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# Changes in soil water dynamics due to variation in precipitation and temperature: An ecohydrological analysis in a tallgrass prairie

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[1] There is considerable evidence that future global climate change will increase temperature and alter precipitation regime. To better understand how these factors will influence soil water dynamics, it is imperative to use multifactorial experiments. A 1 year "pulse" experiment, with 4°C warming and a doubling in precipitation, was performed to evaluate the changes in soil moisture dynamics. Frequency distribution analyses of soil moisture and soil temperature were used to explore the consequences of climate change on ecohydrological processes at different soil depths. There was a decrease in soil moisture frequency from 0 to 120 cm in both warming and warming with increased precipitation experiments. Different soil depths had similar patterns of change in soil moisture and soil temperature frequency. Additionally, we correlated evapotranspiration and soil moisture to look at changes in evapotranspiration from the wilting point ($E_w$) to maximum evapotranspiration ($E_{max}$). These results revealed a shift in the slope and position of $E_w$ to $E_{max}$ with experimental warming. Our results showed that the soil moisture dynamics and the ecohydrology were changed by different global climate change scenarios. Understanding the effects of global warming on soil moisture dynamics will be critical for predicting changes in ecosystem level processes.

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## 1. Introduction

[2] Over the past century the global mean temperature has increased by about 0.6°C and is predicted to increase 1.1–6.4°C in the 21st century [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001, 2007]. With this warming there is a predicted acceleration in the water cycle due to an exponential increase in specific humidity [*Huntington*, 2006] and an associated increase in the intensity and severity of precipitation events [*Easterling et al.*, 2000]. Changes in temperature and alterations in the precipitation patterns have been shown to cause multiple changes to ecosystem processes (e.g., net primary production, root biomass, and soil respiration) [*Knapp et al.*, 2008]. A central component controlling ecosystem processes is soil water balance. However, our understanding of the response to climate change on ecosystem water balance is largely limited.

[3] A National Ecological Observatory Network (NEON) report (2004) stated that is important to understand how biologically available water in terrestrial ecosystems will respond to climate change. Evidence has shown that changes in climate variables (e.g., rainfall) will cause shifts in net primary production and community composition, which will likely impact soil water balance [*Knapp et al.*, 2002; *Sherry et al.*, 2008; R. Sherry, unpublished data, 2009]. Other plant responses (e.g., photosynthesis) and biogeochemical cycling (e.g., carbon and nitrogen) are also closely linked to changes in soil water balance [*Knapp et al.*, 2008]. For example, a change in plant-level response can be seen when there is a reduction in biologically available soil moisture that causes a loss in turgor, xylem cavitation, stomatal closure and a decrease in photosynthesis [*Nilsen and Orcutt*, 1996; *Porporato et al.*, 2001; *Porporato et al.*, 2004].

[4] A multitude of factors can influence soil water loss due to climate change. The most explicit cause of reduced soil moisture is higher rates of soil water evaporation due to increased thermal radiation. Further decrease in soil moisture could also occur as increased temperatures influence plant-level processes [*Mellander et al.*, 2004], although this may vary in specific circumstances [*Jones*, 1992; *Daly et al.*, 2004]. However, greater amounts of precipitation as a result of climatic change should in general increase the amount of soil moisture present. This contradiction leads to interesting and perplexing questions about how multiple climate change factors will contribute to changes in soil moisture dynamics.

[5] It is important to understand how climate change will alter soil moisture given its importance for vegetation growth, plant physiological processes and biogeochemical cycles [*Stephenson*, 1990]. One global modeling study suggested a decrease in soil moisture in semiarid regions under future climate change [*Wetherald and Manabe*, 2002]. Whereas, a modeling study by *Gerten et al.* [2007] found varying soil moisture changes in different regions, with a predominant pattern of decreased soil moisture with increased temperatures. However, different model scenarios have shown vast differences in soil water balance [*Cramer et al.*, 2001; *Gordon and Famiglietti*, 2004]. According to

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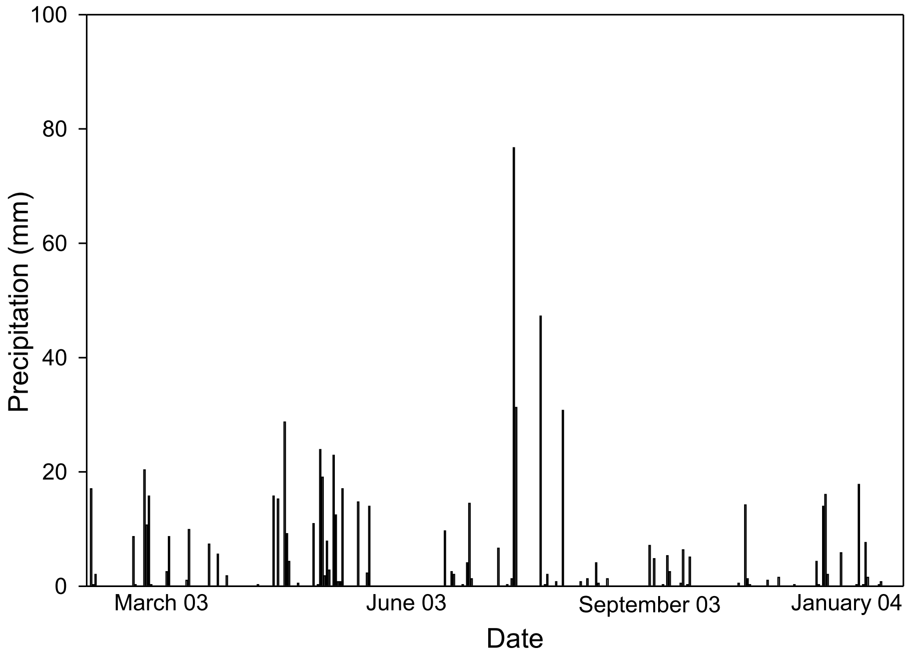


**Figure 1.** Daily precipitation amount during the experimental season from February 2003 to February 2004. (Mesonet, Oklahoma Climatological Survey [*McPherson et al.*, 2007])

actual long-term soil moisture measurements from the Global Soil Moisture Data Bank, soil moisture has increased over the last half century [*Robock et al.*, 2000].

