

## Ecohydrological responses to multifactor global change in a tallgrass prairie: A modeling analysis

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[1] Relative impacts of multiple global change factors on ecohydrological processes in terrestrial ecosystems have not been carefully studied. In this study, we used a terrestrial ecosystem (TECO) model to examine effects of three global change factors (i.e., climate warming, elevated CO<sub>2</sub>, and altered precipitation) individually and in combination on runoff, evaporation, transpiration, rooting zone soil moisture content, water use efficiency (WUE), and rain use efficiency (RUE) in a North American tallgrass prairie. We conducted a total of 200 different scenarios with gradual changes of the three factors for 100 years. Our modeling results show strong responses of runoff, evaporation, transpiration, and rooting zone soil moisture to changes in temperature and precipitation, while effects of CO<sub>2</sub> changes were relatively minor. For example, runoff decreased by 50% with a 10°C increase in temperature and increased by 250% with doubled precipitation. Ecosystem-level RUE increased with CO<sub>2</sub>, decreased with precipitation, and optimized at 4–6°C of warming. In contrast, plant-level WUE was highest at doubled CO<sub>2</sub>, doubled precipitation, and ambient temperature. The different response patterns of RUE and WUE signify that processes at different scales responded uniquely to climate change. Combinations of temperature, CO<sub>2</sub>, and precipitation anomalies interactively affected response magnitude and/or patterns of ecohydrological processes. Our results suggest that ecohydrological processes were considerably affected by global change factors and then likely regulate other ecosystem processes, such as carbon and nitrogen cycling. In particular, substantial changes in runoff to different climate change scenarios could have policy implications because it is a major component to replenishing freshwater. These modeling results should be tested by and could influence design of field experiments on ecohydrological processes.

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### 1. Introduction

[2] The atmospheric concentration of carbon dioxide (CO<sub>2</sub>) has increased from preindustrial levels of 280 ppm to the present level of around 379 ppm [*Intergovernmental Panel on Climate Change (IPCC)*, 2007]. Consequently, the Earth surface's temperature has increased by 0.76°C over the last 150 years and at a rate of 0.13°C per decade over the last 50 years [*IPCC*, 2007]. It was predicted that Earth surface temperature will continue to increase by 1.1 to 6.4°C over the next century [*IPCC*, 2007]. This expected increase in temperature will likely result in alterations in the hydrological cycle at regional and global scales. *Huntington* [2006], for example, predicted an almost exponential increase in the specific humidity due to the increase in temperature; whereas, modeling analysis showed a 3.4% increase in precipitation

per degree Kelvin [*Allen and Ingram*, 2002]. This leads to a question: how will the hydrological cycle in terrestrial ecosystems respond to multifactor climate change?

[3] Individual ecohydrological processes may differentially respond to global change, leading to complex patterns and changes in ecosystem water balance [*Gerten et al.*, 2007]. *Wetherald and Manabe* [2002] showed that modeled runoff decreased globally with an increase in temperature for a 30 year period due to increased evapotranspiration. However, an increase in precipitation in a given year results in increased runoff due to oversaturation of soil moisture. The two components of climate change (i.e., warming and altered precipitation) could interplay to affect evaporation. In addition, plant transpiration is regulated by atmospheric CO<sub>2</sub> concentration [*Lockwood*, 1999] and length of growing seasons. *Sherry et al.* [2007] have showed that an increase in temperature extended the growing seasons. This extension in the growing season could increase the amount of water transpired, while an increase in CO<sub>2</sub> can decrease the amount of transpiration from a plant due to a more efficient stomatal opening [*Farquhar and Sharkey*, 1982]. The processes of

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evaporation, transpiration, and runoff all influence soil moisture content [Yang *et al.*, 2003]. The Lund-Potsdam-Jena model demonstrated varying effects of different climate change scenarios on soil moisture in different regions [Gerten *et al.*, 2007] and consequently on biomass growth and net primary production (NPP) [Cramer *et al.*, 2001]. To improve our understanding of complex ecohydrological responses to climate change, we need to systematically examine interactions of multiple factors in influencing components of the terrestrial hydrological cycle, such as runoff, soil moisture, transpiration, and evaporation.

[4] Additionally, the hydrological cycle in the terrestrial ecosystem is closely coupled with biogeochemical cycles. The hydrological-biogeochemical coupling may strongly respond to climate change. For example, plant water use efficiency (WUE), a major index of carbon-water coupling, usually increases with an increase in atmospheric CO<sub>2</sub> concentration but decreases with an increase in temperature [Allen *et al.*, 2003] and with an increase in rainfall. It is also essential to understand how WUE responds to multifactor global change scenarios. Carbon-water coupling at ecosystem and regional scales is usually indicated by rain use efficiency, which, to the best of our knowledge, has not been carefully studied under different climate change scenarios using experimental approaches.

[5] Comparative studies of ecosystem rain use efficiency (RUE) and plant WUE is helpful in revealing different processes that influence carbon and water coupling. RUE, defined by a ratio of aboveground net primary productivity (ANPP) over yearly precipitation, measures the amount of biomass production per unit of precipitation over 1 year. Plant-level WUE, defined by a ratio of ANPP over transpiration, measures the amount of water lost via plant transpiration for production of one unit of plant biomass. Plant WUE primarily reflects changes in leaf photosynthesis and transpiration in response to climate change; whereas ecosystem RUE measures changes in plant growth biomass in association with changes in all hydrological processes at the ecosystem scale under different climate change scenarios. An increase in precipitation, for example, usually results in increases not only in plant biomass but also in runoff and soil evaporation. Plant WUE can only measure the plant-level responses. We need ecosystem RUE, to describe changes in other ecosystem processes. Similarly, climate warming and rising atmospheric CO<sub>2</sub> concentration are likely to differentially influence plant WUE and ecosystem RUE.

[6] Ecohydrological processes are influenced by climate change factors individually or in combination. There have been studies on how single-factor climate change influences ecohydrological processes. For example, Knapp *et al.* [2002] showed that an increase in rainfall variability resulted in a reduction of net primary production and shifts in community composition. Nilsen and Orcutt [1998] showed that decreases in soil moisture will reduce the amount of plant water potential. However, responses of ecohydrological processes to one factor are likely modified by other global change factors. A few experiments have examined ecosystem responses to multifactor global change, primarily on carbon and nutrient processes. How covarying multifactor climate change will alter ecohydrological processes has not been carefully examined. Modeling studies have the potential to

provide insight on the effects of multifactor global change on ecohydrological processes [Knapp *et al.*, 2008].

