

BIO-MICROMETEOROLOGY OF A SIERRA NEVADA MONTANE MEADOW

A Thesis submitted to the faculty of  
San Francisco State University  
In partial fulfillment of  
the requirements for  
the Degree

Master of Arts

In

Geography

by

Suzanne Cozzolino Maher

San Francisco, California

December 2015

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2015

## CERTIFICATION OF APPROVAL

I certify that I have read Bio-micrometeorology of a Sierra Nevada montane meadow by Suzanne Cozzolino Maher, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirement for the degree Master of Art in Geography at San Francisco State University.

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# BIO-MICROMETEOROLOGY OF A SIERRA NEVADA MONTANE MEADOW

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2015

This study examines the role of restoration on the ecologic characteristics and functioning of meadow ecosystems, particularly vegetation and soil characteristics and atmospheric exchanges of carbon, water, and energy. The rate and sign of the exchanges were measured using eddy covariance in a restored montane meadow during the growing season. During the total study period the large daily gross primary production (GPP) and respiration ( $R_e$ ) values ( $-30$  and  $+27$   $\text{g C m}^{-2}\text{d}^{-1}$  respectively) produced an atmospheric sink of  $\text{CO}_2$  of  $-2.32$   $\text{g C m}^{-2} \text{d}^{-1}$ . The available energy ( $Q_N$ ) is predominantly utilized by evapotranspiration, with most of the available energy going into water phase change. A large reduction in soil moisture content over the study period correlates to a shift in NEE from a sink to a source of atmospheric  $\text{CO}_2$ , a decline in the latent heat flux ( $Q_E$ ) ( $17.6$  to  $11.7$   $\text{MJ m}^{-2} \text{d}^{-1}$ ) and increase in the sensible heat flux ( $Q_H$ ) ( $-0.7$   $\text{MJ m}^{-2} \text{d}^{-1}$  to  $1.8$   $\text{MJ m}^{-2} \text{d}^{-1}$ .) Sampling and analysis of vegetation and soil was conducted both within the measurement footprint and in a degraded meadow for comparison. The restored meadow had greater live vegetation cover, litter, species richness, and biomass both above and below the ground in comparison to the degraded meadow. There were also fewer invasive species and xeric plants such as shrubs and the soils contained more moisture and organic material. The improved ecosystem characteristics at the restored site in addition to  $Q_E$  and NEE sensitivity to soil moisture, illustrate the important impact of restoring water table levels for ecosystem functioning.

I certify that the Abstract is a correct representation of the content of this thesis.

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Chair, Thesis Committee

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Date

## ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Andrew Oliphant and Jerry Davis. Their extensive knowledge in the fields of bio-micrometeorology and geomorphology was instrumental for the completion of this project. In addition, their commitment to the project, support and enthusiasm pushed me to accomplish more than I thought I was capable of. I would also like to thank Michael Vasey and Vanessa Stevens for contributing their botanical expertise including vegetation identification and characteristics and for spending a grueling day in the field with us. Thanks also to Leonhard Blesius for support of soil analysis and Siobhan Lavender for collaboration both with Matlab and Eddy Covariance theory. Lastly, I would like to thank my family for the immeasurable assistance and encouragement throughout this project and my partner for providing an anchor of stability with his unending love and support.

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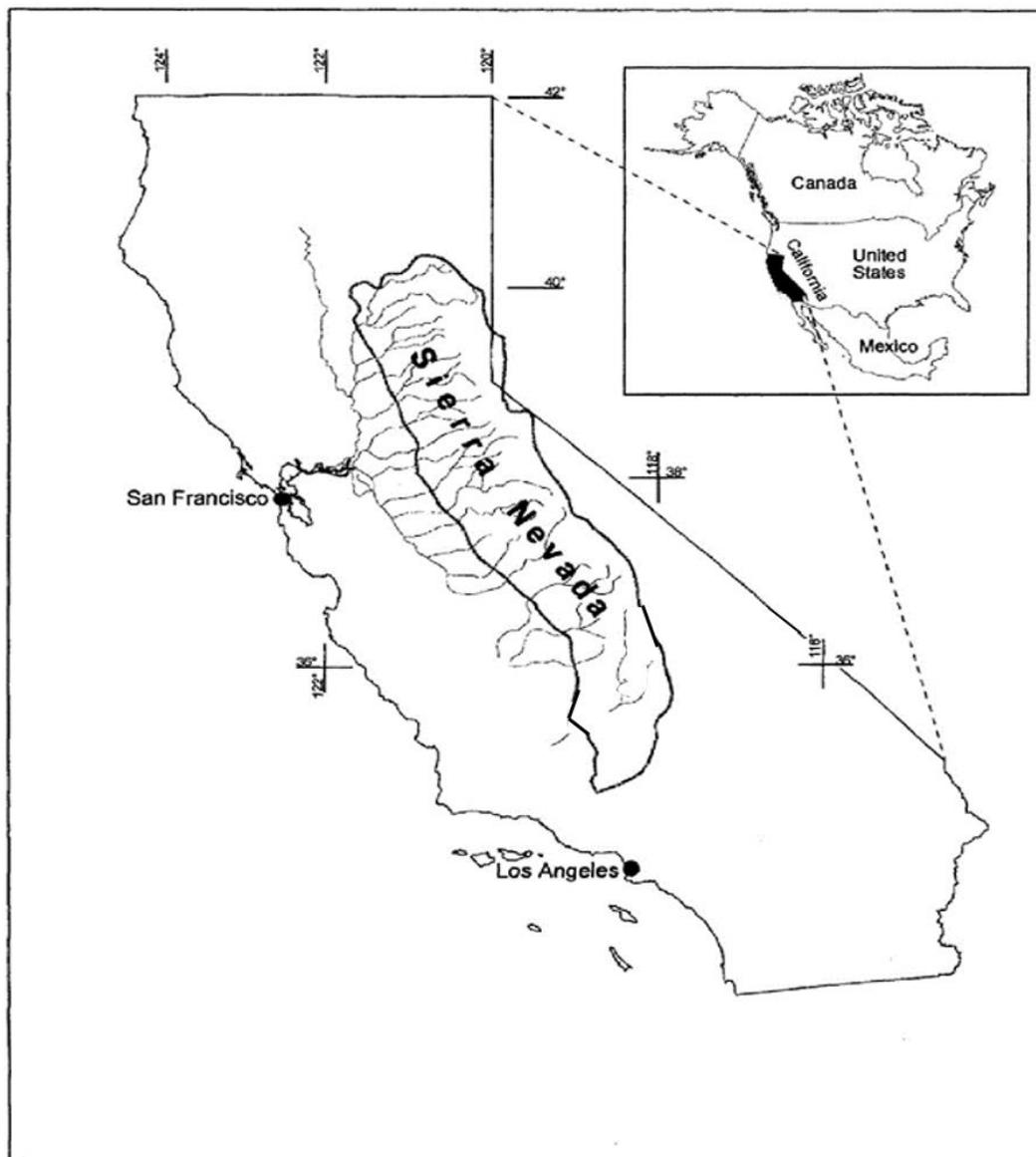
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## **1. Introduction**

The western Sierra Nevada (SN) mountain range supplies about 60% of the surface water used by the California's cities and farms (Downing, 2015). The mountain range runs nearly 640 kilometers (400 miles) in length along the eastern edge of the state, is approximately 80-130 km (50-80 miles) wide and over 4,418 m (14494 ft) in elevation (Figure 1). Much of the precipitation that falls on the mountain range occurs between November and March (Loheide et al. 2009) and is stored in snow pack that melts in spring and summer, recharging streams and supplying water to cities, industry, agriculture, and ecosystems through the state's rivers and reservoir system.



**Figure 1:** The Sierra Nevada mountain range of California including the stream system. From Dull (1999).

According to climate models, temperatures in California are expected to rise 3 to 6°C by the end of the century (California Climate Change Center 2003) and precipitation events in the SNs are expected to be less frequent, more extreme,

and warmer (IPCC 2013). Pulses of flash flood events at lower elevations are expected to be more common as existing reservoir infrastructure is ill equipped to accommodate the projected change in flow volume and intensity (IPCC 2013). If global warming emissions continue unabated, SN snowpack is projected to decline 70 to 90% (California Climate Change Center 2003) and the remaining snow pack will melt earlier in the season. The higher temperatures expected also have the potential to alter vegetation and increase drought conditions through enhanced evaporation. This will contribute to the growing water scarcity issue, particularly as this region relies on stored water for the dry summer months consistent with the Mediterranean climate of California. The projected decline in water supply and lack of adequate storage for liquid water has water managers currently searching for multiple ways to store and regulate water.

Montane meadows in the Sierra Nevada are moist, flat zones with a high water table and ephemeral streams (Kattelman and Embury 1996; Kondolf et al. 1996; Loheide et al. 2009; Purdy and Moyle 2006). They absorb runoff in the spring and winter months and store it underground, slowly releasing it into stream systems throughout the year (Loheide et al. 2009; Ratliff 1985). Unfortunately, deep stream channels have formed in most of the SN meadows, which drain the stored water and reduce the height of the water table (Kondolf et al. 1996; Loheide et al. 2009; NFWF 2010; Purdy and Moyle 2006; Ratliff 1985). Restoration techniques are being utilized in select meadows to redress the

gullying and return the water table to pre-disturbance levels in an attempt to create more liquid water storage in the SN. These projects have been successful in re-wetting the meadow, increasing water storage and regulating release to lower elevations (NFWF 2012; SVRCD 2004).

The increase in available water from restoration also has the potential to reduce local temperature through evaporative cooling, provide moisture to the atmosphere, and increase vegetation productivity which will result in an enhanced sink of CO<sub>2</sub> out of the atmosphere as plants sequester carbon through photosynthesis. The objective of this study is to examine the role of restoration practices using an interdisciplinary approach to shed light on the interactions between land, water, plants and atmosphere in these important mountain landscape features. In particular I aim to: compare vegetation and soil characteristics between a degraded and restored meadow in the same valley; and investigate surface-atmosphere interactions in a restored meadow using eddy covariance, with particular focus on CO<sub>2</sub>, water and energy exchanges.

This project is intended to function as a pilot study that should be expanded both in spatial and temporal extent. The pertinence of such a project is likely to increase in the coming years due to concern over water scarcity from the current drought in addition to the shift to rainfall dominated precipitation in the mid-elevations of the Sierra Nevada due to climate change. NFWF states that the potential for water storage in Sierra Nevada meadows is comparable to the

estimates of other water supply proposals such as a new reservoir at sites in Colusa County (470,000 to 640,000 ac-ft/yr) and the Inland Empire Regional Water Recycling Initiative (100,000 ac-ft/yr) (NFWF 2010). Man made reservoirs and water recycling plants can be expensive to build and reservoirs may result in loss of habitat for native species and/or displacement of human communities. In contrast, meadow restoration has the potential to be less expensive as the underlying geology that forms an impermeable basin is naturally occurring infrastructure. As a secondary result, the restoration efforts contribute positively to the ecological health of the region because the return of the high water table results in the return of wet meadow vegetation (Loheide 2009).

This thesis will first describe the biophysical properties of montane meadows in the SN. Next, I will address the current state and discuss the impact of historical land use on meadows and restoration. The results of the study are broken into two chapters. Chapter 4 addresses the difference in soil and vegetation characteristics between a restored meadow and nearby degraded meadow. Chapter 5 looks at ecosystem functioning in the restored meadow through micrometeorological measurements. This thesis is concluded with a discussion of the overall results and comparison to other studies.

## **2. Background**

### **2.1 MONTANE MEADOWS OF THE SIERRA NEVADA**

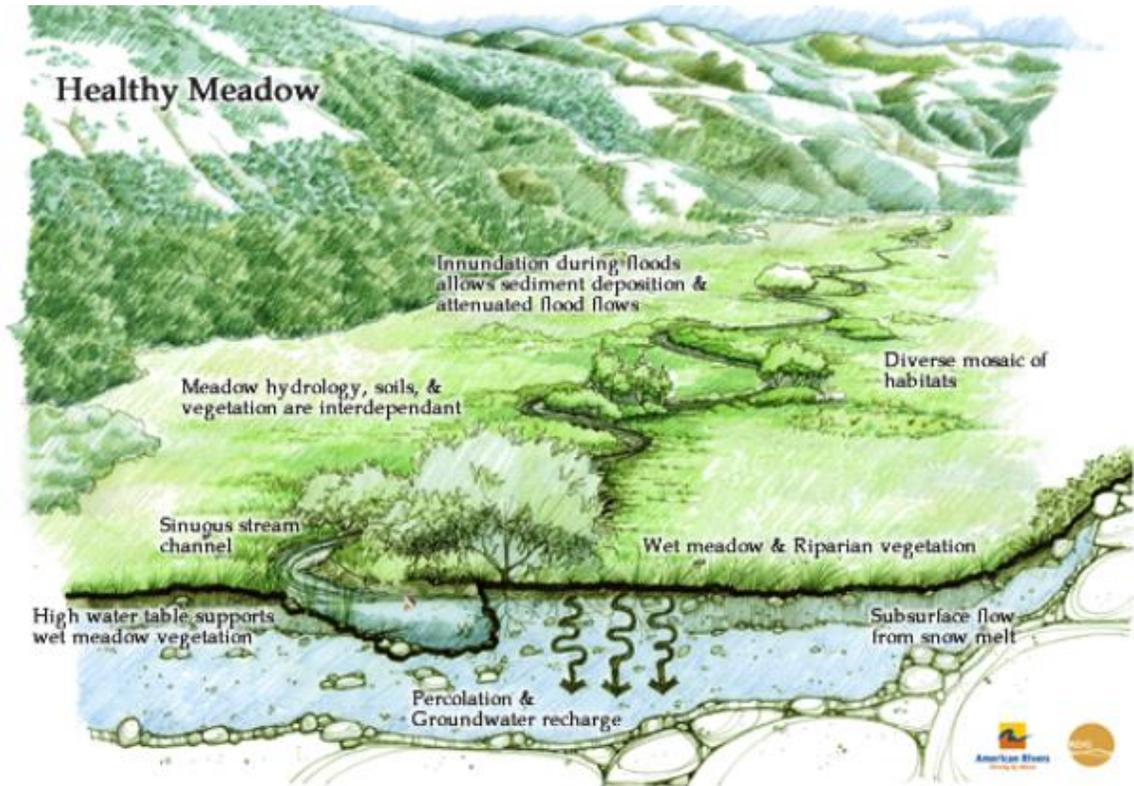
Montane meadows of the SN are found at elevations between 600 and 3,500 m where sediment or low-permeability soils accrue in a basin on an impermeable surface, which results in water accumulation (Rundel et al. 1977). Many meadows in the Sierra Nevada are formed in shallow alluvial basins of extinct lakes of various elevations fed by moderate to small drainage basins (Ratliff 1985; Slocombe 2012).

These specific geomorphic conditions and resulting water accumulation form a shallow water table, which is the defining characteristic of montane meadows (Kattelman and Embury 1996; Kondolf et al. 1996; Loheide et al. 2009; Purdy and Moyle 2006). Further meadow specification is governed by range type, altitude, wetness, vegetation, soils, and site location (Ratliff 1985). Annual precipitation in the Sierra Nevada has a great range from 20 to 200 cm due to orographic effects with the greatest precipitation occurring on the western slope (Loheide et al. 2009). Indicative of a Mediterranean climate, summers are dry and warm with a majority of the precipitation falling between November and March. In these months, most of the precipitation above 1,500 meters falls as snow (Loheide et al. 2009). In the dry, summer growing season, montane meadows rely on shallow ground water recharged from local infiltration,

watershed groundwater discharge to the meadow, or recharge from the stream (Kattelman and Embury 1996; Kondolf et al. 1996; Loheide et al. 2009; Ratliff 1985).

Montane meadows of the Sierra Nevada commonly support wet meadow riparian vegetation dominated by sedges, rushes, grasses, and other herbaceous species (Loheide et al. 2009). Genera and species common to montane meadows in the SN include: *Agrostis* (Bentgrass), *Artemisia rothrockii* (Rothrock sagebrush), *Calamagrostis breweri* (Shorthair), *Carex exserta* (Short-hair sedge), *Carex nebraskensis* (Nebraska sedge), *Carex rostrata* (Beaked sedge), *Deschampsia caespitosa* (Tufted hairgrass), *Eriogonum* (Buckwheat), *Gentiana newberryi* (Newberry gentian), *Heleocharis acicularis* (Slender spikerush), *Heleocharis pauciflora* (Fewflowered spikerush), *Hypericum anagalloides* (Tinkers penny), *Juncus* (Rush), *Muhlenbergia filiformis* (Pullup muhly), *Muhlenbergia richardsonis* (Mat muhly), *Penstemon heterodoxus* (Heretic penstemon), *Poa* (Bluegrass) *Trifolium longipes* (Longstalk Clover), and *Trifolium monanthum* (Carpet Clover) (Ratliff, 1985).

## 2.2 THE HYDROLOGIC, ECOLOGIC, AND GLOBAL VALUE OF MONTANE MEADOWS



**Figure 2:** Schematic diagram of a montane meadow in its natural state illustrating the linkages between the landform, subsurface water and vegetation (NFWF 2010).

