THESIS

CHARACTERISTICS OF HUMMOCKS AND HUMMOCKED WETLANDS IN COLORADO

Submitted by

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ABSTRACT

CHARACTERISTICS OF HUMMOCKS AND HUMMOCKED WETLANDS IN COLORADO

There is considerable uncertainty regarding mechanisms of hummock formation. The first step in assessing hummocks in Colorado was to compare the characteristics associated with hummocked and non-hummocked sites. To do this, site characteristics of hummocked and non-hummocked riparian areas and wetlands across Colorado were sampled. Two site characteristics were positively related, and three site characteristics were negatively related to hummock occurrence. Three groups of hummocked wetlands with distinct morphological, vegetative and climatic characteristics were identified.

A finer-scale approach was then used to examine mechanisms of hummock formation. Four hummocked sites in north-central Colorado were selected for detailed research. Soil temperature regimes and presence of water in interspaces were evaluated to determine whether or not conditions described in the most widely accepted theories of hummock formation occurred. Hummock/interspace pairs were instrumented with soil temperature sensors and water level indicators. Results indicate that there were sufficient air freeze-thaw cycles to support hummock formation by needle ice. Conditions supporting differential frost heave through ice lensing were also documented. Numerous temperature differentials were detected between the hummock top, hummock base and

interspace creating temperature gradients that could lead to hummock formation by differential frost heave.

The final step was to evaluate soil and vegetation characteristics of hummocks and interspaces with respect to hummock formation theories based on differential frost heave and plant biomass accumulation. Soil cores were collected from hummocks and interspaces to evaluate soil horizon orientation and thickness of the surface organic horizon. Bulk density, vegetation cover and herbaceous biomass production were also determined. Bent soil horizons indicative of differential frost heave were observed in four hummock/interspace pairs. The organic horizon was thicker and bulk density was lower in the hummocks compared to interspaces but the amount of organic matter in the two positions was similar. Accumulation of plant biomass may lead to increased hummock height.

The finer-scale study revealed evidence supporting multiple mechanisms of hummock formation and development. These mechanisms may form different hummock types which is consistent with the findings of the larger-scale study.

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Preface

Hummocks occur in some riparian areas and wetlands in Colorado. Management decisions in these invaluable ecosystems are often based on assumptions about the presence of hummocks. Therefore, more information about the site characteristics related to hummock occurrence and mechanisms of hummock formation is needed. There are a wide variety of theories to describe hummock formation. The majority of research on hummocks has been conducted in arctic and alpine areas on several continents and research in the Rocky Mountains of the contiguous United States is limited. The research described in this thesis was conducted to identify characteristics of hummocks and hummocked wetlands in Colorado. Specifically, the objectives of this study were to:

1) Identify and describe the edaphic, climatic, topographic and vegetative characteristics of riparian areas and wetlands in Colorado that do and do not support hummocks and to classify hummocks into different types (Chapter 1).

2) Determine if temperature and moisture conditions described in several theories of hummock formation occur in Colorado wetlands that support hummocks of different heights (Chapter 2).

3) Evaluate theories of hummock formation related to differential frost heave and organic matter accumulation by comparing soil and vegetation characteristics of hummocks and interspaces (Chapter 3).

The chapters are formatted for submission to peer-review journals and contain some repetition in introduction, methods and discussions. Each chapter addresses the respective study objective described above.

Chapter 1: Characteristics of Hummocked and Non-Hummocked Sites in Colorado Riparian Areas and Wetlands

ABSTRACT

There is considerable uncertainty regarding the mechanisms of hummock formation. Hummocks have been studied on five continents but there has been limited research in the Rocky Mountains of the contiguous United States. The first step in assessing hummocks in Colorado was to determine which site characteristics were associated with hummocked sites. The first objective of this study was to identify and describe the edaphic, climatic, topographic and vegetation characteristics of riparian areas and wetlands in Colorado that do and do not support hummocks. The second objective was to group hummocked sites according to hummock characteristics. Twenty-five natural resource professionals throughout Colorado identified ten sites each that were a mix of hummocked and non-hummocked in proportion to their local abundance. From these sites, 40 hummocked and 40 non-hummocked sites were randomly selected for sampling. Canopy cover of plant functional groups was determined using Daubenmire cover classes. Soil samples were collected and numerous site characteristics were recorded. Hummock size, shape and density were measured at hummocked sites. Forward model selection and multiple logistic regression were used to determine which site factors were related to odds of hummock occurrence. Mean winter precipitation, mean annual temperature and forb cover were negatively related to hummock occurrence while soil silt

content and number of species were positively related to the odds of hummock occurrence. Hummocked sites were grouped using cluster analysis. Three groups of hummocked sites emerged with different hummock morphological characteristics, species compositions and climate characteristics. The characteristics related to hummock occurrence are indicative of conditions present in several mechanisms of hummock formation and the different hummock types may be a product of different or combinations of formation mechanisms.

INTRODUCTION

Hummocks in riparian areas and wetlands are vegetated mounds that are typically less than one meter in height and diameter and create uneven ground. There are many theories about mechanisms of hummock formation. Grab's (2005) review of hummock geomorphology, genesis and environmental significance included identification of several hypotheses for hummock formation. Differential frost heave is the most widely accepted theory (Van Vliet-Lanoë 1991; Grab 2005) but others include cryoexpulsion of clasts (Van Vliet-Lanoë and Seppälä 2002), hydrostatic or cryostatic pressure (Lundqvist 1969; Tarnocai and Zoltai 1978) and the cellular circulation model (Mackay 1980). Other hypotheses not mentioned in the review include formation through biotic processes such as plant litter accumulation (Dawkins 1939), bird nesting (Verbeek and Boasson 1984) and ant activity (Lesica and Kannowski 1998). Another hypothesis described in the management literature but not explored in the scientific literature is hummock formation facilitated by domestic livestock grazing (Girard et al. 1997; Jankovsky-Jones 1999). As is illustrated by the numerous formation theories, there is considerable uncertainty concerning hummock formation mechanisms. However, it is possible that there are different types of hummocks formed by different mechanisms.

Hummocks are found in a variety of settings including at high latitudes, in alpine environments and in riparian areas or wetlands around the world. They have been studied on five continents (Grab 2005) but there has been limited research on hummocks in the Rocky Mountains of the contiguous United States (Billings and Mooney 1959; Benedict 1969; Lesica and Kannowski 1998). Most studies are conducted at a small scale in an attempt to discern hummock formation processes. Considering the variety of environments in which hummocks occur and the numerous formation theories, a better approach may be to study hummocks at a larger scale and attempt to identify characteristics common to sites with and without hummocks. This might provide insight into why hummocks occur in some riparian areas and wetlands and not others. Similarly, it might help identify differences in formation processes between hummock types.

The objectives of this study were to identify and describe the edaphic, climatic, topographic and vegetation characteristics of riparian areas and wetlands in Colorado that do and do not support hummocks and to classify hummocked sites. It was hypothesized that: 1) Hummocked riparian areas and wetlands would occur at higher elevations, have higher cover of caespitose vegetation, higher rock cover, have a higher silt content in the soil and be grazed by domestic livestock; and 2) There will be different groups of hummocked sites based on hummock shape and size.

METHODS

The objectives of this study were addressed in a large-scale field investigation of riparian and wetland sites throughout Colorado. The goal was to locate riparian areas and wetlands in all regions of the state, across a range of elevations, soil types, plant communities, topographic positions and grazing history. In order to locate suitable sites, twenty-five natural resource professionals throughout Colorado identified ten sites each that were a mix of hummocked and non-hummocked in proportion to their local abundance. Office locations for natural resource professionals are included in Figure 1.1. From these sites, 40 hummocked and 40 non-hummocked sites were randomly selected for sampling. Several sites were unsuitable due to size of area or inadequate hummock cover. Therefore, 73 (35 hummocked and 38 non-hummocked) sites were sampled across Colorado (Fig. 1.1).

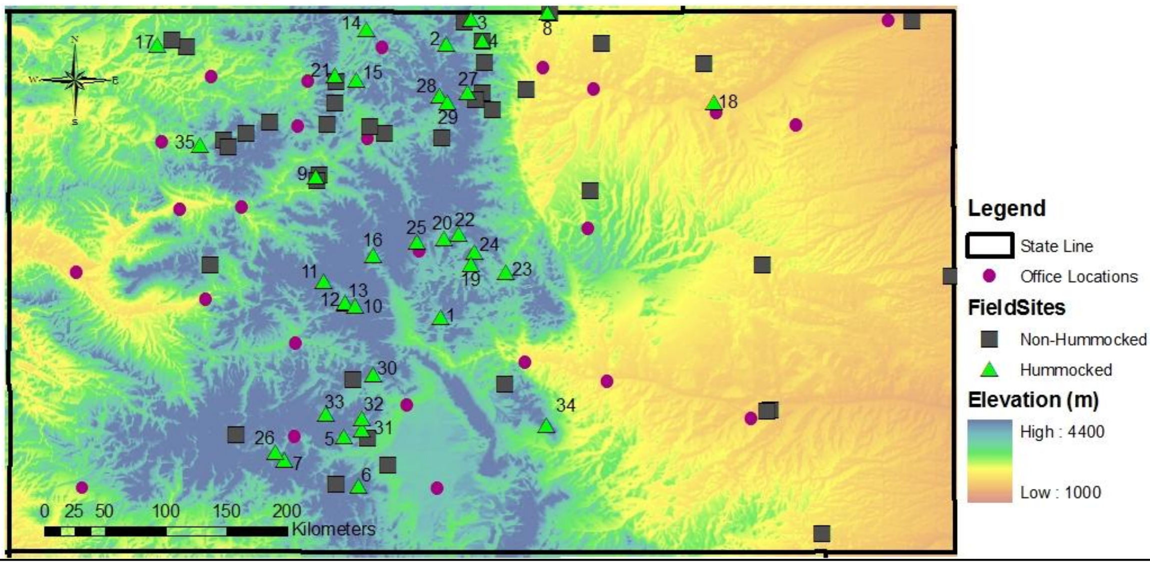

Figure 1.1. Map of Colorado showing field sites and office locations of natural resources professionals who provided potential study sites. The hummocked sites are numbered for reference to Figure 1.2.

At each site, three temporary 25 m transects were established. Canopy cover by functional group (tree, shrub, forb, rhizomatous grass, caespitose grass, rhizomatous grass-like and caespitose grass-like) was estimated using the Daubenmire method (Daubenmire 1959) along each temporary transect. Fifteen soil cores (2 cm diameter x 20 cm depth) from random locations throughout the site were collected and pooled into one composite soil sample at each site. The soils were analyzed for particle size, organic matter, pH, lime and salt content.

At hummocked sites, the size, shape and density of hummocks were measured. Three-, 2- by 5- m plots were systematically established along each transect. Within each plot, hummocks were counted and density was calculated. Two hummocks were randomly selected for size measurements and shape determination. The longest diameter,

diameter perpendicular to the longest diameter, height and hummock side curvature were recorded for each of the selected hummocks. Hummock side curvature was visually determined and described as gentle, moderate, steep or mixed side slope. Other descriptive information was collected at each site including elevation, hydrogeomorphic class (riverine, slope or depressional following Carsey et al. [2003]), estimated valley slope and aspect. Average monthly precipitation and temperature data were obtained from the PRISM Climate Group (2008). Seasonal climate data were calculated by averaging the months December, January and February for winter; March, April and May for spring; June, July and August for summer; and September, October and November for fall.

Relationships between the 31 site characteristic variables and the odds of hummock occurrence were investigated using logistic regression (Table 1.1). Odds of hummock occurrence is defined as a ratio of the probability of hummock presence to the probability of no hummocks. Forward model selection in SAS 9.2 (SAS Institute, Inc. 2008) was used to determine the best model ($\alpha = 0.05$). PC-Ord v.5 (McCune and Mefford 2006) was used to classify hummocked sites. Euclidean distance, hierarchical agglomerative cluster analysis and Ward's linkage method were used to determine clusters. The hummock size dimensions were in the main matrix and the site characteristic variables were in the second matrix. Once groups of hummocked sites were determined, analysis of variance (ANOVA) and Tukey-Kramer's method were used to test which individual variables differed by hummock group.

Table 1.1. Site characteristic variables used in forward model selection for the logistic regression model to determine which variables were related to odds of hummock occurrence.

Site Level	**Canopy Cover**	**Soils**	**Climate**
Elevation	Litter	Soil pH	Mean Annual Precipitation
Hydrogeomorphic Class	Bare Ground	Salts	Mean Winter Precipitation
Number of Species	Water	Lime	Mean Spring Precipitation
Domestic Livestock	Rock	Organic Matter	Mean Summer Precipitation
Grazing within 5 years	Green Moss	Percent Sand	Mean Fall Precipitation
	Tree	Percent Silt	Mean Annual Temperature
	Shrub	Percent Clay	Mean Winter Temperature
	Forb		Mean Spring Temperature
	Rhizomatous Graminoids		Mean Summer Temperature
	Caespitose Graminoids		Mean Fall Temperature

RESULTS

Five site characteristics variables were related to hummock occurrence and were selected for the final logistic model (Table 1.2). Number of species was positively related to hummock occurrence. As number of plant species increased by one, odds of hummock occurrence were over three times greater when the other variables in the model were held constant. In addition, for each 1% increase in soil silt content, odds of hummock occurrence were 12% greater. Forb canopy cover, mean winter precipitation and mean annual temperature were negatively related to odds of hummock occurrence. For each 1% increase in forb canopy cover and 1 cm increase in winter precipitation, hummock occurrence was 16 and 18% less likely, respectively. The odds of hummock occurrence decreased by 50% with each one degree increase in annual temperature. Presence of domestic livestock grazing was not related to odds of hummock occurrence but the sample size of ungrazed sites was low (n=3 hummocked, n=6 non-hummocked).

The cluster analysis produced three groups when pruned at the level corresponding to 75% of the information remaining (Fig. 1.2). Groups one and two were the most similar and group three the most distinct.

Table 1.2. Final site characteristic variables related to odds of hummock occurrence and selected for the logistic regression model. Odds ratio is the probability of hummocks over the probability of no hummocks.

Variable	**Odds Ratio**	**95% Confidence Limits**		**p-value**
Number of Plant Species	3.17	1.43	7.51	0.009
Forb Canopy Cover (%)	0.84	0.75	0.95	0.004
Soil Silt Content (%)	1.12	1.01	1.24	0.026
Mean Winter Precipitation (cm)	0.82	0.72	0.92	0.001
Mean Annual Temperature (°C)	0.50	0.32	0.77	0.002

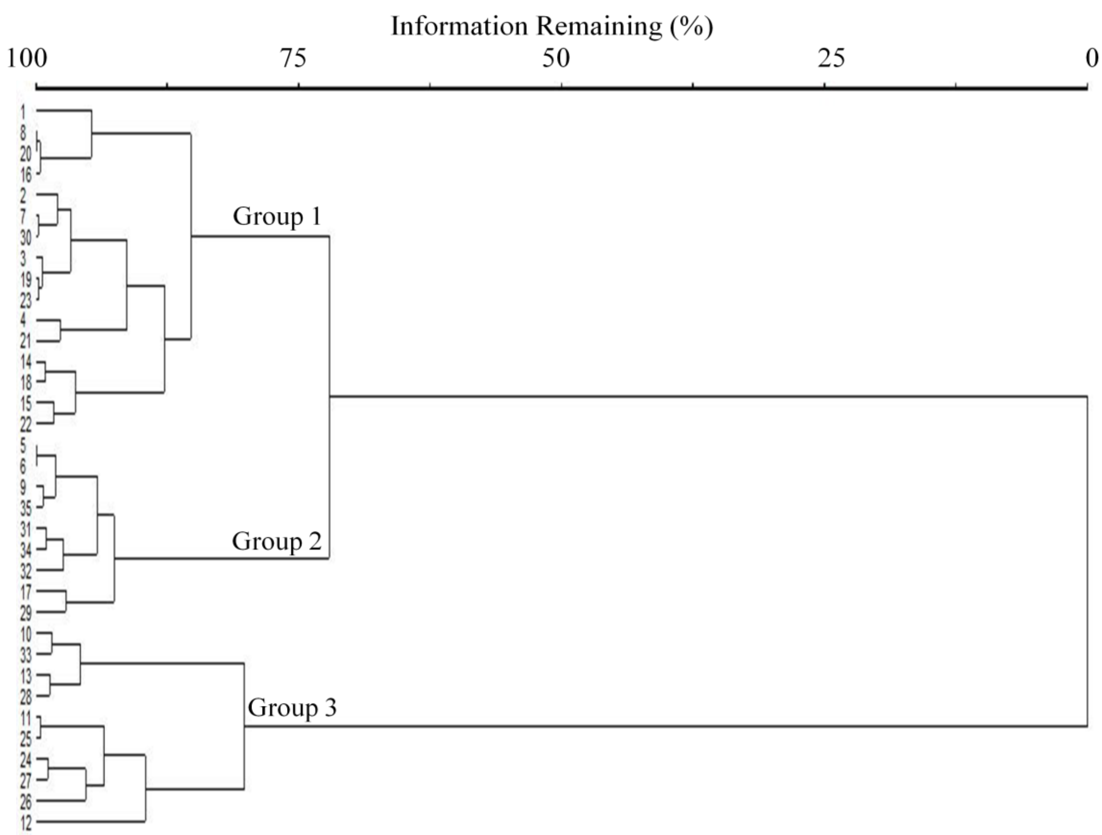

Figure 1.2. Dendrogram depicting grouping of hummocked sites using cluster analysis. Site characteristics and hummock dimensions were used to determine similarity between sites. Euclidean distance, hierarchical agglomerative cluster analysis and Ward's linkage method were used to determine clusters. Site number is shown on the y-axis and groups are identified within the figure.

Group one included the most sites (n = 16) followed by group three (n = 10) and group two (n = 9). Detailed descriptions of characteristics that varied by group are presented in Table 1.3. Group one had medium sized, medium density hummocks that occurred in areas with lower precipitation and higher winter temperatures. Group two was characterized by short, small diameter, high density hummocks with greater rhizomatous graminoid and lower shrub cover in high precipitation areas. Group three was characterized by large, low density hummocks with greater shrub cover in areas with low winter temperatures.

Table 1.3. Means for hummock and site characteristics that differed by hummocked site group. Hummocked site groups were determined using cluster analysis (Fig 1.2) and variables that differed by group were determined using ANOVA. Means in a row with the same letter are not different (Tukey-Kramer, α=0.05).

Variable	**Group 1**	**Group 2**	**Group 3**
Number of Sites	16	9	10
Hummock Height (cm)	21.3a	14.4b	24.4a
Hummock Density (No./m^2)	1.5b	2.1a	0.75c
Longest Diameter (cm)	66.9b	47.9c	112.8a
Shrub Canopy Cover (%)	6.9b	1.2b	25.3a
Rhizomatous Graminoid Canopy Cover (%)	37.4ab	48.8a	28.4b
Mean Annual Precipitation (cm)	48.3b	66.6a	57.6ab
Mean Winter Temperature (°C)	-6.4a	-7.1ab	-8.5b

DISCUSSION

Hummocked versus Non-Hummocked Site Characteristics

A relatively large-scale field study was conducted in Colorado in an attempt to identify characteristics common to hummocked and non-hummocked riparian areas and wetlands. This provides a foundation for consideration of hummock formation mechanisms. Certain site characteristics were positively related to odds of hummock occurrence while others exhibited a negative relationship.

The increase in odds of hummock occurrence with increasing soil silt content observed in this study (Table 1.2) was consistent with the findings of others. Several researchers have argued that fine-grained soils with a high percentage of silt are especially susceptible to frost heave which contributes to hummock development (Zoltai and Tarnocai 1981; Van Vliet-Lanoë 1991; Konrad 1999). Differential frost heave is the most widely accepted theory of hummock formation (Van Vliet- Lanoë 1991; Grab 2005). In addition, hummocks often have higher silt content than interspaces resulting from sorting associated with differential freeze-thaw activity (Van Vliet-Lanoë 1991; Grab 1997). The positive relationship between silt and hummock presence and the role of silt in frost heave processes suggests that differential frost heave may be a mechanism in hummock development at the research sites. Hummocks may not be present at some riparian areas and wetlands because soil textures are not conducive to their development.

Other conditions required for differential frost heave include presence of water and freezing soil temperatures. The combination of these factors is sufficient to create differentials which are responsible for ice lensing and differential heave (Mark 1994; Grab 1997; Scott et al. 2008). This was consistent with the findings that odds of hummock occurrence increased with decreasing mean annual temperatures (Table 1.2) and the negative relationship observed between mean annual temperature and mean annual precipitation. The combination of low temperatures and ample water supply from higher annual precipitation may have created favorable conditions for hummock formation through differential frost heave.

Freeze-thaw dynamics may have been dampened by snow cover as indicated by the decreased odds of hummock occurrence with increasing winter precipitation (Table

1.2). Winter precipitation usually comes in the form of snow because of Colorado's high mean elevation and climate characteristics. Snow has low thermal conductivity so it is a good insulator (Jones et al. 2001). Seppälä (1994) found seasonal frost penetration was inhibited on the snow-covered side of palsas, which are very large mounds similar in form to hummocks. Adequate snow cover may have inhibited hummock formation by limiting frost penetration and differential frost heave.

Accumulation of plant litter and organic matter is another theory of hummock formation (Dawkins 1939). Vegetation may be responsible for hummock development or may be a product of pre-existing climatic and topographical conditions. Tyrtikov (1969) suggested that vegetation modifies soil freezing characteristics and this modification of freezing was an important factor in hummock building. In addition, different plant species are present at different stages of hummock development (Tyrtikov 1969). If there were hummocks in different stages of development, more species may have been present which supports the findings of a positive relationship between number of species and odds of hummock occurrence. The negative relationship with forb cover suggested that this life form was not a factor in hummock development.

The composition of plant species may be a product of the environmental conditions present at a hummocked site rather than a factor that influences hummock formation. Some studies have shown that hummocks are relict features formed thousands of years ago when the climate was much colder (Scotter and Zoltai 1982, Van Vliet-Lanoë et al. 1998). If this is the case, present plant communities almost certainly do not represent those that were present at the time of hummock formation. Plant species have different environmental tolerances for temperature, precipitation, topography, soil type, disturbance and many other factors (Knight 1994). The positive relationship found between number of species and odds of hummock occurrence may be related to the heterogeneous microtopography created by the hummocks at those sites. Vivian-Smith (1997) found greater diversity in hummocked areas. Microtopography influences changes in soil nitrogen transformation and retention (Reddy and Patrick 1984, Ford et al. 2007), soil texture distribution (Grab 1997), bulk density (Benscoter et al. 2005, Quinton and Marsh 1998), and moisture and temperature within hummocks (Mark 1994, Grab 1997, Scott et al. 2008). Temperature and amount of radiation differs with position on the hummock as well as in the hollow (Shen et al. 2006). All of these factors likely influence plant species diversity. Several plant species are found only where hummocks create favorable habitat due to their heterogeneous microtopography. *Ptilagrostis porteri* (Rydb.) W.A. Weber is a threatened species that grows on hummock shoulders and sides in Colorado (Mayo 2005). Other threatened or rare plant species that grow on hummock shoulders and sides in Rocky Mountain States are *Antennaria arcuata* Cronquist and *Primula alcalina* Cholewa & Douglass M. Hend. (Bayer 1992; Muir & Moseley 1994).

One theory of hummock formation is cryoexpulsion of clasts which involves the upward movement of stones caused by frost push and pull action resulting in stone-cored hummocks (Van Vliet-Lanoë and Seppälä 2002). If this process was a factor in hummock formation at the sites used in this study, an increase in the odds of hummock occurrence with increasing rock cover would have been expected because of the rock migration to the surface. However, rock cover was not a significant factor selected for inclusion in the final model and rocks were not encountered in the hummocks while collecting soil samples for this and other components of the study. Therefore, cryoexpulsion of clasts was not likely a factor in hummock formation at these sites. This confirms the conclusion reached by Grab (2005) that "cryoexpulsion of clasts is an exception rather than the rule for earth hummock formation" (p. 185).

There was no relationship between odds of hummock occurrence and presence of domestic livestock grazing at the sites. This finding does not support the theory that livestock grazing leads to hummock formation (Girard et al. 1997; Jankovsky-Jones 1999). However, the finding of no relationship could have been a product of small sample sizes for ungrazed hummocked and non-hummocked sites. The majority of the sites identified by the natural resource professionals were grazed by domestic livestock and there was no control over sample size of ungrazed sites. Domestic livestock grazing could have been a factor in hummock formation but was not captured in this study. In addition, grazing by wild ungulates was not quantified and could have contributed to hummock formation. The results of this study support the idea that there are many possible mechanisms of hummock formation in Colorado.

Classification of Hummocked Sites

Because there are many possible mechanisms of hummock formation likely in Colorado, different hummock types are possible. Considerable morphological variation in hummocks was observed across Colorado. The analysis of hummocked site characteristics produced three groups of hummocked sites with different vegetation and climatic characteristics (Fig. 1.2; Table 1.3). Photographs of representative hummocks in each group are shown in Figure 1.3.

The dilemma of determining whether plants are products of hummock/hollow microtopography or factors contributing to hummock formation also exists in this discussion about hummock types. Two of the groups were characterized by specific plant functional groups. If plants were a factor in hummock formation, different plant functional groups may be related to different types of hummocks.

Figure 1.3. Photographs of example hummocks in each group produced by the cluster analysis. **A** Group One; **B** Group Two; **C** Group Three

The vegetation of group two hummocks was dominated by rhizomatous graminoids including grasses, sedges and rushes. Field observations suggest these hummocks were smaller and contained less mineral soil than other hummocks encountered. This group appears similar to tussocks, which are defined as "a compact tuft especially of grass or sedge; *also* an area of raised solid ground in a marsh or bog that is bound together by roots of low vegetation (Merriam-Webster's Collegiate Dictionary 2005)." Dawkins (1939) found that the sedge, *Schoenus nigricans* L., formed tussocks in a peat marsh. The tussock height grew as the water eroded the peat from around the plants. Other species may form tussocks in meadows (Costello 1936; Peach and Zedler 2006), marshes (Crain and Bertness 2005) and uplands (Gibson 1988). Group two was also characterized by high mean annual precipitation which resulted in high water tables and saturated soil conditions. Studies indicate that adaptations of some graminoids to anaerobic conditions include upward tillering and litter accumulation that ultimately lead to tussock formation (Costello 1936; Dawkins 1939; Yabe 1985; Nishikawa 1990).

Accumulation of plant litter and organic matter by rhizomatous graminoids may contribute to hummock formation at sites in the second group.

Group three was dominated by shrubs rather than graminoids. This group was termed "shrummocks." The hummocks at these sites may be associated with shrubs either because shrubs played a role in hummock formation or the hummocked topography created favorable conditions for the development of shrub-dominated plant communities. There may be a positive feedback between the two factors. Tyrtikov (1969) suggested that shrubs play a role in hummock formation in peat bogs following fire by modifying the movement of snow and influencing subsequent freeze-thaw processes that increase hummock size. Hummock size increases until conditions become unsuitable for shrubs. Carsey et al. (2003) described a number of shrub communities in Colorado where shrub abundance increased following hummock development. In one plant community description Carsey et al. (2003) stated that, "As peatland hummocks develop or become more pronounced, they may become more heavily dominated by *Salix* (willow) species" (p. 279). This group also had the lowest mean winter temperature which could be related to freeze-thaw dynamics or favorable environmental conditions for shrub growth.

There were no obvious links between characteristics of group one sites and theories of hummock formation considered here. Group one included the most sites and the hummocks were medium-sized when compared to groups two and three. This group was not associated with a particular plant functional group. Group one sites occurred in areas with lower average annual precipitation and higher winter temperatures. The overall sample size of ungrazed hummocked sites was low but all of the sites in this group had domestic livestock grazing. It is possible that groups two and three were at the ends of a spectrum and group one captured the sites in between. It is also possible that factors indicative of alternative formation processes, such as domestic livestock grazing or other land management practices were not captured with this study.

