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Similar responses of soil carbon storage to drought and irrigation in terrestrial ecosystems but with contrasting mechanisms: A meta-analysis

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A B S T R A C T

Global climate models predict that future precipitation regimes will largely change across the globe due to the intensification of the global water cycle under climate warming, which may generate considerable impacts on ecosystem carbon (C) dynamics. Although substantial manipulative experiments have been conducted to probe the responses of ecosystem C processes to altered precipitation, how soil C storage responds to both drought and irrigation is still unclear across biomes and the globe. A meta-analysis of 179 published studies was carried out to examine responses of soil C storage and associated C fluxes and pools to drought and irrigation. Our results showed that, on average across all biomes, drought and irrigation similarly induced minor increases in soil C pool (SCP) by 1.45% and 1.27%, respectively. However, drought and irrigation oppositely affected both C fluxes and plant C pools as well as in agroecosystems (e.g., croplands and grasslands). The drought-induced increases in root: shoot ratio and decreases in heterotrophic respiration and soil C turnover rate mostly contributed to minor increase in SCP, while an increase in newly fixed C inputs in soil was more important under irrigation. In addition, the relative changes in precipitation intensity in manipulative experiments were positively correlated with response ratios of plant C pool (PCP), net primary production (NPP), microbial biomass C, ecosystem, soil and heterotrophic respiration. The drought-induced responses of SCP exhibited a positive correlation with experimental duration but not under irrigation and for other C pools and fluxes. These results indicate that more attention should be paid to the responses of C allocation and turnover rate to drought and irrigation, which should be incorporated into land surface models to better project effects of altered precipitation on ecosystem C cycling in terrestrial ecosystems.

1. Introduction

As a consequence of climate change (especially global warming), air circulation and the hydrological cycle have largely been intensified, leading to rapid shifts in precipitation regimes across the globe (IPCC, 2007). For example, global precipitation was estimated to increase by 7.4% ± 2.6% with each 1 °C increment in temperature over the period 1987–2006 (Wentz et al., 2007). Altered precipitation may directly and indirectly affect terrestrial C dynamics and then ecosystem structure and function (Cable et al., 2008), which may impact interactions with other global change drivers (e.g., elevated CO_2, climate warming). The shifts in precipitation regimes (i.e., amount, intensity, and frequency, IPCC, 2007) were suggested to have an even greater impact on ecosystem dynamics than the singular or combined effects of rising atmospheric CO_2 concentration and temperature (Weltzin et al., 2003). Therefore, understanding the responses of ecosystem

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C cycle to precipitation changes is of key importance to accurately project the rate and extent of climate change (Houghton, 2007).

Changes in precipitation not only affects soil physical processes (e.g., water infiltration, runoff, and leaching) but also impacts biotic processes (e.g., plant growth, CO_2 and N_2O production in soil) in ecosystems (Linn and Doran, 1984; Pastor and Post, 1986). Previous studies have mainly focused on precipitation-derived impacts on aboveground C processes, including leaf photosynthesis (e.g., Santiago and Mulkey, 2005), aboveground net primary productivity (NPP, Knapp et al., 2002), and species composition (Fauset et al., 2012). However, their responses to altered precipitation remain controversial among individual studies and biomes (Gerten et al., 2008). For example, aboveground NPP has been demonstrated to increase with mean annual precipitation in arid and semi-arid regions, while to decrease in moist ecosystems (Fay et al., 2003). The underlying mechanisms for the diverse responses of aboveground NPP to precipitation changes may be the different antecedent moisture conditions among the study sites (Yan et al., 2010). In contrast, understanding the responses of belowground C processes to altered precipitation (drought and irrigation) are relatively incomplete, largely due to methodological difficulties for estimating belowground C processes and the complex biotic interactions in soil- root interface (Luo and Zhou, 2006). For example, in a meta-analysis, the limited data (only four points) of belowground NPP made it difficult to evaluate the effects of altered precipitation (Wu et al., 2011), although belowground NPP accounts for more than one-half of NPP, especially in arid and semi-arid ecosystems.