[6] A copious amount of research has looked at different ways of manipulating an ecosystems' climate [*Harte et al.*, 1995; *Marion*, 1997; *Hobbie and Chapin*, 1998; *Melillo et al.*, 2002; *Wan et al.*, 2002]. Warming has had different magnitudes of effect on soil moisture with each of these experiments. For example, *Wan et al.* [2002] saw little to no change in soil moisture with a 2°C increase in temperature alone; but with clipping and warming there was an 11% decrease in soil moisture. Whereas, an experimental warming site in a montane meadow showed a reduction in soil moisture as a result of an increased physiological response of the vegetation [*Saleska et al.*, 1999]. This large amount of variability in soil moisture response to climate change among individual ecosystem makes it important to understand how different systems will respond if predictions are to be made at regional and global scales.

[7] In this study, we examine the effects of two different climate change variables including increased temperature and precipitation intensity, and their combination, on the soil water balance of a prairie ecosystem. Not only do we consider the potential change in soil moisture, but also, the change in soil temperature. This is one of the first studies focusing on the extent to which biologically available soil moisture is altered under single and multifactor scenarios of climate change. Also, our evaluation is one of the first to analyze the response of soil temperature and soil moisture to different climate scenarios in multiple soil layers. Included in our analyses is an evaluation of the effects of experimental climate change on evapotranspiration/leakage (water loss) at wilting point ($E_w$) and at maximum evapotranspiration/leakage ($E_{max}$) [*Rodriguez-Iturbe*, 2000]. Shifts in $E_w$ and $E_{max}$ provide insight on the impact climate conditions have on an ecosystem's ability to use and conserve water [*Rodriguez-Iturbe*, 2000].

[8] Our study used a multifactor experiment with levels of change in warming and precipitation consistent with those predicted for the region [*Wan et al.*, 2002]. We hypothesized (1) increase in temperature would decrease soil moisture, (2) increase in precipitation would increase soil moisture, and (3) treatment of increased temperature and doubled precipitation would have an intermediate effect. The experiment was a short-term, 1 year "pulse" experiment using a probabilistic/frequency approach to evaluate changes in soil moisture dynamics and fully incorporate the stochastic nature of soil moisture dynamics.

## 2. Methods

### 2.1. Study Site

[9] The experiment was located at the Kessler's Farm Field Laboratory in McClain County, Oklahoma (34 59′N, 97 31′W), approximately 40 km southwest of the University of Oklahoma. The area is a 137.6 ha field station positioned in the Central Redbed Plains [*Tarr et al.*, 1980]. The study site is predominately a tallgrass prairie mix of *Panicum virgatum, Schizchyrium scoparium, Andropogon gerardii, Sorgastrum nutans, Ambrosia psilostachyia*, and *Bromus japonicus*. Mean annual temperature is 16.3°C, with monthly air temperature ranging from 3.3°C in January to 28.1°C in July. Mean annual precipitation is 915 mm, with monthly precipitation ranging from 30 mm in January to 135 mm in May (average values from 1948 to 1998, via the Oklahoma Climatological Survey) (Figure 1). The soil is part of the Nash-Lucian complex with a neutral pH, a high available water capacity, and a deep, moderately penetrable root zone [*Moebius and Sparwasser*, 1979].

### 2.2. Experimental Design

[10] The 1 year pulse experiment was set at a target treatment of a 4.0°C increase in soil temperature at a depth

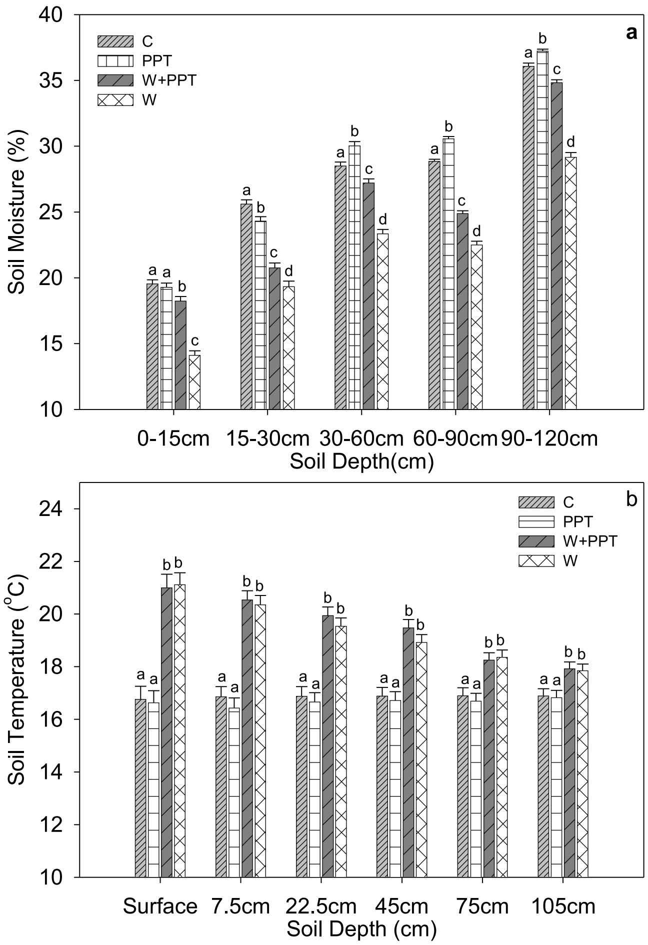


**Figure 2.** (a) Soil moisture responses to different climate change treatments (C, PPT, W+PPT, and W). Depth of soil is divided into different segments. Each treatment was statistically compared with other treatment types (mean ± SE n = 365). Statistical difference was shown with *a*, *b*, *c*, and *d*. (b) Soil temperature responses to different climate change treatments (C, PPT, W+PPT, and W). Depth of soil is divided into different segments. Each treatment was statistically compared with other treatment types (mean ± SE n = 365). Statistical difference was shown with *a*, *b, c,* and *d*.