Figure 2 describes meadow impact on local hydrology such as their capacity to store, filter, and regulate water, reduce erosion, and capture bed-load (Mitsch and Gosselink 2000; Ratliff 1985). The fine-grained sediment and sod that make up the meadow basin filters snowmelt and rainfall flowing from surrounding slopes and then regulates the release into streams (Mitsch and Gosselink 2000; Ponce and Lindquist 1990; Ratliff 1985). Flooding cycles help flatten the meadow, contribute to the development of the high water table, and diminish

flood events for communities at lower elevations (Bennett 2010; Mitsch and Gosselink 2000; Lindquist et al. 1997). The subsequent reduced bed-load downriver diminishes the erosional capacity of the streams, damage to water system infrastructure, and reservoir storage capacity (Mitsch and Gosselink 2000; NFWF 2010).

Nutrients from high flow periods support healthy vegetation growth and sod formation (Bennett 2010; NFWF 2010). Meadow sedges native to the ecosystem have long densely matted root networks that hold together unconsolidated, fine soils, maintain moisture, and contribute to sediment stabilization (Micheli and Kirchner 2002; Purdy and Moyle 2006). Furthermore, streambanks colonized by 'wet' graminoid meadow vegetation are 5 times more resistant to erosion than those colonized by 'dry' xeric meadow and scrub vegetation (Micheli and Kirchner 2002).

Riparian ecosystems form in proximity to fresh water (Purdy and Moyle 2006). In the SN, they are usually limited to a narrow strip immediately adjacent to lakes, ponds, streams, and rivers before the increased depth of the water table forces a change to an upland plant community (Bennett 2010; Kattelman and Embury 1996; Kondolf et al. 1996). Montane meadows are particularly valuable as local habitat as both the high water table and multiple meandering stream channels that develop through the meadow allow a riparian habitat to spread through the entire basin (Kattelman and Embury 1996). The increased

vegetation density provides diverse habitat and contributes to soil health, both providing organic matter and retaining moisture in the dense root structures to provide growing conditions that are often more moist and nutrient-rich than surrounding areas (Kondolf et al. 1996). The resulting unique assemblage of plants is the most biologically active plant community in the SN (Ratliff 1982), providing living conditions for the greatest number of species found in all habitat types (Kauffman and Krueger 1984). Several threatened, endangered, and sensitive fishes, amphibians, reptiles, and rodents are dependent on them (NFWF 2010; Ratliff 1985) and they are considered the single most important habitat for SN birds (NFWF 2010). Nearly one-quarter (24%) of the species dependent on the riparian community area are at risk of extinction (Kondolf et al. 1996).

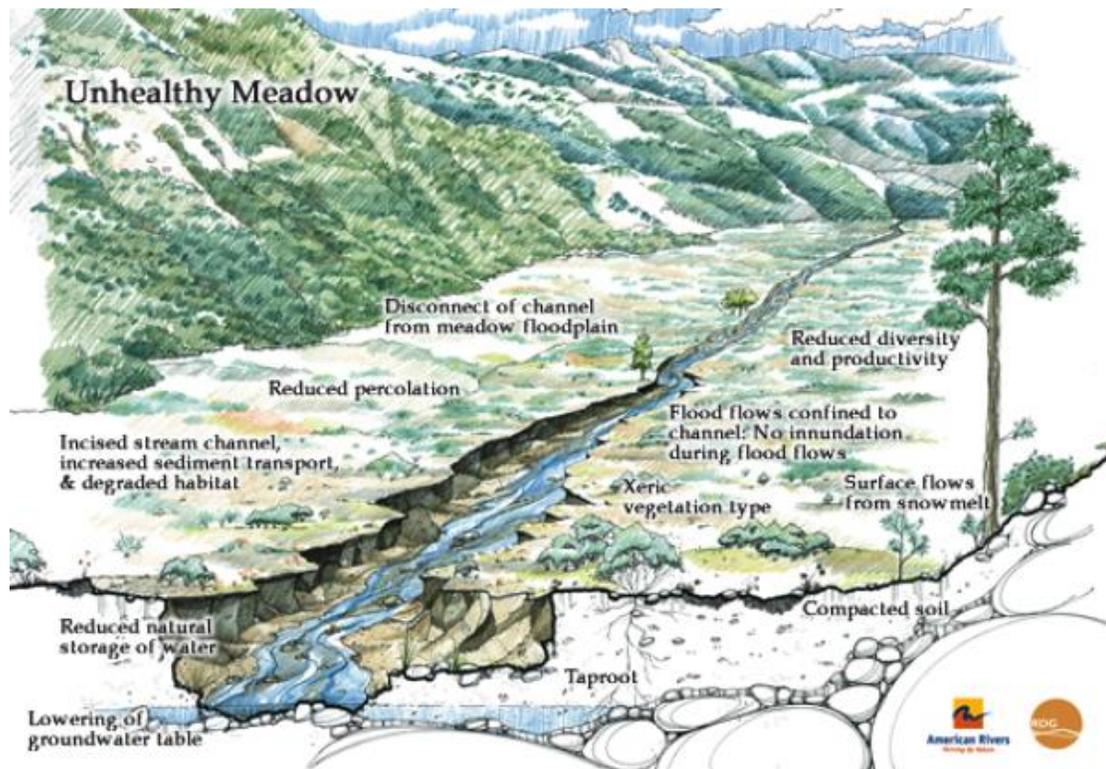
There are no data on the carbon sequestration potential of montane meadows in the SN, but the data found in this study can be compared with wetland, grassland and sagebrush-steppe ecosystems as the meadows have vegetation characteristics found in all three ecosystems. Ecosystems can show carbon sequestration variability between sites and from year to year depending on latitude, elevation, environmental and land management conditions (Gilmanov et al. 2010; Kato et al. 2006; Lund et al. 2010; Luo et al. 2007; Marcolla et al. 2011; Novick et al. 2004). Of the limited annual measurements of carbon dioxide taken up by wetlands, Lund et al. (2010) found in a 7 site synthesis, that all sites acted

as annual net sink for atmospheric CO<sub>2</sub> with an average annual net CO<sub>2</sub> uptake of -103 g C m<sup>-2</sup> yr<sup>-1</sup> in the biosphere. Grasslands are typically characterized as weak sinks, or approaching a near neutral state (Gilmanov et al. 2010), but their contribution to the global carbon cycle remains uncertain due to the lack of comprehensive research (Gilmanov et al. 2010). A range of annual values have been recorded, from a sink of atmospheric carbon of -800 g m<sup>-2</sup> y<sup>-1</sup> to an emission of 521 g C m<sup>-2</sup> y<sup>-1</sup> (Novick et al. 2004). However, most annual values fall into a much lower range of plus or minus 200g C m<sup>-2</sup> y<sup>-1</sup> (Marcolla et al. 2011). Sagebrush-steppe environments are also underrepresented in the literature but in the limited studies have been either a net source or sink of atmospheric carbon depending on soil moisture and precipitation timing with values found to range from -50 to + 50 g C m<sup>-2</sup> y<sup>-1</sup> (Kwon et al. 2008; Novick et al. 2004).

### **2.3 CURRENT STATE**

As the meadow ecosystem is directly or indirectly attributed to the behavior of the local streams, it is easily damaged by rapid changes in stream hydrology (Jurmu and Andrie 1997). Most montane meadows in the Sierra Nevada are degraded due to local historic land use such as grazing, mining, logging, road and rail road construction, dams and diversions, and ditching/channelization (Kondolf et al. 1996; Loheide et al. 2009; Purdy and Moyle 2006; Ratliff 1985). Figure 3 shows how these factors in the watershed can damage vegetation, alter

soils, and change the quantity, quality, and timing of runoff into meadow systems (Hammersmark et al. 2008; Kondolf et al. 1996; Loheide et al. 2009; Purdy and Moyle 2006; Ratliff 1985).



**Figure 3:** Schematic diagram of a degraded montane meadow illustrating the channel trapped in a gorge, the lowered ground water, reduced natural storage of water and shift to xeric vegetation (NFWF 2010).

## 2.4 HISTORY OF LAND USE

Grazing is considered the most pervasive source of upland and riparian habitat degradation (Belsky et al. 1999). Sheep grazing in meadow systems began in 1769 due to the Gold Rush and intensified with droughts in the 1860's and 1870's that pushed herders to higher elevations for water and grazing land (Ratliff 1985). By the time grazing declined in the 1900s, the combined sheep and cattle grazing had already created widespread deterioration of montane meadows due to defoliation of meadow plants, damage to plants due to trampling and soil compaction, cutting of sod, and nutrient concentration from animal waste (Belsky et al. 1999; Ratliff 1985).

Mining resulted in multi-faceted damages including water diversions and the rapid release of sediment (Curtis et al. 2005). Hydraulic mining in the northern Sierra Nevada foothills produced an estimated 1.1 billion cubic meters of sediment alone (James et al. 2009). Sediment from mining aggraded the stream systems all the way to the San Francisco Bay (James 1989; Kondolf et al. 1996). Significant amounts of sediment are still stored at high elevations in the SN where they are mobilized in large storm events (Curtis et al. 2005). High levels of sediment in streams have the potential to divert channels, clog natural meanders, and impact water quality and habitat characteristics for numerous aquatic organisms (James et al. 2009). Mining also resulted in the release of harmful quantities of substances such as lead and mercury that further harm

sensitive meadow habitats (Kondolf et al. 1996). Lead in soil and water works its way up the food chain with sometimes severe toxic effects on animals, including reproductive impairment, and increased mortality rates (Besser et al. 2009; Lead Action Group 1993). Sediment bound with mercury is still being worked through SN aquatic systems where it can be transformed into methylmercury, a potent neurotoxin that is readily accumulated by aquatic biota (Ullrich et al. 2001).

The cumulative impact of roads, dams, diversions, ditching and channelization in the SN have altered the natural meandering of local streams, impacting habitat and water quality in meadows (Belsky et al. 1999; Kondolf et al. 1996).

Over time the damage to vegetation and soil, the change in the quantity, quality, and timing of runoff into meadow systems and subsequent lowering of the water table can result in a shift from wet meadow riparian vegetation dominated by sedges, rushes, grasses, and other herbaceous species (Loheide et al. 2009) specified above, to a dry meadow (Jurmu and Andrie 1997; Purdy and Moyle 2006). Dry meadows are different from wet meadows as they do not retain the species that grow in the water saturated interfluvies and swales because the groundwater is generally deeper than 1 m for most or all of the growing season (USDA Forest Service 2011). They are dominated by grasses (*Poaceae* family), dryland sedges (*Carex* spp.), and rushes (*Juncus* spp.) (USDA Forest Service 2011).

If drying of the meadow continues, the ecosystem changes to a sagebrush scrub (American Rivers 2012) or sagebrush steep ecosystem. These ecosystems consist of shrubs, forbs, and grasses including mountain big sagebrush (*Artemisia tridentata var. vaseyana*) and perennial grasses (Kwon et al. 2008). Shifts in vegetation and decreased availability of water negatively impact the species dependent upon them for food and habitat. Insect, amphibian, reptile, fish, bird, bat, and other wildlife all decline in a degraded meadow (Purdy and Moyle 2006; SVRCD 2004).

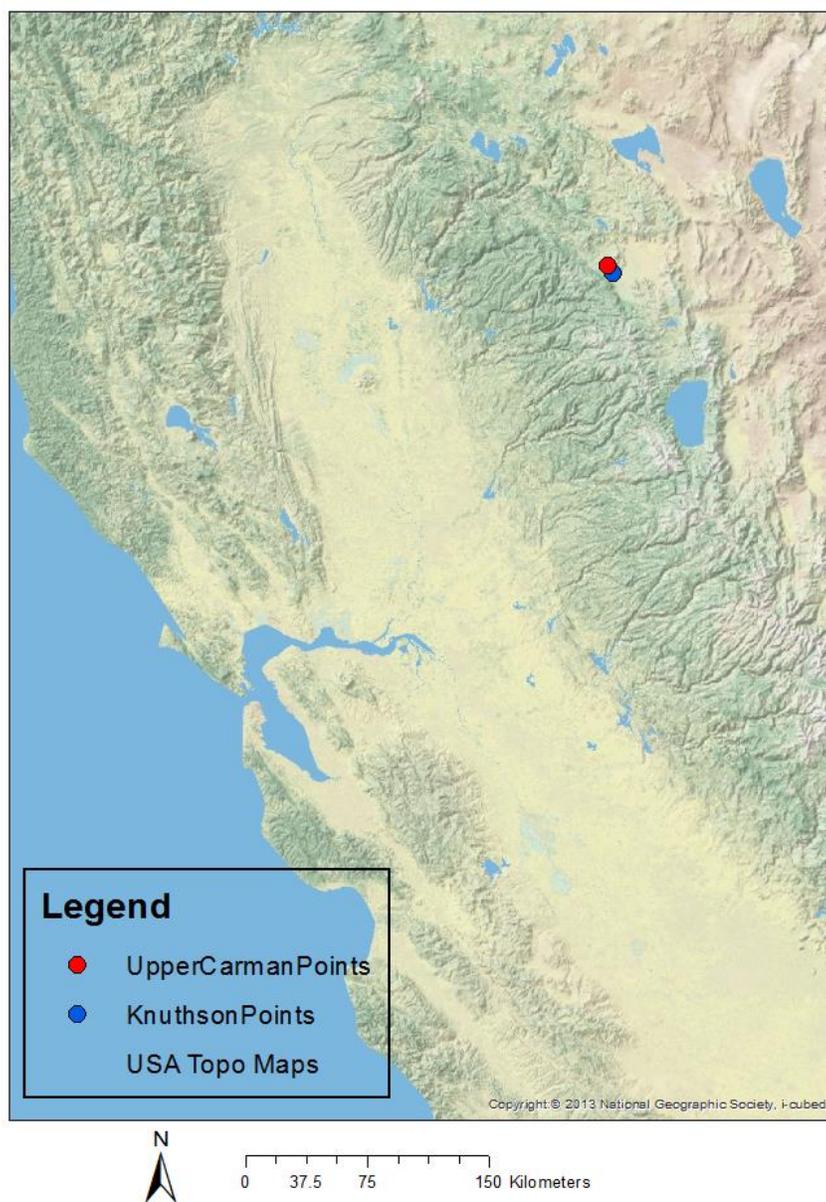
## **2.5 RESTORATION**

In recent years there has been a concerted effort by land managers to restore montane meadows especially in the northern Sierra Nevada. One method, called “pond and plug” is a relatively new restoration technique being utilized in select montane meadows with straightened and incised stream channels. Heavy machinery such as bulldozers are used to excavate soils and aggregate from select sites in the channel to create depressions that will become ponds. Excavated material is used to intermittently plug other sections of the channel, reduce channel depth and slope, and encourage meanders so that the end result is shallow, meandering channels with a broad floodplain (Loheide et al. 2009). With responsible land management in the surrounding watershed and the removal of invasive species, the return of the high water table should facilitate the return of riparian vegetation and the species that depend on it.

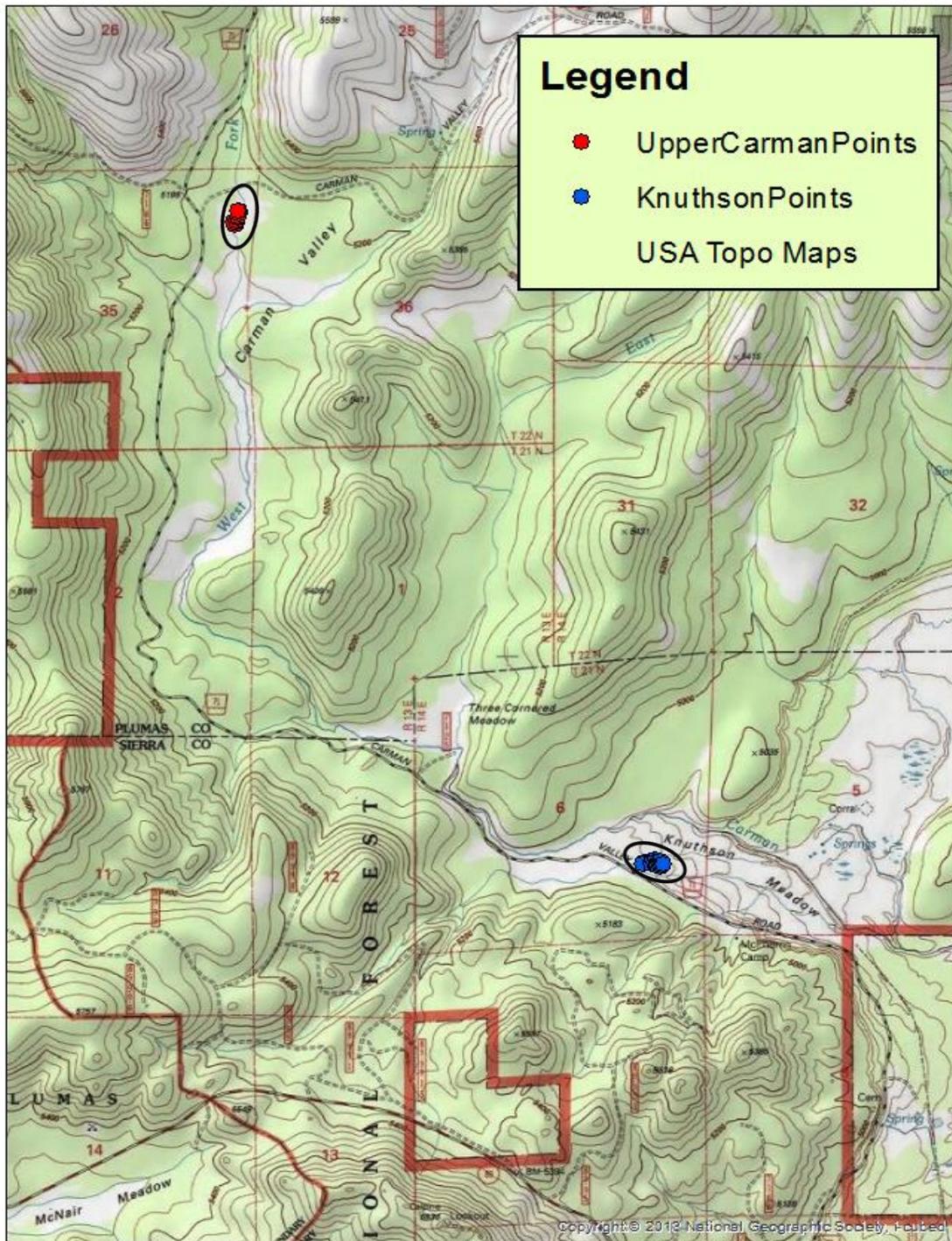
### **3. Study Site Location and Background**

#### **3.1 LOCATION**

The Carman Valley watershed is located in Sierra County at 1510 m above sea level (Figure 4). This region of the Sierra Nevada experiences precipitation primarily in the spring and winter months and does not typically receive any precipitation in summer from late May through August. The primary site studied in this watershed was Knuthson meadow, a restored meadow with a surface area of approximately 60 ha (150 acres) (SVRCD 2004). Both Knuthson and a nearby degraded meadow in the same watershed, Upper Carman meadow, are shown in Figure 5. Upper Carman was included for a portion of the study to compare characteristics of a degraded and restored meadow in close proximity.



