Perspectives in Plant Ecology, Evolution and Systematics 22 (2016) 36–46

Contents lists available at ScienceDirect

Perspectives in Plant Ecology, Evolution and Systematics

journal homepage: www.elsevier.com/locate/ppees

Hydrological and ecological responses of ecosystems to extreme precipitation regimes: A test of empirical-based hypotheses with an ecosystem model

Jian-Sheng Ye[a], James F. Reynolds[a,b,*], Fernando T. Maestre[c], Feng-Min Li[a]

[a] State Key Laboratory of Grassland Agro-ecosystems, Institute of Arid Agroecology, School of Life Sciences, Lanzhou University, No. 222, South Tianshui Road, Lanzhou 730000, China
[b] Nicholas School of the Environment and Department of Biology, Duke University, Durham, NC 27708, USA
[c] Departamento de Biología y Geología, Física y Química Inorgánica, Escuela Superior de Ciencias Experimentales y Tecnología, Universidad Rey Juan Carlos, 28933 Móstoles, Spain

ARTICLE INFO

Article history:
Received 14 December 2015
Received in revised form 7 August 2016
Accepted 9 August 2016
Available online 10 August 2016

Keywords:
Tibetan Plateau
BIOME-BGC
Intra-annual variability of precipitation
Drought
Extreme events
Extreme precipitation regimes

ABSTRACT

Many uncertainties exist in our quest to understand and predict how terrestrial ecosystems will respond to climate change. A particularly challenging issue is how increases in extreme precipitation regimes, which are characterized by larger but fewer individual precipitation events, will impact ecosystems. Based on a wide-ranging review of empirical studies of both hydrological and ecological processes, Knapp et al. (2008) generated a suite of hypotheses positing how these processes would respond to an increase in extreme precipitation regimes and, from this, concluded that mesic ecosystems would be more detrimentally impacted than xeric ones. In this study we present the first thorough test of these hypotheses by examining how forest, shrubland, grassland and desert ecosystems of the Tibetan Plateau, having very different vegetation and climate characteristics, respond to more extreme rainfall regimes. We accomplished this by using a simulation model (Biome-BGC) to examine the integrated behavior of these ecosystems based on the *simultaneous* responses and interactions of 10 hydrological and ecological processes: runoff, canopy evaporation, soil evaporation, soil water storage, transpiration, net primary productivity, soil respiration, net ecosystem exchange, nitrogen [N] mineralization, and N leaching. We ran forty-year simulations (1986–2008) where we manipulated mean growing season precipitation to create more extreme intra-annual precipitation regimes characterized by lower precipitation frequencies, longer dry periods, and larger individual (daily) precipitation events. When compared to ambient conditions, our simulations showed that increases in extreme rainfall regimes (1) impacted all hydrological processes in mesic ecosystems, resulting in a reduction of soil mineral N due to increased leaching; and (2) enhanced plant growth in xeric ecosystems, leading to larger and denser canopies and higher light interception. The responses of hydrological processes tended to follow Knapp et al.'s hypotheses more so than ecological responses. Overall, responses of mesic ecosystems closely followed the hypotheses but xeric ecosystems were highly variable and only weakly consistent with them. Our findings provide new insights as to how more extreme rainfall regimes may potentially affect the functioning of terrestrial ecosystems.

1. Introduction

Anticipating how terrestrial ecosystems will respond to climate change is one of the greatest challenges in ecology (Fay et al., 2011; Heisler-White et al., 2008; Knapp et al., 2015; Smith, 2011; Zhang et al., 2013). Of special interest are changing precipitation regimes because the variability of rainfall and the frequency of extreme events are increasing worldwide (Easterling et al., 2000; Groisman et al., 2005; Min et al., 2011). Observations reveal an increased intensity of extreme precipitation events at mid and high latitudes (Liu and Zipser, 2015) and climatic models predict that intra-annual rainfall variability will intensify, which will shift current rainfall regimes towards more extreme ones with lower precipitation frequency, longer dry periods, and larger individual precipitation events worldwide (IPCC, 2013). This is significant because alterations in the frequency and size of rainfall events – alone or in combination with changes in the total amount of rainfall received

* Corresponding author at: Nicholas School of the Environment and Department of Biology, Duke University, Durham, NC 27708, USA.
E-mail address: james.f.reynolds@duke.edu (J.F. Reynolds).