of 2 cm. Twenty plots were placed in two rows that were separated by approximately 3 m and each plot was 3 × 2 m. The distance between plots within one row was 1.5 m. Ten out of the twenty plots were randomly selected to receive warming treatments and had 2 infrared heaters suspended in the middle of the plots at the height of 1.5 m above the ground. The other 10 plots had "dummy" heaters made of metal flashing suspended at the same height as in the warmed plots. Five of both the warmed and unwarmed plots were randomly selected to receive doubled precipitation using a "rain catchment" device, which is an angled catchment the same size as the plot. The "rain catchment" device was designed to funnel water onto these plots to provide an additional amount of precipitation that would normally fall on the control. Piping was used to evenly distribute the rainwater across the plots. Several variations were tested before the final design was selected for the experiment based on the most even distribution of precipitation. It should be noted that this experiment was designed to increase rainfall intensity and had no impact on the frequency of rainfall. There were four treatments of control (C), warmed (W), precipitation doubling (PPT), and warmed plus precipitation doubling (W+PPT), and each treatment had five replicates. The duration of the experiment was from 20 February 2003 to 20 February 2004.

### 2.3. Soil Moisture and Temperature Measurements

[11] Soil Moisture was measured using automatic TDR probes (time domain reflectometry; E.S.I. Equipment, Environmental Sensors Inc. Sidney, Canada). Each probe recorded hourly measurements at 5 different depths 0–15 cm, 15–30 cm, 30–60 cm, 60–90 cm, and 90–120 cm (Figure 2a). Data were logged through a CR10X measurement and control system (Campbell Scientific, Inc., Logan, Utah). Nine of the TDR probes experienced damage or malfunction during the study. Complete data sets were available for only 11 of the 20 plots.

[12] Soil Temperature was measured hourly at six depths using thermocouple wires attached to a 25 channel solid state multiplexor (AM25T) (Campbell Scientific, Inc., Logan, Utah). Each measurement was automatically measured at six depths starting at the soil surface, 7.5 cm, 22.5 cm, 45 cm, 75 cm, and 105 cm (Figure 2b).

[13] To show changes in soil moisture and temperature at different depths, we constructed graphs of yearly average soil moisture and temperature. The data was collected from the entire experimental period. Additionally, similar graphs were configured for seasonal variation. The four seasons of winter (22 December to 19 March), spring (20 March to 20 June), summer (21 June to 20 September), and fall (21 September to 21 December) were based on the standard division of a temperate zone in the Northern Hemisphere.

### 2.4. Water Loss (Evapotranspiration and Leakage)

[14] Water loss ($\mathbf{W}_l$), an estimate of evapotranspiration and leakage, was calculated using the daily average of bulk soil moisture at a given day ($\mathbf{S}_t$) minus the daily average of bulk soil moisture from the following day ($\mathbf{S}_{t+1}$). Rainfall (**R**) was then added as a water input:

$$W_l = (S_t - S_{t+1}) + R$$

Soil moisture measurements were taken from the TDR probes and rainfall data were collected from the Oklahoma Mesonet. Our analysis used bulk soil moisture to account for the entire root profile.

[15] Points were collected between an estimated $E_w$ and $E_{max}$ to analyze changes in the different experiment conditions on water loss. Estimations of $E_w$ and $E_{max}$ were derived from the calculations of ($\mathbf{W}_l$) during the longest dry period in the summer of the experiment year. This rainless period occurred during a 21 day stretch from day 139 to day 160 after the beginning of the experiment. $\mathbf{W}_l$ was then correlated with daily average bulk soil moisture for days 139 to 160. From the data, a graphical representation was made of the correlation between the points within $E_w$ and $E_{max}$ with the sequential bulk soil moisture to show changes in the four climate change scenarios. *Rodriguez-Iturbe* [2000] gave an illustrative diagram of the relationship between soil moisture and water loss.

**Table 1.** Analysis of Variance of Soil Moisture Content at Different Depths[a]

| Source | Degrees of Freedom | Sum of Squares | F Ratio | p Value |
|---|---|---|---|---|
| Surface | 3 | 6965.799 | 27.36 | <0.0001 |
| 7.5 cm | 3 | 5322.511 | 35.99 | <0.0001 |
| 22.5 cm | 3 | 3267.211 | 25.55 | <0.0001 |
| 45 cm | 3 | 2166.116 | 19.33 | <0.0001 |
| 75 cm | 3 | 846.8216 | 9.14 | <0.0001 |
| 105 cm | 3 | 389.741 | 4.98 | 0.0019 |

[a]At these depths $\alpha = 0.05$.

### 2.5. Statistical Analysis

[16] The analysis of variance (ANOVA) was conducted using the Statistical Analysis System (SAS) software (SAS Institute Inc., Cary, NC, USA). The one-way ANOVAs were performed for a comparison of soil moisture and temperature between the four treatments (C, PPT, W, and W+PPT) for the entire experimental period (Tables 1 and 2). A post hoc of multiple comparisons was done using the least significant difference (LSD) method for both moisture and temperature across the four different treatment types (Figure 2). Additionally, soil moisture and temperature dynamics, at multiple depths, were evaluated by analyzing frequency distributions using histograms in Statistical Analysis System (SAS, SAS Institute Inc., Cary, NC, USA) (Figures 3 and 4). The bins for the histograms were designated by 5°C segments for temperature and 5% segments for soil moisture.

## 3. Results

### 3.1. Soil Moisture

[17] We found that soil moisture varied between different experimental conditions for the investigational period. Within each treatment (C, PPT, W, and W+PPT), a statistically significant difference in soil moisture was found at all soil depths (0–15, 15–30, 30–60, 60–90, and 90–120 cm) (Table 1) (Figure 2). PPT and C plots had the wettest soil moisture conditions at all depths; furthermore, C plots had slightly wetter soil moisture values in 0–30 cm while PPT plots had higher values in 30–120 cm. W+PPT and W plots had the driest soil moisture values in all levels, with W consistently having the lowest value. Furthermore, an increase in soil moisture with depth was also seen under all experimental conditions (Figure 5a). Likewise, the same patterns were observed when soil moisture was analyzed over seasons (Figures 5b–5e).