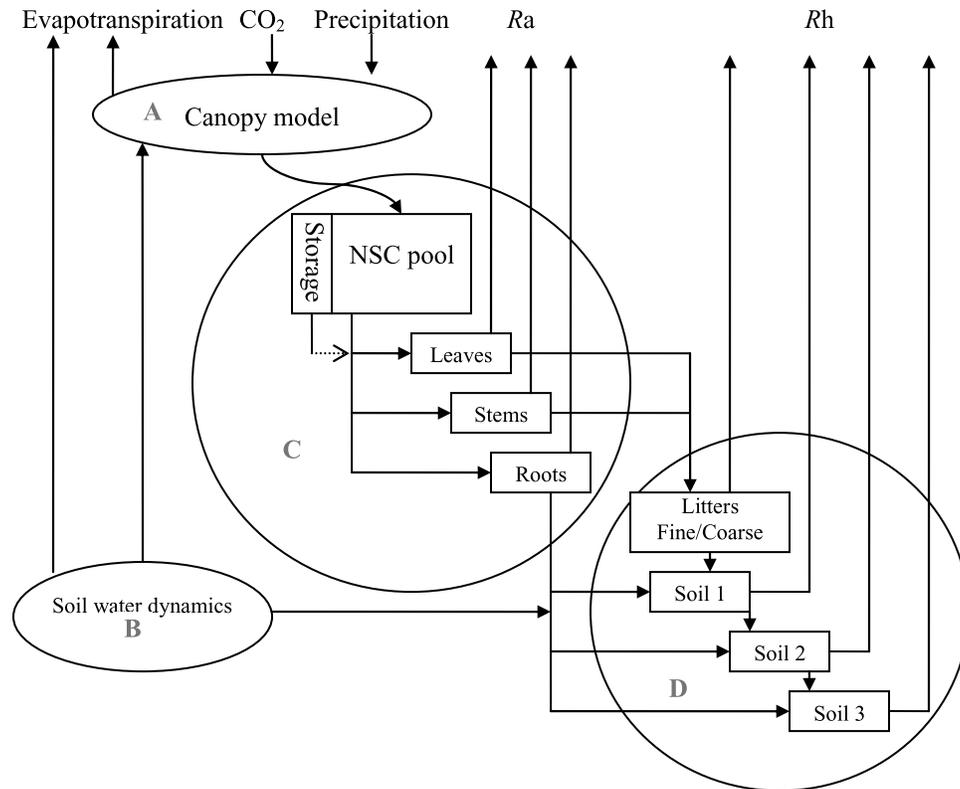
[7] This study was designed to understand ecohydrological responses to global change factors (i.e., altered precipitation, warming, and elevated atmospheric CO<sub>2</sub> concentration) individually or in combination. We used the terrestrial ecosystem (TECO) model [Weng and Luo, 2008] to examine changes in ecohydrological processes under 150 scenarios from 6 levels of climate warming (i.e., increases in temperature by 0, 2, 4, 6, 8, and 10°C above the ambient), 5 levels of CO<sub>2</sub> concentration from ambient to doubled CO<sub>2</sub> with each increment of 25%, and 5 levels of precipitation from -25 to 75% of the ambient with each increment of 25%. In addition, we also examined ecosystem responses to combinations of various temperature and precipitation levels at subambient CO<sub>2</sub> concentration (280 ppm) for studying three-way interactions. This modeling analysis was focused on responses of runoff, evaporation, transpiration, rooting zone soil water content, water use efficiency (WUE) and rain use efficiency (RUE) to climate warming, elevated CO<sub>2</sub>, and altered precipitation.

## 2. Materials and Methods

### 2.1. Model Description

[8] The terrestrial ecosystem (TECO) model is a process-based ecosystem model [Weng and Luo, 2008], which evolved from the terrestrial carbon sequestration (TCS) model developed by Luo and Reynolds [1999]. TECO and its precursor, TCS model, have been applied to study responses of forest ecosystems to elevated CO<sub>2</sub> [Luo *et al.*, 2001, 2003; Xu *et al.*, 2006] and examine nonlinear patterns of grassland responses to multifactor global changes [Zhou *et al.*, 2008]. The TECO model has four components: a canopy photosynthesis submodel, a soil water dynamic submodel, a plant growth submodel, and a soil carbon transfer submodel (Figure 1). The canopy photosynthesis and soil water dynamic submodels run at hourly steps while the plant growth and soil carbon transfer submodels run at daily steps. The TECO model was described in detail by Weng and Luo [2008]. Here we provide a brief description of carbon submodels and a full description of the soil water dynamics submodel because the latter is the focus of this study.

[9] The canopy submodel is from a two-leaf photosynthesis model simulating canopy conductance, photosynthesis, transpiration, and energy partitioning [Wang and Leuning, 1998]. The submodel is composed of foliage levels that are divided in sunlit and shaded leaf area index (LAI). Leaf photosynthesis is estimated based on the Farquhar photosynthesis model [Farquhar *et al.*, 1980] and the Ball and Berry stomatal conductance model [Ball *et al.*, 1987]. The Plant Growth submodel simulates allocation of assimilates to plant pools, plant growth, plant respiration, and carbon transfer to litter and soil carbon pools. Allocation of assimilates depends on growth rates of leaves, stems and roots, and varies with phenology based on the ALFALFA model [Luo *et al.*, 1995] and parameterization of litter fall by Arora and Boer [2005]. Seasonal dynamics of phenology is represented by the variation of LAI. Commencement of leaf onset is regulated by growing degree days (GDD) and leaf fall is determined by low temperature and dry soil conditions. The end of the growing season occurs at LAI < 0.1. The Carbon Transfer submodel simulates carbon movement from plant



**Figure 1.** Structural diagram of the TECO model. (a) Canopy model, (b) soil water dynamics model, (c) plant growth model, and (d) carbon transfer model. Boxes represent the carbon pools.  $R_a$  is autotrophic respiration.  $R_h$  is heterotrophic respiration. NSC is nonstructure carbohydrates.

pools to litter and soil pools in three layers. Carbon releases from litter and soil carbon pools are based on decomposition rates and pool sizes [Luo and Reynolds, 1999].

[10] The soil water submodel divides soil into ten layers as in the ALFALFA model [Luo *et al.*, 1995] while soil carbon submodel has three layers for carbon dynamics. The submodel simulates dynamics of soil water content based on precipitation, runoff, evapotranspiration, and the amount of water content in the previous time step as:

$$W_{soil} = W_{soil0} + P - Runoff - ET \quad (1)$$

where  $W_{soil}$  is soil water content,  $W_{soil0}$  is soil water content in the previous time step,  $P$  is precipitation, and  $ET$  is evapotranspiration equaling the amount of plant transpiration and soil surface evaporation. Transpiration is calculated based on the canopy model for simulating canopy conductance, photosynthesis and energy partitioning of sunlit and shade leaves separately. Evaporation ( $E_s$ ) is controlled by the amount of water lost from the soil surface based on evaporative demand [Sellers *et al.*, 1996]:

$$E_s = \frac{e^*(T_{soil}) - e_a}{r_{soil} + r_d} \frac{\rho c_p}{\gamma} \frac{1}{\lambda} \quad (2)$$

where  $e^*(T_{soil})$  is the saturation vapor pressure at temperature of the soil,  $e_a$  is the atmospheric vapor pressure,  $r_{soil}$  is soil resistance,  $r_d$  is the aerodynamic resistance between ground and canopy air space,  $\rho$  is the density of air,  $c_p$  is the specific heat capacity of air,  $\gamma$  is the psychrometric constant,  $\lambda$  is the latent heat of evaporation [Sellers *et al.*, 1996].

