VV agricultural site. Shown with standard deviation and significance of difference between years.

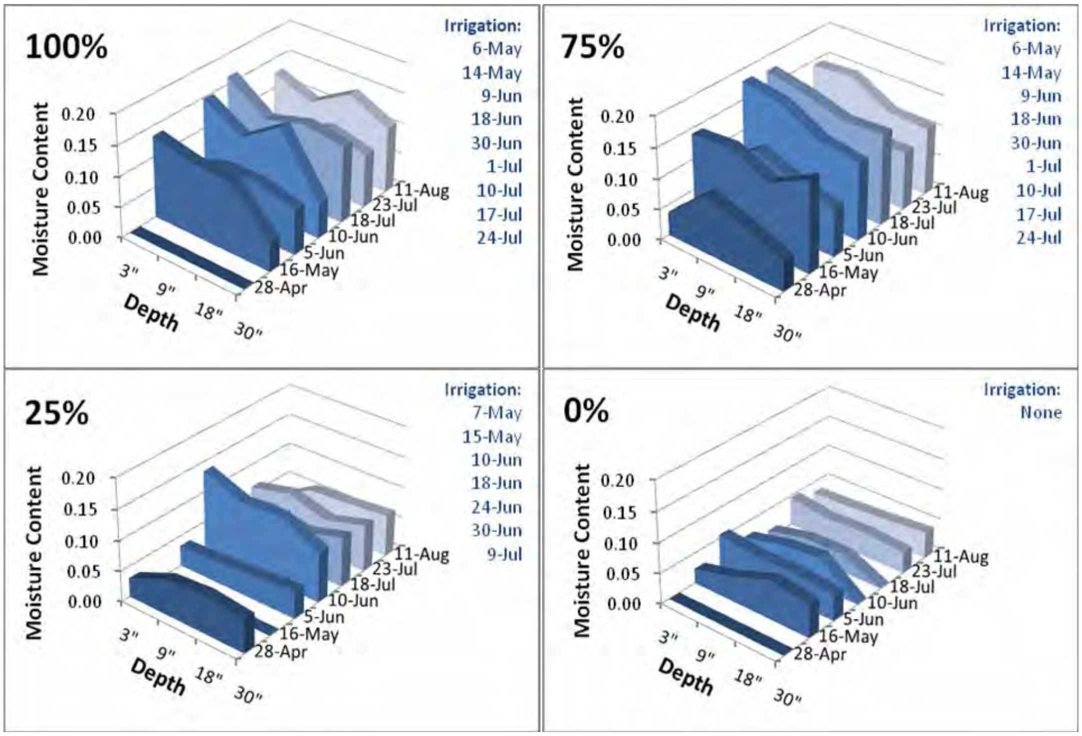

Figure 19. Soil moisture profile at VV agricultural site as mass water content for 100% and 75% water treatments on alternative agriculture field and 0% and 25% water treatments on restoration field for 2008 growing season.

Valley Vista (VV) Ranch Site 2009

The 50%, 75% and 100% water treatments all had similar impacts on the soil moisture distribution throughout the soil profile (Figure 20) early in the irrigation season. Although the surface moisture in the 50% water treatment diminished more rapidly in the weeks following the end of irrigation compared to the other treatments, moisture content in the lower profile seemed to be retained at levels similar to 75% and 100% treatments well into the end of August (SMC 10-15%). Future studies will consider whether or not crop species with greater rooting depths may have greater growth ability in 50% water treatments than those of lesser rooting depths and if that growth is comparable to that in 75% and 100% treatments.

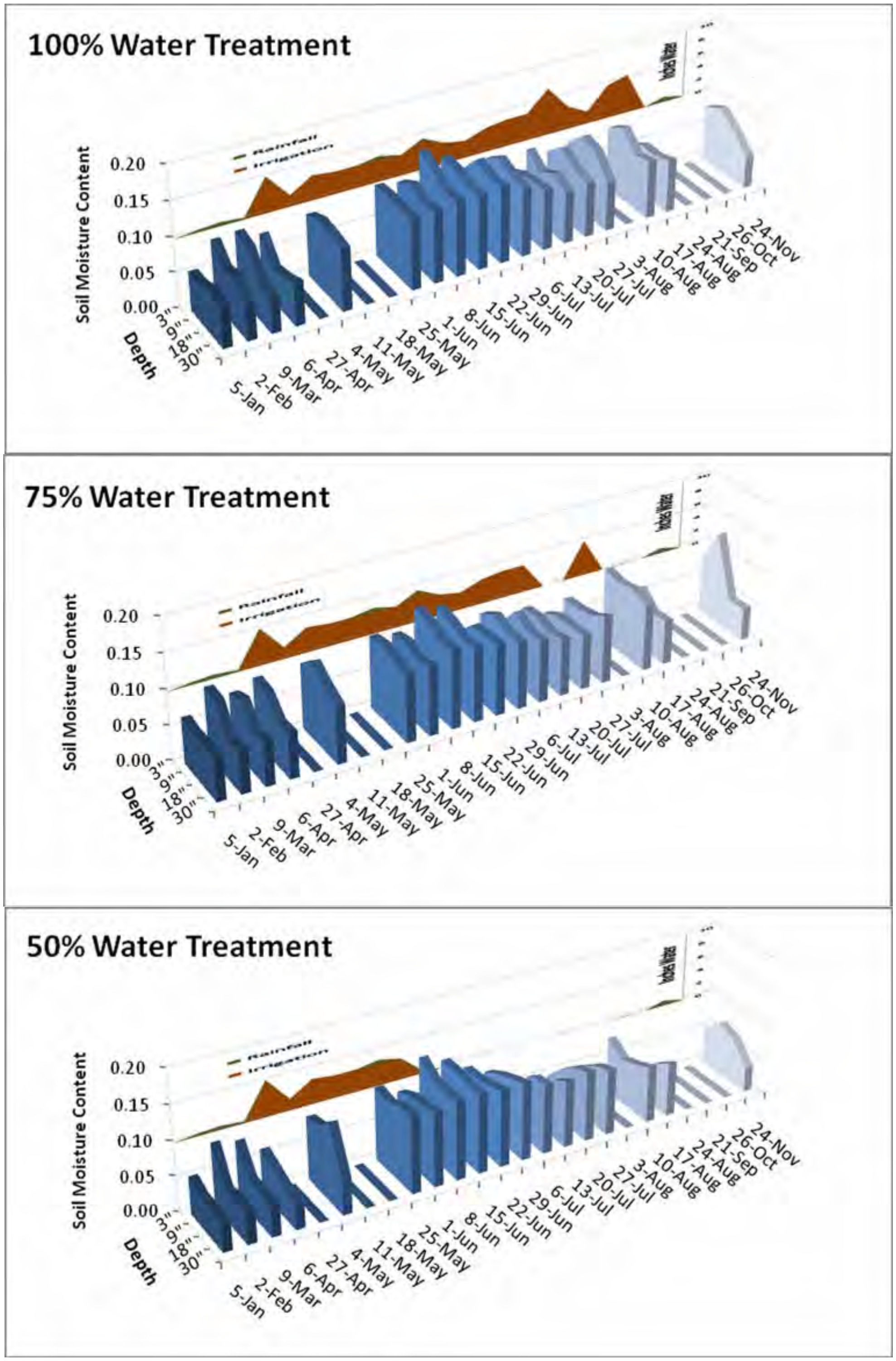

Figure 20. Soil moisture profile at VV agricultural site as mass water content for 100%, 75%, and 50% water treatments on alternative agriculture field for 2009. Precipitation and irrigation application are superimposed.

Soil moisture profiles in 0% and 25% revegetation treatments proved were similar (Figure 21) and as expected were lower than those found in the higher water treatments for alternative agriculture (SMC 5% and less compared to SMC 5-10%, respectively). Surface moisture content was slightly higher in 25% water treatment, but at depth there was not much difference. These results are as expected as surface soils are more easily dried out after irrigation while soils at depth have a greater ability to retain moisture in the absence of root extraction.

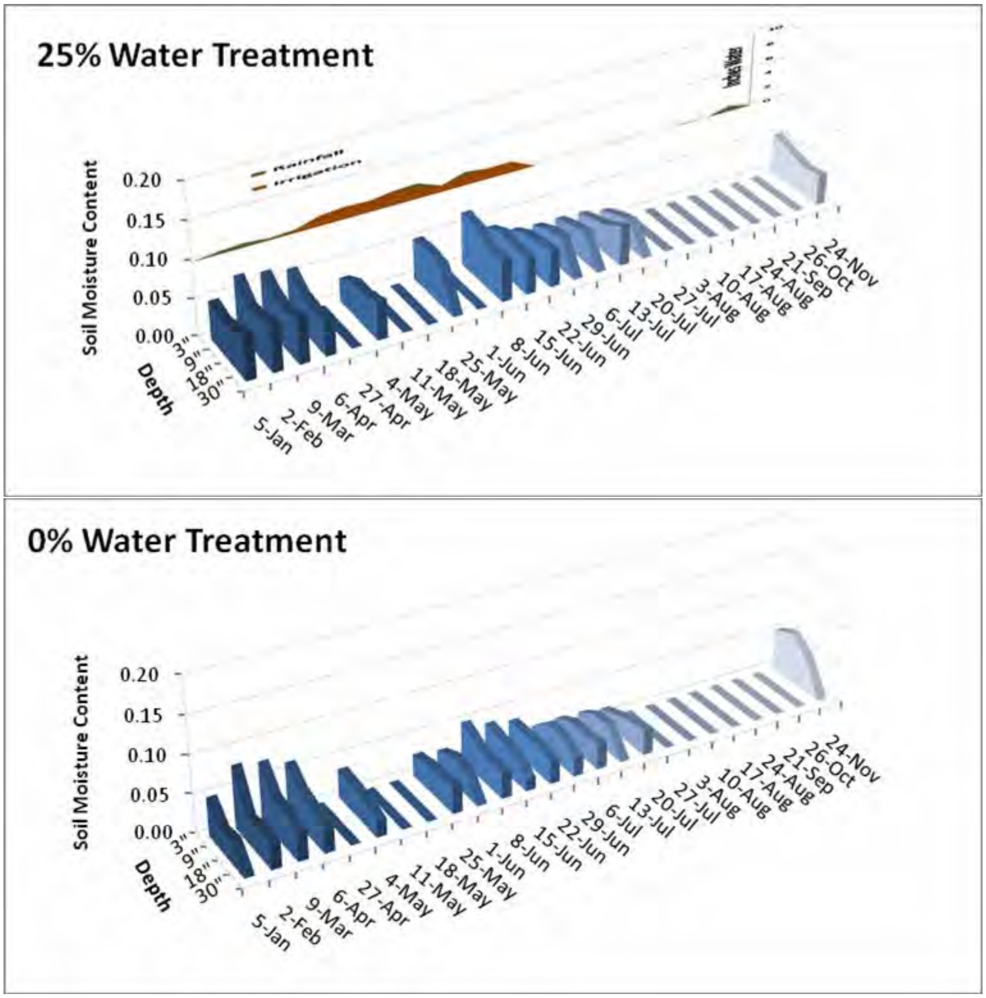

Figure 21. Soil moisture profile at VV agricultural site as mass water content for 0% and 25% water treatments on restoration field for 2009. Precipitation and irrigation application are superimposed.

5C Cottonwood (5C) Ranch Site 2008

This site is somewhat coarser in texture than that of the VV and does not appear to retain soil moisture for long periods following irrigation. The first few irrigations exhibit no significant difference in moisture content between the non-irrigated and irrigated plots within 24 hours following irrigation (All SMC ≤ 5%). This situation improved with continued irrigation over time, wherein a base of higher soil moisture content seemed to accumulate deeper within the soil profile and was not as rapidly depleted (Figure 22).

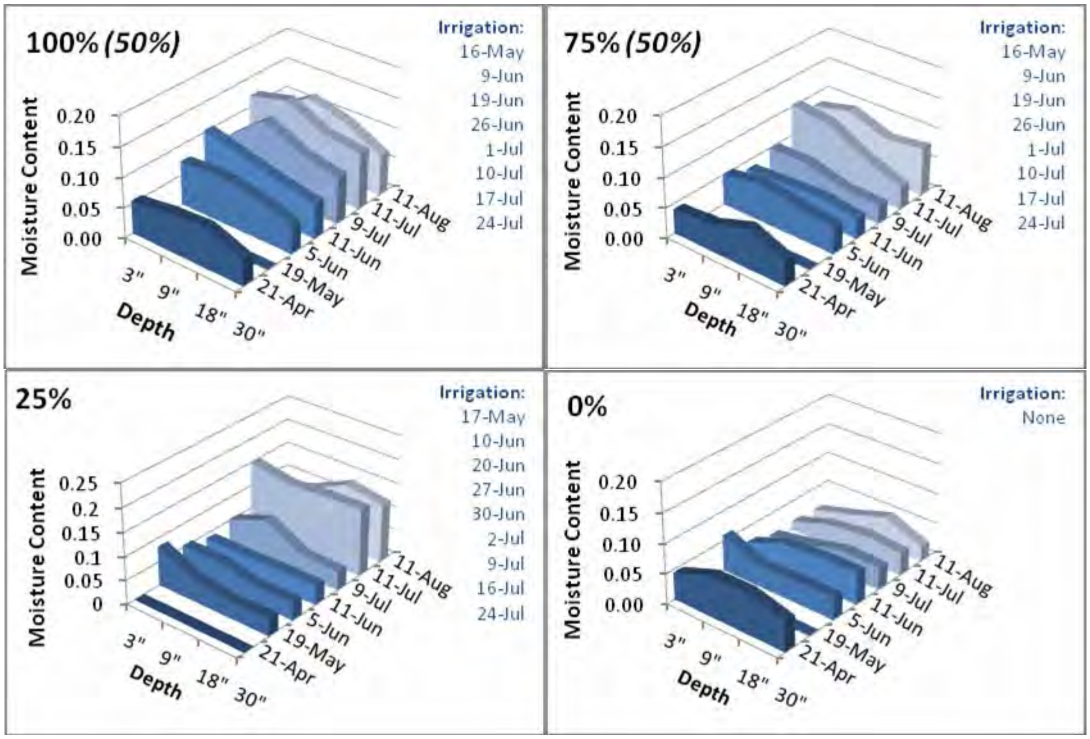

Figure 22. Soil moisture profile at 5C agricultural site as mass water content for 100% and 75% water treatments on alternative agriculture field and 0% and 25% water treatments on restoration field for 2008 growing season.

5C Cottonwood (5C) Ranch Site 2009

Once again, the difference between soil moisture profiles for the 75% and 100% water treatments was small for the alternative agriculture study (Figure 23). The disparity between SMC of the higher water treatments (SMC 5-10%) and the 50% water treatment post-irrigation (SMC < 5%) was much greater. Furthermore, moisture was not well retained with depth. This may be attributed in part lower water holding capacity associated with the sandier textured soils of the 5C study site.

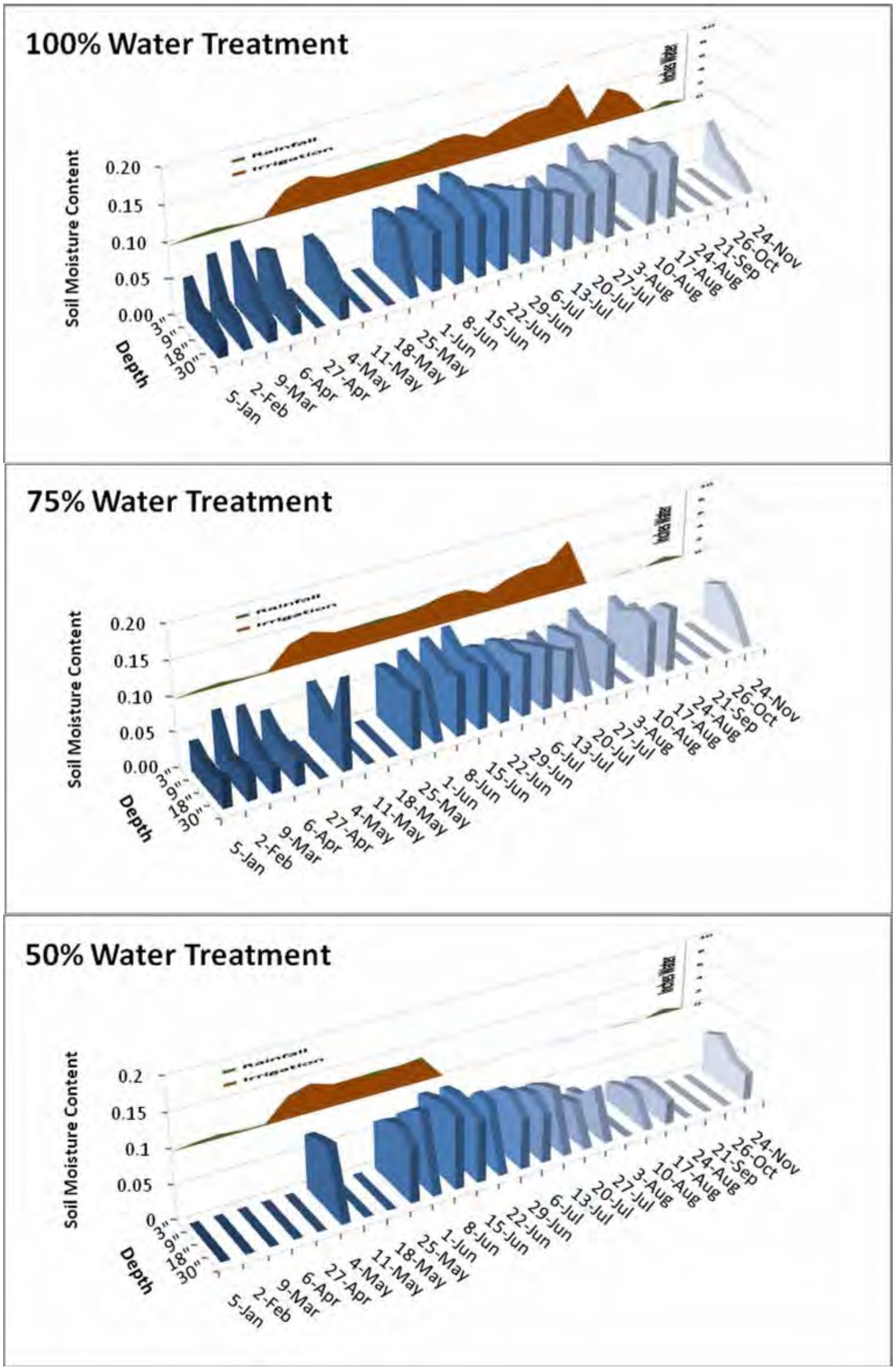

Figure 23. Soil moisture profile at 5C agricultural site as mass water content for 100%, 75%, and 50% water treatments on alternative agriculture for 2009. Precipitation and irrigation application are superimposed.

Differences between 25% and 0% water treatment soil moisture profiles were more apparent at the 5C site than at the VV site (Figure 24). This again, is likely due to the inability of coarser textured soils to retain soil moisture, even at greater depths.

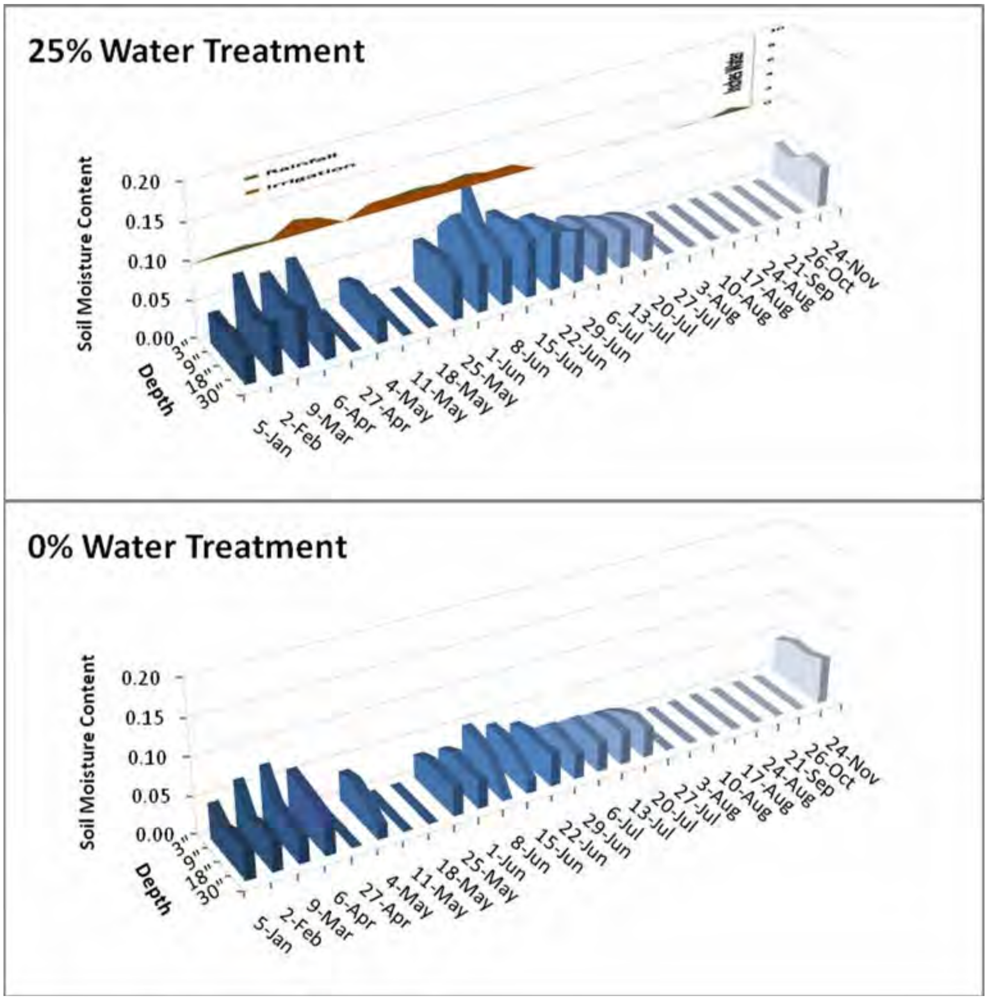

Figure 24. Soil moisture profile at 5C agricultural site as mass water content for 0% and 25% water treatments on restoration field for 2009. Precipitation and irrigation application are superimposed.

Mason Valley Wildlife Management Area: Wildlife Habitat Well (WMW) and Flood (WMF) Sites 2008

Soil at the WMW site was found to wet down 2 to 3 feet following irrigation, and a significant increase in soil moisture content was observed as long as 1 week later (Figure 25). Water holding capacity was greater than that found at either the VV or 5C study sites due to the finer soil texture. Soil moisture distribution with depth was similar for the 100% and 75% irrigation treatments that received <25% water allocation, but was notably less for the 25% restoration treatment and the control. At the WMF restoration site, the soil was found to wet only to about 6 inches immediately following irrigation; albeit a significant increase in soil moisture content remains up to 1 week later (Figure 26). The difference in profile wetting at the WMF site may be attributed in part to the method of irrigation (flood vs sprinkler), but is more likely due to the presence of highly sodic soils which would result in reduced penetration and more substantive water retention from poor subsurface drainage.

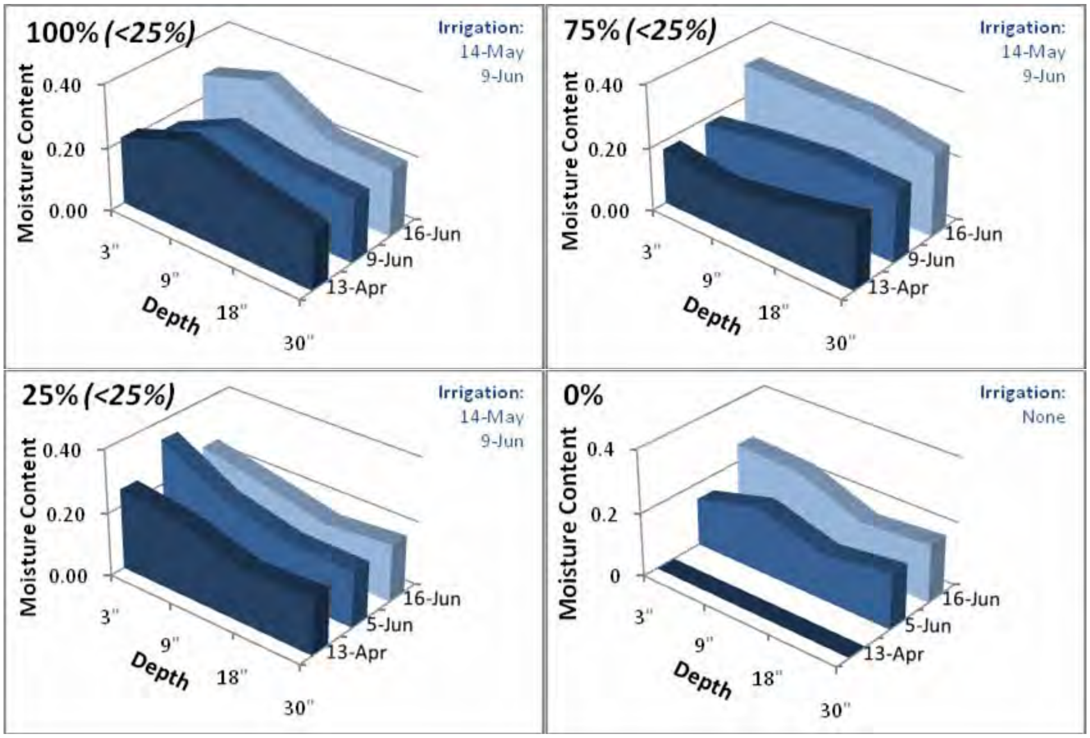

Figure 25. Soil moisture profile at WMW agricultural site as mass water content for 100% and 75% water treatments on alternative agriculture field and 0% and 25% water treatments on restoration field for 2008 growing season.

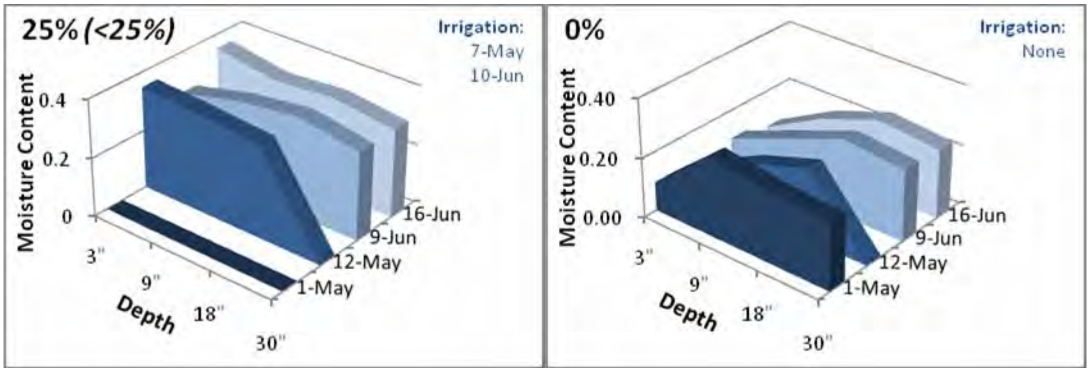

Figure 26. Soil moisture profile at WMF restoration site as mass water content for 0% and 25% water treatments on restoration field for 2008 growing season.

Dust Profiles

Since dust was collected at four elevations, it can be displayed as a profile of the air column up to 1 m. These profiles were subtracted from one another, according the prevailing wind direction, to determine the amount of dust generated (if the soil surface is eroding; represented as a positive amount) or deposited (if dust already in the profile is settling on the soil surface; represented as a negative amount). Wind direction was then applied to calculate the length of field over which the generation or deposition occurred. Wind events were selected to compare different event qualities such as duration, average wind speed, and maximum gust speed, and their effects on the various sites selected for study.

Effects of Event Duration

Two events of varying duration were compared, a long duration event consisting of 50 hrs and a short duration event of 17 hrs of average wind speed greater than 10 mph (Figure 27). Both events were characterized by the same general wind direction, average wind speed, and maximum gust speed throughout, leaving the duration as the primary variable between the two. Results from control plots were variable but exhibited no discernable difference between duration events. The 0% water treatment plots showed greater dust generation with increasing event duration whereas the 25% water treatment plots demonstrated greater deposition compared to the controls. These findings indicate that dust was continually deposited or generated over the course of the overall event.

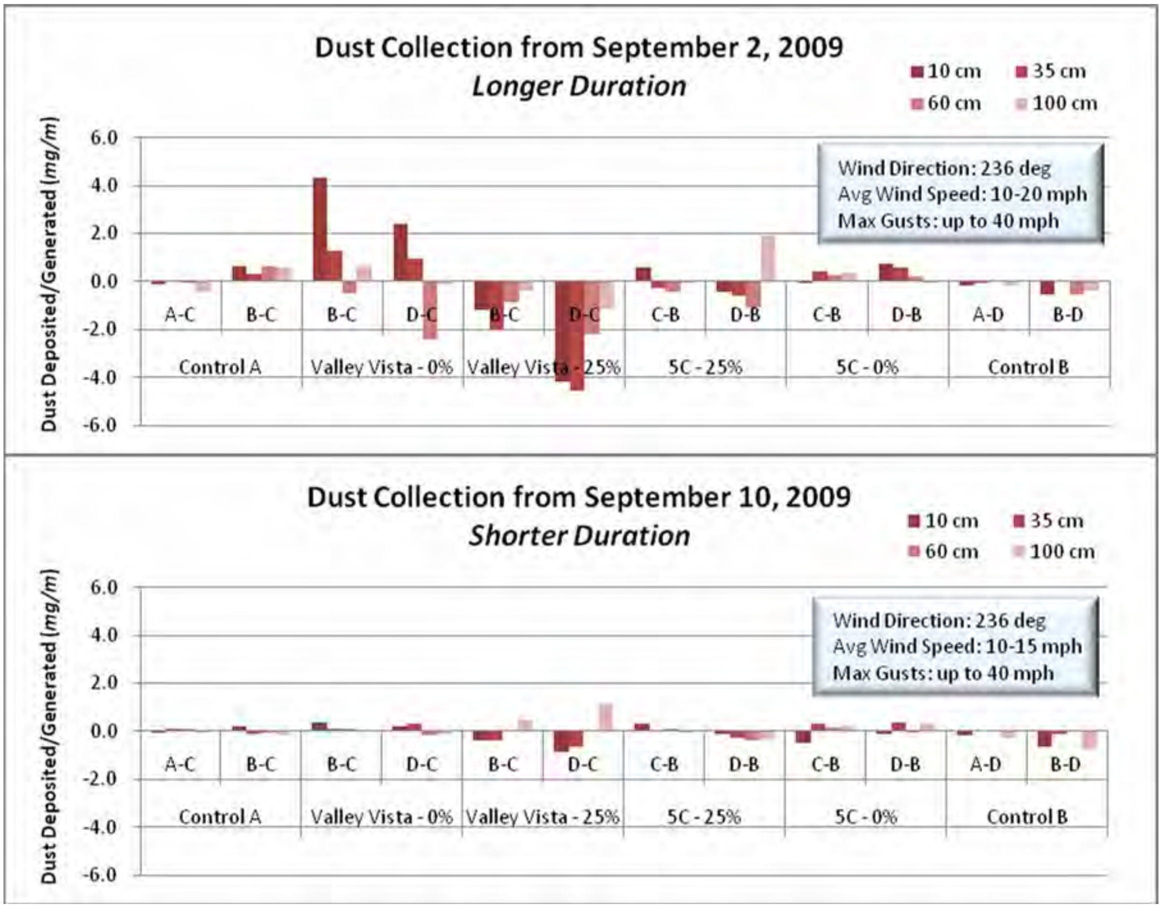

Figure 27. Dust deposited and generated collected from each group of nests on two separate dates. The conditions of the wind events (duration, direction, average wind speed, and maximum gusts) were all similar with the exception of event duration.