[18] Frequency distributions of soil moisture were constructed at multiple soil depths to demonstrate the probabilistic changes in available soil moisture among the different experiment treatment types (Figure 3). Patterns of change in the frequency distributions closely resembled the mean soil moisture results in Figure 2a. However, frequency distributions allow for a better illustration of the actual probabilistic nature of soil moisture dynamics with each experimental treatment type. C and PPT had the wettest soil moisture frequency distributions at all depths while W+PPT and W had the driest soil moisture frequencies. Overall, the driest soil moisture frequency distributions were found in the W plots.

### 3.2. Soil Temperature

[19] Both experimental warming treatments (W and W +PPT) showed significantly higher temperatures at all depths (soil surface, 7.5, 22.5, 45, 75, and 105 cm) compared to nonwarming treatments (C and PPT) (Table 2). No significant difference was found on soil temperature between C and PPT at any depth and a similar nonsignificant pattern was also established between W and W+PPT (Figure 2b). PPT and C plots had little to no change in temperature with depth; however, W and W+PPT had nearly a 3°C decrease in temperature from the soil surface to 105 cm. W+PPT and W plots had the lowest soil temperature values in all levels, with W having consistently the lowest value. This is further illustrated with Figure 6a, showing the average yearly soil temperature for the different treatment types. Additionally, there were similar patterns when the treatments were divided into seasons (Figures 6b–6e).

[20] Frequency distributions of soil temperature were plotted at multiple soil depths to illustrate the probabilistic nature of soil temperature within the different experimental treatment types (Figure 4). Frequency distributions were similar to the mean soil temperature patterns seen in Table 2. Furthermore, C and PPT had the lowest temperature frequencies distributions at all depths while W+PPT and W had the highest temperature frequencies distributions.

### 3.3. $E_w$ and $E_{max}$

[21] We found that the points between the estimated $E_w$ and $E_{max}$ showed changes in both slope and position, based on the different experimental conditions (Figure 7). The experimental warming plots had the greatest change, of any experimental treatment, with $E_w$ to $E_{max}$ occurring in the driest soil moisture conditions (Figure 7). Thus, the wilting point in the experimental warming plots occurred at a soil moisture percentage around 7%. However, little to no change occurred in the soil moisture between $E_w$ to $E_{max}$ with the PPT plots and C plots and the wilting point was occurring in soil moisture conditions of around 10%. There was also a change in the position of the points between $E_w$ to $E_{max}$ for the W+PPT plots, resulting in the area between the wilting point and maximum evaporation to occur in wetter soil moisture conditions (around 12%).

## 4. Discussion

[22] To our knowledge, this is the first study conducted with the goal to understand the impacts of different climate change scenarios on soil conditions at multiple depths. Furthermore, the data presented here clearly show that warming and precipitation change alters soil moisture dy-

**Table 2.** Analysis of Variance of Soil Temperature Content at Different Depths[a]

| Source | Degrees of Freedom | Sum of Squares | F Ratio | p Value |
|---|---|---|---|---|
| Segment 0–15 cm | 3 | 6834.217 | 54.35 | <0.0001 |
| Segment 15–30 cm | 3 | 9343.574 | 62.24 | <0.0001 |
| Segment 30–60 cm | 3 | 8578.948 | 77.34 | <0.0001 |
| Segment 60–90 cm | 3 | 14132.709 | 281.56 | <0.0001 |
| Segment 90–120 cm | 3 | 13371.408 | 186.74 | <0.0001 |

[a]At these depths $\alpha = 0.05$.

