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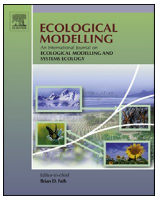

Modeled ecosystem responses to intra-annual redistribution and levels of precipitation in a prairie grassland

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ABSTRACT

Global models projected that, precipitation in Great Plains of the United States will decrease in summer and increase in spring and winter. However, few studies had carefully examined ecosystem responses to this intra-annual redistribution of precipitation. Here we used a process-based model, Terrestrial ECOsystem (TECO) Model, to evaluate responses of ecosystem carbon processes (including net primary production (NPP), heterotrophic respiration (R_h), and net ecosystem production (NEP)) and hydrological cycles (including evapotranspiration, and runoff) to precipitation redistribution at three levels (−50%, ambient, and +50% precipitation) in five soil textures (sand, sandy loam, loam, silt loam, and clay loam). Redistribution was designed by subtracting 40% summer precipitation and adding to spring and fall. Results showed that precipitation redistribution decreased NPP, R_h, and NEP at all three precipitation levels. Responses of NPP, R_h, and NEP differed in five soil textures. Redistribution slightly increased runoff and decreased evapotranspiration. Runoff was higher in coarse textured soils and lower in fine textured soils. Responses of evapotranspiration were contrary to runoff. Precipitation levels and redistribution had little effect on mean annual soil water content (SWC), especially in coarse textured soils. Our results indicated that, besides amount and timing of precipitation, the intra-annual redistribution could also affect ecosystem carbon and water processes. Moreover, the extent to which the ecosystem responses to redistribution of precipitation is largely controlled by soil texture.

1. Introduction

Ongoing global warming may alter regional precipitation regime (Harper et al., 2005). Global mean precipitation may not change significantly, but regional and temporal patterns have changed (IPCC, 2013). Magnitude of precipitation directly affects ecosystem productivity. For example, aboveground net primary productivity (ANPP) increases 0.64% when precipitation increases by 1% (Hsu et al., 2012). Precipitation is the most limiting factor for belowground net primary productivity and its fraction to total net primary productivity (NPP) in tallgrass prairie (Xu et al., 2012). Increased precipitation stimulates plant growth and ecosystem C fluxes, whereas decreased precipitation had the opposite effects (Wu et al., 2011). Meanwhile, timing of precipitation is crucial to ANPP across a broad range of ecosystems and plant types (Robinson et al., 2013). A 27 years observation in tallgrass prairie of Kansas also suggests that the timing of precipitation is as important as the precipitation amount for plant productivity (Craine, 2013; Craine et al., 2012). Changing in timing of precipitation will change intervals between rainfall events (Fay et al., 2000), which affects the seasonal availability of soil water.

Climate change projections suggest there will be a slight increase in annual precipitation, while a slight decrease in summer precipitation in the western and central United States (IPCC, 2007; Parton et al., 2012). In southern part of the Great Plains, spring will be wetter, and summer will be drier in mid twenty-first century (Patricola and Cook, 2013). In the southern USA, precipitation will not have a discernible upward or downward trend in the twenty-first century, but fall and winter will become wetter than the late twentieth century (Liu et al., 2012). The precipitation in Kansas is also likely to slightly increase in winter, but decrease in summer and fall in the twenty-first century (Brunsell et al., 2010). Therefore, the Great Plains is likely to have a drier summer, but wetter spring and winter. Intra- and inter- annual variability of precipitation is likely to increase (Hsu et al., 2012; Knapp et al., 2002), while annual precipitation amount has little change.

The tallgrass prairie of the Great Plains stores huge amount of carbon (An et al., 2013). This ecosystem is primarily driven by

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rainfall patterns (Knapp et al., 2006). Precipitation significantly alters ecosystem processes, which affects carbon dynamics (An et al., 2013; Knapp et al., 2002). Meanwhile, soil texture highly affects ecosystem productivity (Epstein et al., 1997). Precipitation events will be translated to potential biological activity by soils (Huxman et al., 2004). The ability of soil to store water, which could be quantified by the available water capacity (Weng and Luo 2008), is crucial for ecosystem carbon processes and hydrologic cycles.

Effects of amount and timing of precipitation to ecosystem carbon cycle had been well documented (Austin et al., 2004; Chou et al., 2008; Harper et al., 2005; Heisler-White et al., 2008; Jongen et al., 2011; Knapp et al., 2002; Parton et al., 2012; Takemi, 2010). However, most of these studies were experimental research. Few modeling studies concerned about this issue. Besides, the effects of intra-annual rainfall redistribution without altering timing and amount of precipitation were rarely reported. In this study, we used a process-based ecological model to estimate ecosystem responses to precipitation patterns. In this paper, we hypothesized that carbon processes (NPP, heterotrophic respiration (R_h), and net ecosystem production (NEP)) and hydrological cycles (evapotranspiration and runoff) will be affected by precipitation redistribution, and the responses of these processes was different in diverse soil textures. Thus, our objectives are to evaluate the effect of precipitation redistribution to ecosystem carbon processes and hydrological cycles at three precipitation levels (−50%, ambient, and +50%), and to evaluate different responses under these precipitation levels in diverse textured soils.