Effects of Wind Gusts

Two events of similar characteristics were compared wherein maximum wind gust was the primary variable. One event was characterized by gusts up to 40 mph and the other by gusts to 30 mph (Figure 28). Increased gust speed resulted in little to no difference in dust generation or deposition except for the VV site 25% water treatment plots and one aspect of the Control A site. Interestingly, both of these sites appear to have experienced a large increase in deposition with the increased gust speed which is contrary to expectations. The cause of this effect is unclear at this time.

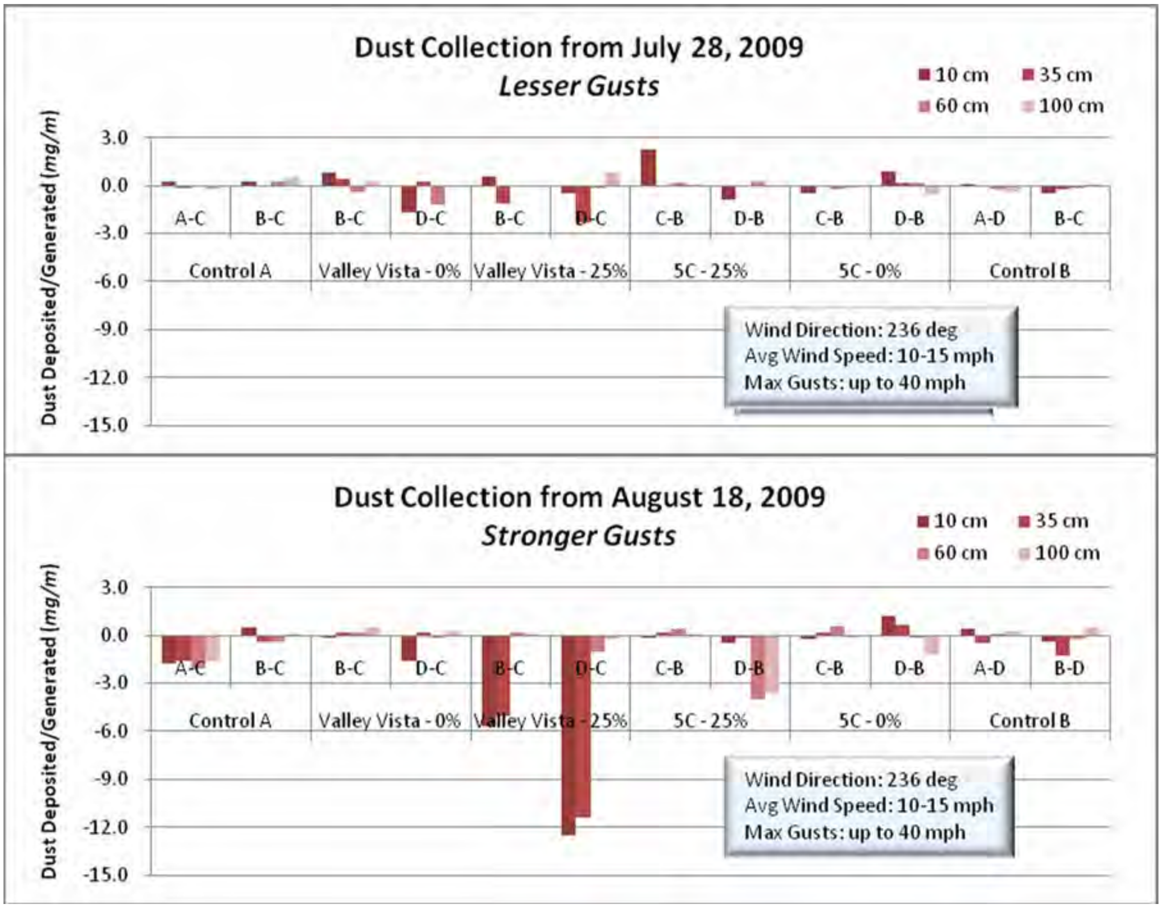

Figure 28. Dust deposited and generated collected from each group of nests on two separate dates. The conditions of the wind events (duration, direction, average wind speed, and maximum gusts) were all similar with the exception of maximum gust speed.

Effects of Sustained Winds

Two events of similar characteristics with differing average wind speed were next compared (Figure 29). The lesser of the two events maintained average wind speeds in the 10 to 15 mph range, whereas the greater of the two maintained average wind speeds in the 10 to 20 mph range. An increase in average wind speed demonstrated a corresponding increase in dust deposition at both 5C and VV sites for the 25% water treatment compared to the controls. For both VV and 5C sites the 0% water treatment plots exhibited a variable response with increased soil erosion in some instances and a greater reduction to the dust profile for collectors located in the shadow of the 25% water treatment vegetation.

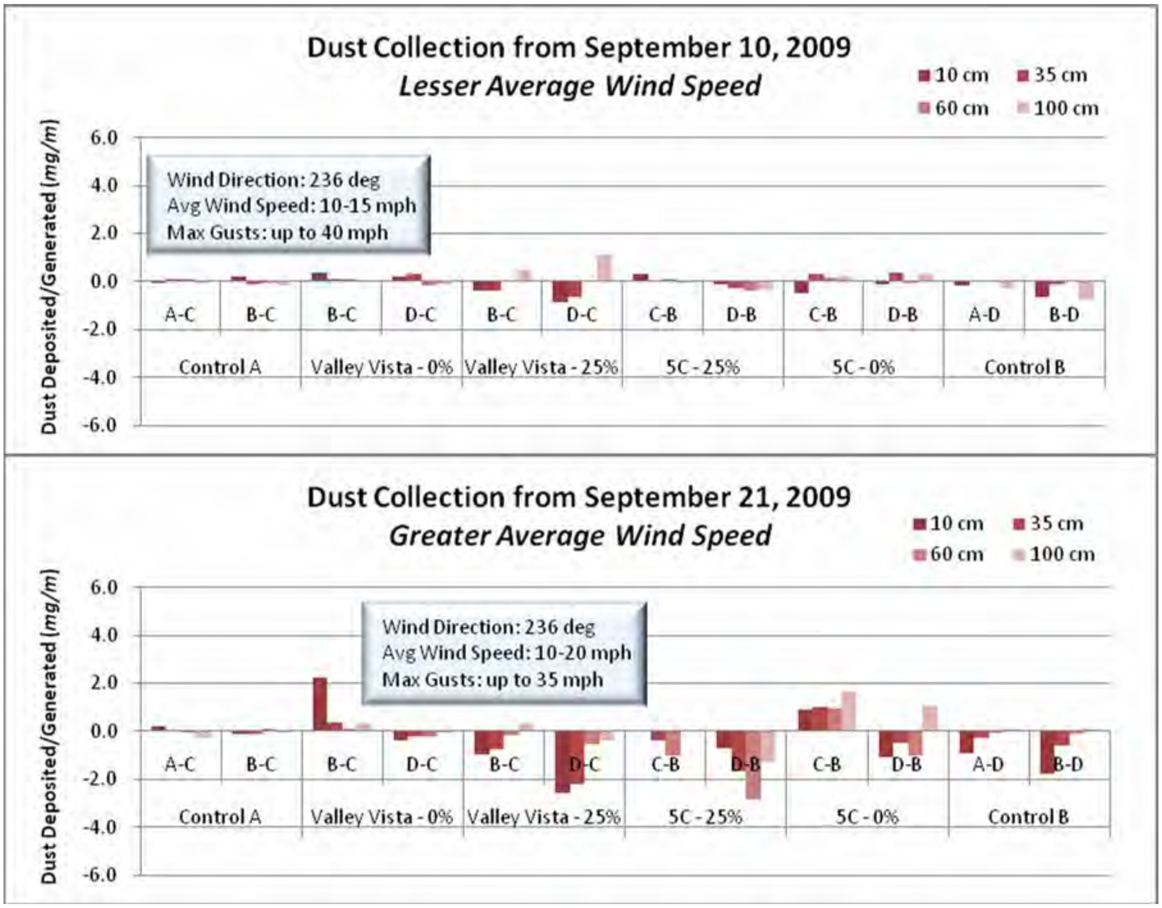

Figure 29. Dust deposited and generated collected from each group of nests on two separate dates. The conditions of the wind events (duration, direction, average wind speed, and maximum gusts) were all similar with the exception of sustained winds or average wind speed.

Effects of Overall Storm Intensity

Three events of varying intensity were compared to determine the combined effects of duration, average wind speed, and maximum gust speed on dust generation and deposition (Figure 30). Low intensity events exhibited variable and unpredictable deposition and generation of dust at all sites. Dust collection was limited and patterns in deposition or generation were riddled with anomalies. As the events increased in intensity, more definitive patterns began to emerge.

An increase in deposition at all heights except 10 cm was found for Control Site B. However, there was an apparent increase in dust generation 10 cm above the land surface. This was likely symptomatic of the grain size distribution present at the surface of control areas or the presence of surface crusting. Finer sized particles may have been depleted leaving largest sand grains at the surface. These particles, while erodible, do not lift as easily into the air column. Their presence then dominates the lowest portions of the dust profile. Without the presence of smaller soil particles to erode with these larger grains, the dust profile then becomes bottom heavy, producing the odd results observed at the Control B site.

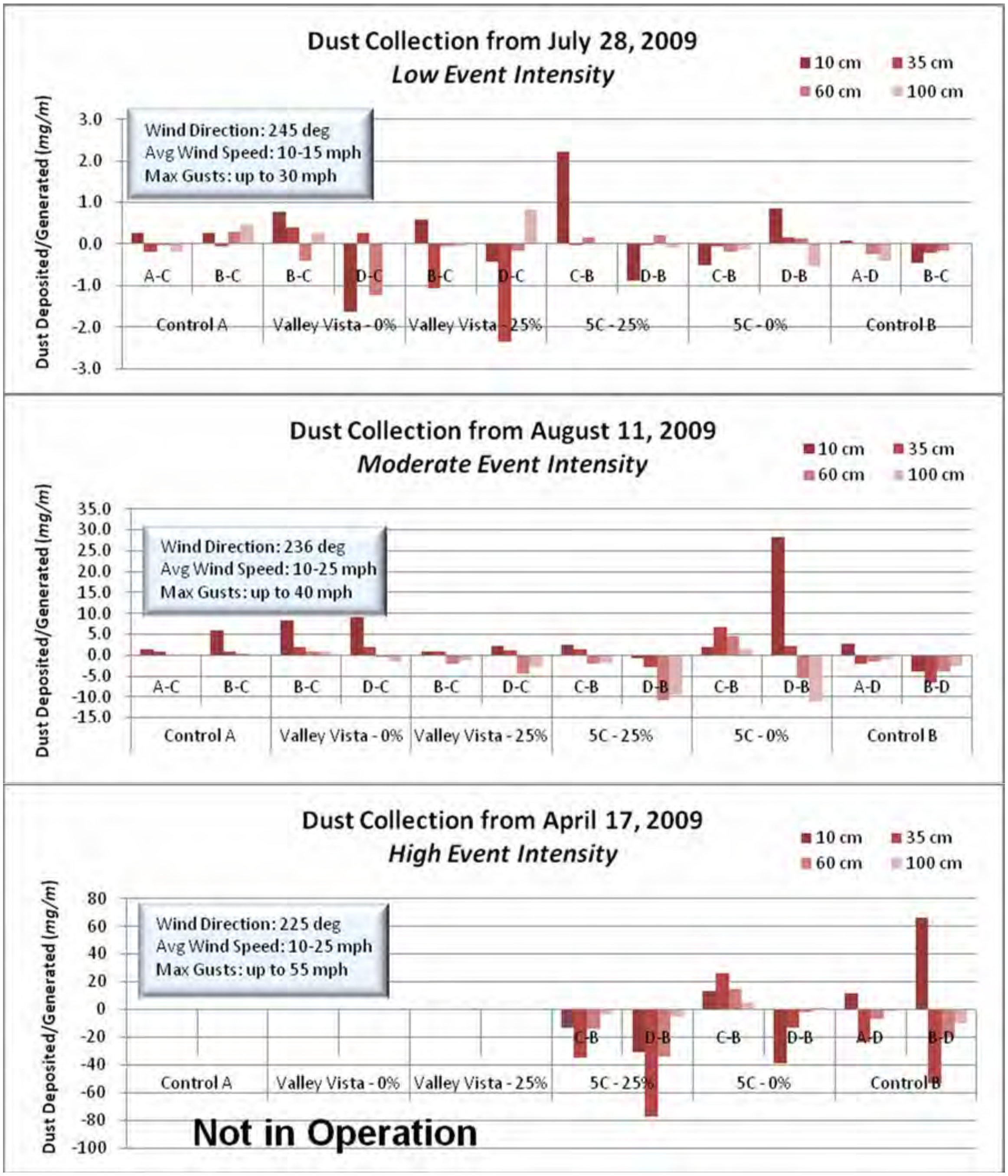

Figure 30. Dust deposited and generated collected from each group of nests on three separate dates. The conditions of the wind events (duration, direction, average wind speed, and maximum gusts) all varied in intensity adding up to three events covering low, moderate, and high event intensities. Please note that the scales for each event vary from the others.

A similar distribution was observed for the 25% water treatment plots during moderate intensity events, where there was a reduction in dust profile at the 60 and 100 cm heights but an increase at 10 and 35 cm. This display, however, may be the result of a different phenomenon. Vegetation produced by the higher water treatment may be effectively keeping the dust from moving higher in the profile. This distribution was also found on one side of the 0% water treatments. Closer examination revealed that where reductions in dust are seen collectors were located in the lee of the vegetation produced by the 25% water treatment, and where dust generation was observed collectors were located on the far side away from the shadow of the vegetation. Furthermore, the outgoing collector is more greatly influenced by the increased dust produced by the road (Figure 5).

Full profiles of accumulation were observed in the 25% water treatment plots during high intensity events, as well as in those collectors on the 0% treatment located to the lee of the 25% treatment vegetation. Erosion increased in 0% water treatment plots as event intensity increased.

Summary

Totals calculated for each event were summed for the 2009 growing season to illustrate the overall effect each specific site had on the dust profile (Figure 31). Overall, the 25% water treatments were far more effective at reducing dust generation and increasing dust deposition than the 0% water treatments and, in some instances more so than even the controls. The 0% water treatments were found to be far more erosive than natural conditions.

When the VV site was compared to the 5C site we generally observed greater dust deposition in the 25% water treatment of the former over the latter. This was likely due to a greater density of biomass present on the VV site. There was no discernable difference between the sites on the 0% water treatment plots.

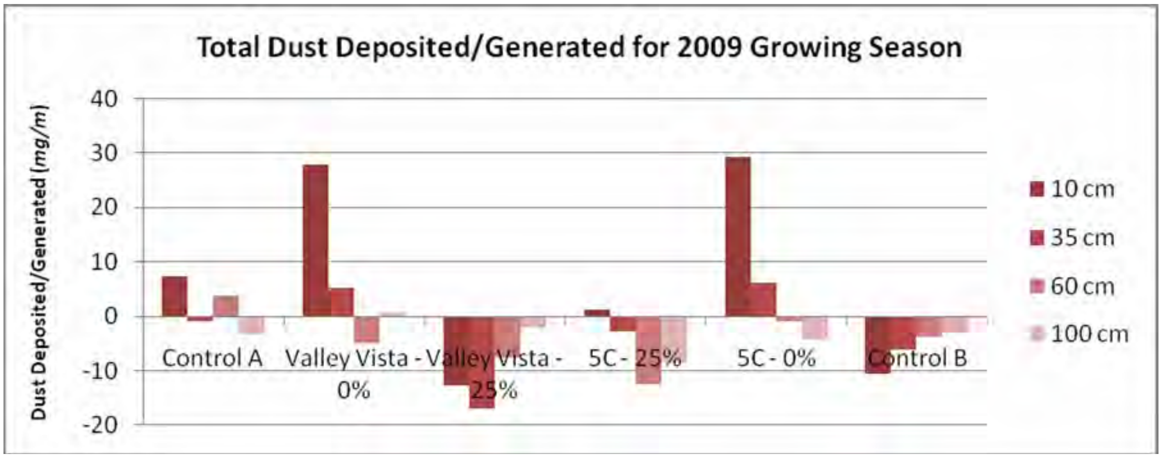

Figure 31. Total dust generated/deposited during the 2009 growing season (April through September) at all six collector sites.

Soil Temperature Sensing and Relationship to Soil Moisture Content

Several field campaigns were conducted at both the WMW and VV study sites during the summer of 2008. Preliminary data showed a clear delineation of differences in soil moisture and soil bulk density. Figure 32 shows the spatial distribution of differences in soil temperatures between night and day taken 15 cm below the soil surface. Those portions of the cable that exhibit larger day to night differences represent zones of moist soil, as heat transfer is facilitated by higher moisture content and the surface temperature pulse travels deeper and faster into the soil.

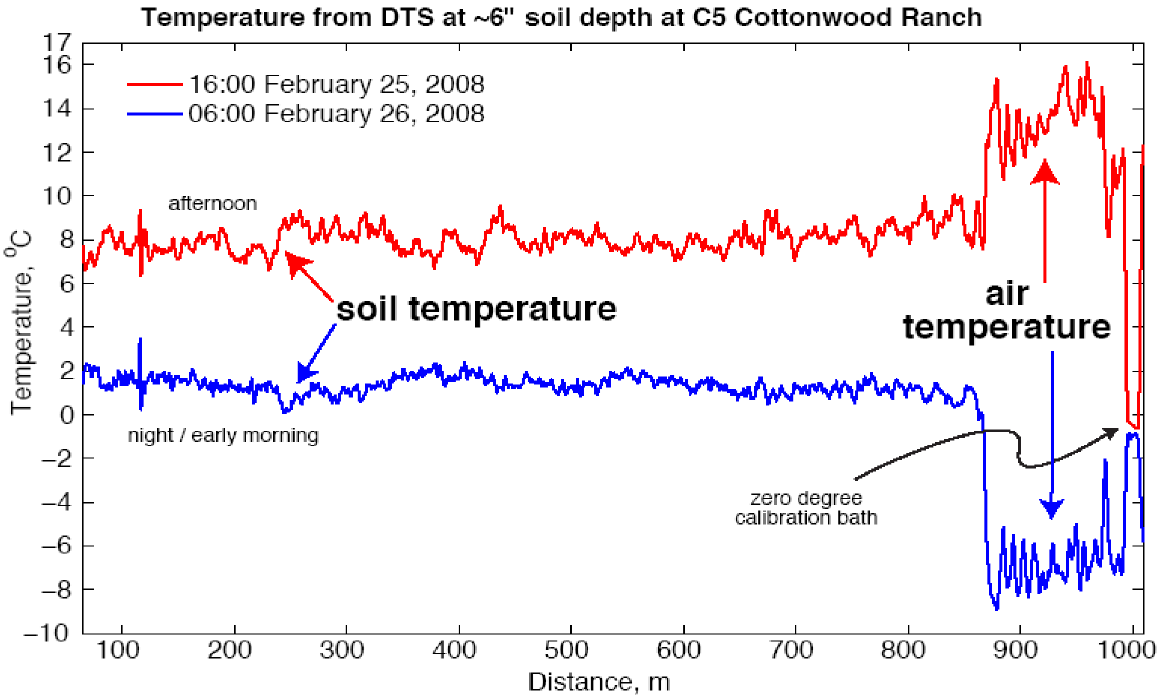

Figure 32. Soil temperatures at 15 cm below surface as measured using DTS. The X-axis represents distance along the fiber optic cable and the final 1~130 m of the fiber are located above the soil surface. Those portions of the fiber optic cable showing the largest differences between day and night temperatures are in areas of higher moisture content.

The effects of irrigation can also easily be seen in Figure 33, in which two temperature surveys were conducted during a given irrigation cycle. These traces represent “double ended measurements”, in which the two fibers in the cable were joined to produce a 2,000 meter long fiber. The data taken from 1,000 to 2,000 m in Figure 33 represents measurements in the same portion of the soil profile, but simply folded back on the original signal. Following irrigation (red trace), the soil temperatures were much cooler, in spite of the fact that the trace was taken in the middle of the day. In this case, the irrigation reduced the soil temperature everywhere, and was also likely aided by latent heat flux during evaporation.

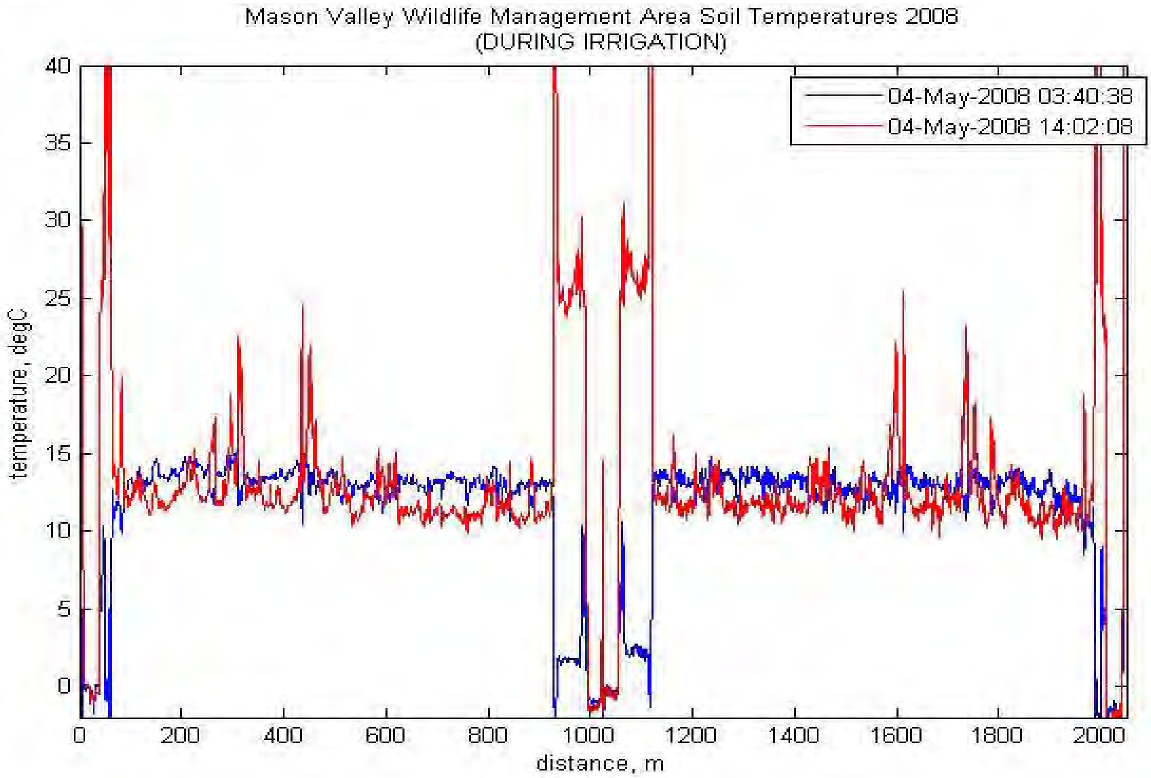

Figure 33. Soil temperatures at 15 cm below surface following an irrigation period. The soil temperatures decreased during the daytime period, in response to the infiltration of cool water. The measurements were conducted in "double-ended" mode, and data from the 1,000 to 2,000 m of the cable represents duplication of the first 100 m. The second 1,000 meter is much noisier than the first 1,000 m and is the result of connector losses at 1,000 m.

The bulk of the field data thus far from this study was collected in April 2009, and the entire data set comprises meteorological data, ground surface temperatures, subsurface temperatures, and soil water contents measured by both TDR and destructive sampling. The meteorological data, including air temperature, wind speed, and net radiation are shown in Figure 34. Shown in Figure 35 are the wind speed and the calculated evapotranspiration rate (expressed in mm day^{-1}) for each five-minute period as determined by the Penman-Monteith equation (Allen *et al.*, 1998).

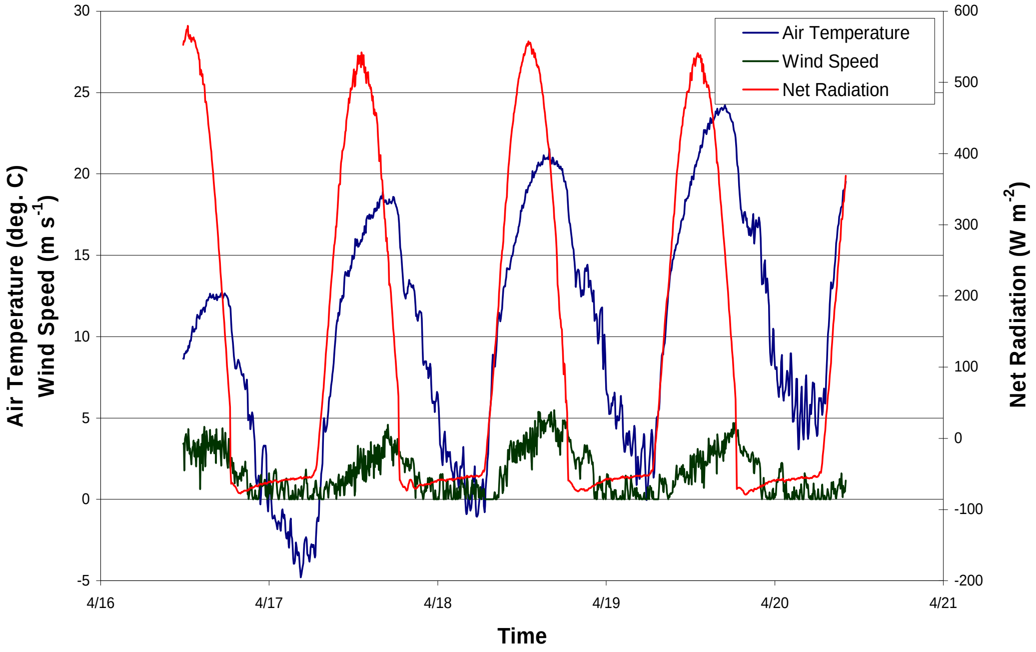

Figure 34. Meteorological data recorded at Valley Vista Ranch, April 2009

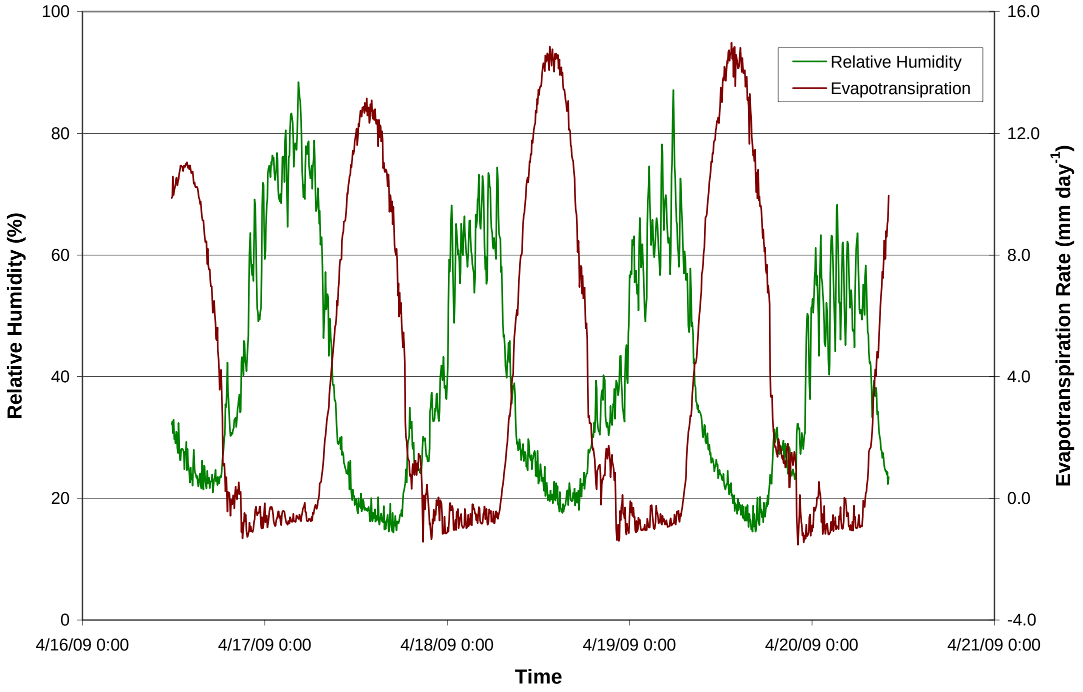

Figure 35. Relative humidity and Penman-Monteith evapotranspiration rate

The analysis in this study focuses on the west side of the VV site, where the revegetation study component was located. This area was divided into five plots, each approximately 30 meters wide, as depicted in Figure 36 below. Plots 1, 3, and 5 in this figure were not irrigated, whereas plots 2 and 4 were irrigated at 25% of a typical water year budget for crop production. Although the entire area had been seeded with native species, the only established vegetation was confined to plots 2 and 4 (irrigated). Plots 1, 3, and 5 had exposed bare soil at the surface and little or no vegetation within the plot area itself.

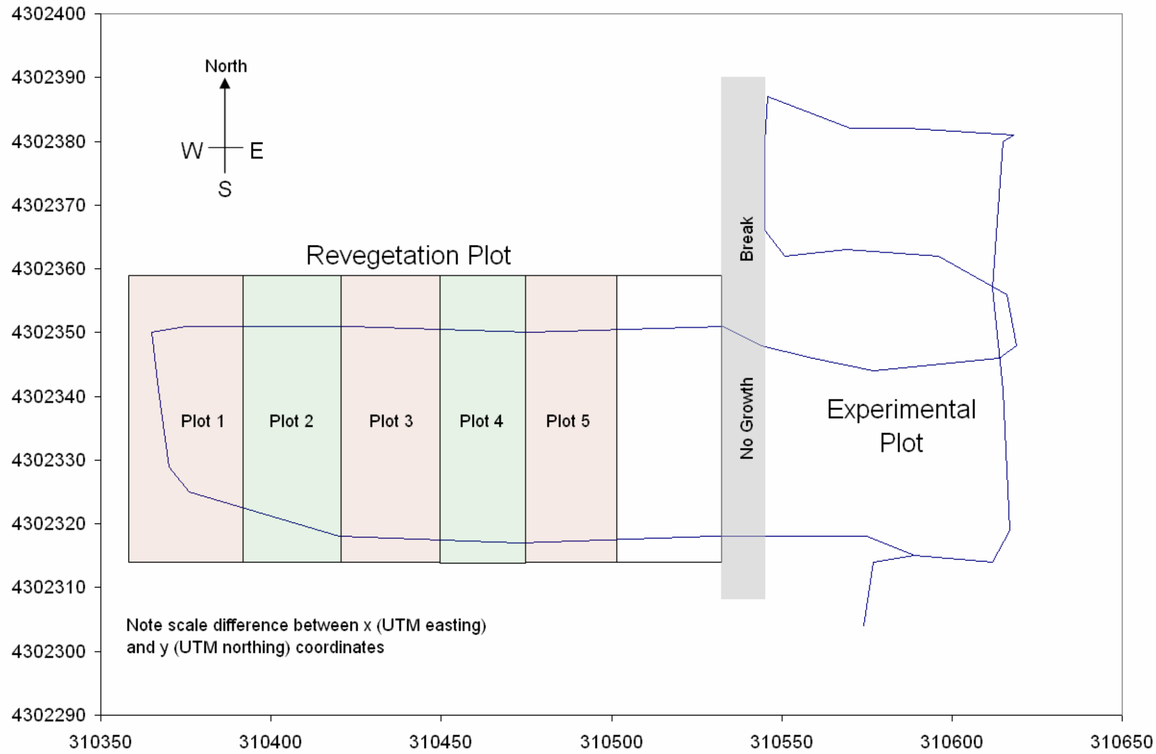

Figure 36. Alternating non-irrigated (#1, 3, 5) and 25% irrigated (2, 4) sections on the west side of the Valley Vista Ranch field site

The buried fiber-optic cable (shown in blue in Figure 36) passed through plots 2-5 two times (once on the south side and again on the north side of the section), and the cable made two 90° turns in plot 1 (as shown above). For each section, the points on the cable located within that section were identified and a composite temperature trace was calculated. The set of points within the section was trimmed, eliminating the first and last temperature reading (2 meters on either side of each plot) to minimize interference between vegetated and bare sections. The composite trace for each section was calculated by taking the mean temperature within the trimmed data set at each sampling time. The nine composite traces are shown in Figure 37.