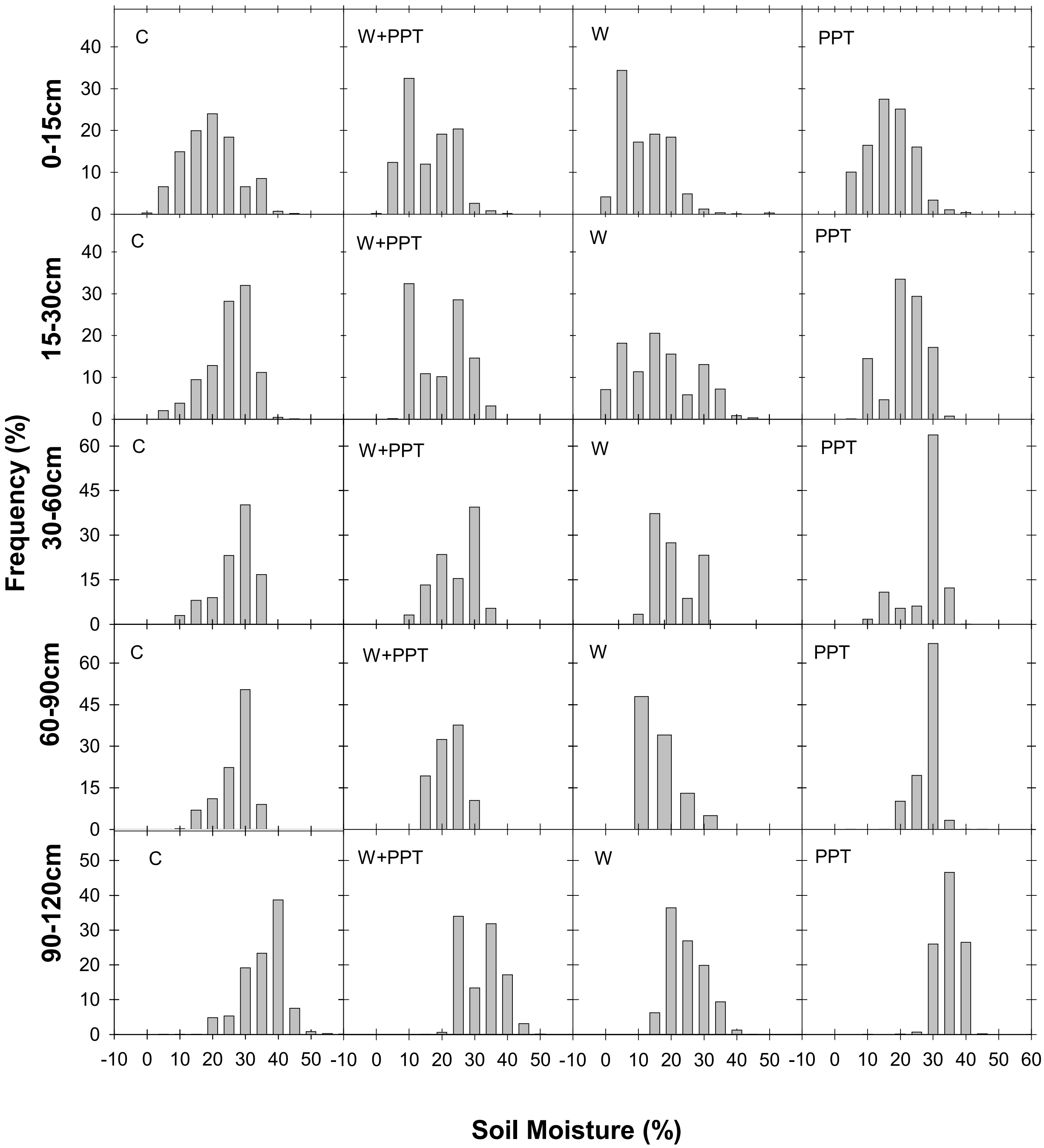


**Figure 3.** Soil moisture change in frequency at different soil depths. Each treatment type: C, control; W+PPT, warmed and doubled precipitation; W, warmed; and PPT, doubled precipitation.

namics and change soil moisture frequency in a tallgrass prairie ecosystem. The changes in soil moisture and temperature are particularly significant for understanding the consequences of climate change for belowground plant and soil processes. For example, *Day et al.* [1991] showed that changes in soil temperature alter the ability of roots to uptake water and nutrients; furthermore, increase in soil water, or lack there of, directly affects their ability to access water. Other studies also coincide with changes in root biomass and function with changes in temperature [*Bowen*, 1991; *Li et al.*, 1994; *Majdi and Ohrvik*, 2004].

### 4.1. Observed Patterns of Change in Soil Moisture and Temperature

[23] Our results confirm earlier experimental findings that climate change will have an impact on belowground soil hydrological conditions [*Harte et al.*, 1995; *Saleska et al.*, 1999; *Melillo et al.*, 2002; *Wan et al.*, 2002]. However, these previous studies have not explained the extent to which different climate change scenarios would alter soil hydrological conditions at multiple depths. Our study focused on the impacts on soil moisture dynamics and changes in temperature in deep soil, with different climate change scenarios (warming, warming and increased precipitation,

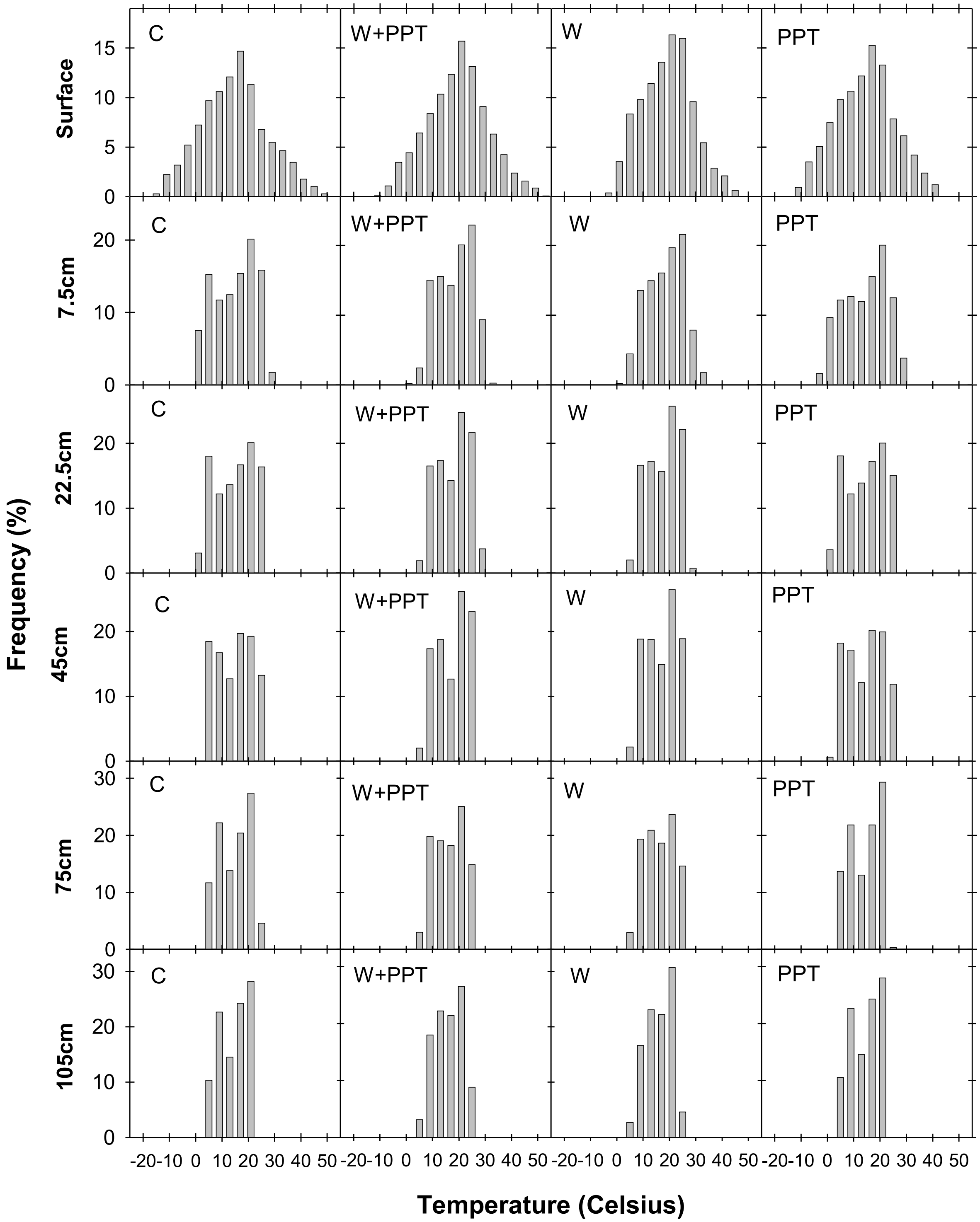


**Figure 4.** Soil temperature change in frequency at different soil depths. Each treatment type: C, control; W+PPT, warmed and doubled precipitation; W, warmed; and PPT, doubled precipitation.

