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Changing rainfall frequency rather than drought rapidly alters annual soil respiration in a tropical forest

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ABSTRACT

Tropical forests play an important role in global carbon (C) cycling due to high primary productivity and rapid litter and soil organic C decomposition. However, it is still unclear how changing rainfall will influence soil CO_2 losses (i.e. via soil respiration) in tropical forests. Here, using a rainfall and litter manipulation experiment in a tropical forest, we show that enhanced litter-leached dissolved organic carbon (DOC) production with increased rainfall frequency drives substantial CO_2 loss via soil respiration. A 50% increase in rainfall frequency (no change in total rainfall amount) enhanced inputs of DOC by 28%, total dissolved nitrogen (TDN) by 17%, and total dissolved phosphorus (TDP) by 34% through leaching from litter layer to soil surface likely due to faster litter decomposition rate, and stimulated soil respiration by ~17% (about 1.16 t C ha^{-1} yr^{-1}). Soil respiration responded to altered rainfall frequency with limited when litter layer was removed. Accordingly, soil microbial biomass C (MBC) and fine root biomass were increased by 23% and 20%, respectively only in the plots with litter layer. A 50% reduction in total rainfall (no change in rainfall frequency) did not change litter-leached DOC and nutrients fluxes, soil MBC, fine root biomass, or annual mean soil respiration rates. The new finding – that enhanced leached-DOC production with increased rainfall frequency drives profound increases in soil respiration in tropical forests – suggests that future climate changes may have significant impacts on soil C dynamics and global C budget, and argues for the importance of incorporating this underappreciated feedback into prognostic models used to predict future C-climate interactions.

1. Introduction

Tropical forests are a critical component of the global carbon (C) cycle. They contain approximately 20% of the global soil C stock and account for roughly 35% of terrestrial net primary productivity (Jobbagy and Jackson, 2000). Responses of tropical forest C dynamics to climate change could significantly influence atmospheric carbon dioxide (CO_2) concentrations and thus affect the pace of future climate change (Houghton et al., 2015). Climate models generally predict more drought events and changes in rainfall frequency around the tropics in the future (Zhou et al., 2011; IPCC, 2013), with potentially profound effects on tropical forest productivity and tree mortality (Doughty et al., 2014). However, the effects of shifting rainfall patterns on tropical forest soil CO_2 fluxes (e.g., via soil respiration) and the underlying mechanisms are still not fully understood (Knapp et al., 2008; Bond-Lamberty and Thompson, 2010). As a result, model predictions of soil respiration in tropical forests were often inconsistent with experimental observations, making the impact of potential changes in rainfall patterns on the tropical forest C balance highly uncertain (Powell, 2014).

Both field experiments and model simulations have identified soil temperature and soil moisture as two important controls on soil respiration (Davidson and Janssens, 2006; Falloon et al., 2011). Changing rainfall can affect soil respiration mainly via altered soil moisture (Fig. 1a; Gabriel and Kellman, 2014; Vicca et al., 2014; Liu et al., 2016). Indeed, rainfall-manipulation experiments in temperate ecosystems mostly show declines in soil respiration in response to simulated drought and increases in soil respiration with simulated increases in rainfall (Wu et al., 2011; Liu et al., 2016). However, the paucity of studies conducted to date in tropical forests have produced different results (Sotta et al., 2007; Davidson et al., 2008; Cleveland et al., 2010;

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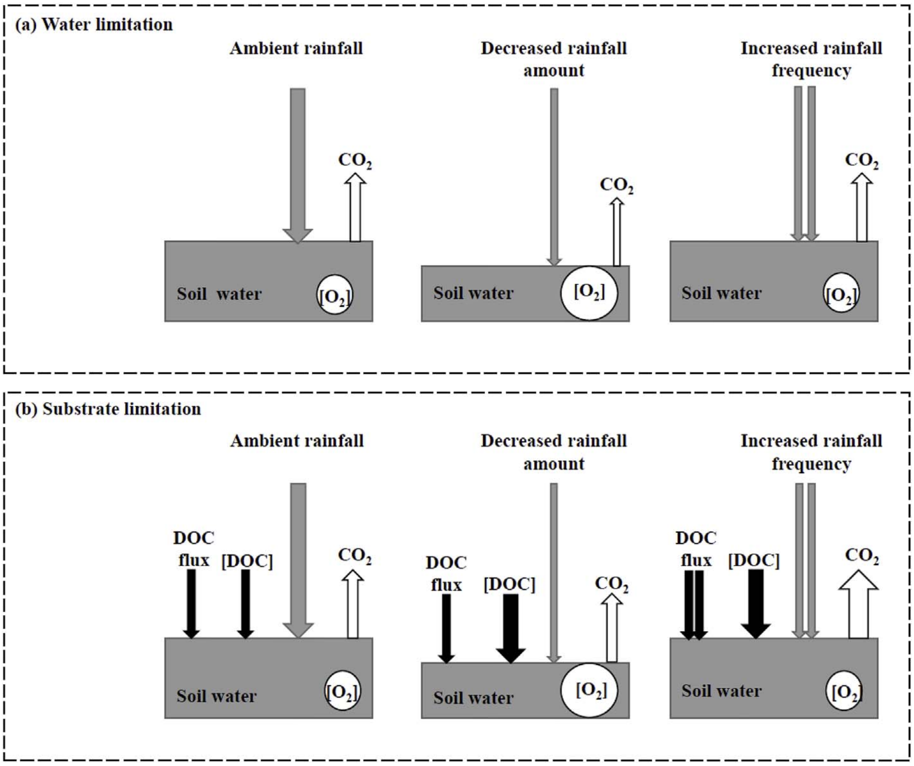