[11] When rainfall input into soil is more than water recharge to soil water holding capacity, runoff occurs and is estimated by the following equation:

$$Runoff = W_{soil} - W_{max} \quad (3)$$

where,  $W_{max}$  is soil water holding capacity. The soil moisture scalar is important in regulating photosynthesis, plant growth rate, and soil carbon turnover time. We estimated the scalar by:

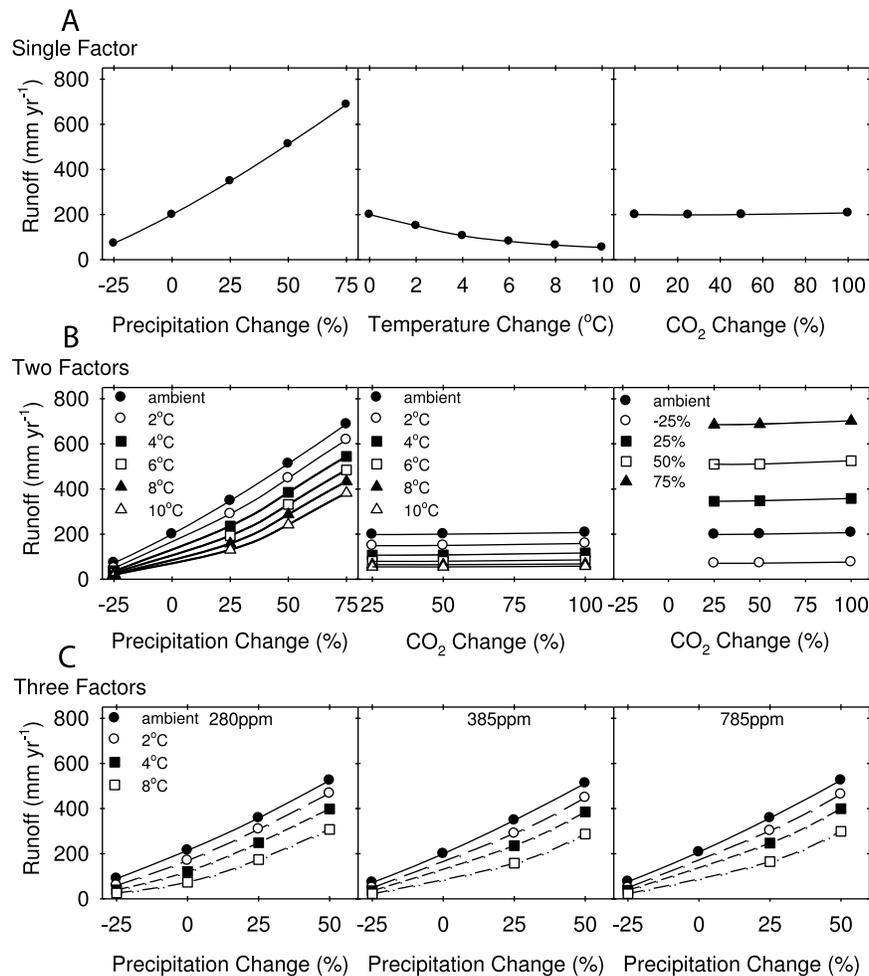
$$f_w = \min\left(1.0, 3.33 \cdot \left(\frac{W_{soil} - W_{min}}{W_{max} - W_{min}}\right)\right) \quad (4)$$

where,  $W_{min}$  is the permanent wilting point.

[12] Model input data included air temperature, soil temperature, relative humidity, precipitation, and photosynthetically active radiation. Vapor pressure deficit was estimated from relative humidity and temperature. All of the daily climate data from 2000 to 2005 were from a MESONET station near Washington, Oklahoma. The model was run to an equilibrium state using 6 year repeated cycles of the climate data. The spin-up simulations were done for 100 years before we applied different scenarios.

## 2.2. Validation

[13] We validated the model using data collected from a long-term warming experiment that has been ongoing at the Kessler's Farm Field Laboratory (KFLL) in McClain County, Oklahoma (34°59'N, 97°31'W) since November 1999. The dominant species at the site were  $C_4$  grasses,



**Figure 2.** Runoff results from TECO model. (a) Single factor climate change scenarios, (b) two factor combinations of precipitation, temperature, and CO<sub>2</sub>, and (c) three-way interactions with multiple combinations of temperature and precipitation; under 280 ppm, 385 ppm, and 780 ppm CO<sub>2</sub> concentrations, respectively.

*Schiachyrium scoparium*, *Sorghastrum nutans*, and *Eragrostis curvula*, and C<sub>3</sub> forbs, *Ambrosia psilostachya* and *Xanthocephalum texanum*. Average annual rainfall is about 915 mm and average annual temperature is 16.3°C. Data sets that were used in the model validation were above-ground and belowground biomass, soil moisture, and soil respiration. The measurements of aboveground biomass were done once a year for 6 years and belowground biomass only twice [Wan *et al.*, 2005]. Measurements of soil moisture and respiration were done twice a month [Luo *et al.*, 2001; Wan *et al.*, 2005; Zhou *et al.*, 2006]. All of the model patterns matched closely with the observed data. A full description and graphical representation of model validation are given by Weng and Luo [2008].

### 2.3. Scenarios

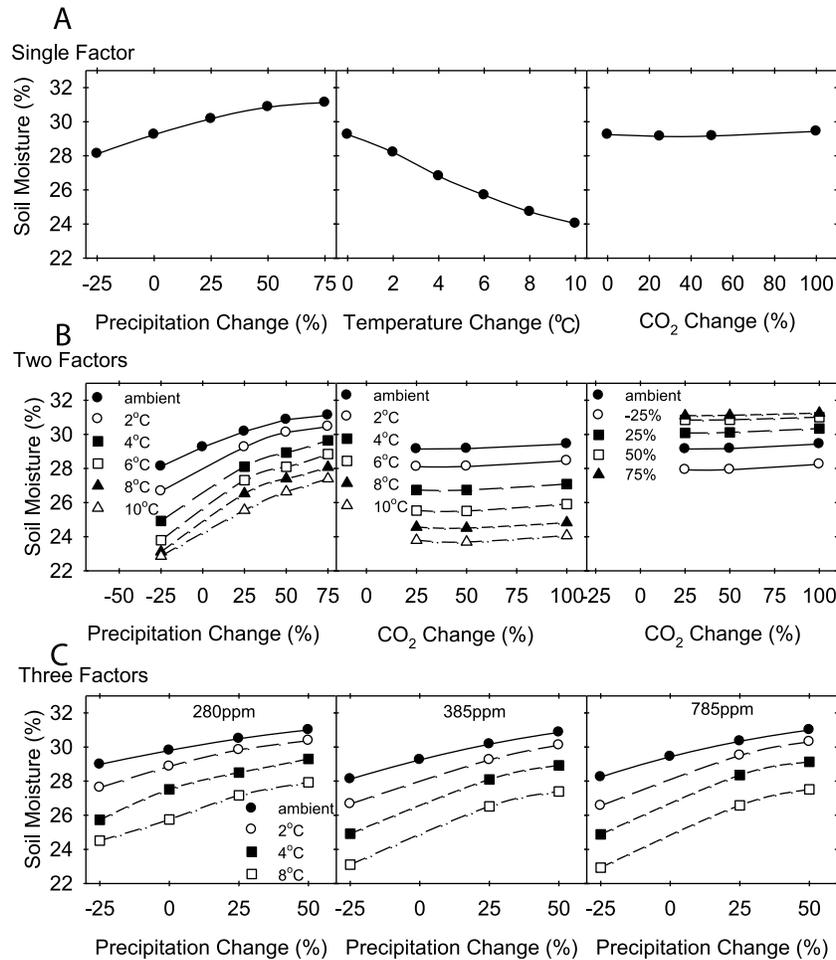
[14] The validated TECO model was used for this study. We developed 6 levels of climate warming (i.e., increases in temperature by 0, 2, 4, 6, 8, and 10°C above the ambient), 5 levels of CO<sub>2</sub> concentration from ambient at 385 ppm to doubled CO<sub>2</sub> with each increment of 25%, and 5 levels of precipitation from -25 to 75% of the ambient with each