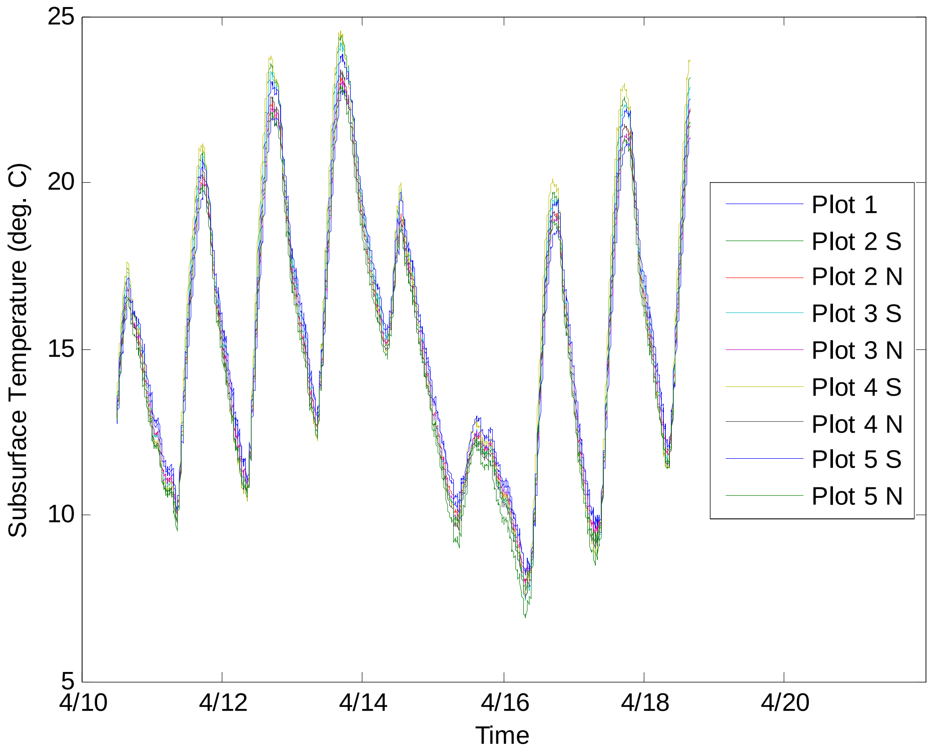

Figure 37. Composite temperature traces for the nine sections of cable comprising the western side of the VV study area.

Amplitude damping and phase shifts were calculated for each of the composite traces shown above. The ground surface temperature in each section was observed using a chromal-constantan thermocouple (Type E). Two different thermocouples were deployed: one in a barren area, and one in located beneath the canopy within a vegetated plot. The surface temperature traces evaluated here are shown below in Figure 38, along with the air temperature recorded by the meteorological monitoring station on site. Plots 1, 3, and 5 used the bare surface temperature as the basis for amplitude damping and phase shift calculations; plots 2 and 4 used the vegetated surface temperature trace for this purpose.

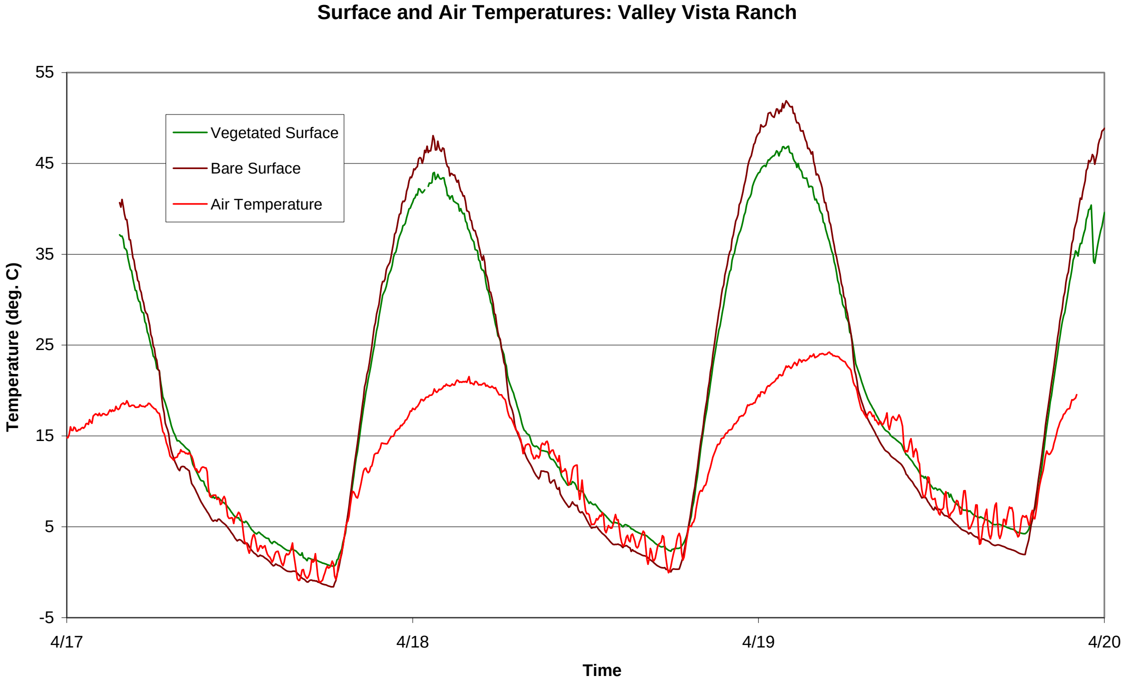

Figure 38. Representative temporal temperature evolution between air temperature and soil DTS temperatures measured beneath bare soil (brown) and vegetated soil (green). As expected, the bare soil peaks with higher temperatures due to increased soil heat flux.

Figure 39 shows the calculated thermal diffusivities from the measured phase lag and amplitude attenuation. Overall, the phase shift calculations are bias higher than the amplitude method, and are likely more robust as they do not rely on selecting a single point of maximum temperature, but rather make use of the entire temporal evolution of temperature.

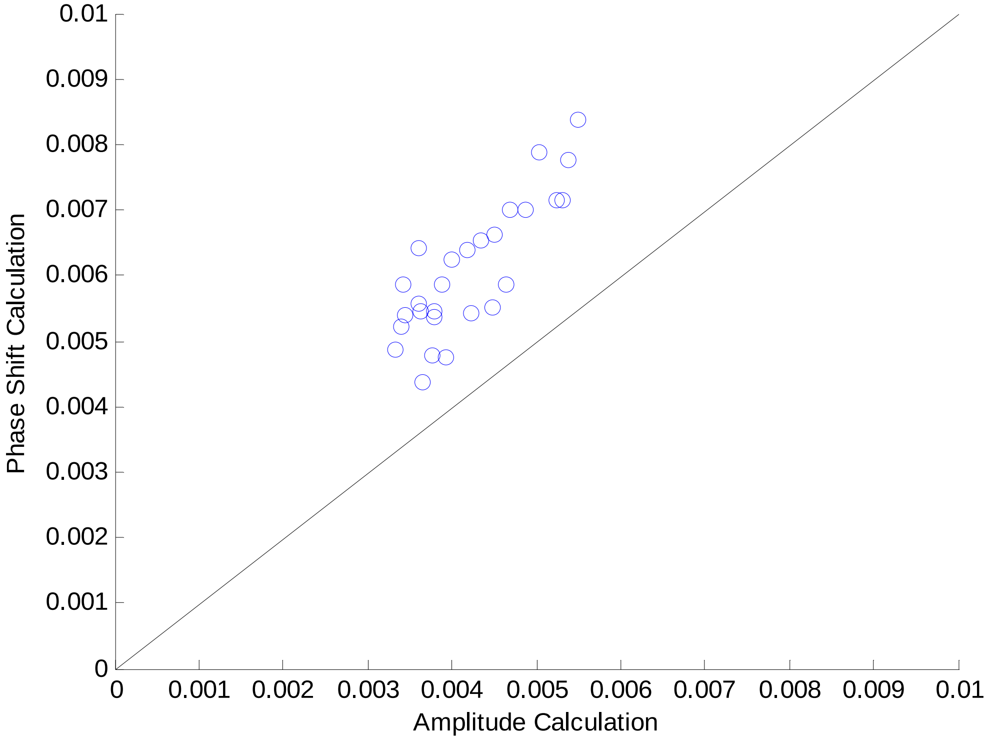

Figure 39. Calculated thermal diffusivities using both phase and amplitude shifts.

The calculated thermal diffusivities are somewhat lower than would be expected for the observed and calculated moisture contents, assuming commonly used models relating moisture content to thermal conductivity and heat capacity. However, during this period of study, the upper most portion of the soil profile was very dry, violating the assumption of uniform moisture content with depth over the top 15 cm. In addition, the undulating variability of cable installation depth lead to significant uncertainty in the calculated volumetric water contents.

To avoid these difficulties in the future, a multiple depth cable with finer vertical depth control will be implemented. Dunne-Steele et al (2009) have shown the advantages of multiple fibers at depth. These techniques reduce the impacts of cable burial uncertainty, and also remove the variability due to very dry surface soils, which will always bias the thermal diffusivities towards lower water contents.

Soil Nutrient availability

Soil Texture

The < 2mm soil fraction at the Wildlife Management Area revegetation field plots (WMF) had significantly higher percent clay (14.7 %) and silt content (54.7 %) and significantly lower percent sand content (30.6 %) than all other fields (Figure 40). There was no difference in texture between revegetation and alternative agriculture field plots at either the 5C Cottonwood and Valley Vista locations, although the Valley Vista plots had a significantly higher silt content (20.4 %) than the 5C Cottonwood plots (16.9 %) and a significantly lower sand content (75.7 %) than either of the Cottonwood fields (79.7 %).

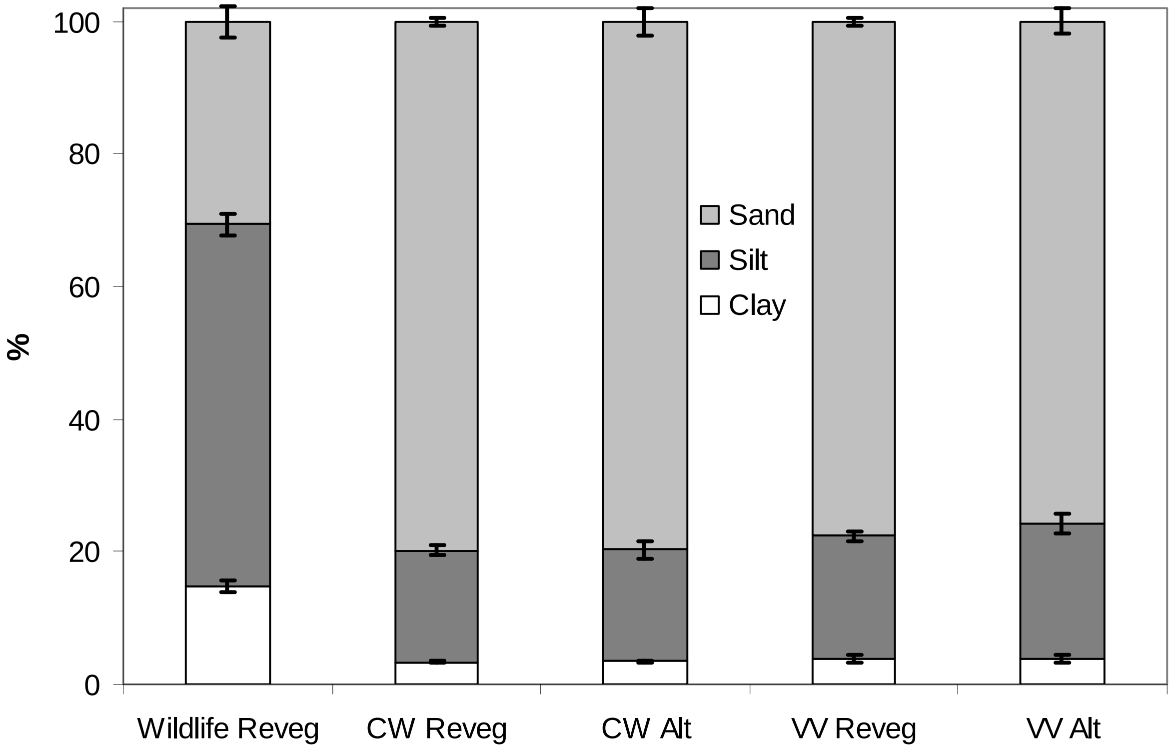

Figure 40. Particle size distribution for Wildlife Refuge, Cottonwood (CW), and Valley Vista (VV) revegetation (Reveg) and alternative agriculture (Alt) soils.

<u>Soil C and N</u>

Prior to planting, the WMF revegetation field had a significantly higher C (1.64 %) and N (0.13 %) concentration and C/N ratio (12.9) than all other fields (Figures 41 and 42). The Cottonwood revegetation plots had a significantly higher concentration of C (0.80 %) and N (0.07 %) and C/N ratio (10.8) than the Cottonwood alternative crops area (C=0.46%; N=0.05 %; C/N=9.2). Although soil C and N concentrations were measured in samples following planting, no significant changes were observed following one planting season.

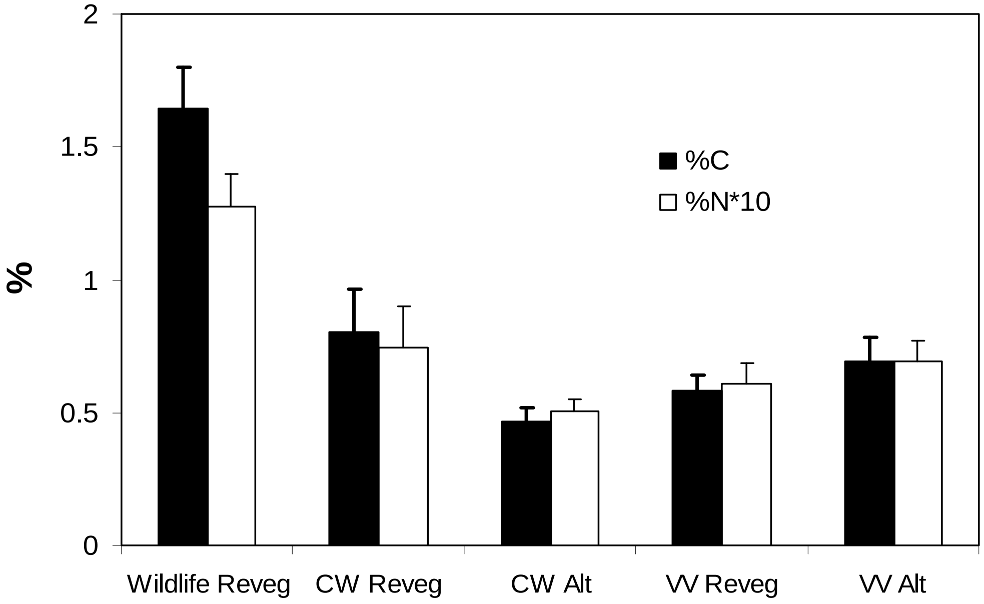

Figure 41. C and N concentrations for Wildlife Refuge, 5C Cottonwood (CW), and Valley Vista (VV) revegetation (Reveg) and alternative agriculture (Alt) soils used in the pre-planting incubation.

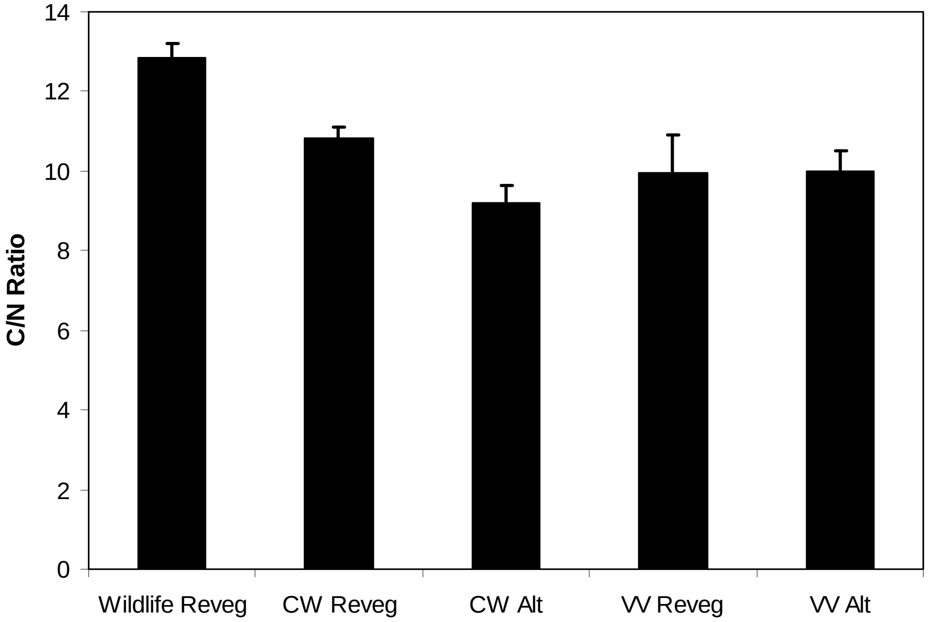

Figure 42. C/N ratios for Wildlife Refuge, 5C Cottonwood (CW), and Valley Vista (VV) revegetation (Reveg) and alternative agriculture (Alt) soils used in the pre-planting incubation.

Laboratory Study Results

Cumulative C mineralization - The MANOVA analysis showed that moisture and field significantly affected the cumulative C production per gram of soil in the pre-planting incubation (Table 4). Carbon mineralization was lowest for the 0.05 moisture treatment (1.42 ± 0.32 µgC g_s^{-1} d^{-1}) compared to the 0.15 (4.96 ± 0.74 µgC g_s^{-1} d^{-1}), and 0.30 (6.65 ± 0.71 µgC g_s^{-1} d^{-1}) moisture treatments (Figure 43). Carbon mineralization was highest in the Cottonwood revegetation (6.79 ± 1.37 µgC g_s^{-1} d^{-1}) followed by the Valley Vista revegetation (4.67 ± 0.89 µgC g_s^{-1} d^{-1}), Wildlife Area revegetation, (4.02 ± 0.90 µgC g_s^{-1} d^{-1}), Valley Vista alternative (3.88 ± 0.67 µgC g_s^{-1} d^{-1}), and Cottonwood alternative fields (3.41 ± 0.91 µgC g_s^{-1} d^{-1}).

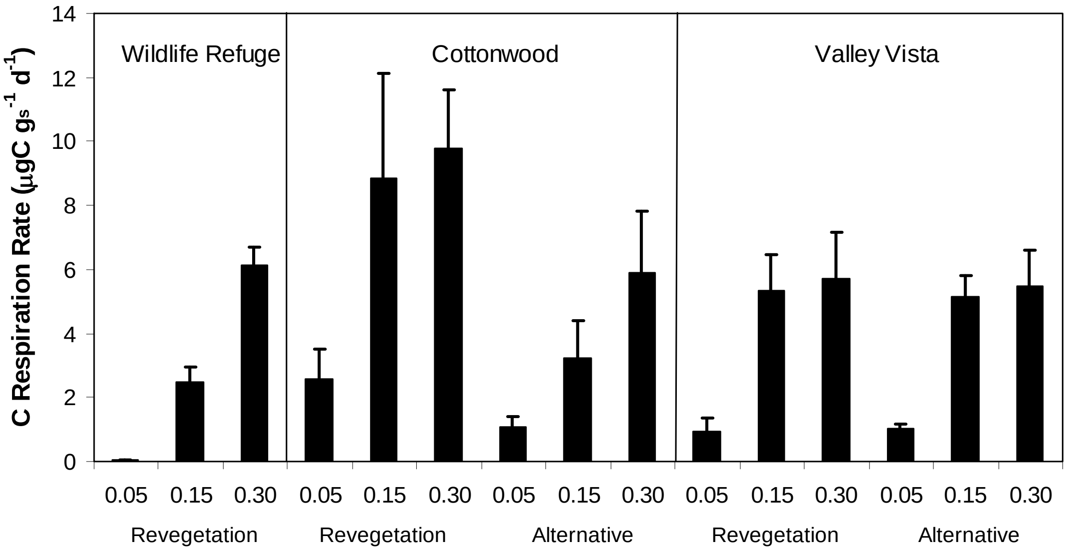

Figure 43. C respiration rate for the pre-planting incubation at the Wildlife Refuge, Cottonwood, and Valley Vista revegetation and alternative agriculture fields as a function of soil moisture content. Error bars represent standard error (n = 3).

For the post-planting incubation the MANOVA analysis showed that moisture and vegetation significantly affected the C mineralization (Table 4). Carbon mineralization rates were lowest for the 0.05 moisture treatment (5.08 ± 0.47 µgC g_s^{-1} d^{-1}) compared to the 0.15 (10.32 ± 1.02 µgC g_s^{-1} d^{-1}), and 0.30 moisture treatments (9.81 ± 1.01 µgC g_s^{-1} d^{-1}; Figures 44 and 45). Respiration rates were highest for Tef (11.64 ± 1.29 µgC g_s^{-1} d^{-1}), followed by Switchgrass (7.29 ± 0.86 µgC g_s^{-1} d^{-1}), Alfalfa (7.61 ± 1.02 µgC g_s^{-1} d^{-1}), and Amaranth (7.08 ± 1.07 µgC g_s^{-1} d^{-1}).

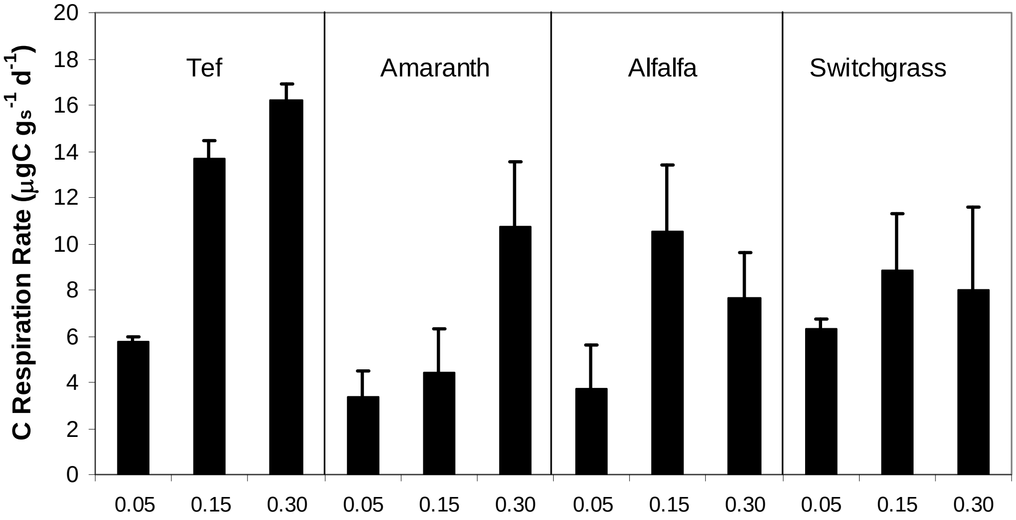

Figure 44. C respiration rates for the post-planting incubation in the Valley Vista field as a function of soil moisture content and vegetation type. Error bars represent standard error (n = 3).

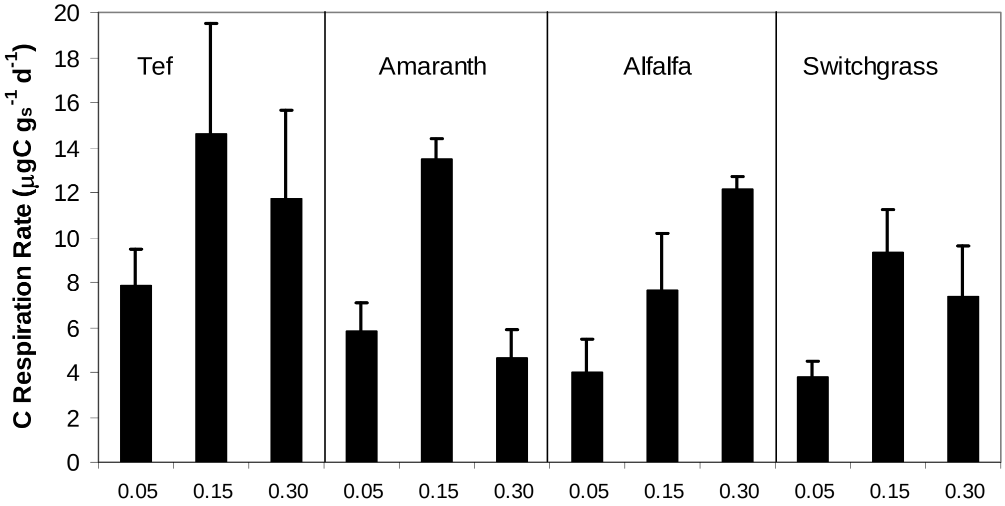

Figure 45. C respiration rate for the post-planting incubation in the Cottonwood field as a function of soil moisture content and vegetation type. Error bars represent standard error (n = 3).

Cumulative respiration rates also showed a significant moisture*field*vegetation interaction (Table 4) indicating that effects of moisture and vegetation were not consistent among fields. Respiration rates were similar in all Valley Vista and Cottonwood soils in the 0.05 moisture treatment. For the Valley Vista site, respiration rates were significantly higher in the Tef soils than in the Amaranth soils in the 0.15 moisture treatment. In contrast, at this moisture level respiration rates were the same for all the vegetation types in the Cottonwood field. For the Valley Vista field, respiration was higher in Tef than in Alfalfa soils in the 0.30 moisture treatment while for this moisture treatment, Amaranth soils had higher respiration rates than Alfalfa soils in the Cottonwood field. The overall C mineralization rate combining both fields and all moisture treatments in the post-planting incubation was 8.40 ± 0.57 μgC g_s^{-1} d^{-1}, which was significantly higher than the pre-planting incubation.

Net N mineralization - Moisture and field significantly affected the net N mineralization in the pre-planting incubation (Table 5). Net N mineralization was dominated by NO_3 production, or nitrification. The net N mineralization was lowest for the 0.05 moisture treatment (9.33 ± 1.95 mg N kg^{-1}), followed by the 0.15 (44.78 ± 6.56 mg N kg^{-1}), and 0.30 moisture treatments (74.85 ± 7.64 mg N kg^{-1}; Figure 34). The net N mineralization was highest in the Cottonwood revegetation (75.24 ± 14.81 mg N kg^{-1}) followed by the Valley Vista alternative fields (44.80 ± 8.41 mg N kg^{-1}), Cottonwood alternative (43.45 ± 8.11 mg N kg^{-1}), Valley Vista revegetation, (33.92 ± 7.39 mg N kg^{-1}), and Wildlife Area revegetation field (17.52 ± 4.44 mg N kg^{-1}). The overall net N mineralization for the pre-planting soils was 42.99 ± 4.59 mg N kg^{-1}.

Table 5. MANOVA results for the pre-planting incubation.

Factor	Moisture	Field	Mst*Fld
C mineralization	***	**	ns
Net N mineralization	***	***	ns

* = p<0.05; ** = p<0.01; *** = p<0.001; ns = not significant

In the post-planting incubation moisture, field, the moisture*field interaction, vegetation, and the field*vegetation interaction significantly affected the net N mineralization (Table 6). In contrast to the pre-planting incubation, net N mineralization did not increase with moisture. Instead, net N mineralization was highest in the 0.15 moisture treatment (34.33 ± 1.12 mg N kg^{-1}) compared to the 0.05 (8.68 ± 0.52 mg N kg^{-1}), and 0.30 moisture treatments (8.52 ± 2.69 mg N kg^{-1}; Figures 46 and 47). Net N mineralization was significantly lower for the Valley Vista (14.68 ± 2.31 mg N kg^{-1}) than for the Cottonwood fields (19.67 ± 2.56 mg N kg^{-1}). For the 0.15 moisture treatment, N mineralization was significantly lower in the Valley Vista field (31.70 ± 0.92 mg N kg^{-1}) compared to the Cottonwood field (36.97 ± 1.78 mg N kg^{-1}). For the 0.30 moisture treatment, N mineralization rates were lower in Valley Vista (3.26 ± 2.95 mg N kg^{-1}) than in Cottonwood (13.78 ± 4.07 mg N kg^{-1}).

Table 6. MANOVA results for the post-planting incubation.

Factor	Moisture	Field	Mst*Fld	Veg Type	Mst*VT	Fld*VT	Mst*Fld*VT
Cumulative C g_s^{-1}	***	ns	ns	**	ns	ns	*
Net N mineralization	***	**	*	**	ns	*	ns

* = p<0.05; ** = p<0.01; *** = p<0.001; ns = not significant

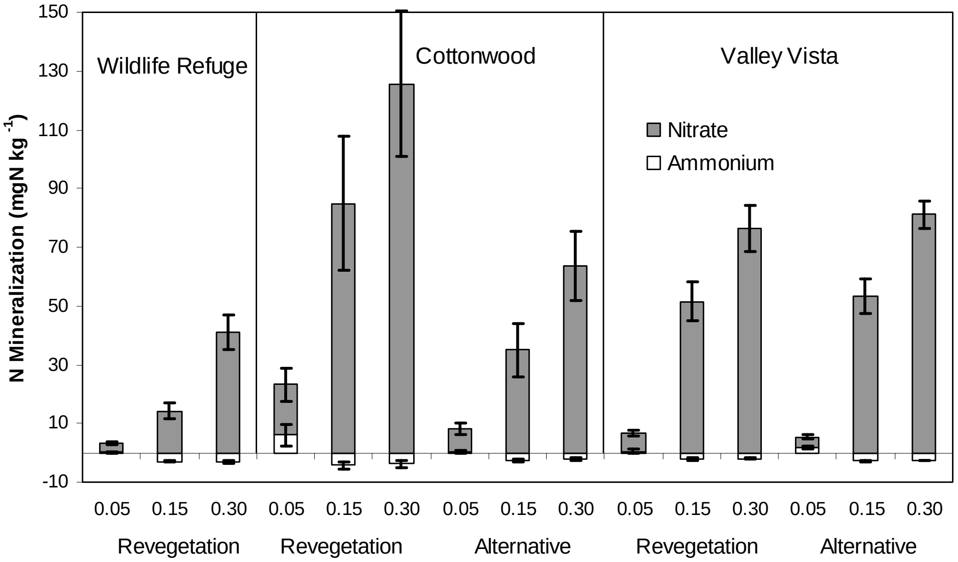

Figure 46. Average net N mineralization at the Wildlife Refuge, Cottonwood, and Valley Vista revegetation and alternative agriculture fields in the pre-planting incubation as a function of soil moisture content. Error bars represent standard error (n = 3).