**Figure 4:** Map of a portion of California showing study site location with GPS coordinates of Knuthson and Upper Carman Meadows in the Carman Valley watershed.



0 0.5 1 2 Kilometers

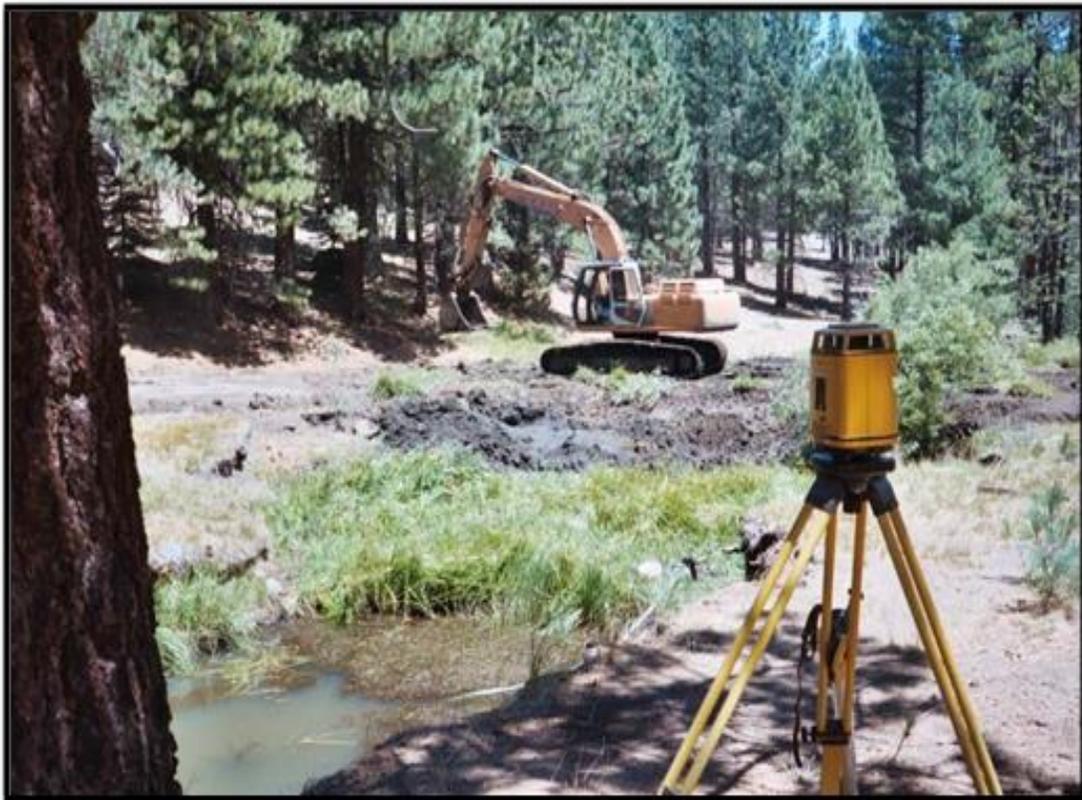
**Figure 5:** Topographic map showing the Carman Valley watershed and locations of the degraded meadow (Upper Carman) and restored meadow (Knuthson). GPS points mark soil/vegetation sampling sites within the macroplot (marked on the map with an oval).

### **3.2 RESTORATION AT KNUTHSON MEADOW**

The Carman Valley watershed in the Tahoe National Forest was listed as an impaired ecosystem as early as the 1950's. In 2000 the Sierra Nevada Resource Conservation District in collaboration with the US Forest Service and other parties began a project with the aim to improve and restore the hydrologic function and watershed habitats in the Carman Valley watershed. Carman Creek at Knuthson Meadow was the first watershed restoration project undertaken by the coalition and was completed in 2002. (SVRCD 2004).

The three distinct components of the project included hydrologic intervention, shaded fuelbreak, and grazing strategy at a cost of \$213,000 (SVRCD 2004). The hydrologic aspect at Knuthson included the pond-and-plug technique (Figure 6) on the incised channel (Figures 7 and 8a) and spillway expansion at the bottom of the Knuthson Meadow (Figure 8b). The more improved spillway expands the riparian wetland, can contain more water, and can handle larger storm events. Vegetation in the construction zone was removed, maintained and later placed on the plugs to re-vegetate with on-site material (SVRCD 2004). Old railroad grades upstream from the Knuthson Meadow that were diverting natural

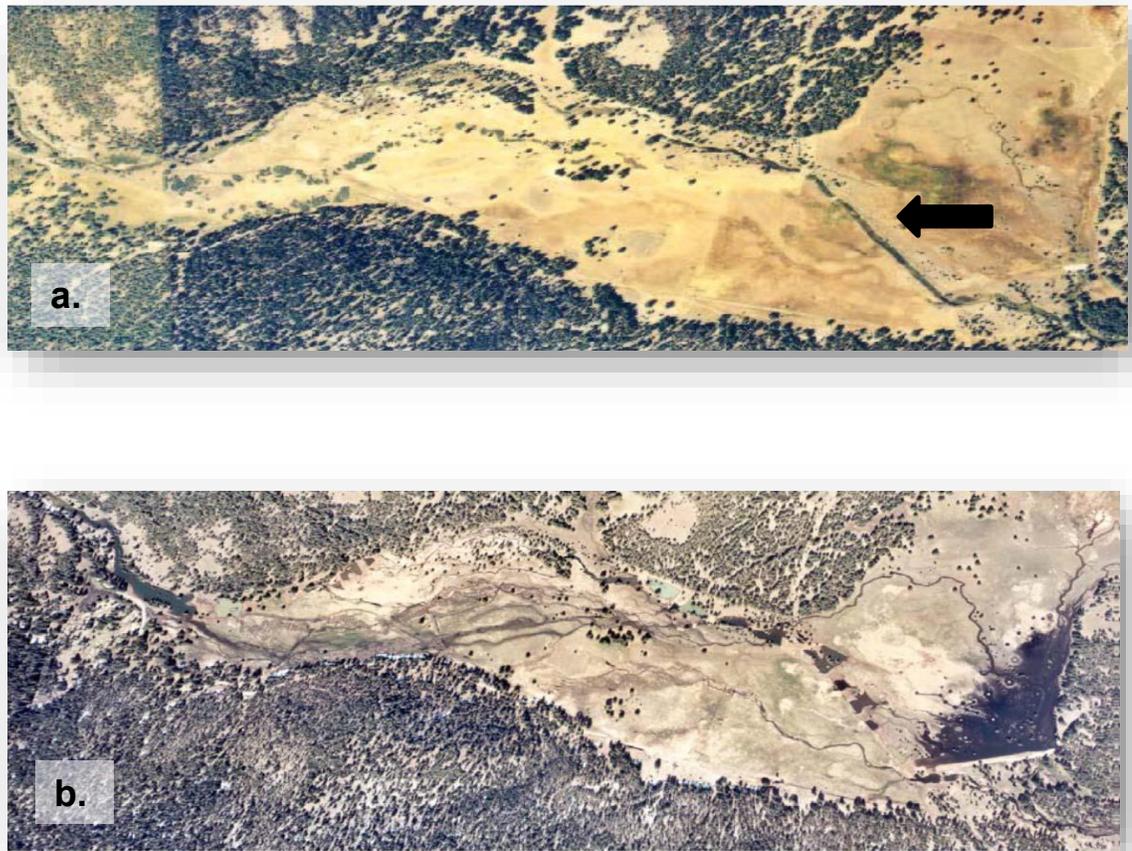
creek meandering were re-contoured and a road was removed and rerouted to an area out of the stream zone (SVRCD 2004).



**Figure 6:** Example of pond and plug restoration at Two Cone Meadow (SVRCD 2004).



**Figure 7:** Eroded gully in Knuthson Meadow before restoration. Predominantly xeric plant community on the meadow surface, though presumably more hydric at (the incised) channel level. (Photo courtesy of Paul Jones, EPA).



**Figure 8:** Aerial view of Knuthson Meadow pre-restoration (a) with the incised channel seen as a straight line cutting across the meadow, see arrow. Post-restoration (b) shows the ponds created by restoration located where the incised channel used to be, multiple meandering streams in the meadow, and expanded spillway on the right. Source, SVRCD 2004.

The second aspect of the project addressed local land management so that the meadow did not become degraded again. Overstocked sections of National Forest land within the Carman Valley Watershed were cleaned to reduce the potential of intense fire in the meadow and grazing locations at Knuthson were

selected where they would have the least impact on riparian vegetation and stream corridors (SVRCD 2004).

### **3.3 RESTORATION RESULTS**

According to the SVRCD final report (2004), three years after the restoration was complete, the meadows had already dramatically improved (Figure 9). The water table is higher, the meadows have increased water storage and capacity and the length of time the meadow remains wet per year has increased. The improved hydrologic conditions enlarged riparian habitat resulting in a markedly increased biologic activity including insects, bird and bat populations. Birds and mammals are using or staying in the meadows for longer durations and species absent since monitoring began in 1992 are returning to breed. These returning populations are expected to increase in abundance, a trend unique to the regional bird population decline. Wetland plant species such as willow, forbs, rushes and grasses are prospering while dry land species such as sagebrush are dying. Overall, the expectation by the SVRCD is that post-restoration abundance will increase in years ahead as the ecosystem continues to recover (SVRCD 2004).



**Figure 9:** Knuthson Meadow after restoration in the spring of 2004 shortly after snow melt (the very wet conditions represented in this photograph are seasonal and do not last through spring). (SVRCD 2004).

#### **4. Vegetation and Soil Characteristics**

Sampling and analysis of vegetation and soil from the restored meadow (Knuthson) and a nearby degraded meadow (Upper Carman) were used to compare ecosystem characteristics including; species composition and cover, above-ground and below-ground living biomass, and soil composition. Site macroplots of approximately 100 m<sup>2</sup> were located at the restored and degraded meadow sites (Figure 5). The location of the macroplot in the restored meadow (Knuthson) was selected to co-locate vegetation sampling with the micrometeorological measurements (Ch. 5). Visual estimates of the surface area within the macroplot was 64% low relief swales and perennial channels, 25% wide flat interfluves, 10% small interfluve ridges, and 1% bare ground (Figure 10). The low relief swales and perennial channels had dense hydric vegetation dominated by sedges with saturated or near saturated soils. The wide flat interfluves were dominated by dense mesic vegetation of primarily graminoids and other herbs with moist, but not saturated soils. The patches of high ground had dry soils and were not sampled at Knuthson due to time constraints. However, the vegetation found at these locations was similar to that found at the degraded meadow. The vegetation height at all locations was dependent on species type and season. The vegetation height at sample acquisition (July

2014) ranged from a 5 cm to 50 cm. The hydric communities appeared the most densely vegetated followed by the mesic, while the dryland areas were sparsely vegetated.



**Figure 10:** Knuthson Meadow (restored meadow) in the Carman Valley watershed, Tahoe National Forest on July 3rd, 2014. Photo: Vanessa Stevens.

The degraded meadow was 100% degraded with xeric plant species, including sagebrush (*Artemisia tridentata*) and non native grasses (Figure 11). There was only one stream, trapped in a linear incised channel approximately 4 m deep. There were a series of stagnant pools (10 cm in diameter) at the base of the channel with associated hydric species, indicating proximity to the water table.

Samples were acquired on the meadow floor on either side of the incised channel (Table 1).



**Figure 11:** Upper Carman Meadow (degraded meadow) in the Carman Valley watershed, Tahoe National Forest on July 3rd, 2014. Photo: Vanessa Stevens

**Table 1:** General features of the three plant communities documented at the two meadow sites.

	<b>Hydric Restored Meadow</b>	<b>Mesic Restored Meadow</b>	<b>Dryland Restored and Degraded Meadow</b>
Percent area in meadow	64%	25%	10% Restored meadow 100% Degraded meadow
Microscale topography	Low relief swales and perennial channels <0.3 m deep	Wide, flat interfluves	Gently sloped surface incised by 4m deep gully
Soil Moisture	Wettest	Moist	Dry
Primary Vegetation	Perennial graminoids (mainly sedges)	Mixed grass, herbaceous	Non-native grasses and sagebrush dominant

#### 4.1 METHODS

Vegetation and soil sampling was conducted at both the restored and degraded meadow macroplots on July 3<sup>rd</sup> 2014 by 5 individuals. Within each community, 10 random locations were selected for sampling within a 1m<sup>2</sup> quadrat. A GPS point was recorded at each location (Figure 5). Two field

botanists identified as many species as possible within each quadrat and made ocular estimates of the areal cover of each, as well as thatch (litter) and bare ground.

Following vegetation identification, above ground vegetation, roots and soil samples were collected from a randomly located 100 cm<sup>2</sup> area of the quadrat (Figure 12 a and b). Because this was more time consuming, relatively fewer samples were collected (hydric and mesic n=6, dryland at degraded meadow n=8). Vegetation was first hand clipped at ground level from a 10x10 cm square within the plot and litter was discarded. The sample was oven dried at 70°C for 24 hours in a well ventilated oven and weighed to obtain above ground biomass (Bell and Fischer 1994).



a.

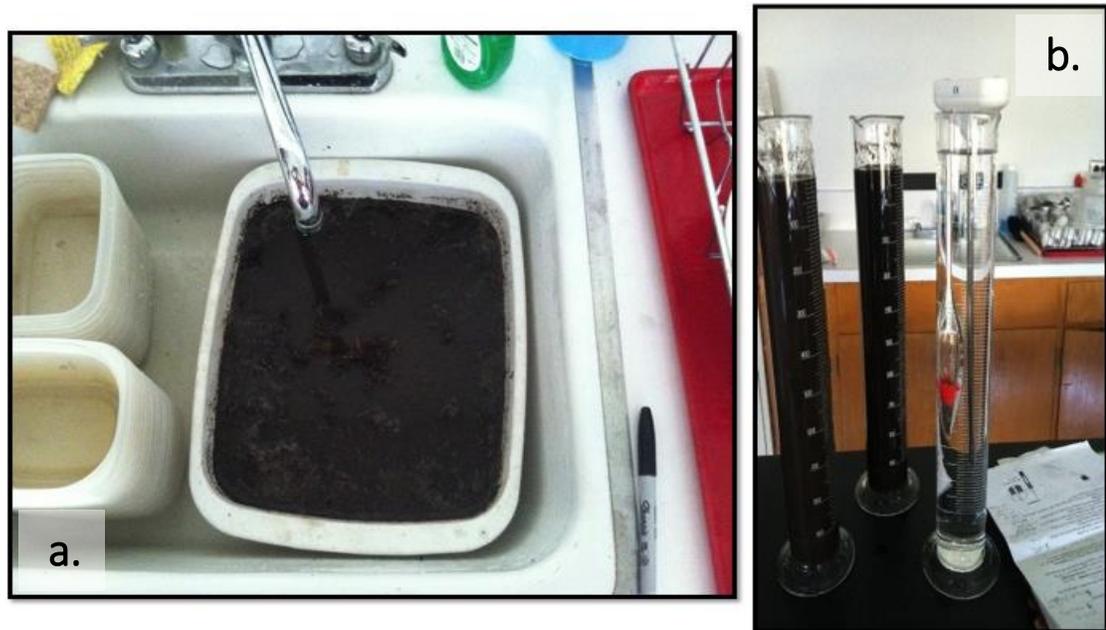


b.