increment of 25%. We used full combinations of three factors with their respective levels individually and in combinations and examined a total of 150 scenarios. The two- and three-factorial design allowed us to examine interactive effects of different combinations of climate change. For the simultaneous changes in three factors: temperature, CO<sub>2</sub>, and precipitation, we only show modeled results under four precipitation scenarios (-25%, ambient, 25%, and 50%) and three CO<sub>2</sub> concentrations (280, 385, and 780 ppm), representing preindustrial, current, and future conditions. All the combinations were run until conditions mimicked present-day and then a gradual linear change of all three factors began for the ensuing 100 years. Simulation results averaged of these last 6 years were reported in the paper for comparative study of ecosystem responses to different climate change scenarios.

## 3. Results

### 3.1. Runoff

[15] Runoff greatly varied with global change scenarios in precipitation, CO<sub>2</sub>, and temperature (Figure 2). When pre-



**Figure 3.** Rooting zone soil moisture results from TECO model. (a) Single factor climate change scenarios, (b) two factor combinations of precipitation, temperature, and CO<sub>2</sub>, and (c) three-way interactions of with multiple combinations of temperature and precipitation; under 280 ppm, 385 ppm, and 780 ppm CO<sub>2</sub> concentrations, respectively.

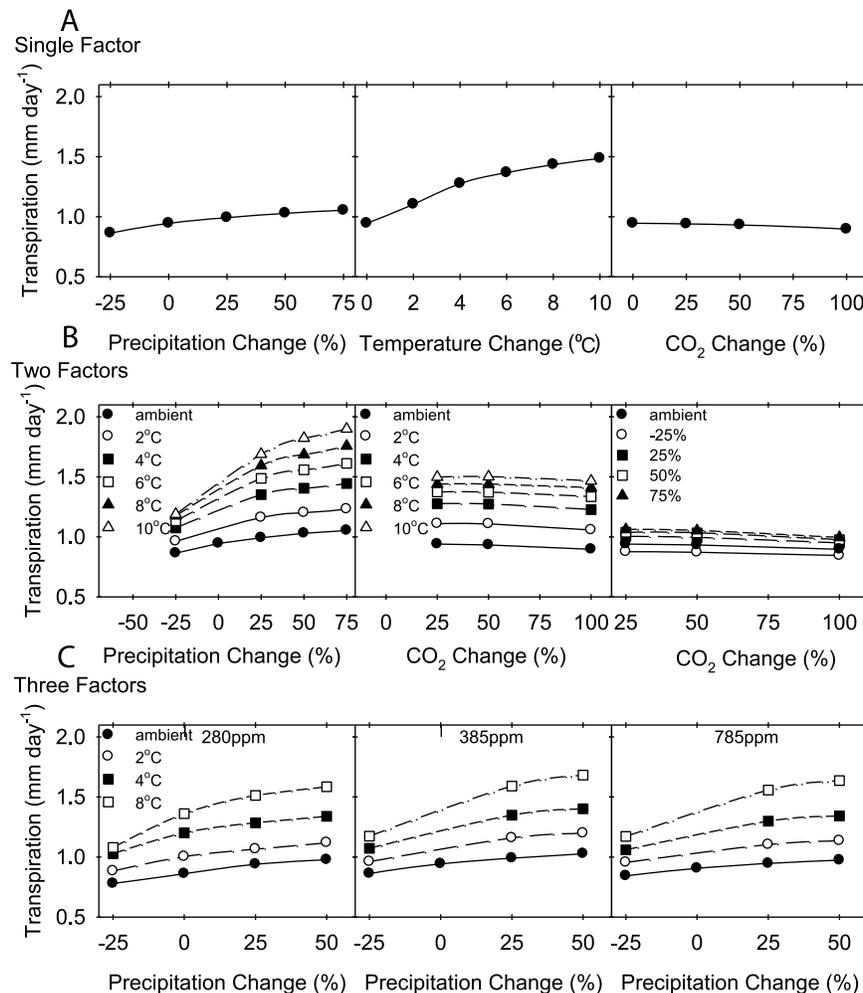
precipitation changed from a decrease of 25% to increases of 25, 50 and 75% from the control (i.e., ambient precipitation), there was a change in runoff by a decrease of 64% to the increases of 75, 157 and 245%, respectively (Figure 2a, left). When temperature increased by 2–10°C, runoff decreased by 25–73% (Figure 2a, middle). Changes in atmospheric CO<sub>2</sub> concentration had little impact on runoff as a single global change factor (Figure 2a, right).

[16] Two-factor climate change had a varying effect on runoff (Figure 2b). For example, when temperature increased by 10°C with precipitation changes of –25, 25, 50 and 75%, runoff varied from –90, –35, 21 and 92%, respectively (Figure 2b, left). Precipitation was the primary cause for a change in runoff with different combinations of CO<sub>2</sub> and precipitation scenarios (Figure 2b, right). Interactive effects of CO<sub>2</sub> and temperature on runoff were minor (Figure 2b, middle). Three-factor climate change also had varying changes in runoff depending on the scenario (Figure 2c). However, changes in CO<sub>2</sub> concentration were miniscule when compared to the changes in precipitation or temperature. Precipitation was the most influential on changes in runoff under three-factor change.

### 3.2. Rooting Zone Soil Moisture

[17] Simulated rooting zone soil moisture had a relatively small change in percent response to single or multifactorial global climate change compared to other ecohydrological variables (Figure 3). The largest change caused by a single global change factor was an 18% decrease in rooting zone soil moisture due to a temperature increase by 10°C (Figure 3a, middle). When precipitation decreased by 25% from ambient, there was a decrease in rooting zone soil moisture by 3.9% (Figure 3a, left). A precipitation increase by 75% resulted in a rooting zone soil moisture increase of 6.4%. An increase in atmospheric CO<sub>2</sub> concentration had the lowest impact on rooting zone soil moisture (Figure 3a, right).