Across all fields (Figure 48), net N mineralization was highest for Amaranth (22.49 ± 3.62 mg N kg^{-1}) followed by Alfalfa (16.12 ± 3.48 mg N kg^{-1}), Switchgrass (16.08 ± 3.24 mg N kg^{-1}) and Tef (14.02 ± 3.52 mg N kg^{-1}). The overall net N mineralization was significantly lower for the post-planting incubation (17.18 ± 1.74 mg N kg^{-1}) compared to the pre-planting incubation (42.99 ± 4.59 mg N kg^{-1}).

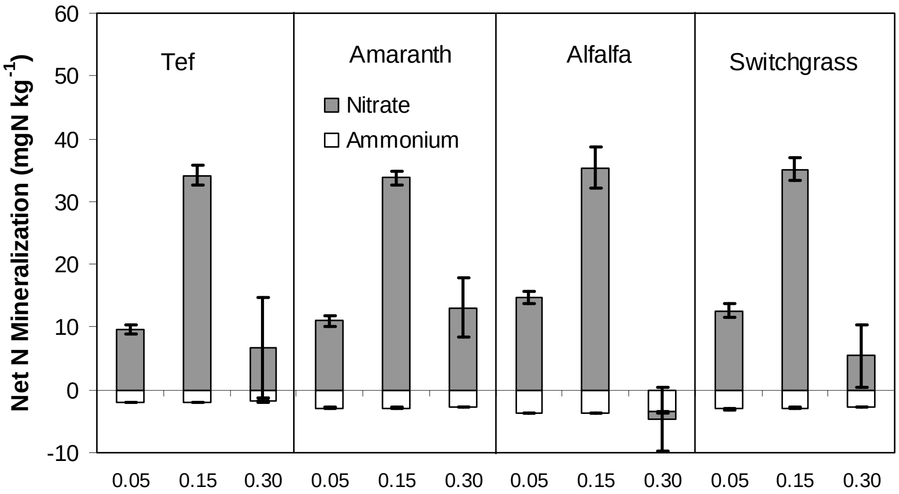

Figure 47. Net N mineralization in the Valley Vista field during the post-planting incubation as a function of vegetation type and soil moisture content. Error bars represent standard error (n = 3).

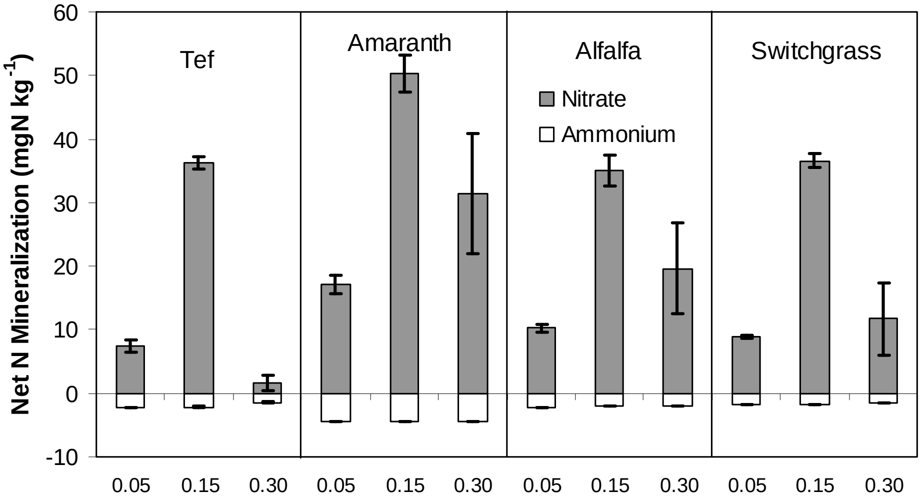

Figure 48. Net N mineralization in the Cottonwood field during the post-planting incubation as a function of vegetation type and soil moisture content. Error bars represent standard error (n = 3).

Multiple Regression Analysis - The multiple regression analysis showed that the cumulative C production over the incubation period was affected by moisture, percent clay, percent silt, and initial percent organic N in the pre-planting incubation (R^2 = 56.4%; Table 5), where only percent silt affected the cumulative C production negatively. Moisture, percent clay, initial percent C, and initial C/N were significant factors in the post-planting incubation (R^2 = 27.7%), where percent clay and initial percent C affected the cumulative C production (Table 5). Moisture, percent clay, initial C/N ratio, and initial percent organic N were significant factors affecting the net N mineralization in the pre-planting incubation (R^2 = 66.3%; Table 7). There were no significant factors for the net total N mineralization in the post-planting incubation (R^2 = 11.6%; Table 8). Performing the regression analysis with only moisture, percent clay, percent silt, initial C/N, and initial percent organic N as factors resulted in a R^2 of only 48.2% and the only factors affecting the N mineralization significantly were percent clay (p = 0.0019), percent silt (p = 0.0005), and initial percent organic N (p = 0.0004).

Table 7. Linear multiple regression results for the pre-planting incubation.

Factor	C Mineralization	Net N mineralization
Moisture	****	****
%Clay	*	****(-)
%Silt	*(-)	ns
%Sand	ns	ns
Initial %N	ns	ns
Initial %C	ns	ns
Initial C/N	ns	*
Initial %Org-N	****	***
Initial %Inorg-N	ns	ns

* = p<0.05; ** = p<0.01; *** = p< 0.001; ns = not significant; (-) indicates negative correlation

Table 8. Linear multiple regression results for the post-planting incubation.

Factor	C mineralization	N mineralization
Moisture	**	ns
%Clay	*(-)	ns
%Silt	ns	ns
%Sand	ns	ns
Initial %N	ns	ns
Initial %C	*(-)	ns
Initial C/N	*	ns
Initial %Org-N	ns	ns
Initial %Inorg-N	ns	ns

* = p<0.05; ** = p<0.01; *** = p<0.001; ns = not significant; (-) indicates negative correlation.

Field Study Results

Moisture - Soil moisture showed significant temporal variability with moisture being highest on June 11th in both fields (Figure 49). At most dates, soil moisture was highest at the Valley Vista site and season-average soil moisture was significantly higher in the Valley Vista soils (0.112 ± 0.005 m^3 m^{-3}) than the Cottonwood soils (0.078 ± 0.002 m^3 m^{-3}; Figure 49). The Valley Vista site received almost 70% more irrigation than the Cottonwood site (Figure 50). When averaged over the growing season soil moisture was significantly higher in the Valley Vista Switchgrass than the Valley Vista Tef plots (Figure 51). Soil moisture was the same in all vegetation types at the Cottonwood site.

Temperature and Relative Humidity - The average fifteen minute air temperature measured using the HOBO sensor at the Valley Vista site was 22.4ºC from June 6th, 2008 to August 12th, 2008. The maximum temperature during this time period was 38.0ºC and the minimum was -0.6ºC. The average fifteen minute soil temperature, measured at a depth of 10cm, at the Valley Vista site from the same time period was 30.3ºC with a maximum soil temperature of 40.4ºC and minimum of 16.1ºC. The average soil temperature measured between 10:30 AM and 3:30 PM at a depth of 5cm on August 13th, August 21st, and August 28th, 2008, was 36.6ºC in the Valley Vista field and 40.1ºC in the Cottonwood field (Figure 52). The maximum soil temperature was 46.0ºC in the Valley Vista field and 49.4ºC in the Cottonwood field. The minimum soil temperature was 24.8ºC in the Valley Vista field and 26.8ºC in the Cottonwood field. The average relative humidity during this time period was 31.0% with a maximum of 87.7% and a minimum of 4.5%.

Soil CO_2 efflux - Soil CO_2 efflux rates showed clear seasonal patterns with rates during the second through the fifth measurements being significantly higher than during the other three measurements (Figure 53). Overall, soil rates were significantly higher in the Valley Vista field (2.23 ± 0.08) than in the Cottonwood fields (1.36 ± 0.07 µmol CO_2 m^{-2} s^{-1}; Figures 53 and 54, Table 7). Vegetation significantly affected soil CO_2 efflux with Alfalfa having the highest rate (2.05 ± 0.15) and Switchgrass the lowest (1.52 ± 0.08 µmol CO_2 m^{-2} s^{-1}; Figure 54). Soil CO_2 efflux rates in Tef and Amaranth were similar (1.82 ± 0.10 and 1.80 ± 0.10). The MANOVA results showed that the vegetation*field*date interaction was significant indicating that effects of vegetation on soil CO_2 efflux varied by field and measurement date.

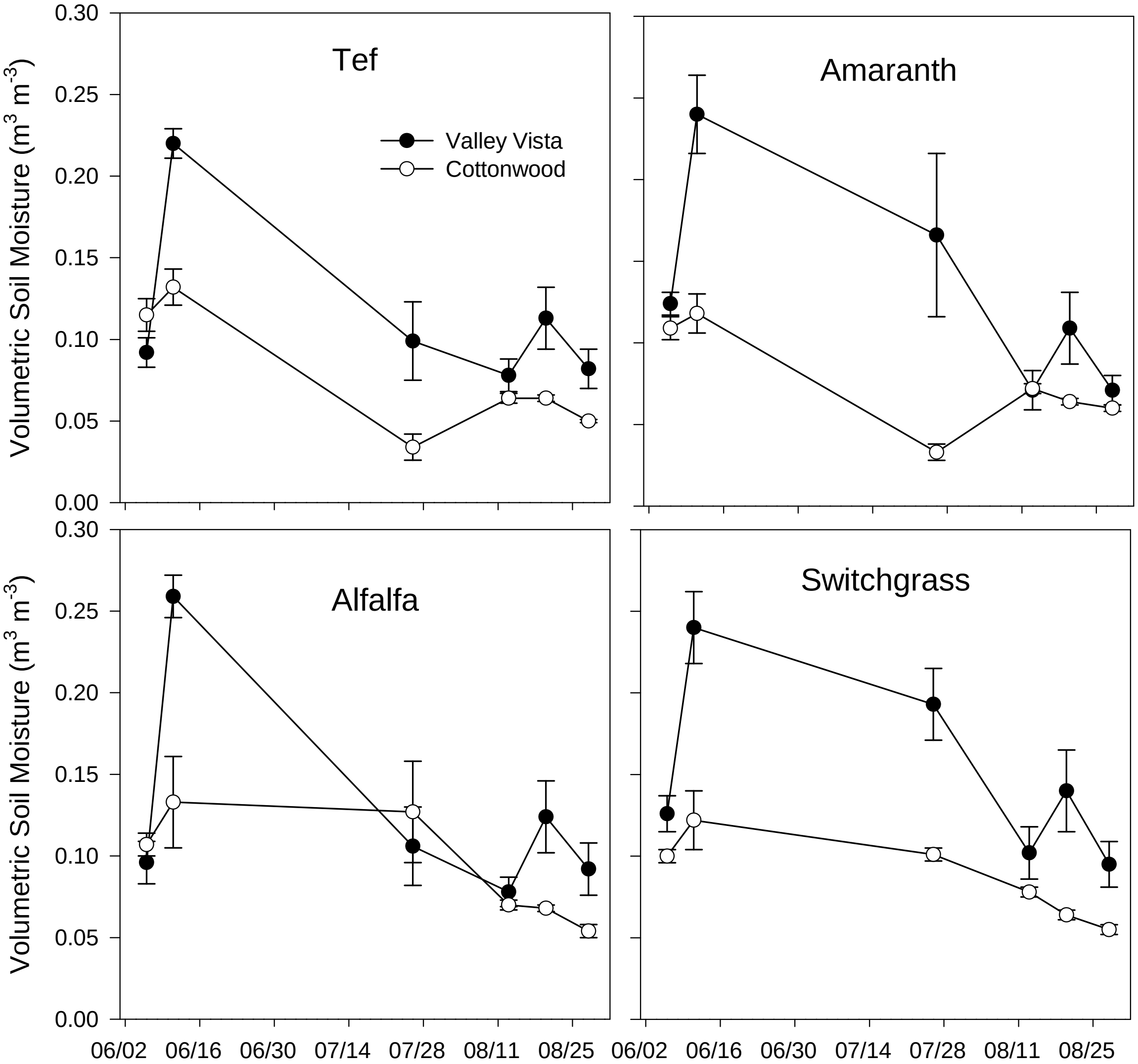

Figure 49. Average soil moisture contents over the 2008 growing season at the Valley Vista and Cottonwood sites for the four vegetation types.

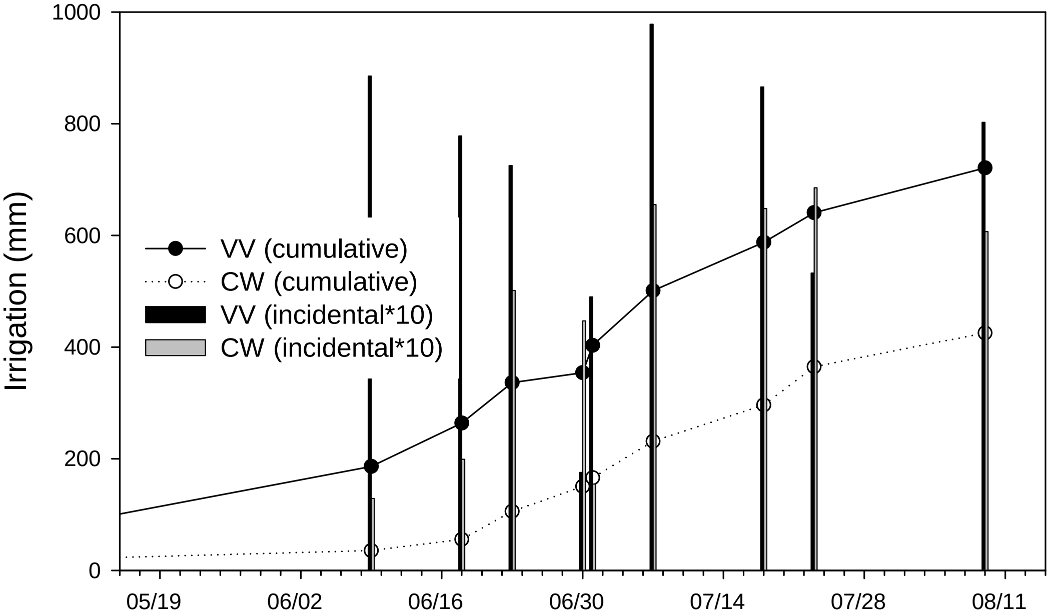

Figure 50. Timing and amounts of irrigation during the measurement period at the Valley Vista (VV) and Cottonwood (CW) sites.

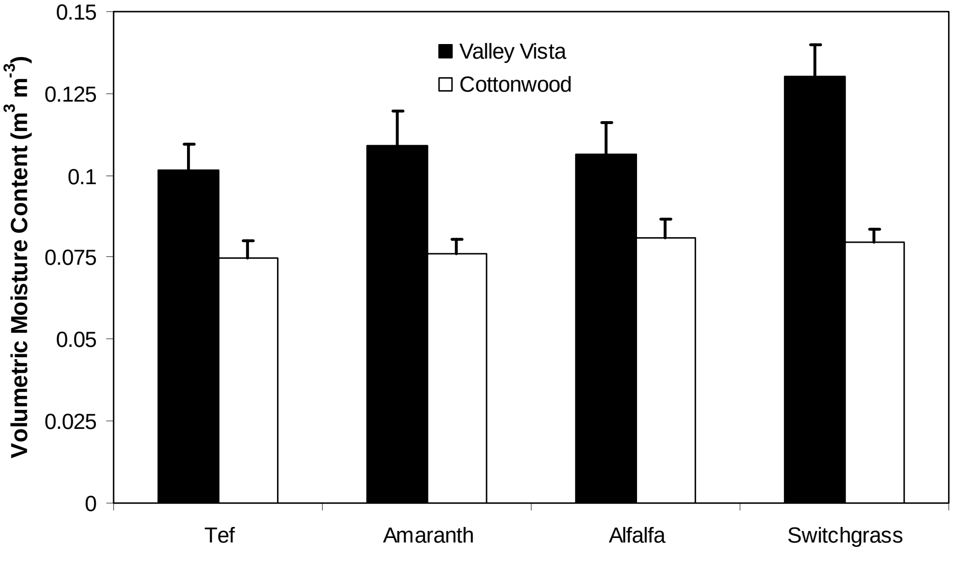

Figure 51. Season-average soil moisture contents over the 2008 growing season at the Valley Vista and Cottonwood sites for the four vegetation types.

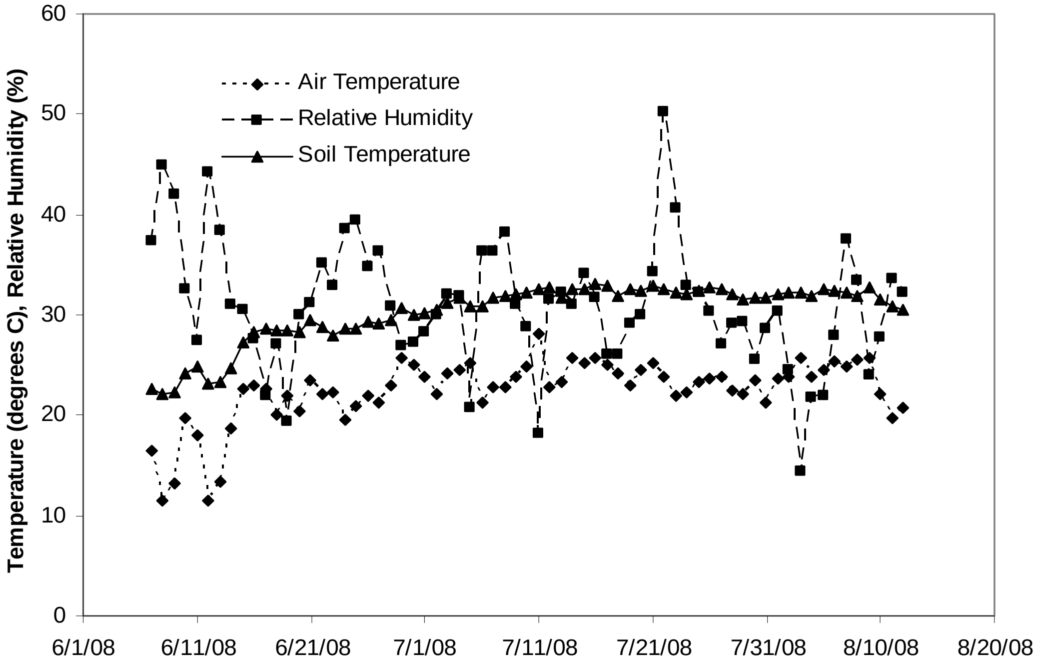

Figure 52. Average daily soil and air temperature (ºC) and relative humidity (%) values measured throughout the growing season.

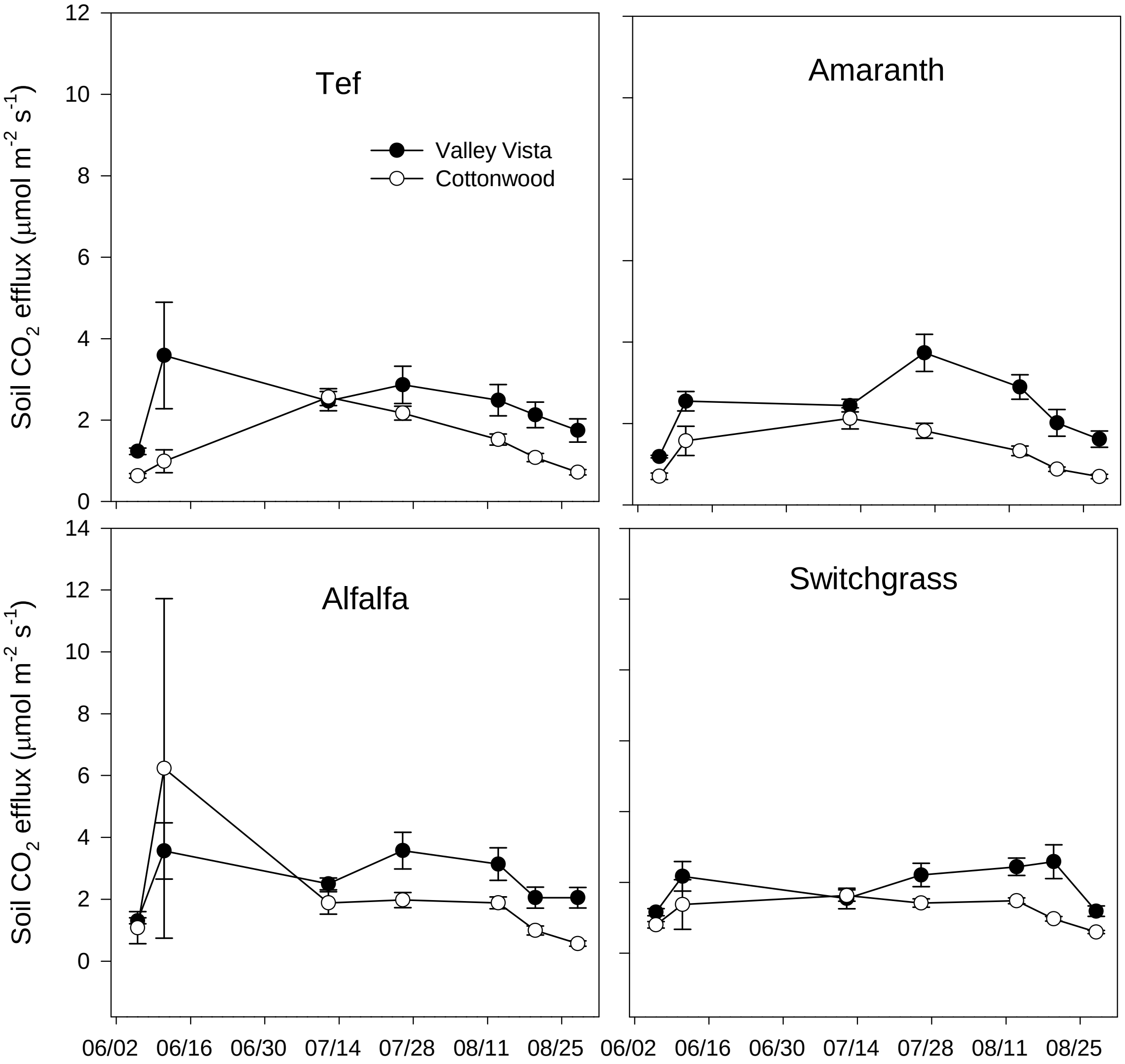

Figure 53. Average soil CO$_2$ efflux rates for the four vegetation types at the Valley Vista and Cottonwood fields. Error bars represent standard errors (n=9).

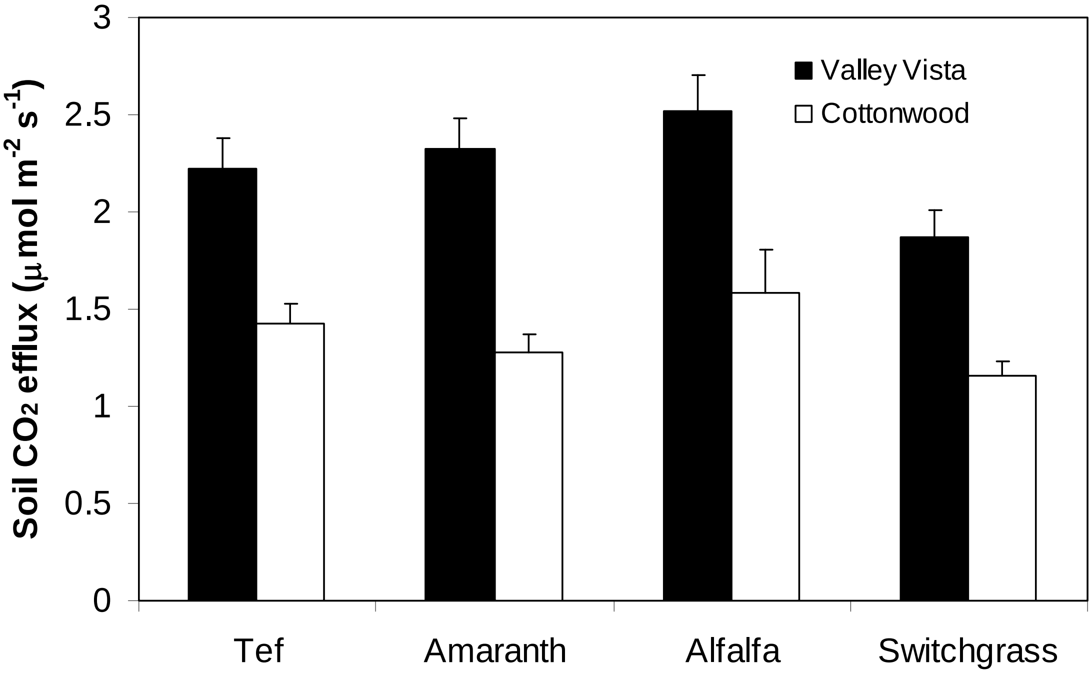

Figure 54. Season-averaged soil CO_2 efflux in the Valley Vista and Cottonwood fields as a function of vegetation type. Error bars represent standard errors (n=9).

Change in inorganic N - The MANOVA results show that only field and the vegetation*field interaction significantly affected the net change in inorganic N (Table 9). At the Valley Vista site, the soils showed an average increase in inorganic N of 4.16 ± 1.09 mg N kg^{-1} while in the Cottonwood field, the soils showed an average decrease of -4.44 ± 0.85 mg N kg^{-1} (Figure 55). At the Valley Vista site, the increase in inorganic N was significantly higher in Alfalfa (7.12 mg N kg^{-1}) than Amaranth (0.92 mg N kg^{-1}). In the Cottonwood soils, the change in inorganic N was the same for all vegetation types.

Table 9. MANOVA results for C and N fluxes

Factor	Soil CO_2 efflux	ΔInorganic N	ΔNO_3	ΔNH_4
Vegetation (VT)	***	ns	ns	ns
Field (Fld)	***	***	***	ns
Date	***	-	-	-
VT*Fld	ns	*	ns	ns
VT*Date	***	-	-	-
Fld*Date	***	-	-	-
VT*Fld*Date	*	-	-	-

* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; ns = not significant; - = not included in analysis.

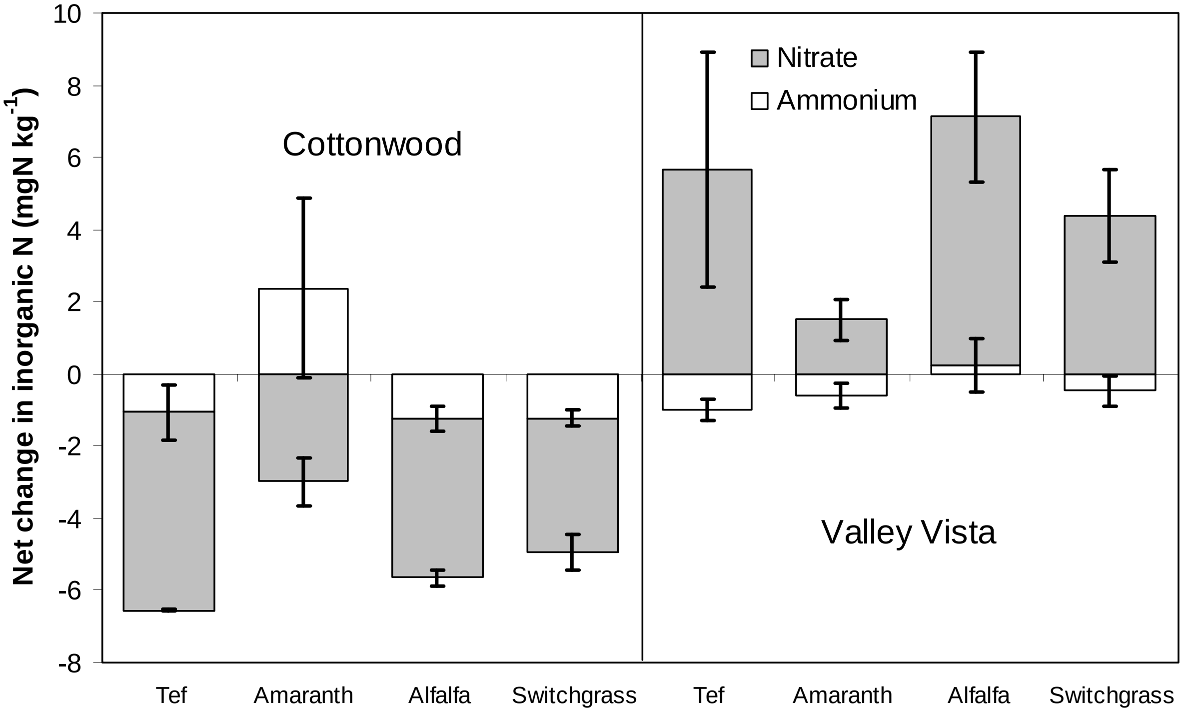

Figure 55. Net change in inorganic N during the growing season at the Cottonwood and Valley Vista sites as a function of vegetation type. Error bars represent standard errors (n=9).

Net nitrate and ammonium - The MANOVA analysis revealed that the net change in NO_3 was only affected by field (Table 7). The Valley Vista soils showed an average increase in NO_3 content of 4.61 ± 1.01 mg N kg^{-1} while all Cottonwood soils showed an average decrease of -4.15 ± 0.26 mg N kg^{-1} (Figure 55). Changes in NH_4 were the same for both fields with NH_4 decreasing by -0.45 ± 0.24 mg N kg^{-1} at the Valley Vista site and by -0.29 ± 0.68 mg N kg^{-1} at the Cottonwood site (Figure 55).

Vegetation biomass - At the Valley Vista site Tef had a significantly higher biomass than Amaranth, Alfalfa, and Switchgrass (Figure 56). The same was true at the Cottonwood site but Amaranth biomass was also higher than Alfalfa and Switchgrass. The Cottonwood Tef had the largest average biomass (307.3 ± 28.8 g) while the Cottonwood Switchgrass had the lowest average biomass (37.3 ± 5.6 g) across all fields. Both Tef and Amaranth biomass were significantly higher at the Cottonwood site than at the Valley Vista site while Switchgrass biomass was lower. Alfalfa biomass was similar in both fields.

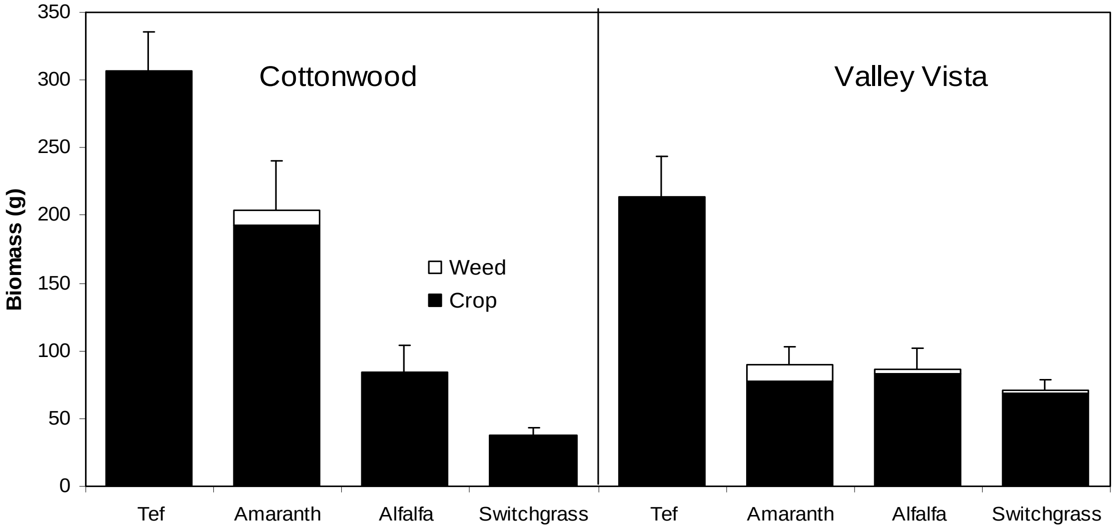

Figure 56. Average aboveground vegetation biomass at the Cottonwood and Valley Vista sites. Error bars represent standard errors (n=9).