IMPLICATIONS

This study was designed to identify the key characteristics correlated with hummock occurrence in Colorado riparian areas and wetlands in an effort to provide information for future work on mechanisms of hummock formation. Several soil, climatic and vegetation characteristics associated with hummocked areas were identified. This is a valuable starting point for further investigations into hummock distribution and theories of hummock formation. There was consistency among several characteristics in this study and theories of hummock formation including differential frost heave and plant biomass accumulation. However, conditions expected to occur in response to cryoexpulsion of clasts were not observed and domestic livestock grazing was not related to odds of hummock occurrence. Overall, the observations of this study support Grab's (2005) assertion that hummocks may be polygenetic assuming the different groups of hummocked sites identified are the product of different formation processes. Further research is required concerning hummock location and extent, formation mechanisms and response due to land management.

Hummocky microtopography may be important for increasing biodiversity. This can have important implications for restoration. Heterogeneous microtopography is often lacking in wetland restoration projects (Barry et al. 1996). Recent studies have shown the value of including hummock- hollow microtopography when restoring wetlands (Bruland and Richardson 2005, Vivian-Smith 1997).

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Chapter 2: Evaluation of Freeze-Thaw Dynamics in Hummocked Wetlands

ABSTRACT

Land management changes are sometimes made in an effort to reduce hummock formation. However, there is uncertainty about the mechanisms of hummock formation and if they form under present-day conditions. The approach of this study was to determine whether or not conditions described in the most widely accepted hummock formation theories are present in Colorado wetlands supporting hummocks of different heights. Specifically, the objectives were to 1) determine if there were adequate air freeze-thaw cycles to result in needle ice formation; 2) evaluate whether or not conditions conducive to ice lens formation in the interspaces between unfrozen hummocks were present; and 3) determine whether or not soil temperature differentials between the hummock tops, hummock bases and interspaces were sufficient to drive water and sediment movement into the hummock. These objectives were addressed at four hummocked sites in north-central Colorado. At each site, soil temperature sensors were installed in 4 hummock tops, 4 hummock bases and 4 interspaces, and water sensors were installed in 4 interspaces. One air temperature sensor was installed at the sites. Hourly data were recorded from October 2009 through May 2010. Minimum temperatures and daily temperature ranges were determined and differences between sensor locations were analyzed with t-tests. Results indicate that there were sufficient air freeze-thaw cycles to

support hummock development by needle ice formation. Differential freeze-thaw conditions were also found that support the formation of ice lenses in the interspaces adjacent to unfrozen hummocks. As ice expands, it can contribute to hummock formation or maintenance by pushing the soil up in the unfrozen hummock. There were numerous temperature differentials between the hummock top, base and interspace with the top being the coldest through fall and winter creating a temperature gradient. The extent and magnitude of these differentials differed by site and were influenced by hummock height, air temperature and snow depth. Soil disturbance and vegetation removal by overgrazing may promote conditions suitable for mechanisms of hummock formation. Fall and early winter are times when conditions supporting differential freeze-thaw are most likely.

INTRODUCTION

Hummocks in riparian areas and wetlands are relatively small, vegetated mounds that are typically less than one meter in height and diameter and create uneven ground. Hummocks are often used as an indicator of degraded wetland condition and land management changes, such as reduction of livestock grazing, are made based on this assumption in order to reduce hummock formation. However, there is considerable uncertainty about the mechanisms of hummock formation and if conditions suitable for formation are present today (Grab 2005). Many studies conclude that hummocks formed long ago under colder conditions (Scotter and Zoltai 1982; Ellis 1983). Using tephro-stratigraphy, Van Vliet- Lanoë et al. (1998) found that there were several periods of time with active hummock formation from about 4500 to 250 years BP. They also mentioned that, even when truncated by agricultural activity or animal tracks, hummocks regrew. If hummocks are capable of forming at the present time, land managers may be able to influence formation.

Ideally, a researcher would study actual hummock genesis from near level ground by experimentally manipulating conditions hypothesized to produce hummocks and then document their formation. Fahey's (1973) study of frost boil heave and subsidence, is one of very few field attempts to document hummock genesis from initially flat ground. Corte (1967) conducted a freezer experiment where he created soil mounds by imposing numerous freeze-thaws cycles resulting in needle ice formation. Given the logistical difficulties of creating or observing actual hummock genesis in the field, an alternative approach was identified to study hummock formation/maintenance processes in sites with preexisting microtopography. The approach was to determine whether or not conditions described in the most widely accepted hummock formation theories are present in Colorado wetlands. If conditions described in these theories are detected in hummocks of different heights (spanning the range of hummock heights in Colorado), it is reasonable to conclude that these conditions are at least capable of maintaining hummock-hollow topography; are probably responsible for hummock development; and may be responsible for hummock genesis.

One theory for hummock genesis, as observed by Corte (1967) and Fahey (1973), is the creation of small mounds by needle ice formation induced by air freeze-thaw cycles. Corte (1967) found that after 28-37 air freeze-thaw cycles, small mounds formed. The most widely accepted hummock formation theory is differential freeze-thaw which is induced by differences in ground temperature or moisture conditions (Grab 2005). The specific conditions and mechanisms identified as being responsible for these differentials vary by researcher. Van Vliet-Lanoë (1991) suggested that ice lensing in the interspace compresses unfrozen sediment in the hummock and injects material either upwards or laterally. Many other studies (Van Vliet-Lanoë 1988; Mark 1994; Grab 1997; Scott et al. 2008) suggest that temperature and moisture differentials between the hummock and interspace are sufficient for water movement to areas of lower pressure creating pockets of frozen ground and localized frost heave resulting in the maintenance of hummocked microtopography.

The objectives of this study were to determine if conditions described in these three mechanisms of hummock formation occur in Colorado wetlands supporting hummocks of different heights. Specifically I determined if there were adequate air freeze-thaw cycles to result in needle ice formation. I predicted that there would be at least 37 air freeze-thaw cycles for potential needle ice formation. I also evaluated whether or not ice lensing occurred in the interspace between unfrozen hummocks. I predicted that there would be times when there was water in the interspace and freezing air temperatures resulting in ice lensing in interspaces while the hummock base remained unfrozen. Finally, I determined whether or not there were soil temperature differentials between the hummock tops, hummock bases and interspaces sufficient to drive water and sediment movement into the hummock. I predicted that the interspaces would be warmer than the hummock tops and bases and be frozen for the least amount of time. I also predicted that hummock tops would freeze first and be the coldest and most variable through fall and winter. These differentials were expected to produce a temperature gradient from the interspace to hummock top providing suitable conditions for water and sediment movement and the gradient was expected to be more pronounced at sites with taller hummocks.

METHODS

Study Locations

Four sites in north-central Colorado were selected for this study (Fig. 2.1). Mean hummock heights for each site were measured by establishing three temporary 25 m transects. Along each transect, three 2- by 5- m plots were systematically established. In each plot, two hummocks were randomly selected and their heights were recorded. Elevation, mean annual temperature and precipitation (PRISM Climate Group 2008), and hummock heights are shown in Table 2.1. All sites are slope wetlands on gentle to moderate slopes fed by groundwater that creates a seasonally high water table (Carsey et al. 2003).

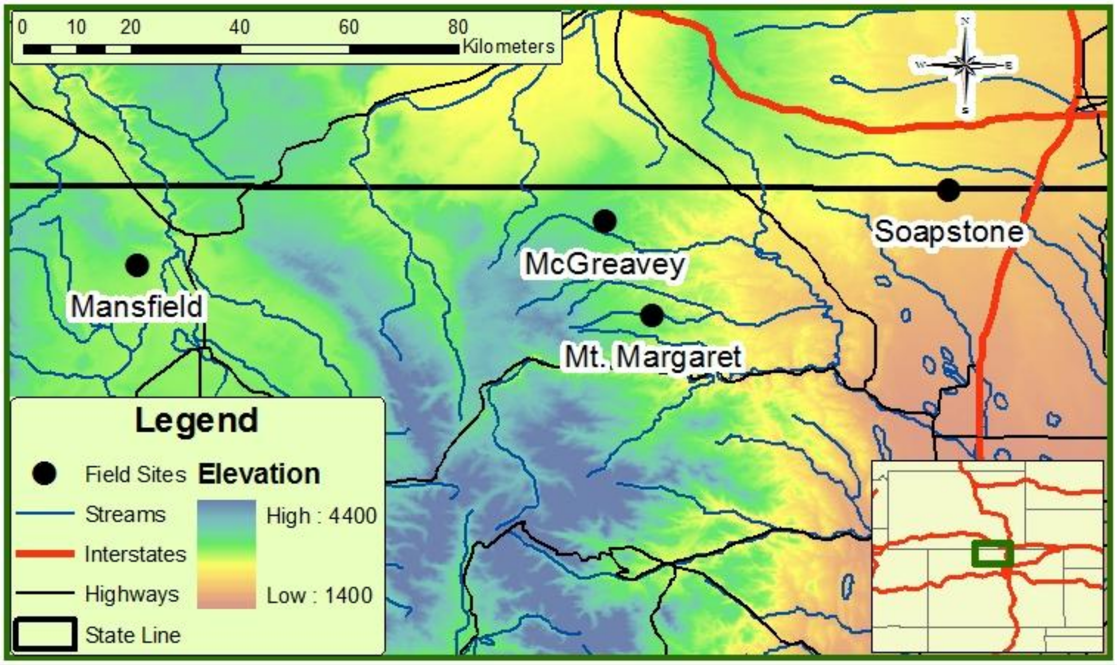

Figure 2.1. Map of field sites located in North-central Colorado. NAD 1983 UTM 13 North

Table 2.1. Site characteristics of the field sites. Temperature and precipitation were acquired from PRISM Climate Group (2008).

Site Name	Elevation (m)	Mean Annual Temperature (°C)	Mean Annual Precipitation (cm)	Hummock Height (cm)
Mansfield	2470	2.9	39.2	29
McGreavey	2610	3.5	48.0	18
Mt. Margaret	2460	4.7	42.6	16
Soapstone	1980	6.9	41.8	24

Temperature

At each site, four monitoring locations were randomly selected. Each monitoring location was equipped with a HOBO® U12 4-channel external data logger with four sensors (Onset Computer Corporation, Bourne, MA, USA). Two soil temperature sensors were inserted horizontally 5 cm into the soil; one at two-thirds of the hummock height and the other at the hummock base. The other soil temperature sensor was inserted to a depth of 5 cm in the adjacent interspace. A water sensor constructed of a DC voltage input cable encased in tubing was placed in the interspace at a height of 2 cm to determine when there was standing water in the interspace. An air temperature sensor with an internal logger programmed to record at the same logging interval as the soil and water sensors was enclosed in a radiation shield and placed at the site at a height of 1.5 m. Hourly data were recorded from 4 October 2009 to 31 May 2010.

Data Analysis

A diurnal air freeze-thaw cycle was defined as a drop in air temperature from above 0°C to below -2.2°C followed by a rise above 0°C in a 24 hour period (Russell 1943, Fahey 1973). These air freeze-thaw cycles were totaled by month at each site.

Conditions suitable for ice lensing were analyzed by documenting coincidence of water in the interspace (less than 1.5 volts) and freezing air temperatures or ice in the interspace (greater than 2 volts) in addition to the base of the hummock having a temperature greater than 0°C.

Daily maximum and minimum temperatures were obtained for each temperature sensor and the daily temperature ranges were calculated from those values. These data were averaged by week. Differences between each pair of the three soil temperature monitoring locations (hummock top, base and interspace) were calculated based on the weekly averages. Freeze days (a 24 hour period where the minimum temperature was below 0°C) were averaged for each sensor position to determine time frozen.

Statistical Analysis Software 9.2 (SAS Institute, Inc. 2008) was used for data analyses. T-tests were conducted to determine if the weekly temperature differences between sensor locations were significantly different from zero with an alpha level of 0.05. Analysis of variance (ANOVA) was used to determine if the number of freeze days for the sensor locations varied by site. Tukey-Kramer's method was used to compare treatment means.

RESULTS

There were 68, 80, 109 and 101 air freeze-thaw cycles from October to the end of May at Mansfield, McGreavey, Mt. Margaret and Soapstone, respectively (Table 2.2).

Table 2.2. Number of diurnal air freeze-thaw cycles where the air temperature went from above 0°C to below -2.2°C and returned to 0°C within 24 hours.

Site Name	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**March**	**Apr**	**May**	**Total**
Mansfield	10	13	1	0	0	8	19	17	**68**
McGreavey	8	21	4	9	1	10	15	12	**80**
Mt Margaret	13	25	4	18	3	15	20	11	**109**
Soapstone	6	15	7	24	14	16	11	8	**101**

There was coincidence of water or ice in the interspace, air freeze-thaw cycles and unfrozen hummock base at all of the sites. Mansfield and Mt. Margaret had the greatest number of freeze-thaw cycles with the conditions described above and McGreavey and Soapstone had the least (Table 2.3). Temperature and water sensor readings for Mansfield from 31 October 2009 through 11 November 2009 are presented in Figure 2.2. This provides an example of water in the interspace freezing diurnally while the internal hummock temperature was above 0°C.

Table 2.3. Number of air freeze-thaw cycles where there was water or ice in the interspace and the internal temperature at the base of the hummock was greater than 0°C. mean (SD), n=4 at each site

Site Name	Before Hummock Base Freeze (Fall & Winter)	After Hummock Base Thaw (Spring)
Mansfield	8 (9.8)	14 (13.6)
McGreavey	0	2 (2.8)
Mt Margaret	8.8 (10.8)	10.5 (11)
Soapstone	4 (8)	0.25 (0.5)

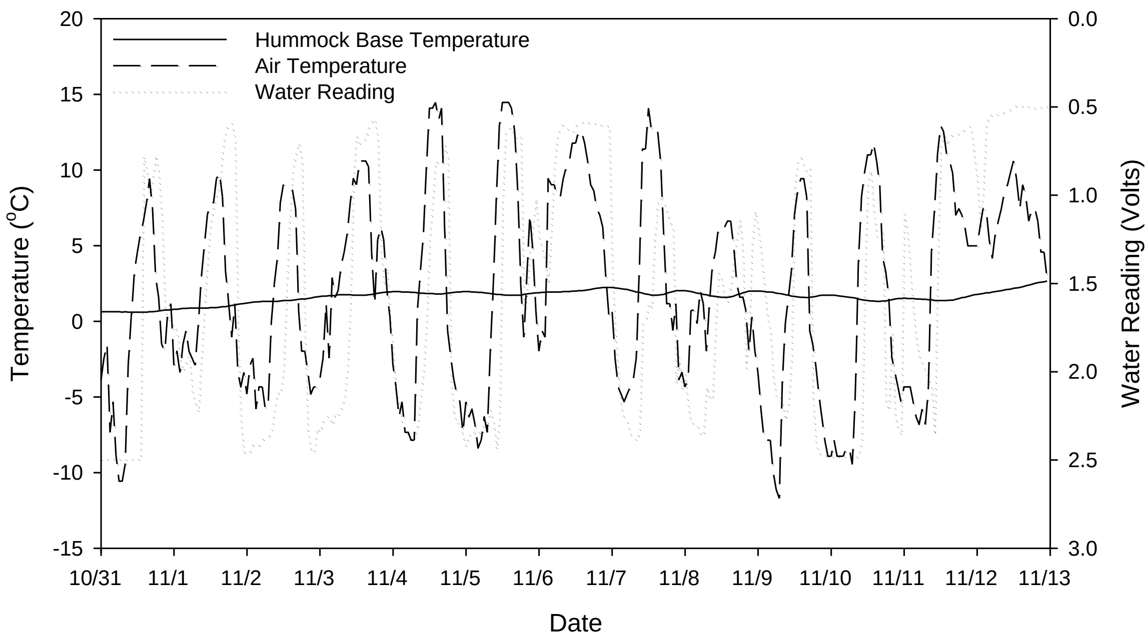

Figure 2.2. An example of diurnal air freeze-thaw cycles between 31 October 2009 and 12 November 2009 at the Mansfield site resulting in freezing water in the interspace while the internal hummock base temperature remained above 0°C. Water readings closer to 0.5 V signify presence of water while readings closer to 2.5 V signify presence of ice.

At all sites except McGreavey, the three sensor positions had the same number of freeze days (Table 2.4). At McGreavey, there were 20% fewer freeze days in the interspace than either hummock position. Although the number of freeze days did not vary by sensor position for three sites, the timing of first freeze is important to establish a temperature gradient. On average for all four sites, the hummock top froze five days earlier than either the base or interspace.

Table 2.4. The mean number of days when the minimum temperature for the sensor location was below 0°C (Freeze Days). Means for a site with the same letter are not different, Tukey-Kramer, $\alpha=0.05$.

	Soil Temperature Sensor Position			Air
Site Name	Top	Base	Interspace	Sensor
Mansfield	163a	159a	152a	234
McGreavey	153a	153a	34b	227
Mt Margaret	150a	139a	132a	220
Soapstone	130a	121a	119a	192

There were temperature differentials between soil temperature sensors at all sites. For the Mansfield site (Fig. 2.3), the hummock top was significantly colder than the base for the first 16 weeks, after which there was no difference. The top was significantly colder than the interspace for 12 weeks and the base was significantly colder than the interspace for 10 weeks. The top was more variable than the base (13 weeks) and interspace (10 weeks). There were no significant differences in daily minimum temperature and only one significant difference in the daily temperature range after the week ending January 23rd.

At the McGreavey site, there were only six weeks where the top was significantly colder than the base (Fig. 2.4). The greatest number of differences occurred between the hummock sensors and the interspace. The hummock top and base were colder than the interspace for 24 and 23 weeks, respectively. The differences between the top and base occurred before week 13 beginning 20 December 2009 while the interspace differences mostly occurred before the middle of March. There were few differences in the mean daily temperature range but those that did occur were mostly in December or early January.

At Mt. Margaret, the top was significantly colder than the base for nine weeks (Fig. 2.5). The top was colder than the interspace for 18 weeks while the base was colder than the interspace for 8 weeks. All of the differences occurred before week 23 beginning 7 March 2010. There were more differences in the mean daily temperature range between the top and interspace (13 weeks) than between the top and base (3 weeks), or between that base and interspace (5 weeks).

At Soapstone, the top was significantly colder than the base for 23 weeks and warmer for two weeks in the middle of April while the daily range was greater for the top than the base for 22 weeks (Fig. 2.6). The top was colder than the interspace for 17 weeks and had a greater daily range for 11 weeks. Contrary to the other sites, the base was warmer than the interspace for eight weeks and colder for one week. The base also had a smaller daily temperature range than the interspace for 11 weeks.

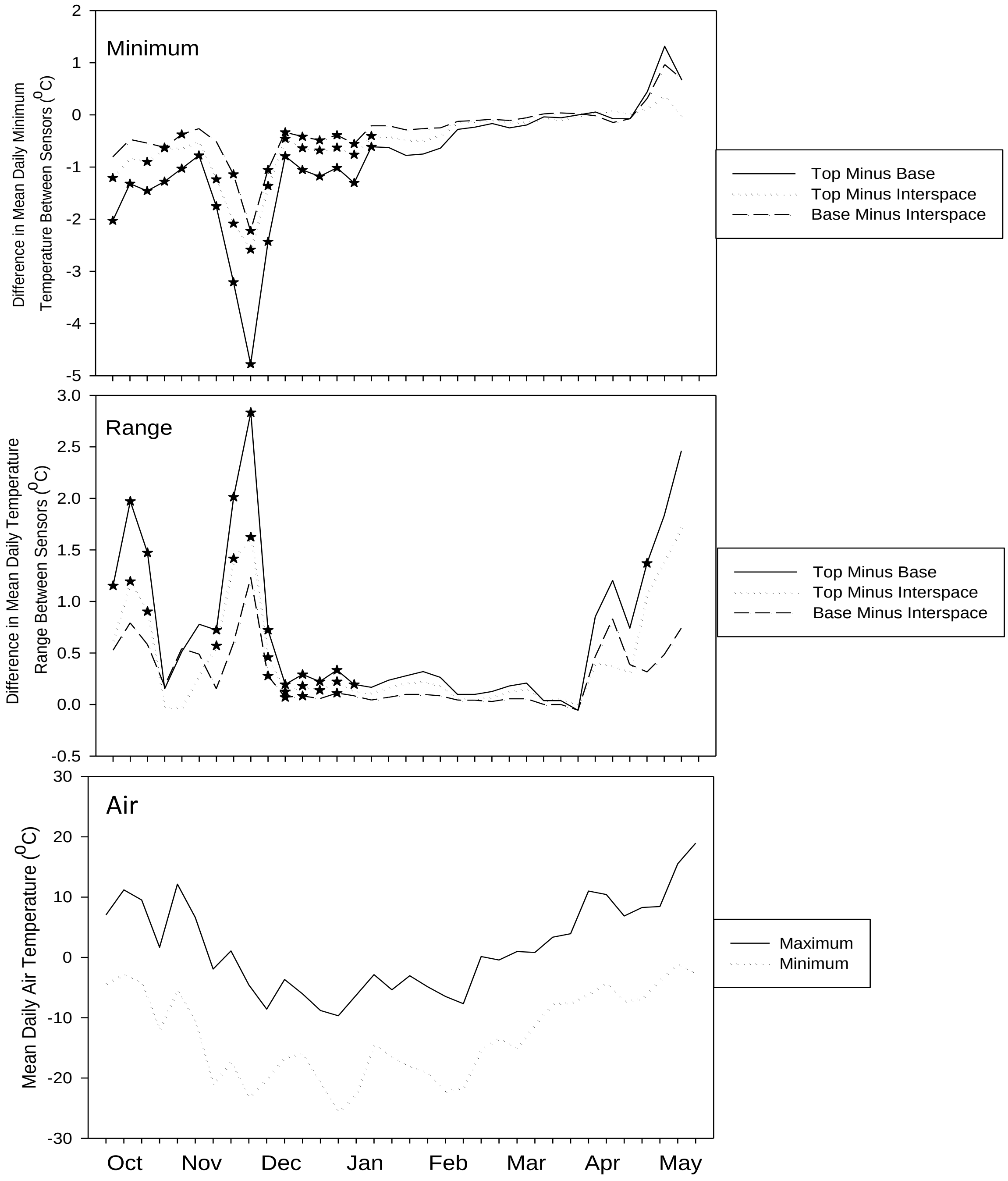

Figure 2.3. **Mansfield Site** temperature differences for soil sensor locations and mean air temperatures. Differences were obtained by subtracting the weekly mean for the daily minimum temperature and daily temperature range values of one sensor location from another. Weeks with significant differences (paired t-tests, α=0.05, n=4) are indicated with a star. The weekly means for the maximum and minimum air temperature are shown in the bottom panel.

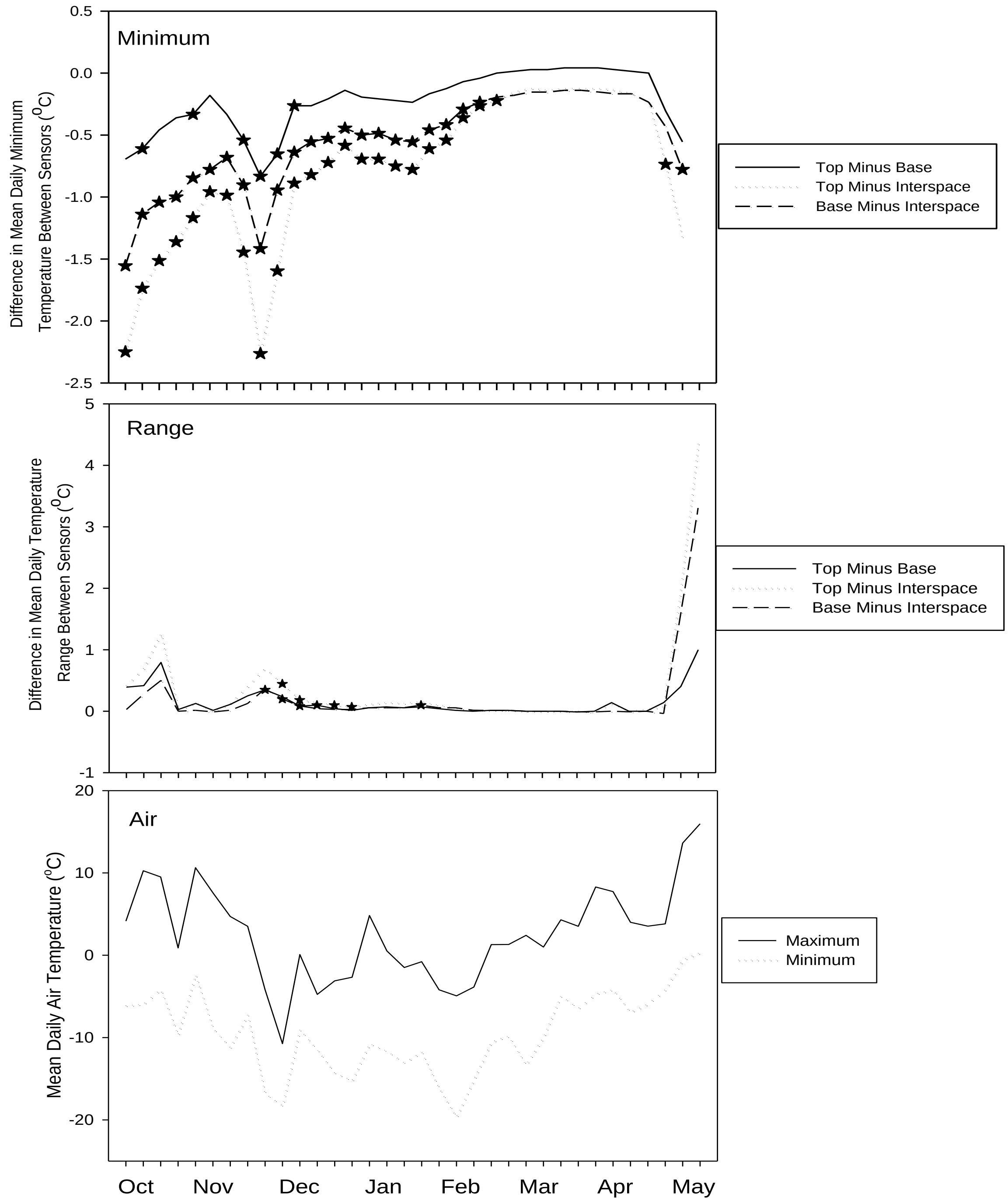

Figure 2.4. **McGreavey Site** temperature differences for soil sensor locations and mean air temperatures. Differences were obtained by subtracting the weekly mean for the daily minimum temperature and daily temperature range values of one sensor location from another. Weeks with significant differences (paired t-tests, α=0.05, n=4) are indicated with a star. The weekly means for the maximum and minimum air temperature are shown in the bottom panel.