2. Materials and methods

2.1. Model description

In this research, we used a process-based model: Terrestrial ECOsystem (TECO) Model (Weng and Luo, 2008). The TECO model had four components: canopy photosynthesis submodel, soil water dynamic submodel, plant growth submodel, and soil carbon transfer submodel. The canopy photosynthesis and soil water dynamic submodels ran at hourly steps, while the plant growth and soil carbon transfer submodels ran at daily steps. The TECO model was described in detail by Weng and Luo (2008). Here we provide a brief overview.

The canopy submodel photosynthesis referred from a two-leaf model developed by Wang and Leuning (1998). Two-leaf meant sunlit and shaded leaves. This submodel simulated canopy conductance, photosynthesis, and partitioning of available energy. For leaf photosynthesis, the model combined Farquhar model (Farquhar et al., 1980) and a stomatal conductance model developed by Harley et al. (1992). In the soil water dynamic submodel, soil was divided into 10 layers. The surface layer was 10 cm deep and the other 9 layers were 20 cm deep. Soil water content (SWC) of these layers was determined by the mass balance between water influx (from the precipitation in the surface layer and percolation in deeper layers) and efflux (by adding evapotranspiration and runoff). In this model, runoff include both surface runoff and the water flow out from the bottom (190 cm). The plant growth submodel could simulate the carbon allocation and phenology. Allocation of the carbon among different plant components, such as leaves, stems and roots, depended on growth rates of these components, and varied with phenology. And the phenology dynamics was represented by the variation of leaf area index. Leaf onset was triggered by the growing degree days, while leaf senescence was determined by low temperature and soil moisture. The end of the growing season was recognized when leaf area index was less than 0.1. The carbon transfer submodel estimated carbon transferring from plant to litter and soil. The soil profile was divided into three layers, carbon moved from upper to deeper layers. Soil carbon influx from root growth and dead root residues were partitioned into these three layers.

The model was driven by climate data, which included air and soil temperature, vapor-pressure deficit, relative humidity, incident photosynthetically active radiation, and precipitation at hourly steps. Climate data was collected from the Washington MESONET site, Oklahoma from 1998 to 2012. The simulated results were recorded after the model was run 1200 years and reached the equilibrium state. After precipitation was redistributed, all following years' results exhibited the same pattern. We used the first year's results to illustrate the impact of precipitation redistribution on grassland.

2.2. Model validation

The TECO model was validated by observation data from a long-term warming experiment at the Kessler's Farm Field Laboratory in McClain County, Oklahoma, USA (34°59′N, 97°31′W). The validating dataset included soil respiration, above and below ground biomass, net ecosystem exchange (NEE), and soil moisture. Soil respiration and soil moisture were measured approximately once a month from 2000 to 2005. Soil respiration showed no significant difference between simulated and observed ($P = 0.21$). And simulated soil moisture was slightly higher than the measured values when soil was very dry. Aboveground biomass were measured once a year in these 6 years, and belowground biomass were measured in 2002 and 2004. the simulated results are in good agreement with observational data. Full description and graphical representation of the validation could be found in Weng and Luo (2008) and Zhou et al. (2008). The modeled outputs matched well with observed data.

2.3. Simulation scenarios

In order to test ecosystem responses, we defined 30 simulation scenarios from combinations of five soil textures and six precipitation patterns. Soil textures were classified according to their field capacities and wilting points. Five soil textures named sand, sandy loam, loam, silt loam, and clay loam (Table 1) (Weng and Luo, 2008). In order to simplify the interpretation of modeling results, we assumed all soil layers have the same field capacity and wilting point.

Six precipitation patterns were denoted as 1.0P, 1.5P, 0.5P, 1.0PR, 1.5PR, and 0.5PR. 1.0P stood for ambient scenario. 1.5P and 0.5P were defined by increasing and decreasing 50% precipitation for each rainfall event of 1.0P. 1.0PR represented the scenario in which precipitation of each rainfall event was subtracted by 40% in summer (May–September) and evenly added to rainfall events in spring (March and April) and fall (October and November). 1.5PR and 0.5PR followed previous redistribution method at +50% and −50% precipitation levels. Each rain day was treated as a rainfall event in this study. This redistribution method could well represent the intensified summer drought and seasonal rainfall alternation (Volder et al., 2013). Fig. 1 represented monthly precipitation of 6 precipitation patterns. We also defined three precipitation levels: increased, ambient, and decreased as P+, C, and P− levels to facilitate analyzing.

Table 1
Field capacities and wilting points of the five soil texture types.

Soil texture	Sand	Sandy loam	Loam	Silt loam	Clay loam
Field capacity(%)*	10.0	15.0	25.0	35.0	45.0
Wilting point(%)*	5.0	7.5	10.0	12.0	15.0

* The parameters was cited from Weng and Luo (2008).