Multiple Regression Analysis - Multiple regression analysis showed that the C respiration rate for these soils was positively affected by soil moisture (p=0.0177) and negatively affected by percent relative humidity (p=0.0329) when moisture, texture, air temperature, and relative humidity were included (Table 10). However, these two variables however explained only 20.8% of the observed variability in soil respiration. A regression of natural log transformed respiration rate data resulted in a slightly higher R^2 of 26.4%. When conducting a regression using data obtained at the end of the growing season, moisture ($p<0.0001$), vegetation biomass (p=0.0328), and soil temperature (p=0.0001) significantly affected the C respiration rate (R^2 = 64.2%) with soil temperature affecting the rate negatively when moisture, texture, biomass (vegetation and weed), percent N, percent C, and soil temperature were included. Regression of natural log transformed respiration rate data resulted in a slightly lower R^2 of 63.2%.

Two separate analyses were run for the soil CO_2 efflux. The first analysis (A) included parameters measured throughout the growing season and while the second analysis (B) included parameters that were only measured at the end of the growing season. Step-wise regression analyses were conducted on the N fluxes. Only the results from the regressions with the two highest R^2 values (C and D) are shown.

Multiple regression analysis revealed that there were no significant factors affecting the net change in total inorganic N (R^2 =41.2%) when moisture, texture, biomass (vegetation and weed), percent N, percent C, and soil temperature were included as main factors (Table 8). Moisture (p=0.0105), percent clay (p=0.0044), weed biomass (p=0.0262), and percent C (p=0.0028) significantly affected the net change in total inorganic N when all other factors were excluded (R^2 =36.9%) (Note: only these first two regression results are shown in the table). When percent clay, weed biomass, and percent N were included all three were significant factors (p=0.004, 0.0314, and 0.0127 respectively) but these variable only explained 27.5% of the observed variability.

Table 10. Linear multiple regression results of C and N fluxes against main factors.

Factor	Soil CO_2 efflux		ΔInorganic N		ΔNO_3		ΔNH_4	
	A	B	C	D	C	D	C	D
Moisture	*	***	ns	*	*	*	ns	ns
%Clay	ns	ns	ns	**	ns	-	ns	ns
%Silt	ns	ns	ns	-	ns	-	ns	-
%Sand	ns	ns	ns	-	ns	-	ns	-
Air Temp	ns	-	-	-	-	-	-	-
%RH	*	-	-	-	-	-	-	-
Crop biomass	-	*	ns	-	ns	*	ns	ns
Weed biomass	-	ns	ns	*	ns	-	***	***
%N	-	ns	ns	-	ns	-	ns	-
%C	-	ns	ns	**	ns	*	ns	ns
Soil Temp	-	***	ns	-	*	***	ns	*

* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; ns = not significant; - = not included.

In this study, moisture was the most commonly important factor affecting the C and N fluxes in this study for both laboratory and field studies. Carbon and N fluxes showed differential response to moisture following one growing season most likely as a result of differences in the quality of C inputs following planting. In addition, microbial community structure may have changed in response to planting. The laboratory incubations showed that generally higher C fluxes were found in the Tef plots compared to the other vegetation types which may have been caused by differences in organic matter quality. Although aboveground Tef biomass yields were largest compared to other crops, no differences in soil C content were found. In addition, the higher yields for Tef did not translate into increased soil CO_2 efflux rates. Effects of vegetation on N fluxes were not consistent. Perhaps most surprisingly N fluxes in Alfalfa soils were not much different from Switchgrass and Amaranth, despite Alfalfa being an N fixing species. In addition, differences in initial C, N and inorganic N concentrations between Valley Vista and Cottonwood sites were not significant even though previous land use was dramatically different (vacant/grazing for Cottonwood and Alfalfa for Valley Vista). Post-planting differences in inorganic N between the two sites were obvious with the higher accumulation of inorganic N at the Valley Vista site. This difference may have been caused by the higher amount of irrigation received by the Valley Vista site, thereby stimulating N mineralization. Still, several factors were not studied that could explain differences found between fields. Future studies should include (1) root biomass measurements to allow for calculation of N uptake by vegetation, (2) organic matter fractionation to assess differences in organic matter quality as affected by inputs from different plant species, and (3) microbial assays to determine how microbial communities respond to differences in irrigation and vegetation type. Finally, the short duration of this study only allows for preliminary assessment of the effects of alternative crops on soils. Continuous planting for multiple years will most likely amplify effects of species in soils due to longer-term inputs of organic C from plants. This may have cascading response to microbial processes which, in turn will affect nutrient cycling in these systems.

Nitrate Removal in the Riparian Zone of the Walker River.

Groundwater surveys (Wilson, 2008) along denitrification transects indicated that groundwater flow was in the direction toward the Walker River and away from the direction of the nearby irrigation ditches (Figure 57). At the points where nitrate removal was measured, the groundwater surface was 1.2 to 1.8 m below the soil surface. When groundwater amended with labeled nitrate and a conservative tracer was injected into shallow wells and later extracted, there was substantial loss of nitrate compared to tracer levels (Table 11). These rates of nitrate loss were on the order of 10% per day. The nitrate removal rates in this study were on the same order, or higher, than in other riparian studies in which denitrification was measured. Nitrate removal rates were correlated to soil organic matter. Buried soil organic matter deposits provided the energy for nitrate removal, likely through denitrification, at depths up to 3 m below soil surface. N^{15}enrichment ratios in the nitrogen gas dissolved in the water suggested the presence of denitrification but low recovery of product gases prevented quantitative measurement of denitrification rate (Table 12). Nitrate removal rates in the Walker River riparian zone appear to be sufficient, even at some depth, to mitigate nitrate leaching.

The removal of nitrate flowing through the riparian zone of the Walker River depends not just on the rate of nitrate removal, but also on the residence time of groundwater flowing toward the river. Modeling of groundwater using MODFLOW showed that the residence time of water and nitrate removal rates are sufficient to remove nearly all nitrate from hypothetical ‘slugs” of water originating from the agricultural ditches and flowing through the riparian groundwater zone before entering the river. An example of the reduction in nitrate concentration in groundwater flow under a relatively high rate of flow is shown in Figure 58.

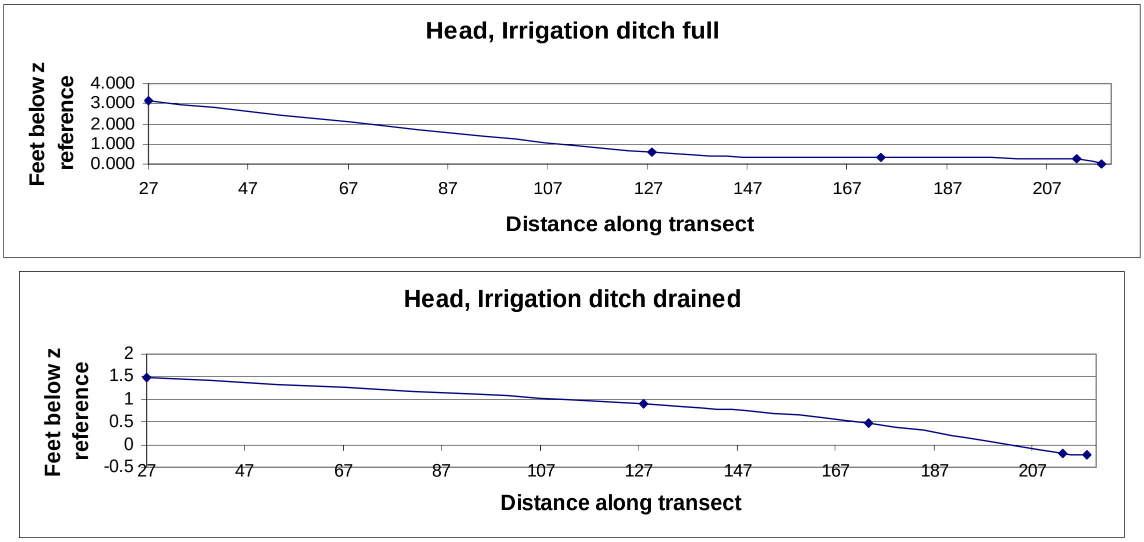

Figure 57. Observed heads in piezometers. Measured as feet below surveyed reference z. Ditch is left most point on x- axis, points in between are piezometers A2, A3, and A4, and the Walker River is the final data point on the right side.

Table 11. First order nitrate removal rates from in-situ push pull tests done in this study. PPT 5 denitrification rate was not calculated because injection recovery was too low. Values for first order denitrification rates result from fitting two points (initial nitrate concentration, and tracer corrected nitrate concentration at time t) on the nitrate vs. tracer recovery curves to the first order decay equation.

Push-Pull Test #	**Distance from river (ft.)**	**Soil Texture**	**Injection depth (ft. below soil surf.)**	**Injection depth (ft. below water)**	**1st order nitate removal rate (d^-1)**
1	43	sandy loam	8.1	1.9	-0.163
2	65	sand-clay	6.5	2.5	-0.072
3	8	sand	4.5	1.2	-0.136
4	190 (drain ditch)	sand	6.5	1.5	-0.085
5	101	course sand	11.2	5.2	*

Table 12. Maximum amounts of ^{15}N - N_2 and ^{15}N - N_2O recovered and maximum enrichment ratios.

Push-Pull Test #	**Maximum ^{15}N-N_2 recovered (umol)**	**Maximum ^{15}N-N_2O recovered (umol)**	**Maximum ^{15}N enrichment ratio N_2**	**Maximum ^{15}N enrichment ratio N_2O**
2	0.044	0.012	0.48	95.05
3	0.067	0.001	0.38	97.78
4	0.068	0.001	0.38	96.76
5	0.067	0.00001	0.37	61.56

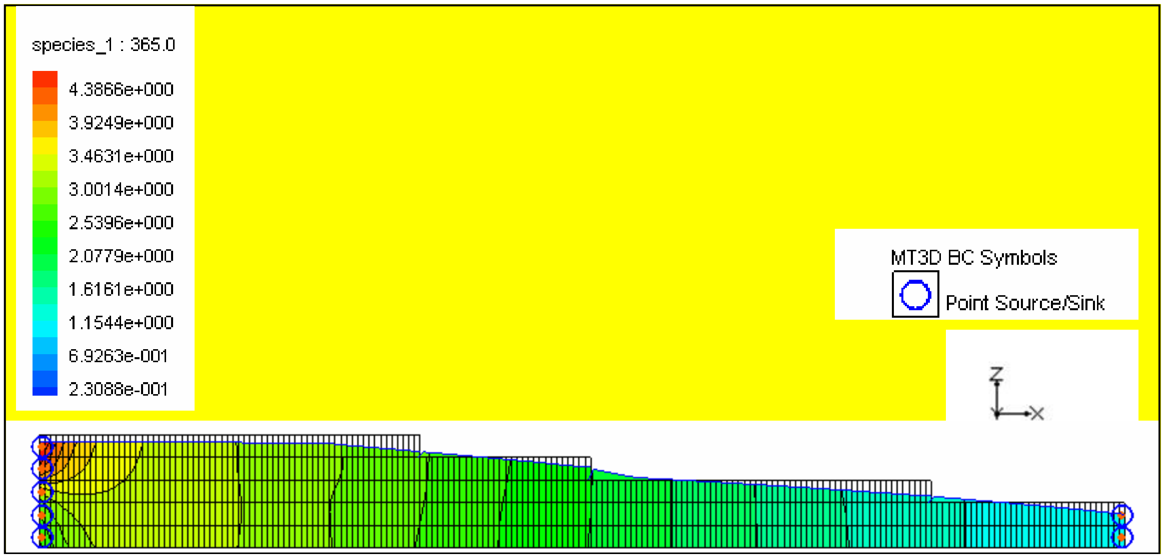

Figure 58. Modeled nitrate plume after 1 year under high gradient scenario with flow of nitrate. Units are in mg/L. Nitrate input at upper left cells corresponding to the drain ditch was set at 10 mg/L.

Effects of Altered Water Use on Invasive Species in the Walker River Riparian Zone

Based on the existing gradient of isotopic ratios found in the water from the soil profile, the ratio of ^2H to ^1H (δD) from water within the *L. latifolium* plants reflected the depth from which the water was taken up (Figure 59) (Dean, 2009). Water in the upper portion of the soil profile was more highly evaporated. At all three field sites *L. latifolium* used shallow water sources early in the growing season and deeper water sources later in the growing season. Use of water from deeper sources correlated with a decrease in moisture of shallow soils (Figure 60). Early in the growing season isotopic signatures of *L. latifolium* reflected the isotopic signatures of shallow soils (≤10 cm) whereas later in the growing season the isotopic signature of *L. latifolium* reflected the isotopic signatures of deeper soils (≥ 100 cm) and groundwater. In the field surveys done in this study it was found that *L. latifolium* has a deep root system that extracts water throughout the soil profile. Consequently, even late in the season, this invasive plant *L. latifolium* was consuming groundwater which may otherwise have contributed to late season flow in the river channel.

In competition experiments were carried out in barrels, soil matric water potentials were maintained at either -10 kPa, -600 kPa, or -600 kPa with a water table that was 1.1 m below the soil surface. *L. latifolium* was able to distribute its roots and utilize the artificially maintained water table to maintain high stomatal conductance rates throughout the growing season under drought conditions. In fact stomatal conductance rates of *L. latifolium* were very high (not shown), suggesting that it would be consuming water at high rates in the field even late in the season. However, the native grass that is the main native herbaceous species in the areas surveyed, *E. trachycaulus*, maintained most of its roots within the first 43 cm of the soil profile, had a low stomatal conductance rate under drought conditions and had limited access to the artificial water table. Despite these differences in response to water regime, there was no significant inhibitory competitive effect of *L. latifolium* on *E. trachycaulus* (Figures 61, 62, and 63). The presence of *L. latifolium* growing with *E. trachycaulus* in the mixed species treatment did not cause a statistically significant reduction in the biomass of *E. trachycaulus.* This lack of a negative competitive effect in the presence of *L. latifolium* may indicate its ability to persist in areas invaded by *L. latifolium* and that it may be useful in restoration of native riparian vegetation.

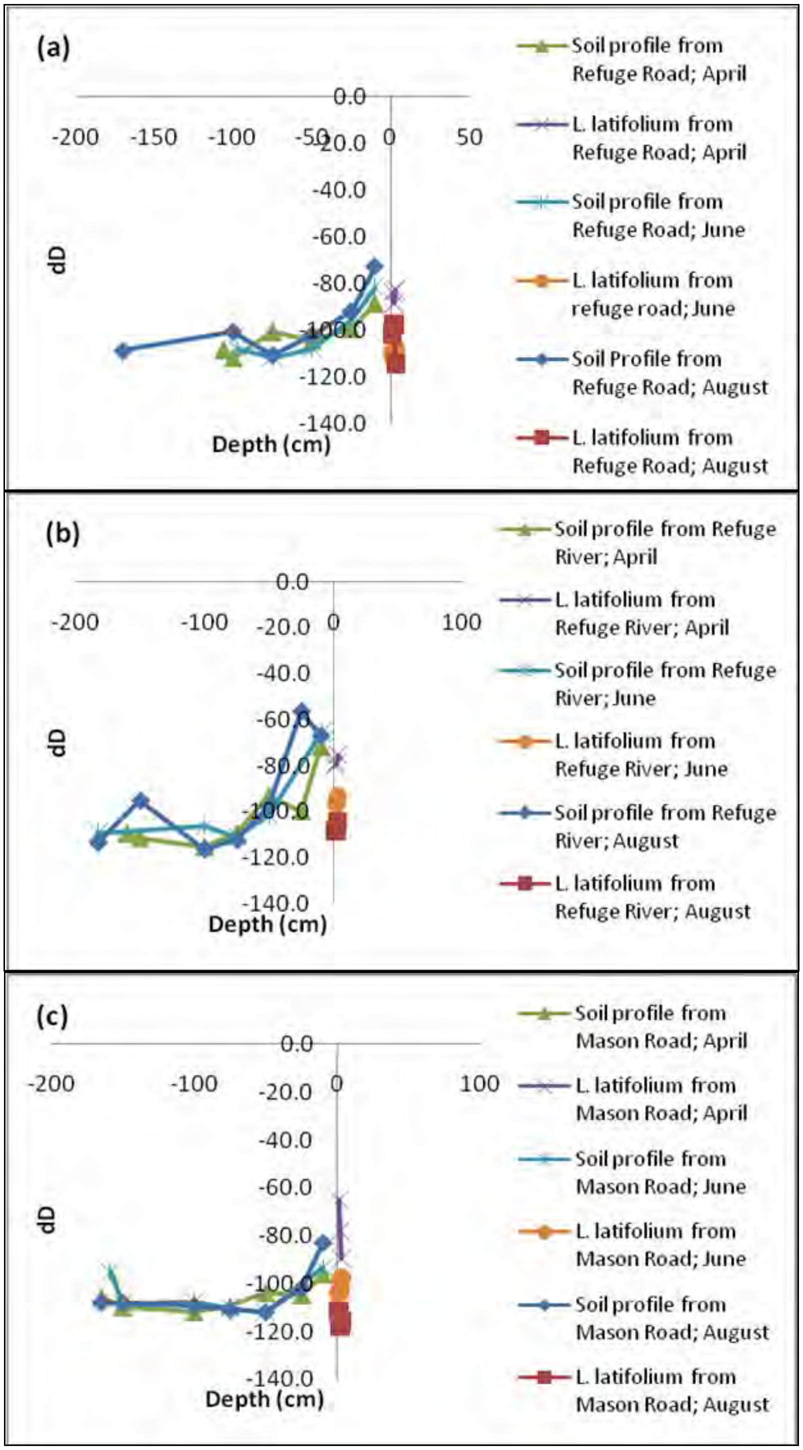

Figure 59. Isotopic signatures of water in *L. latifolium* and the corresponding soil profiles at various times throughout the growing season at a) Refuge Road Site b) Refuge River Site and c) Mason Road Site. The isotopic signature of water extracted from the roots is shown on the vertical axis and the signature of soil and groundwater is indicated as a function of depth. The correspondence between the isotopic signatures of the plant water and soil water indicates the depth at which it was taken up.

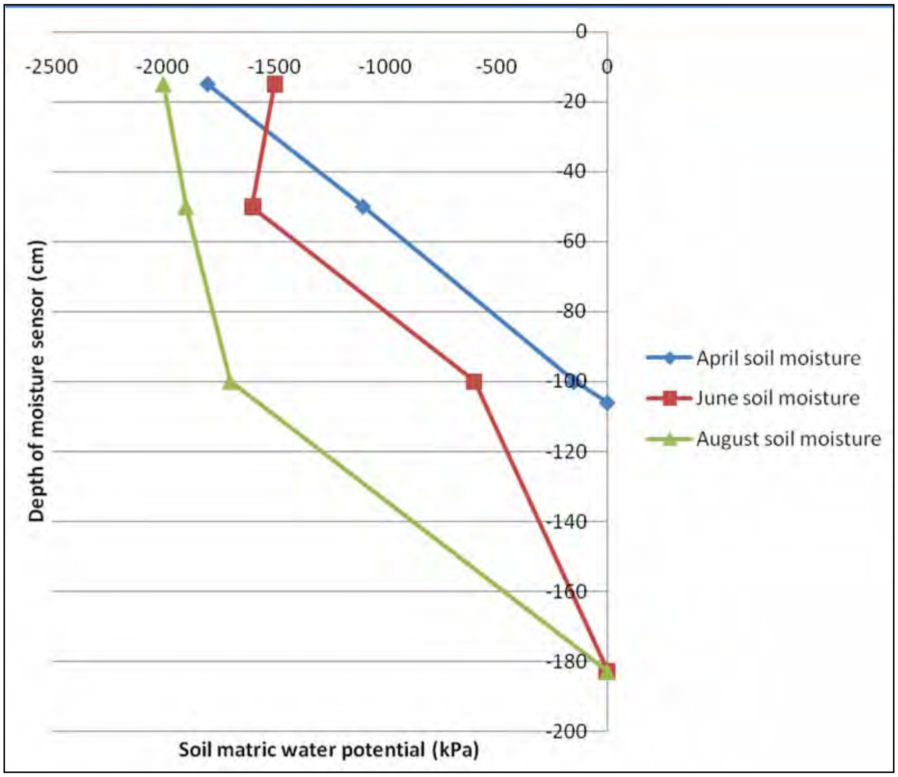

Figure 60. Field soil moisture (soil matric water potential) readings in kPa at different depths down to ground water at various times throughout the growing season in the plots in which *L. latifolium* was monitored. Points at 0 kPa represent the depth of groundwater (0 kPa by definition) at each period.

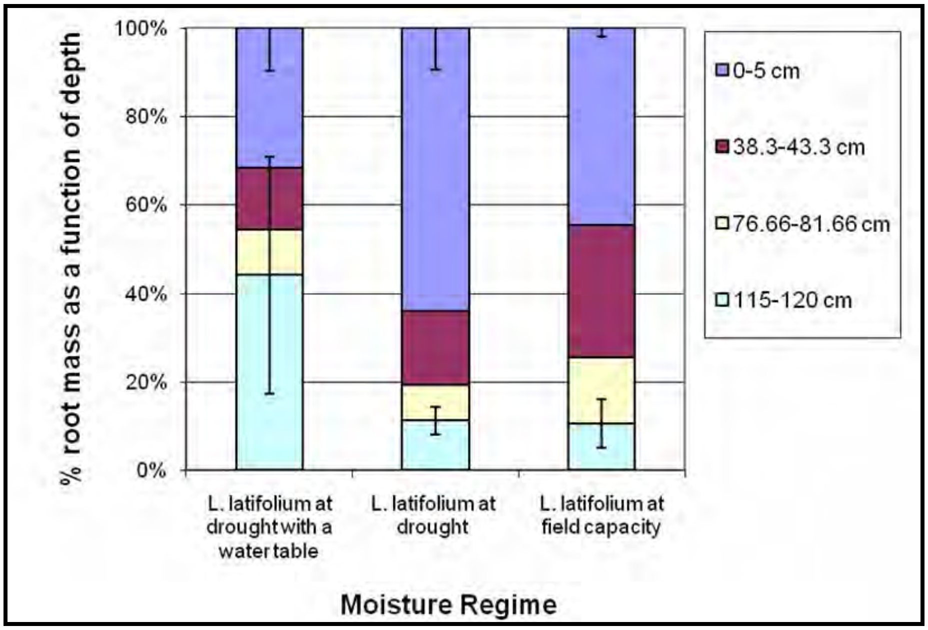

Figure 61. Distribution of below ground root biomass of *L. latifolium* in mixed species competition barrels at different moisture regimes expressed as a % of total of all depth increments.

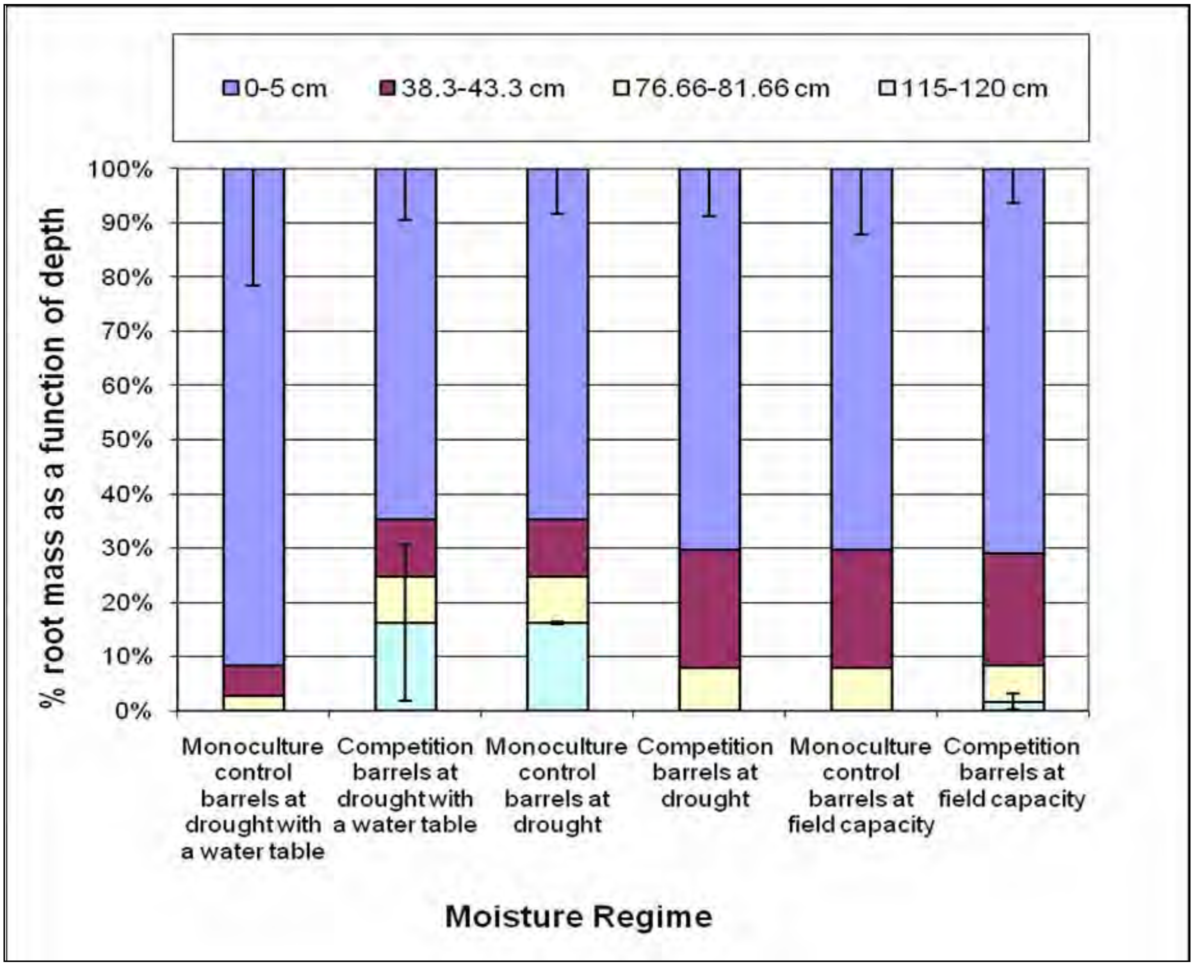

Figure 62. Distribution of below ground root biomass of *Elymus trachycaulus* (Slender wheatgrass) in monoculture control and mixed species competition barrels under different moisture regimes expressed as a % of total of all depth increments.

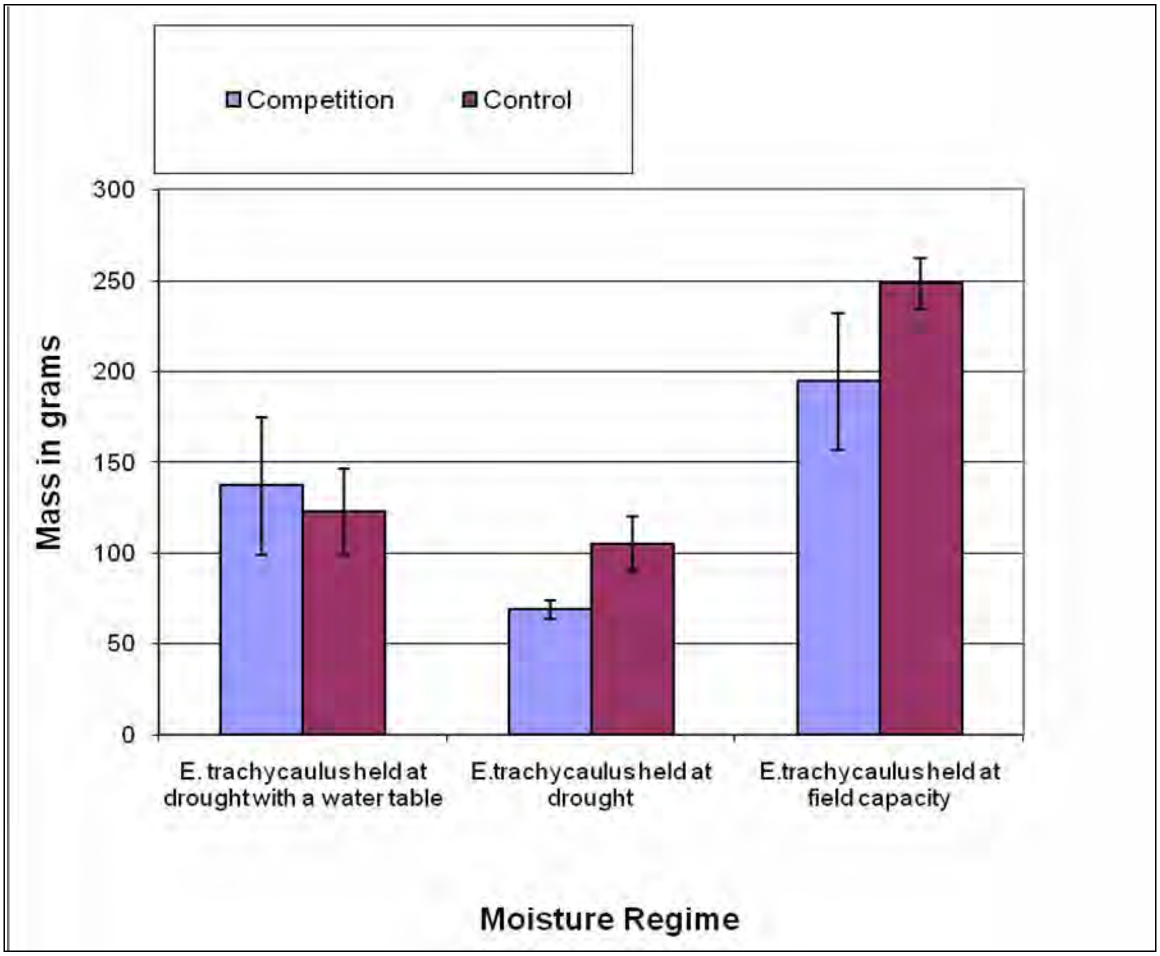

Figure 63. Above ground biomass of *E. trachycaulus* in monoculture control and mixed species (grown with *L. latifolium*) competition barrels at different moisture regimes.

This experiment confirmed that *L. latifolium*, because of its very deep root distribution, is capable of seeking-out and consuming groundwater throughout the growing season, even when surface soils are too dry to maintain water consumption by native grasses. In this way, this invasive herbaceous species resembles *Tamarix* species that have been implicated in undesirable consumption of riparian groundwater. Alteration of groundwater levels by decreases in irrigation in the Walker Basin is likely to have important influences in the spread of *L. latifolium*, throughout the riparian and ditch areas of the Walker Basin. Likewise, its spread could have a significant impact on in stream flow. However, the actual estimation of water consumption by *L. latifolium* in the segments of the Walker Basin would require scaling-up, using leaf area, plant density and evapotranspiration models.