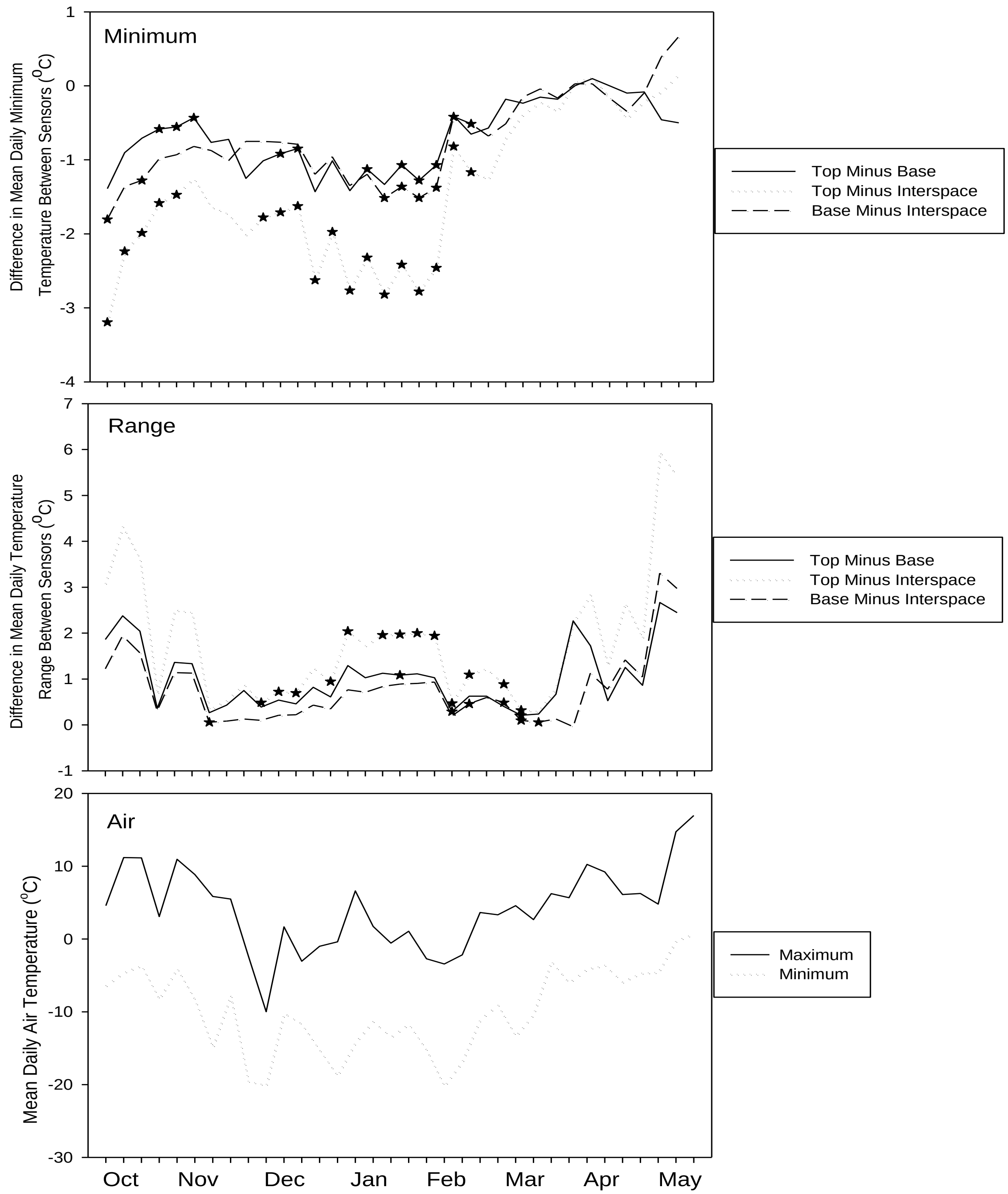

Figure 2.5. **Mt. Margaret Site** temperature differences for soil sensor locations and mean air temperatures. Differences were obtained by subtracting the weekly mean for the daily minimum temperature and daily temperature range values of one sensor location from another. Weeks with significant differences (paired t-tests, α=0.05, n=4) are indicated with a star. The weekly means for the maximum and minimum air temperature are shown in the bottom panel.

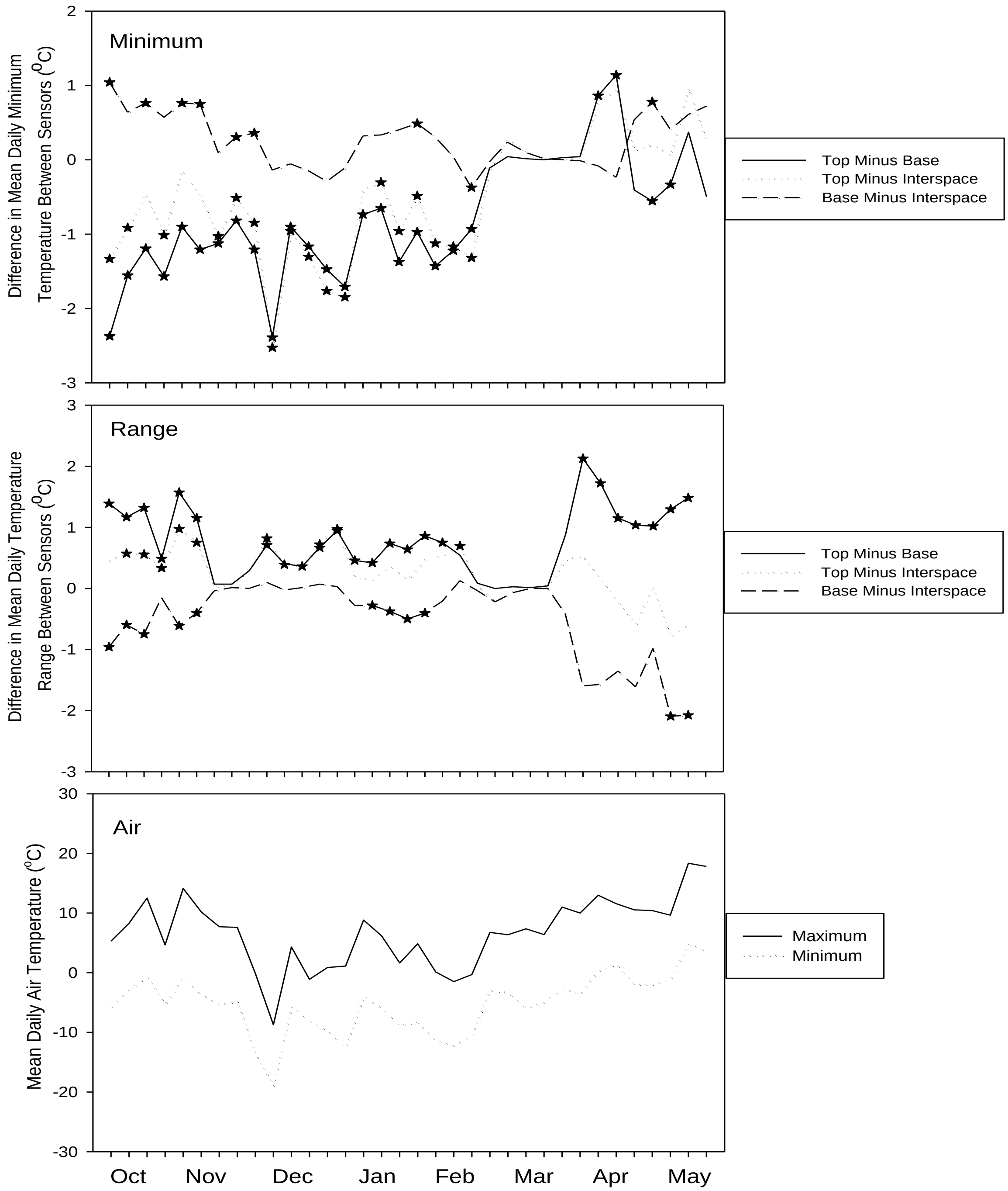

Figure 2.6. **Soapstone Site** temperature differences for soil sensor locations and mean air temperatures. Differences were obtained by subtracting the weekly mean for the daily minimum temperature and daily temperature range values of one sensor location from another. Weeks with significant differences (paired t-tests, $\alpha=0.05$, $n=4$) are indicated with a star. The weekly means for the maximum and minimum air temperature are shown in the bottom panel.

DISCUSSION

Needle Ice

One of my objectives was to determine if there were suitable conditions to support frost heave due to needle ice that has been shown to create microtopography. Corte (1967) experimentally created soil mounds through numerous freeze-thaw cycles. He found that soil mounds were most numerous and reached maximum height after 28-37 cycles. The number of freeze-thaw cycles observed at all field sites was greater than 37 (Table 2.2) suggesting that mound formation could easily be initiated in one winter season if the other environmental conditions favorable for needle ice were also present. Fahey (1973) reported that a diurnal air freeze-thaw cycle did not always produce a diurnal frost heave. However, he concluded that needle ice activity gives rise to the development of micro-hummocks. The environmental conditions that promote greatest frost heave include absence of prolonged snow cover, scant vegetation cover and a water table close to the surface (Fahey 1974). This suggests that the air freeze-thaw cycles that occurred in the fall and spring (Table 2.2) when there was limited snow cover may have resulted in more successful heave events. There may have also be more opportunity for needle ice in areas where the vegetation and soil were disturbed because of the exposed surface. Livestock or wildlife grazing may disturb the soil surface and reduce vegetation cover creating favorable conditions for needle ice. The number of air freeze-thaw cycles observed was sufficient to produce frost heave from needle ice and this mechanism could have produced the initial variation in soil surface elevation but may not be capable of producing hummocks of the size observed at field sites. Other formation mechanisms may rely on the initial soil mounds for subsequent hummock development.

Ice Lensing

The most widely accepted theory for hummock formation is differential frost heave (Grab 2005). Most studies supporting differential frost heave rely on preexisting microtopography because of the challenges associated with experimentally creating hummocks by manipulating conditions believed to produce them. Mechanisms for creating microtopography include frost heave due to needle ice or other types of soil surface disturbance such as hoof prints from large ungulates.

Diurnal air freeze-thaw cycles may have played a role in maintenance or development of hummock microtopography when the water table was high enough for standing water in the depressions or interspaces. Van Vliet-Lanoë (1991) reported that one type of differential frost heave occurred when there was ice lensing adjacent to unfrozen material that created external pressure compressing the material and injecting sediment either upwards or laterally depending on frost susceptibility of the materials. The most crucial time for this to occur was just prior to freezing (Van Vliet-Lanoë 1991). All of the study sites had a high water table and there was often water in the interspace while the hummock tops were exposed. There was coincidence of water or ice in the interspace and air freeze-thaw cycles while the base of the hummock was greater than 0°C both in the fall and spring suggesting that this type of differential frost heave may be a mechanism for hummock development or maintenance at these sites. In fact, several of the water sensors indicated ice forming in the interspaces diurnally while the hummock was above 0°C (e.g. Fig. 2.2.)

The hummocks were randomly selected for temperature monitoring which resulted in several that did not meet the requirement of water in the interspace necessary for this type of differential frost heave. For example, at the McGreavey site no cycles were recorded in the fall. However, field observations confirm that there was standing water in some interspaces at all of the sites in the fall and spring. If hummock selection criteria had included water in the interspace, the number of "successes" would have been much greater. The water table in the fall and spring depends on precipitation which varies annually. When October 2009 through May 2010 monthly precipitation for five of the nearest weather stations were compared to the long-term averages at these stations, precipitation was found to be only slightly higher than average (Western Regional Climate Center 2011). However, years with higher precipitation totals would result in a higher water table.

Temperature Differentials

A 9% volume increase is expected when there is a phase change from water to ice (Hallet 1990). However, several studies report heave magnitudes in excess of this volume increase. Fahey (1974) found heave magnitudes as high as 30 cm associated with frost boils at high elevation sites in Colorado's Front Range, which was greater than a 9% volume increase. High heave magnitudes are achieved when temperature differentials and adequate moisture are present in the soil. The freezing front moves through the soil which creates a pressure gradient and causes water to move to the area of low temperatures in response to this gradient. The water forms ice lenses as it freezes creating frost heave (Hallet 1990).

One hypothesis was that the interspace would have the lowest number of freeze days which would result in temperature differentials. There were no differences in freeze days between the sensor locations except at the McGreavey site where the interspace had fewer freeze days than the other sensor positions. Scott et al. (2008) also reported limited differences between hummock crests and furrows with trends toward more freeze days in the hummock. He hypothesized that the order of freezing may be more important than time frozen because the freezing of one location before another creates short-term temperature gradients that are sufficient for hummock maintenance. I found that the hummock tops froze before the hummock base and interspace which could lead to water movement and differential freezing in the hummock. In addition, water is mobile in soil at temperatures as low as -10 to -30°C (Hallet 1990) so differences in temperature may be a better indicator of differential frost heave than the number of freeze days.

The temperature differentials were statistically significant between the hummock top, base and interspace. At all sites, the top was significantly colder than the base and interspace which could lead to water moving toward the colder region even in subzero temperatures. McGreavey and Mt. Margaret had the shortest hummocks with fewer temperature differences between the top and base that resulted in the temperature gradient being primarily between the hummock and interspace.

Rate of ground freezing, along with other factors, influences the magnitude of ground expansion (Rieger 1983; Williams and Smith 1989). The hummock tops had the greatest mean daily temperature range at all sites that could result in more rapid freezing rates. The extreme temperature fluctuation also results in the greatest potential for water movement. Fine particles may be locally redistributed as water migrates in response to temperature differentials (Rieger 1983). Water moving to the hummock top carries fine particles that precipitate out of solution as the temperature decreases or the particles may be pressed against mineral surfaces by ice pressure and remain in place as the water continues to move (Rieger 1983). Over a long period of time, these fine particles may become concentrated in thin bands within the hummock. Hummocks often have higher content of fine-grained particles than interspaces resulting from sorting associated with differential freeze-thaw activity (Van Vliet-Lanoë 1991; Grab 1997).

Role of Snow in Creating Temperature Differentials

The McGreavey site had fewer freeze days for the interspace than the hummock (Table 2.3). The top and base of the hummock were frozen while the interspace remained predominantly unfrozen. Both Mark's (1994) and Grab's (1997) studies reported temperature differentials similar to these results. The McGreavey site occurs at the highest elevation and receives the most precipitation (Table 2.1) that results in the deepest and most continuous snow cover. Snow has low thermal conductivity and is a good insulator (Jones et al. 2001). Seppälä (1994) found that seasonal frost penetration was inhibited on the snow-covered side of palsas which are large peat mounds with a perennial frozen core found in sub-Arctic regions. The snow cover at McGreavey insulated the depressions from the subzero air temperatures before the depressions froze. The initial snow cover was not sufficient to insulate the hummock tops so they reached subzero temperatures resulting in temperature differentials. As the snow continued to accumulate, the hummocks were covered and insulated which reinforced the temperature differentials. I suspect that this may have occurred around the beginning of January when the mean daily temperature ranges of the hummocks and interspaces became similar and the differences in minimum daily temperature stabilized (Fig. 2.4). The large difference in daily temperature ranges during the last few weeks of monitoring are probably driven by snow melt and exposure of the hummocks to air temperature fluctuations and radiation. The presence of snow cover in the fall may have inhibited conditions necessary for hummock formation by ice lensing because the interspace was insulated preventing water in the interspace from freezing.

Snow also played an important role in creating temperature differentials at the other sites. Snow at Mansfield and Mt. Margaret often covered the interspace and left the hummocks exposed (Fig. 2.7). Mansfield had the tallest hummocks so the snow did not accumulate to a depth great enough to cover the tops which was evidenced by the number and magnitude of temperature differentials in the fall and early winter (Fig. 2.3). Taller hummocks were characterized by more extreme temperature gradients between hummock and interspace that could have resulted in a positive feedback loop. Mt. Margaret had the shortest hummocks (Table 2.1). It is likely that snow covered the hummocks at this site from late November through December when there were few significant differences in minimum temperature and the temperature ranges were smaller. However, the air temperature increase in January probably exposed hummock tops. This was followed by a decrease in air temperature resulting in significant temperature differentials between the hummock and interspace (Fig. 2.5).

Soapstone had the least snow cover because of low elevation and lack of precipitation (Table 2.1) which left the interspace exposed to subzero air temperatures. This was evidenced by the interspace being significantly colder than the hummock base and having a greater daily temperature range (Fig. 2.6). The temperature differentials between the hummock top and interspace were more numerous than the differentials between the hummock base and interspace which could lead to greater heave magnitudes in the hummock than interspace. Grab (1998) found that maximum heave varied from 0.18 to 0.86 cm for hummocks relative to the interspace.

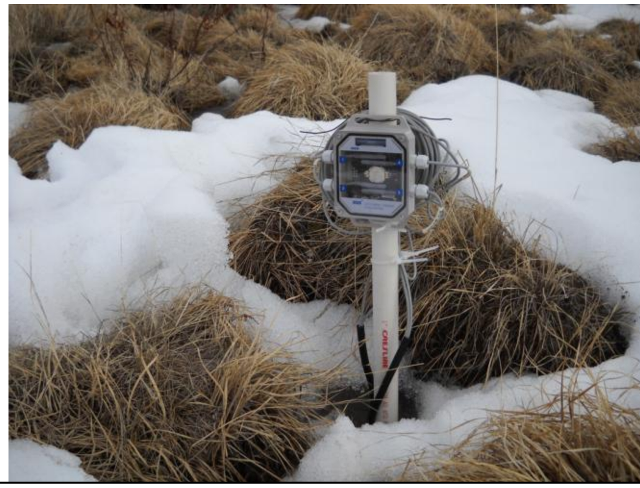

Figure 2.7. Photo of one of the field sites showing snow covering the interspaces while the hummocks were exposed. The temperature data logger is in the foreground.

The 'zero curtain' occurs when the soil remains at a stable temperature between 0 and -0.6°C while the soil water freezes (Kelley and Weaver 1969). This phase change requires much energy and results in a stable soil temperature. When all of the soil sensors were in the 'zero curtain,' the temperature differentials were no longer significant and the mean daily temperature range values were close to one. This stable temperature occurred earliest and was most pronounced at the Mansfield site because it had the lowest mean annual temperature, so the earliest onset of soil freezing (Fig. 2.3; Table 2.1). The 'zero curtain' occurred much later at McGreavey and was enhanced by snow insulation. Mt. Margaret lacked a pronounced 'zero curtain' effect (Fig. 2.5) and Soapstone had a brief period of stable temperatures in the spring just prior to thaw (Fig. 2.6).

Temperature differentials in the fall and early winter most likely drove differential frost heave processes at our study sites. Sediment injection from ice lenses in the interspace has been shown to occur prior to freeze (Van Vliet-Lanoë 1988). Also, temperature differentials were established prior to the arrival of insulating snow. If the snow depth was insufficient to cover the hummocks, the interspace was insulated while the hummock was exposed (Grab 1997). This perpetuated differentials until stable temperatures were established throughout the soil from soil water freezing. During spring thaw, temperatures were variable which led to very few significant differences in temperature between soil sensor locations. Future research should include monitoring the soil and air temperatures for several years to insure that the full range of temperatures and potential differentials are captured and to investigate year-to-year dynamics.

IMPLICATIONS

The results of this study confirmed that conditions described in the most widely accepted hummock formation theories occur in Colorado wetlands supporting a range of hummock heights. In fact, hummocks may be polygenetic in origin (Grab 2005). This provides a valuable foundation for future study of the mechanisms responsible for hummock development and maintenance.

There are several factors that enhance conditions found in hummock formation theories. Soil disturbance and reduction of vegetation cover likely increase the opportunity for needle ice formation and ice lensing. Fall and early winter were times when conditions supporting differential frost heave were most likely. Weather and climatic conditions, such as water table depth, air temperature and snow depth, influence temperature differentials between hummocks and interspaces. Hummock formation may be a very slow process so, even if conditions are right, it may take decades or centuries to build hummocks. Changes in land management targeted at reduction of suitable conditions for hummock formation may not produce an immediate or long-term response. More research is necessary to determine the relationship between land management practices and hummock formation.

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Chapter 3: Evaluation of Soil and Vegetation Characteristics as They Relate to Hummock Formation Theories

ABSTRACT

Some, but not all Colorado wetlands support hummocks and relatively little is known about the mechanisms leading to their formation. The most widely accepted theory for hummock formation is differential frost heave, but there are many others. The first objective of this study was to test whether differential frost heave could explain hummock formation in Colorado evidenced by the existence of bent soil horizons. The second objective was to determine if evidence exists to support the theory that plant litter accumulation builds hummocks. To address these objectives, four hummocked sites were selected for study in north-central Colorado. At each site, six hummock/interspace pairs were randomly selected to collect soil cores. Organic horizons were collected and their thickness was measured. Soil cores were sampled in 8 cm increments and sand/silt ratios for each increment were calculated and compared to identify horizons in hummocks and interspaces. Ten hummock/interspace pairs were also randomly selected for bulk density measurements. Plant biomass and canopy cover by species were determined using ten, 20 m transects. Paired t-tests were used to determine if organic horizon depth, total mass of organic matter, bulk density, aboveground biomass production and vegetation composition differed between hummocks and interspaces (α=0.05). Evidence of bent horizons and differential frost heave were observed in four

hummocks at two different sites. There was also evidence of straight soil horizons where hummocks might have formed through hummock expansion or interspace erosion and compaction. Hummocks had thicker organic horizons, lower bulk density, greater herbaceous biomass production and higher plant cover than interspaces suggesting that plants may contribute to hummock development. The results did not support interspace erosion or compaction. There was no association detected between plant functional group present and occurrence of hummocks because plant species composition varied by site.

INTRODUCTION

Hummocks in riparian areas and wetlands are relatively small, vegetated mounds that are typically less than one meter in height and diameter and create uneven ground. The processes that lead to hummock formation are not well understood and several different hypotheses exist in the literature. Grab's (2005) review of hummock geomorphology, genesis and environmental significance discussed several hypotheses for hummock formation. Differential frost heave is the most widely accepted theory (Van Vliet-Lanoë 1991; Grab 2005) and requires differences in moisture and temperature during freezing resulting in ice lenses and local frost heave in hummocks (Mark 1994; Grab 1997; Scott et al. 2008). Another hypotheses for hummock formation not mentioned in Grab's (2005) review is formation through biotic processes such as plant biomass accumulation (Dawkins 1939; Shaver and Cutler 1979; Gibson 1988). However, there is a multiplicity of terms used to describe forms similar to hummocks that are found in a variety of environmental settings with different morphological characteristics and formation mechanisms (Grab 2005). Mounds formed through plant biomass accumulation are commonly referred to as tussocks (Shaver and Cutler 1979) rather than hummocks but these terms may describe the same feature or have similar formation mechanisms. There is considerable uncertainty regarding hummock formation mechanisms.

Some suggest that hummocks are relict features that formed thousands of years ago when the climate was much colder (Scotter and Zoltai 1982, Van Vliet-Lanoë et al. 1998). If hummocks formed long ago, soil horizons may provide the best insight into processes that formed them even if present conditions are different from conditions that existed when hummocks formed. Convoluted soil horizons in hummocks have been found in several areas of the world and these features have been attributed to differential frost heave (Zoltai and Tarnocai 1981; Scotter and Zoltai 1982; Schunke and Zoltai 1988; Van Vliet-Lanoë 1991; Van Vliet-Lanoë et al. 1998; Van Vliet-Lanoë and Seppälä 2002). If convoluted horizons are not observed, a mechanism other than differential frost heave may have caused hummock formation. Hummocks may be recent features that formed as a result of biotic processes so current conditions should also be considered when investigating formation mechanisms. For example, Van Vliet-Lanoë et al. (1998) claimed that truncated hummocks regrew rapidly.

The best approach to study hummock formation would be to experimentally create conditions believed to result in hummock formation and then document their genesis and growth. However, given the logistical difficulties associated with this approach, hummock height was used as a proxy for hummock development and areas supporting hummocks of different heights were studied.

This research was conducted to evaluate two hummock formation theories in Colorado. The objectives of this study were to 1) determine if convoluted (bent) soil horizons characteristic of differential frost heave occur in hummocks found in Colorado and 2) assess whether or not there is evidence that plant litter accumulation contributes to hummock formation. I expected that if differential frost heave contributed to hummock formation, the uneven ground surface produced by hummock/interspace topography would be underlain by near surface bent mineral soil horizons. A number of conditions were expected if hummocks developed in response to accumulation of plant litter. First, I expected hummocks would have an organic horizon and it will be thicker than those found in the interspaces. Second, plant biomass accumulation should result in lower bulk densities in hummocks than interspaces. Finally, I expected more herbaceous biomass production and plant cover on hummocks than interspaces, and caespitose graminoids would be more abundant on hummocks than interspaces.

METHODS

Study Locations

Four hummocked sites in north-central Colorado were selected for this study (Fig. 3.1). Mean hummock heights for each site were measured by establishing three temporary 25-m transects. Along each transect, three 2- by 5- m plots were systematically located. Within each plot, two hummocks were randomly selected and their heights were recorded. Elevation, average hummock heights, mean annual temperature and precipitation (PRISM Climate Group 2008) for the sites are located in Table 3.1.

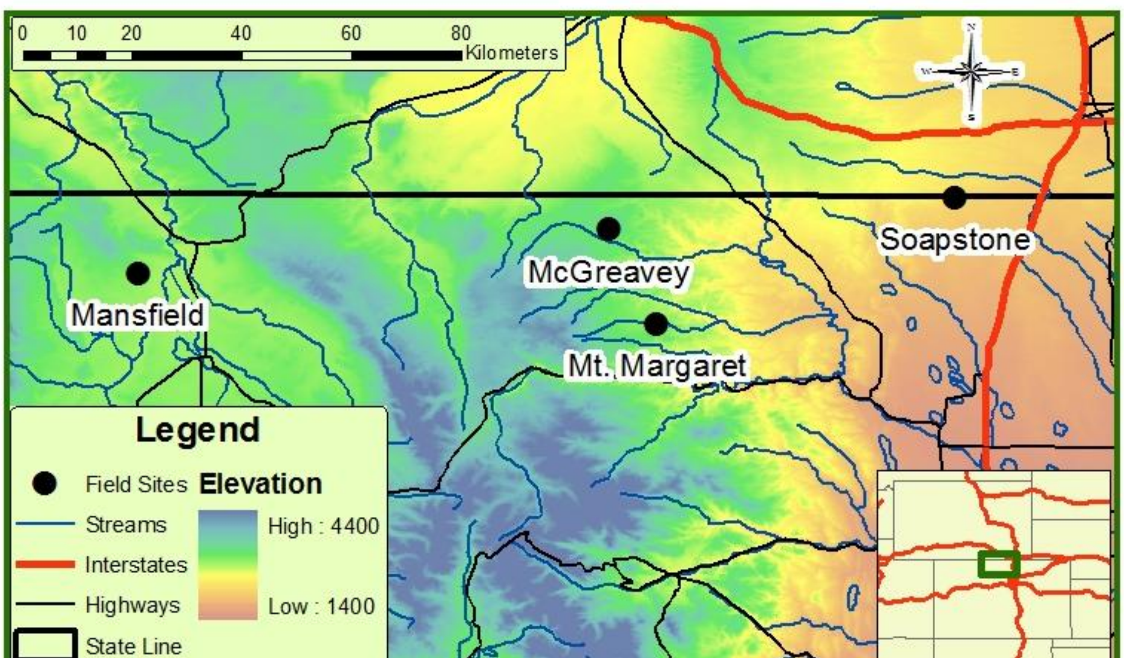

Figure 3.1. Map of field sites located in North-central Colorado. NAD 1983 UTM

Table 3.1. Site characteristics of the field sites. Temperature and precipitation were acquired from PRISM Climate Group (2008).				
Site Name	**Elevation (m)**	**Mean Annual Temperature (°C)**	**Mean Annual Precipitation (cm)**	**Hummock Height (cm)**
Mansfield	2470	2.9	39.2	29
McGreavey	2610	3.5	48.0	18
Mt. Margaret	2460	4.7	42.6	16
Soapstone	1980	6.9	41.8	24

Soil

Convoluted horizons have been identified through detailed tephro-stratigraphy when a characteristic layer such as a buried organic or ash layer exists to assist visualization of the convolutions (Zoltai and Tarnocai 1981; Scotter and Zoltai 1982; Schunke and Zoltai 1988; Van Vliet-Lanoë 1991; Van Vliet-Lanoë et al. 1998; Van Vliet-Lanoë and Seppälä 2002). However, in the absence of these visually distinguishable layers, other methods can be used to determine differences in soil horizons (Soil Survey Staff 1999; Schaetzl 1998; Tsai and Chen 2000). Schaetzl (1998) and Tsai and Chen (2000) concluded that sand/silt ratios were useful in distinguishing lithologic discontinuities. Sand/silt ratios were used to distinguish mineral soil horizons in soil cores collected from hummocks and their adjacent interspaces. I assumed that bent horizons would be evidenced by upper mineral horizons in the hummock and interspace that had similar sand/silt ratios and different sand/silt ratios between the surface of the interspace and the sample under the hummock at the same elevation as the interspace surface (Fig. 3.2., scenario 1). Scenarios 2 and 3 in Figure 3.2 represent other potential outcomes.