**Figure 12:**  
Vegetation  
and soil  
sampling of  
(a.) Knuthson  
Meadow  
(restored  
meadow) and  
(b.) Carman  
Creek  
(degraded  
meadow) on  
July 3rd, 2014.  
Photo:  
Vanessa  
Stevens

Root samples were taken from the  $1000 \text{ cm}^3$  soil volume directly below the vegetation sample (Figure 12 a and b). The soil volume was dug out with a shovel and stored in a zip lock bag. In the laboratory, loose soil was first shaken from the roots and then the roots were rinsed in multiple baths (Figure 13a) to remove as much sediment as possible (Manning et al. 1989). To avoid accidental loss of roots in the washing process, the sample was washed in a plastic bin and fine sieved to retain small roots (Manning et al. 1989). Very small roots and heavy mulch clumps mixed with soil could have been accidentally discarded and small amounts of soil that did not wash off the root samples would

have changed the weight of the below ground biomass. The exact size of these two errors is unknown although they are both expected to be a small fraction of the total root mass extracted from the process. In addition, the sign of the two errors are opposite, so their net effect is likely to be very small. Also, these errors should have been consistent among samples. Once clean, roots were dried at 70°C in a well ventilated oven and weighed for below ground biomass estimates (Manning et al. 1989; Bell and Fischer 1994).



**Figure 13:** Laboratory analysis of samples (a.) root washing and (b.) texture analysis of soil.

Soil samples were acquired at 10 cm depth from the vertical sidewall where the root sample was removed. Samples were sealed in soil tins, weighed that evening to minimize moisture loss through evaporation then dried in a well

ventilated oven for 24 hours at 105°C (Carter and Gregorich 2008). The weight of the water ( $W_{H_2O}$ ) was calculated by

$$W_{H_2O} = W_s - W_d \quad [1]$$

where  $W_s$  is the wet soil weight and  $W_d$  is the dry soil weight. The percent water ( $\%_{H_2O}$ ) was calculated by

$$\%_{H_2O} = (W_{H_2O}/W_d) * 100 \quad [2]$$

Next, the sample was baked in a furnace for 2 hours at 360°C (Salehi et al. 2011) to incinerate the organic content. After reweighing the remaining mineral soil, the organic content ( $W_o$ ) was calculated by

$$W_o = (W_d - W_f) \quad [3]$$

where  $W_d$  is the dry soil weight (g),  $W_f$  is the furnaced soil weight (g). The  $\%_{org}$  was calculated by

$$\%_{org} = (W_o/W_d) * 100 \quad [4]$$

It was assumed that all organics had cooked off and none of the minerals.

A second soil sample was taken in each quadrat at approximately 1 meter below the surface using a hand corer (Figure 12 a and b). The same laboratory analysis was employed to determine the organic and mineral contents. The water weight was not used due to unintentional loss of water by evaporation.

The percent composition of sand, silt and clay in the soil was determined using texture analysis (Elliot et al. 1999). Four soil samples per plant community were randomly selected from the unprocessed portion of the sample at 5 cm below the surface. The samples were oven dried at 10°C for 24 hours, cooled in a desiccator and then passed through a 2 mm sieve. 50 g of the fraction that passed through the sieve for each sample was slowly added into 100 mL of 5% Calgon solution. The mixture was gently stirred for 5 minutes and let stand overnight. The next morning the sample was transferred into a graduated cylinder, brought to the 1000 mL mark with tap water, and stirred thoroughly (Figure 13 b). Hydrometer and temperature readings were taken at 40 s and 2 h to determine the percent composition based on the time it took each particulate type to fall out of suspension.

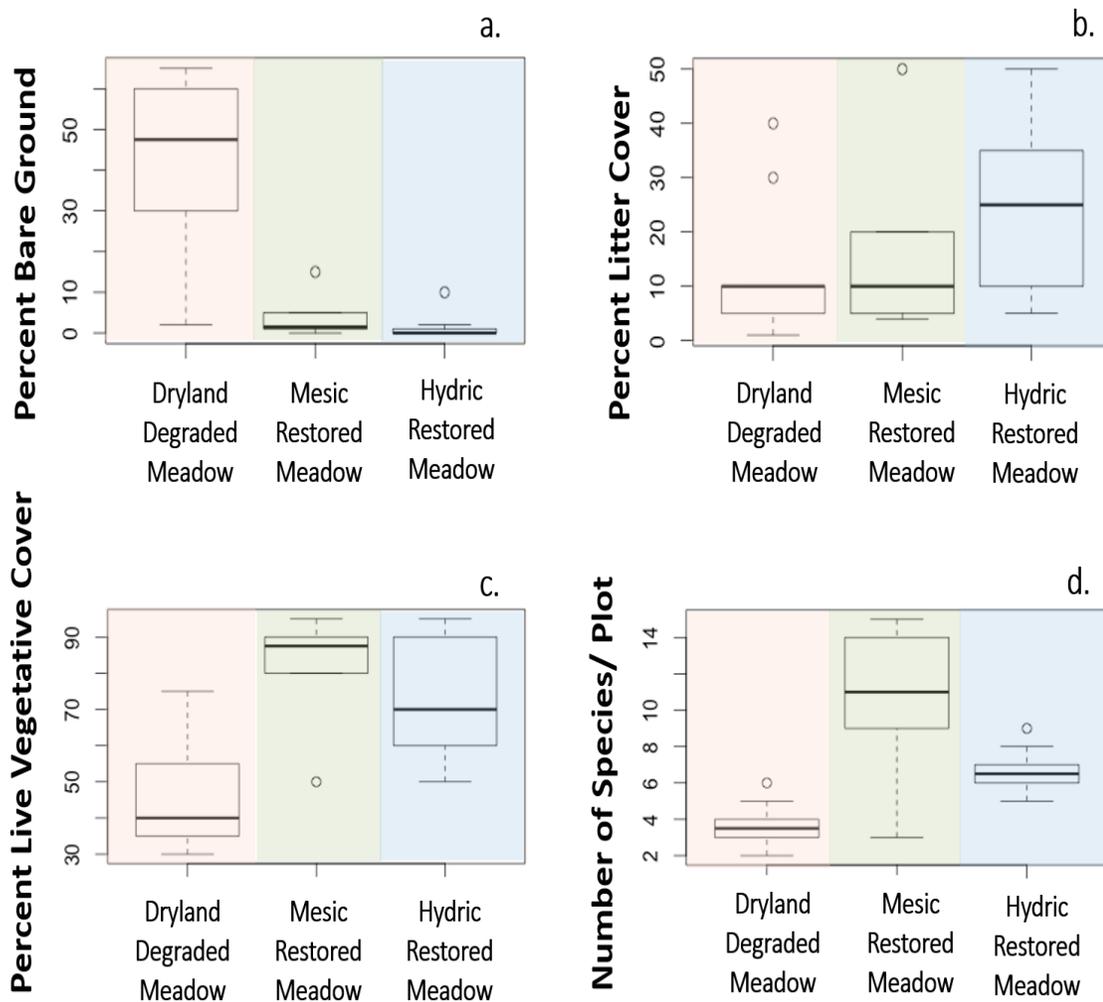
## **4.2 RESULTS**

The results found by the analysis of ecosystem characteristics; species composition and cover, above-ground and below-ground living biomass, and soil composition is shown below and compared between the restored and degraded meadow.

### **4.2.1 Species composition and cover**

The hydric and mesic plant communities in the restored meadow had higher mean richness values compared to the dryland plant community (Figure 14 and Table 2). The average number of species per plot was the highest in the mesic community (10.7) which was presumably better drained than the hydric community (7.0) which was dominated by species that are specially adapted to wet meadow conditions. The dryland plant community had a mean of 3.6 species per plot.

The degraded meadow had much higher mean percent bare ground (40.7%) when compared to the restored meadow, 1.3% and 3.4% for the hydric and mesic plant communities, respectively (Figure 14). At the degraded meadow, the percent bare ground was almost equal to the live vegetation cover (44.5%). By comparison, the restored site was almost twice this, with mean values of 74.5% and 84.0% for the hydric and mesic plant communities, respectively. The high litter cover (23.6%) found in the hydric community compared to the litter cover for the mesic community (13.9%) and dryland community (13.1) suggests that it is the most productive, at least for species like the sedges that can tolerate water saturation.



**Figure 14:** Vegetation characteristics of the three dominant plant communities observed in degraded and restored meadows of Carman Valley, California, July 3<sup>rd</sup>, 2014.

**Table 2:** Characteristics of the three dominant plant communities observed in degraded and restored meadows of Carman Valley, California, July 3<sup>rd</sup>, 2014.

\* Invasive

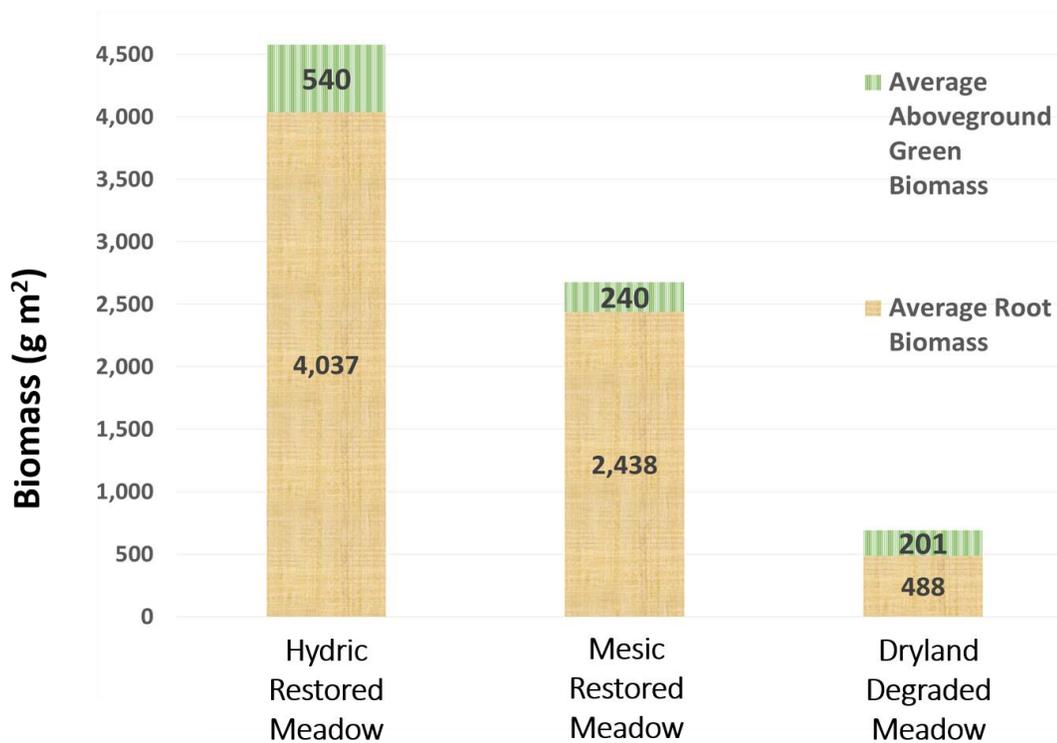
	<b>Hydric Restored Meadow</b>	<b>Mesic Restored Meadow</b>	<b>Dryland Degraded Meadow</b>
Mean Richness per plot	7.0	10.7	3.6
Dominant Species	Northwest Territory sedge ( <i>Carex utriculata</i> )	Longstalk clover ( <i>Trifolium longipes</i> )	*Cheatgrass ( <i>Bromus tectorum</i> )
	*Creeping buttercup ( <i>Ranunculus repens</i> )	Tufted hair grass ( <i>Deschampsia caespitosa</i> )	*Bulbous Bluegrass ( <i>Poa bulbosa</i> )
	Baltic rush ( <i>Juncus balticus</i> )	Little green sedge ( <i>Carex nevadensis</i> )	Big sagebrush ( <i>Artemisia tridentate</i> )
	Nebraska Sedge ( <i>Carex nebrascensis</i> )	Alpine timothy ( <i>Phleum alpinum</i> )	Antelope bitterbrush ( <i>Purshia tridentate</i> )
		Northwest Territory sedge ( <i>Carex utriculata</i> )	
		Bolander's yampah ( <i>Perideridia bolanderi</i> )	
Average Bare Ground	1.3%	3.4%	40.7%
Average Vegetation Cover	74.5%	84.0%	44.5%
Average Litter Cover	23.5%	13.9%	13.1%

The hydric community is dominated by perennial graminoids (mainly sedges), the mesic community has graminoids and forbs, and the dryland community in the degraded meadow was dominated by non-native grasses, woody shrubs and unidentified sedge species (Table 2). The largest number of species (29) was found in the mesic community at the restored meadow where no single species clearly dominated but six were prominent. This is in contrast to both the hydric community, where *Carex utriculata* was found in 100% of the plots with a mean plot cover of 63.6%, and the degraded community where non-native grasses (*Bromus tectorum* and *Poa bulbosa*) dominated cover and frequency. The degraded meadow was the only community where shrub species such as *Artemesia tridentata* and *Purshia tridentata* are present, with *Artemesia* relatively frequent (30% of plots) and abundant where found (19% cover).

#### **4.2.2 Above ground and below ground living biomass and soil composition**

The degraded meadow had lower average biomass than both sites at the restored meadow, though the biomass in the hydric community was greater than the biomass in the mesic community (Figure 15). The average above ground biomass at the degraded meadow was 201 g m<sup>-2</sup>, with 240 g m<sup>-2</sup> found at the mesic sites and 540 g m<sup>-2</sup> at hydric sites in the restored meadow (Figure 15). The difference between the degraded meadow and restored meadow below ground biomass was even larger with an average of 488 g m<sup>-2</sup> found at the degraded meadow, 2,438 g m<sup>-2</sup> found at mesic restored meadow sites and 4,037

$\text{g m}^{-2}$  found at hydric restored meadow sites. The students t test was used to determine if the difference between the three datasets was statistically significant, Table 3.



**Figure 15:** Above and below ground biomass for the three vegetation communities of Carman Valley, California, July 3<sup>rd</sup>, 2014.

**Table 3:** Students t test values of statistical significance of the difference between each plant community.

**(\*) Significant difference (\*\*) Extremely or very significant difference (ns) Not significant**

	Aboveground Biomass (g m <sup>-2</sup> )		Root Biomass (g m <sup>-2</sup> )	
	Statistical Significance	Two tailed P value	Statistical Significance	Two tailed P value
<b>Hydric-Mesic</b>	*	0.0026	ns	0.0855
<b>Hydric-Dryland</b>	*	0.0201	*	0.0001
<b>Mesic-Dryland</b>	ns	0.7573	*	0.0020

A table of the average and standard deviation of plant and soil characteristics in the three meadow types is shown in Table 4. The results appear to show significant difference in the vegetation and soil characteristics between the degraded and restored meadow, but the sample size should be expanded to validate findings.

**Table 4:** Average and standard deviation of plant and soil characteristics in the three main plant communities of Carman Valley, California, July 3<sup>rd</sup>, 2014.

	Hydric Restored Meadow		Mesic Restored Meadow		Dryland Degraded Meadow	
	Av	SD	Av	SD	Av	SD
Aboveground living biomass (g m <sup>-2</sup> )	539	145	239	112	201	280
Roots (g m <sup>-2</sup> )	4036	1597	2437	1289	488	499
Soil water content - 10 cm (% by weight)	26.4	3.4	11.5	3.7	5.6	2.7
Soil organic content - 10 cm (% by weight)	11.1	1.7	9.9	2.6	4.8	1.4
Soil mineral content - 10 cm (% by weight)	62.5	3.9	78.8	5.7	89.7	3.7
% Clay content -10 cm	3.6	0.9	3.3	2.0	3.4	1.8
% Silt content -10 cm	14.9	4.7	18.7	5.8	21.0	8.3
% Sand content -10 cm	81.5	5.1	78.0	7.2	75.7	8.5
Soil organic content -50 cm (% by weight)	3.4	2.9	4.0	1.5	4.0	1.9

The degraded meadow (DM) soil samples contained less water and organic content than both sample sets for the restored meadow, though the hydric sites

had greater water content than the mesic sites in the restored meadow, Table 4. The organic content of the soil was comparable in both restored communities, with 9.89% at the mesic sites, and 11.07% at the hydric sites, Table 4. In contrast, the average water content at the DM was 5.56%, Table 4. The students t test was performed to determine if the difference between sites was statistically significant (Table 5).