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PROJECT C: PLANT, SOIL, AND WATER INTERACTIONS

LAND COVER CHANGE AND PLANT WATER USE IN AN AGRICULTURAL RIPARIAN LANDSCAPE

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ABSTRACT

Over the past 150 years, the Walker River riparian zone has experienced massive land cover conversion from native riparian vegetation to extensive agricultural landscapes characterized by irrigated pastures and alfalfa fields. Water withdrawals and diversions for agriculture have greatly reduced flows of water to the terminal lake, influencing aquatic ecosystem integrity. River regulation and reduced in-stream flows have altered riparian vegetation even in locations not devoted to agricultural use. In response to recent environmental concerns, purchase of water rights from agricultural producers is being considered. However, past abandonment of irrigated fields in the region has resulted in ecologically and economically undesirable effects, including surface soil erosion, salinization, and spread of invasive plant species. Careful orchestration is required for land use conversion to result in benefits for ecosystems and society.

Our research supports the potential for well-planned land use conversion by: (1) utilizing historical data to quantify historical land use/land cover change from the late 1800s to the present; (2) quantifying contemporary species-environment relationships for vegetation to characterize reference conditions for ecological restoration of irrigated agricultural fields; and (3) predictive modeling of the implications of historical and future land cover change for plant water use. These three tasks are supported by direct historical reconstruction of land use/land cover change, extensive mapping and mensurative vegetation sampling throughout the Basin, integration of detailed results from irrigation experiments, and development of spatial models that allow assessment of water use by vegetation given alternative land cover scenarios.

INTRODUCTION

Many riparian landscapes throughout the arid and semi-arid western United States have been dramatically transformed by irrigated agriculture. In our Walker Basin study area, the onset of irrigated agriculture occurred as early as 1861 when several of the early irrigation ditches were constructed in Mason Valley (Matheus 1995), and production of livestock feed is still the dominant land use throughout much of the riparian corridor at lower elevations with alfalfa hay accounting for 64% of the total crop area in Mason and Smith Valleys.

Although irrigated agriculture has proved essential for socioeconomic development and maintenance of a viable livestock industry in this semi-arid region, this land use practice has not been without environmental costs. Surface water diversions augmented by groundwater pumping have resulted in lowered water tables, reduced in-stream flows in the lower portions of the drainage, and lowered surface elevations in the terminal lake. Such changes have likely exerted substantial negative impacts on water quality, aquatic ecosystems, native vegetation communities, and ultimately on the sustainability of the agricultural industry itself as costs increase with reduced river flows and decreased groundwater levels.

Additional environmental costs are associated with invasion by exotic plant species, which is often facilitated by altered hydrologic regimes associated with agricultural land uses in riparian areas. In riparian ecosystems, exotic plant invasions have been linked to altered fluvial dynamics associated with dams and water diversions

(Nilsson and Berggren 2000; Richardson et al. 2007). Reductions in the magnitude of peak flows, and shifts in the timing of flooding, reduce availability of suitable microsites for establishment of native woody species and may benefit exotic species that are adapted to the modified flow regime, such as *Tamarix* species (Stromberg et al. 2007).

In the Walker River Basin, riparian areas have been heavily invaded by several weed species including *Tamarix ramosissima* Ledeb., *Elaeagnus angustifolia* L., *Lepidium latifolium* L., *Cirsium arvense* (L.) Scop., *Onopordum acanthium* L., *Acroptilon repens* (L.) DC., *Tribulus terrestris* L., *Cardaria draba* (L.) Desv., *Sonchus arvensis* L., *Cynoglossum officinale* L., *Cicuta maculata* L., and *Hydrilla verticillata* (L. f.) Royle. Efforts to restore Walker Basin riparian ecosystems through changing land use practices must consider the influence of exotic plant species. Furthermore, efforts to increase water flows to the terminal lake through changing agricultural practices should take into account the water use by exotic plant species, many of which are phreatophytes with high evapotranspiration rates (Glenn and Nagler 2005).

In response to recent environmental concerns, purchase of water rights from agricultural producers is being considered. However, past abandonment of irrigated fields in the region has resulted in ecologically and economically undesirable effects, including surface soil erosion, salinization, and spread of invasive plant species. Careful orchestration is required for land use conversion to result in benefits for ecosystems and society. In many situations, it will be viable to replace crop types requiring intensive irrigation with other, more water-efficient crop types. However, where planned land use changes involve the complete abandonment of agricultural practices, it is likely that active restoration and management will be required to produce the desired effects of water recovery to the terminal lake, improvement of water quality, and suitable habitat for fish and wildlife species.

An important component of ecological restoration is characterization of appropriate reference conditions (Richter and Richter 2000, Bainbridge 2007). In highly agricultural landscapes the need for historic reconstruction is especially important because the lack of contemporary reference areas that can be used for restoration. Reference conditions can be derived directly from reconstruction of historical conditions that predate intensive agriculture or other anthropogenic land uses, or can be interpreted from current species-environment relationships evident in natural areas. Our study used both a direct approach and predictive modeling approach to quantify ecologically based reference conditions for restoration of irrigated fields and riparian sites dominated by invasive plant species such as *Tamarix ramosissima*, *Elaeagnus angustifolia*, and *Lepidium latifolium*. The direct approach incorporated historical data, including General Land Office (GLO) surveys, archival maps and historical aerial photography, to reconstruct the vegetation present at a site before land-use conversion. In particular, the GLO surveys allowed us to identify precise boundaries of major vegetation community transitions and provided us with georeferenced data on the distribution of vegetation prior to and during the establishment of large-scale irrigated agriculture. GLO surveys contain both section line descriptions that can be analyzed as transect data for quantification of long-term land cover change (Andersen and Baker 2006), and witness tree data that can be analyzed as variable-radius plot sampling for quantifying changes in tree distribution, density, size class, and species composition over time (Bourdo 1956, He et al. 2000).

The predictive modeling approach used statistical models to identify major abiotic gradients that influence the current distribution of plant species and vegetation types, and to produce maps that predict potential vegetation distribution. Potential vegetation distribution was compared with current vegetation distribution, which was defined using a map photo-interpreted from 1-m true color NAIP orthophotography, combined with quantitative vegetation surveys stratified by map classes. Both map and field data were developed in collaboration with the U.S. Fish and Wildlife Service.

A primary goal of the overall Walker Basin project is to "explore the best means by which to get additional water to the lake while maintaining the Basin's economy and ecosystem" (http://www.nevada.edu/walker/about/index.html). In collaboration with Dr. Greg Pohll and his research group at DRI (TASK F) we have applied the newly developed Rip-ET modeling approach to compare with current groundwater modeling approaches, and improve estimates of basin-wide plant water use such that effects of riparian vegetation are more realistically incorporated.

Thus, our research approach spans historical, contemporary, and planned future time periods, and extrapolates known data and ecological relationships regarding vegetation, agricultural land use, and plant water use to the extent of the riparian area within the Walker Basin (Figure 1). We reconstructed historical land use/land cover change, developed statistical models of plant species distribution according to environmental gradients that can be used to define reference conditions, and used simulation modeling approaches to develop improved estimates of plant water use over basin-wide scales.

METHODS

Although the entire Walker River Basin was of interest to this project, certain tasks required different study areas with extents dictated by research questions and data needs. Modeling of species-environment relationships (i.e. vegetation modeling) was limited to the riparian areas of the Walker River Basin for which high-resolution LiDAR data were available. This encompassed most of the East and West Forks of the Walker River as well as the main stem and forms a swath up to 16 km in width. The reconstruction of historic vegetation task was concentrated in the agricultural and riparian areas of the Walker River Basin. Townships containing significant agricultural areas or that intersect the Walker River were included in this study. The ecological simulation models of plant water use were applied only to Mason and Smith Valleys because of the availability of monitoring wells of sufficient density for modeling.

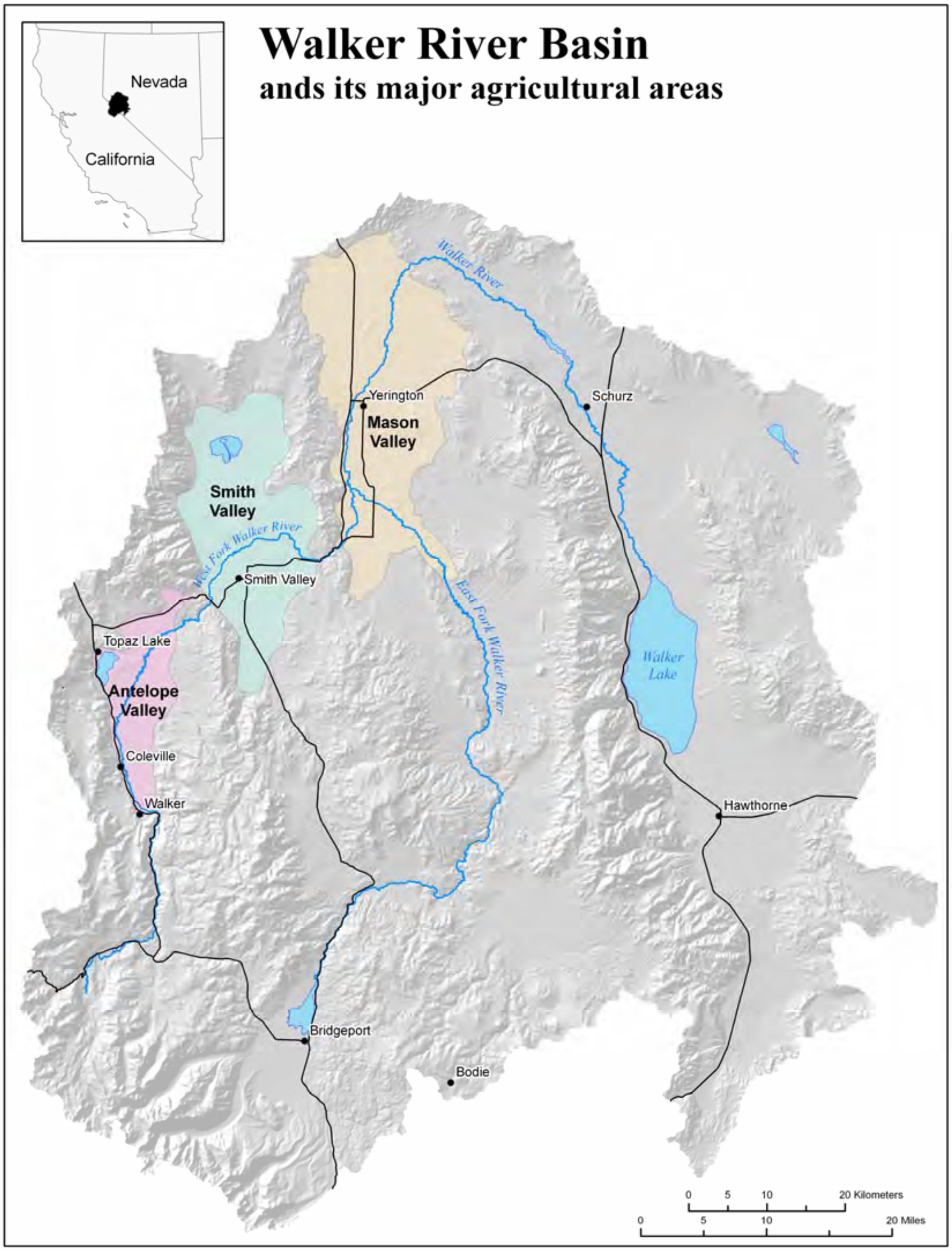

Figure 1. The Walker River Basin, showing its major agricultural and riparian areas.

Characterization of Reference Conditions and Historical Change

Our historical approach used numerous archival documents, including General Land Office survey notes, Bureau of Reclamation Service maps, and aerial photographs to characterize vegetation composition prior to and following the establishment of large-scale intensive agriculture in the Basin.

General Land Office surveys

General Land Office (GLO) survey notes were acquired from the Bureau of Land Management Nevada and California state offices. The earliest notes recorded were in 1857 while the latest notes were recorded in 1989. The majority of survey notes were recorded between 1859 and 1900 (Figure 2). Most surveys were implemented prior to the establishment of large-scale irrigated agriculture; however, small farms are evident in many of the notes.

The original survey methods were standardized with the 1855 publication of the first General Land Office Manual of Instructions, and were refined in subsequent manuals. Surveyors walked along section lines and recorded locational information about cultural features such as roads, fences, and buildings as well as natural features such as stream crossings, ravines, and transitions from one vegetation type to another. The survey notes also included the distance and bearing to witness trees at the beginning and end of each section line if trees were available to blaze. General descriptions were written about the vegetation of each survey line walked. Survey notes were then used to compile a plat map of the township.

The survey notes, originally provided on microfiche, were scanned, digitized and saved electronically in a geographic information system. Notes were interpreted from their original handwritten form and pertinent section line and witness tree data were entered manually into spreadsheet format. Survey notes from forty-six townships were included in the analysis with 15,767 segments totaling 6,396 kilometers. Vegetation descriptions varied from surveyor to surveyor; however, we classified all descriptions into one of nineteen categories, corresponding with categories used in the 2007 Walker River Vegetation Map. After classification the data were converted into ESRI shapefiles using the GLO Analyst extension for ArcView 3.3 (Andersen and Baker 2006).

Witness tree data were generated from the same survey notes as the section line data, and were entered into the GIS using the coordinates at the section line end point or midpoint. Coordinates were taken from the Bureau of Land Management's Geographic Coordinate Data Base. Witness tree attributes included distance from the section end or midpoint, the bearing from the end/midpoint to the tree, and the diameter of the tree. An overview of the GLO data for a small area is shown in Figure 3.

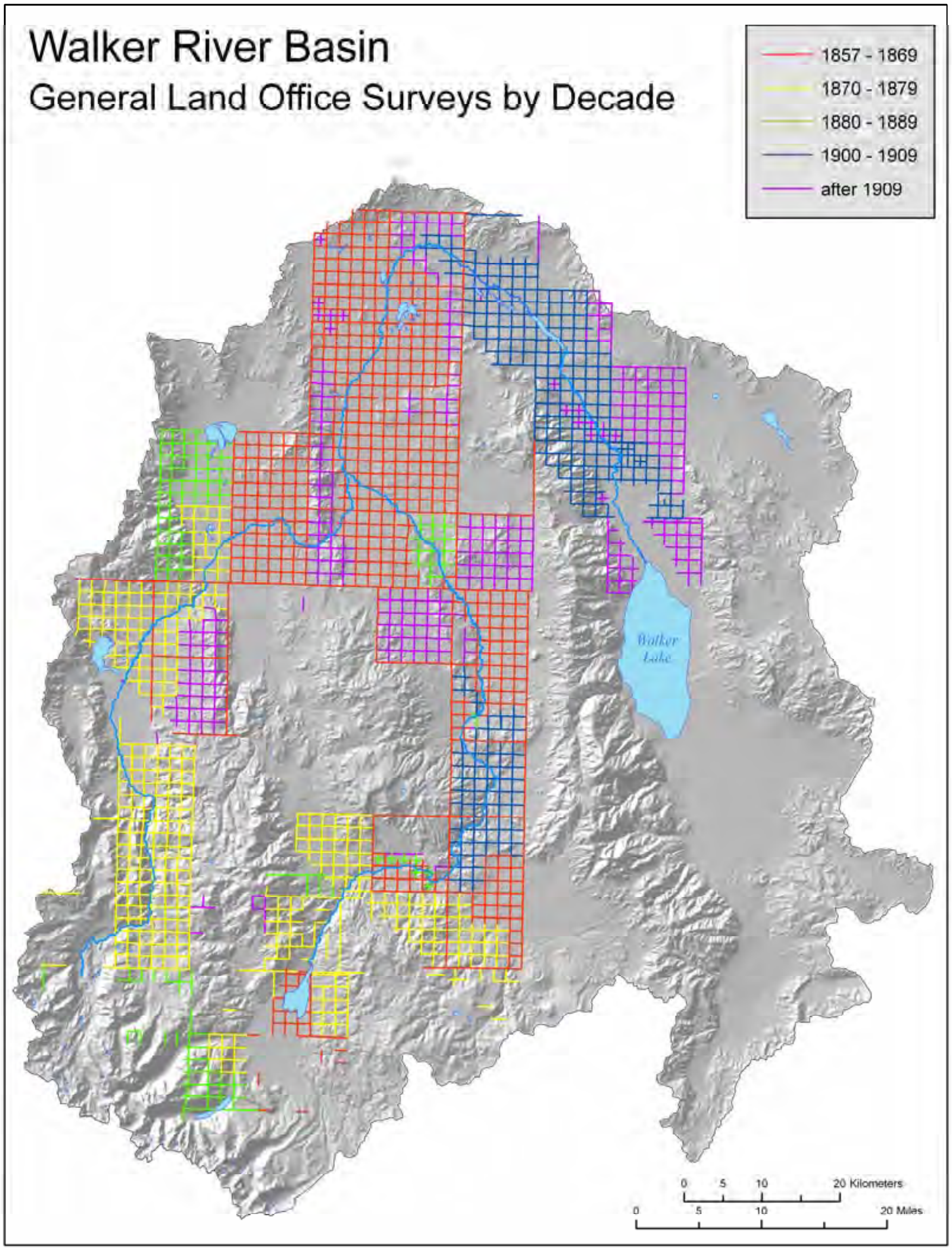

Figure 2. Earliest known General Land Office survey by decade for the Walker River Riparian/Agricultural areas.

Figure 3. Overview of data sources for a small area near Schurz. (a) GLO section line with two witness trees, overlaid on the 2007 vegetation map developed in collaboration with U.S. Fish and Wildlife Service. In 1904, agriculture existed where there is now an alkali shrubland (left) and there are now fields where there was once a cottonwood forest (right). The middle portion of the map shows cottonwood forest both today and formerly. (b)The corresponding portion of the 1-m, true-color NAIP orthophotograpy from which the vegetation map was derived. (c) The GLO survey plat map from 1904.

Particular research questions motivating our analysis of historical LULC change in the Walker Basin included:

1. What was the extent of riparian gallery forest along the Walker River prior to intensive agriculture use? Have cottonwood forests declined along the main stem as a result of changing hydrologic regimes, groundwater withdrawals, and land use conversion, as has been observed for other areas of the western U.S. (Fenner et al. 1985; Rood and Mahoney 1990)?
2. Has the relative dominance of woody vs. herbaceous vegetation types changed throughout the Walker Basin riparian corridor, in areas not directly converted to agricultural use? Are there indirect effects of irrigated agriculture on adjacent plant communities, perhaps due to water subsidies and reduced depth to groundwater?
3. Which types of natural communities have been preferentially converted to agricultural use? Following historical abandonment of agricultural land use, have plant communities reverted to their pre-agricultural vegetation type?
4. How does the probability of invasion by exotic phreatophytes such as *Tamarix ramosissima* and *Elaeagnus angustifolia* vary with plant community type or historical land use?

Walker River service maps

In 1905, the US Reclamation Service undertook a survey of the irrigable lands within the Walker River Basin. They produced detailed maps showing the extent of agriculture as well as the crop types, diversions, homesteads, and other features of interest. These maps have been digitized in order to assess changes that occurred immediately after the establishment of large scale irrigated agriculture in the basin.

Historical air photos

In order to assess vegetation change during the middle of the 20th century, aerial photographs were acquired from the US Geological Survey for the years of 1938 and 1952. The photos were georeferenced using ArcMap maintaining a root mean square error of less than 4 meters. Control points were selected as close as possible to the Walker River and a second order transformation was applied to the image. Images were then mosaicked together into tiles.

Analysis of historical conditions

Distribution of cottonwood forest

Historical and current cottonwood distributions were analyzed using both the GLO section corner witness tree data and the GLO section line data. GLO section corners were extracted for all townships in the Walker River Basin that intersected the Walker River. Section corners that were recorded after 1910 were not included in the analysis because most areas of the river had been settled by that point in time. To compare the presence and absence of cottonwood at the time of settlement with the current distribution of cottonwood we used a GIS to buffer each section corner by 100 and 200 meter buffers, and we manually examined aerial photographs to determine whether cottonwood were present or not. The maximum distance from a section corner to a witness tree that was recorded in the survey notes was approximately 200 meters. To generate a more conservative estimate we also used the 100 meter buffer. Images from the National Aerial Imagery Program (1 meter resolution) and an aerial photograph from Digital Globe (0.3048 meter resolution) were used in the analysis.

GLO section lines and the Walker River vegetation map were used to compare changes in the density and distribution of cottonwood patches between the time of early settlement (late 1800s) and 2007. A GIS was used to extract modern cottonwood patches using the Walker River vegetation map so that three states of cottonwood could be identified: 1) cottonwood patches that were present at the time of settlement and are present now, 2) areas of cottonwood that were present at settlement and are no longer cottonwood, and 3) areas of cottonwood that are present today but were not present at the time of settlement.

Conversion of natural communities to agriculture

We created a dataset that showed the distribution of agriculture for the entire Walker River Basin at three time periods: 1857 to 1899, 1905, and 2007. Polygons were digitized from the GLO survey maps to provide a dataset of settlement-era agriculture. The Bureau of Reclamation Walker River Service Maps were used as the data source for the 1905 map. The modern dataset was provided to us by Tim Minor at Desert Research Institute and covered Smith and Mason Valleys as well as areas along the East Fork of the Walker River. To provide a consistent map covering all areas of the basin we digitized additional polygons in Antelope Valley and in the Walker River Paiute Reservation. The GLO section line GIS layer was intersected with the polygons to generate a transition matrix showing the vegetation types that were converted to agriculture.

Changes in the distribution of non-agricultural plant communities

We compared changes in dominance and distribution of non-agricultural vegetation types using GLO section lines and the Walker River vegetation map. The GLO section line GIS layer was overlaid on the Walker River vegetation map and section lines were attributed with both historic and modern vegetation types. The Walker River vegetation map identified 19 major vegetation classes while the GLO data could only discern nine vegetation classes; therefore modern vegetation classes were cross-walked to match the coarser thematic resolution of the GLO data. Changes in vegetation type were assessed using a transition matrix, and areas where major changes occurred were distinguished and used for subsequent analyses of the spatial distribution of vegetation change in the Basin.

Predictive Modeling of Vegetation-Environment Relationships

The predictive modeling approach used detailed field inventory data to model the relationship between species composition and abiotic gradients. A combination of ordination techniques, generalized regression models, and other analyses (reviewed in Guisan and Zimmermann 2000) was used to predict the distribution of plant species according to environmental variables for which we have extensive spatial databases.

Geodatabase development

We identified a set of environmental gradients that are expected to affect spatial distribution of Walker Basin riparian vegetation at a landscape scale and developed a geodatabase to assemble these environmental gradients in GIS formats (summarized in Table 1). Because of the linear nature of riparian corridors, these variables can be classified as either transverse (i.e., lateral) or longitudinal types according to the direction of the pathway along which the corresponding environmental processes affect vegetation distribution (Bendix 1994, Wiens 2002). For example, depth to the groundwater and inundation frequency are transverse variables that vary considerably within a given cross section perpendicular to the river channel, while temperature and precipitation are longitudinal variables that are generally invariant within a cross section but vary along the entire course of a river. In general, variations of transverse variables are measured at fine scales (e.g. meters) whereas variations of longitudinal variables are measured at broad scales (e.g. kilometers). Soil variables were derived from the Natural Resource Conservation Services' SSURGO database. Annual, maximum, and minimum precipitation and temperature datasets were downloaded from the PRISM group website. LiDAR data was flown in late September of 2006 by Fugro Horizons, Inc. and was provided to us as a digital elevation model. To derive variables that could be used as proxies for groundwater and flooding we created custom models in ArcGIS Model Builder to generate proxies for height above river (HAR) and flood height (FH). These models have been made publicly available for download at url: http://www.cabnr.unr.edu/weisberg/downloads/ and at the ESRI ArcScripts site. Height above river was calculated as the difference between the elevation at a particular location (raster cell) and the weighted average of the elevation of cells designated as river segments. The height above river variable is analogous to the elevation of a particular cell minus river base flow. Flood height was calculated by discretizing the height above river data into centimeter increments and using a *costdistance* function to identify all cells below each centimeter height above river that are physically-connected to the river channel.

Vegetation mapping

Current vegetation distribution and structure were quantified in three different ways: (1) vegetation mapping (from aerial photography), conducted primarily by the U.S. Fish and Wildlife Service (USFWS), with accuracy assessment conducted as a collaborative effort between USFWS and our research group at UNR; (2) sampling of understory plant community composition (herbaceous and shrub layers), implemented collaboratively between USFWS and UNR; and (3) sampling of overstory tree canopy structure, implemented collaboratively between our research group at UNR and Dr. Will Richardson, working with Dr. Dennis Murphy at UNR.

Table 1. List of environmental gradients assembled in the geodatabase

Scale of the variable	Abbreviation	Variable
Longitudinal		
	TMIN	Average annual minimum temperature (^oC)
	TMAX	Average annual maximum temperature (^oC)
	PRECIP	Annual precipitation (cm)
	PPT01	Average January precipitation (cm)
	PPT07	Average July precipitation (cm)
	TMIN01	Minimum January temperature (^oC)
	TMAX07	Maximum July temperature (^oC)
	PRICIRSD	Residual of precipitation against elevation (cm): an indicator of rain shadow effect
	ELEV	Elevation: 10 m resolution (m)
Transverse		
	D2RV	Distance to the Walker River (m)
	HAR	Height above river channel (m)
	FH	Flood height (m)
	SLOPE	Slope (^{o})
	SWNESS	Cosine(aspect – 225^o) (Franklin et al. 2000)
	AWS	Available water storage for the soil to a depth of 1m (cm)
	PH	Soil pH
	CEC	Soil cation exchange capacity
	DRAINAGE	Natural drainage conditions of the soil: ordinal variable ranges from 1 to 5 with higher values indicating more well drained
	TPI	Topographic position index
	TCI	Topographic convergence index: a type of soil wetness index (Wolock and McCabe 1995)

The vegetation mapping effort was implemented during the summer and autumn of 2007. Mapping was implemented through photo-interpretation, by manually digitizing polygons from the National Agriculture Inventory Program imagery at 1:2,000 scale. A total of 19 vegetation classes was mapped, including 8 classes that are not generally considered riparian but were included in the map because of their proximity to the Walker River (Table 2).

Table 2. Area of each mapped vegetation class, developed in collaboration with the U.S. Fish and Wildlife Service. Vegetation classes marked by an asterisk are not true riparian vegetation types. Note that this is a preliminary vegetation type classification, subject to further modification.

Vegetation Type	**Hectares**	**Percent of Total Area Mapped**
Early Successional Riparian	287	0.65
High Density Riparian Shrub	2,307	5.19
Low Density Riparian Shrub	324	0.73
Mature Cottonwood w/ Xeric Understory	487	1.09
Mature Cottonwood w/ Riparian Shrub	445	1.00
Wet Meadow	647	1.46
Emergent Marsh/Wetland	526	1.18
Alkali Meadow	728	1.64
Alkali Shrub	2,833	6.37
Big Sagebrush*	7,284	16.38
Big Sagebrush w/ high Bitterbrush*	368	0.83
Big Sagebrush w/ high Rabbitbrush*	61	0.14
Silver Sagebrush	16	0.04
Pinyon-Juniper Woodland*	2,752	6.19
Jeffery Pine Forest*	1,093	2.46
Xeric Shrub*	10,117	22.76
Playa*	142	0.32
Tamarisk	1,093	2.46
Agricultural and Developed Land*	12,950	29.13
TOTAL ACREAGE MAPPED	44,459	

Accuracy assessment of vegetation map

Stratified random sampling was used in a GIS environment to generate 449 random points within each of the nineteen classes. Visual analysis of the distribution of sample points indicated that the points tended to be well distributed throughout the range of their respective classes in terms of abiotic predictor variables.

Map accuracy was assessed through a combination of field visits and comparison with other, high-precision maps. Validation points were overlaid with a digitized irrigated crop map produced by the Desert Research Institute. Points that did not fall in irrigated fields were visited in the field. The Walker River Basin contains land under a variety of different ownership categories. Within the riparian corridor of the Walker River public lands account for 41.1% of total the total area while private lands account for 39.0%, and tribal lands for 19.9%. Typically, access to private lands was very limited and, in many instances, not feasible within the time frame of this project. Therefore, due to primarily to access limitations, sampling was only conducted on 291 out of 449 potential sites.

Field visitation was implemented by navigating to the correct point location using a Garmin GPS. Once at the location the map accuracy was assessed within a 17.84 meter radius of the point (equivalent to 0.1 hectares). The following information was recorded at each site: whether the point was accurately mapped, what the correct vegetation class should have been, ocular estimates of cover by genus or functional types, general notes about the site, and photographs of the site.

The resulting data were entered into an error matrix from which agreement and kappa statistics were calculated. The kappa statistic has the advantage of accounting for unevenness in the number of samples in different classes, because it compares actual agreement with chance agreement (Congalton and Green 1999).

LiDAR analysis of vegetation structure

The Walker River was flown in November of 2006 and light detection and ranging (LiDAR) data were collected along the river corridor above Wabuska. LiDAR data were assessed for quality and processed to remove anomalous data by Wes Newton of the US Geological Survey and were provided in the form of digital elevation models. Work is ongoing to create canopy surface models and to derive estimates of canopy cover, canopy height, and biomass estimates in a spatially-explicit manner. Digital elevation models derived from the LiDAR data were the primary data source for the species-environment relationship modeling because they provide very high resolution information on surface topography and morphology. Canopy cover data derived from LiDAR will be merged with the Walker River Vegetation Map to provide accurate cover estimates for each plant structural class within polygons. LiDAR is also being used for single tree delineation of cottonwood trees and is being compared to the witness tree data to estimate how the extent of gallery cottonwood forests has changed since the late 19th century.

Plant community sampling

A total of 168 sample sites was located using a random stratified sampling of vegetation types, classified according to soil type, landscape position relative to the river and species composition. Field sampling followed the point intercept procedures of Forbis *et al.* (2007). All vascular plants encountered during the field survey were identified to the lowest taxonomic level possible. Wetland plant species were subsequently classified within one of five national wetland indicator categories, each of which represents a probability of occurrence in wetlands (Reed 1988).

Plant community classification and species-environment modeling

Classification of species into major community types in the 168 plots was performed with the TWINSPAN (two-way indicator species analysis) procedure (Hill 1979) using the program PC-ORD. This procedure was used with the cut-off levels of 0, 2, 5, 10, 15, 20, 30, and 40% to translate species abundance into presence/absence of pseudo-species. After major community types were constructed, Indicator Species Analysis (ISA) was then used to assign species to the community type for which they had the highest indicator value (Dufrene and Legendre 1997). The indicator value is the product of species relative abundance and species relative frequency. Relative abundance, a measure of specificity, was calculated as the total coverage of a species in a given community type divided by total coverage over all types. Relative frequency, a measure of fidelity, is the percentage of sites in which a species was present for a given community type. The indicator value is maximized when all individuals of a species are found in a single group of sites and when the species is observed in all sites of that group.

We used Detrended Correspondence Analysis (DCA, Hill and Gauch 1980) to examine the major vegetation gradients in the specie-level sampling data. Graphic examination, correlation statistics, and regression analysis were then used to assess the importance of environmental variables in determining the major DCA axes. In the resulting ordination diagram, selected important environmental variables were depicted as vectors.

Dynamic Simulation Modeling of Groundwater and Plant Water Use

Although the project has ended we are continuing to develop linked models of land use/land cover (LULC) change with models of evapotranspiration and groundwater dynamics (Figure 4), to quantify the effects of changing agricultural practices on plant water use at the watershed scale. During the timeframe of the project, we have applied the RIP-ET package to improve plant water use estimation, and have developed a modeling system for dynamic linkage of vegetation and water use models. In future efforts, we will use MODFLOW to model groundwater flow alteration due to LULC change. The cascading effect of groundwater change on vegetation distribution will be examined by a vegetation/groundwater model. We will then use RIP-ET to examine the reciprocal interaction between vegetation change and groundwater depth through ET. We are collaborating with Greg Pohll on this effort, and making use of groundwater models for Mason and Smith Valleys that his group has already developed. Results will allow us to place water savings from changing agricultural and LULC practices in the context of a basin-level water budget, as well as to gauge the overall effects of irrigated agriculture on vegetation water use relative to pre-settlement conditions.