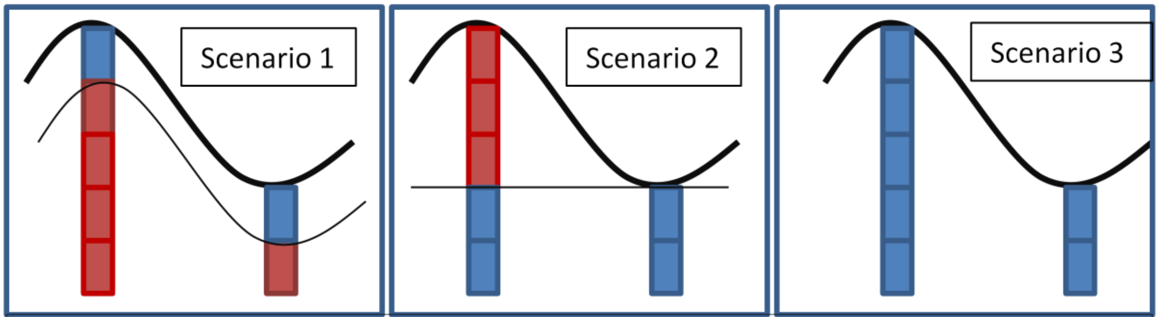

Figure 3.2. Three of many idealized scenarios for results of mineral horizon soil core sample comparisons. Samples of similar color have sand/silt ratios with less than 0.6 difference. Scenario 1 represents hypothesis 1 of bent soil horizons. Scenario 2 represents straight horizons from hummock building or erosion/compaction in the interspace. Scenario 3 shows no detection of soil horizons.

Six hummock/interspace pairs were randomly selected at each site for soil core analysis. Cores to a depth of 1 m were collected from hummock centers and adjacent interspaces with a 6 cm diameter soil sampling tube. With the sampling tube fully inserted in the ground, the distance from ground surface to the top of the sample in the tube was recorded to quantify the amount of compression that occurred during sampling. Samples were taken to the lab and allowed to air dry. Visual soil characteristics were recorded and the top of the mineral soil horizon was identified. Two mineral horizon samples were collected from the interspace cores in 8 cm increments (Fig. 3.3). Three or more mineral horizon samples were collected from the hummock in 8 cm increments depending on the hummock height in order to obtain two samples below the surface level of the interspace. Dry weights of the samples were recorded, particle size analysis was conducted using the hydrometer method (Day 1965) and percent organic matter was determined by loss on ignition (Black 1965). Results of particle size analyses were used to calculate the sand/silt ratios. The ratios of the two samples in the interspace (0-8 and 8-16 cm) were compared to the ratios in the top two hummock samples (0-8 and 8-16 cm). In addition, ratios for the two interspace samples were compared to ratios of the two samples under the hummock at a depth corresponding to 0-8 and 8-16 cm below the ground surface in the interspace (samples at comparable level). A difference of less than 0.6 between sand/silt ratios was used as a threshold for similarity of samples following Schaetzl (1998) and Tsai and Chen (2000). The sampling scheme and comparisons conducted are shown in Figure 3.3.

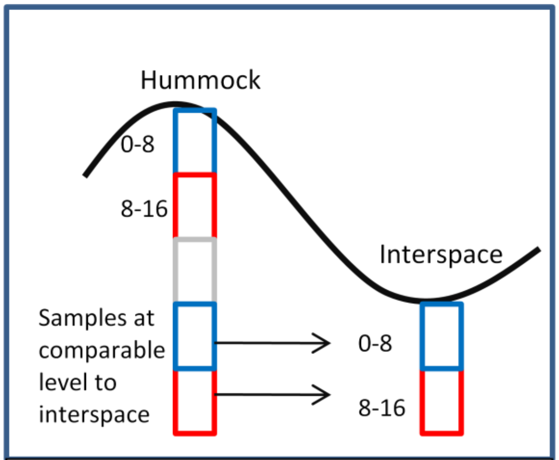

Figure 3.3 Schematic showing core sampling procedure and comparisons between the hummock and interspace. Comparisons made are shown in the same color.

Using the same soil cores, the thickness of each organic (O) horizon was recorded and then the organic material was collected for further analysis. The total thickness of the O horizon was calculated by adding the thickness of the O horizon collected in the core to the amount of compression that occurred when sampling with the assumption that all compression occurred in the O horizon rather than the mineral horizons. The samples were dried, weighed and percent organic matter was determined by loss on ignition (Black 1965). Total mass of organic matter was determined by multiplying the percent organic matter by the dry weight of the O horizon and top two- 8-cm mineral soil increments resulting in grams of organic matter for each sample increment.

In addition to the soil cores, ten hummock/interspace pairs were randomly selected for bulk density measurements at each site. Soil bulk density samples were collected at a depth of 10 cm below the soil surface from the hummock and interspace using a 5.4 cm diameter metal ring. Samples were dried at 105°C until they reached a constant weight. Weights were recorded and bulk densities were calculated using the ring volume.

SAS 9.2 software (SAS Institute, Inc. 2008) was used for data analyses. Paired t-tests were used to determine if hummocks and interspaces differed in terms of total O horizon thickness, total mass of organic matter and soil bulk densities with an alpha level of 0.05.

Vegetation

Vegetation composition and herbaceous biomass data were collected from ten, temporary 20 m transects at each site. The current year's aboveground herbaceous biomass was clipped and collected from two randomly selected hummock/interspace pairs along each transect by using a 20 cm diameter ring. Samples were dried at 55°C until they achieved a constant weight and dry weights were measured.

Because of the irregular shape of the hummocks and interspaces, a modified point-intercept method and a laser pointer with a bubble level were used to determine canopy cover (Interagency Technical Team 1996). At each meter along the transect, the nearest hummock and corresponding interspace were identified where canopy intercepts by plant species were recorded for 10 points resulting in 200 points for hummocks and 200 points for interspaces along each transect.

From these data, canopy cover was determined by functional groups (trees, shrubs, forbs, rhizomatous grasses, caespitose grasses and rhizomatous grass-likes). Relative abundance of each functional group was calculated for each transect by dividing the number of hits for a functional group by the total number of plant hits. Non-plant cover (water, bare ground and litter) was expressed as total non-plant hits divided by the total number of points observed along each transect. Paired t-tests with an alpha level of 0.05 were conducted using SAS 9.2 software (SAS Institute, Inc. 2008) to investigate differences in herbaceous biomass production and relative abundance of plant functional groups between hummocks and interspaces.

RESULTS

Differential Frost Heave

Analysis of soil cores from Mansfield revealed very few differences. One hummock/interspace pair was in highly organic soil and mineral horizons were not evident. Differences among sand/silt ratios in the various positions for four other hummock/interspace pairs were all less than 0.6 (Fig. 3.2, scenario 3), which was the threshold for similarity of samples (Schaetzl1998; Tsai and Chen 2000). The 8-16 cm depth sample in the interspace was the only sample that differed from all other positions in the final hummock/interspace pair at this site.

At McGreavey, cores from two hummock/interspace pairs included only organic horizons so comparisons of mineral layers were not possible. Sampling errors eliminated one pair and another pair depicted scenario three (Fig. 3.2) with no differences in sand/silt ratios. The other two pairs at this site did not fit into the scenarios presented in Figure 3.2. The samples in the interspace were similar to the upper samples in the hummock as well as the samples under the hummock at the level comparable to the upper samples in the interspace. These results could support either scenario one or two.

There was evidence of bent soil horizons in one hummock/interspace pair at Mt. Margaret. In this pair, the 0-8 cm hummock and interspace samples were similar and the

8-16 cm interspace sample was similar to all hummock samples below 8 cm. These data match the prediction of scenario one (Fig. 3.2). The results for two pairs suggest that the 0-8 cm interspace sample was similar to the top hummock samples and the 8-16 cm sample in the interspace was similar to the sample at comparable level in the hummock which depicts the straight soil horizon of scenario two (Fig. 3.2). The final three pairs revealed no difference in sand/silt ratios (Fig. 3.2, scenario 3).

Three hummock/interspace pairs at Soapstone revealed evidence of bent horizons. The top two samples for the hummock and interspace were similar, but the samples in the interspace differed from those under the hummock at comparable levels (Fig. 3.2, scenario 1). No differences were detected in another pair (Fig. 3.2, scenario 3). The final two samples did not fit the scenarios presented in Figure 3.2. In one pair, the 0-8 cm sample of the interspace was dissimilar from both the 0-8 cm hummock sample and the sample at comparable level but similar to samples in the middle of the hummock. In another pair, the only similarity in sand/silt ratios was between the 8-16 cm sample in the interspace and its corresponding sample in the hummock.

Plant Biomass Accumulation

The thickness of the organic horizon was significantly greater in hummocks than interspaces at McGreavey and Soapstone (Table 3.2). However, total mass of organic matter was not significantly different between hummocks and interspaces (Table 3.2). The bulk density was lower in hummocks than interspaces at three sites (Fig. 3.4).

Herbaceous biomass production was greater on hummocks than in interspaces at all sites except McGreavey (Fig. 3.4). McGreavey was the only site with shrub cover, which was much higher on the hummocks (Fig. 3.5). The sites differed in terms of the relative abundances of functional groups. The hypothesis that greater caespitose grass cover would be found on hummocks was only supported at Mt. Margaret where rhizomatous grasses and forbs were also more abundant on hummocks (Fig. 3.5). The relative abundance of rhizomatous grass-likes was significantly greater in the interspaces at three sites (Fig. 3.5). In addition, the percent of non-plant hits was significantly greater in interspaces at three sites. This was not observed at Soapstone where there was high plant litter cover on hummocks.

Table 3.2. Results of paired t-tests for comparison of total organic horizon thickness and total mass of organic matter in the organic horizon and top 16cm of mineral soil between hummock and interspace.

Site Name	**Total Organic Horizon Thickness (cm)**		**p-value**	**Total Mass of Organic Matter (g)**		**p-value**
	Hummock	Interspace		Hummock	Interspace	
Mansfield	36	33	0.425	106	88	0.122
McGreavey	75	61	<0.0001	121	105	0.156
Mt. Margaret	40	27	0.056	59	53	0.403
Soapstone	28	20	0.011	28	31	0.498

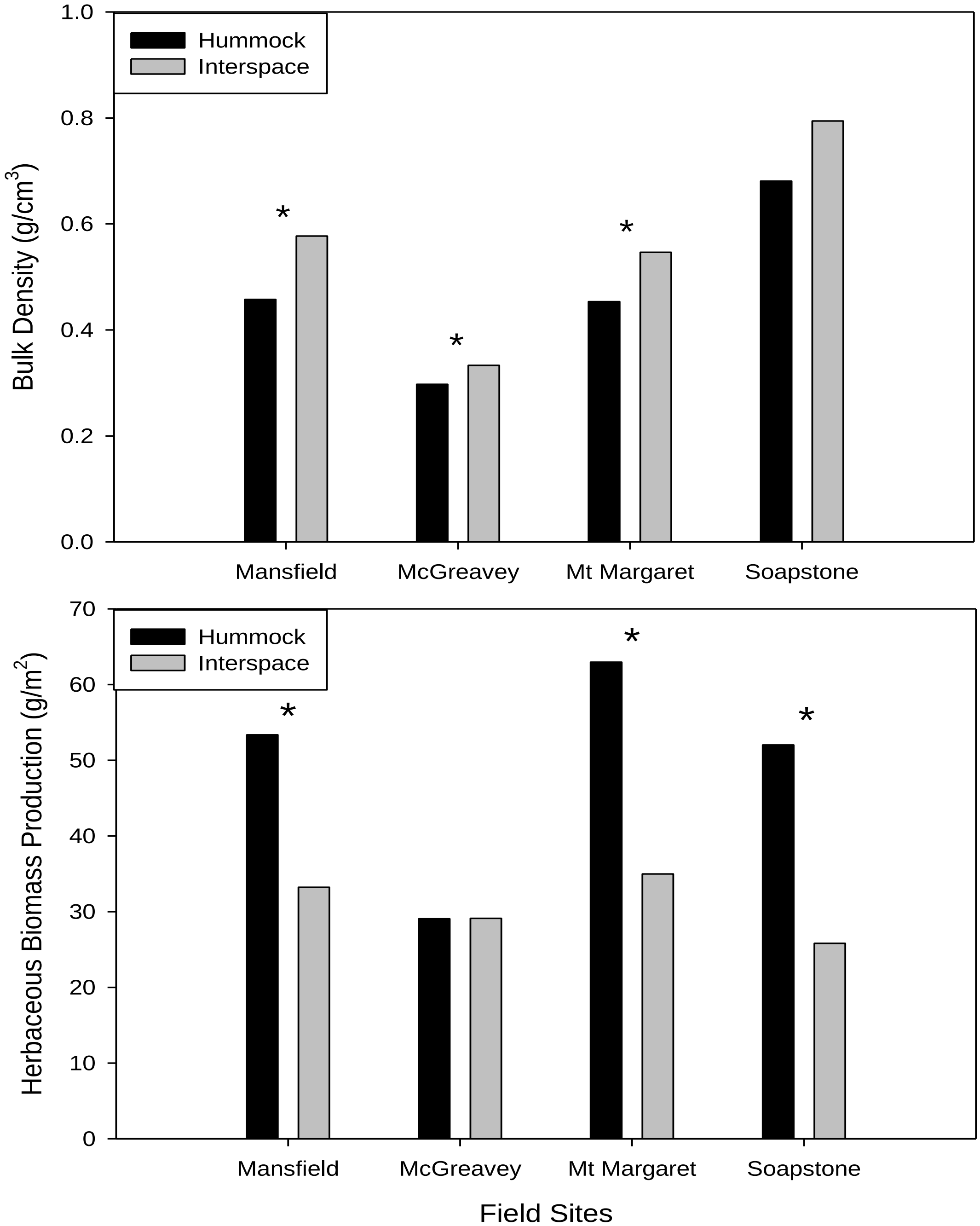

Figure 3.4. Soil bulk density (top panel) and herbaceous biomass production (bottom panel) for hummocks and interspaces at field sites. Asterisks denote that hummocks and interspaces are significantly different (Paired t-test, $\alpha=0.05$).

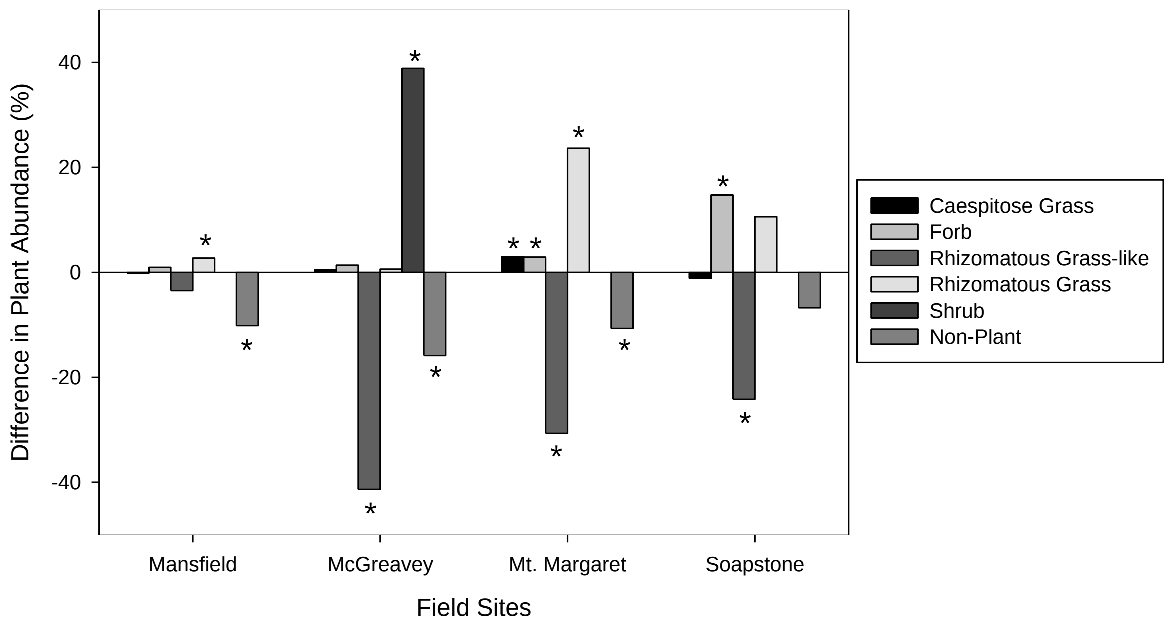

Figure 3.5. Difference in plant abundance between hummocks and interspaces for functional groups at the field sites. Positive numbers signify higher abundance on hummocks. Asterisks denote differences in abundance between hummocks and interspaces that are significantly different than zero (Paired t-test, α=0.05).

DISCUSSION

Differential Frost Heave

Evidence of bent soil horizons suggesting hummock formation by differential frost heave was found in three hummocks at Soapstone and one hummock at Mt. Margaret. This finding agrees with other studies that describe cryogenic processes resulting in convoluted horizons (Zoltai and Tarnocai 1981; Scotter and Zoltai 1982; Schunke and Zoltai 1988; Van Vliet-Lanoë 1991; Van Vliet-Lanoë et al. 1998; Van Vliet-Lanoë and Seppälä 2002). Therefore, differential frost heave resulting in bent soil horizons may be a factor in hummock formation at Soapstone and Mt. Margaret.

The results from two hummock/interspace pairs at McGreavey could lead to an interpretation of either bent or straight soil horizons because the top hummock and interspace samples were similar as were the hummock and interspace samples at comparable levels. The hypothesis of bent soil horizons could be supported in these hummocks if there were multiple bent horizons that were below the level of sampling so were not captured. The results from the hummock/interspace pairs could also support the hypothesis of straight soil horizons if there were straight layers that were missing from the top of the interspace.

The results from two hummocks at Mt. Margaret supported scenario two (Fig. 3.2) if the straight horizon was depicted at a depth of 8 cm in the interspace. The greater depth of the horizon in the hummock could have resulted from erosion or compaction of the straight horizon in the interspace or the layer in the hummock could have built or expanded. Lower bulk densities in hummocks may help explain either interspace compaction or hummock expansion (Fig. 3.4). Livestock and wildlife may trample interspaces causing compaction and erosion (Heidel and Thurston 2004). However, the mean bulk densities of the interspaces at all sites was less than one suggesting limited compaction (Fig. 3.4). Erosion would eliminate the top mineral soil horizons which contain the greatest amount of organic matter. However, total mass of organic matter was not significantly different between hummocks and interspaces (Table 3.2) and the sites were on a gentle slope so erosion was probably not a factor. Biotic factors such as ant activity may be a contributing factor to hummock expansion. Lesica and Kannowski (1998) concluded that hummocks were a product of nest building by ants. Ants were observed in some hummocks at the field sites. Plant biomass accumulation may also contribute to an increase in hummock height.

The remaining samples either supported scenario three with no differences in the sand/silt ratios or did not fit into one of the idealized scenarios leading to inconclusive results. It is possible that differential frost heave processes were at work in these hummocks, but were not evidenced by bent horizons. One of the assumptions in using sand/silt ratios to detect lithologic discontinuities was that there were different horizons in the near surface mineral soil. This appears to be the case at Soapstone because different horizons and their orientation were detected. However, at Mansfield, lithologic discontinuities were not detected in any of the samples. This finding was confirmed by visual observations of the cores. The soil could have been convoluted but there were no distinguishable layers. Frost heave could have also resulted in mixing of soil and layers (Williams and Smith 1989) which would have negated the detection of differences in sand/silt ratios. Other biotic factors such as ant activity in the hummocks (Lesica and Kannowski 1998) and livestock or wildlife trampling in the interspace could have resulted in soil mixing. Tarnocai and Zoltai (1978) concluded that hummocks form through cryoturbation processes but some are old and have been inactive for thousands of years so have well developed soil horizons that do not show disruption. This and other indicators of differential frost heave would not have been detected with the sampling scheme used in this study.

Plant Biomass Accumulation

Based on the discussion above, differential frost heave could have led to hummock formation at several sites. However, bent horizons were not detected in all hummocks suggesting that they might have formed through other mechanisms in addition to frost heave. Grab (2005) suggested that hummocks may be polygenetic. Another hummock formation theory is plant biomass accumulation. Schunke and Zoltai (1988) suggested that vegetation development is important in hummock growth once formed, but little is known about the role of plants in hummock initiation. Initiation may begin by upward tillering and litter accumulation which are adaptation strategies of some graminoids to anaerobic conditions (Costello 1936; Dawkins 1939; Yabe 1985; Nishikawa 1990). There has been much more research related to tussock formation by plants. A tussock, defined as "a compact tuft, especially of grass or sedge; *also* an area of raised solid ground in a marsh or bog that is bound together by roots of low vegetation (Merriam-Webster's Collegiate Dictionary 2005)" may be a form of embryonic hummocks or a type of hummock formed by plants (Chapter 1). Tussock formation processes may be similar to mechanisms of hummock formation by the plant biomass accumulation theory.

In order for plants to form hummocks, or contribute to their height, they must produce biomass which accumulates on the hummocks. Morton (1974) found a positive correlation in grasslands between height of microtopography and standing crop dry weight and observed that this was due to highly productive vegetation patches building mounds of litter and matted roots. One hypothesis was that herbaceous biomass production would be higher on hummocks than interspaces which was supported at all sites except McGreavey. McGreavey was the only site with shrub cover that most likely suppressed herbaceous biomass production on hummocks. Not only do the plants have to produce biomass, this biomass also has to accumulate on hummocks to increase the height. The organic horizons were significantly thicker on the hummocks at McGreavey and Soapstone and marginally significant at Mt. Margaret ($p=0.06$; Table 3.2). Grab (1997) found that percent organic matter in hummocks was almost twice that of interspaces. However, I found that total mass of organic matter in the organic horizon and top 16cm of mineral soil did not differ between hummocks and interspaces at any site (Table 3.2). The difference in findings between this study and Grab's could be due to reporting of percent organic matter instead of total mass of organic matter. Benscoter et al. (2005) found that total mass of organic matter was greater for hummocks than interspaces at one of their sites but not the other. This suggests that if plant biomass was leading to growth of hummocks, it produced taller, less solid hummocks, but the total amount of organic matter in the hummock was not significantly greater. This was supported by the significantly lower bulk density observed in hummocks compared to interspaces at three sites. Although the bulk densities of hummocks were lower than interspaces, the overall bulk densities were less than one. This finding, along with no difference in total mass of organic matter, provides more evidence for plant biomass accumulation than interspace erosion or compaction by grazing animals.

The often anaerobic conditions occurring in interspaces may lead to decreased decomposition rates and may help explain the lower plant litter input, but comparable total mass of organic matter in the interspaces (Table 3.2; Fig. 3.4). Kim and Verma (1992) found that CO_2 evolution from hummocks were much higher than from interspaces and this difference was directly related to the temperature and water levels of the two positions. In addition, higher microbial activity could lead to increased nutrient availability and more favorable conditions for plant growth on hummocks.

If plant biomass accumulation contributed to hummock building, it is of interest to know which plants were the major contributors. One hypothesis was caespitose grass species would be responsible for plant biomass accumulation because of their compact growth form. Dawkins (1939) found that *Schoenus nigricans* L., a caespitose grass-like species, formed tussocks in a peat marsh. The tussock height grew as the water eroded the peat soil around the plants. Cottongrass tussock tundra is a widespread vegetation type in the northern latitudes of North America and is dominated by *Eriophorum vaginatum* L. that forms tussocks (Shaver and Cutler 1979). In addition, Carsey et al. (2003) claim that *Kobresia*, a genus of a caespitose grass-like species, is responsible for hummock formation in fens of South Park, Colorado. Caespitose grasses were more abundant on hummocks than interspaces at only one site and the difference in relative abundance was only about 3% (Fig. 3.5). This suggests that caespitose graminoids were probably not significant contributors to hummock building at these sites.

Shrubs may have contributed to hummock formation at sites where they were present (Chapter 1). Only one of the sites had shrub cover but, at that site, the relative abundance of shrubs was much higher on the hummocks than in the interspaces. Tyrtikov (1969) suggested that shrubs play a role in hummock formation but not through biomass accumulation. Rather, shrubs were believed to have modified the movement of snow and influence subsequent freeze-thaw processes which led to an increase in hummock size (Tyrtikov 1969). However, others report that shrub litter decomposes more slowly than sedge litter (Hobbie 1996). This difference in decomposition rate between the dominant species type found on the hummock and in the interspace may lead to differential litter accumulation (Fig. 3.5).

Factors driving the difference in plant species composition on hummocks and interspaces may relate more to the growing conditions and microenvironment than hummock building processes (Ashworth 1997). Hummocks are typically drier than interspaces during the growing season (Admiral and Lafleur 2007, Quinton and Marsh 1998). In addition, temperatures and amounts of radiation differ between hummocks and interspaces (Shen et al. 2006). These factors contribute to unique microenvironments in which some plants are better adapted than others. When reconstructing microtopography in a restored wetland, Bruland and Richardson (2005) found that upland species mainly colonized the hummocks while water-inundated hollows supported obligate-wetland species. I also found that species more typical of uplands, including some rhizomatous grasses and forbs, were more abundant on the hummocks while grass-likes were more abundant in the interspaces (Fig. 3.5). Recent studies have shown the value of including hummock- hollow microtopography when restoring wetlands (Bruland and Richardson 2005, Vivian-Smith 1997).

IMPLICATIONS

If hummocks formed long ago, evaluation of soil characteristics may be the most beneficial tool in determining formation. Evidence of bent soil horizons characteristic of differential frost heave processes was found in hummocks at two sites. Differential frost heave could have been a mechanism in hummock formation at the other sites but lack of distinguishable soil horizons or soil mixing may have limited detection of bent soil horizons. Soil characteristics and vegetation may provide useful clues for mechanisms of formation if hummocks formed recently. Evidence of straight soil horizons would support the hypotheses of hummock expansion or interspace erosion or compaction. Plant biomass accumulation was supported as a possible mechanism of hummock building. The results did not support the hypothesis of interspace erosion or compaction from livestock grazing at these sites. Current land management changes to reduce the development of hummocks may not be effective if hummocks formed long ago or if the mechanisms leading to hummock formation are not targeted. This research provides a starting point for further research into hummock formation mechanisms, the role of different plant species in hummock initiation and development and the influence of land management changes on hummock formation in Colorado wetlands.

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Synthesis

This research was conducted to evaluate the characteristics of hummocks and hummocked wetlands in Colorado. The presence of hummocks in wetlands is often used as an indicator of degraded condition and management decisions based on this assumption are often made to reduce hummock presence. However, there is uncertainty regarding the mechanisms of hummock formation. This research was conducted at a large scale to determine which site characteristics were related to hummock occurrence and at a small scale to evaluate hummock formation theories.

The large scale component was addressed by sampling attributes of sites across Colorado. These attributes were then evaluated to determine which characteristics were related to hummock occurrence. Number of plant species was positively related to hummock occurrence which was most likely a result of the heterogeneous microtopography of hummocks rather than formation mechanisms. Soil silt content was also positively related to hummock occurrence and soils with high silt content are susceptible to frost heave. Mean winter precipitation and mean annual temperature were negatively related to hummock occurrence. These relationships may have also be a factor of greater freeze-thaw dynamics at lower temperatures and in the absence of snow.

Hummocked sites were also grouped to determine if there were different types of hummocks possibly formed by different mechanisms. The three groups of hummocked sites were characterized by different hummock dimensions, climatic regime and dominant plant species. Group one included the most sites and had the greatest mean annual temperature but formation mechanisms were not identified. Group two sites had the smallest, most numerous hummocks in areas with high annual precipitation and may have been formed by plant biomass accumulation. Group three sites had the largest hummocks dominated by shrub species in areas with low mean annual temperature. These hummocks may have been formed by differential frost heave or plant biomass accumulation.

Hummocks were more likely to occur at sites in Colorado with high soil silt content and in areas with low mean annual temperatures and low winter precipitation. They provided suitable conditions for a diverse plant community. Different hummock types may have formed as a result of different formation mechanisms. This information will help managers identify sites where hummock formation is most likely and provide a foundation for further research into hummock formation.

The large scale component of the study provided information for deciding how and where to focus the small scale investigations. Differential frost heave and plant biomass accumulation were two theories of hummock formation that were identified as possibly being active at these Colorado sites. In addition, the least conclusions were drawn about the mechanisms of formation at the group one hummocked sites. Four hummocked sites in north-central Colorado that were included in group one were identified for further investigation of the two mechanisms of hummock formation identified.