**Table 5:** Students t test values of statistical significance of the difference between the soil composition at the three sites

**(\*) Significant difference (\*\*) Extremely or very significant difference (ns) Not significant**

	% Water in soil		% Organic's in soil	
	Statistical Significance	Two tailed P value	Statistical Significance	Two tailed P value
<b>Hydric-Mesic</b>	**	0.0001	ns	0.3706
<b>Hydric-Dryland</b>	**	0.0001	**	0.0001
<b>Mesic-Dryland</b>	**	0.0045	**	0.0005

To validate the findings of the soil composition analysis, a texture analysis was performed. This test determined percent composition of sand, silt and clay in the samples to ascertain if there was significant difference in the sediment that could affect the way water and organic material is contained in the soil between sites. When applied to a soil texture triangle, the samples were found to be either sandy loam (5 samples) or loamy sand (7 samples). According to the students

unpaired t test, the difference between % sand, % silt and % clay at all three meadow locations was not statistically significant.

## **5. Microclimate Theory and Measurements**

### **5.1 INTRODUCTION**

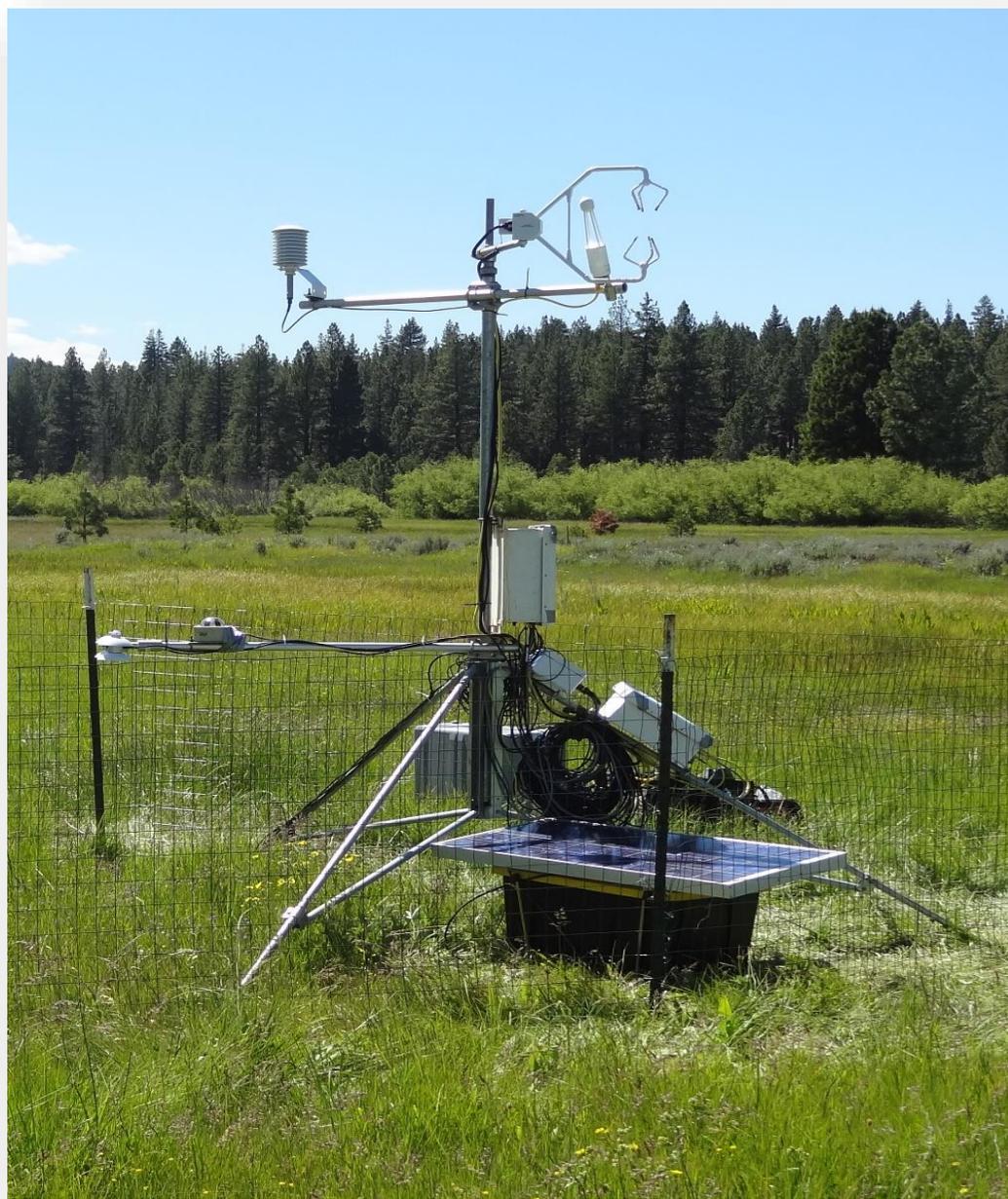
This chapter is broken into two main parts: experimental design, and results. The experimental design section (5.2) first lists instruments followed by 6 sub sections; eddy covariance siting and footprint assessment, eddy covariance theory and method, CO<sub>2</sub> fluxes, the surface energy budget, ancillary measurements, and data selection. In the results section (5.3), the surface radiation budget, surface energy balance, water and CO<sub>2</sub> fluxes are presented.

### **5.2 EXPERIMENTAL DESIGN**

Micrometeorological variables and terrestrial ecosystem exchanges of CO<sub>2</sub>, water vapor, and heat were measured in Knuthson Meadow June 15, to July 15, 2012 to determine the characteristics of the microclimate. Instruments were either mounted on a tower or buried in the substrate. Power for all instruments was supplied by a 12 V battery charged by a 75 W solar panel. All data were collected at 10 Hz to reduce the loss of high frequency data and eddy covariance (EC) block averages were created every 30 minutes to reduce the loss of low frequency data (Burba et al. 2011). 30-minute block averages were stored in a CR3000 data logger and eddy covariance data were used to calculate mean convective fluxes. All basic instrument specifications including mounting height are listed in Table 6 and shown in Figure 16.

**Table 6:** Micrometeorological Instrument and specifications used to measure microclimate and terrestrial ecosystem exchanges of CO<sub>2</sub> at Knuthson meadow June 15<sup>th</sup> to July 15<sup>th</sup> 2012.

<b>Instrument</b>	<b>Type</b>	<b>Variable Measured</b>	<b>Units</b>	<b>Height of Instrument</b>
Sonic Anemometer	CSAT3 3D Campbell Scientific Inc., Logan Utah	3-D wind speed and sonic temperature	m/s Deg. C	2.4 m
Infrared Gas Analyzer	LiCor 7500 Lincoln Nebraska	CO <sub>2</sub> , water vapor	mg/m <sup>3</sup>	2.4 m
Thermistor	HMP45C Vaisala, Helsinki, Finland	Ambient Temperature	Deg. C	2.4 m
Hygristor		Humidity	%	2.4 m
Pyranometer	NR01 HukseFlux, Helsinki, Finland	Shortwave radiation	W m <sup>-2</sup>	1.5 m
Pyrgeometer		Longwave radiation	W m <sup>-2</sup>	1.5 m
Ground Temp. Sensors	CS107	Soil Temp	C	-5 & -10 cm
T-type spatial averaging thermocouples	Omega, Stanford, Connecticut	Soil Temp	C	Between -1 and -5 cm
Heat Flux Plates	HukseFlux HFP01, Helsinki, Finland	Soil heat flux	W m <sup>2</sup>	-5 cm
Soil Moisture Probe	CS616, Campbell Scientific, Logan Utah	Soil moisture content	%	-1 and -15 cm



**Figure 16:** Micrometeorological equipment at Knuthson Meadow, June 15<sup>th</sup> to July 15<sup>th</sup>, 2012. See instruments in Table 7. Photo: Andrew Oliphant

### 5.2.1 Eddy covariance siting and footprint assessment

A 3-m tripod tower was used to mount the eddy covariance EC and ancillary meteorological instruments (Figure 17). This was deployed in the center of the valley to gain representative meadow measurements during both up valley and down valley wind directions. Along the axis of the valley, the meadow surface extended for approximately 1 km in either direction. Although rare, EC data collected during cross valley winds were rejected to be sure that the measurements were not influenced by coniferous forest on the side-walls of the valley.

The area where the majority of measured flux will come from is called the flux footprint or flux source area (Burba 2013). The size of the footprint is affected by 3 main variables: EC instrument height, surface roughness, and atmospheric stability (Burba et al. 2011). The size of the footprint increases with instrument height, increased atmospheric stability, and decreased surface roughness (Burba et al. 2011). This also results in a shift of the peak contribution away from the instrument (Burba et al. 2011).



**Figure 17:** Deployment of Micrometeorological equipment at Knuthson Meadow, June 15<sup>th</sup> to July 15<sup>th</sup>, 2012. Instruments listed in Table 7. Photo: Jerry Davis

An approximate analytical footprint model by Hsieh et al. (2000) was used to estimate the flux footprint for each 30-minute block average. This one-dimensional model relates atmospheric stability, measurement height, and surface roughness length to flux and footprint (Hsieh et al. 2000). Data were rejected when the 90% boundary of the flux source area fell outside of the meadow surface.

The eddy covariance measurement height was 2.4 m above the ground, insuring the instruments were located above the roughness sublayer but low enough to maintain a footprint that was consistently within the meadow area. The Sonic Anemometer was used to measure 3-D wind speed and sonic temperature. A Infrared Gas Analyzer was used to determine instantaneous concentrations of CO<sub>2</sub> and water vapor. The two EC instruments had a horizontal separation of 10 cm to reduce problems associated with sampling different eddies (Burba 2013).

### **5.2.2. Eddy covariance theory and method**

Eddy covariance has been used to monitor terrestrial-ecosystem exchanges of CO<sub>2</sub>, water vapor, momentum and heat (Oliphant 2012) since the late 1950's (Baldocchi 2003). Eddy covariance measures fluxes, or the rate of flow of atmospheric scalars by simultaneously sampling vertical wind velocities driven by turbulent motions and the scalar of interest (Baldocchi 2003; Oke 1987). It produces direct measurements and it is capable of measuring across a spectrum of timescales, from hours to years (Baldocchi 2003).

All atmospheric entities near the surface show short term fluctuations about their longer term mean value due to turbulence (Oke 1987). Eddies carry with them properties derived from the underlying surface, such as heat energy and

trace gasses (Oke 1987). Based on this concept, the equation for eddy covariance is

$$F_s = \rho \overline{w's'} \quad [5]$$

where the flux of a scalar ( $F_s$ ) is equal to the air density ( $\rho$ ) multiplied by the time average of the instantaneous covariance of vertical velocity ( $w'$ ) and the concentration of the scalar of interest ( $s'$ ) (Baldocchi 2003; Burba et al. 2011; Oke 1987). The overbar indicates the mean of the instantaneous covariance, or degree to which the vertical velocity and the scalar vary over the selected time average (Burba et al. 2011). The prime denotes the instantaneous deviation from the mean (Burba et al. 2011).

### 5.2.3. CO<sub>2</sub> fluxes

The eddy covariance equation was used to derive the CO<sub>2</sub> flux by:

$$CO_2 = \overline{w'\rho_c'} \quad [6]$$

where  $w$  is the vertical velocity and  $\rho_c$  is the CO<sub>2</sub> partial density (Fuehrer and Friehe 2002; Oke 1987).

The observed CO<sub>2</sub> flux can be considered the net ecosystem exchange of CO<sub>2</sub> (NEE). This term is comprised of two opposing exchange processes, gross

primary production by photosynthesis (GPP), which causes CO<sub>2</sub> to be transferred from the atmosphere to the surface and respiration (Re), which produces the opposite flux. Assuming that nighttime CO<sub>2</sub> fluxes were composed entirely of Re values, since there was no light for photosynthesis, all CO<sub>2</sub> flux values were isolated between 9pm and 5am and plotted against simultaneous measurements of soil temperature, since Re has been shown to be controlled most strongly by temperature. From this an empirical model for estimating RE was determined from linear regression.

$$Re = (0.022 \cdot Tg) - 0.078 \quad [7]$$

where Tg is the ground temperature at -5 cm depth. Following this, GPP was calculated as the residual of the other two terms

$$GPP = NEE - Re \quad [8]$$

#### **5.2.4. Surface Energy Budget**

Energy is exchanged between the atmosphere and the Earth's surface (Bonan 2002). Shortwave radiation from the sun in addition to longwave radiation from the atmosphere warms the earth's surface, and provides the energy that drives weather and climate (Bonan 2002). The energy is either stored in the ground or returned to the atmosphere (Bonan 2002). Due to the great variability in surface makeup, the amount of incoming energy reflected, absorbed and emitted is

unique both geographically and temporally due to the influence of elevation, latitude, and season (Bonan 2002). The surface radiation budget is expressed as:

$$Q_N = (K_{dn} - K_{up}) + (L_{dn} - L_{up}) \quad [9]$$

where  $Q_N$  is net all-wave radiation which is governed by the balance of incoming ( $dn$ ) outgoing ( $up$ ) shortwave ( $K$ ) and longwave ( $L$ ) radiation. The variables  $K$  and  $L$  are measured with pyranometer and pyrgeometer pairs. The surface radiation budget is the primary driver of the surface energy balance ( $Q_N$ ):

$$Q_N = Q_H + Q_E + Q_G \quad [10]$$

where  $Q_E$  is the latent heat flux (heat released or absorbed in phase change of water),  $Q_H$  is the sensible heat flux (heat energy transferred by convection) and  $Q_G$  is the ground heat flux (by conduction through the substrate). In theory, the component parts of the energy flux density ( $Q_H, Q_E, Q_G$ ) combined will equal  $Q_N$ . The  $Q_E$  and  $Q_H$  terms in addition to vapor flux ( $E$ ) are derived from the eddy covariance method so that:

$$Q_H = \rho c_p \overline{w'T'} \quad [11]$$

$$E = \overline{\rho_v'w'} \quad [12]$$

$$Q_E = L_v E \quad [13]$$

Where  $\rho$  is the mean dry air density,  $w$  is vertical velocity,  $c_p$  is the specific heat of dry air at constant pressure,  $T$  is the temperature,  $\rho_v$  is the water vapor density, and  $L_v$  is the latent heat of vaporization of water (Fuehrer and Friehe 2002; Oke 1987).

The ground heat flux ( $Q_G$ ) was determined by the following formula:

$$Q_G = Q_{G\ 5cm} + Q_S \quad [14]$$

where  $Q_{G\ 5cm}$  is the average of the direct heat flux measurement from two heat flux plates buried at a depth of 5 cm, and  $Q_S$  is the heat storage flux in the 5 cm soil column between the surface and the heat flux plates. In order to include the heat stored above the heat plates in the ground heat flux measurement, thermocouples and a soil moisture probe were installed between -5 and 0 cm. These measurements were used along with soil characteristic measurements (see chapter 4) to estimate the heat stored there. The storage term was derived from:

$$Q_S = C_S \cdot (\Delta T / \Delta t / z) \quad [15]$$

where  $C_S$  is the soil heat capacity,  $\Delta T$  is the change in temperature determined by four averaging thermocouples,  $\Delta t$  is the change in time (in this case 1800 seconds) and  $z$  is the depth of the heat flux plates (5 cm).  $C_S$  was derived from:

$$C_S = (1.92 * VOL_{min}) + (2.5 * VOL_{org}) + (4.18 * VWC) \quad [16]$$

where  $VOL_{min}$  is the volume fraction of the soil occupied by minerals,  $VOL_{org}$  is occupied by organic material, and  $VWC$  is occupied by water (de Vries et al. 1975). The volume occupied by air was not included as it is considered too small to calculate (Oke 1987).  $VWC$  was determined from the average of the two Soil Moisture Probes between the surface and -15 cm of substrate.  $VOL_{min}$  and  $VOL_{org}$  were derived from:

$$VOL_{min} = (1 - VWC) * FRAC_{min} \quad [17]$$

$$VOL_{org} = (1 - VWC) * FRAC_{org} \quad [18]$$

where the  $FRAC_{min}$  and  $FRAC_{org}$  (fraction mineral and fraction organic respectively) were determined as the mean of fraction of organic and mineral content of the soil from the mesic and hydric soil samples at Knuthson meadow. The soil sampling and analysis is described in chapter 4.

### **5.2.5. Ancillary Measurements**

Ambient temperature and percent humidity were measured by a thermistor/hygristor covered with a radiation shield to minimize solar loading. The pyranometer and pyrgeometer pair were oriented to the south to avoid tower shading. The spectral response of the pyranometer is 305 to 2800 nm. It measures both incoming SW radiation from the sun ( $K_{dn}$ ) and reflected from the surface ( $K_{up}$ ). The Pyrgeometer spectral response is 4,500 to 50,000 nm. It measures both down-welling longwave ( $L_{dn}$ ) and up-welling longwave radiation ( $L_{up}$ ).

### **5.2.6 Data Selection**

Data were downloaded from the data logger and processed in Matlab. Data were rejected from further analysis under the following 3 conditions: (1) when friction velocity ( $u^*$ ) < 0.15 m/s due to low turbulence to avoid the underestimation of flux variables (2) when data fell out of plausible thresholds (3) when the 90% boundary of the flux source area fell outside the meadow boundary.