[18] Two-factor climate change scenarios had variations in output; however, most of the variation occurred with combinations of precipitation and temperature. Hence, a combination of a 10°C increase in temperature and a precipitation decrease of 25% resulted in a decrease of 22% in rooting zone soil moisture in comparison to that at ambient conditions (Figure 3b, left). Interactive effects of CO<sub>2</sub> concentration with changes in either temperature or precipitation on rooting zone soil moisture were minor (Figure 3b,



**Figure 4.** Transpiration results from TECO model. (a) Single factor climate change scenarios, (b) two factor combinations of precipitation, temperature, and CO<sub>2</sub>, and (c) three-way interactions with multiple combinations of temperature and precipitation; under 280 ppm, 385 ppm, and 780 ppm CO<sub>2</sub> concentrations, respectively.

middle and right). The patterns of three-factor changes were similar to the patterns of two-factor changes; however, there was a slight decrease in rooting zone soil moisture with an increase in CO<sub>2</sub> concentration (Figure 3c).

### 3.3. Evaporation and Transpiration

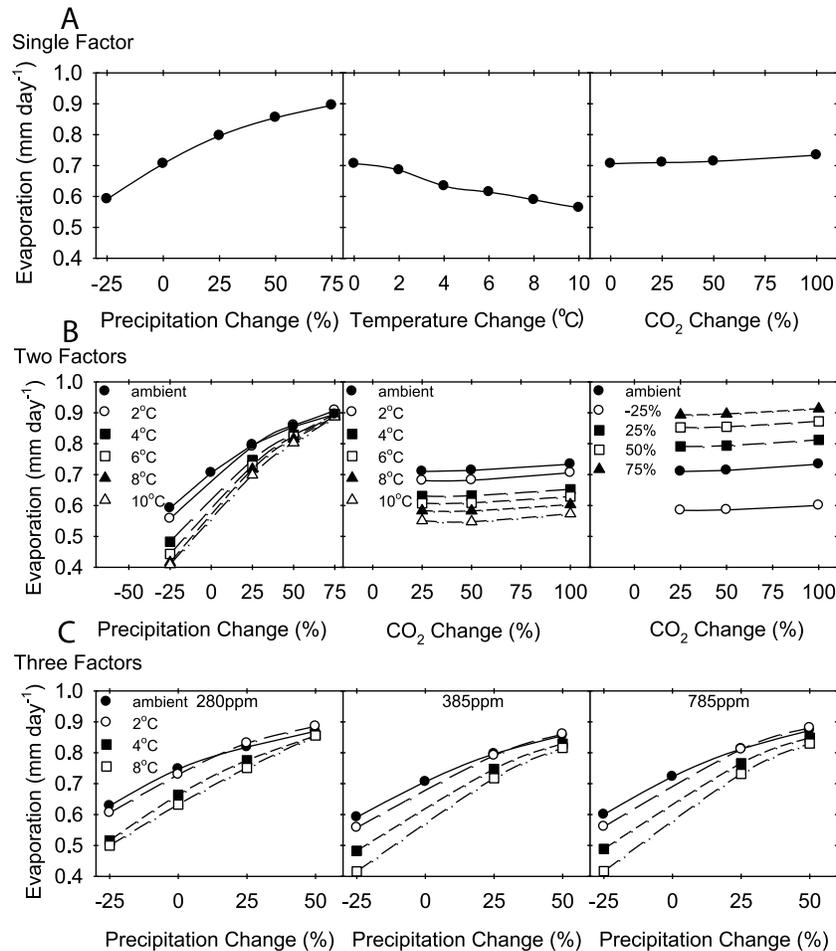
[19] Simulated transpiration from the TECO model responded positively to most climate change scenarios. Single-factor precipitation change had the least impact, whereas an increase in temperature had the greatest impact on transpiration (Figure 4a, left and middle). Transpiration varied from -9 to 11% as precipitation varied from -25 to 75% from the control, whereas transpiration increased by 57% with an increase in temperature by 10°C. Doubled CO<sub>2</sub> concentration caused a minor decrease in transpiration (Figure 4a, right).

[20] Two-factor climate change caused some variations under different scenarios. The greatest degree of change in transpiration occurred with different combinations of both precipitation and temperature (Figure 4b, left). The largest percent change in transpiration came from combined increases in temperature by 10°C and precipitation by 75%;

which resulted in a simulated increase of transpiration by 101%. Two-factor change with CO<sub>2</sub> had little impact on the rate of transpiration (Figure 4b, middle and right). Three-factor climate change scenarios had little variation from two-factor precipitation and temperature change (Figure 4c).

[21] Simulations of the TECO model showed variable responses of evaporation to different single and multifactor scenarios of climate change (Figure 5). Single-factor precipitation had the largest impact on evaporation among the three global change factors. For example, evaporation decreased by 16% from control when precipitation was reduced by 25%, and increased by 27% when precipitation increased by 75% from the ambient level (Figure 5a, left). Temperature caused the next largest percentage change; a 10°C increase in temperature resulted in a decrease in evaporation by 20% from that of the control (Figure 5a, middle). Single-factor CO<sub>2</sub> concentration had a marginal effect on evaporation (Figure 5a, right).

[22] Two-factor change had a linear response with all combinations (Figure 5b). When temperature increased by 10°C and precipitation decreased by 25%, simulated evaporation rate was reduced by 42%. With a CO<sub>2</sub> increase of 100%



**Figure 5.** Evaporation results from TECO model. (a) Single factor climate change scenarios, (b) two factor combinations of precipitation, temperature, and CO<sub>2</sub>, and (c) three-way interactions of with multiple combinations of temperature and precipitation; under 280 ppm, 385 ppm, and 780 ppm CO<sub>2</sub> concentrations, respectively.

and a precipitation increase of 75%, evaporation increased by 29%. Three-factor climate change had a response that was most similar to precipitation change. Evaporation had some slight changes under increased temperature and negligible changes under varying CO<sub>2</sub> concentrations.