increased precipitation). There were significant changes in soil temperature and moisture with all experimental conditions. Soil moisture measurements were highest in both the C and PPT plots followed by the PPT+W plots and then W plots. Therefore, more biologically available water is accessible by plants in the C and PPT plots and compared to both of the warming plots. The deeper layers of the PPT plots showed the highest amount of soil moisture. This could be attributed to increased movement of water to deeper layers as a result of the higher precipitation, and less evaporative demand because of the lower temperatures. Both W and W+PPT had the lowest soil moisture at all depths, and this could be a response mechanism of plants to higher temperatures. Two factors could interplay to cause more moisture uptake in the warming plots. First, more water could be lost to the atmosphere from an increase in transpiration and evaporation. Plants could then increase the amount of water uptake to compensate for the additional

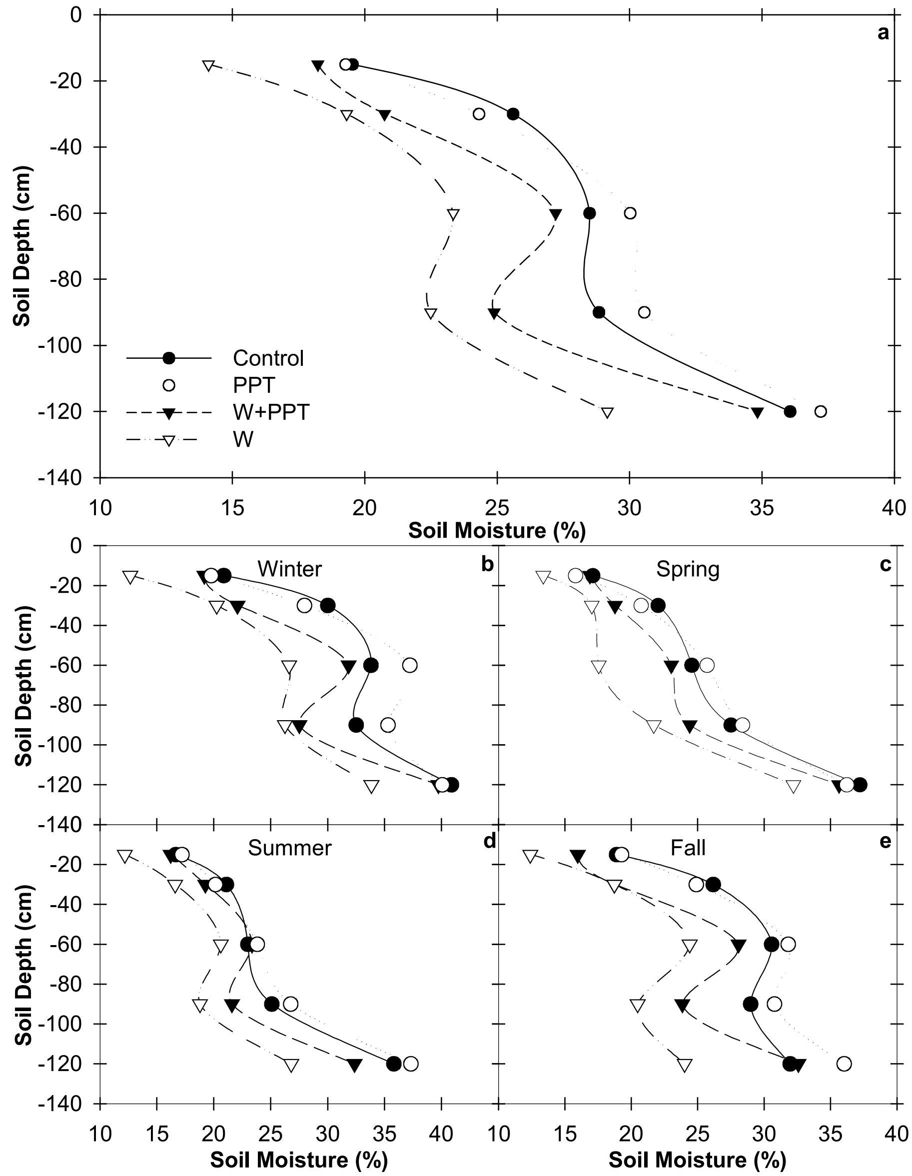


**Figure 5.** Average soil moisture profile: (a) yearly average, (b) winter, (c) spring, (d) summer, and (e) fall for the different experimental treatments.

transpirational loss. Second, there is a significant increase in temperature at the lower soil depths due to warming and this should increase root activity [*Bowen*, 1991]. Previously, experimental evidence showed that there was an increase in root biomass under warming in the experimental plots (S. Fei et al., unpublished data, 2009). Both of these factors could together explain the decrease in soil moisture with an increase in temperature from experimental warming.

[24] Increase in deep soil temperature from higher atmospheric temperatures could result in unexpected changes. Changes in temperature around deep roots have been shown to change moisture uptake [*Day et al.*, 1991] and there is evidence that higher soil temperatures can increase transpiration [*Mellander et al.*, 2004]. Additionally, evapotranspiration is a driving force for changing atmospheric weather patterns and has been cited in causing changes in storm severity [*Raddatz and Cummine*, 2003]. Questions on how climate change alters soil moisture in different systems and how these feedbacks impact ET's ability to change boundary layer conditions, need to be addressed.