## **5.3 RESULTS**

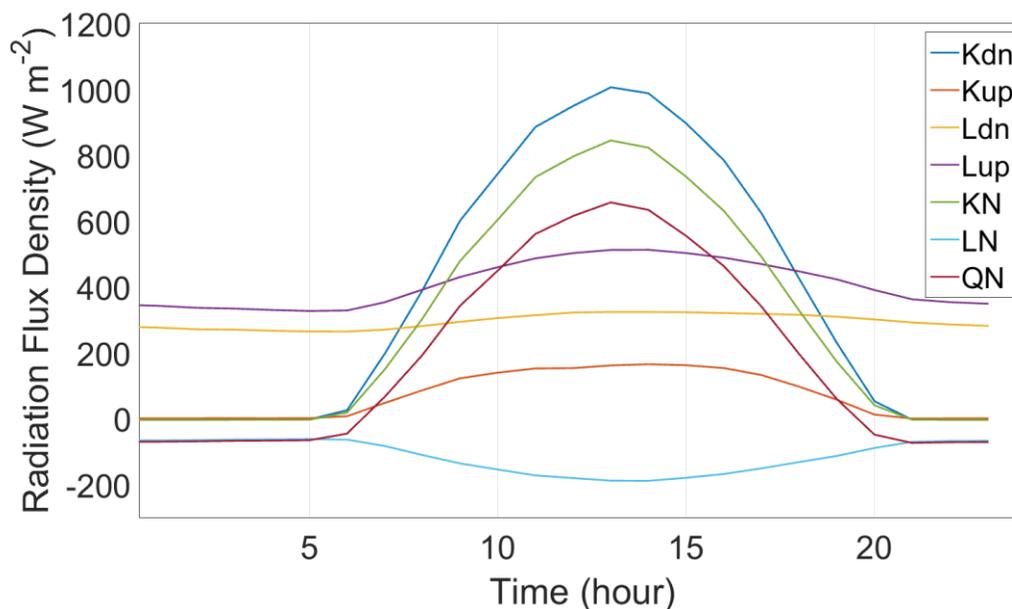
In this section, results of the surface energy balance, water and CO<sub>2</sub> fluxes are presented. Rejection of data under the above conditions lead to gaps in the

time series. Therefore 30-minute ensemble statistics were calculated for the diurnal cycle from data covering the entire study period and on a weekly basis.

### **5.3.1 Surface Radiation Budget**

30-minute ensemble averages of the surface radiation budget for the entire study period are shown in Figure 18. Incoming shortwave radiation ( $K_{dn}$ ) peaked at approximately  $1000 \text{ W m}^{-2}$  in the afternoon between 12:00 and 14:00 PST. Reflected shortwave radiation ( $K_{up}$ ) increased following sunrise until 9:00 PST and remained fairly consistent at this level of reflection throughout the diurnal cycle until 18:00 PST. The average reflectivity of the meadow surface for the total study was 18.9% with very little variability on a weekly basis (Table 7).

Incoming longwave radiation ( $L_{dn}$ ) remained relatively constant at approximately  $300 \text{ W m}^{-2}$  throughout the 24 hour period. The relatively low  $L_{dn}$  value reflects little cloud cover.  $L_{up}$  hovered at  $300 \text{ W m}^{-2}$  from 20:00 PST through the night until approximately 6:00 PST where it rose gradually to approximately  $500 \text{ W m}^{-2}$  as the soil slowly warmed.  $L_{up}$  remained at approximately  $500 \text{ W m}^{-2}$  for a majority of the day. The  $L_{up}$  is greater than  $L_{dn}$  producing a surface deficit, or net loss from the surface. Net radiation ( $Q_N$ ) was strongly positive during the day, reaching an average diurnal maximum of over  $600 \text{ W m}^{-2}$ , and weakly negative at night with an average minimum of approximately  $-60 \text{ W m}^{-2}$ .



**Figure 18:** Hourly ensemble averages of the surface radiation budget, where  $Q_N$  is net all-wave radiation which is governed by the balance of incoming (dn) and outgoing (up) shortwave (K) and longwave (L) radiation.

### 5.3.2 Surface Energy Balance

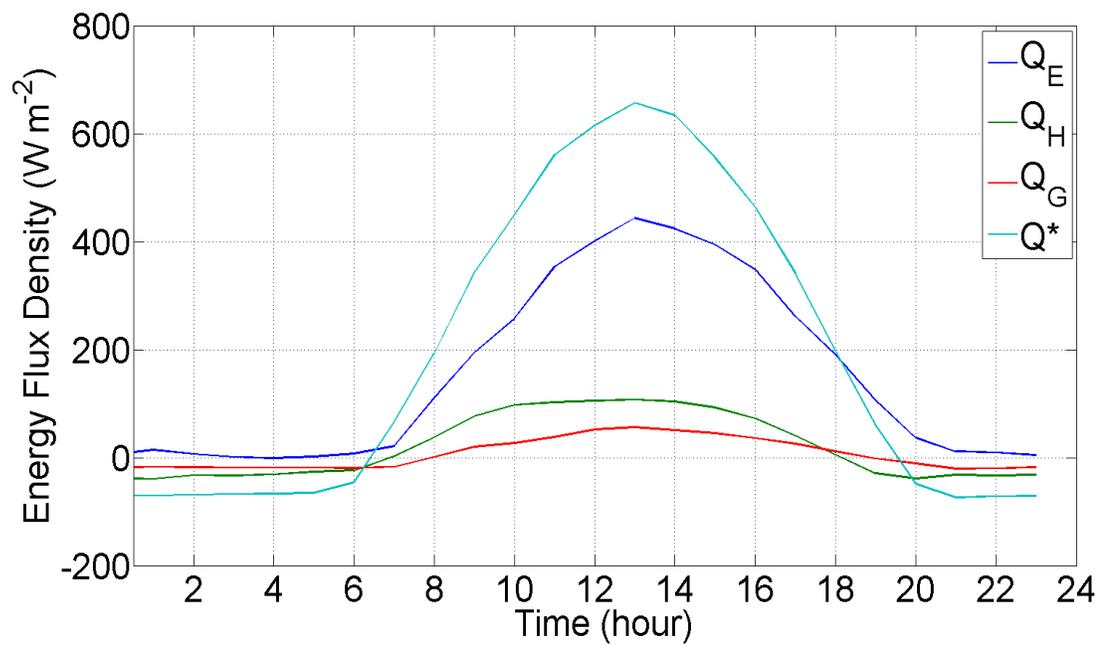
The surface energy balance components for the total study period are shown in Figure 19.  $Q_N$ ,  $Q_E$ ,  $Q_H$ , and  $Q_G$  are computed into 30 minute ensemble averages to investigate the mean diurnal characteristics.  $Q_E$  dominates the partitioning of available energy with a diurnal peak of over  $400 \text{ W m}^{-2}$  at around 13:00 PST. In contrast,  $Q_H$  peaks earlier in the day (about 10:00 PST) but maintains relatively constant for a longer period, at approximately  $100 \text{ W m}^{-2}$  until 15:00 PST.  $Q_G$  represented the smallest amount of partitioned energy (approximately  $50 \text{ W m}^{-2}$ ) and had a similar hourly trajectory to  $Q_H$ .  $Q_H$  registered

daylight heating first with  $Q_E$  and  $Q_G$  following almost an hour later.  $Q_H$  and  $Q_G$  became negative at night with  $Q_H$  ( $-25 \text{ W m}^{-2}$  to  $-50 \text{ W m}^{-2}$ ) a little lower than  $Q_G$  ( $-20 \text{ W m}^{-2}$ ).  $Q_E$  barely became negative at night ( $-5$  to  $-10 \text{ W m}^{-2}$ ).

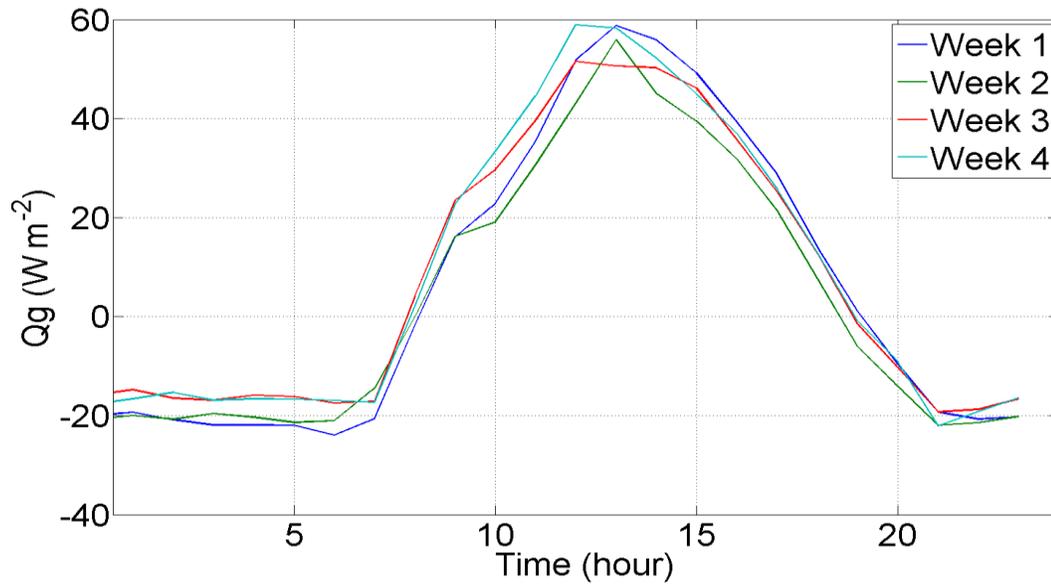
$Q_E$  exceeds  $Q_N$  around 19:00 PST, suggesting an **Oasis** effect whereby relatively warm dry air imported from surrounding terrain enhances ET ( $Q_E$ ) to the point where it can be larger than the energy that  $Q_N$  provides (Oke 1987). This suggests that the meadow is cooler and moister than the surrounding area due to localized evaporative cooling, likely as a result of the larger moisture source in the meadow relative to the surrounding upland surfaces. When this effect was strongest (Week 1) the daily total sensible heat flux was negative. There was no significant variability of  $Q_G$  on a week to week basis (Figure 20).

**Table 7:** Average daily total fluxes and derivatives of surface energy related values at Knuthson meadow for the study period.

	Total Study	Week 1	Week 2	Week 3	Week 4
<b>Albedo</b>	0.189	0.187	0.191	0.186	0.192
<b>Bowens Ratio</b> ( $Q_H/Q_E$ )	0.127	-0.04	0.20	0.24	0.16
<b>Evapotranspiration</b> ( $\text{mm d}^{-1}$ )	5.29	7.19	5.26	4.27	4.80
<b><math>Q_N</math> (<math>\text{MJ m}^{-2} \text{ d}^{-1}</math>)</b>	15.89	16.97	15.81	16.26	14.83
<b><math>Q_E</math> (<math>\text{MJ m}^{-2} \text{ d}^{-1}</math>)</b>	13.0	17.6	12.9	10.5	11.7
<b><math>Q_H</math> (<math>\text{MJ m}^{-2} \text{ d}^{-1}</math>)</b>	1.6	-0.7	2.6	2.5	1.8

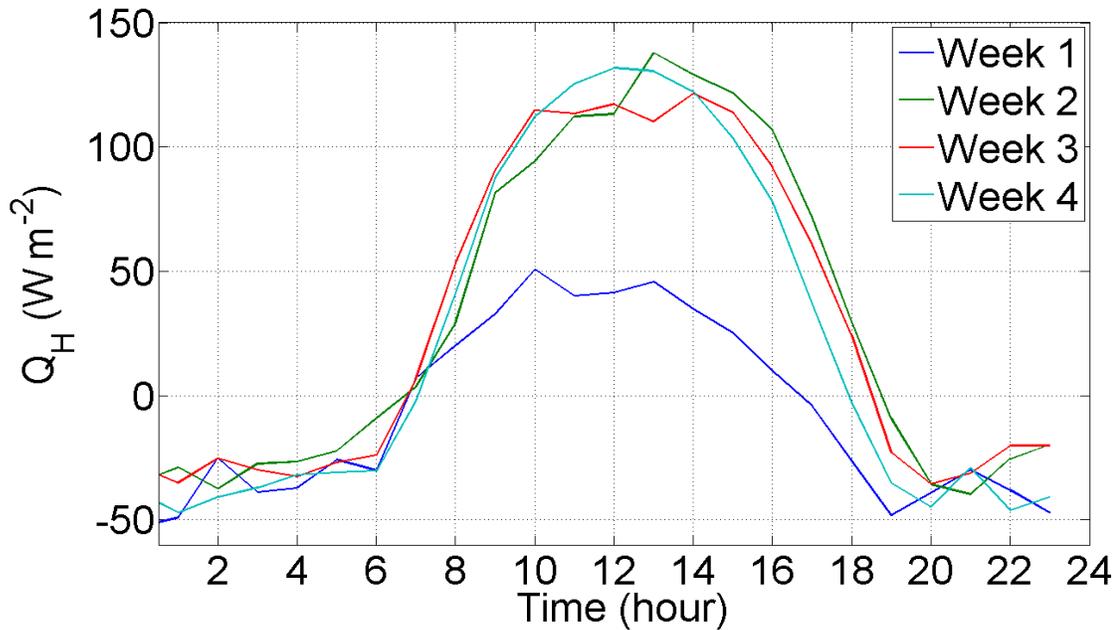


**Figure 19:** Surface energy balance components of energy flux density where  $Q_E$  is the latent heat flux (heat released or absorbed in phase change),  $Q_H$  is the sensible heat flux (heat energy transferred by convection and conduction) and  $Q_G$  is the ground heat flux.



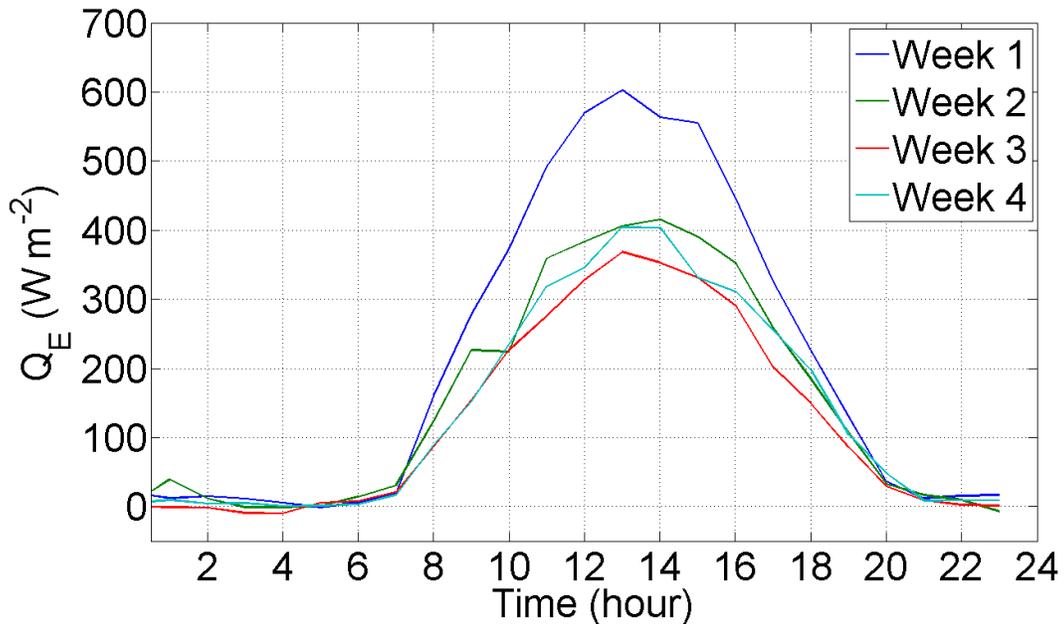
**Figure 20:** The partitioning of weekly hourly ensemble averages of the ground heat flux ( $Q_G$ ) for each of the four weeks in the observation period.

The weekly ensemble averages of the sensible heat flux show a general increase in heat transferred by convection over the course of the study period, though most of the change occurs between Week 1 and Week 2, (Figure 21). The diurnal cycle of  $Q_H$  in Week 1 is distinctly different from the following three weeks with a lower daily maximum, and slightly different trajectory. The average daily maximum in the first week was approximately  $50 \text{ W m}^{-2}$ , more than  $100 \text{ W m}^{-2}$  less than the maximum found in the following 3 weeks. The daily maximum also peaked around 2 hours earlier in the day when compared to weeks 2, 3, and 4.



**Figure 21:** The partitioning of weekly hourly ensemble averages of the sensible heat flux ( $Q_H$ ) (heat energy transferred by convection) for each of the four weeks in the observation period.