Groundwater model

Groundwater flow was simulated using MODFLOW-2000 (Harbaugh et al. 2000). MODFLOW is a well-documented and widely applied FORTRAN code (Anderson and Woessner 1992) that uses difference equation methods to numerically solve a set of differential equations governing the flow of groundwater. For our simulation of groundwater in the Mason Valley, the model domain was one unconfined layer in thickness. It contained 90,790 blocks or nodes. Block spacing were 100 m, with each node representing 1 ha area. Simulations were run with the Layer-Property Flow (LPF) package, Recharge (RCH) package, Well (WEL) package, Drain (DRN) package, and a newly developed Riparian Evapotranspiration (RIP-ET) package, described in the next section.

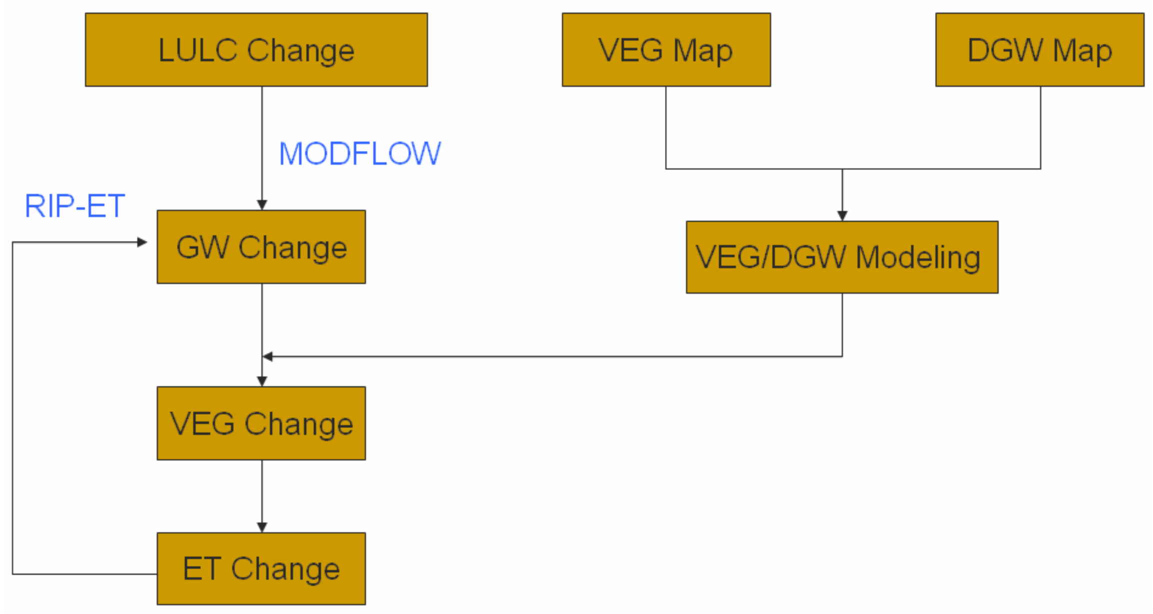

Figure 4. Modeling of the interaction between land use land cover change, groundwater, vegetation and evapotranspiration.

Simulating riparian evapotranspiration

We used the RIP-ET package (Baird et al. 2005) to link dynamics of riparian vegetation and groundwater. RIP-ET improves on the traditional groundwater models such as MODFLOW by providing a more realistic representation of evapotranspiration from riparian systems. Traditional approaches for modeling ET are based on a single, quasi-linear relationship between ET flux rate and hydraulic head (groundwater depth), which lacks consideration of ET differences among different riparian plant species. RIP-ET uses multiple, non-linear flux curves that reflect species-specific ecophysiological characteristics. Our simulation included six plant functional subgroups (PFSG) based on rooting depth and plant size. These are obligate wetland plants, shallow-rooted riparian, large-size deep-rooted riparian, medium-size deep-rooted riparian, small-sized transitional (upland) plants, and bare soil/water. The ET flux curve of each PFSG is derived from Baird and Maddock (2005). Because MODFLOW cells are generally large (1 ha in our study), some cells are likely to comprise a mixture of plant functional subgroups. In order to handle this problem, RIP-ET allows for fractional coverage of multiple PFSGs within a cell. For our simulation, the fractional coverage was computed from USFWS Walker River Corridor vegetation map and vegetation height and canopy coverage data derived from LiDAR.

Vegetation modeling at the community level

We have developed a steady-state (statistical) vegetation model to examine the potential effects of changing water tables on the composition and distribution of Walker River riparian vegetation. We used field vegetation data and spatial covariates to develop an empirical relationship between riparian plants community and environmental gradients associated with groundwater availability, flooding potential, and climate. We developed four random forest models for modeling 1) plant communities at a fine level of classification, 2) plant communities at a coarse level of classification, 3) riparian plant communities only, and 4) adjacent upland communities only.

PRELIMINARY RESULTS AND DISCUSSION

Validation of Modern-day Vegetation Map

Access limitations had the effect of limiting sampling on certain portions of the river, as well as within certain vegetation classes. In general, areas of the river corridor with a larger proportion of public or tribal lands had greater sampling intensity compared to those with more private lands. Table 3 shows the number of sites validated according to land ownership category. Access limitations also had the effect of limiting sampling on certain portions of the river, as well as within certain vegetation classes. In general, areas of the river corridor with a larger proportion of public or tribal lands had greater sampling intensity compared to those with more private lands. Table 4 shows the number of sites validated within six general sections of the Walker River.

Table 3. Number of sites validated by land owner type.

Land owner	Sites validated	Total sites	Percent validated
Public	190	216	88.0
Tribal	74	121	61.1
Private	27	112	24.1

Table 4. Number of sites validated by river section.

River section	Sites validated	Total sites	Percent validated
Lower river (below Wabuska)	86	143	60.1
Mason Valley	50	88	56.8
Smith Valley	3	20	15
Antelope Valley	14	28	50
West Walker River	72	78	92.3
East Walker River	70	91	76.9

Access limitations also led to uneven sampling among different vegetation types. Vegetation types that had the highest representation included Jeffrey pine, emergent wetland/marsh, and big sagebrush with bitterbrush. Mature cottonwood classes and tamarisk were least represented by the sampling effort. The number of samples from each class ranged from six (mature cottonwood with a riparian shrub understory) to 24 (Jeffrey pine).

Overall map accuracy was 79% with 230 out of 291 samples correctly classified. However, both producer's accuracy (1 – error of omission) and consumer's accuracy (1 – error of commission) differed among the vegetation types (Figure 5). Only tamarisk had 100% producer's and consumer's accuracy. Producer's accuracy ranged from a low of 41% (high density riparian shrub) to 100% (emergent riparian, playa, tamarisk, sagebrush/rabbitbrush, and sagebrush/bitterbrush). Consumer's accuracy ranged from 47% (sagebrush/rabbitbrush) to 100% (tamarisk, pinyon juniper woodlands, cottonwood with a riaparian shrub understory, and emergent marsh/wetland). Average producer's accuracy was 83.48% while average consumer's accuracy was 79% when all classes are weighted equally. The overall kappa value was 78%.

Overall accuracy of the map was good, but not remarkable. At 79% the value is slightly below the 85% threshold that is frequently used to as a cutoff between acceptable and unacceptable results (Congalton and Green 1999). However, the distribution of error among vegetation classes is not uniform, and some classes were classified correctly at high rates of accuracy. Certainly, many classes have distinctive spectral and/or textural properties that would have made them easier to identify from imagery. One example of a class that was mapped with a high degree of accuracy was tamarisk. Along the lower stretch of the Walker River it has invaded and out-competed native shrubs such as willow to form dense thickets. The surrounding vegetation is primarily xeric shrub and there isvery little overstory to obscure tamarisk. Therefore, spectrally and texturally tamarisk is very different than its neighbors, and it tends to be relatively easy to delineate patches. Issues with misclassification may arise due to inability to distinguish between classes with similar spectral properties (agriculture versus wet meadow), dense canopy cover that obscures the understory (cottonwood with riparian shrub understory versus xeric shrub understory), or successional state (abandoned agriculture versus big sagebrush/high rabbitbrush).

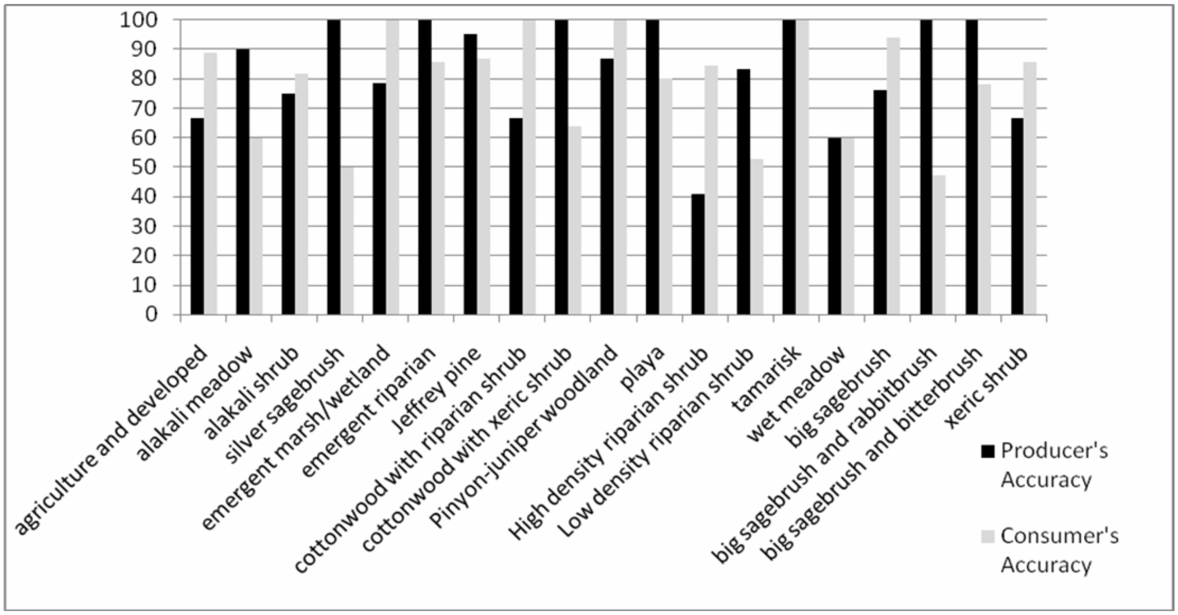

Figure 5. Producer's and consumer's accuracy for each vegetation class.

Characterization of Reference Conditions and Historical Change

Historical conditions: Cottonwood distribution

Analyses of the witness tree data from 1857 to 1910 showed a noticeable lack of gallery riparian forest across most of the Walker Basin (Figs. 6 & 7). Of 431 section corners only 16 had cottonwood trees present, and seven of these section corners were restricted to the lower river near present-day Schurz. Four corners contained cottonwood in Mason Valley. Along the West Fork there were four corners where cottonwood was present, while the East Fork only had one corner with cottonwood. Cottonwood presence at the time of settlement was limited to only 0.46% of section corners included in this study. The modern distribution of cottonwood, on the other hand, was widespread throughout most of the riparian areas of the basin and was present at 12% of section corners using the 200 meter buffer. Using the more conservative 100 meter buffer cottonwood trees were present at 9% of section corners. These estimates indicate that cottonwood trees today are likely 19 to 26 times more widespread than at the time of settlement.

The GLO section line data show a similar trend in increased cottonwood abundance throughout the basin. Of 34,071 meters of section line 23,938 (70.3%) had gained cottonwood while only 6,221 meters (18.3%) had lost cottonwood. Line segments with no change in cottonwood totaled 3,911 meters or 11.5% of the total. In contrast, areas where cottonwood had existed at the time of settlement showed decline in the total amount of cottonwood. The area below present-day Weber Reservoir where cottonwood existed prior to Euro-American settlement showed a loss of 3,514 meters or 56.1% of the historic length. Furthermore, the number of individual line segments increased from 29 at the time of settlement to 46 while the average length of the line segments decreased from 216 meters to 60 meters. The transition matrix of vegetation change from early settlement to the present-day along GLO section lines (Table 5) show that roughly equal proportions of settlement-era cottonwood segments had converted to upland shrub and agriculture (21.6% and 20.1%, respectively) with the remaining changes accounting for 20.7% of the total.

Across the western United States, gallery cottonwood forests along river systems have been in steep decline due to a lack of recruitment caused by river regulation (Rood and Mahoney 1990; Rood et al. 2005; Braatne et al. 2007). The relative lack of cottonwood along the Walker River at the time of settlement is surprising given the historical presence of large cottonwood groves on the nearby Carson and Truckee Rivers by John C. Fremont in his journals about his expedition in 1844. Analyses of aerial photographs taken in the 1930s and the 1970s showed large declines in cottonwood extent and canopy closure on the Truckee River due to a lack of recruitment from low flows (Lang et al. 1990; Rood et al. 2003). The Walker River, which is similar to the Truckee River climatologically and geographically, has been characterized by many of the same types of disturbances, such as diversions for agriculture, dam construction, channel straightening, and wetland drainage. Given its close proximity to the Carson and Truckee Rivers, similar geographic characteristics, and similar pattern of river regulation one might expect pre-settlement vegetation patterns on the Walker River to be similar to neighboring rivers. The lack of trees in Mason Valley was noted by author Samuel Post Davis in his 1913 book the History of Nevada in which he stated “There were no trees except a few in the southern part of the valley.”

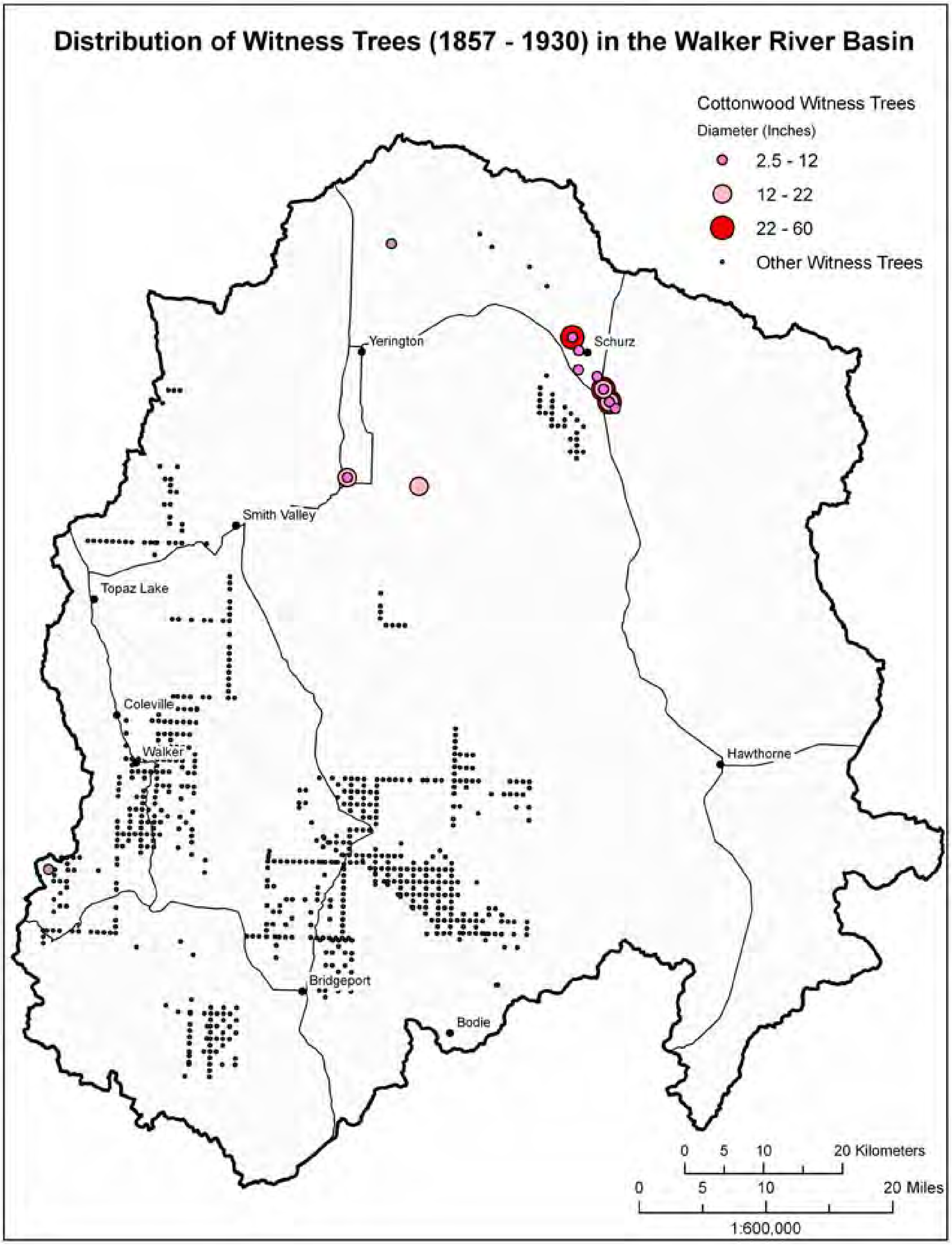

Figure 6. Distribution of witness trees from GLO surveys (1857 – 1930) in the Walker River Basin. Cottonwood trees are shown in color, with increasing symbol size reflecting increasing tree diameter.

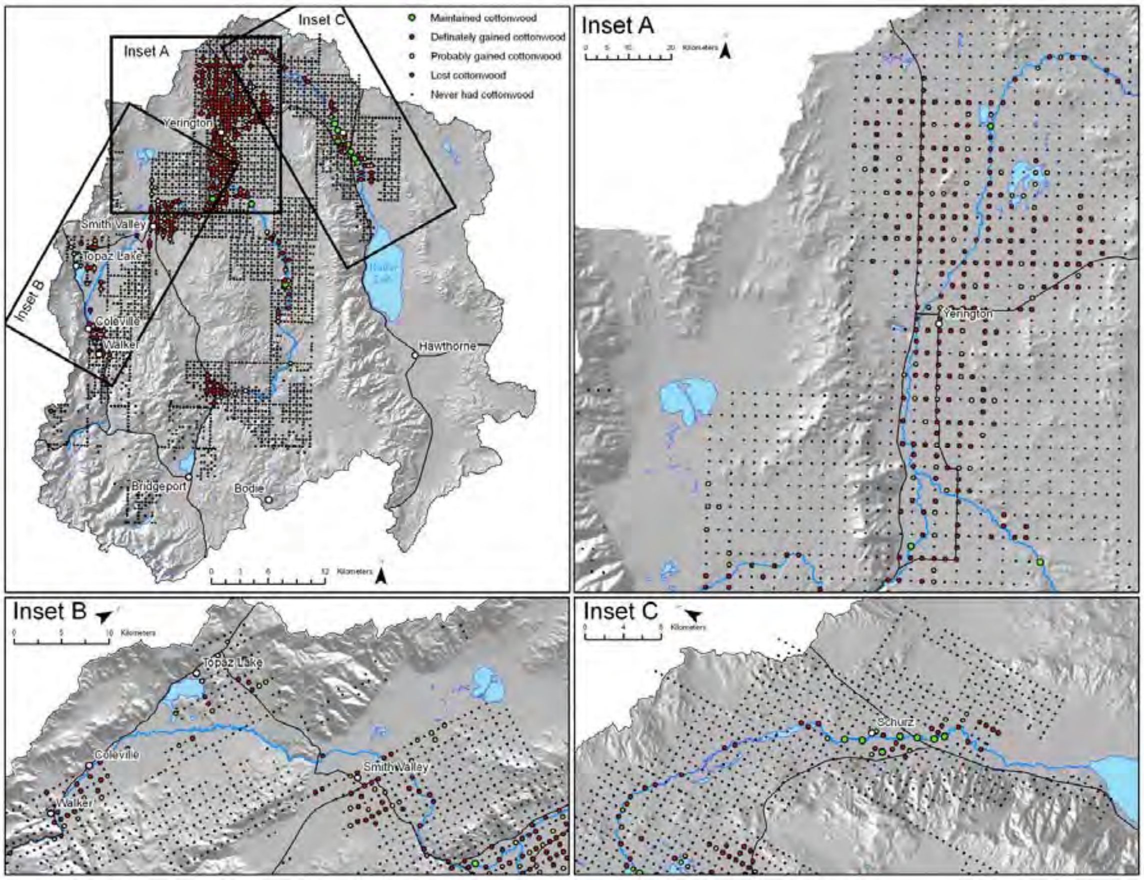

Figure 7. Presence-absence of cottonwood at 3,454 witness tree observation in the Walker River Basin, identifying sites that have changed with respect to occurrence of cottonwood over the period of study.

After Euro-American settlement, cottonwood expansion in the Walker River Basin was probably rapid. Valued for shade, they were planted near homes and along roadways. The construction of a ditch network in Mason Valley during the 1860s brought water and suitable regeneration surfaces to new areas. Early ditches required long hours of manual labor to keep them clear of debris (Young and Sparks 2002) which may have resulted in continuous deposition of sediments suitable for cottonwood germination. Large spring floods favored for germination are likely to have been common prior to construction of the first dam in 1922. The combination of a more geographically-dispersed seed source due to planting, new habitat, suitable germination surfaces, favorable floods and changes in grazing practices may have accounted for subsequent cottonwood proliferation after settlement.

Loss of cottonwood from its historical range along the river as evidenced by the GLO section line data appears to be equally due to conversion to agriculture and conversion to more xeric vegetation types. The net result is that the cottonwood patches along this section of river exhibit a more fragmented pattern compared to the more closed canopy forest that probably existed prior to white settlement. Conversion to more xeric vegetation types is consistent with river regulation having reduced the frequency of flows suitable for cottonwood recruitment. Cottonwoods require specific flow regimes that scour and expose moist sites, followed by a decline in the water table that is gradual enough for roots to maintain contact with the water (Mahoney and Rood 1998). The lowest reaches of the Walker River have been subject a two-thirds reduction in flow from 1882 to 1994, and correspondingly the lake level has experienced a 45 meter drop in surface elevation (Meyers 1997) resulting in severe incision along the lower river.

Historical conditions: Conversion of natural communities to agriculture

Conversion of natural communities to agriculture was the most frequent transition in the study area accounting for 59.4% of total change. Agricultural lands came from all previous land cover types including water and playa. However, the majority of agricultural lands came from upland shrub (58.5%) followed by meadow/wetland (23.1%) and riparian shrub (5.0%) (Table 5). Agriculture gained 111,958 meters along section lines while the next highest community, riparian shrub, only gained 18,044 meters. Tamarisk and cottonwood both showed net gains while meadow/wetland and upland shrub showed large losses.

Vegetation communities varied in the amount and proportion that they were converted to agriculture (Table 5). Meadow/wetland showed the largest percentage loss at 94.7%, of which conversion to agriculture accounted for 41.4% of the historic total. Riparian shrub had the largest proportion converted to agriculture (48.8%) and was second highest in the percentage of overall change (82.9%). Cottonwood experienced over half its total line length converting to other classes (62.3%) with 20.1% being due to agricultural conversion. Upland shrub experienced 42.2% change to other communities with agriculture accounting for 31.1% of that change. The percentage of the modern total that was retained from the original was smallest for riparian shrub (7.5%) followed by cottonwood (19.2%), meadow/wetland (32.2%), and playa (35.2%). Tamarisk was not present in the Basin at the time of survey.

Agricultural expansion was more common than agricultural abandonment. Most agricultural lands were established after 1905 rather than before 1905 (20,554 ha versus 7,831ha). Although agricultural abandonment was relatively rare, at total of 3,965 ha of agricultural land were abandoned or converted to other land uses. Abandonment was most common in the present-day Mason Valley Wildlife Management Area in the northern part of Mason Valley and off of the East Fork downriver from Bridgeport.

In the Walker River Basin 94.7% of meadow and wetland has converted to agriculture or upland vegetation types with much of the remaining meadow/wetland being located at high elevations close to the river’s source. According to Samuel Davis in the History of Nevada, “Before the white man turned his face westward, Mason Valley was inhabited by the Piute tribe of Indians. It was a fertile country with meadows of wild grass along the river, which was filled with trout.” Maps created by the General Land Office surveyors seem to corroborate this description showing large areas along the rivers as meadow. The first agriculture in Mason Valley was largely focused around grazing cattle and harvesting wild hay, while subsequent efforts involved converting native hay meadows to alfalfa fields. James Young (2006) describes the native hay meadows. “These fields featured a mixture of native and introduced grasses, sedges, rushes, tules, and willows, all of which were cut for low-quality hay.”

Table 5. Transition matrix showing change in land cover type from the period of settlement (1857 – 1910) to present-day.

	Cottonwood	Riparian Shrub	Mead./Wet.	Upland Shrub	Woodland	Jeffery Pine	Playa	Ag.	Tamarisk	Water	Historic Total
Cottonwood	2,514	600	434	1,440				1,338		348	6,674
Riparian Shrub	1,268	2,417	270	2,810				6,878		458	14,101
Meadow/Wetland	2,874	9,934	4,086	25,601	848			31,937		1,807	77,088
Upland Shrub	3,483	10,130	7,444	150,031	1,818	352	1,147	80,881	118	4,301	259,703
PJ Woodland	25	852	1	1,438	23,159			660		278	26,413
Jeffrey Pine		1,476	90	7,815		12,026		54		511	21,972
Playa				697			623	312			1,632
Agriculture	2,097	5,404	27	3,748				14,255		769	26,300
Water	859	1,331	326	10,085	31	87		1,942	10,850	638	26,150
Modern Total	13,120	32,144	12,678	203,665	25,855	12,465	1,770	138,258	10,968	9,111	460,023

The advent of irrigation allowed large areas of upland shrub communities within Mason and Smith Valleys to be converted to agriculture. Some of the most productive alfalfa lands in Nevada were former sagebrush lands with well-drained loamy soils. Drainage and leveling of fields were essential for alfalfa production, and the expansion of agriculture led to the disappearance of the native hay meadows and the cultivation of former upland shrub areas.

Historical conditions: Changes in the distribution of non-agricultural plant communities

Transitions from one natural community type to another were frequent throughout the basin, although taken together they were less frequent than transitions to agriculture. The most common natural community transition was meadow/wetland conversion to upland shrub which accounted for 11.0% of overall change. This conversion generally occurred on the downstream end of most large valleys (Mason, Smith, and Antelope). Conversions from upland shrub to riparian shrub and meadow/wetland to riparian shrub accounted for 4.35% and 4.27% of the change respectively. Areas where conversion from upland shrub to riparian shrub was common included areas of the lower portion of the Walker River upstream from Weber Reservoir, parts of Mason Valley, and sections of the river between Antelope and Smith Valleys. Conversion from meadow/wetland to riparian shrub occurred in most parts of the upper portion of the watershed including the large valleys (Mason, Smith, and Antelope) and the East and West Forks. The creation of tamarisk habitat was the fourth largest transition accounting for 4.66% of the total change. The majority of mapped tamarisk patches (98.9%) occur in areas that were formerly part of Walker Lake itself.

Natural plant communities in the vicinity of agricultural areas are subject to physical and hydrological effects that result from agricultural practices. For example, agricultural practices can result in raising or lowering the water table through irrigation or groundwater pumping. This has been shown to lead to changes in vegetation communities that can occur rapidly once the water table drops below the rooting zone (Elmore et al. 2006). The conversion from meadow/wetland to upland shrub may serve as an indicator of changing groundwater conditions due to pumping or river channelization. In Walker Basin, extensive areas of historical conversion from meadow/wetland to upland shrub communities are generally located near the downriver portions of large valleys.

Conversion from upland shrub to riparian shrub was most common above Weber Reservoir on the lower Walker River. This conversion may be the result of higher water tables resulting from the creation of the reservoir. Conversion from meadow/wetland to riparian shrub was common throughout much of the river system. One especially notable area is the portion of the river that is downstream of the diversion to Topaz Lake, but upstream of where the outflow of the lake returns to the river. Changes in flow regime have resulted in a narrowing of the river channel in areas where water was diverted from as well as a loss of sinuosity. These changes may have favored the expansion of woody shrubs, such as willow.

Current conditions – Description of current vegetation

Agricultural and other developed land occupies nearly 30% of the area mapped. Xeric shrub and big sagebrush communities form the next most dominant vegetation communities (23% and 16%, respectively; Table 2). Cottonwood forests and invasive *Tamarix* stands each occupy approximately 2-3% of the area mapped, although much of the *Tamarix* is concentrated on the lower portion of the main stem of the Walker River, and on the delta where the river flows into the lake.

Species composition and community structure

We encountered 314 species over the 168 plots sampled during field surveys. Dominant woody species and herbaceous species are provided in Table 6, along with their frequencies of occurrence and wetland indicator scores. A total of 112 rare species (absolute frequency of occurrence < 3 plots) were excluded from further analysis.

Table 6. Ten most frequent woody species and ten most frequent herbaceous species observed on 168 plots, reported with their wetland indicator scores (Reed 1988).

Symbol	Scientific name	Common name	Wetland score	Frequency (%)
Woody species				
CHNA	*Chrysothamnus nauseosus*	rabbitbrush	5	47.0
SAEX	*Salix gooddingii*	narrowleaf willow	1	41.1
ARTR2	*Artemisia tridentata*	big sagebrush	5	40.4
SAVE4	*Sacrobatus vermiculatus*	greasewood	4	29.7
ROWO	*Rosa woodsii*	Woods' rose	2	23.8
SHAR	*Shepherdia argentea*	silver buffaloberry	1-2	20.8
TACH2	*Tamarix chinensis*	five-stamen tamarisk	2	18.5
POFR2	*Populus fremontti*	Fremont cottonwood	2	16.7
ATTO	*Atriplex torreyi*	Torrey's saltbush	3	16.0
ATCO	*Atriplex confertifolia*	shadscale saltbush	5	13.7
Herbaceous species				
LETR5	*Leymus triticoides*	beardless wildrye	2-3	47.0
JUBA	*Juncus balticus*	baltic rush	2	39.3
DISP	*Disichlis spicata*	inland saltgrass	3	38.1
ORHY	*Oryzopsis hymenoides*	ricegrass	5	26.2
IVAX	*Iva axillaris*	povertyweed	2	25.0
BRTE	*Bromus tectorum*	cheatgrass	NA	23.8
ACMI2	*Achillea millefolium*	common yarrow	4	23.2
EQHY	*Equisetum hyemale*	scouringrush horsetail	2	19.6
CAREX	*Carex*	sedge	1	16.7
IRMI	*Iris missouriensis*	Rocky Mountain iris	1	16.1

We identified 10 community types based on the TWINSPAN results. These 10 communities were shown as terminal nodes that varied at levels in the TWINSPAN dendrogram (Figure 8). The division at the first level separated the riparian sites (n = 107) from upland sites (n = 61). At the second level, a xeric desert scrub (XS) community that is associated with *Atriplex confertifolia* and *Sarcobatus baileyi* was identified (n = 19) from the other upland sites. At the third level, an emergent wetland (EM WET) community (n = 2) associated with *Cirsium vulgare* and *Scirpus microcarpus* and a wet meadow (WET MED) community (n = 21) were identified for the riparian sites allied with obligate wetland species *Carex* L. and *Juncus balticus*. A riparian shrub (RIP SHR) community (n = 38) associated with *Rosa woodsii* and *Salix goodingii* was singled out from other riparian sites at this level as well. The other two upland communities were also classified at the third level. They are the upland sagebrush community (n=36) and pinyon-juniper woodland (PJW) community (n = 6). Four additional riparian communities were classified at finer levels. They are the cottonwood community (n = 11) characterized by *Populus fremontti*, an alkali meadow (Alk MED) community (n = 6) associated with high coverage of *Leymus triticoides* and low coverage of *Juncus balticus*, an alkali shrub (ALK SHR) community (n = 21) associated with *Sacrobatus vermiculatus* and *Disichlis spicata*, and a tamarisk-dominated community (n = 7).

