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Drought: The most important physical stress of terrestrial ecosystems ☆

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ABSTRACT

Drought is projected to become more prevalent in the future due to climate change, and its impact on the fate of terrestrial ecosystems has aroused great concern in the scientific community over the past decade. Mounting evidence suggests that drought may be the most important physical stress of terrestrial ecosystems: drought limits vegetation growth, increases wildfires, and induces tree mortality, among other impacts. Drought not only weakens the carbon sink function of terrestrial ecosystems but also may interfere directly or indirectly with biosphere–atmosphere interactions, further exacerbating climate change. This paper reviews the current evidence of the impacts of drought on terrestrial ecosystems, with particular emphasis on the ways in which drought alters the biological, biogeophysical and biogeochemical processes underlying the interaction between the biosphere and the atmosphere.

Contents

1. Introduction

Terrestrial ecosystems play a key role in global carbon cycling [43], as they currently sequester 20–30% of global anthropogenic CO_2 emissions [46]. Conversely, global terrestrial NPP is also a major driving force of the interannual CO_2 growth rate [67]. Over the past several decades, climate change seems to have had a generally positive impact on terrestrial ecosystems [24,8], a phenomenon known as “the green trend” [3,41]. However, an increasing number of studies have shown that the reduction of net primary production in the global terrestrial ecosystem due to warming and drought has greatly weakened this “positive feedback” [67,24,17,31]. For example, severe drought in moist tropical forests should provoke large carbon emissions by increasing forest flammability and tree mortality and by suppressing tree growth [38]. The benefits of climate change for middle and high latitude terrestrial ecosystems are also being weakened by severe drought [64,32]. Drought frequency and severity are predicted to increase across numerous continental interiors [21], and the consequences of these changes for the dominant plant species are largely unknown [36]. A comprehensive knowledge of drought impacts and related disturbances is critical for understanding the interactions between terrestrial ecosystems and the atmosphere.

Drought could cause terrestrial ecosystems to act as carbon sources to the atmosphere in several ways, such as by suppressing tree growth, reducing both autotrophic and heterotrophic

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respiration, causing plant mortality and disease or increasing rates of fire intensity. All of these impacts could significantly reduce terrestrial ecosystem productivity [67,54]. Drought impacts on terrestrial ecosystems have received relatively little scientific attention and may therefore be greatly underestimated. The existing studies do provide substantial evidence for the effects of drought on terrestrial ecosystems, but the possible consequences of these effects remain poorly understood.

This paper reviews the primary direct and indirect impacts of drought on terrestrial ecosystems, as well as the biological and chemical processes of interaction between drought, terrestrial ecosystems and climate change. This study aims to further the understanding of the role drought playing in terrestrial ecosystems.

2. History drought situation and future projection

As a normal part of climate variability, drought has occurred many times over the past 1000 years across many parts of the world [20]. Since the 20th century, however, drought has increased on both the regional and global scales [20]. The global area impacted by drought has increased sharply since the 1970s, a rise attributed, in part, to global warming [19,28]. Some recent research proposes that the increase in global drought conditions has been overestimated due to the inherent deficiencies of the drought index and that little change in global drought has occurred over the past 60 years [51]. However, an analysis of global drought trends using the SPEI index develop by Vicente-Serrano [60] suggests that areas impacted by severe and extreme drought have increased dramatically. Although the effects of this drought may have been overestimated, the severity of the drought has actually intensified.

The drought induced temperature extremes had been reported in several studies [26,37], and the basic mechanism behind this phenomenon is soil moisture variations affecting the partitioning of sensible and latent heat [37]. This issue can be traced back to the relationship between precipitation and temperature. In early studies, more stresses were play on the impacts of temperature on precipitation. For example Isaac and Stuart [27] computed temperature-precipitation relationships for Canadian stations using daily data. For the east and west coasts and northern Canada, more precipitation accompanies warm conditions in winter and cool conditions in summer, thereby reversing the correlation with seasons. Therefore, we think that it is still hard to determine the causal relationship between temperature and water deficiency. This also implies the great importance for the further study of the relationship between drought and temperature, which is crucial for attributes analysis for drought event and the reduction of the uncertainty of future drought projection.

Global warming and regional droughts are predicted to intensify and become more frequent during this century due to anthropogenic climate change [15]. Future drought trends have also been projected using a multi-model under multi-scenario method [21]. Nearly all simulation results suggest that, as a result of decreased precipitation and/or increased evaporation, future droughts will become increasingly serious [21,50,14]. Although, current studies indicates that the future rise in drought and its impacts is potentially dramatic, these projections should be further improved based on more in-depth understanding of the contribution of the natural factors and human activities to drought, respectively.

3. Drought reduces terrestrial ecosystem productivity

Research suggests that frequent drought and heat have great impacts on terrestrial carbon cycling by reducing ecosystem productivity, although there remain some uncertainties regarding their effects [17]. Several studies have proposed that dry conditions may actually boost tropical productivity through increases in available solar radiation [45,9]. The terrestrial biosphere could contribute significant amount of CO_2 emission during major drought events, such as those evoked by the 1997–1998 El Niño event [43]. These impacts occurred on both the global and regional scales. Table 1 displays a number of major drought events and their impacts on the carbon cycles of their respective terrestrial ecosystems. Among those areas presently studied, the Amazon rainforest is particularly important due to its special status in the global carbon cycle and climate change. This area can process 18 Pg C annually, more than twice the amount of annual anthropogenic fossil fuel emissions [33]. During the 2005 Amazon drought, the total loss of carbon biomass carbon was 1.2–1.6 Pg C [42]. In 2010, the Amazon experienced a second 100 year drought, and the carbon impact of the 2010 drought may eventually exceed 5 billion tons of CO_2 released [31]; this figure accounts for 16.6% of global industrial emissions (30.1 Pg C) in 2010. The research warns that, if extreme droughts like these events become more frequent, the Amazon rainforest may lose its ability to act as a natural buffer for anthropogenic carbon emissions [31]. Two other critical ecosystems to Earth's climate, the boreal forests and the temperate forests, are facing the same fate, their carbon sinks weakened by increasingly frequent drought events [32,57].

At the global scale, a reduction in terrestrial NPP of 0.55 petagrams over the past decade (2000–2009) has been estimated using the global MODIS NPP algorithm. Furthermore, the drying trend of the Southern Hemisphere has decreased the NPP in that area, counteracting the increase in NPP observed over the Northern Hemisphere [67].

Although a number of studies have examined the influences of drought on plant productivity and the terrestrial carbon cycle, the physiological mechanism targeted by drought remain unclear. Drought has generally been considered to reduce photosynthesis

Table 1
Main drought events and their impacts on the carbon cycle of terrestrial ecosystems.

ID	Study area	Years of drought	Reduction of carbon	Refs.
1	Northern Hemisphere midlatitude regions	1998–2002	0.9 Pg C yr^{-1}	[64]
2	European	2003	0.5 Pg C yr^{-1}	[17]
3	Amazon forest	1997–1998	Reduced by 20–30%	[44]
		2001	0.2 Pg C	[38]
		2005	1.2–1.6 Pg C	[42]
		2010	More than 5 Pg C	[31]
4	China	Droughts over the period 1901–2002	Most droughts generally reduced NPP and NEP in drought-effect area	[63]
5	Canada's boreal forests	Drought over 1963–2008	Drought reduced the biomass carbon sink	[32]
6	Southwestern China	2010	100–200 g C m^{-2} yr^{-1}	[66]
7	Global	2000–2009	0.5 Pg C	[67]