Carbon storage in soil (i.e. soil C pool), the largest terrestrial C pool in the biosphere, is more than that in the atmosphere and vegetation combined (Post et al., 1982; Amundson, 2001) and is predicted to play a significant role in the changing climate (Lal, 2004). Altered precipitation affects soil C stocks by impacting soil C inputs from aboveground and belowground biomass and outputs from soil organic matter (SOM) decomposition (Fröberg et al., 2008). Drought may increase the physical protection of SOM and inhibit the decomposition rates, while irrigation may stimulate both C inputs and SOM decomposition via increased substrate availability (Vasconcelos et al., 2004). Altered water availability has been demonstrated to change the partitioning of photosynthetically assimilated C between shoots and roots (Asch et al., 2005), and thus influenced C allocation between plants and soil (Gill and Jackson, 2000). Since soil organic C often has a longer C turnover time than plant C pools, C allocation between soil and plants is of importance for forecasting the future global climate (Weltzin et al., 2003). However, how soil C storage and C allocation respond to decreased or increased precipitation (i.e., drought or irrigation) is largely unclear in terrestrial ecosystems, which may limit our mechanistic understanding on the responses of ecosystem C budget to altered precipitation (Houghton, 2007).

To better comprehend the effects of altered precipitation on the terrestrial C cycle (especially soil C storage), we conducted a meta-analysis from diverse experimental precipitation changes to quantify a general tendency of the precipitation effects on soil C storage, related C fluxes and pools, C allocation (e.g., root: shoot ratio), and soil C turnover rate. This study focuses on effects of changes in precipitation amount (i.e., irrigation and drought treatments), although the precipitation changes include many aspects of precipitation regimes at the global scale (Alexander et al., 2006; IPCC, 2007). Totally 179 published studies were included to examine the responses of ecosystem C pools and fluxes to drought and/or irrigation before May 2013. The concerned variables in the study mainly included soil and plant C pools, microbial biomass C, and the related C fluxes (e.g., NPP, ecosystem respiration, soil respiration and its components). The meta-analysis was used to address the three following questions. First, to what extent was soil C storage affected by drought and irrigation? Second, what the mechanisms for the responses of soil C storage to drought and irrigation, respectively? Third, how did experimental variables affect the responses of C pools and fluxes to precipitation changes?

2. Materials and methods

2.1. Data sources

Peer-reviewed journal articles related to precipitation manipulation (i.e., drought and/or irrigation) published before May 2013 were searched using Web of Science (1900–2012) with the following search term combinations: (water OR rain* OR precipitation OR moist* OR drought OR dry OR irrigat* OR humid) AND

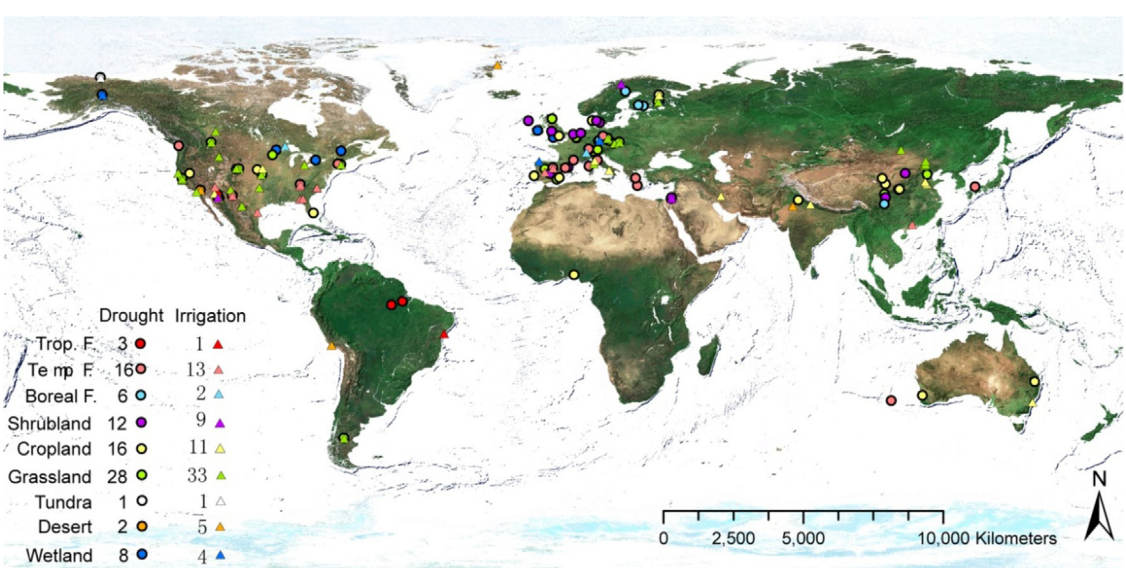

Fig. 1. Global distribution of manipulative experiments with precipitation changes selected in this meta-analysis. Circular and triangular symbols are sites with drought or irrigation treatments, respectively. Numbers before symbols are actual amount of sites in each biome from 179 papers, in which drought and irrigation treatments were conducted in 111 and 84 studies, respectively, and 16 studies included both of them. Trop. F.: Tropical forests; Temp. F.: Temperate forests; Boreal F.: Boreal forests.