[25] Our results also indicated that this experimental system was affective in influencing climatic change among all treatment types. Similar results were obtained in a congruent experiment using similar methods [*Wan et al.*, 2002]. In addition, our results further explain how experimental warming, from infrared heaters, alters temperature along a soil profile. Other infrared warming studies have identified changes in soil temperature and moisture [*Harte et al.*, 1995; *Bridgham et al.*, 1999; *Wan et al.*, 2002]; whereas, our study identifies that there are significant changes in temperature and moisture at multiple depths.

### 4.2. Change in Probability Distribution and the Environment

[26] Changes that occur in soil moisture frequency distribution also affect the overall climate-vegetation-soil in-

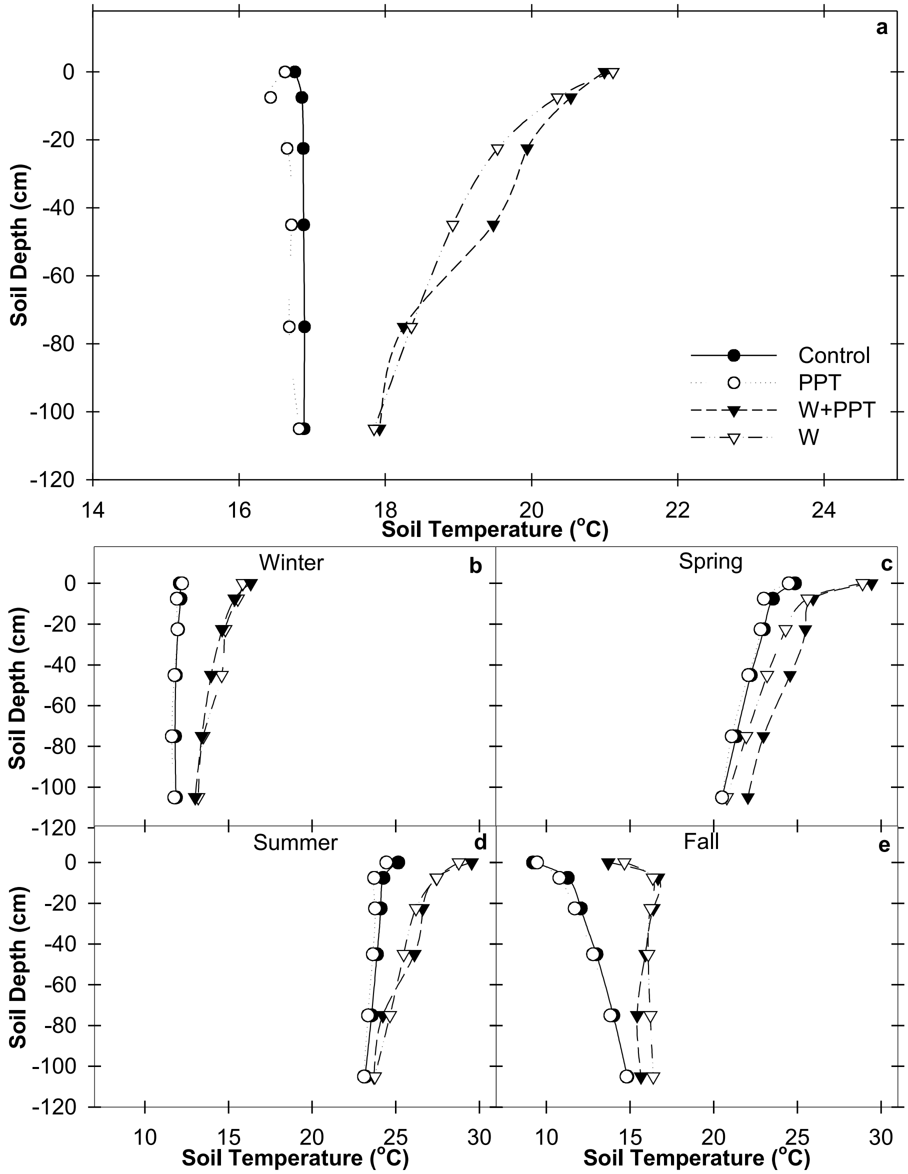


**Figure 6.** Average soil temperature at multiple depths: (a) yearly average, (b) winter, (c) spring, (d) summer, and (e) fall divided among different treatments.

teraction. Our study used frequency distributions to understand potential climate change impacts on soil moisture dynamics; these results could be helpful for future probabilistic modeling studies [*Porporato et al.*, 2003b]. Both W and W+PPT plots had changes in frequency distributions to lower soil moisture conditions. These results indicate that there is a higher likelihood of changes in other ecosystem processes due to lower soil moisture availability.

[27] Soil moisture dynamics are directly linked to both the carbon and nitrogen cycle [*Porporato et al.*, 2003b]; hence, the change in soil moisture frequency will likely alter other nutrient cycles. Furthermore, earlier articles have highlighted that our experiment should expect a decrease in litter quality and lower rates of organic matter decomposition in W and W+PPT plots [*Rodriguez-Iturbe et al.*, 2001; *Porporato et al.*, 2003b]. Thus, there would be less microbial activity and enzymatic oxidation of organic matter to produce soil respiration [*Howard and Howard*, 1979; *Davidson et al.*, 1998]. However, *Zhou et al.* [2006] showed the opposite results with an increase in soil CO2 efflux with experimental warming; additionally, increases in soil moisture content caused greater soil CO2 efflux, but the change was smaller than increased temperature. This suggests that increases in temperature will have a larger impact on microbial activity than moisture availability. Furthermore, the changes in the carbon cycle should cause an associated change in the nitrogen cycle (i.e., ammonification and nitrification).