Hummocks and interspaces were instrumented with soil temperature sensors in addition to water sensors and air temperature sensors at each site. This was done to evaluate if the conditions for needle ice and the differential frost heave mechanisms of ice lensing and temperature differentials could be responsible for initial mound genesis, further development and maintenance. There were adequate air freeze-thaw cycles for needle ice which could initiate mound microtopography. There were also cycles of ice lensing in the interspaces which may expand and inject sediment into the hummock. There were numerous temperature differentials between the hummock top, hummock base and interspace with the hummock top being the coldest through fall and early winter. The freezing of the hummock top may create an area of low pressure where water rushes to the freezing front and creates differential heave. Fall and early winter provided the most favorable conditions for these mechanisms which included water in the interspace with diurnal air freeze-thaw cycles and snow cover that was insufficient to cover hummocks. Soil disturbance and removal of vegetation may also create favorable conditions for these mechanisms. Needle ice and soil disturbance, such as hoof prints of large ungulates, may create the initial microtopography needed for the differential frost heave mechanism of hummock formation through ice lensing and temperature differentials.

The conditions for differential frost heave were observed at the study sites so soil horizons were then examined for evidence of this mechanism. The soil and vegetation were also investigated to evaluate plant biomass accumulation identified in the large scale component as a theory of hummock formation. The organic and mineral soil from soil cores was examined and compared between hummocks and interspaces. Canopy cover of plant species was also measured. Evidence of bent mineral soil horizons characteristic of differential frost heave was found at Mt Margaret and Soapstone which had the greatest number of diurnal air freeze-thaw cycles. Bent horizons were not detected at Mansfield and McGreavey even though there were suitable conditions for ice lensing and temperature differentials. These sites had the lowest mean annual temperatures and the highest total mass of organic matter. It is possible that differential frost heave was active at these sites but was not detected because of the lack of distinguishable layers in the organic soil or soil mixing occurred from frost heave or biotic activity such as ants or large ungulates.

Straight mineral soil horizons were also detected which could have resulted from hummock expansion or interspace erosion and compaction. Organic horizons were thicker and plant cover was greater on hummocks than interspaces suggesting that plants may contribute to hummock development through biomass accumulation. However, insulation provided by the organic horizon and plant cover may reduce temperature differentials in hummocks and influence freeze-thaw dynamics. It was hypothesized that caespitose grasses would be more abundant on hummocks and contribute to plant biomass accumulation but there was limited evidence to support this at the study sites. The overall low bulk densities of interspaces and comparable mass of organic matter in hummocks and interspaces suggest that erosion and compaction by grazing was not a factor in hummock formation at these sites.

There may have been multiple mechanisms that formed different types of hummocks across Colorado. There was evidence for hummock formation through differential frost heave and plant biomass accumulation but a relationship between hummocks and livestock grazing was not found. Hummocks may have formed long ago so land management changes designed to reduce hummock formation may have limited impact, especially if the mechanisms of hummock formation are not targeted.

APPENDIX A

Basic site characteristic data for Chapter 1.

Table A1.1. Site and soil characteristics for field sites used in Chapter 1.

Site Number	Hummocked	HGM Class[1]	Elevation (m)	Grazing[2]	Soil pH	Salts (mmho/cm)	Excess Lime	Organic Matter (%)	Sand (%)	Silt (%)	Clay (%)
1	yes	Slope	2772	1	7.3	1.55	HIGH	20.9	25	64	11
2	yes	Slope	2980	1	5	0.26	NONE	18.3	29	46	25
3	yes	Slope	2610	1	5.6	0.5	NONE	30.9	37	50	13
4	yes	Slope	2460	1	5.7	0.37	NONE	15.9	41	36	23
5	yes	Slope	3345	1	4.8	0.3	NONE	16.2	25	56	19
6	yes	Slope	3340	1	4.8	0.42	NONE	39.5	34	52	14
7	yes	Slope	2841	1	5.7	0.31	NONE	17.5	31	54	15
8	yes	Slope	1979	1	7.5	0.52	HIGH	8.1	51	36	13
9	yes	Slope	2343	1	7.9	0.72	HIGH	3.9	33	48	19
10	yes	Slope	2860	1	6	0.76	NONE	47.8	39	56	5
11	yes	Slope	3110	1	5.6	0.58	NONE	58.7	49	46	5
12	yes	Slope	2860	1	5.6	0.52	NONE	61.5	50	41	9
13	yes	Slope	2982	1	5.7	0.4	NONE	15.8	35	50	15
14	yes	Slope	2467	1	6.7	1.78	NONE	19	26	55	19
15	yes	Slope	2534	1	7.5	1.04	NONE	9.9	23	46	31
16	yes	Riverine	2875	1	7.2	0.76	NONE	12.7	45	42	13
17	yes	Slope	2080	1	6.9	1.61	NONE	5.9	53	36	11
18	yes	Slope	1347	1	7.6	2.85	HIGH	3.1	49	45	6
19	yes	Riverine	2701	1	6.9	1.9	NONE	11.7	43	45	12
20	yes	Riverine	2887	1	7.6	0.86	HIGH	9.8	33	52	15
21	yes	Slope	2751	1	5.2	0.23	NONE	40.5	39	51	10
22	yes	Riverine	2900	1	6.9	0.9	NONE	9.5	49	33	18
23	yes	Slope	2472	1	6.3	0.52	NONE	11	45	42	13
24	yes	Slope	2928	1	6.9	0.66	NONE	19.8	45	45	10
25	yes	Riverine	3267	1	7.7	0.6	HIGH	19.1	47	41	12

Table A1.1 continued

Site Number	Hummocked	HGM Class[1]	Elevation (m)	Grazing[2]	Soil pH	Salts (mmho/cm)	Excess Lime	Organic Matter (%)	Sand (%)	Silt (%)	Clay (%)
26	yes	Slope	2688	1	6.6	0.4	NONE	4.6	39	47	14
27	yes	Riverine	2811	0	5	0.26	NONE	28.9	49	43	8
28	yes	Riverine	2726	0	4.9	0.23	NONE	4.3	43	45	12
29	yes	Riverine	2919	0	5	0.15	NONE	68.3	44	51	5
30	yes	Riverine	3294	1	5.2	0.26	NONE	17.1	27	51	22
31	yes	Riverine	2742	1	6.1	0.65	NONE	10.6	35	47	18
32	yes	Slope	2958	1	5.6	0.45	NONE	12.1	23	43	34
33	yes	Riverine	2922	1	7.1	0.7	NONE	8.9	43	43	14
34	yes	Slope	3411	1	4.7	0.15	NONE	59.7	51	45	4
35	yes	Slope	2353	1	7.3	0.48	NONE	7.5	45	35	20
36	no	Riverine	2295	1	7.7	0.65	NONE	0.8	82	16	2
37	no	Riverine	2602	1	6	0.35	NONE	9.5	50	40	10
38	no	Riverine	2410	1	6.3	0.2	NONE	6.3	51	41	8
39	no	Riverine	2466	1	5.8	0.35	NONE	10.5	37	49	14
40	no	Riverine	1441	1	7.9	0.65	HIGH	1.4	77	15	8
41	no	Riverine	2603	1	6.5	0.3	NONE	4.5	51	39	10
42	no	Riverine	3167	1	5.6	0.18	NONE	5.5	45	43	12
43	no	Depressional	1964	1	7.7	0.75	HIGH	9.4	55	31	14
44	no	Riverine	2316	1	6.1	0.26	NONE	7.6	55	33	12
45	no	Riverine	1557	1	7.3	0.15	NONE	1	89	10	1
46	no	Slope	2449	0	5.2	0.25	NONE	9.2	57	27	16
47	no	Riverine	1672	0	7.5	1.07	LOW	2.8	41	37	22
48	no	Slope	3223	1	4.8	0.16	NONE	35.3	39	51	10
49	no	Slope	2343	1	8.3	3.34	LOW	7.9	33	41	26
50	no	Riverine	2845	1	5.5	0.39	NONE	24.7	56	36	8

Table A1.1 continued

Site Number	Hummocked	HGM Class[1]	Elevation (m)	Grazing[2]	Soil pH	Salts (mmho/cm)	Excess Lime	Organic Matter (%)	Sand (%)	Silt (%)	Clay (%)
51	no	Depressional	2624	1	7.9	0.7	HIGH	5.3	17	53	30
52	no	Depressional	2539	1	7.4	0.85	HIGH	31.8	35	49	16
53	no	Slope	2801	1	7.6	2.29	LOW	6.9	21	59	20
54	no	Slope	3387	1	4.3	0.64	NONE	24.5	39	49	12
55	no	Riverine	1545	1	7.7	1.76	LOW	3.2	75	18	7
56	no	Slope	2156	1	6.6	2.52	NONE	7.3	49	33	18
57	no	Riverine	2109	1	7.3	1.14	NONE	3.3	78	16	6
58	no	Riverine	1224	0	7.6	0.66	HIGH	1.8	57	31	12
59	no	Depressional	1195	0	7.8	0.89	HIGH	3.4	21	47	32
60	no	Riverine	2603	1	7.5	0.34	LOW	2.6	55	37	8
61	no	Depressional	2819	1	5	0.15	NONE	54.6	51	44	5
62	no	Riverine	1561	1	7.8	0.32	NONE	2.9	69	19	12
63	no	Riverine	1444	1	7.8	1.87	HIGH	2.5	65	25	10
64	no	Riverine	2245	1	6.5	0.52	NONE	9.8	53	39	8
65	no	Riverine	2449	0	7.2	0.75	LOW	9.6	53	33	14
66	no	Riverine	2965	1	5.9	0.35	NONE	17.6	43	47	10
67	no	Slope	1103	0	7.7	0.86	HIGH	6.7	36	48	16
68	no	Slope	3109	1	5.7	0.33	NONE	6.6	41	39	20
69	no	Depressional	2319	1	6.4	0.23	NONE	6.5	49	39	12
70	no	Slope	2516	1	6.7	1.04	NONE	25.5	39	53	8
71	no	Riverine	2791	1	5.2	0.19	NONE	12.8	31	49	20
72	no	Riverine	2799	1	6.5	0.61	NONE	8.8	57	33	10
73	no	Riverine	3054	1	6.1	0.62	NONE	33.2	45	45	10

[1]HGM Class = Hydrogeomorphic class as defined by Carsey et al. (2003).

[2]Grazing = Domestic livestock grazing within 5 years. 1=Grazed, 0=Not Grazed

Table A1.2. Plant characteristics and canopy cover for sites used in Chapter 1.

Site Number	Number of Species	Litter (%)	Bare Ground (%)	Water (%)	Rock (%)	Green Moss (%)	Tree (%)	Shrub (%)	Forb (%)	Rhizomatous Graminoid (%)	Caespitose Graminoid (%)
1	3.7	11.7	18.9	0.0	0.0	0.1	0.0	0.0	25.2	29.4	3.3
2	5.5	27.6	1.2	1.0	0.0	0.3	0.0	1.6	13.7	42.2	8.3
3	4.3	65.0	0.5	11.0	0.2	5.7	1.3	37.7	0.8	22.4	6.4
4	8.3	25.1	4.4	1.3	0.0	14.8	0.0	2.7	12.6	51.1	3.9
5	5.2	43.4	4.2	0.0	0.0	0.8	0.0	0.0	14.9	25.6	28.6
6	4.8	8.3	19.0	12.8	0.0	6.6	0.0	0.0	9.2	59.5	6.7
7	4.7	20.0	6.3	5.1	0.0	1.3	0.0	4.3	4.6	55.3	4.6
8	5.7	49.3	7.5	2.8	0.0	4.0	0.0	0.0	8.4	45.3	0.0
9	4.3	58.2	4.4	1.2	1.3	1.7	0.0	0.0	12.7	31.4	0.0
10	4.8	25.1	0.1	3.3	0.0	16.0	0.0	17.1	5.0	33.0	0.0
11	7.9	25.2	0.0	0.5	0.0	28.1	0.2	32.7	27.8	25.2	1.3
12	5.7	22.7	0.0	0.0	0.0	12.4	0.0	31.3	12.4	19.2	0.0
13	8.6	31.2	9.8	0.0	0.1	1.2	0.0	29.4	17.2	23.5	12.7
14	4.9	35.8	12.4	0.0	0.0	1.0	0.0	0.0	14.1	44.3	8.3
15	7.0	21.2	11.1	0.0	0.0	2.0	0.0	0.1	34.5	32.3	0.0
16	4.4	46.1	0.2	0.0	0.0	0.1	0.0	0.8	6.5	42.7	0.1
17	4.3	10.2	35.0	23.0	0.0	2.8	0.0	0.0	7.3	40.2	1.3
18	4.4	59.1	3.4	0.0	0.0	0.0	0.0	0.0	6.2	35.1	19.7
19	3.8	46.0	25.5	0.0	0.0	0.0	0.0	0.0	5.5	32.5	0.0
20	9.2	36.5	12.6	0.0	0.0	0.0	0.0	8.6	24.2	25.4	9.3
21	4.9	31.9	0.1	16.1	0.0	2.9	0.0	1.3	5.6	39.0	1.7
22	3.4	13.1	19.2	18.9	0.5	2.4	0.0	0.7	4.7	23.0	3.4
23	5.5	37.8	3.4	0.5	0.0	18.6	0.0	19.3	5.5	39.2	1.3
24	6.1	12.3	4.7	0.0	0.0	1.1	0.0	23.8	29.9	32.2	0.0
25	5.0	43.0	0.7	0.0	0.0	10.4	0.0	27.2	6.8	10.0	3.6

Table A1.2 continued

Site Number	Number of Species	Litter (%)	Bare Ground (%)	Water (%)	Rock (%)	Green Moss (%)	Tree (%)	Shrub (%)	Forb (%)	Rhizomatous Graminoid (%)	Caespitose Graminoid (%)
25	5.0	43.0	0.7	0.0	0.0	10.4	0.0	27.2	6.8	10.0	3.6
26	8.7	36.5	1.6	0.0	0.0	1.1	0.0	38.2	14.2	27.8	0.5
27	4.8	15.7	3.2	0.0	0.0	0.6	1.3	17.6	15.8	42.1	0.0
28	6.6	38.0	3.1	1.3	0.0	0.3	0.0	26.5	14.9	36.4	0.2
29	5.0	42.9	2.8	10.2	0.0	11.4	0.0	10.4	3.8	41.8	0.8
30	6.4	15.4	3.7	9.9	0.5	2.8	0.5	32.9	22.8	38.7	2.1
31	7.3	16.6	2.2	1.8	0.0	9.9	0.0	0.0	16.3	61.6	6.8
32	4.9	30.5	1.6	0.0	0.0	0.3	0.0	0.0	10.4	32.2	19.9
33	6.7	31.9	2.7	2.6	0.0	3.0	0.0	8.8	31.4	34.9	0.1
34	5.8	59.8	2.1	0.3	0.0	2.1	0.0	0.6	17.3	38.3	1.8
35	5.7	7.5	7.9	12.6	0.0	0.5	0.0	0.0	7.6	74.0	0.0
36	4.0	33.8	1.4	7.8	0.0	2.3	0.0	0.0	12.0	60.7	0.0
37	6.7	33.4	2.5	0.0	0.0	1.0	2.1	16.3	24.3	41.3	0.0
38	6.8	32.3	7.6	0.0	0.0	0.0	0.0	0.0	48.3	32.3	0.0
39	7.8	17.9	5.8	10.2	0.0	5.8	0.0	2.8	45.2	41.7	0.7
40	4.4	20.1	3.8	0.0	0.0	0.0	2.1	10.3	19.1	18.9	52.9
41	6.0	25.8	10.1	2.7	3.1	0.1	0.0	33.1	15.4	19.6	4.8
42	6.6	24.4	9.0	0.6	0.0	9.6	0.0	17.6	12.8	39.4	2.3
43	4.6	53.3	3.6	0.0	0.0	0.0	0.0	1.0	8.9	52.0	0.0
44	6.8	22.3	1.9	0.0	0.0	0.3	62.9	3.7	40.7	27.5	0.0
45	4.2	26.2	0.1	0.0	10.3	0.0	0.5	38.9	10.9	26.0	0.0
46	4.2	14.1	0.0	1.3	0.0	0.0	0.0	8.0	7.9	75.4	0.5
47	4.0	7.7	6.0	10.1	0.0	0.0	0.0	48.1	26.3	16.4	2.5
48	2.6	55.8	5.2	0.0	0.0	2.2	0.0	0.0	3.5	37.1	0.8
49	3.1	43.3	9.1	3.6	0.0	1.0	0.0	0.0	5.0	45.3	2.3

Table A1.2 continued

Site Number	Number of Species	Litter (%)	Bare Ground (%)	Water (%)	Rock (%)	Green Moss (%)	Tree (%)	Shrub (%)	Forb (%)	Rhizomatous Graminoid (%)	Caespitose Graminoid (%)
50	6.0	33.3	0.8	15.9	0.0	1.3	0.1	1.3	23.8	35.8	0.1
51	4.0	18.6	11.0	17.3	0.6	0.0	0.0	0.0	11.6	50.3	0.0
52	4.3	27.9	0.3	0.0	2.6	0.8	4.1	46.3	49.5	11.5	0.5
53	3.7	24.2	3.1	4.8	0.0	0.2	0.0	0.0	2.3	66.1	2.5
54	1.5	43.9	0.0	2.1	0.0	18.1	0.0	0.0	1.7	38.5	0.0
55	4.1	43.8	11.2	4.8	0.0	0.0	8.6	2.2	5.9	34.3	0.3
56	3.1	28.6	0.5	0.0	0.0	0.0	0.0	0.0	4.2	70.2	0.2
57	5.4	24.0	12.1	0.0	0.0	0.0	30.8	0.0	7.3	59.1	5.5
58	4.0	67.8	5.9	0.0	0.0	0.0	0.5	27.5	19.9	9.3	0.0
59	4.7	22.0	0.0	8.0	0.0	0.0	0.0	0.0	20.8	53.3	30.9
60	8.0	16.2	12.2	0.0	2.8	9.5	4.9	32.8	25.4	21.5	0.0
61	2.1	26.0	9.3	34.2	0.0	0.1	0.0	0.0	3.3	32.3	0.0
62	6.3	26.2	16.8	0.0	0.3	0.0	0.0	0.1	10.3	64.1	0.0
63	6.8	20.8	9.7	0.0	4.3	0.6	0.0	0.0	15.1	62.2	3.0
64	5.7	25.4	25.9	0.0	0.6	0.0	22.7	1.0	17.5	39.3	0.2
65	5.0	10.6	6.3	2.8	0.0	0.0	0.0	0.6	29.4	57.0	0.0
66	5.9	24.6	9.8	0.0	4.6	0.0	3.8	19.9	31.6	29.2	1.1
67	4.8	2.8	1.0	0.0	0.0	0.0	2.1	0.0	10.8	85.3	11.3
68	6.4	13.3	17.5	24.3	0.0	0.7	0.0	0.0	38.9	20.0	6.7
69	4.3	25.4	6.3	0.0	0.0	0.1	0.0	0.0	5.3	41.0	35.7
70	5.3	53.5	0.8	3.7	0.0	2.5	0.0	12.8	10.9	32.4	0.0
71	5.4	18.0	4.5	3.8	0.0	8.1	0.0	21.8	14.8	33.3	10.7
72	2.4	58.1	2.8	0.5	0.0	0.1	0.0	16.9	1.3	33.3	0.0
73	5.7	19.3	0.8	14.8	0.0	2.5	0.0	23.4	15.2	37.2	0.3

Table A1.3. Mean precipitation and temperature for sites used in Chapter 1. Data collected from PRISM (2008).

Site Number	Mean Precipitation (cm)					Mean Temperature (°C)				
	Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall
1	32	5	9	11	8	2.7	-7.0	1.6	12.8	3.4
2	71	16	25	13	16	0.9	-8.4	-0.5	11.0	1.3
3	48	6	17	15	10	3.5	-5.5	1.8	13.5	4.0
4	43	4	14	15	9	4.7	-4.1	3.1	14.7	5.2
5	97	24	26	20	26	1.0	-7.7	-0.6	10.6	1.7
6	98	22	28	21	27	0.6	-8.0	-1.0	9.9	1.3
7	55	12	13	15	15	1.6	-8.9	0.7	12.0	2.8
8	42	4	14	16	8	6.9	-2.9	5.5	17.6	7.2
9	34	15	18	13	12	3.4	-8.2	2.8	14.6	4.4
10	51	14	14	12	12	1.1	-10.2	0.0	12.0	2.6
11	77	23	22	13	18	0.3	-8.9	-1.3	10.2	1.1
12	51	14	14	11	12	1.1	-10.2	0.0	12.1	2.6
13	52	14	14	12	12	0.4	-10.3	-0.6	11.0	1.7
14	39	9	11	10	9	2.9	-7.0	2.0	13.4	3.4
15	43	11	11	11	10	2.6	-7.6	1.7	13.0	3.3
16	33	6	8	11	7	2.1	-7.6	0.5	12.2	3.0
17	45	9	13	10	12	6.2	-5.4	5.4	18.1	6.7
18	35	2	12	15	7	9.7	-2.2	9.1	21.9	10.0
19	49	7	15	17	10	3.0	-6.9	2.0	13.1	3.5
20	39	5	12	15	7	2.3	-7.2	1.0	12.4	3.0
21	88	30	26	12	21	1.7	-8.1	0.7	11.9	2.4
22	48	7	14	17	9	2.5	-6.5	1.1	12.2	3.1
23	49	5	15	19	10	5.3	-3.8	4.1	15.2	5.8
24	47	7	13	18	9	3.4	-5.7	2.2	13.0	3.9
25	70	15	22	17	16	0.8	-8.0	-0.5	10.4	1.6

Table A1.3 continued

Site Number	Mean Precipitation (cm)					Mean Temperature (°C)				
	Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall
26	40	6	9	14	11	2.2	-9.1	1.1	13.0	3.6
27	67	14	23	15	14	2.9	-6.1	1.3	12.9	3.6
28	62	17	18	13	14	1.9	-8.1	0.9	12.2	2.6
29	77	22	23	14	17	1.4	-7.9	0.0	11.4	2.0
30	59	18	17	12	12	1.1	-8.2	-0.3	11.0	1.9
31	50	7	12	18	14	2.2	-8.0	1.2	12.4	3.3
32	63	11	16	17	18	2.6	-7.1	1.3	12.5	3.5
33	60	13	15	16	16	1.6	-8.2	0.3	11.6	2.7
34	80	12	26	26	17	0.6	-7.4	-0.9	9.5	1.4
35	57	14	16	12	15	5.6	-4.3	4.2	16.2	6.2
36	43	5	14	16	9	7.1	-2.5	6.1	17.2	7.4
37	50	7	17	15	11	3.0	-6.0	1.4	13.1	3.5
38	48	5	18	15	10	5.0	-3.9	3.5	14.9	5.4
39	43	4	14	15	9	4.7	-4.1	3.1	14.7	5.2
40	42	3	13	19	8	11.6	1.1	10.9	22.6	11.9
41	41	4	9	17	10	3.3	-7.8	2.8	13.8	4.3
42	113	30	30	21	32	1.6	-7.1	0.1	11.1	2.4
43	41	3	14	16	8	6.9	-2.9	5.6	17.7	7.3
44	44	6	14	15	9	5.4	-3.4	4.0	15.2	5.9
45	44	4	17	14	9	9.0	-1.4	8.2	20.0	9.1
46	54	8	20	16	11	5.1	-3.8	3.5	15.0	5.6
47	50	5	19	16	10	9.9	-0.1	8.6	20.9	10.0
48	44	13	16	12	13	10.5	-0.8	9.6	22.4	10.9
49	33	3	13	21	7	3.2	-8.8	2.8	14.5	4.2
50	58	6	9	10	8	3.3	-6.0	1.9	13.3	3.9

Table A1.3 continued

Site Number	Mean Precipitation (cm)					Mean Temperature (°C)				
	Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall
51	49	6	9	11	8	4.3	-5.6	3.4	14.4	4.9
52	49	11	15	12	12	4.6	-5.4	3.5	15.0	5.4
53	54	11	14	11	12	3.7	-6.0	2.6	13.9	4.3
54	107	28	28	19	31	-0.6	-8.6	-2.3	8.5	0.1
55	38	3	11	18	6	9.4	-1.8	8.7	21.1	9.7
56	49	11	14	10	13	6.1	-5.4	5.2	17.9	6.6
57	42	9	12	9	12	6.1	-5.5	5.3	18.1	6.7
58	32	3	10	13	5	12.0	-0.2	11.8	24.4	12.1
59	31	2	10	13	5	12.0	-0.2	11.7	24.4	12.1
60	69	19	19	13	17	4.2	-5.6	2.7	14.6	4.9
61	91	31	27	12	21	1.2	-8.6	0.2	11.5	1.8
62	36	3	13	14	7	8.8	-2.0	7.9	20.3	8.9
63	37	2	12	16	7	9.1	-2.2	8.3	21.1	9.3
64	22	2	5	9	6	5.4	-6.5	5.6	16.1	6.2
65	46	6	15	15	9	5.0	-4.0	3.5	14.8	5.5
66	54	15	15	12	12	3.2	-6.7	1.9	13.5	4.1
67	45	3	16	18	8	10.1	-1.8	9.4	22.5	10.2
68	107	36	35	13	24	1.5	-8.1	0.2	11.7	2.0
69	62	16	17	13	16	3.7	-6.7	2.9	14.5	4.3
70	68	20	19	13	17	3.3	-6.8	2.1	13.9	4.0
71	89	31	26	11	20	1.6	-8.2	0.6	11.9	2.3
72	78	22	27	13	17	2.8	-6.9	1.7	12.9	3.5
73	94	29	31	13	21	1.1	-8.5	-0.3	11.3	1.7

APPENDIX B

Summarized temperature data for Chapter 2.

Table A2.1. Dates for weeks used in temperature sensor analysis.

Week	Day Start	Day End	Week	Day Start	Day End	Week	Day Start	Day End
1	10/4/09	10/10/09	**13**	12/27/09	1/2/10	**25**	3/21/10	3/27/10
2	10/11/09	10/17/09	**14**	1/3/10	1/9/10	**26**	3/28/10	4/3/10
3	10/18/09	10/24/09	**15**	1/10/10	1/16/10	**27**	4/4/10	4/10/10
4	10/25/09	10/31/09	**16**	1/17/10	1/23/10	**28**	4/11/10	4/17/10
5	11/1/09	11/7/09	**17**	1/24/10	1/30/10	**29**	4/18/10	4/24/10
6	11/8/09	11/14/09	**18**	1/31/10	2/6/10	**30**	4/25/10	5/1/10
7	11/15/09	11/21/09	**19**	2/7/10	2/13/10	**31**	5/2/10	5/8/10
8	11/22/09	11/28/09	**20**	2/14/10	2/20/10	**32**	5/9/10	5/15/10
9	11/29/09	12/5/09	**21**	2/21/10	2/27/10	**33**	5/16/10	5/22/10
10	12/6/09	12/12/09	**22**	2/28/10	3/6/10	**34**	5/23/10	5/29/10
11	12/13/09	12/19/09	**23**	3/7/10	3/13/10			
12	12/20/09	12/26/09	**24**	3/14/10	3/20/10			

Table A2.2. Mansfield Site. Mean weekly temperature differences between soil sensor positions.