Fig. 1. Conceptual models illustrating the potential effects of rainfall changes on soil respiration. a) A traditional model that includes the trade-off between soil water and O_2 concentration ($[O_2]$). b) A revised model (Cleveland et al., 2010) that integrates the potential effects of litter-leached dissolved organic carbon (DOC) concentration ([DOC]) and DOC flux into the traditional model. Our revised model includes the potential effects of the mechanistic controls from water limitation to substrate limitation. The sizes and the number of the arrows or lettering reflect relative differences in response to rainfall changes.

Van Straaten et al., 2010; Deng et al., 2012; Wood and Silver, 2012), with inconsistencies often attributed to a trade-off between soil water content and soil O_2 concentrations (Fig. 1a).

In addition to soil temperature and soil moisture, C substrate (quality and quantity) also strongly regulates rates of soil respiration (Davidson and Janssens, 2006; Xu et al., 2014; Campbell et al., 2016). Studies using rainfall simulations or laboratory incubations have demonstrated that pulses of rainfall can transport large quantities of dissolved organic carbon (DOC) from the litter layer, and leached DOC fluxes can stimulate large episodic CO_2 pulses from the soil surface (Cleveland et al., 2007; Wu and Lee, 2011). Given the consistently warm temperatures and ample rainfall in many tropical forests, frequent litter-leached DOC inputs may have disproportionately strong effects on soil respiration, although the intensity of such effects may depend on the quality of C input and the status of soil organic matter in the study sites (Cleveland et al., 2007; Qiao et al., 2014; Zhou et al., 2016). Thus, rainfall changes may significantly affect tropical forest soil respiration by altering annual input of litter-leached DOC. Cleveland et al. (2010) showed that experimental drought did not change total amount of litter-leached DOC flux, but significantly enhanced its concentration, and stimulated CO_2 fluxes from soils. Change in rainfall *frequency* has been shown to exert a greater influence on litter decomposition rates than changes in total rainfall amount (Vanlauwe et al., 1995; Wieder et al., 2009; Anaya et al., 2012), implying that altered rainfall frequency could have more profound effects on litter-leached DOC fluxes and soil respiration rates (Fig. 1b). Unfortunately, few, if any, field experiments have explicitly manipulated rainfall frequency in a tropical forest ecosystem, severely limiting our ability to predict how climate change-driven shifts in rainfall patterns may alter the C cycle in this important biome (Beier et al., 2012; Liu et al., 2016).

We conducted a one-year rainfall manipulation experiment in an old-growth tropical forest southern China (23°10′ N and 112°10′ E). Three rainfall treatments were chosen: 1) an ambient rainfall as a control (CK); 2) a 50% increase in rainfall frequency with no change in total rainfall amount (increased rainfall frequency treatment; IRF); and 3) a 50% reduction of rainfall amount with no change in rainfall frequency (drought treatment; DRA) (Fig. S1). We hypothesized that the DRA treatment would decrease soil respiration due to reduced soil moisture (Fig. 1a), while the IRF treatment would increase soil respiration due to enhanced input in litter-leached DOC flux (Fig. 1b). To test this hypothesis, we further quantified the contributions of different soil CO_2 sources, and specifically isolated the indirect soil CO_2 flux driven by litter-leached DOC (R_{DOC}) through either permanently or temporally removing litter layer (See more details in the methods). We expected that the IRF treatment would increase R_{DOC}, without significant changes in the other soil CO_2 sources.

2. Materials and methods

2.1. Experimental design

This study was carried out in an old-growth tropical forest at the Dinghushan Biosphere Reserve (DBR) in the Guangdong Province in southern China (23°10′ N and 112°10′ E). The forest is dominated by *Castanopsis chinensis, Cryptocarya concinna, Schima superba, Machilus chinensis*. No disturbances were recorded for the past 400 years in this forest (Zhou et al., 2016). Soil properties and major stand information of this tropical forest have been shown in Table S1. Climate is typical south subtropical monsoon climate, with mean annual temperature of 21.4 °C, and mean annual precipitation of 1956 mm, of which nearly 80% falls in the hot-humid wet/rainy season (April–September) and 20% in the cool-dry season (October–March). However, long-term observation records in this region showed that rainfall frequency, intensity and seasonal patterns have been highly variable for the past three decades (Zhou et al., 2011).

A randomized block design with three blocks was established in June 2013. The rainfall treatments were randomly assigned to plots in each block. Each plot was $5 \times 10\,m^2$, and the distance between plots was more than 5 m. A 5-m PVC panel was inserted in the middle of the plot to divide each plot into two subplots ($5 \times 5\,m^2$). One subplot was used for litter removal treatment and another subplot received normal litter fall.