Journal of Hydrology 406 (2011) 225–233

Contents lists available at ScienceDirect

Journal of Hydrology

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

Decreased streamflow in semi-arid basins following drought-induced tree die-off: A counter-intuitive and indirect climate impact on hydrology

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ARTICLE INFO

Article history:
Received 6 December 2010
Received in revised form 30 March 2011
Accepted 30 June 2011
Available online 7 July 2011
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Michael Bruen, Associate Editor

Keywords:
Die-off
Piñon pine (*Pinus edulis*)
Water yield
Runoff coefficient
Drought
Southwestern USA

SUMMARY

Drought- and infestation-related tree die-off is occurring at regional scales and is projected to increase with global climate change. These large-scale changes in vegetation are expected to influence hydrological responses, but the ecohydrological consequences of die-off have rarely been studied empirically and consequently remain uncertain. Here we evaluate observed hydrologic responses to recent regional-scale die-off of piñon pine (*Pinus edulis*) in Southwestern USA. Basins with the most tree die-off showed a significant decrease in streamflow over several years following die-off, and this decrease was not attributable to climate variability alone. The results are counterintuitive compared to responses to reductions in tree cover by harvest that have shown an increase in streamflow, although such increases are more substantial for locations with higher precipitation than where the piñon pine die-off occurred. We are unable to isolate the cause of the increase, but note that it is consistent with a reported increase in understory herbaceous cover post-die-off and associated increase in solar radiation reaching near-ground (below the tree canopy overstory), which together would be expected to reduce overland flow. Our study highlights the need to more fully evaluate hydrological responses to drought-induced tree die-off empirically, in addition to modelling studies. More generally, the result illustrate potential indirect effects of climate on hydrological responses mediated through ecohydrological changes in vegetation, which will need to be considered in future water resources assessments.

1. Introduction

Land cover is rapidly being altered, not only by direct anthropogenic interventions due to population growth, but also potentially as a result of global climate change. Of particular concern are growing indications that regional-scale tree die-off events associated with drought and heat, along with biotic agents such as insect pests and pathogens, currently occurring around the world may be linked to the increase in global temperature and perturbations in the hydrologic cycle (Allen et al., 2010; IPCC, 2007). Large-scale land cover changes in vegetation might be further aggravated, as even the most conservative climate predictions anticipate further rise of global temperature and intensification of extreme droughts (IPCC, 2007). Although extensive research exists on the topic, we are far from understanding the linkages between climate fluctuations and vegetation dynamics, and their impacts and feedbacks to hydrological processes, particularly in water-limited ecosystems (Rodriguez-Iturbe, 2000). Water-limited ecosystems include environments where the annual evapotranspiration exceeds the annual precipitation, and where there are extended periods with little or no precipitation. In these ecosystems, not only is there a very tight coupling between climate fluctuations and vegetation response, but the type and even the structure of vegetation influences basin hydrological response (Newman et al., 2006). Thus, in light of the current trends in global climate there is an imperative need to better understand these climate-ecosystem-hydrology linkages and feedback mechanisms to predicting future changes in the availability of land and water resources (Newman et al., 2006; Jones et al., 2009).

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doi:10.1016/j.jhydrol.2011.06.017

One important approach for evaluating climate-soil-vegetation interactions is to combine stochastic modelling of the water balance with predictions of vegetation dynamics (Rodriguez-Iturbe, 2000; Rodriguez-Iturbe et al., 2001; Porporato et al., 2002), the latter of which in turn is the result of a number of complex and mutually interacting hydrologic processes (Porporato et al., 2002). These studies enable direct assessments of feedbacks, but empirical studies are also needed, particularly to verify if system responses to unusual perturbations such as die-off are consistent with predictions. A more traditional approach for assessing climate-soil-vegetation interactions is to use direct empirical observations of basin response after vegetation manipulation in paired catchment studies (Bosch and Hewlett, 1982; Brown et al., 2005) to unravel the consequences of the vegetation changes.

Most literature on hydrologic implications of tree cover reduction focuses either on forest harvest or prescribed and natural wildfires. Even though these perturbations have in common a loss of canopy tree cover, there are important differences in their effects on hydrologic response compared to tree die-off (Adams et al., 2011). Fire not only consumes canopy but also understory vegetation, litter cover, and, depending on severity, creates water repellency in the soil surface that can result in dramatic increases of surface runoff and soil erosion (DeBano, 2000; Shakesby and Doerr, 2006). Mechanical harvest can also result in soil disturbance (e.g. compaction) depending on the method and machinery used, resulting in reduction of infiltration and enhanced surface runoff (Ziegler et al., 2004). Harvest, by which we mean cutting down and removing overstory trees, has reduced soil disturbance when done with handsaws. Overall, the effects of harvest are more similar to those of die-off (e.g. reduced transpiration and interception) than are those of fire, which also directly affects the soil surface (Adams et al., 2011) and merit consideration in the context of eco-hydrological responses following die-off.