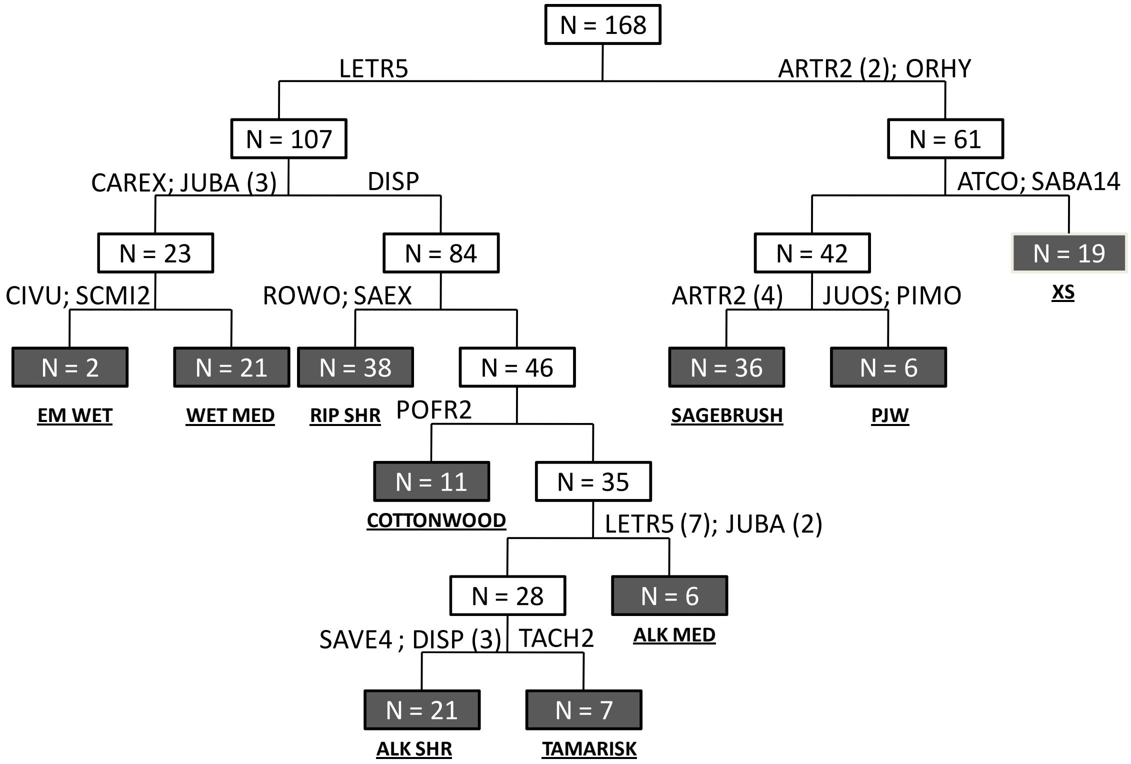

Figure 8. Dendrogram from TWINSPAN results. The 10 terminal nodes, filled with gray color, are paired with their corresponding community names. The number shown in each box is total number of sites belonging to this node.

The indicator species identified by the TWINSPAN and the ones identified by the ISA were combined, and their highest and second highest indicator values and corresponding communities are presented in Table 7. Communities EM WET, WET MED, PJW, and XS are strongly distinctive from others in terms of floristic characteristics as their indicator species are exclusively confined. Other communities are less so, particularly ALK MED and ALK SHR. The indicator species of ALK MED are observed in relatively large abundance or frequency for WET MED and RIP SHR; and each of the three indicator species for ALK SHR has a high indicator value for TAMARISK, COTTONWOOD, and XS communities correspondingly.

Table 7. Indicator species for each of the ten plant communities.

Indicator Species	Community with the highest IV	The highest indicator value	Community with the second highest IV	The second highest IV
ELPA3	<u>EM WET</u>	100	NA	0
SCAM2		100	NA	0
SCMI2		100	NA	0
CIVU		99	NA	0
CAREX	<u>WET MED</u>	68	ALK MED	1
IRMI		65	ALK MED	2
MURI		45	NA	0
LETR5	<u>ALK MED</u>	49	WET MED	12
JUBA*		32	WET MED	31
MEAL2*		17	RIP SHR	16
DISP	<u>ALK SHR</u>	54	TAMARISK	23
ATTO		36	COTTONWOOD	4
SAVE4		35	XS	27
TACH2	<u>TAMARISK</u>	63	COTTONWOOD	16
CHNA		44	SAGEBRUSH	10
SAEX	<u>RIP SHR</u>	59	COTTONWOOD	3
SHAR		48	COTTONWOOD	1
ROWO		41	SAGEBRUSH	5
POFR2	<u>COTTONWOOD</u>	48	RIP SHR	5
XAST		11	TAMARISK	7
ARTR2	<u>SAGEBRUSH</u>	62	PJW	20
SIHY		40	PJW	14
PUTR2		34	PJW	16
JUOS	<u>PJW</u>	82	NA	0
POSE		67	NA	0
PIMO		65	NA	0
TEGL	<u>XS</u>	60	PJW	1
ATCO		53	ALK SHR	8
SABA14		53	NA	0

* The highest and the second highest indicator value are too close for these species to be indicators in a strict sense.

Predictive Modeling of Vegetation-Environment Relationships

The relative distribution of species along axis 1 of the DCA ordination space was generally in line with species' wetland indicator status (Figure 9). For example, obligate wetland species ELPA3, SCAM3, SCMI2, and CIVU had the lowest DCA axis 1 score, immediately followed by facultative wetland species such as SHAR, SAEX, JUBA, POFR2, and TACH2. Facultative species DISP, ATTO and XAST were distributed towards the center of DCA axis 1. Facultative upland species (e.g., SAVE4, MURI) and upland species (e.g., SABA14, ARTR2) were distributed on the right side. The first axis was strongly correlated with the transverse-scale variables, HAR, FH, AWS, and SLOPE. Elevation was also highly correlated with the first axis, but was much more so with the second axis. The top three environmental gradients correlated with axis 2 were the longitudinal-scale variables, elevation, temperature, and precipitation. The relationship between the variables and ordination scores of species assemblages is represented in the joint plot (Figure 10), where the angle and length of the radiating lines indicate the direction and strength of relationships of the variables with the ordination scores. The joint plot shows that the overall influence of longitudinal variables (ELEV, TMIN, TMAX, and PRECIP) was stronger than that of transverse variables (HAR, FH, SLOPE, and AWS). The joint plot also showed that most sites were clustered according to their communities in the ordination space, although a few outliers overlapped with other communities.

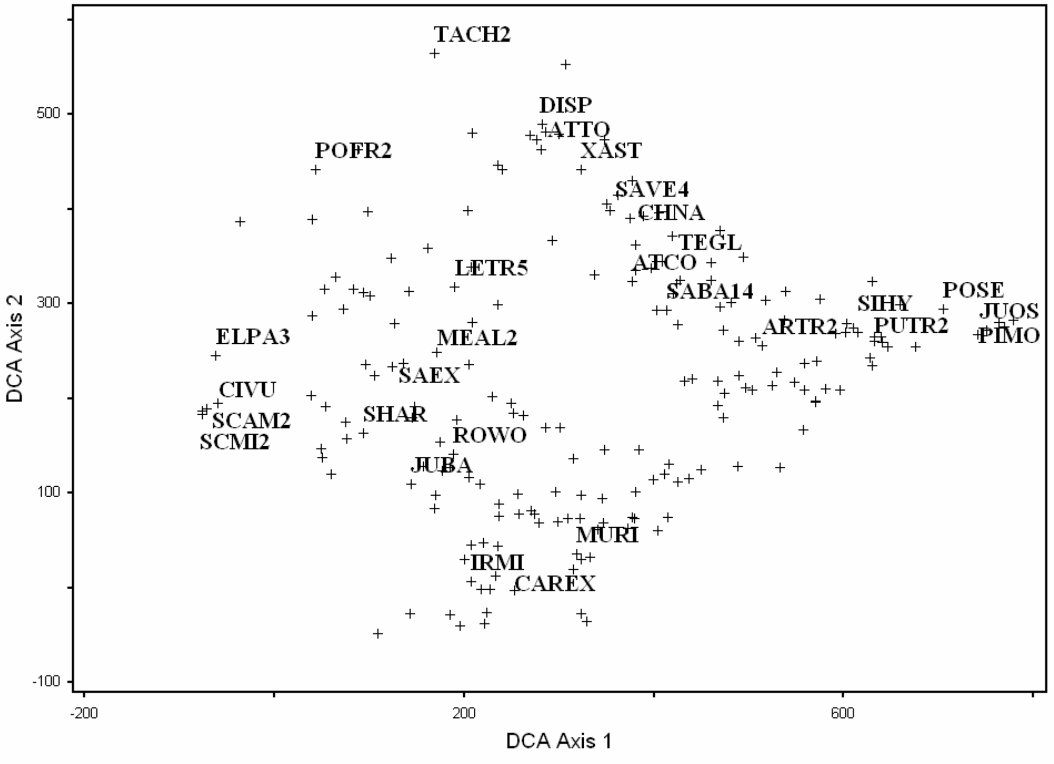

Figure 9. Distribution of Walker River woody and herbaceous species (n = 202) in DCA ordination space. The names of 29 indicator species listed in Table 3 are shown in this figure.

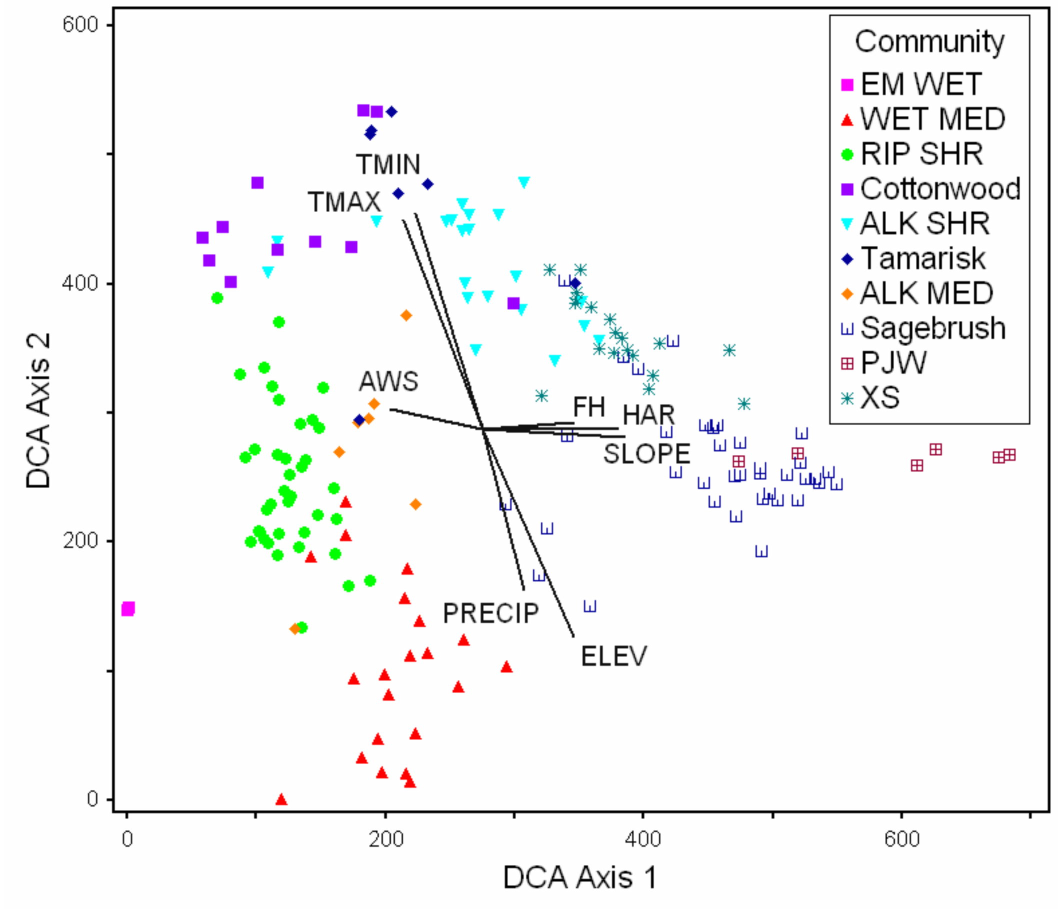

Figure 10. DCA ordination scores of 168 sites and the correlations with the major environment gradients.

The ability of a random forest classification model to discriminate plant communities varied with the level of classification and scope of plants included in the study. When modeling Walker River Basin riparian corridor species assemblages at a fine level with 7 riparian and 3 adjacent upland plant communities, the overall Cohen's Kappa was 0.56, reflecting a moderate level of agreement. This agreement was substantially improved when modeling species assemblages at a coarse level with two aggregated types only (Model 2, Table 8). The Kappa value was high (0.84) when modeling only upland species assemblages, but became lower (0.46) when modeling only riparian types.

However, the classification model including only riparian types improved prediction power for WET MED, RIP SHR, COTTONWOOD, and ALK MED (Model 3 vs. Model 1, Table 8).

Table 8. Modeling performances measured by Cohen's KAPPA, overall classification error, and error rate of each community type for four random forest models: 1) modeling plant communities at a detailed level of 10 types 2) modeling plant communities at a coarse level of two aggregated types 3) modeling seven riparian communities only and 4) modeling three adjacent upland communities.

	Model 1	Model 2	Model 3	Model 4
KAPPA	0.56	0.77	0.46	0.84
Overall classification error	0.38	0.11	0.44	0.09
Error rate by Community type				
Riparian Type		0.08		
EM WET	0.16		0.20	
WET MED	0.29		0.22	
RIP SHR	0.58		0.39	
COTTONWOODS	0.62		0.58	
AL SHR	0.82		0.86	
TAMARISK	0.15		0.15	
AL MED	0.72		0.69	
Adjacent Upland Type		0.16		
SAGEBRUSH	0.22			0.06
PJ W	0.17			0.21
XS	0.19			0.08

The relative importance of predictor variables identified by the random forest models also varied with the level of classification. When modeling the full set of ten communities, the two most important predictor variables were HAR and FH, indicating groundwater availability and flood potential. For this model, the five most important variables were all at the transverse scale. Among all the longitudinal gradients, PPT01 was the most important; but its importance was ranked only sixth among all the variables (Figure 11a). The longitudinal scale variables such as ELEV, PPT01 and TMAX07 increased their importance for modeling plant communities at the coarse level of classification distinguishing only riparian from upland vegetation types (Figure 11b). When the modeling scope was limited to riparian communities, distance to the river (D2RV) replaced HAR as the most important predictor variable, followed by the longitudinal variables such as PPT01, TMAX07 and ELEV (Figure 11c). Variables that represented temperature and precipitation, which are of longitudinal scale, were identified as the most important predictors for models that only included upland communities (Figure 11d).

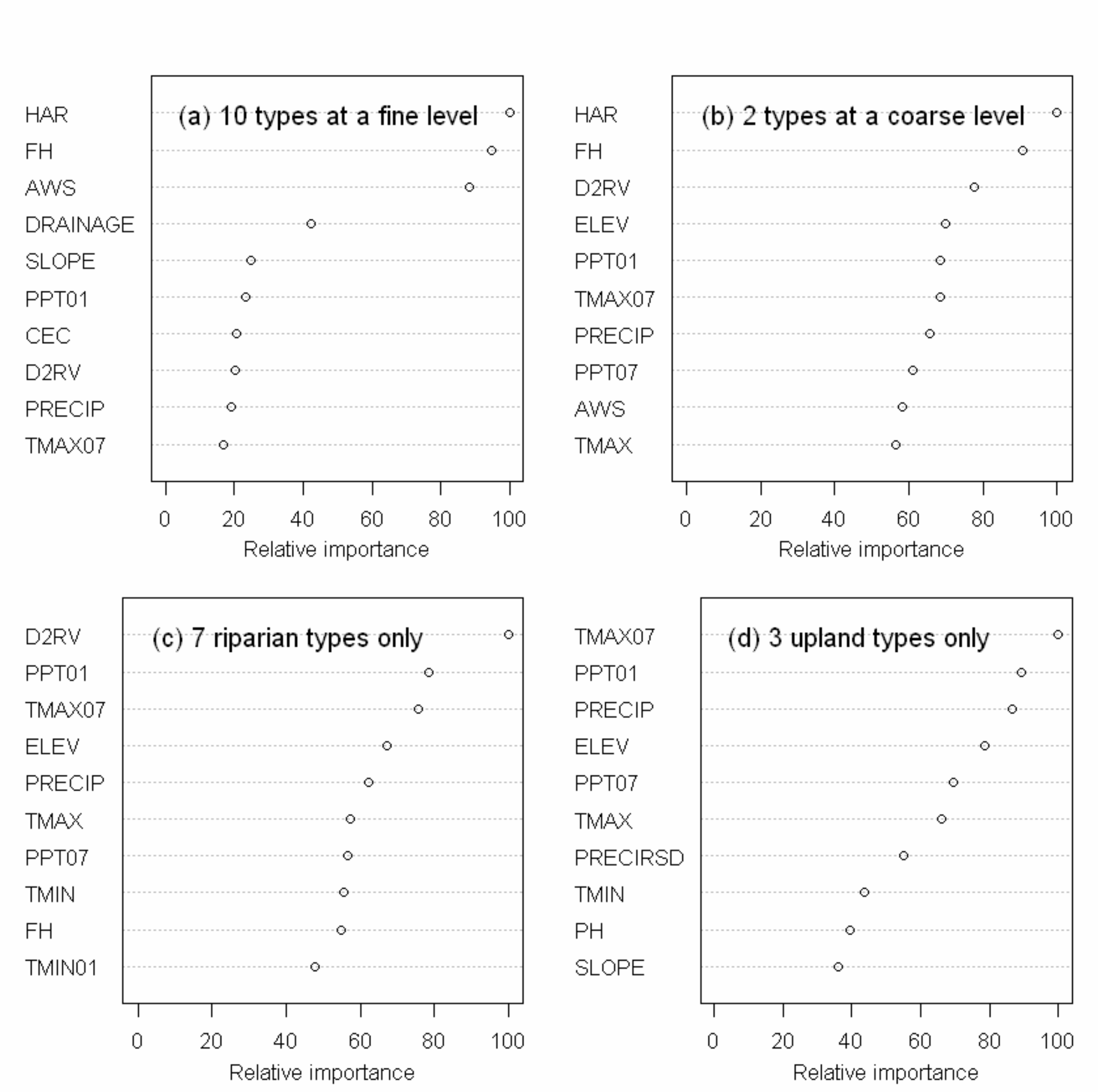

Figure 11. Relative variable importance when modeling (a) the 10 riparian and adjacent upland community types all together, (b) the 2 aggregated types riparian vs. upland, (c) the seven riparian types only, and (d) the 3 adjacent upland types only. Only the top 10 important variables are shown here.

Refinement of riparian plant water use estimates

The annual fluctuation of simulated ET rates within the riparian areas of Mason valley is correlated with climatic fluctuations. For example, ET rates peaked in the wet years of 1998 and 2006 and reached low values in the dry years of 2003 and 2004 (Figure 12). We found a significant (> 30,000 m^3/day on average) reduction of ET estimations when using the RIPET package (Figure 12) comparing to the ones simulated using the original EVT package of MODFLOW. Because lower ET losses were simulated using the RIPET package, the simulated water table elevations were higher (~ 0.2 m) than those simulated using the EVT package (Figure 13).

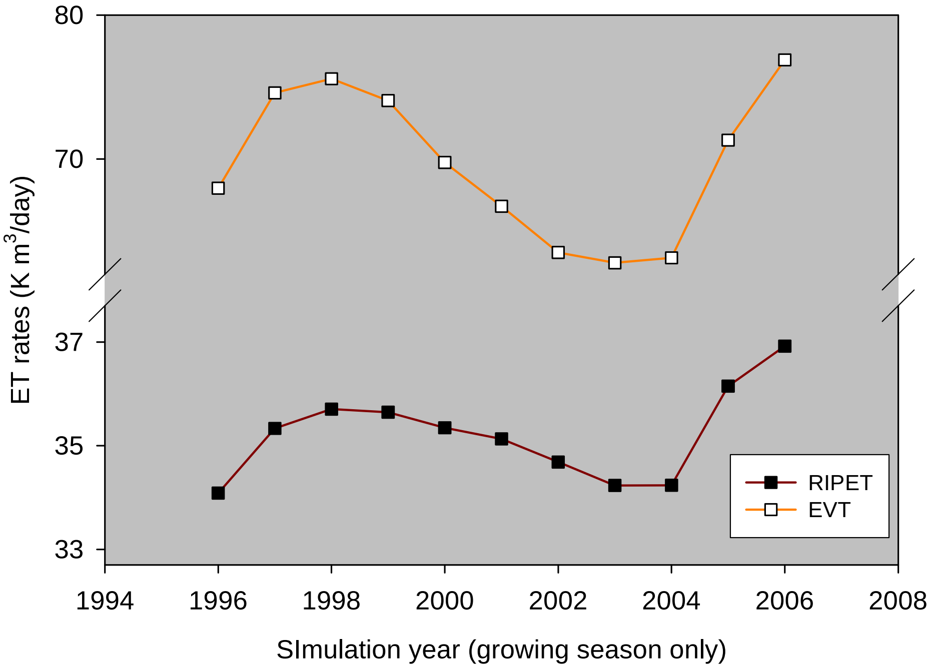

Figure 12. Simulated ET rates for riparian areas of Mason Valley using the original EVT package and the newly developed RIPET package.

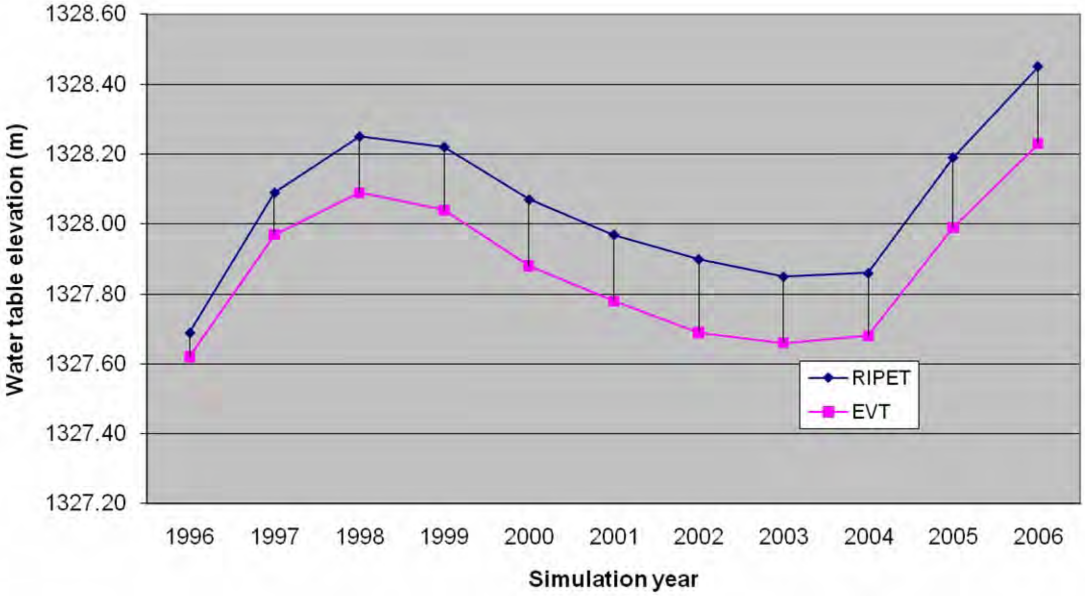

Figure 13. Simulated water table elevations for riparian areas of Mason Valley using the original EVT package and the newly developed RIPET package.

Simulated mean water table elevations were then subtracted from land surface elevation to derive depth to groundwater. The box plots of simulated mean depth to groundwater across different vegetation types show the upland vegetation (WSS/BSS and XS) occupying sites with higher depth to groundwater than phreatophytes (ALK SHR) or obligate wetland vegetation (Figure 14). The general ranking of mean depth to groundwater across these vegetation types is similar to the order exhibited in the ordination scores along axis 1 (Figure 14 vs. Figure 10), suggesting that the groundwater model using the newly developed RIPET package has produced reasonable outputs for modeling groundwater effects on riparian vegetation distribution.

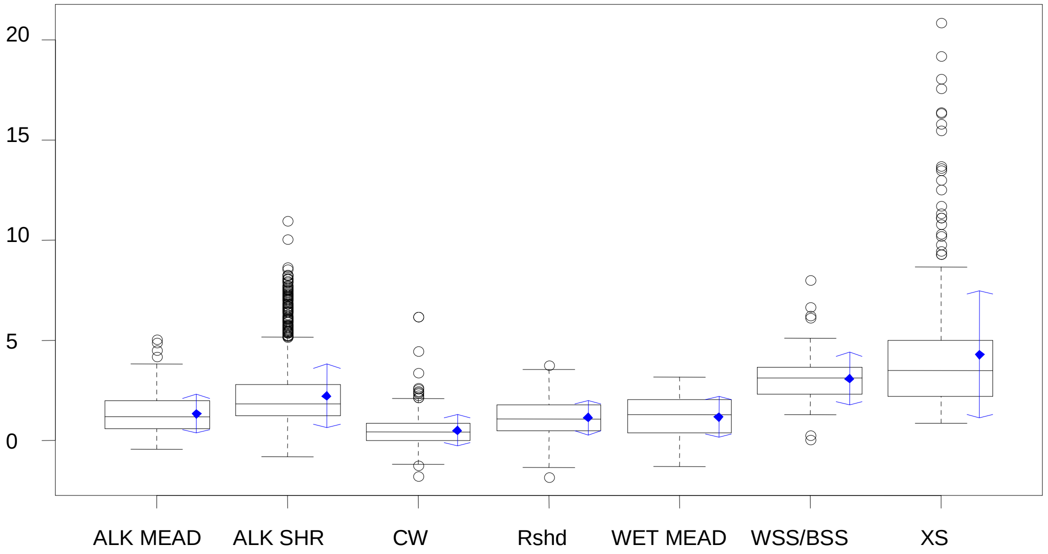

Figure 14. Box plots of simulated mean depth to groundwater (m) during growing seasons across vegetation types. Blue dots and arrows indicate mean values and standard deviations.

CONCLUSIONS

This study provides critical information regarding the baseline conditions that existed prior to intensive agriculture in the Basin. Our analyses of historical changes show a general tendency for transitions to more xeric communities for those vegetation patches that have not directly been converted to agriculture. Much of the historical riparian area in the lower river was dominated by wet meadow and emergent wetland habitats, of which the great majority that was not directly converted to agriculture has transitioned to riparian shrub, or desert shrub communities. The dominant direction of change observed in the historical analysis indicates a riparian environment that has become narrower, more channelized, and with reduced groundwater availability. Just as changes associated with river regulation and water withdrawal have altered the Walker Lake ecosystem, riparian environments in the floodplain have also experienced extensive alteration that likely result from the indirect effects of the hydrologic modifications needed to sustain an agricultural economy at the watershed scale. Changes to natural plant communities that do not result from agricultural conversion have been of a similar areal extent as transitions resulting from direct conversion to intensively managed agricultural land.

One of the more striking historical changes has been the redistribution of Fremont cottonwood trees from a few areas of floodplain forest, with the most extensive of these occurring at the former delta of the Walker River when lake levels were higher, to numerous small patches and individual trees scattered throughout the riparian and agricultural portions of the Basin. The cottonwood habitat type is at the same time more extensive and more fragmented than during the early Euro-American settlement period. Riparian grassland and wet meadow communities, however, have experienced great areal reductions through both direct and indirect influences of irrigated agriculture; climate change may also play a role. Ecological restoration efforts in the Walker Basin aimed at historical reference conditions might consider fostering the development and long-term maintenance of meadows. Such native "hay meadows" could also be compatible with sustainable livestock grazing practices, as they likely were prior to the introduction of alfalfa to the Basin.

Ongoing ecological modeling research will address the likely response of vegetation to current and future land and water use scenarios. Historical effects of flow alteration, river incision and groundwater withdrawal have apparently altered riparian plant communities in ways that are predictable and mappable, lending validity to our ecological modeling efforts. Current vegetation distribution is closely associated with measurable longitudinal and transverse predictor variables, including proxies for changing groundwater availability. Models of vegetation response to groundwater availability and climatic variables can be used to extrapolate future responses of plants to alternative agriculture scenarios and ecological restoration activities. Knowledge gained will be valuable for directing future changes in land management and water allocation, for restoration of former agricultural lands or lands currently dominated by invasive plants, and for management of associated plant and wildlife resources.

RESEARCH PRODUCTS

Papers

Dilts, T.E., Yang, J., Weisberg, P.J., Olson, T.J., Turner, P.L., and Condon, L.A. (in revision) Direct and indirect effects of irrigated agriculture on vegetation change in an arid lands watershed.

Yang, J., Dilts, T.E., Turner, P.L., Condon, L.A, and Weisberg, P.J. (in review) Modeling longitudinal- and transverse-scale environmental influences on riparian vegetation.

Dilts, T.E., Yang, J., Weisberg, P.J. (2010) Mapping riparian vegetation with LiDAR data: Predicting plant community distribution using height above river and flood height. ArcUser Magazine, Winter 2010 Issue.

Presentations

February 3, 2010: Historical ecology and GIS: an example from the Walker River Basin. An invited talk for the University of Nevada Reno, Department of Geography Colloquium. Reno, Nevada.

October 27, 2009: Reconstructing the vegetation of the Walker River Basin at the time of Euro-American settlement using General Land Office survey notes. International Symposium on Terminus Lakes. Reno, Nevada.

October 26, 2009: An Ecohydrologic Approach to Simulating the Interactions between Groundwater Flow and Riparian Vegetation at the Landscape Level. International Symposium on Terminus Lakes. Reno, Nevada.

May 18, 2009: Integrating R with ArcGIS for Mapping Riparian Vegetation Distribution along the Walker River. The 19th Nevada GIS Conference, Reno, NV.

April 14, 2009: Land use change in an arid agricultural landscape: reconstructing the historical vegetation at the time of settlement. United States Regional Association of the International Association of Landscape Ecology Symposia, Snowbird, Utah.April 14, 2009: Environment Influences on Riparian Vegetation Distribution: Scale and Level of Ecological Organization. United States Regional Association of the International Association of Landscape Ecology Symposia, Snowbird, Utah.

Posters

Dilts, T.E., Yang, J., Weisberg, P.J., Turner, P.L., and Condon, L.A. Multiple approaches to modeling vegetation communities in the Walker River Basin. Presented at the Report to the Basin public meeting. Yerington, Nevada. June 24, 2009.

Yang, J., Dilts, T.E., Wesiberg, P.J. Landscape-scale Modeling of Riparian Vegetation Distribution. Society of American Foresters 2008 National Convention. November 5, 2008.

Software/Scripts/Models

Riparian Topography Tools for ArcGIS - Tools for deriving topographic variables from a high-resolution DEM - http://www.cabnr.unr.edu/weisberg/downloads/ and http://arcscripts.esri.com

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