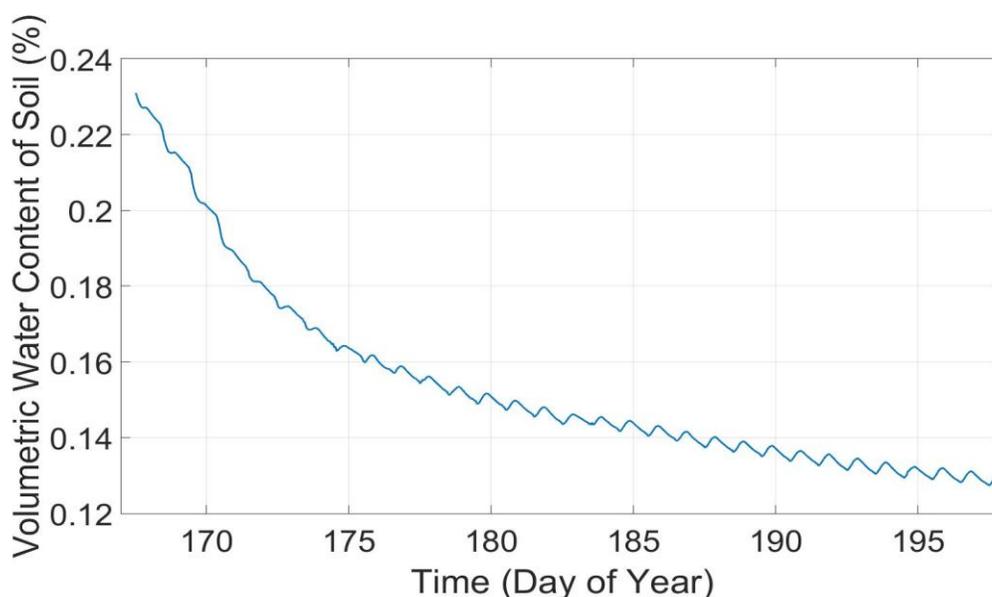
The weekly partitioning of  $Q_E$  was opposite  $Q_H$ . Figure 22 shows that distinctly more available energy was utilized by evaporation in the 1<sup>st</sup> week in comparison to the following 3 weeks. The average maximum of approximately  $600 \text{ W m}^{-2}$  in Week 1 was about double the average maximum found in weeks 2, 3, and 4 ( $350\text{-}400 \text{ W m}^{-2}$ ). The average daily maximum in Week 1 also appeared to peak approximately 2 hours earlier than in the later 3 weeks.



**Figure 22:** The partitioning of weekly hourly ensemble averages of the latent heat flux ( $Q_E$ ) (heat energy transferred by evaporation and condensation) for each of the four weeks in the observation period.

The larger  $Q_E$  term ( $13.0 \text{ MJ m}^{-2} \text{ d}^{-1}$ ) in comparison to  $Q_H$  ( $1.6 \text{ MJ m}^{-2} \text{ d}^{-1}$ ) shows that the available energy ( $Q_N$ ) is predominantly utilized by evapotranspiration, with a very low Bowen ratio ( $Q_H/Q_E$ ) by comparison to other ecosystems (Table 7). This shows that most of the available energy is going into water phase change at the beginning of the study. Over the study period the average daily total of ET declines from  $7.19$  to  $4.8 \text{ mm d}^{-1}$ ,  $Q_E$  from  $17.6$  to  $11.7 \text{ MJ m}^{-2} \text{ d}^{-1}$  and  $Q_H$  increases from  $-0.7$  to  $1.8 \text{ MJ m}^{-2} \text{ d}^{-1}$ . This captures a shift in the energy budget as less energy goes into phase change and more energy goes into heating the air.

A reduction in volumetric water content (VWC) from 24% to 12% (Figure 23) was correlated with the reduction in  $Q_E$  and increases of  $Q_H$ . The steep decline in VWC from day of year 165 to 175 correlates to the first week of the  $Q_E$  and  $Q_H$  ensemble averages.



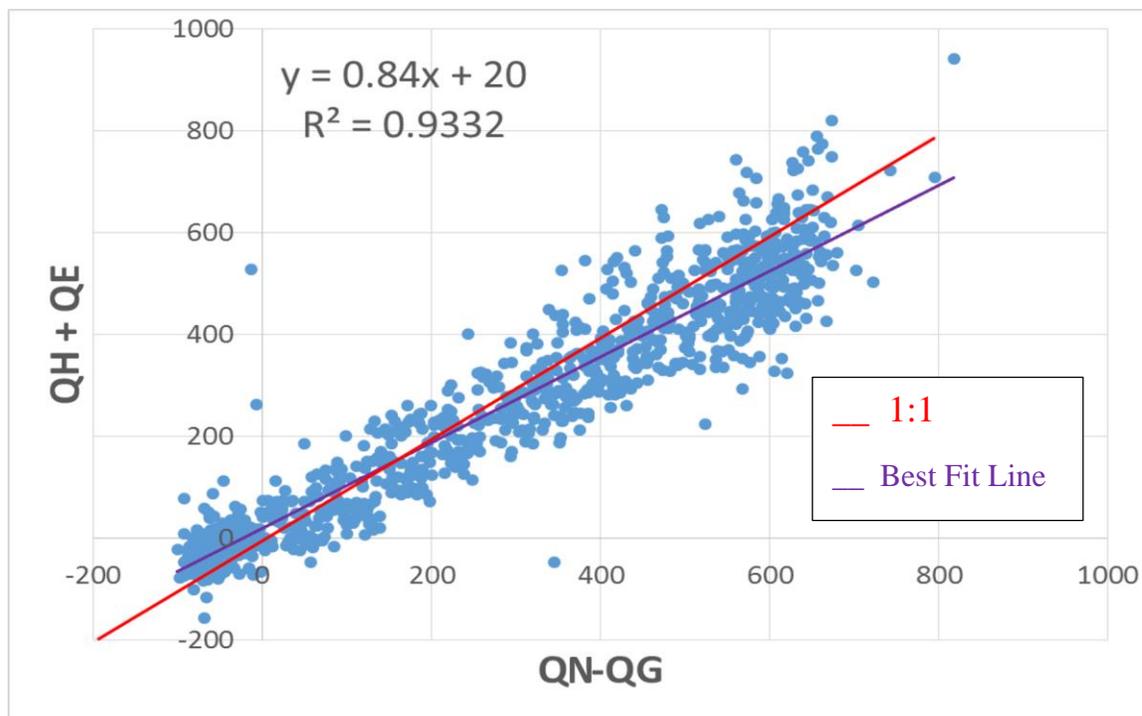
**Figure 23:** 30- minute volumetric water content of the soil over the total study period.

### 5.3.3 Energy Balance Closure

Due to the first law of thermodynamics, the component parts of the surface energy equation ( $Q_E$ ,  $Q_H$ , and  $Q_G$ ) combined should equal  $Q_N$ . Energy balance closure is used to determine if energy is being over- or under- estimated by the EC technique. Turbulent fluxes are isolated from the ground heat flux by plotting the sum of  $Q_E$  and  $Q_H$  against available energy ( $Q_N - Q_G$ ) for all available 30 minute periods. Energy balance closure would be accomplished if the plotted

variables fall along a 1:1 line. Practitioners of EC widely experience lack of closure, in particular an underestimation of the turbulent fluxes (Baldocchi 2003). Potential reasons for lack of closure include: systematic errors in instrumentation, energy components that are not considered in the equation, and the underestimation of turbulent fluxes due to incomplete measurement of all turbulent fluxes.

Similar to other studies, the energy balance equation for this study did not close, with an underestimation of turbulent fluxes of approximately 16% (Figure 24). The purple linear regression line (line of best fit) is described by the y-intercept equation  $y=0.84x +20$ . 93% of the variability in the data is represented by this line, as shown by the  $R^2$  value.



**Figure 24:** Energy balance closure for the total study period at Knuthson Meadow, where the red line is the 1:1 ratio, the purple line is the linear regression, and the  $R^2$  value is the degree to which the scatter is represented by the linear regression ( $y=0.84x + 20$ ).

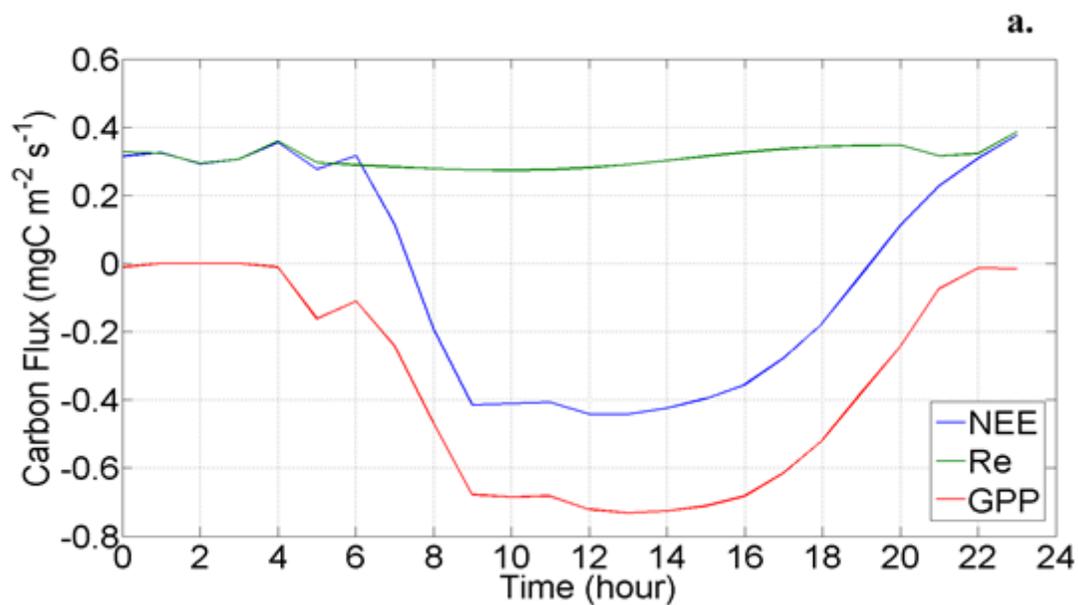
### 5.3.4 Ecosystem $\text{CO}_2$ exchange

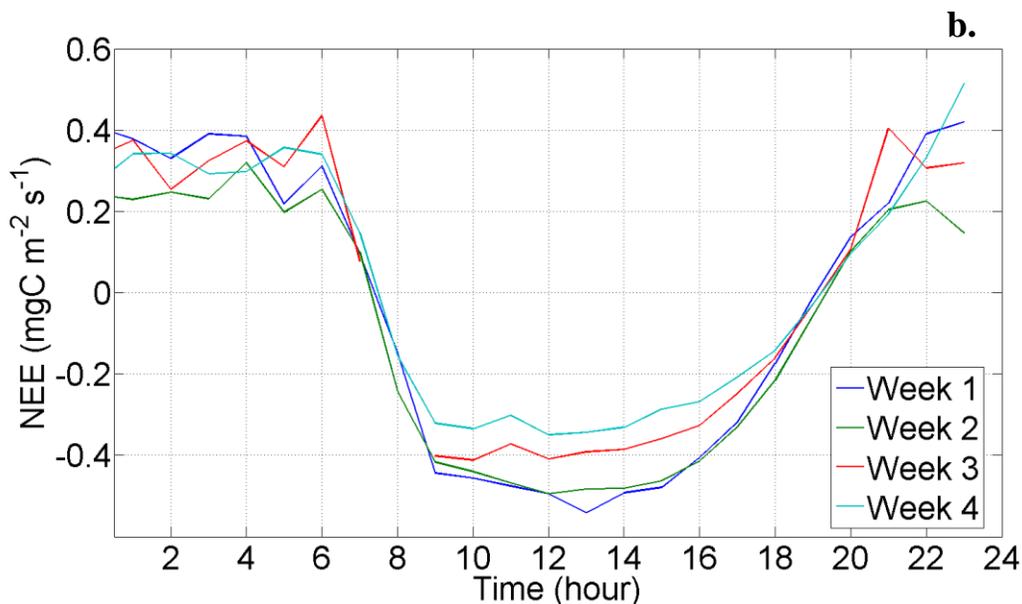
For analysis of net ecosystem  $\text{CO}_2$  exchange (NEE), this paper uses the sign convention of negative values representing carbon sequestration in the biosphere and positive values representing carbon addition to the atmosphere. The large daily GPP and  $R_e$  values (approximately  $-30$  and  $+27 \text{ gC m}^{-2} \text{ d}^{-1}$  respectively) produce a daily sink of  $\text{CO}_2$  of  $-2.3 \text{ gC m}^{-2} \text{ d}^{-1}$  when averaged over the total study period (Figure 24 and Table 9). As shown in Figure 25 (a), diurnal ensemble averages for the entire study period show carbon uptake rates (GPP) with a greater range than carbon release rates ( $R_e$ ). Photosynthetic uptake

(GPP) began at sunrise around 4:00 PST and increased to a diurnal maximum of  $-0.7 \text{ mgC m}^{-2} \text{ s}^{-1}$  from 9:00-16:00 PST. GPP declined after 16:00 PST, but continued to sequester  $\text{CO}_2$  until 22:00 PST when the sun set. Modeled Re rates remained generally constant over a 24 hour period (between 0.2 and 0.4  $\text{mgC m}^{-2} \text{ s}^{-1}$ ).

**Table 8:** Diurnal total fluxes and derivatives of net ecosystem exchange, respiration, and gross primary production at Knuthson meadow.

	Total Study	Week 1	Week 2	Week 3	Week 4
NEE Observed ( $\text{gC m}^{-2} \text{ d}^{-1}$ )	-2.3	-2.1	-7.2	-2.1	1.6
Re modeled ( $\text{gC m}^{-2} \text{ d}^{-1}$ )	26.9	27.5	23.3	28.0	29.3
GPP as residual ( $\text{gC m}^{-2} \text{ d}^{-1}$ )	-30.5	-31.5	-31.7	-30.0	-29.3





**Figure 25:** Diurnal ensemble average CO<sub>2</sub> fluxes **(a)** for the entire study period and **(b)** on a weekly basis, where NEE is the net ecosystem-atmosphere flux of CO<sub>2</sub>, GPP is gross primary production and Re is ecosystem respiration. Negative CO<sub>2</sub> values represent carbon uptake by the ecosystem.

For each of the 4 weeks of the study, the site acted as a carbon source in the evening, through the night and into the morning from approximately 19:00 PST to 7:00 PST (Figure 25 b). The site was a carbon sink during the day (7:00 PST to 19 PST). Over the 4 week period, NEE shifted from a sink to a source of atmospheric CO<sub>2</sub> as GPP weakened and Re increased (Table 8). The largest sink occurred in the second week of study, when GPP has the largest sink (-31.7 gC m<sup>-2</sup> d<sup>-1</sup>) and Re has the weakest source (23.33 gC m<sup>-2</sup> d<sup>-1</sup>). The strongest environmental difference this week was relatively low temperature which has been found to enhance photosynthesis and thus GPP due to the reduction in heat stress (Jones 1998; Kato et al. 2006; Kwon et al. 2008; Saleska et al. 1999).

However, as the change in  $R_e$  was more significant than GPP, the increase in the NEE sink was likely due to a lowering of ecosystem  $R_e$ .

The EC technique may be underestimating  $\text{CO}_2$  fluxes as well as turbulent fluxes. Based on closure analysis presented in the previous section and assuming that turbulence transports heat, water and  $\text{CO}_2$  with similar efficiency, these fluxes might be as much as 16% larger. In addition, there may be some storage of  $\text{CO}_2$  in the layer between the surface and the instrument, although this is typically small for low vegetation.

### **5.3.5 Environmental Conditions and Carbon**

Table 9 displays total study averages and weekly averages of environmental conditions at the site. PAR and specific humidity decreases minimally over the course of the study period while mean wind speed, soil temperature and air temperature increased minimally. As shown in Figure 23, soil moisture decreased substantially. It was the most dramatic environmental change over the study period. As air temperature and specific humidity are dependent on available water and evaporation, the decrease in VWC of the soil likely drove the increase in air temperature and decrease in humidity.