Since early 1900s paired basin studies have provided hundreds of examples of how vegetation changes affect basin's water yield (Wilcox and Huang, 2010; Brown et al., 2005; Bosch and Hewlett, 1982). Initial compilations of paired catchment studies broadly reported a highly variable response. Streamflow generally increases proportionally with the magnitude of the disturbance in terms of amount of reduction in forest cover. This increased discharge typically lasts at least a few years after vegetation removal, but ultimately depends on the ecological response of the basin (Bosch and Hewlett, 1982). Later compilations classified basins according to their climate and the specific treatment (Brown et al., 2005), with the largest yield increases occurring where more than around 20% tree cover was removed (Stednick, 1996; Brown et al., 2005) in basins that were not water-limited (Brown et al., 2005; Newman et al., 2006; Wilcox et al., 2006). These relationships are likely to be particularly pronounced in basins receiving more than 500 mm annual precipitation, based in part on grassland versus forest evapotranspiration relationships summarized by Zhang et al. (2001); a similar threshold has also been reported in previous paired catchment studies (Hibbert, 1979, 1983).

In more arid environments, where potential evapotranspiration greatly exceeds precipitation, reductions in vegetation cover generally have been observed to have a substantially smaller effect on altering the overall water budget (Wilcox, 2002; Huxman et al., 2005). In these ecosystems, the ratio of plant transpiration to soil evaporation may shift, but the total evapotranspiration flux remains limited by total precipitation.

Greater uncertainty arises in semi-arid environments, where the overlap between total annual precipitation and total evapotranspiration depends on the current vegetation water needs (total annual precipitation around 500 mm). Under this climate, only changes in cover of certain vegetation types will trigger changes in water yield (Hibbert, 1979, 1983; Collins and Myrick, 1966; Baker, 1984, 1999; Lopes et al., 1999; Clary, 1975). Extensive areas of piñon–juniper woodlands were converted to grasslands during the 1950s and 1960s in an effort to increase grassland cover for grazing and water availability in the semi-arid Southwest (Mac et al., 1998; Tennesen, 2008). Small paired catchment studies suggested little or negligible effects on annual water yield when piñons are removed (Hibbert, 1983; Baker, 1984; Bosch and Hewlett, 1982). A short-lived increase in water yield following disruption was observed after the basin was treated with herbicide minimizing understory growth (Lopes et al., 1999), but no significant increase in yield was observed when other mechanical methods were used (either cabling or felling (Lopes et al., 1999; Clary, 1975)). Thinning and forest harvest have however produced a several fold increase in herbaceous cover in some cases, and an associated substantial decrease in runoff (Tausch and Hood, 2007; Jacobs and Gatewood, 1999). In some of these semi-arid watersheds, the lack of higher streamflows was attributed to increased transpiration of the herbaceous undergrowth (Zou et al., 2010).

There is a notable lack of studies in semi-arid systems documenting post-die-off hydrological response in large basins. Debate still remains regarding hydrologic response in semi-arid environments to perturbations in small catchments, and larger uncertainty prevails when scaling up to regional scales and over longer periods of time (Newman et al., 2006; Jones et al., 2009; Zou et al., 2010; Wilcox and Huang, 2010). Resolving this debate is urgently needed given projected increases in regional scale events of drought-triggered tree die-off observed with global warming (Allen et al., 2010; Adams et al., 2009). The objective of this paper is to quantify streamflow change in several large basins in the south-western United States affected by regional die-off of piñon pine (*Pinus edulis*) at the turn of this century.

2. Materials and methods

2.1. Study sites

We selected eight basins located within the Four Corners Region of the Southwestern US that were impacted by the 2000s drought (Fig. 1). Their size ranges from 700 km^2 to 68,000 km^2 (Table 1). Four of the selected basins had substantial piñon die-off (Mancos River – MN, La Plata River – PL, Rio Ojo Caliente – OC, Dolores River – DO). The other four basins were chosen as control or reference basins, with either (1) significant piñon pine present but no die-off (the Gila nested catchments: Gila River at Gila – GG and Gila River at Red Rock – GR), (2) similar increase in temperature but covered by higher elevation vegetation rather than piñon pine (Los Pinos River basin above Vallecito dam – PV), and (3) a large scale basin with a negligible proportion of piñon pine die-off (Little Colorado River – LC) (Table 1). The selection of the basins was based on the following criteria: long-term streamflow, precipitation and temperature data and the absence of large dams affecting the yearly discharge. Only the selected eight basins in the region met all of these criteria.

2.2. Streamflow and climate data

The outlet of each basin coincides with a long-term streamflow gauge maintained by US Geological Survey (Table 1). Annual, seasonal and monthly streamflow data were computed using daily streamflow values. Monthly values were only considered when less than 5 days were missing. Daily precipitation was obtained from the National Climatic Data Center (NCDC), or from the MOPEX experiment website. The closest available climate stations for each basin were selected to estimate average climatic conditions (temperature and precipitation) for the entire basin (Table 1).