### 3.4. Rain Use Efficiency

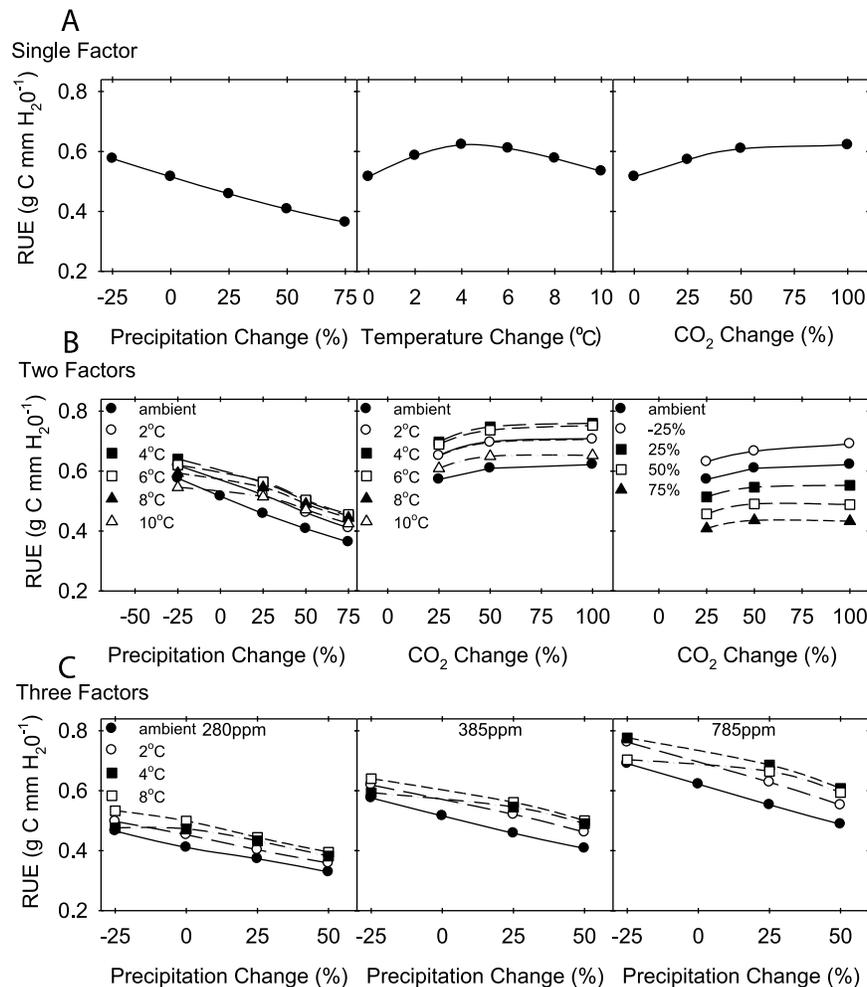
[23] Simulated rain use efficiency (RUE) was calculated from NPP and annual rainfall ( $RUE = NPP/rainfall$ ). Single-factor climate change caused varying changes in RUE; with precipitation causing the largest percent change. The largest change in RUE, by 31%, came with a 75% increase in precipitation from ambient (Figure 6a, left). When precipitation decreased by 25%, RUE increased by 14% in comparison to that of control. Increases in temperature caused nonlinear changes in RUE by 17, 28, 27, 21 and 13%, respectively, with temperature increases of 2, 4, 6, 8 and 10°C from the ambient (Figure 6a, middle). When CO<sub>2</sub> concentration increased from ambient by 25, 50, and 100%, RUE increased by 11, 18, and 20% (Figure 6a, right).

[24] Two- and three-factor climate change scenarios had multiple interactive effects on RUE. For example, a temperature increase of 10°C combined with multiple levels of

precipitation change (decrease by 25% to increases by 25, 50 and 75%) resulted in corresponding changes in RUE by 16, 9, 0.5, and -9% (Figure 6b, left). However, at a 10°C increase in temperature with CO<sub>2</sub> increases by 25, 50, and 75% there were increases in RUE by 28, 36, and 38%, respectively (Figure 6b, middle). The optimal RUE with two-factor climate change occurred with doubled CO<sub>2</sub> and a 25% decrease in precipitation (Figure 6b, right), a 4°C increase in temperature and a 25% decrease in precipitation (Figure 6b, left), and a 4°C increase in temperature and doubled CO<sub>2</sub> (Figure 6b, middle). The responses of RUE to three-factor climate change scenarios were largely influenced by precipitation; when temperature and CO<sub>2</sub> concentrations also had an impact on RUE (Figure 6).

### 3.5. Water Use Efficiency

[25] Plant-level water use efficiency (WUE) was calculated from NPP divided by the amount of transpiration ( $WUE = NPP/Transpiration$ ). Nonlinear responses in WUE were seen with single-factor changes in precipitation (Figure 7a, left), temperature (Figure 7a, middle), and CO<sub>2</sub> (Figure 7a, right). WUE increased with precipitation and CO<sub>2</sub> concentration but decreased with an increase in



**Figure 6.** Rain use efficiency results from TECO model. (a) Single factor climate change scenarios, (b) two factor combinations of precipitation, temperature, and  $\text{CO}_2$ , and (c) three-way interactions of with multiple combinations of temperature and precipitation; under 280 ppm, 385 ppm, and 780 ppm  $\text{CO}_2$  concentrations, respectively.

temperature. 10% stimulation in WUE occurred with a single-factor 75% increase in precipitation (Figure 7a, left) and doubled single-factor  $\text{CO}_2$  concentration caused an increase of 26% (Figure 7a, right). However, WUE decreased by 34% when temperature increased by  $10^{\circ}\text{C}$  from control (Figure 7a, middle).

[26] Two-factor scenarios altered WUE in the same nonlinear patterns (Figure 7b). Simulated optimal WUE occurred under the scenarios of doubled  $\text{CO}_2$  and a 75% increase in precipitation (Figure 7b, right), a 75% increase in precipitation at the ambient temperature (Figure 7b, left), and doubled  $\text{CO}_2$  at the ambient temperature (Figure 7b, middle). However, the highest percent change in WUE, i.e., a 39% increase, occurred with a doubled  $\text{CO}_2$  concentration and a 75% increase in precipitation. Three-factor scenarios also caused various nonlinear patterns of change in WUE with different conditions (Figure 7c).

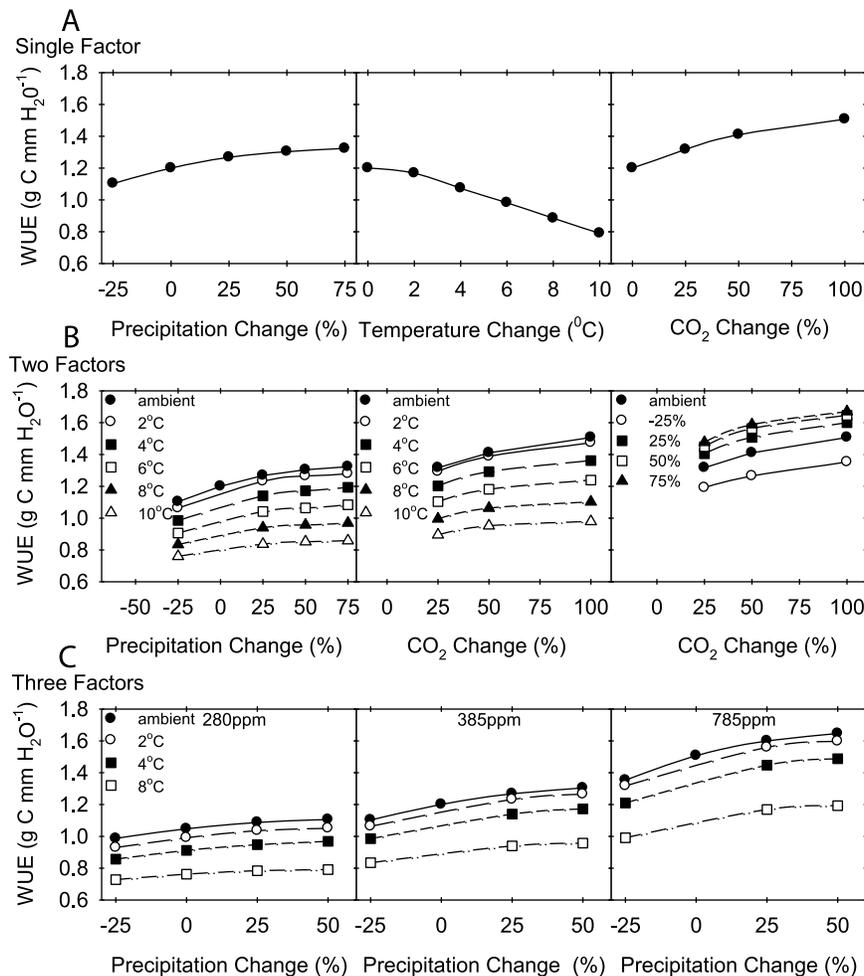
#### 4. Discussion

[27] Little is known about how different ecohydrological processes will respond to varying combinations of  $\text{CO}_2$ ,

precipitation and temperature in the future [Knapp *et al.*, 2008]. Our modeling results show that all components of the terrestrial hydrological cycle are changed under different scenarios of climate change. These results are important in explaining potential ways in which the ecosystem will respond given future climate alterations. Hopefully, our modeling results can be tested by and help in the design of future multifactor experiments. To further illustrate our results, we will first explain how climate change altered ecosystem rain use and plant level water use, and then further explain effects of single- and multiple-factor climate change on the rest components of the water cycle.