**Table 9:** Diurnal totals and derivatives of environmental conditions at the site.

	Total Study	Week 1	Week 2	Week 3	Week 4
Photosynthetically Active Radiation ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	784	792	761	799	781
Soil water Content (% vol)	15.40	19.48	15.62	14.32	13.26
Soil Temperature 10 cm ( $^{\circ}\text{C}$ )	17.54	16.99	16.27	17.63	18.83
Air Temperature ( $^{\circ}\text{C}$ )	16.25	17.14	12.01	16.53	18.60
Specific Humidity ( $\text{g kg}^{-1}$ )	5.74	5.47	5.01	7.08	5.42
Mean Wind Speed ( $\text{m s}^{-1}$ )	2.23	2.15	2.36	2.18	2.26

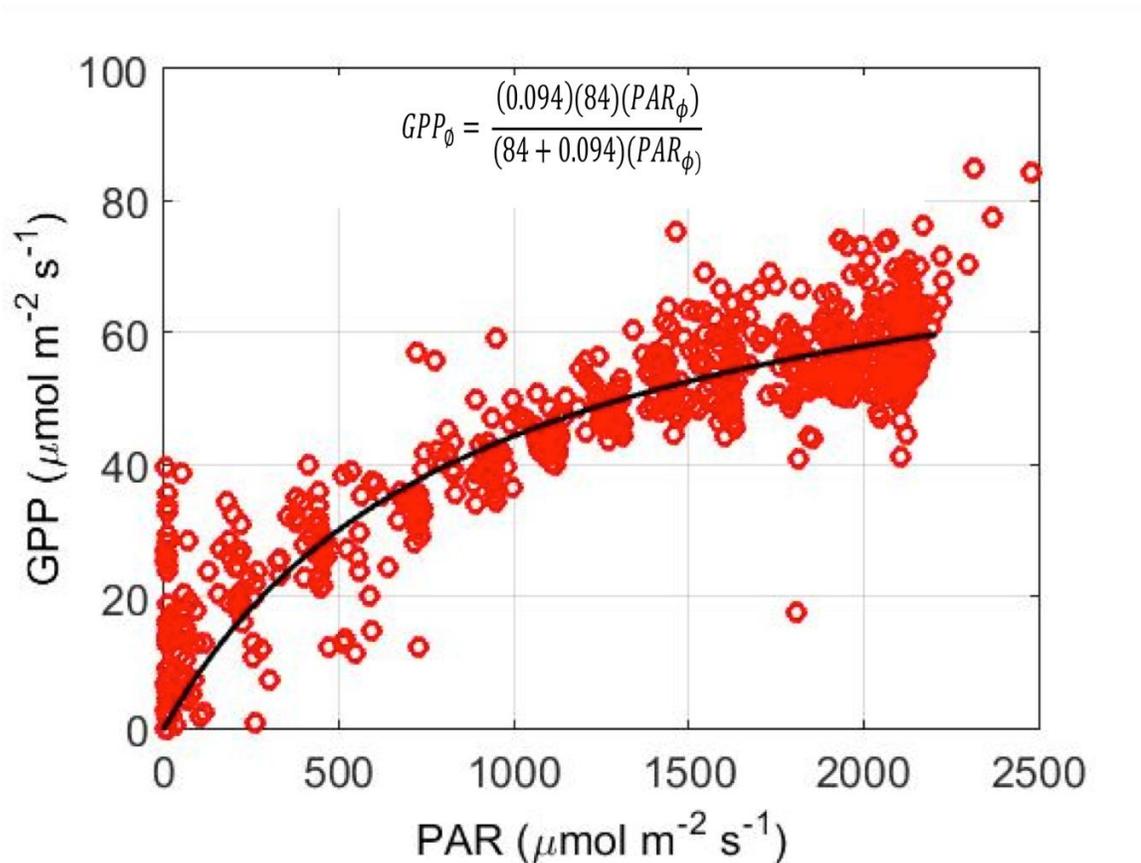
PAR was the primary driver of GPP, as shown by the strength of the positive correlation in Figure 26. Using the method used by Oliphant et al. (2011) a standard rectangular hyperbola light response model (below) was fit to the curve:

$$GPP_{\phi} = \frac{(\alpha)(A_{\max})(PAR_{\phi})}{(A_{\max} + \alpha)(PAR_{\phi})} \quad [19]$$

where alpha ( $\alpha$ ) is the effective quantum efficiency (the initial slope of the light response),  $A_{\max}$  indicates the individual hourly average GPP level of light saturation and the subscript  $\phi$  represents data analyzed in  $\phi$  bins (Figure 26).

The alpha value of 0.094 represents a strong initial response in GPP to PAR from 0 to  $400 \mu\text{mol m}^{-2} \text{sec}^{-1}$ . The alpha value is more than 2 times the value found in a deciduous forest (Oliphant et al. 2011) showing that the restored meadow has a high light use efficiency in comparison to other ecosystem types. GPP does not saturate on the graph (reach horizontal). The shape of the curve

is still inclined, showing that GPP continues to increase through the full range of available light. This suggests the ecosystem is adapted to quite high levels of light. The model results show that it saturates at  $84 \mu\text{mol m}^{-2} \text{sec}^{-1}$  at a much higher PAR, whereupon any addition of light will not result in increased carbon mass through photosynthesis. The high  $R^2$  value (0.93) of the fitted hyperbola shows that GPP is strongly correlated with light, suggesting it is by far the dominant control. However, in water stressed conditions, other studies have found reduction in GPP associated with low specific humidity and high air temperature, which produce a high vapor pressure deficit (Jones 1998; Kato et al. 2006; Kwon et al. 2008; Saleska et al. 1999).



**Figure 26:** Gross Primary Production and Photosynthetically active radiation for the total study period.

Daily total light use efficiency (lue) values averaged over the total study period and partitioned by week were determined in an attempt to shed light on this hypothesis, Table 10. Values were determined by dividing the sum of daily mean GPP by the sum of daily mean PAR. Light use efficiency changes very little over the study period. As GPP is normalized by PAR in the lue values, the similarity

in values by week suggests that environmental changes, such as air temperature and specific humidity, are having very little impact on the GPP.

**Table 10:** Diurnal totals and derivatives of light use efficiency of the vegetation at Knuthson, found by dividing gross primary production by photosynthetically active radiation. GPP/PAR represents a normalization, and thus doesn't have units.

	Total Study	Week 1	Week 2	Week 3	Week 4
GPP/PAR	$4.51 \times 10^{-7}$	$4.67 \times 10^{-7}$	$4.68 \times 10^{-7}$	$4.38 \times 10^{-7}$	$4.35 \times 10^{-7}$

The average soil temperature increased from 17 to 18.8°C (Figure 30) over the 4 week period. An increase in soil temperature during this time period is not unusual as the warm dry summer in California generally results in increases in air and soil temperatures through July at these elevations. It is also possible that the decline in VWC increased the surface soil temperature due to the higher specific heat of water.

Overall, the large reduction in soil moisture content over the study period was correlated with a shift in NEE from a sink to a source of atmospheric CO<sub>2</sub> (Table 8). The drop in soil moisture is the most dramatic environmental change over the study period, negatively impacting carbon uptake by GPP and increasing the rate of carbon release through respiration.

## 6. Discussion

Overall, EC shows a significant carbon sink on a daily basis and a large rate of evaporation and associated cooling. The ecosystem comparison revealed this effect is likely much stronger in the restored than degraded meadow due to the increased biomass and available water found at the restored site. This implies that there are additional important ecosystem services provided by restored meadows other than the known hydrologic and ecologic impacts outlined in Chapter 2.

When compared to synthesis studies of other ecosystems in the northern hemisphere for the same approximate time period (day of year 167-197) the daily total net ecosystem exchange at the restored meadow was the most similar to values found at a wheat crop ( $-2 \text{ g C m}^{-2} \text{ d}^{-1}$ ) (Baldocchi 2008). The total study average NEE values at Knuthson was greater than the averages found in tundra, macchia, and annual grasslands (range  $-1$  to  $+1 \text{ g C m}^{-2} \text{ d}^{-1}$ ) and smaller than evergreen forests, perennial grasslands and deciduous forests ( $-3$  to  $-6 \text{ g C m}^{-2} \text{ d}^{-1}$ ) (Baldocchi 2008). On a weekly basis, the largest maximum weekly average NEE value at Knuthson found in week two ( $-7.2 \text{ g C m}^{-2} \text{ d}^{-1}$ ) was greater than all ecosystems in the comparison (tundra, macchia, annual grasslands, evergreen forests, perennial grasslands and deciduous forests) (Baldocchi 2008).

When directly compared to the three ecosystems with overlapping vegetation types; wetlands, grasslands, and sagebrush-steppe ecosystems, the NEE values at Knuthson (+1.6 to -7.2 g C m<sup>-2</sup> d<sup>-1</sup>) were similar. In a synthesis of 12 wetland sites across Europe and North America collected over a year, a maximum average weekly uptake by the biosphere of -4 g C m<sup>-2</sup> d<sup>-1</sup> was found (Lund et al. 2010). These sites varied from ombrotrophic and minerotrophic peatlands, in both temperate and boreal climates, to wet tundra ecosystems (Lund et al. 2010). Grassland studies had daily maximum NEE values of -4.8 g C m<sup>-2</sup> d<sup>-1</sup> in a Mediterranean annual grassland in the Sierra Nevada foothills of California (Xu and Baldocchi 2004), -5.0 g C m<sup>-2</sup> d<sup>-1</sup> over a temperate C3 grassland near Alberta, Canada (Flanagan et al. 2002) and -6.3, -7.6, and -6.0 g C m<sup>-2</sup> d<sup>-1</sup> over tallgrass prairies in Kansas and Oklahoma (Kim et al. 1992; Dugas et al. 1999; and Suyker and Verma 2001), respectively. The NEE daytime sums found at a sagebrush-steppe ecosystem in south-central Wyoming across two growing seasons was -5 to +1 g C m<sup>-2</sup> d<sup>-1</sup> for day of year 165 to 200 (Kwon et al. 2008). This ecosystem was co-dominated by *Artemisia tridentata* and perennial grasses in the northwestern Sierra Madre at 2260 m elevation (Kwon et al. 2008). Considering that the values found in the wetland, grassland, and sagebrush-steppe ecosystems were the maximum daily NEE totals found over the growing season and the values for Knuthson were daily averages for what we are

assuming was in the declining portion of the growing season, the values fell into the lower range found in all three ecosystems.

Average weekly GPP and Re values at Knuthson (-30 and +26 g C m<sup>-2</sup> d<sup>-1</sup> respectively) were most closely comparable to growing season maximums found in grassland and sagebrush-steppe ecosystems. A synthesis of grassland ecosystems found GPP maxima of -10 to -60 g C m<sup>-2</sup> d<sup>-1</sup> and Re maxima of +10 to +40 g C m<sup>-2</sup> d<sup>-1</sup> (Gilmanov et al. 2010). However, in a very water limited and lower elevation grassland in the foothills of Lone, California the GPP values were much lower around -10 g C m<sup>-2</sup> d<sup>-1</sup> (GPP) and 5 g C m<sup>-2</sup> d<sup>-1</sup> (Re) (Xu and Baldocchi 2004). As the vegetation type and reduced water availability is similar to what was found at Upper Carman meadow, GPP values measured there are likely to fall within a similar low range. A multi-year study in US intermontane sagebrush- steppe ecosystems in Oregon (1995-2001) and Idaho (1996-2001) found GPP maxima of -20 and -37 g C m<sup>-2</sup> d<sup>-1</sup> and Re maxima of + 20 and + 35 g C m<sup>-2</sup> d<sup>-1</sup> (Gilmanov et al. 2006). Wetland ecosystems have significantly lower GPP and Re values with growing season GPP maximums of -7 and g C m<sup>-2</sup> d<sup>-1</sup> and Re maximum values of 4.5 g C m<sup>-2</sup> d<sup>-1</sup> (Lund et al. 2010). GPP and Re values found in an alpine meadow in Qinghai-Tibetan Plateau were also much lower than the values found at Knuthson, with GPP ranging from 0 to -7 g C m<sup>-2</sup> d<sup>-1</sup> and Re values from 2 to 5 g C m<sup>-2</sup> d<sup>-1</sup> (Kato et al. 2004).

Grassland ecosystem NEE was found to be driven by radiation and temperature in cold and temperate climates and water availability in arid climates (Gilmanov et al. 2010). Studies in sagebrush-steppe ecosystems have found that carbon-budget inter-annual variability is explained by water availability and resulting herbaceous production (Kwon et al. 2008). In these ecosystems, drought drives the magnitude and response of NEE by regulating availability of soil moisture during the summer seasons for both shallow rooted herbaceous vegetation such as grasses and forbs and deep rooted species such as shrubs allowing carbon uptake until soil and air become dry in the late growing season (Kwon et al. 2008). Wetland ecosystems, which are rarely water stressed, have found stronger correlations with environmental variables and  $R_e$  as compared with GPP (Lund et al. 2010). The one notable exception is leaf area index (LAI) due to the high light absorption capacity and therefore high photosynthetic uptake found on plants with greater leaf area (Lund et al. 2010). Wetland ecosystems with water-logged conditions have been found to be persistent sinks of atmospheric  $CO_2$  in part due to limited oxygen diffusion into the soil, restraining decomposition (Lund et al. 2010).

Water availability is important for these three ecosystems not only for direct vegetation uptake for photosynthesis and relationship to  $R_e$ , but also because it alters the energy balance of the local atmosphere due to the increased evaporation. For the same vegetation species, the degraded site is likely to have

a lower GPP than the restored site as the dryer, warmer conditions are associated with a reduction in photosynthesis (Jones 1998).

Though micrometeorological measurements were not made at the degraded meadow for comparison, the Bowen's ratio at the restored meadow is low when compared to other ecosystems (Jarvis 1976; Oke 1987; Eugster et al. 2000). The total study average value of 0.13 was found within the range of values of three ecosystems: tropical wet forests, irrigated crops, and forest, wet canopy (Chapin et al. 2011). These three ecosystems had the lowest Bowen's ratio values of the 11 ecosystems in the comparison by Chapin et al. (2011). The values at the restored site were below all other ecosystems: arctic tundra, temperate forest, grassland, boreal forest, water stressed crops, semi-arid landscapes, and desert ecosystems (Chapin et al. 2011).

In order to estimate the difference in the sensible heat flux between the restored and degraded meadow, a Bowen's ratio representing a comparatively dryer ecosystem was used to calculate the approximate  $Q_H$ . As the mean Bowen's ratio of 1.6 is found in arid grasslands (Raja et al. 2013) and 1-1.6 is found at water stressed crops (Chapin et al. 2011), the value of '1' was selected to approximate the dry conditions found at the degraded site. When the higher Bowen's ratio was substituted into the energy budget equation using the average  $Q_N$  and  $Q_G$  values found at the restored site, the change in the partitioning between  $Q_H$  and  $Q_E$  resulted in an increase in  $Q_H$  from 1.39 (restored site) to 7.68

MJ m<sup>-2</sup> d<sup>-1</sup>. Consequently, the dryer conditions estimated constituted an increase in 6.29 MJ m<sup>-2</sup> d<sup>-1</sup> of energy that would go into heating the air at the degraded site.

The biomass both above and below the ground and the organic content in the soil was significantly higher at the restored meadow (over about 2 times the aboveground biomass, 5 times the root biomass and 2 times the organic content in the soil) in comparison to the degraded site. Therefore restoration of the high water table and available moisture has an important impact on increasing ecosystem biomass, biodiversity and atmospheric carbon uptake as well as their cooling and humidifying impact on the overlying atmosphere.

## 7. Conclusions

This study looked at ecosystem characteristics and functioning at a restored montane meadow in the Sierra Nevada. Vegetation and soil characteristics were compared to a nearby-degraded meadow to determine the difference in species cover and composition, litter, above and below ground biomass, and soil makeup. To examine ecosystem functioning, the study also provided measurements of terrestrial ecosystem exchanges of CO<sub>2</sub>, water vapor, and heat including the component parts of the surface radiation budget, the surface energy balance, and the carbon budget at the restored ecosystem study site. Microclimate variables such as photosynthetically active radiation, soil water content, soil temperature, air temperature, specific humidity, and mean wind speed were also assessed. From the interdisciplinary analysis of the site, the following conclusions can be made.

The restored meadow had greater live vegetation cover, litter, species richness, and biomass both above and below the ground in comparison to the degraded meadow. There were also fewer invasive species and xeric plants such as shrubs and the soils contained more moisture and organic material.

The surface radiation budget components (shortwave and longwave both incoming and outgoing) did not change in magnitude over the course of the study period. The larger Q<sub>E</sub> term (13.0 MJ m<sup>-2</sup> d<sup>-1</sup>) in comparison to Q<sub>H</sub> (1.6 MJ m<sup>-2</sup> d<sup>-1</sup>)

shows that the available energy ( $Q_N$ ) is predominantly utilized by evapotranspiration, with a very low Bowen ratio ( $Q_H/Q_E$ ) of 0.127 by comparison to other ecosystems (Table 7). This shows that most of the available energy is going into water phase change at the beginning of the study. Over the study period the average daily total of ET declines from 7.19 to 4.8 mm d<sup>-1</sup>,  $Q_E$  from 17.6 to 11.7 MJ m<sup>-2</sup> d<sup>-1</sup> and  $Q_H$  increases from -0.7 to 1.8 MJ m<sup>-2</sup> d<sup>-1</sup>. This captures a shift in the energy budget as less energy goes into phase change and more energy goes into heating the air.

The negative Bowen ratio in Week 1 and late afternoon negative  $Q_H$  suggests an Oasis effect, whereby relatively warm dry air imported from surrounding terrain enhances ET ( $Q_E$ ) to the point where it can be larger than the energy that  $Q_N$  provides.

The large daily GPP and Re values (-30 and +27 gC m<sup>-2</sup> d<sup>-1</sup> respectively) produce a sink of 2.3 gC m<sup>-2</sup> d<sup>-1</sup> of CO<sub>2</sub> over the study period. A large reduction in soil moisture content over the study period correlated with a shift in NEE from a sink to a source of atmospheric CO<sub>2</sub>. The largest sink occurred in the second week of study, when the strongest environmental difference was relatively low temperature, suggesting the increase in sink was due to a lowering of ecosystem Re. As the degraded meadow is experiencing drought-like conditions due to the significantly lower quantity of available water, and previous studies suggest that

grassland ecosystems shift between carbon sources in drought years and carbon sinks in other years (Zhang et al. 2011) it is likely that the degraded meadow's NEE values would be more positive than those found at the restored site.

Both the overall magnitudes of carbon fluxes and their sensitivity to soil moisture are comparable to observations of grassland CO<sub>2</sub> fluxes elsewhere. This illustrates the important impact that restoring meadow water table levels has on increasing ecosystem biomass, biodiversity and atmospheric carbon uptake as well as their cooling and humidifying impact on the overlying atmosphere.

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