		Top Minus Base			Top Minus Interspace			Base Minus Interspace		
Week[1]	Sensor	Max[2]	Min[3]	Range[4]	Max	Min	Range	Max	Min	Range
1	161	-0.7	-2.4	1.7	0.0	-2.1	2.1	-0.7	-0.2	-0.4
1	164	1.3	-2.4	3.7	-0.4	-0.9	0.4	1.7	-1.5	3.3
1	160	-4.3	-5.5	1.2	-2.6	-4.1	1.5	-1.7	-1.4	-0.3
1	154	-2.6	-4.3	1.7	-1.0	-1.6	0.5	-1.5	-2.7	1.2
2	161	1.4	-1.4	2.7	1.6	-1.7	3.4	-0.3	0.4	-0.6
2	164	3.5	-1.6	5.1	0.5	-0.4	0.9	3.1	-1.1	4.2
2	160	-0.8	-3.4	2.5	-0.2	-2.7	2.5	-0.6	-0.7	0.0
2	154	0.8	-3.1	3.9	0.7	-1.1	1.8	0.0	-2.0	2.1
3	161	0.4	-1.7	2.1	0.6	-2.1	2.7	-0.2	0.4	-0.6
3	164	1.3	-2.1	3.4	0.1	-0.6	0.6	1.3	-1.5	2.8
3	160	-1.1	-3.3	2.2	-0.6	-2.7	2.1	-0.5	-0.6	0.1
3	154	-0.5	-3.4	2.9	-0.1	-1.1	1.1	-0.4	-2.2	1.9
4	161	-1.6	-1.8	0.1	-1.5	-1.5	0.0	-0.2	-0.3	0.1
4	164	-1.0	-1.8	0.9	-0.8	-0.3	-0.5	-0.1	-1.5	1.4
4	160	-3.1	-3.0	-0.1	-1.9	-1.8	-0.1	-1.2	-1.1	-0.1
4	154	-2.4	-2.6	0.2	-0.7	-1.0	0.4	-1.7	-1.6	-0.1
5	161	-2.2	-2.6	0.5	-1.9	-2.5	0.6	-0.2	-0.1	-0.2
5	164	3.0	-1.3	4.3	-0.7	-0.3	-0.4	3.8	-0.9	4.7
5	160	-3.4	-2.3	-1.2	-2.0	-1.5	-0.5	-1.4	-0.8	-0.6
5	154	-1.1	-1.2	0.1	-0.1	-0.3	0.1	-1.0	-0.9	0.0
6	161	-0.1	-1.8	1.8	-0.2	-2.0	1.8	0.2	0.2	0.0
6	164	2.7	-1.1	3.8	0.2	-0.3	0.4	2.5	-0.8	3.4
6	160	-1.8	-1.8	0.0	-1.4	-1.3	-0.1	-0.5	-0.5	0.1
6	154	-0.9	-0.9	0.0	-0.1	-0.1	0.0	-0.8	-0.8	0.0
7	161	-2.9	-3.6	0.7	-3.0	-3.3	0.3	0.1	-0.3	0.4
7	164	-1.3	-3.0	1.7	-0.1	-1.2	1.1	-1.2	-1.8	0.6
7	160	-2.2	-3.4	1.2	-1.3	-2.4	1.1	-0.9	-1.0	0.1
7	154	-1.0	-2.6	1.6	-0.4	-2.0	1.6	-0.6	-0.6	0.0
8	161	-2.8	-5.2	2.4	-1.8	-4.3	2.4	-1.0	-0.9	0.0
8	164	-1.3	-6.5	5.2	-0.2	-3.0	2.7	-1.1	-3.6	2.5
8	160	-2.9	-5.5	2.6	-1.8	-3.9	2.1	-1.1	-1.6	0.5
8	154	-1.7	-5.9	4.3	-0.8	-3.8	3.0	-0.9	-2.1	1.3
9	161	-4.8	-8.9	4.1	-3.1	-6.5	3.4	-1.7	-2.5	0.8
9	164	-2.1	-9.1	7.0	-0.2	-3.6	3.4	-1.9	-5.6	3.6
9	160	-4.1	-7.3	3.1	-2.6	-4.8	2.2	-1.5	-2.5	1.0
9	154	-2.9	-9.1	6.2	-1.0	-3.7	2.7	-1.9	-5.4	3.5
10	161	-3.4	-4.6	1.2	-2.1	-2.9	0.8	-1.3	-1.7	0.4
10	164	-3.3	-5.0	1.7	-1.5	-2.5	1.0	-1.8	-2.5	0.7
10	160	-3.3	-4.5	1.2	-2.1	-3.0	1.0	-1.2	-1.4	0.3
10	154	-2.2	-3.4	1.1	-0.9	-1.4	0.5	-1.3	-2.0	0.6

Table A2.2 Mansfield continued

Week	Sensor	Top Minus Base			Top Minus Interspace			Base Minus Interspace		
		Max	Min	Range	Max	Min	Range	Max	Min	Range
11	161	-1.3	-1.7	0.4	-0.8	-1.1	0.3	-0.5	-0.6	0.1
11	164	-0.8	-1.1	0.3	-0.3	-0.5	0.2	-0.5	-0.6	0.1
11	160	-1.3	-1.7	0.3	-0.8	-1.1	0.2	-0.5	-0.6	0.1
11	154	-0.8	-1.2	0.4	-0.3	-0.6	0.2	-0.5	-0.6	0.2
12	161	-1.8	-2.4	0.6	-1.1	-1.6	0.5	-0.7	-0.8	0.1
12	164	-1.0	-1.4	0.5	-0.5	-0.8	0.2	-0.4	-0.7	0.2
12	160	-1.7	-2.1	0.5	-1.1	-1.4	0.4	-0.6	-0.7	0.1
12	154	-1.2	-1.7	0.5	-0.6	-0.8	0.2	-0.6	-0.8	0.2
13	161	-2.1	-2.6	0.5	-1.3	-1.6	0.4	-0.8	-1.0	0.1
13	164	-1.2	-1.5	0.3	-0.6	-0.7	0.1	-0.7	-0.8	0.1
13	160	-2.2	-2.6	0.4	-1.4	-1.8	0.3	-0.8	-0.8	0.0
13	154	-1.3	-1.8	0.4	-0.6	-0.8	0.2	-0.7	-0.9	0.2
14	161	-1.4	-2.0	0.6	-0.9	-1.4	0.5	-0.5	-0.6	0.1
14	164	-0.3	-0.9	0.6	-0.2	-0.5	0.4	-0.2	-0.4	0.2
14	160	-1.9	-2.5	0.6	-1.3	-1.7	0.4	-0.6	-0.8	0.2
14	154	-1.3	-1.9	0.6	-0.6	-0.9	0.3	-0.7	-1.0	0.3
15	161	-1.8	-2.2	0.4	-1.2	-1.5	0.3	-0.6	-0.7	0.1
15	164	-1.3	-1.4	0.2	-0.6	-0.7	0.0	-0.6	-0.8	0.2
15	160	-3.0	-3.2	0.2	-1.9	-2.1	0.2	-1.2	-1.1	0.0
15	154	-1.9	-2.6	0.6	-0.8	-1.2	0.4	-1.1	-1.4	0.3
16	161	-0.8	-1.2	0.4	-0.6	-0.9	0.3	-0.3	-0.3	0.0
16	164	0.0	-0.1	0.0	-0.1	-0.2	0.0	0.1	0.1	0.0
16	160	-1.4	-1.7	0.3	-0.9	-1.1	0.2	-0.5	-0.6	0.1
16	154	-0.9	-1.4	0.5	-0.4	-0.7	0.3	-0.5	-0.7	0.2
17	161	-1.1	-1.7	0.6	-0.7	-1.2	0.5	-0.4	-0.5	0.1
17	164	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0
17	160	-1.2	-1.6	0.4	-0.8	-1.1	0.3	-0.5	-0.5	0.1
17	154	-0.6	-1.3	0.7	-0.3	-0.7	0.4	-0.3	-0.6	0.3
18	161	-1.4	-2.2	0.8	-0.9	-1.5	0.7	-0.5	-0.7	0.2
18	164	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0
18	160	-1.4	-1.8	0.4	-0.9	-1.2	0.4	-0.5	-0.6	0.1
18	154	-0.9	-1.7	0.8	-0.4	-0.8	0.4	-0.6	-0.9	0.4
19	161	-0.6	-1.3	0.7	-0.5	-1.1	0.6	-0.1	-0.2	0.1
19	164	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0
19	160	-1.6	-2.1	0.5	-1.0	-1.4	0.4	-0.6	-0.7	0.1
19	154	-1.0	-2.1	1.1	-0.4	-1.0	0.6	-0.6	-1.1	0.5
20	161	-0.7	-1.4	0.7	-0.5	-1.0	0.5	-0.2	-0.4	0.2
20	164	0.2	0.2	0.0	0.2	0.2	0.0	0.1	0.1	0.0
20	160	-1.4	-1.9	0.5	-0.9	-1.3	0.4	-0.5	-0.7	0.1
20	154	-0.8	-1.5	0.7	-0.3	-0.7	0.4	-0.5	-0.8	0.3

Table A2.2 Mansfield continued

		Top Minus Base			Top Minus Interspace			Base Minus Interspace		
Week	Sensor	Max	Min	Range	Max	Min	Range	Max	Min	Range
21	161	0.2	0.2	0.0	0.1	0.1	0.0	0.1	0.1	0.0
21	164	0.0	-0.1	0.1	0.1	0.1	0.0	-0.1	-0.1	0.1
21	160	-0.9	-1.2	0.3	-0.6	-0.8	0.2	-0.4	-0.4	0.1
21	154	-0.6	-0.9	0.3	-0.3	-0.4	0.2	-0.4	-0.5	0.1
22	161	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0
22	164	-0.3	-0.4	0.1	-0.1	-0.1	0.0	-0.2	-0.3	0.1
22	160	-0.6	-0.8	0.3	-0.3	-0.5	0.2	-0.2	-0.3	0.1
22	154	-0.3	-0.6	0.3	-0.1	-0.3	0.2	-0.2	-0.3	0.1
23	161	0.2	0.2	0.0	0.0	0.0	0.0	0.1	0.1	0.0
23	164	-0.2	-0.4	0.2	-0.1	-0.1	0.1	-0.2	-0.3	0.1
23	160	-0.3	-0.6	0.3	-0.1	-0.4	0.2	-0.2	-0.2	0.0
23	154	-0.1	-0.4	0.4	0.0	-0.2	0.2	-0.1	-0.2	0.1
24	161	0.2	0.2	0.0	0.0	0.0	0.0	0.1	0.1	0.0
24	164	-0.3	-0.6	0.3	-0.1	-0.2	0.1	-0.2	-0.4	0.2
24	160	-0.3	-0.6	0.3	-0.1	-0.4	0.3	-0.2	-0.2	0.0
24	154	-0.1	-0.8	0.7	0.0	-0.5	0.5	-0.1	-0.3	0.2
25	161	0.1	0.1	0.0	0.0	-0.1	0.1	0.1	0.2	0.0
25	164	-0.1	-0.4	0.3	0.0	-0.1	0.1	-0.1	-0.3	0.2
25	160	0.0	-0.3	0.3	0.1	-0.2	0.2	-0.1	-0.1	0.0
25	154	0.1	-0.8	0.9	0.1	-0.6	0.7	0.0	-0.2	0.2
26	161	-0.1	-0.2	0.1	-0.2	-0.3	0.1	0.1	0.1	0.0
26	164	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0
26	160	0.0	-0.1	0.1	0.1	-0.1	0.1	-0.1	-0.1	0.0
26	154	.	.	.	.	.	.	.	.	.
27	161	-0.1	-0.1	0.0	-0.1	-0.2	0.1	0.1	0.1	0.0
27	164	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0
27	160	-0.1	-0.3	0.2	-0.1	-0.3	0.2	0.0	0.0	0.0
27	154	.	.	.	.	.	.	.	.	.
28	161	-0.3	0.0	-0.3	-0.1	-0.1	0.0	-0.2	0.1	-0.3
28	164	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0
28	160	-0.1	-0.1	0.0	0.0	0.0	0.0	-0.1	-0.1	0.0
28	154	.	.	.	.	.	.	.	.	.
29	161	-0.9	-0.1	-0.8	1.1	0.1	1.0	-1.9	-0.2	-1.8
29	164	4.2	0.3	3.9	-0.4	0.0	-0.4	4.6	0.2	4.4
29	160	1.7	0.1	1.5	1.8	0.2	1.6	-0.2	-0.1	-0.1
29	154	.	.	.	.	.	.	.	.	.
30	161	1.2	-0.7	1.8	2.5	0.2	2.3	-1.3	-0.9	-0.4
30	164	4.2	0.2	4.0	-1.3	0.1	-1.4	5.5	0.1	5.4
30	160	0.8	0.1	0.7	1.3	0.1	1.1	-0.4	0.0	-0.5
30	154	.	.	.	.	.	.	.	.	.

Table A2.2 Mansfield continued

		Top Minus Base			Top Minus Interspace			Base Minus Interspace		
Week	Sensor	Max	Min	Range	Max	Min	Range	Max	Min	Range
31	161	0.4	-0.8	1.2	1.5	-0.2	1.7	-1.2	-0.6	-0.6
31	164	2.5	0.2	2.3	-0.8	0.1	-0.9	3.4	0.1	3.2
31	160	0.7	0.2	0.5	1.1	0.2	0.9	-0.4	0.1	-0.5
31	154	.	.	.	.	.	.	.	.	.
32	161	2.0	-0.1	2.1	2.6	-0.3	2.9	-0.6	0.2	-0.8
32	164	4.1	1.0	3.0	0.9	0.3	0.6	3.2	0.7	2.4
32	160	3.8	1.5	2.3	2.9	0.7	2.3	0.9	0.8	0.1
32	154	.	.	.	.	.	.	.	.	.
33	161	2.6	0.2	2.4	4.5	0.3	4.3	-1.9	0.0	-1.8
33	164	8.8	3.7	5.0	0.4	0.9	-0.6	8.4	2.8	5.6
33	160	5.7	3.2	2.5	4.5	0.8	3.8	1.2	2.4	-1.2
33	154	.	.	.	.	.	.	.	.	.
34	161	3.8	0.0	3.9	4.5	-0.3	4.8	-0.6	0.3	-0.9
34	164	8.3	1.8	6.6	0.3	-0.1	0.4	8.0	1.8	6.2
34	160	4.7	1.8	2.8	4.3	0.2	4.1	0.4	1.6	-1.3
34	154	.	.	.	.	.	.	.	.	.

Periods (.) in data represent data logger malfunction
[1]Dates of weeks are located in Table A2.1
[2]Max = Maximum temperature in 24 hr period
[3]Min = Minimum temperature in 24 hr period
[4]Range = Maximum temperature minus minimum temperature in 24 hr period

Table A2.3. McGreavey Site. Mean weekly temperature differences between soil sensor positions.

		Top Minus Base			Top Minus Interspace			Base Minus Interspace		
Week[1]	Sensor	Max[2]	Min[3]	Range[4]	Max	Min	Range	Max	Min	Range
1	166	-3.5	-2.9	-0.6	-0.6	-1.1	0.5	-2.9	-1.8	-1.1
1	165	-1.1	-5.2	4.1	0.0	-2.6	2.6	-1.1	-2.7	1.5
1	158	-4.1	-3.7	-0.4	-1.2	-0.9	-0.3	-2.9	-2.8	-0.1
1	156	-4.5	-4.4	-0.1	-0.4	-0.4	0.0	-4.1	-3.9	-0.1
2	166	-0.9	-1.7	0.8	0.1	-0.7	0.8	-1.1	-1.0	-0.1
2	165	0.3	-3.4	3.7	0.9	-1.9	2.8	-0.6	-1.5	0.9
2	158	-3.1	-3.3	0.2	-1.5	-1.2	-0.3	-1.7	-2.1	0.5
2	156	-3.8	-4.1	0.3	-0.9	-0.6	-0.3	-2.9	-3.6	0.7
3	166	-0.9	-1.5	0.6	0.4	-0.6	1.0	-1.2	-0.9	-0.3
3	165	1.2	-4.2	5.3	1.3	-2.3	3.5	-0.1	-1.9	1.8
3	158	-0.9	-2.1	1.2	0.0	-0.4	0.5	-0.9	-1.7	0.8
3	156	-1.1	-3.1	2.0	0.6	0.0	0.7	-1.7	-3.0	1.3
4	166	-1.3	-1.4	0.0	-0.3	-0.5	0.2	-1.1	-0.9	-0.2
4	165	-3.1	-3.3	0.2	-1.5	-1.6	0.0	-1.6	-1.7	0.2
4	158	-2.3	-2.2	-0.1	-0.4	-0.4	0.0	-1.8	-1.8	0.0
4	156	-2.9	-2.9	0.0	-0.1	-0.1	0.0	-2.8	-2.8	0.0
5	166	-0.8	-1.2	0.4	-0.1	-0.5	0.4	-0.7	-0.7	0.0
5	165	-1.3	-2.0	0.8	-0.5	-1.0	0.6	-0.8	-1.0	0.2
5	158	-2.4	-2.3	-0.1	-0.7	-0.6	-0.1	-1.7	-1.7	0.0
5	156	-3.1	-2.9	-0.1	-0.3	-0.3	0.0	-2.8	-2.7	-0.1
6	166	-0.5	-0.8	0.3	0.1	-0.2	0.3	-0.6	-0.5	0.0
6	165	-2.7	-2.6	-0.1	-1.1	-1.0	0.0	-1.6	-1.6	0.0
6	158	-1.9	-1.7	-0.1	-0.3	-0.1	-0.1	-1.6	-1.6	0.0
6	156	-2.0	-1.8	-0.2	-0.1	0.0	-0.1	-2.0	-1.9	-0.1
7	166	-0.6	-0.8	0.2	-0.2	-0.3	0.1	-0.5	-0.5	0.1
7	165	-2.1	-2.1	0.0	-1.0	-1.0	0.0	-1.1	-1.1	0.0
7	158	-1.9	-2.6	0.7	-0.4	-1.1	0.7	-1.6	-1.6	0.0
7	156	-1.6	-1.6	0.0	0.0	0.0	0.0	-1.7	-1.7	0.0
8	166	-1.4	-2.7	1.4	-0.2	-0.8	0.6	-1.2	-1.9	0.7
8	165	-2.0	-2.0	0.0	-1.0	-1.0	0.0	-1.0	-1.0	0.0
8	158	-2.4	-3.6	1.2	-0.7	-1.6	0.9	-1.7	-2.0	0.2
8	156	-1.8	-2.1	0.3	-0.2	-0.5	0.3	-1.6	-1.6	0.0
9	166	-2.7	-4.8	2.1	-0.3	-0.8	0.5	-2.4	-3.9	1.5
9	165	-2.1	-2.6	0.5	-1.1	-1.5	0.5	-1.0	-1.1	0.1
9	158	-3.9	-5.8	1.8	-1.6	-2.7	1.1	-2.4	-3.1	0.7
9	156	-2.5	-3.1	0.6	-0.7	-1.0	0.4	-1.8	-2.1	0.3
10	166	-0.7	-1.3	0.6	-0.2	-0.3	0.1	-0.5	-1.0	0.5
10	165	-2.4	-2.9	0.5	-1.0	-1.3	0.3	-1.4	-1.6	0.2
10	158	-2.5	-3.7	1.2	-0.9	-1.8	0.8	-1.5	-1.9	0.4
10	156	-2.7	-3.6	0.9	-0.8	-1.3	0.5	-2.0	-2.3	0.3

Table A2.3 McGreavey continued

Week	Sensor	Top Minus Base			Top Minus Interspace			Base Minus Interspace		
		Max	Min	Range	Max	Min	Range	Max	Min	Range
11	166	-0.5	-0.7	0.2	-0.1	-0.1	0.0	-0.5	-0.6	0.2
11	165	-1.5	-1.9	0.4	-0.5	-0.7	0.2	-1.0	-1.2	0.1
11	158	-1.3	-1.4	0.2	-0.3	-0.4	0.1	-1.0	-1.1	0.1
11	156	-1.9	-2.4	0.5	-0.4	-0.7	0.3	-1.5	-1.7	0.2
12	166	-0.6	-0.8	0.1	-0.1	-0.1	0.1	-0.6	-0.7	0.1
12	165	-1.5	-1.9	0.4	-0.5	-0.8	0.2	-1.0	-1.1	0.1
12	158	-1.1	-1.2	0.1	-0.2	-0.3	0.1	-0.9	-0.9	0.0
12	156	-1.6	-2.0	0.4	-0.5	-0.7	0.3	-1.1	-1.3	0.1
13	166	-0.7	-0.8	0.2	0.0	-0.1	0.1	-0.7	-0.8	0.1
13	165	-1.6	-1.8	0.3	-0.6	-0.7	0.1	-1.0	-1.1	0.1
13	158	-1.2	-1.3	0.1	-0.3	-0.3	0.0	-1.0	-1.0	0.0
13	156	-1.2	-1.3	0.1	-0.3	-0.4	0.1	-0.9	-0.9	0.0
14	166	-0.4	-0.5	0.1	0.0	0.0	0.0	-0.5	-0.5	0.1
14	165	-1.3	-1.5	0.2	-0.5	-0.6	0.1	-0.8	-0.9	0.1
14	158	-1.2	-1.2	0.1	-0.2	-0.2	0.0	-1.0	-1.0	0.0
14	156	-0.9	-1.0	0.1	-0.2	-0.2	0.0	-0.8	-0.8	0.0
15	166	-0.6	-0.7	0.2	0.0	-0.1	0.0	-0.5	-0.7	0.1
15	165	-1.3	-1.8	0.4	-0.5	-0.7	0.2	-0.9	-1.1	0.2
15	158	-1.3	-1.4	0.1	-0.3	-0.3	0.1	-1.0	-1.0	0.0
15	156	-1.0	-1.1	0.1	-0.2	-0.3	0.1	-0.8	-0.8	0.1
16	166	-0.6	-0.7	0.2	-0.1	-0.1	0.0	-0.5	-0.7	0.2
16	165	-1.3	-1.8	0.5	-0.5	-0.7	0.3	-0.9	-1.1	0.2
16	158	-1.3	-1.5	0.2	-0.3	-0.4	0.1	-1.0	-1.0	0.0
16	156	-0.9	-1.0	0.1	-0.2	-0.3	0.1	-0.7	-0.7	0.0
17	166	-0.5	-0.7	0.2	0.0	0.0	0.0	-0.5	-0.7	0.1
17	165	-1.5	-1.9	0.5	-0.5	-0.8	0.2	-0.9	-1.2	0.2
17	158	-1.4	-1.6	0.1	-0.4	-0.5	0.1	-1.0	-1.1	0.1
17	156	-1.1	-1.2	0.1	-0.2	-0.3	0.1	-0.9	-0.9	0.0
18	166	-0.5	-0.8	0.2	0.0	-0.1	0.0	-0.5	-0.7	0.2
18	165	-1.4	-2.0	0.6	-0.5	-0.8	0.3	-0.9	-1.2	0.3
18	158	-1.3	-1.4	0.1	-0.3	-0.4	0.1	-1.0	-1.0	0.1
18	156	-1.3	-1.4	0.2	-0.3	-0.4	0.1	-1.0	-1.1	0.1
19	166	-0.4	-0.5	0.1	0.0	0.0	0.0	-0.4	-0.5	0.1
19	165	-1.2	-1.7	0.5	-0.4	-0.7	0.2	-0.8	-1.0	0.3
19	158	-1.1	-1.1	0.0	-0.2	-0.3	0.0	-0.9	-0.9	0.0
19	156	-1.0	-1.1	0.1	-0.1	-0.2	0.1	-0.9	-0.9	0.0
20	166	-0.4	-0.5	0.1	0.0	0.0	0.0	-0.4	-0.5	0.1
20	165	-1.2	-1.5	0.3	-0.5	-0.6	0.1	-0.7	-0.9	0.2
20	158	-1.1	-1.1	0.0	-0.3	-0.2	0.0	-0.8	-0.9	0.1
20	156	-0.8	-0.8	0.0	-0.1	-0.1	0.0	-0.7	-0.7	0.0

Table A2.3 McGreavey continued

		Top Minus Base			Top Minus Interspace			Base Minus Interspace		
Week	Sensor	Max	Min	Range	Max	Min	Range	Max	Min	Range
21	166	-0.2	-0.2	0.0	0.0	0.0	0.0	-0.2	-0.2	0.0
21	165	-0.9	-0.9	0.1	-0.4	-0.4	0.0	-0.5	-0.5	0.1
21	158	-0.8	-0.8	0.0	-0.1	-0.1	0.0	-0.7	-0.7	0.0
21	156	-0.7	-0.7	0.0	0.0	0.0	0.0	-0.7	-0.7	0.0
22	166	-0.1	-0.1	0.0	0.0	0.1	0.0	-0.2	-0.2	0.0
22	165	-0.5	-0.6	0.1	-0.3	-0.3	0.1	-0.3	-0.3	0.1
22	158	-0.6	-0.6	0.0	-0.1	-0.1	0.0	-0.6	-0.5	0.0
22	156	-0.6	-0.6	0.0	0.1	0.0	0.0	-0.7	-0.7	0.0
23	166	0.0	-0.1	0.0	0.1	0.1	0.0	-0.1	-0.1	0.0
23	165	-0.4	-0.5	0.1	-0.2	-0.3	0.1	-0.1	-0.2	0.1
23	158	-0.4	-0.4	0.0	0.1	0.1	0.0	-0.5	-0.5	0.0
23	156	-0.6	-0.6	0.0	0.1	0.1	0.0	-0.7	-0.6	0.0
24	166	0.0	0.0	0.0	0.1	0.1	0.0	-0.1	-0.1	0.0
24	165	-0.3	-0.3	0.0	-0.2	-0.2	0.0	-0.1	-0.1	0.0
24	158	-0.4	-0.3	0.0	0.1	0.1	0.0	-0.4	-0.5	0.0
24	156	-0.5	-0.5	0.0	0.1	0.1	0.0	-0.6	-0.6	0.0
25	166	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0
25	165	-0.2	-0.2	0.0	-0.2	-0.2	0.0	0.0	0.0	0.0
25	158	-0.3	-0.3	0.0	0.1	0.1	0.0	-0.4	-0.5	0.0
25	156	-0.5	-0.5	0.0	0.2	0.2	0.0	-0.6	-0.6	0.0
26	166	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0
26	165	-0.1	-0.2	0.0	-0.1	-0.1	0.0	0.0	0.0	0.0
26	158	-0.3	-0.4	0.0	0.1	0.1	0.0	-0.4	-0.5	0.0
26	156	-0.5	-0.5	0.0	0.2	0.1	0.0	-0.6	-0.6	0.0
27	166	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.1	-0.1
27	165	-0.1	-0.1	0.0	-0.1	-0.1	0.0	0.0	0.0	0.0
27	158	-0.4	-0.4	0.0	0.1	0.1	0.0	-0.5	-0.5	0.0
27	156	-0.5	-0.5	0.0	0.1	0.2	-0.1	-0.6	-0.6	0.0
28	166	0.1	0.1	-0.1	0.1	0.1	0.0	0.0	0.1	-0.1
28	165	-0.1	-0.1	0.0	-0.1	-0.1	0.0	0.0	0.0	0.0
28	158	-0.4	-0.4	0.0	0.1	0.1	0.0	-0.5	-0.5	0.0
28	156	-0.5	-0.5	0.0	0.1	0.2	0.0	-0.6	-0.6	0.0
29	166	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0
29	165	0.8	-0.1	0.9	0.8	-0.1	0.9	0.0	0.0	0.0
29	158	-0.4	-0.4	0.0	0.1	0.1	0.1	-0.5	-0.5	0.0
29	156	-0.5	-0.5	0.0	0.1	0.2	0.0	-0.6	-0.6	0.0
30	166	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0
30	165	-0.2	-0.2	0.0	-0.1	-0.1	0.0	-0.1	-0.1	0.0
30	158	-0.4	-0.4	0.0	0.1	0.1	0.0	-0.5	-0.5	-0.1
30	156	-0.5	-0.5	0.0	0.2	0.1	0.0	-0.6	-0.6	0.0

Table A2.3 McGreavey continued

		Top Minus Base			Top Minus Interspace			Base Minus Interspace		
Week	Sensor	Max	Min	Range	Max	Min	Range	Max	Min	Range
31	166	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0
31	165	-0.2	-0.2	0.1	-0.1	-0.1	0.0	-0.1	-0.1	0.0
31	158	-0.5	-0.6	0.1	0.0	0.0	0.0	-0.5	-0.5	0.0
31	156	-0.5	-0.5	0.0	0.2	0.1	0.0	-0.7	-0.6	0.0
32	166	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0
32	165	0.5	-0.3	0.7	0.7	-0.1	0.9	-0.3	-0.1	-0.1
32	158	-0.6	-0.6	0.0	0.0	-0.1	0.1	-0.6	-0.6	0.0
32	156	-1.1	-0.9	-0.2	0.2	0.1	0.0	-1.3	-1.0	-0.2
33	166	-0.9	-0.7	-0.1	4.1	0.2	3.9	-4.9	-0.9	-4.0
33	165	12.1	-1.5	13.6	4.4	-1.4	5.8	7.7	-0.1	7.8
33	158	-4.7	-1.9	-2.8	-2.2	-0.2	-2.0	-2.5	-1.7	-0.8
33	156	2.4	-1.2	3.6	-5.6	-0.8	-4.8	8.0	-0.4	8.4
34	166	1.4	-2.0	3.4	2.7	-0.6	3.3	-1.3	-1.4	0.0
34	165	13.7	-4.7	18.5	5.8	-3.0	8.7	8.0	-1.7	9.7
34	158	-0.3	-3.2	2.9	-3.9	-1.5	-2.4	3.6	-1.7	5.2
34	156	6.8	0.3	6.5	-1.4	1.1	-2.4	8.2	-0.8	8.9

[1]Dates of weeks are located in Table A2.1
[2]Max = Maximum temperature in 24 hr period
[3]Min = Minimum temperature in 24 hr period
[4]Range = Maximum temperature minus minimum temperature in 24 hr period

Table A2.4. Mt. Margaret Site. Mean weekly temperature differences between soil sensor positions.