[28] Additionally, drier soil moisture frequency distributions, in the W and W+PPT plots, could also cause plant water stress. Change in water stress has been shown to cause an associated change in the ecosystem vegetative community composition. For example, *Porporato et al.* [2003a] showed how varying amounts of water stress across a precipitation gradient in the Kalahari affected both the plant community type and ecohydrological processes. Other experiments also showed similar results [*Rodriguez-Iturbe et al.*, 1999; *Laio et al.*, 2001]. Plant water stress, caused by changes in the soil moisture dynamics, can in turn cause

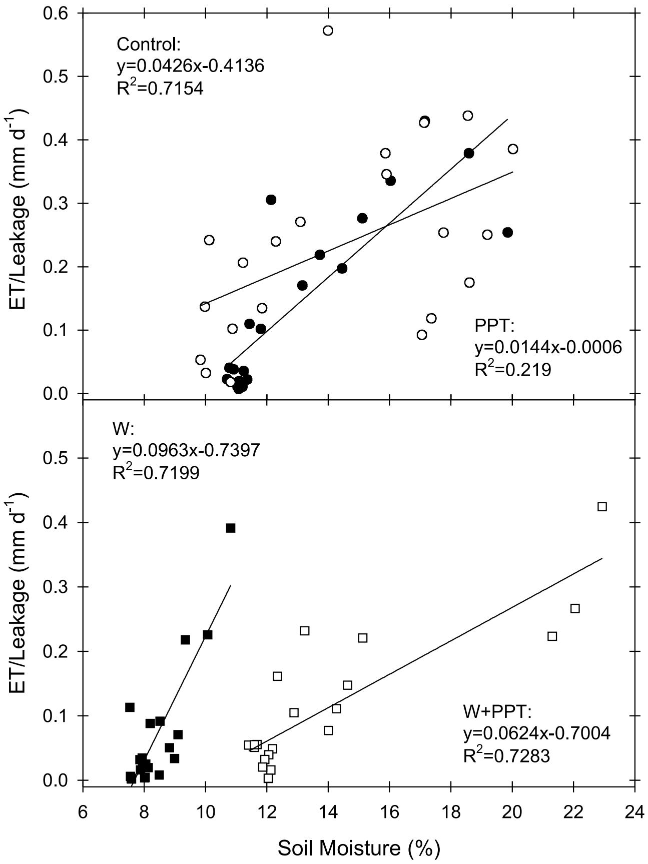


**Figure 7.** $E_w$ and $E_{max}$ were calculated to see changes in different treatments types. C (solid circles) is for experimental control ($p < 0.001$). W (solid squares) is for increased warming ($p < 0.001$). PPT (open circles) is for increased precipitation ($p < 0.023$). W+PPT (open squares) is for increase warming and precipitation ($p < 0.001$).

varying transpiration rates in plant, thus impacting the total amount of evapotranspiration [*Rodriguez-Iturbe*, 2000]. These responses will then cause overall changes in ecohydrological processes.

[29] Other changes in the grassland ecosystem could occur with effects that are consistent with our study but occur on a much larger scale. For example, a change in the frequency distribution of soil moisture could impact the amount of plant biomass [*Sherry et al.*, 2008]; hence, having a direct affect on the nitrogen and carbon cycle [*Rodriguez-Iturbe et al.*, 2001]. Our results hopefully demonstrate the important effects of climate change on soil moisture dynamics, and the possible implications on biogeochemical cycling. In addition, we observed that warming, even combined with increased precipitation, had a drying effect on the soil moisture frequency. This suggests that warming may have a greater impact on soil moisture conditions than increased precipitation.

### 4.3. Changes in $E_w$ and $E_{max}$

[30] To understand the full impact of the four climate change scenarios on ecohydrological processes we analyzed the changes in wilting point ($E_w$) to the maximum evaporation rate ($E_{max}$). These results showed the conditions between $E_w$ and $E_{max}$ changed with each climate change scenario. We were able to make some predictions on how belowground processes of water uptake were changing with different climate conditions.

[31] W+PPT treatment showed a slight change in $E_w$ to $E_{max}$ to wetter soil moisture conditions than the control; additionally, there was a shift to drier soil moisture conditions in the warming plots and little change in the PPT plots. Shifts in the W plots $E_w$ to $E_{max}$ are likely a plant level response to environmental stress. Less soil moisture would cause the plants to increase belowground activity and root growth in search of water [*Turner and Kramer*, 1980]. This increased belowground activity would allow for more soil water to be available for plant use and the plants would be able to withstand lower soil moisture percentages, causing shifts in $E_w$ and $E_{max}$ to drier soil moisture conditions.

[32] Plant level stress response would also be an explanation of why both C and PPT showed similar $E_w$ to $E_{max}$. Hence, the availability of water will cause no stress to the plant. However, this could also be the reason W+PPT has an $E_w$ to $E_{max}$ shift to wetter soil moisture conditions. W+PPT could have lower stress due to higher temperature with the addition of doubled precipitation. Hence, there would be more photosynthesis and increased available water to meet the plant's demand. Thus, W+PPT would show a slight shift in $E_w$ to $E_{max}$ to higher soil moisture conditions, than those of C.

[33] These results suggest that different climate change conditions will possibly shift an ecosystem's ability to use and acquire water, which is critical in understanding the soil-plant-climate interface [*Rodriguez-Iturbe*, 2000]. Additionally, it should be noted, that the warming experiment is not increasing overall atmospheric water demand and that this might change with future climate change [*Huntington*, 2006]; hence, there could be even greater evapotranspiration in actual future scenarios.

## 5. Conclusions

[34] A complete understanding of the effects of climate change on soil moisture dynamics is increasingly important. Particular focus needs to be made on recognizing how changes in available moisture will affect the entire ecosystem. Multifactor experiments must be performed to fully understand the climate-vegetation-soil interaction under different climate change scenarios [*Shaw et al.*, 2002; *Norby and Luo*, 2004]. Experiments similar to this one will help explain changes in nutrient cycles, vegetation and biomass, and numerous other ecosystem components that are influenced by soil moisture changes. This will then enable better predictions of the future alterations to the environment and ecohydrology of natural systems.

[35] **Acknowledgments.** The authors would like to thank Edwin Kessler for donating his farm to the University of Oklahoma for scientific research, Nancy Zehrbach for organization of data and maintaining the experiment, and Tao Zhou for statistical assistance. We would also like to thank J. Janecka, X. Zhou, and E. J. Bradford for editorial comments. This research was financially supported by the U.S. National Science Foundation (NSF) under DEB 0078325 and by the Office of Science (BER), Department of Energy, grant DE-FG03-99ER62800.

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