##### 4.1. Effects of Global Change on Rain and Water Use Efficiency

[28] Our simulations showed that ecosystem rain use efficiency (RUE) was dramatically different from plant water use efficiency (WUE) in response to global change. A decrease in precipitation, for example, caused an increase in RUE but a decrease in WUE (Figures 6 and 7). Our modeled increase in RUE was consistent with the experimental results of Huxman *et al.* [2004], which showed an increase in RUE



**Figure 7.** Water use efficiency results from TECO model. (a) Single factor climate change scenarios, (b) two factor combinations of precipitation, temperature, and CO<sub>2</sub>, and (c) three-way interactions of with multiple combinations of temperature and precipitation; under 280 ppm, 385 ppm, and 780 ppm CO<sub>2</sub> concentrations, respectively.

with decreased precipitation across different biomes, due to an increase in the relative amount of water used for plant production in water limited ecosystems. Our simulated responses of plant-level WUE due to changes in precipitation were similar to the modeling results by *Coughenour and Chen* [1997]. Their results showed that WUE increased with increases in precipitation from 80 to 120% in all studied grasslands, which included Kenya, Colorado, and Kansas. It should be noted that both our modeling results and the results of *Coughenour and Chen* [1997] are dealing with a system level response in WUE and not leaf level responses. Meanwhile, RUE and WUE differentially responded to warming. RUE optimized at 4–6°C temperature increase whereas WUE decreased with temperature (Figures 6 and 7). Similarly, *De Boeck et al.* [2006] showed that plant WUE in Belgium grasslands decreased with warming. Modeled positive responses of both RUE and WUE to an increase in CO<sub>2</sub> were consistent with experimental results in many studies [e.g., *Hui et al.*, 2001; *Owensby et al.*, 1993; *Morgan et al.*, 2004].

[29] Contrasting responses of RUE and WUE to various scenarios of global change resulted from different effects of environmental factors on processes at different scales.

Increased precipitation resulted in dramatic increases in runoff, substantial increases in evaporation, and little changes in transpiration. As a consequence, WUE increased as NPP increased in response to increased precipitation. However, increased precipitation resulted in water loss by evaporation and runoff at a magnitude larger than the magnitude of changes in NPP, resulting in decreased RUE. Warming caused an increase in transpiration in a larger magnitude than that for NPP, leading to decreased plant WUE. Warming increased RUE because NPP was stimulated by warming without a change in precipitation. The stimulation of NPP due to warming was partially caused by increased partitioning of precipitation to transpiration as shown by a modeling study by *Weng and Luo* [2008]. Our modeling analysis demonstrated that plant-level processes to global climate change cannot simply be scaled up to predict ecosystem-level responses, which is especially true of the hydrological cycle. Our results show that the plant level WUE is a poor determinate in explaining the total water budget for an ecosystem. However, ecosystem level RUE is more likely to illustrate changes in the rest of the water budget from alterations based on climate change.

## 4.2. Effects of Single Global Change Factor on Ecohydrological Processes

[30] Simulated effects of single factor global change on hydrological processes in ecosystems with the TECO model were generally consistent with results from field experiments and other modeling studies. For example, our simulated runoff increased with precipitation (Figure 2a) and rising atmospheric CO<sub>2</sub> but decreased with warming. This increase in runoff was due to a plant physiological response of decreased stomatal conductance and transpiration under elevated CO<sub>2</sub>. The single factor simulation of increased temperature, however, caused a decrease in runoff (Figure 2). From previous research [Huntington, 2006], it is known that temperature will accelerate the water cycle (e.g., evaporation), leaving less water available for runoff.

[31] Increases in temperature are known to accelerate rates of evapotranspiration. Based on our modeling results, we were able to conclude that temperature caused the highest magnitude of change, of the three factors studied, on transpiration and evaporation. For example, with a 10°C increase in temperature there was a 20% decrease in evaporation and a 57% increase in transpiration. The simulation results on transpiration are consistent with the leaf level study by Nijs *et al.* [1997] which showed that transpiration rates increased with warming, although it should be noted that in the same document the canopy level transpiration of *Lolium perenne* decreased with warming. An increase in transpiration due to higher temperatures could be responsible for absorbing more biologically available water and decreasing the amount of soil evaporation. The next largest percent change in evaporation and transpiration was due to precipitation, followed by CO<sub>2</sub>. With an increase in precipitation there was a gradual increase in our simulated results for both evaporation and transpiration. These results correspond to Ferretti *et al.*'s [2003] data that an 11.90% increase in rainfall, from 2000 to 2001 in a Colorado grassland, caused a 73% increase in transpiration and a 100% increase in evaporation. They also showed that with an increase in CO<sub>2</sub> there was a slight increase in transpiration and a variable change in evaporation from control under different precipitation amounts [Ferretti *et al.*, 2003]. They attributed the increase in transpiration to an increase in total biomass in the elevated CO<sub>2</sub> plots. Our model results of CO<sub>2</sub> change were not as responsive to changes in ET as other results that have been reported. For example, Ham *et al.* [1995] showed that open-topped chambers with twice the CO<sub>2</sub> enrichment caused a 22% decrease in ET. However, this study was only conducted over a 34 day period during peak biomass; whereas our study was over the entire growing season. Studies over a larger spatial area show that minimal reduction in ET is due to increased leaf area under elevated CO<sub>2</sub> [Kergoat *et al.*, 2002; Schafer *et al.*, 2002].

[32] TECO model results showed that increased temperature had the greatest impact on rooting-zone soil moisture (Figure 3). Reduction in rooting zone soil moisture with increased air temperature was probably a response to a higher rate of transpiration and a longer growing season. In a tallgrass prairie field experiment, Bell *et al.* [2010] showed that single factor temperature increase caused a significant reduction in soil moisture, while having a simultaneous change in ET. Precipitation caused the second greatest

change in percentage with an increase in rooting zone soil moisture. Bell *et al.* [2010] also showed that experimental warming had a greater impact on soil moisture than increased precipitation. Last, CO<sub>2</sub> had the least and most variable influence on rooting zone soil moisture. A doubling of CO<sub>2</sub> caused a slight increase in soil moisture relative to that at control. Other results have shown a similar pattern of soil moisture under elevated CO<sub>2</sub> [Wullschlegel *et al.*, 2002; Morgan *et al.*, 2004].