		Top Minus Base			Top Minus Interspace			Base Minus Interspace		
Week[1]	Sensor	Max[2]	Min[3]	Range[4]	Max	Min	Range	Max	Min	Range
1	155	-2.1	-4.1	1.9	-3.9	-4.6	0.7	-1.8	-0.5	-1.3
1	157	0.0	-0.3	0.3	-1.9	-4.7	2.8	-1.9	-4.5	2.6
1	162	5.3	-3.9	9.2	5.3	-8.6	13.9	0.0	-4.7	4.7
1	167	0.3	-1.7	2.0	-0.3	-5.1	4.8	-0.6	-3.3	2.8
2	155	-1.0	-2.1	1.1	-2.7	-2.4	-0.3	-1.7	-0.3	-1.4
2	157	0.6	-0.7	1.4	-1.1	-2.9	1.9	-1.7	-2.2	0.5
2	162	10.1	-2.9	13.0	15.7	-7.1	22.8	5.6	-4.3	9.8
2	167	0.8	-0.8	1.6	3.0	-3.7	6.7	2.2	-3.0	5.1
3	155	-0.1	-1.6	1.5	-1.4	-2.1	0.7	-1.3	-0.5	-0.8
3	157	0.7	-0.1	0.7	-0.9	-2.3	1.4	-1.6	-2.2	0.7
3	162	8.6	-2.6	11.2	12.1	-6.3	18.4	3.5	-3.7	7.2
3	167	0.5	-0.8	1.3	1.9	-3.6	5.5	1.4	-2.8	4.2
4	155	-1.6	-1.6	0.0	-2.2	-2.1	-0.1	-0.6	-0.5	-0.1
4	157	-0.4	-0.3	0.0	-1.5	-1.5	0.1	-1.1	-1.2	0.1
4	162	0.8	-1.6	2.4	-1.0	-4.8	3.8	-1.8	-3.2	1.4
4	167	-0.5	-0.7	0.2	-2.0	-3.0	1.0	-1.4	-2.2	0.8
5	155	0.6	-1.1	1.7	-0.1	-1.2	1.1	-0.7	-0.1	-0.6
5	157	0.5	-0.9	1.3	-0.3	-1.7	1.4	-0.8	-0.9	0.1
5	162	4.5	-1.4	5.9	6.8	-4.9	11.6	2.3	-3.5	5.7
5	167	0.3	-0.6	0.9	1.1	-2.8	3.9	0.7	-2.2	3.0
6	155	0.6	-0.9	1.5	-0.2	-1.3	1.1	-0.8	-0.4	-0.4
6	157	0.4	-0.4	0.8	-0.2	-0.8	0.6	-0.7	-0.4	-0.2
6	162	5.8	-1.2	7.0	9.2	-4.2	13.3	3.4	-3.0	6.4
6	167	-0.3	-0.6	0.3	0.0	-2.7	2.6	0.2	-2.1	2.3
7	155	-1.1	-1.1	0.0	-1.3	-1.3	0.1	-0.2	-0.2	0.1
7	157	-0.8	-0.8	0.0	-1.3	-1.4	0.1	-0.5	-0.6	0.1
7	162	-1.0	-3.0	1.9	-4.2	-6.3	2.1	-3.2	-3.3	0.1
7	167	-0.6	-0.6	0.0	-2.6	-2.8	0.1	-2.1	-2.2	0.1
8	155	-1.1	-1.4	0.4	-1.5	-1.9	0.5	-0.4	-0.5	0.1
8	157	-0.6	-0.5	-0.1	-1.3	-1.2	-0.1	-0.7	-0.7	-0.1
8	162	-0.1	-2.7	2.6	-3.3	-6.5	3.2	-3.2	-3.8	0.6
8	167	-0.4	-0.6	0.2	-2.7	-2.9	0.2	-2.3	-2.3	0.0
9	155	-2.2	-4.1	1.9	-2.1	-3.9	1.8	0.1	0.3	-0.1
9	157	-0.4	-0.7	0.3	-0.4	-0.7	0.2	0.0	0.0	0.0
9	162	-0.5	-3.1	2.6	-3.2	-6.8	3.5	-2.8	-3.7	0.9
9	167	-0.5	-1.1	0.6	-2.4	-3.1	0.8	-1.9	-2.0	0.1
10	155	-2.2	-3.5	1.2	-2.1	-3.2	1.1	0.2	0.3	-0.1
10	157	-0.7	-1.1	0.4	-1.0	-1.6	0.6	-0.3	-0.5	0.2
10	162	-1.0	-1.9	1.0	-3.9	-5.4	1.4	-3.0	-3.4	0.5
10	167	-0.6	-0.8	0.2	-2.3	-2.6	0.4	-1.7	-1.8	0.1

Table A2.4 Mt. Margaret continued

Week	Sensor	Top Minus Base			Top Minus Interspace			Base Minus Interspace		
		Max	Min	Range	Max	Min	Range	Max	Min	Range
11	155	-1.4	-2.8	1.4	-1.5	-2.8	1.3	-0.1	0.1	-0.1
11	157	-0.5	-0.9	0.4	-0.9	-1.6	0.7	-0.4	-0.7	0.4
11	162	-0.5	-2.1	1.7	-2.8	-5.4	2.5	-2.3	-3.2	0.9
11	167	-0.4	-0.8	0.4	-1.7	-2.5	0.7	-1.3	-1.7	0.3
12	155	-1.5	-2.8	1.4	-1.6	-3.0	1.4	-0.2	-0.2	0.0
12	157	-0.5	-0.8	0.3	-0.9	-1.6	0.7	-0.5	-0.8	0.3
12	162	-0.5	-1.7	1.2	-2.6	-4.6	2.1	-2.1	-3.0	0.9
12	167	-0.4	-0.8	0.4	-1.7	-2.5	0.8	-1.3	-1.7	0.4
13	155	-2.3	-4.8	2.5	-2.5	-4.8	2.3	-0.2	0.0	-0.1
13	157	-0.7	-1.0	0.3	-1.5	-2.2	0.7	-0.8	-1.2	0.4
13	162	-0.7	-3.1	2.4	-3.6	-7.7	4.2	-2.9	-4.6	1.8
13	167	-0.7	-1.4	0.7	-2.5	-4.2	1.7	-1.8	-2.8	1.0
14	155	-1.6	-3.4	1.8	-1.9	-3.6	1.7	-0.3	-0.2	-0.1
14	157	-0.5	-0.8	0.3	-1.2	-1.8	0.6	-0.7	-1.0	0.4
14	162	-0.3	-2.1	1.8	-2.5	-5.6	3.1	-2.1	-3.4	1.3
14	167	-0.5	-1.0	0.5	-1.8	-3.2	1.4	-1.4	-2.3	0.9
15	155	-0.9	-4.9	4.0	-1.5	-5.8	4.3	-0.5	-0.9	0.4
15	157	-0.4	-0.8	0.4	-1.0	-1.9	0.9	-0.6	-1.1	0.5
15	162	0.5	-3.0	3.5	-1.3	-7.4	6.1	-1.8	-4.4	2.6
15	167	-0.1	-1.5	1.4	-1.4	-4.8	3.4	-1.3	-3.3	2.0
16	155	-1.1	-3.5	2.4	-1.7	-4.3	2.7	-0.6	-0.8	0.3
16	157	-0.4	-0.7	0.4	-0.9	-1.7	0.8	-0.5	-1.0	0.5
16	162	0.7	-2.7	3.4	-0.8	-6.8	6.0	-1.5	-4.1	2.6
16	167	0.0	-1.2	1.2	-1.0	-3.9	2.9	-1.0	-2.7	1.7
17	155	-1.6	-4.4	2.8	-2.6	-5.7	3.1	-1.0	-1.4	0.3
17	157	-0.4	-1.0	0.5	-1.2	-2.5	1.2	-0.8	-1.5	0.7
17	162	0.7	-2.9	3.6	-1.1	-7.7	6.6	-1.8	-4.8	3.0
17	167	-0.1	-1.3	1.2	-1.3	-4.4	3.2	-1.2	-3.2	2.0
18	155	-0.6	-3.3	2.7	-1.6	-4.5	2.9	-1.0	-1.3	0.2
18	157	-0.4	-1.0	0.6	-1.1	-2.6	1.5	-0.7	-1.6	0.9
18	162	0.9	-2.3	3.3	-0.2	-6.6	6.4	-1.1	-4.3	3.1
18	167	0.0	-1.1	1.2	-0.3	-3.7	3.4	-0.4	-2.6	2.2
19	155	-1.2	-4.0	2.8	-2.2	-5.0	2.8	-1.0	-1.0	0.0
19	157	-0.6	-1.2	0.6	-1.8	-3.5	1.6	-1.2	-2.3	1.1
19	162	0.8	-2.7	3.5	-0.8	-7.3	6.4	-1.7	-4.6	2.9
19	167	-0.1	-1.3	1.1	-0.6	-4.2	3.6	-0.5	-3.0	2.5
20	155	-0.9	-3.5	2.6	-1.8	-4.8	3.1	-0.9	-1.3	0.5
20	157	-0.4	-1.0	0.6	-1.5	-3.0	1.5	-1.1	-2.0	0.9
20	162	1.0	-2.2	3.3	0.0	-6.3	6.2	-1.1	-4.0	3.0
20	167	-0.2	-1.0	0.9	-0.4	-3.6	3.2	-0.2	-2.6	2.3

Table A2.4 Mt. Margaret continued

		Top Minus Base			Top Minus Interspace			Base Minus Interspace		
Week	Sensor	Max	Min	Range	Max	Min	Range	Max	Min	Range
21	155	-0.6	-1.5	0.9	-0.9	-1.9	0.9	-0.3	-0.4	0.1
21	157	-0.2	-0.4	0.2	-0.6	-1.0	0.4	-0.4	-0.6	0.2
21	162	0.1	-0.6	0.7	-0.6	-1.9	1.3	-0.7	-1.3	0.6
21	167	-0.1	-0.4	0.3	-0.4	-1.1	0.8	-0.3	-0.7	0.5
22	155	-0.5	-2.6	2.0	-0.8	-3.2	2.5	-0.2	-0.7	0.4
22	157	-0.2	-0.4	0.2	-0.4	-1.0	0.6	-0.2	-0.6	0.4
22	162	0.5	-1.1	1.6	0.4	-2.7	3.1	0.0	-1.5	1.5
22	167	0.0	-0.6	0.7	0.1	-1.5	1.7	0.1	-0.9	1.0
23	155	-0.1	-1.7	1.6	-0.8	-3.2	2.4	-0.6	-1.4	0.8
23	157	-0.1	0.0	0.0	0.0	-0.2	0.3	0.1	-0.2	0.3
23	162	0.5	-1.7	2.2	0.3	-3.9	4.2	-0.2	-2.2	2.0
23	167	0.1	-0.7	0.7	0.2	-1.8	1.9	0.1	-1.1	1.2
24	155	0.1	-0.8	0.9	-0.6	-2.4	1.9	-0.7	-1.6	1.0
24	157	-0.1	-0.2	0.1	-0.3	-1.5	1.2	-0.1	-1.3	1.1
24	162	1.5	0.1	1.4	1.7	-0.6	2.3	0.2	-0.7	0.9
24	167	0.1	-0.4	0.5	0.5	-0.6	1.0	0.4	-0.1	0.5
25	155	-0.2	-0.9	0.7	-0.7	-1.6	0.9	-0.5	-0.7	0.2
25	157	-0.2	-0.5	0.3	-0.3	-0.7	0.5	-0.1	-0.3	0.2
25	162	0.3	0.0	0.3	0.2	-0.3	0.5	0.0	-0.2	0.2
25	167	-0.1	-0.3	0.2	0.1	-0.2	0.4	0.2	0.1	0.1
26	155	-0.1	-0.4	0.3	-0.3	-0.7	0.4	-0.3	-0.3	0.1
26	157	-0.1	-0.3	0.2	-0.1	-0.4	0.3	0.0	-0.1	0.1
26	162	0.7	-0.3	1.1	0.7	-0.5	1.2	0.0	-0.1	0.1
26	167	0.0	-0.1	0.1	0.2	0.0	0.2	0.2	0.2	0.1
27	155	-0.1	-0.9	0.8	-0.5	-1.5	1.0	-0.5	-0.6	0.1
27	157	-0.1	-0.2	0.1	-0.2	-0.9	0.7	-0.1	-0.7	0.6
27	162	3.7	-0.2	3.9	3.7	-0.4	4.1	0.0	-0.2	0.2
27	167	0.0	0.0	0.0	0.3	0.3	0.0	0.3	0.3	0.0
28	155	0.0	0.0	0.0	-4.9	-0.3	-4.6	-4.9	-0.2	-4.7
28	157	-0.1	-0.1	0.0	-0.5	0.0	-0.5	-0.4	0.0	-0.4
28	162	15.0	0.1	14.9	19.9	0.3	19.6	4.9	0.1	4.7
28	167	1.4	0.0	1.4	1.9	0.3	1.5	0.4	0.3	0.1
29	155	2.3	0.6	1.7	0.8	0.4	0.4	-1.4	-0.1	-1.3
29	157	-0.2	-0.1	-0.1	-2.9	-0.7	-2.3	-2.7	-0.6	-2.1
29	162	8.2	0.1	8.1	17.1	0.5	16.6	8.9	0.4	8.5
29	167	2.9	0.1	2.7	6.3	0.6	5.7	3.5	0.5	3.0
30	155	1.8	0.0	1.7	-0.8	-0.1	-0.7	-2.5	-0.1	-2.4
30	157	-0.4	-0.1	-0.3	-4.2	-1.6	-2.5	-3.7	-1.5	-2.2
30	162	1.3	0.1	1.2	8.3	0.2	8.1	6.9	0.0	6.9
30	167	1.2	0.0	1.2	4.8	0.4	4.4	3.6	0.4	3.3

Table A2.4 Mt. Margaret continued

		Top Minus Base			Top Minus Interspace			Base Minus Interspace		
Week	Sensor	Max	Min	Range	Max	Min	Range	Max	Min	Range
31	155	3.4	-0.5	3.9	-1.7	-0.8	-0.9	-5.1	-0.3	-4.8
31	157	-0.6	-0.2	-0.4	-3.6	-2.9	-0.7	-3.0	-2.7	-0.3
31	162	4.1	0.0	4.1	14.7	0.1	14.5	10.6	0.1	10.5
31	167	1.4	0.0	1.4	6.6	0.4	6.2	5.2	0.4	4.8
32	155	1.8	-0.4	2.2	-1.0	-1.1	0.1	-2.9	-0.7	-2.2
32	157	0.2	-0.3	0.6	-0.2	-1.3	1.1	-0.4	-1.0	0.6
32	162	2.6	0.0	2.7	9.3	0.3	8.9	6.6	0.4	6.3
32	167	0.8	0.1	0.7	4.2	0.6	3.5	3.4	0.6	2.8
33	155	4.8	-2.4	7.2	2.1	-3.0	5.1	-2.6	-0.6	-2.0
33	157	0.9	-0.6	1.6	2.9	-1.0	3.9	2.0	-0.3	2.3
33	162	8.0	-0.7	8.8	27.8	1.1	26.7	19.8	1.9	18.0
33	167	2.0	0.4	1.6	9.4	2.3	7.1	7.4	1.8	5.5
34	155	2.1	-2.8	4.8	0.6	-3.7	4.3	-1.5	-0.9	-0.6
34	157	0.7	-0.6	1.4	0.8	-1.2	2.0	0.1	-0.6	0.6
34	162	8.6	-0.8	9.4	28.3	1.3	27.0	19.7	2.2	17.6
34	167	2.5	0.6	2.0	10.4	4.7	5.7	7.9	4.1	3.8

[1]Dates of weeks are located in Table A2.1
[2]Max = Maximum temperature in 24 hr period
[3]Min = Minimum temperature in 24 hr period
[4]Range = Maximum temperature minus minimum temperature in 24 hr period

Table A2.5. Soapstone Site. Mean weekly temperature differences between soil sensor positions.

		Top Minus Base			Top Minus Interspace			Base Minus Interspace		
Week[1]	Sensor	Max[2]	Min[3]	Range[4]	Max	Min	Range	Max	Min	Range
1	152	-1.3	-3.4	2.1	-0.2	-1.1	0.8	1.1	2.3	-1.3
1	153	-2.6	-5.1	2.6	-1.9	-3.5	1.6	0.7	1.6	-1.0
1	159	-1.6	-4.6	3.0	-3.3	-3.5	0.3	-1.7	1.1	-2.8
1	163	-1.6	-4.0	2.3	-0.9	-1.5	0.6	0.7	2.5	-1.8
2	152	-0.3	-2.3	2.0	0.4	-0.5	0.9	0.7	1.8	-1.0
2	153	-1.2	-2.9	1.7	-1.3	-2.2	0.9	-0.1	0.7	-0.8
2	159	-0.8	-3.1	2.3	-1.7	-2.8	1.2	-0.9	0.3	-1.2
2	163	-0.6	-2.9	2.4	-0.1	-1.1	1.1	0.5	1.8	-1.3
3	152	0.2	-1.8	2.1	0.6	-0.1	0.7	0.4	1.7	-1.3
3	153	0.1	-2.0	2.1	0.5	-0.8	1.2	0.4	1.3	-0.9
3	159	0.2	-2.3	2.5	-0.8	-1.9	1.1	-1.0	0.4	-1.4
3	163	0.3	-2.5	2.8	0.5	-0.5	1.0	0.3	2.1	-1.8
4	152	-1.6	-2.5	0.9	-0.3	-0.8	0.5	1.3	1.7	-0.4
4	153	-2.1	-2.8	0.7	-1.9	-2.2	0.3	0.2	0.6	-0.4
4	159	-2.3	-3.1	0.9	-2.7	-3.2	0.6	-0.4	-0.1	-0.3
4	163	-1.9	-2.9	1.0	-0.1	-1.1	1.0	1.9	1.9	0.0
5	152	1.3	-1.3	2.6	1.9	0.3	1.7	0.7	1.6	-0.9
5	153	0.9	-1.5	2.4	1.0	-0.3	1.3	0.1	1.2	-1.1
5	159	1.4	-1.8	3.1	1.5	-0.9	2.4	0.1	0.9	-0.8
5	163	1.3	-1.9	3.2	1.5	-0.1	1.6	0.2	1.8	-1.6
6	152	0.1	-1.8	1.9	0.9	-0.1	0.9	0.8	1.8	-1.0
6	153	0.0	-2.0	2.0	0.6	-0.9	1.5	0.6	1.1	-0.5
6	159	0.2	-2.1	2.3	0.1	-1.5	1.6	-0.1	0.6	-0.7
6	163	-0.7	-2.8	2.1	0.5	-0.9	1.4	1.2	1.9	-0.7
7	152	-1.3	-1.9	0.6	-0.9	-1.5	0.6	0.4	0.4	0.0
7	153	-1.8	-1.9	0.1	-1.8	-1.8	0.0	0.0	0.1	-0.1
7	159	-2.2	-2.0	-0.2	-2.9	-2.4	-0.5	-0.7	-0.4	-0.3
7	163	-2.4	-2.3	0.0	-1.6	-1.7	0.1	0.7	0.6	0.1
8	152	-0.8	-1.4	0.6	-0.1	-0.7	0.6	0.7	0.7	0.0
8	153	-1.2	-1.3	0.0	-0.4	-0.4	0.0	0.9	0.9	0.0
8	159	-1.6	-1.4	-0.1	-1.3	-1.2	-0.1	0.3	0.2	0.1
8	163	-1.9	-1.8	0.0	-1.4	-1.4	-0.1	0.4	0.4	0.0
9	152	-1.0	-1.3	0.3	0.0	-0.4	0.4	1.0	0.9	0.0
9	153	-1.7	-2.3	0.6	-1.0	-1.7	0.7	0.7	0.6	0.1
9	159	-1.3	-1.4	0.1	-1.1	-1.3	0.1	0.1	0.1	0.0
9	163	-2.6	-3.7	1.1	-1.6	-2.7	1.1	0.9	1.0	-0.1
10	152	-1.9	-2.4	0.5	-1.2	-1.7	0.6	0.7	0.7	0.0
10	153	-4.8	-6.3	1.4	-5.9	-7.8	1.9	-1.0	-1.5	0.5
10	159	-2.3	-3.2	0.9	-2.7	-3.8	1.1	-0.4	-0.6	0.2
10	163	-3.0	-5.3	2.3	-2.6	-4.9	2.3	0.4	0.4	0.0

Table A2.5 Soapstone continued

Week	Sensor	Top Minus Base			Top Minus Interspace			Base Minus Interspace		
		Max	Min	Range	Max	Min	Range	Max	Min	Range
11	152	-0.9	-1.3	0.4	-0.6	-1.0	0.4	0.3	0.3	0.0
11	153	-1.2	-1.7	0.5	-1.7	-2.3	0.6	-0.5	-0.6	0.1
11	159	-0.8	-1.2	0.4	-1.2	-1.6	0.5	-0.4	-0.4	0.0
11	163	-0.7	-2.3	1.6	-0.7	-2.0	1.3	0.0	0.3	-0.3
12	152	-1.0	-1.2	0.2	-0.8	-1.0	0.2	0.2	0.2	0.0
12	153	-1.5	-2.0	0.5	-1.9	-2.6	0.6	-0.4	-0.6	0.2
12	159	-1.2	-1.8	0.6	-1.9	-2.6	0.7	-0.7	-0.8	0.1
12	163	-2.1	-3.4	1.3	-2.1	-3.2	1.1	-0.1	0.1	-0.2
13	152	-1.1	-1.6	0.5	-0.9	-1.3	0.4	0.2	0.3	-0.1
13	153	-2.1	-3.0	0.9	-2.9	-3.9	1.0	-0.8	-0.9	0.1
13	159	-1.2	-2.3	1.1	-2.1	-3.5	1.4	-0.9	-1.3	0.4
13	163	-1.5	-3.7	2.3	-1.6	-4.0	2.4	-0.1	-0.2	0.1
14	152	-1.3	-2.5	1.1	-0.6	-1.3	0.7	0.8	1.2	-0.4
14	153	-2.1	-3.4	1.4	-2.6	-4.0	1.4	-0.5	-0.5	0.0
14	159	-1.2	-2.4	1.2	-2.0	-3.7	1.7	-0.7	-1.2	0.5
14	163	-1.0	-4.0	3.1	-1.1	-4.3	3.2	-0.2	-0.3	0.1
15	152	-0.7	-1.7	1.0	-0.2	-0.5	0.3	0.5	1.2	-0.7
15	153	-0.8	-1.3	0.5	-1.0	-1.1	0.1	-0.2	0.2	-0.4
15	159	-0.4	-1.1	0.7	-0.6	-1.3	0.7	-0.2	-0.3	0.0
15	163	-0.1	-1.2	1.1	0.3	0.0	0.2	0.4	1.2	-0.9
16	152	-0.4	-1.1	0.7	-0.1	-0.2	0.1	0.3	0.9	-0.6
16	153	-0.7	-1.2	0.5	-0.7	-0.6	-0.1	0.0	0.5	-0.5
16	159	-0.4	-0.9	0.5	-0.4	-0.9	0.5	-0.1	0.0	0.0
16	163	-0.2	-1.5	1.3	-0.1	-0.5	0.5	0.1	1.0	-0.9
17	152	-1.2	-2.7	1.4	-0.7	-1.2	0.4	0.5	1.5	-1.0
17	153	-1.5	-2.8	1.3	-1.7	-2.6	1.0	-0.2	0.1	-0.3
17	159	-1.0	-1.6	0.7	-1.3	-1.3	0.1	-0.3	0.3	-0.6
17	163	-0.9	-2.8	1.9	-0.7	-1.8	1.1	0.2	1.0	-0.8
18	152	-0.7	-1.9	1.2	-0.4	-0.6	0.2	0.3	1.3	-1.0
18	153	-1.0	-1.8	0.9	-1.3	-1.4	0.1	-0.3	0.5	-0.8
18	159	-0.7	-1.2	0.6	-0.9	-0.8	-0.1	-0.3	0.4	-0.7
18	163	-0.2	-2.1	1.9	0.1	-0.7	0.8	0.2	1.3	-1.1
19	152	-1.1	-2.6	1.5	-0.8	-1.5	0.6	0.2	1.1	-0.9
19	153	-1.5	-2.9	1.4	-2.0	-3.1	1.1	-0.5	-0.2	-0.3
19	159	-1.0	-1.7	0.7	-1.4	-1.1	-0.3	-0.4	0.6	-1.0
19	163	-0.5	-3.1	2.6	-0.5	-2.4	2.0	0.0	0.7	-0.7
20	152	-0.7	-1.7	1.0	-0.6	-1.1	0.5	0.1	0.5	-0.5
20	153	-1.3	-2.7	1.4	-1.8	-3.7	1.9	-0.5	-1.0	0.5
20	159	-1.0	-1.7	0.7	-1.6	-1.8	0.2	-0.6	-0.1	-0.5
20	163	-0.4	-2.7	2.3	-0.5	-1.8	1.3	-0.1	0.9	-1.0

Table A2.5 Soapstone continued

Week	Sensor	Top Minus Base			Top Minus Interspace			Base Minus Interspace		
		Max	Min	Range	Max	Min	Range	Max	Min	Range
21	152	-0.2	-0.5	0.3	-0.3	-0.7	0.4	-0.1	-0.2	0.0
21	153	-1.4	-2.7	1.3	-2.1	-3.8	1.7	-0.8	-1.1	0.4
21	159	-0.9	-1.5	0.6	-1.5	-2.4	0.9	-0.6	-0.8	0.2
21	163	-0.3	-2.0	1.7	-0.6	-2.6	2.0	-0.3	-0.6	0.3
22	152	0.1	0.0	0.0	0.0	0.0	0.1	-0.1	-0.1	0.0
22	153	-0.2	-0.4	0.2	-0.3	-0.3	-0.1	-0.2	0.1	-0.3
22	159	-0.2	-0.4	0.2	-0.4	-0.7	0.3	-0.2	-0.3	0.1
22	163	0.2	0.0	0.2	0.2	0.1	0.0	-0.1	0.1	-0.1
23	152	0.1	0.0	0.1	0.1	0.0	0.1	0.0	0.0	-0.1
23	153	0.0	0.1	-0.1	0.1	0.9	-0.8	0.1	0.8	-0.7
23	159	0.0	0.0	0.0	-0.1	0.1	-0.1	0.0	0.1	-0.1
23	163	0.2	0.2	0.0	0.4	1.0	-0.7	0.2	0.8	-0.7
24	152	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.0
24	153	0.0	0.0	0.0	0.1	0.3	-0.3	0.0	0.3	-0.3
24	159	-0.1	-0.1	0.0	-0.1	-0.1	0.0	0.0	0.0	0.0
24	163	0.3	0.2	0.1	0.4	0.5	-0.1	0.1	0.3	-0.2
25	152	0.1	0.0	0.1	0.0	-0.1	0.1	-0.1	0.0	0.0
25	153	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	159	-0.1	-0.1	0.0	-0.1	-0.1	0.0	0.0	0.0	0.0
25	163	0.2	0.2	0.0	0.3	0.3	0.0	0.0	0.1	0.0
26	152	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	153	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
26	159	-0.1	-0.1	0.0	-0.1	-0.1	0.0	0.0	0.0	0.0
26	163	0.5	0.2	0.3	0.6	0.2	0.3	0.0	0.0	0.0
27	152	0.1	0.1	0.0	-0.4	0.1	-0.5	-0.6	-0.1	-0.5
27	153	1.8	0.1	1.7	1.9	0.1	1.7	0.0	0.0	0.0
27	159	0.9	-0.1	1.0	0.1	-0.1	0.2	-0.9	0.0	-0.9
27	163	3.7	0.2	3.6	2.1	0.1	2.0	-1.6	0.0	-1.6
28	152	3.0	0.9	2.1	-0.8	0.3	-1.1	-3.8	-0.5	-3.2
28	153	6.5	2.7	3.8	6.9	3.6	3.4	0.4	0.8	-0.4
28	159	4.4	0.8	3.6	1.2	0.5	0.8	-3.2	-0.3	-2.8
28	163	7.6	1.8	5.8	1.9	1.2	0.7	-5.7	-0.6	-5.1
29	152	3.5	1.8	1.7	0.5	0.4	0.1	-3.1	-1.5	-1.6
29	153	5.0	2.3	2.7	5.6	4.0	1.6	0.5	1.6	-1.1
29	159	2.8	0.8	2.0	0.4	0.0	0.4	-2.4	-0.8	-1.6
29	163	9.3	3.3	6.0	1.3	2.3	-1.0	-8.0	-1.0	-7.0
30	152	1.0	-0.8	1.8	-2.4	0.0	-2.4	-3.4	0.8	-4.2
30	153	2.2	-0.3	2.5	2.3	1.2	1.1	0.1	1.5	-1.4
30	159	0.8	-1.1	1.9	-0.4	-0.5	0.1	-1.2	0.6	-1.7
30	163	.	.	.	.	.	.	.	.	.