http://dx.doi.org/10.1016/j.ppees.2016.08.001
1433-8319/

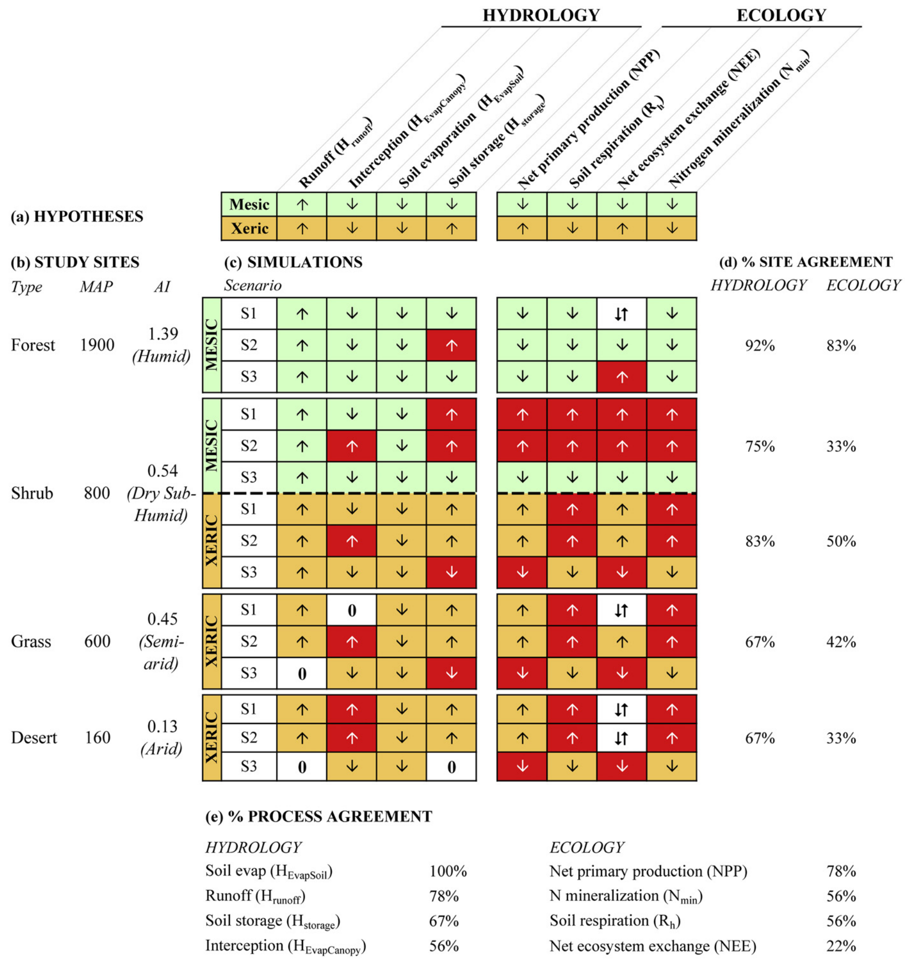

Fig. 1. (a) Knapp et al.'s (2008) hypothesized responses of select hydrological and ecological processes to more extreme precipitation regimes in mesic and xeric ecosystems. The responses – relative to ambient conditions – are depicted as *increases* (up-arrows), *decreases* (down-arrows), *no responses* (0) or *equivocal* (both up- and down-arrows). (b) General characteristics of the four Tibetan Plateau ecosystems used in this study: MAP = mean annual precipitation (mm) and AI = aridity index. (c) Simulations results are based on scenarios S1–S3 where ambient daily precipitation was modified to have fewer and larger individual events (i.e., an increase in extreme regimes) and MGSP (mean growing-season precipitation) over the 40-yr period was unchanged in S1, increased in S2 and decreased in S3. Simulated responses that were *consistent* with Knapp et al.'s (2008) hypothesized responses are shown in green (for mesic) or brown (for xeric); *opposite* responses are in red; and no responses (or *equivocal*) are shown in white. Since the dry sub-humid shrubland site has climatic features intermediate between mesic and xeric, we show results for both the mesic and xeric hypotheses. (d) Percent agreement (across all three scenarios) by site of the hydrological and ecological processes with the hypotheses. (e) Percent agreement (across all three scenarios) of each process with the hypotheses (omitting results for shrub).

– have the potential to affect ecological processes such as the establishment, survival, phenology and growth of plants (Reynolds et al., 1999; Sher et al., 2004), the composition and diversity of ecological communities (Ilg et al., 2008; Knapp et al., 2002), above- and below-ground productivity (Heisler-White et al., 2008; Maestre and Reynolds, 2007), nitrogen cycling (Bloor and Bardgett, 2012; Kong et al., 2013) and soil respiration (Fay et al., 2011; Parton et al., 2012).

Based on a review of the literature, Knapp et al. (2008) generated a suite of hypotheses (presented in Fig. 1a) positing how various hydrological (e.g., runoff, soil water storage) and ecological (e.g., net primary productivity [NPP], nitrogen [N] mineralization) process – in mesic versus xeric ecosystems – would potentially respond to more extreme precipitation regimes. Knapp et al. (2008) concluded that more extreme precipitation regimes will be more detrimental in mesic as compared to xeric ecosystems. They conjecture that larger, but less frequent, precipitation events will increase the duration and severity of soil water stress in mesic ecosystems when intervals between rainfall events increase; in addition, increased water stress will result in decreased NPP and N mineralization. In contrast, in xeric systems more extreme precipitation regimes will potentially decrease overall evaporative losses, which will lead to greater soil water storage and increased NPP.

While the empirical studies synthesized by Knapp et al. (2008) provide key insights on how plants and ecosystems may respond to extreme precipitation regimes, they have limitations. Field and greenhouse/common garden typically focus on a particular species or ecosystem, last for only a few years, are usually limited to a single precipitation extreme regime, and represent only a small fraction of the experiments needed to tease apart the myriad of interactions and feedbacks likely to occur in the future. Furthermore, due to differences in methodologies, sampling designs and measurement variables, experiments usually cannot be easily compared (Vicca et al., 2012) and do not adequately represent the types of precipitation scenarios expected in the future (Beier et al., 2012). Although some of the limitations of empirical studies can be addressed by the establishment of long-term field studies that are event-oriented and/or deal with multiple biophysical and ecosystem response processes (e.g., Fay et al., 2011; Fraser et al., 2012; Jentsch et al., 2007), it is clear that a wholly-empirical approach is not sufficient to understand and predict how terrestrial ecosystems will respond to extreme precipitation regimes.