[33] Some of the modeled results, however, have not yet been carefully explored by field research. This is due to the fact that not all ecohydrological components have been fully evaluated in response to climate change.

## 4.3. Interactive Effects of Multifactor Global Change on Ecohydrological Processes

[34] Multifactor climate change causes both linear and nonlinear interactions of individual factors in influencing ecohydrological processes [Zhou *et al.*, 2008]. These results are important when evaluating how multifactor global change will alter ecohydrological processes. Hence, our results are likely useful to field researchers when considering the importance of multifactor global change on experimental design. Probably the most interesting results were the changes in runoff. There were some interactive effects on runoff with simultaneous changes in precipitation and temperature, while changes in CO<sub>2</sub> had only a marginal effect. Increases in runoff, due to increased precipitation, were dampened with increases in temperature (Figure 2). Our results indicate that if there is a decrease in precipitation, or if the increase in temperature goes past the point at which precipitation can compensate, there will be a decrease in ecosystem-level runoff (Figure 2b, left). It should be noted that because the soil moisture component of the TECO is a bucket model, we were not able to account for water loss to deep water infiltration. This would most likely contribute to slightly higher estimates of runoff. However, the lack of adequate inclusion of deep water loss to infiltration should not impact other ecosystem measurements (e.g., RUE), because the water that is stored regulates the processes. Thus, the manner of the water loss from the ecosystem should be irrelevant.

[35] Our model simulations showed that the interactive effect of temperature and precipitation had the most varying alterations to transpiration and evaporation (Figures 4 and 5). All other combinations of CO<sub>2</sub>, temperature and precipitation varied less from control under differing conditions. However, a decrease in precipitation seemed to cause more change in ecosystem response. Knapp *et al.* [1993] explained that the impact of CO<sub>2</sub> will probably be more detectable during drought conditions. Their results correspond with our results of less transpiration under elevated CO<sub>2</sub> and decreased precipitation. The response of evaporation and transpiration are essential for understanding the potential of terrestrial hydrological feedbacks on weather patterns [Raddatz, 2003].

[36] Multifactor responses produced varying alterations in rooting zone soil moisture from control. The largest percentage change in rooting zone soil moisture was the interactive effect of temperature and precipitation. Rooting zone soil moisture was highest with low temperatures and high precipitation, which was probably due to greater infiltration and decreased water loss via evapotranspiration. However,

when temperatures increased and precipitation stayed constant there was a decrease in rooting zone soil moisture. This decrease was associated with higher evapotranspiration. Other combinations of climate change scenarios showed linear changes from control. *Owensby et al.* [1993] suggest that an increase in soil moisture with higher CO<sub>2</sub> concentrations are likely attributed to higher water use efficiency and lower rates of evapotranspiration. Our results showed similar patterns, but when compared to the effects of temperature and precipitation these changes were not as significant. Any possible changes in soil moisture from control may change additional ecosystem processes. *Rodriguez-Iturbe et al.* [1999], for example, illustrated that changes in soil moisture dynamics could influence nutrient cycling, plant species composition, vegetation stress, and productivity.

[37] Three-factor modeling with TECO was performed to show potential interactive effects of multifactor climate change on WUE and RUE. Both RUE and WUE were lower at 280 ppm CO<sub>2</sub> (Figures 6c, left, and 7c, left) than at the other CO<sub>2</sub> levels (Figure 6c, middle and right, and Figure 7c, middle and right) for each of the temperature and precipitation scenarios. At 785 ppm CO<sub>2</sub> both RUE (Figure 6c, right) and WUE (Figure 7c, right) had greater variability among the various climate change scenarios than at 280 and 380 ppm, suggesting that CO<sub>2</sub> concentration amplified responses of RUE and WUE to changes in temperature and precipitation. Additionally, the values of WUE, when compared to RUE, were much more variable with three-factor changes in temperature, precipitation, and CO<sub>2</sub>.

[38] This research did not address changes in precipitation duration and intensity, but we can explore the potential outcome of our results under these precipitation scenarios. Prolonged duration of precipitation will have more consequences on ecosystem processes in mesic systems than hydric or xeric systems [*Porporato et al.*, 2006; *Knapp et al.*, 2008]. In these systems there will be greater periods of water stress during the periods between precipitation events, and longer time between events will likely cause more stress [*Knapp et al.*, 2008]. Furthermore, an increase in temperature will intensify the plant water stress that occurs in a drought situation [*Lloren et al.*, 2003]. Based on our modeling results, a future scenario that includes a longer duration between rainfall events, increased CO<sub>2</sub> and higher temperature will produce higher water stress than a single factor drought situation. Under this scenario where warming surpasses the affect of CO<sub>2</sub>, changes in both rain duration and intensity will likely cause a decrease in all ecosystem processes [*Knapp et al.*, 2002; *Harper et al.*, 2005; *Knapp et al.*, 2008], an increase in runoff and deep soil filtration [*Porporato et al.*, 2004], and a decrease in all other hydrological processes [*Brady and Weil*, 2002]. Further studies are needed to address the interaction of climate change and decreased rainfall frequency on ecohydrological processes.

[39] Our results set a precedent for research on how different interactive climate change scenarios influence ecohydrological components. To our knowledge, no other modeling study has divided up specific components of ecohydrology and performed a full evaluation of how each specific component responds to different global climate change scenarios. Our study has applications for field researchers studying specific interactions in different ecosystem types under dual climate change scenarios. These

results have helped identify which ecohydrological components have the greatest priority for further research. For example, combinations of temperature and precipitation had the largest interactive impacts on evaporation, runoff, transpiration, and rooting zone soil moisture. Our research also has the possibility of being applicable to regional and global climate modelers, since we have shown that two major contributing factors, transpiration and evaporation, of hydrological feedbacks to the atmosphere change under different climate change scenarios. This feedback could have some importance in understanding climatic changes [*Betts*, 2006]. Last, our runoff component has the potential, but should be approached with great care, in helping determine how climate change could alter the amount of freshwater in local streams and rivers.

## 5. Conclusions

[40] Using the TECO model, we were able to distinguish ecosystem-level ecohydrological responses from that at the plant level. The model showed that combinations of precipitation and temperature had the largest impact on ecosystem-level variables (e.g., runoff, evaporation, and soil moisture), whereas CO<sub>2</sub> and temperature had the largest impact on plant-level variables (e.g., transpiration and WUE). We also explored how each ecohydrological process responded to different climate change scenarios. All of our results showed that the interaction of multiple climate change factors could lead to an assortment of changes in the terrestrial water cycle. Additionally, we found ecosystem-level RUE to be a better indicator of potential changes in the water cycle than plant-level WUE.

[41] To evaluate regional evapotranspiration feedbacks to climate change under different climate change scenarios, we need to use coupled water-carbon models (e.g., TECO) in a wide variety of ecosystem types to examine if some modeled patterns in this paper can be extrapolated across multiple landscapes. Last, further research needs to evaluate if the patterns of runoff change are widespread [*Luo et al.*, 2008]; because these simulations may have an impact on replenishing freshwater supplies for agricultural and human use due to potential changes in the amount of runoff from different climate change scenarios.

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