Table A2.5 Soapstone continued

Week	Sensor	Top Minus Base			Top Minus Interspace			Base Minus Interspace		
		Max	Min	Range	Max	Min	Range	Max	Min	Range
31	152	0.6	-1.1	1.7	-2.9	0.2	-3.1	-3.5	1.4	-4.8
31	153	1.4	-0.7	2.1	1.4	1.2	0.2	0.0	1.9	-1.9
31	159	0.6	-1.2	1.8	-0.5	-0.3	-0.3	-1.1	0.9	-2.0
31	163	.	.	.	.	.	.	.	.	.
32	152	1.1	-0.6	1.7	-1.2	-0.1	-1.1	-2.3	0.5	-2.8
32	153	1.8	-0.5	2.3	2.0	0.6	1.3	0.2	1.1	-1.0
32	159	0.8	-0.7	1.5	-0.1	-0.2	0.0	-0.9	0.6	-1.5
32	163	.	.	.	.	.	.	.	.	.
33	152	2.9	0.8	2.1	-1.6	1.4	-3.0	-4.5	0.6	-5.1
33	153	3.4	0.9	2.5	2.2	2.6	-0.4	-1.2	1.7	-2.9
33	159	2.7	0.3	2.4	0.3	1.2	-0.9	-2.3	1.0	-3.3
33	163	.	.	.	.	.	.	.	.	.
34	152	1.4	-0.9	2.4	-2.6	0.2	-2.8	-4.0	1.1	-5.1
34	153	2.1	-0.5	2.5	1.0	1.5	-0.5	-1.1	2.0	-3.1
34	159	1.8	-1.3	3.1	-0.4	-0.4	0.1	-2.2	0.8	-3.0
34	163	.	.	.	.	.	.	.	.	.

Periods (.) in data represent data logger malfunction
[1]Dates of weeks are located in Table A2.1
[2]Max = Maximum temperature in 24 hr period
[3]Min = Minimum temperature in 24 hr period

APPENDIX C

Soil and vegetation data for Chapter 3.

Table A3.1. Results for mineral soil core sample analysis.

Site Name	Hummock/ Interspace	Pair No.	Start Depth	End Depth	Organic Matter (%)	Total Dry Weight (g)	Organic Matter (g)	% Sand	% Silt	% Clay	%Sand/ %Silt
Mansfield	Hummock	1	0	8	5.8	158	9.2	29	51	20	0.57
Mansfield	Hummock	1	8	16	5.9	133	7.8	26	54	20	0.48
Mansfield	Hummock	1	16	24	5.5	186	10.2	29	47	24	0.62
Mansfield	Interspace	1	0	8	6.3	163	10.3	39	43	18	0.91
Mansfield	Interspace	1	8	16	3.9	149	5.8	47	35	18	1.34
Mansfield	Hummock	2	0	8	7.3	132	9.6	25	53	22	0.47
Mansfield	Hummock	2	8	16	5.1	170	8.7	25	52	23	0.48
Mansfield	Hummock	2	16	24	5.2	155	8.1	19	55	26	0.35
Mansfield	Interspace	2	0	8	13	185	24.1	32	44	24	0.73
Mansfield	Interspace	2	8	16	5.1	223	11.4	25	49	26	0.51
Mansfield	Hummock	4	0	8	33.7	84	28.3	25	69	6	0.36
Mansfield	Hummock	4	8	16	21.8	108	23.5	33	62	5	0.53
Mansfield	Hummock	4	16	24	30.9	68	21.0	41	56	3	0.73
Mansfield	Interspace	4	0	8	34.9	82	28.6	43	53	4	0.81
Mansfield	Interspace	4	8	16	31.1	76	23.6	41	56	3	0.73
Mansfield	Hummock	5	0	8	15.9	106	16.9	25	63	12	0.40
Mansfield	Hummock	5	8	16	14.3	156	22.3	27	57	16	0.47
Mansfield	Hummock	5	16	24	13	142	18.5	23	57	20	0.40
Mansfield	Hummock	5	24	32	13.3	159	21.1	27	55	18	0.49
Mansfield	Hummock	5	32	40	21	116	24.4	39	49	12	0.80
Mansfield	Interspace	5	0	8	19.5	110	21.5	31	60	9	0.52
Mansfield	Interspace	5	8	16	14.8	152	22.5	31	53	16	0.58

Table A3.1 Mineral Soil continued

Site Name	Hummock/ Interspace	Pair No.	Start Depth	End Depth	Organic Matter (%)	Total Dry Weight (g)	Organic Matter (g)	% Sand	% Silt	% Clay	%Sand/ %Silt
Mansfield	Hummock	6	0	8	11.4	192	21.9	25	73	2	0.34
Mansfield	Hummock	6	8	16	5.9	217	12.8	31	53	16	0.58
Mansfield	Hummock	6	16	24	4.5	250	11.3	39	48	13	0.81
Mansfield	Hummock	6	24	29	3.1	271	8.4	60	31	9	1.94
Mansfield	Interspace	6	0	8	8.2	203	16.6	26	72	2	0.36
Mansfield	Interspace	6	8	16	6.1	255	15.6	29	53	18	0.55
McGreavey	Hummock	1	0	8	16.9	160	27.0	49	40	11	1.23
McGreavey	Hummock	1	8	16	3.6	258	9.3	49	36	15	1.36
McGreavey	Hummock	1	16	24	1	389	3.9	57	32	11	1.78
McGreavey	Interspace	1	0	8	30.8	59	18.2	.	.	.	
McGreavey	Interspace	1	8	16	13.7	131	17.9	35	42	23	0.83
McGreavey	Hummock	2	0	8	40.6	69	28.0	.	.	.	
McGreavey	Hummock	2	8	16	12.7	132	16.8	45	38	17	1.18
McGreavey	Hummock	2	16	24	4.1	225	9.2	41	40	19	1.03
McGreavey	Interspace	2	0	8	15.9	127	20.2	41	38	21	1.08
McGreavey	Interspace	2	8	16	4.2	229	9.6	31	46	23	0.67
McGreavey	Interspace	2	16	24	2.6	202	5.3	69	24	7	2.88
McGreavey	Hummock	3	0	8	1	317	3.2	75	20	5	3.75
McGreavey	Hummock	3	8	16	0.7	359	2.5	66	23	11	2.87
McGreavey	Hummock	3	16	24	12	144	17.3	35	42	23	0.83
McGreavey	Interspace	3	0	8	2.7	209	5.6	57	30	13	1.90
McGreavey	Interspace	3	8	16	10.7	151	16.2	.	.	.	
McGreavey	Interspace	3	16	24	5.8	161	9.3	19	52	29	0.37
McGreavey	Interspace	4	0	8	1.8	303	5.5	67	25	8	2.68
McGreavey	Interspace	4	8	16	0.4	401	1.6	67	25	8	2.68

Table A3.1 Mineral Soil continued

Site Name	Hummock/ Interspace	Pair No.	Start Depth	End Depth	Organic Matter (%)	Total Dry Weight (g)	Organic Matter (g)	% Sand	% Silt	% Clay	%Sand/ %Silt
McGreavey	Hummock	5	0	8	0.3	267	0.8	79	16	5	4.94
McGreavey	Hummock	5	8	16	0.2	411	0.8	73	22	5	3.32
McGreavey	Hummock	5	16	24	0.2	336	0.7	73	23	4	3.17
McGreavey	Interspace	5	0	8	2.7	268	7.2	61	29	10	2.10
McGreavey	Interspace	5	8	16	0.3	414	1.2	71	25	4	2.84
McGreavey	Interspace	5	16	24	5.5	186	10.2	43	40	17	1.08
McGreavey	Hummock	6	0	8	4.3	231	9.9	47	37	16	1.27
McGreavey	Hummock	6	8	16	0.8	432	3.5	65	28	7	2.32
McGreavey	Hummock	6	16	24	5.8	238	13.8	57	35	8	1.63
McGreavey	Interspace	6	0	8	3.8	282	10.7	55	33	12	1.67
McGreavey	Interspace	6	8	16	6.6	170	11.2	36	46	18	0.78
Mt. Margaret	Hummock	1	0	8	11.7	131	15.3	21	52	27	0.40
Mt. Margaret	Hummock	1	8	16	8.6	164	14.1	18	40	42	0.45
Mt. Margaret	Hummock	1	16	24	5	202	10.1	24	41	35	0.59
Mt. Margaret	Hummock	1	24	32	3.1	179	5.5	32	38	30	0.84
Mt. Margaret	Interspace	1	0	8	11.4	192	21.9	17	43	40	0.40
Mt. Margaret	Interspace	1	8	16	6.7	246	16.5	16	46	38	0.35
Mt. Margaret	Hummock	2	0	8	12.6	164	20.7	6	69	25	0.09
Mt. Margaret	Hummock	2	8	16	4.2	293	12.3	38	45	17	0.84
Mt. Margaret	Hummock	2	16	24	0.5	313	1.6	74	20	6	3.70
Mt. Margaret	Interspace	2	0	8	9.1	191	17.4	27	47	26	0.57
Mt. Margaret	Interspace	2	8	16	1.8	351	6.3	68	22	10	3.09

Table A3.1 Mineral Soil continued

Site Name	Hummock/ Interspace	Pair No.	Start Depth	End Depth	Organic Matter (%)	Total Dry Weight (g)	Organic Matter (g)	% Sand	% Silt	% Clay	%Sand/ %Silt
Mt. Margaret	Hummock	3	0	8	18	118	21.2	22	49	29	0.45
Mt. Margaret	Hummock	3	8	16	9.9	216	21.4	19	48	33	0.40
Mt. Margaret	Hummock	3	16	24	3.2	287	9.2	39	45	16	0.87
Mt. Margaret	Interspace	3	0	8	10.7	224	24.0	17	50	33	0.34
Mt. Margaret	Interspace	3	8	16	2.1	354	7.4	47	37	16	1.27
Mt. Margaret	Hummock	4	0	8	11.6	140	16.2	21	43	36	0.49
Mt. Margaret	Hummock	4	8	16	4.3	260	11.2	46	34	20	1.35
Mt. Margaret	Hummock	4	16	24	1.1	380	4.2	53	34	13	1.56
Mt. Margaret	Interspace	4	0	8	12.8	165	21.1	19	66	15	0.29
Mt. Margaret	Interspace	4	8	16	1.6	342	5.5	51	35	14	1.46
Mt. Margaret	Hummock	5	0	8	16	142	22.7	25	47	28	0.53
Mt. Margaret	Hummock	5	8	16	8.2	166	13.6	23	42	35	0.55
Mt. Margaret	Hummock	5	16	24	4.5	211	9.5	35	43	22	0.81
Mt. Margaret	Hummock	5	24	32	3.2	242	7.7	47	35	18	1.34
Mt. Margaret	Interspace	5	0	8	13.2	128	16.9	25	48	27	0.52
Mt. Margaret	Interspace	5	8	16	6.1	130	7.9	28	40	32	0.70
Mt. Margaret	Hummock	6	0	8	8.9	217	19.3	46	35	19	1.31
Mt. Margaret	Hummock	6	8	16	4.3	260	11.2	51	31	18	1.65
Mt. Margaret	Hummock	6	16	24	2.2	370	8.1	51	31	18	1.65
Mt. Margaret	Hummock	6	24	32	0.9	262	2.4	57	26	17	2.19
Mt. Margaret	Hummock	6	32	40	0.7	424	3.0	59	26	15	2.27
Mt. Margaret	Interspace	6	0	8	5.8	207	12.0	51	32	17	1.59
Mt. Margaret	Interspace	6	8	16	2.3	303	7.0	53	33	14	1.61

Table A3.1 Mineral Soil continued

Site Name	Hummock/ Interspace	Pair No.	Start Depth	End Depth	Organic Matter (%)	Total Dry Weight (g)	Organic Matter (g)	% Sand	% Silt	% Clay	%Sand/ %Silt
Soapstone	Hummock	1	0	8	4.8	152	7.3	59	27	14	2.19
Soapstone	Hummock	1	8	16	3	230	6.9	65	22	13	2.95
Soapstone	Hummock	1	16	24	2.8	284	8.0	72	14	14	5.14
Soapstone	Hummock	1	24	32	1.1	329	3.6	80	12	8	6.67
Soapstone	Hummock	1	32	40	2.5	219	5.5	56	27	17	2.07
Soapstone	Hummock	1	40	48	1.5	392	5.9	55	27	18	2.04
Soapstone	Interspace	1	0	8	12.3	152	18.7	57	32	11	1.78
Soapstone	Interspace	1	8	16	3.7	174	6.4	64	24	12	2.67
Soapstone	Hummock	2	0	8	4.5	166	7.5	59	29	12	2.03
Soapstone	Hummock	2	8	16	5.2	188	9.8	65	20	15	3.25
Soapstone	Hummock	2	16	24	4.8	222	10.7	69	20	11	3.45
Soapstone	Hummock	2	24	32	2.2	278	6.1	73	22	5	3.32
Soapstone	Hummock	2	32	40	2.1	296	6.2	61	25	14	2.44
Soapstone	Hummock	2	40	48	1.3	296	3.8	59	23	18	2.57
Soapstone	Interspace	2	0	8	18.8	105	19.7	41	47	12	0.87
Soapstone	Interspace	2	8	16	4.9	224	11.0	59	25	16	2.36
Soapstone	Hummock	3	0	8	5.3	191	10.1	59	33	8	1.79
Soapstone	Hummock	3	8	16	3.4	212	7.2	61	26	13	2.35
Soapstone	Hummock	3	16	24	3.3	181	6.0	65	21	14	3.10
Soapstone	Hummock	3	24	32	3.4	206	7.0	66	20	14	3.30
Soapstone	Hummock	3	32	40	1.9	320	6.1	55	27	18	2.04
Soapstone	Hummock	3	40	48	1.3	341	4.4	56	26	18	2.15
Soapstone	Interspace	3	0	8	3.8	278	10.6	59	26	15	2.27
Soapstone	Interspace	3	8	16	1.4	323	4.5	59	25	16	2.36

Table A3.1 Mineral Soil continued

Site Name	Hummock/ Interspace	Pair No.	Start Depth	End Depth	Organic Matter (%)	Total Dry Weight (g)	Organic Matter (g)	% Sand	% Silt	% Clay	%Sand/ %Silt
Soapstone	Hummock	4	0	8	6.4	147	9.4	44	40	16	1.10
Soapstone	Hummock	4	8	16	4.3	186	8.0	57	31	12	1.84
Soapstone	Hummock	4	16	24	4.3	210	9.0	57	30	13	1.90
Soapstone	Hummock	4	24	32	1.3	231	3.0	69	21	10	3.29
Soapstone	Hummock	4	32	40	2.2	295	6.5	63	23	14	2.74
Soapstone	Hummock	4	40	48	3	247	7.4	57	27	16	2.11
Soapstone	Interspace	4	0	8	6.2	190	11.8	56	32	12	1.75
Soapstone	Interspace	4	8	16	2.3	312	7.2	77	17	6	4.53
Soapstone	Hummock	5	0	8	4.6	179	8.2	51	34	15	1.50
Soapstone	Hummock	5	8	16	2.7	216	5.8	59	27	14	2.19
Soapstone	Hummock	5	16	24	2.7	299	8.1	63	23	14	2.74
Soapstone	Hummock	5	24	32	3.3	194	6.4	53	31	16	1.71
Soapstone	Hummock	5	32	40	1.6	350	5.6	64	24	12	2.67
Soapstone	Hummock	5	40	48	1.3	361	4.7	59	27	14	2.19
Soapstone	Interspace	5	0	8	10.6	164	17.4	41	45	14	0.91
Soapstone	Interspace	5	8	16	6.7	189	12.7	55	30	15	1.83
Soapstone	Hummock	6	0	8	5.1	177	9.0	54	32	14	1.69
Soapstone	Hummock	6	8	16	4.2	212	8.9	55	31	14	1.77
Soapstone	Hummock	6	16	24	3.6	267	9.6	54	30	16	1.80
Soapstone	Hummock	6	24	32	3.4	205	7.0	56	27	17	2.07
Soapstone	Interspace	6	0	8	4.5	209	9.4	58	28	14	2.07
Soapstone	Interspace	6	8	16	2.6	318	8.3	59	25	16	2.36

Table A3.2. Results from analyses of organic horizon samples in soil cores.

Site Name	Hummock/ Interspace	Sample No.	Start Depth	End Depth	Compression (cm)	Total Depth with Compression (cm)	Organic Matter (%)	Dry Weight (g)	Organic Matter (g)
Mansfield	Hummock	1	0	6	6	12	11.2	85	9.5
Mansfield	Interspace	1	0	3	6	9	8	30	2.4
Mansfield	Hummock	2	0	6	19	25	11.4	100	11.4
Mansfield	Interspace	2	0	2	30	32	12.2	34	4.1
Mansfield	Hummock	3	0	15	55	Didn't reach mineral	31.9	118	37.6
Mansfield	Hummock	3	15	30			30.1	122	36.7
Mansfield	Hummock	3	30	45			20.8	169	35.2
Mansfield	Hummock	3	45	61			28	122	34.2
Mansfield	Interspace	3	0	15	63	Didn't reach mineral	26.3	121	31.8
Mansfield	Interspace	3	15	30			26.1	140	36.5
Mansfield	Interspace	3	30	45			19.1	146	27.9
Mansfield	Interspace	3	45	51			29.1	48	14.0
Mansfield	Hummock	4	0	15	17	Didn't reach mineral	20.1	137	27.5
Mansfield	Hummock	4	15	30			25.7	181	46.5
Mansfield	Hummock	4	30	45			24.7	183	45.2
Mansfield	Hummock	4	45	58			30.7	124	38.1
Mansfield	Interspace	4	0	15	5	Didn't reach mineral	27.4	156	42.7
Mansfield	Interspace	4	15	30			19.4	184	35.7
Mansfield	Interspace	4	30	39			26.8	77	20.6
Mansfield	Hummock	5	0	6	15	21	15.1	69	10.4
Mansfield	Interspace	5	0	2	11	13	15.7	14	2.2
Mansfield	Hummock	6	0	15	34	86	19.5	161	31.4
Mansfield	Hummock	6	15	30			19.6	235	46.1
Mansfield	Hummock	6	30	45			25.8	161	41.5
Mansfield	Hummock	6	45	52			25.7	90	23.1

Table A3.2 Organic Soil continued

Site Name	Hummock/ Interspace	Sample No.	Start Depth	End Depth	Compression (cm)	Total Depth with Compression (cm)	Organic Matter (%)	Dry Weight (g)	Organic Matter (g)
Mansfield	Interspace	6	0	15	25	76	21.2	165	35.0
Mansfield	Interspace	6	15	30			17.9	214	38.3
Mansfield	Interspace	6	30	45			24.2	135	32.7
Mansfield	Interspace	6	45	51			23.3	92	21.4
McGreavey	Hummock	1	0	18	23	41	42.5	100	42.5
McGreavey	Interspace	1	0	7	x	x	46.8	42	19.7
McGreavey	Hummock	2	0	15	18	65	52.9	64	33.9
McGreavey	Hummock	2	15	30			45.8	87	39.8
McGreavey	Hummock	2	30	47			45.7	111	50.7
McGreavey	Interspace	2	0	15	20	60	55.7	72	40.1
McGreavey	Interspace	2	15	30			46.3	107	49.5
McGreavey	Interspace	2	30	40			53.8	75	40.4
McGreavey	Hummock	3	0	15	22	91	62.7	60	37.6
McGreavey	Hummock	3	15	30			56.2	75	42.2
McGreavey	Hummock	3	30	45			63.7	74	47.1
McGreavey	Hummock	3	45	60			54.9	74	40.6
McGreavey	Hummock	3	60	69			41.2	56	23.1
McGreavey	Interspace	3	0	15	20	74	55.3	68	37.6
McGreavey	Interspace	3	15	30			60.4	70	42.3
McGreavey	Interspace	3	30	45			51.3	79	40.5
McGreavey	Interspace	3	45	64			46.8	44	20.6

Table A3.2 Organic Soil continued

Site Name	Hummock/ Interspace	Sample No.	Start Depth	End Depth	Compression (cm)	Total Depth with Compression (cm)	Organic Matter (%)	Dry Weight (g)	Organic Matter (g)
McGreavey	Hummock	4	0	15	40	118	52.5	63	33.1
McGreavey	Hummock	4	15	30			64.5	77	49.7
McGreavey	Hummock	4	30	45			60.6	68	41.2
McGreavey	Hummock	4	45	60			51.8	68	35.2
McGreavey	Hummock	4	60	78			47.5	87	41.3
McGreavey	Interspace	4	0	15	33	106	48.1	53	25.5
McGreavey	Interspace	4	15	30			54.1	65	35.2
McGreavey	Interspace	4	30	45			54.6	60	32.8
McGreavey	Interspace	4	45	60			46.6	68	31.7
McGreavey	Interspace	4	60	73			23.7	110	26.1
McGreavey	Hummock	5	0	15	42	57	39.6	97	38.4
McGreavey	Interspace	5	0	25	18	43	44.4	74	32.9
McGreavey	Interspace	5	15	25			33.6	66	22.2
McGreavey	Hummock	6	0	16	20	36	12.6	205	25.8
McGreavey	Interspace	6	0	3	18	21	43	20	8.6
Mt. Margaret	Hummock	1	0	11	35	46	28.3	76	21.5
Mt. Margaret	Interspace	1	0	10	9	19	46.2	65	30.0
Mt. Margaret	Hummock	2	0	13	14	27	36.7	84	30.8
Mt. Margaret	Interspace	2	0	13	18	31	53.8	58	31.2
Mt. Margaret	Hummock	3	0	20	16	36	33.6	158	53.1
Mt. Margaret	Interspace	3	0	9	17	26	50	59	29.5
Mt. Margaret	Hummock	4	0	7	35	42	45.1	35	15.8
Mt. Margaret	Interspace	4	0	8	25	33	43	45	19.4

Table A3.2 Organic Soil continued

Site Name	Hummock/ Interspace	Sample No.	Start Depth	End Depth	Compression (cm)	Total Depth with Compression (cm)	Organic Matter (%)	Dry Weight (g)	Organic Matter (g)
Mt. Margaret	Hummock	5	0	12	21	33	37.9	59	22.4
Mt. Margaret	Interspace	5	0	10	17	27	58.5	40	23.4
Mt. Margaret	Hummock	6	0	6	48	54	19.6	70	13.7
Mt. Margaret	Interspace	6	0	8	18	26	48.1	43	20.7
Soapstone	Hummock	1	0	7	17	24	22.5	37	8.3
Soapstone	Interspace	1	0	2	x	x	22.2	16	3.6
Soapstone	Hummock	2	0	10	19	29	12.1	74	9.0
Soapstone	Interspace	2	0	7	x	x	20.8	55	11.4
Soapstone	Hummock	3	0	11	25	36	10.9	101	11.0
Soapstone	Interspace	3	0	10	19	29	20.7	117	24.2
Soapstone	Hummock	4	0	15	12	27	15.8	108	17.1
Soapstone	Interspace	4	0	10	7	17	23.2	34	7.9
Soapstone	Hummock	5	0	6	16	22	17.7	94	16.6
Soapstone	Interspace	5	0	3	11	14	16.8	23	3.9
Soapstone	Hummock	6	0	7	18	25	10.1	99	10.0
Soapstone	Interspace	6	x	x	15	x			

Table A3.3. Composition of plant functional groups on hummocks and interspaces.

Site Name	Transect	Caespitose Grass (%)		Rhizomatous Grass (%)		Rhizomatous Grass-Like (%)		Forb (%)		Shrub (%)		Non-Plant (%)	
		Humm	Int	Humm	Int	Humm	Int	Humm	Int	Humm	Int	Humm	Int
Mansfield	1	9	1	7	0	85	99	1	1	0	0	9	17
Mansfield	2	8	4	2	1	89	95	2	0	0	0	4	11
Mansfield	3	15	3	10	0	72	94	3	2	0	0	5	39
Mansfield	4	12	40	4	1	68	30	15	29	0	0	6	15
Mansfield	5	12	24	3	0	70	71	15	5	0	0	3	21
Mansfield	6	5	2	1	0	79	88	15	11	0	0	5	16
Mansfield	7	2	6	0	0	88	94	10	0	0	0	9	19
Mansfield	8	19	13	0	0	79	82	2	4	0	0	18	9
Mansfield	9	8	1	2	0	78	91	11	8	0	0	17	32
Mansfield	10	14	10	0	0	69	69	17	21	0	0	7	5
McGreavey	1	5	6	0	0	26	89	1	1	68	4	3	32
McGreavey	2	1	2	0	0	25	92	0	1	75	5	5	23
McGreavey	3	1	0	2	1	31	89	2	1	66	9	4	26
McGreavey	4	7	9	12	8	26	71	0	1	55	11	1	9
McGreavey	5	4	0	6	6	20	69	4	2	65	23	2	24
McGreavey	6	0	0	0	0	48	83	5	0	46	17	25	23
McGreavey	7	3	2	1	1	67	97	3	1	26	0	5	12
McGreavey	8	1	5	3	1	55	83	2	3	39	7	8	31
McGreavey	9	3	0	0	0	74	100	4	0	18	0	8	28
McGreavey	10	3	0	0	1	82	94	5	2	9	4	10	22
Mt. Margaret	1	1	1	47	3	48	96	0	1	0	0	16	21
Mt. Margaret	2	0	0	38	12	62	88	0	0	0	0	12	18
Mt. Margaret	3	2	0	30	15	51	85	11	0	0	0	8	28

Table A3.3 Composition continued

Site Name	Transect	Caespitose Grass		Rhizomatous Grass		Rhizomatous Grass-Like		Forb		Shrub		Non-Plant	
		Humm	Int	Humm	Int	Humm	Int	Humm	Int	Humm	Int	Humm	Int
Mt. Margaret	4	2	1	37	6	53	93	8	0	0	0	11	25
Mt. Margaret	5	4	0	43	32	51	68	2	0	0	0	4	13
Mt. Margaret	6	5	1	27	19	66	81	3	0	0	0	4	18
Mt. Margaret	7	2	1	22	5	75	93	2	1	0	0	6	17
Mt. Margaret	8	7	1	30	12	63	87	1	1	0	0	11	18
Mt. Margaret	9	8	1	42	20	43	77	7	2	0	0	5	10
Mt. Margaret	10	5	0	49	4	45	95	1	1	0	0	3	18
Soapstone	1	10	15	28	60	29	13	33	11	0	0	8	8
Soapstone	2	7	9	42	38	26	45	25	8	0	0	15	16
Soapstone	3	12	11	31	8	39	77	17	4	0	0	16	15
Soapstone	4	17	12	17	15	57	72	10	2	0	0	19	12
Soapstone	5	0	0	29	20	63	77	8	3	0	0	17	28
Soapstone	6	1	3	43	12	41	83	16	2	0	0	13	18
Soapstone	7	2	9	40	26	42	64	16	1	0	0	21	31
Soapstone	8	6	1	29	8	40	89	26	2	0	0	13	41
Soapstone	9	0	4	34	17	48	76	17	2	0	0	10	24
Soapstone	10	3	5	32	13	46	78	19	4	0	0	9	15