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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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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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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 ecohydrological 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).

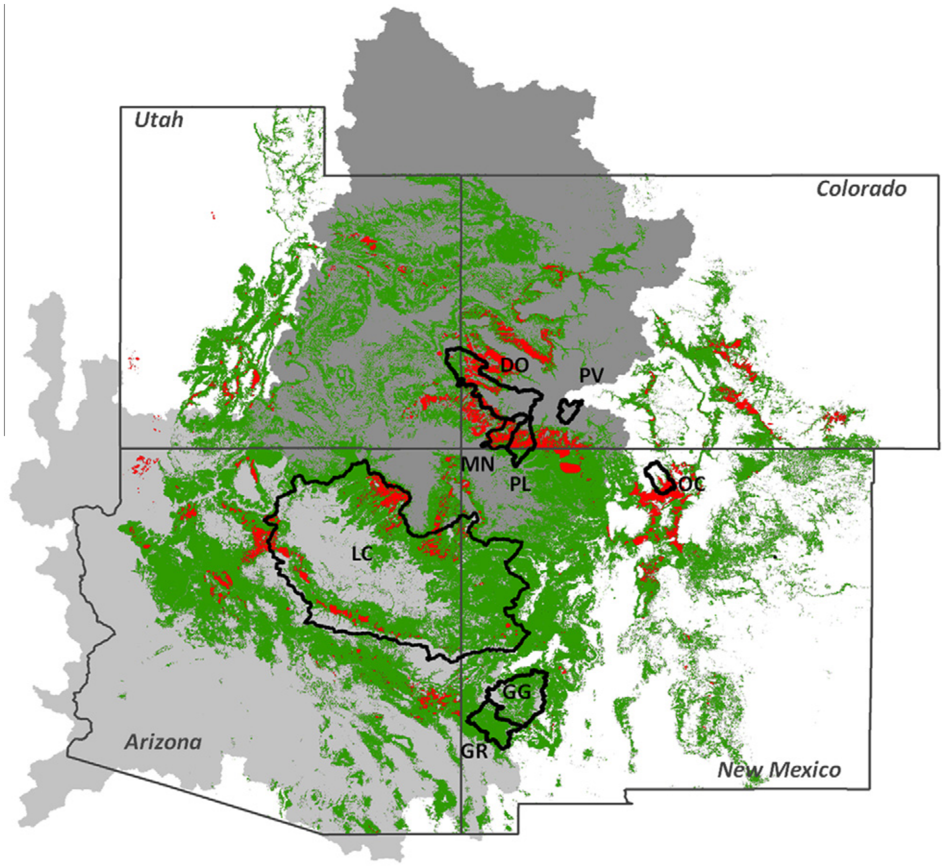

Fig. 1. Study basins in the Four Corners region in southwest USA. Dark grey: Upper Colorado basin; light grey: Lower Colorado basin; green: piñon–juniper Woodland (USGS National Gap Analysis Program, 2004); red: extent of the 2002–2007 piñon pine die-off (DIREnet, 2009). The black lines delineate the eight basins used in this study: PV: Los Pinos River at Vallecito dam, OC: Rio Ojo Caliente; MN: Mancos River; PL: La Plata River; DO: Dolores River; GG: Gila River at Gila; Gila River at Redrock; LC: Little Colorado River. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Characteristics of the study basins and observed runoff coefficients.

	Basin statistics					Runoff coefficient (RC)		
	% Dead Piñon	Drainage area (km^2)	Precipitation (mm)	Discharge (mm)	Temperature (°C)	Climatology (1971–2000)	2002	Post die-off (>2002)
Die-off								
Mancos (MN)	20.8	1362	480	39	9.3	0.075	0.013	0.047
Ojo Caliente (OC)	18.6	1085	323	60	9.5	0.183	0.036	0.123
Plata (PL)	16.3	1510	218	20	11.3	0.085	0.075	0.018
Dolores (DO)	11.2	5555	320	67	11.7	0.196	0.021	0.088
Little Colorado (LC)	2.6	68,500	325	3.2	10.4	0.009	0.006	0.007
Control								
Pinos-Vallecito (PV)	0	768	705	473	5.6	0.664	0.323	0.659
Gila at Gila (GG)	0	4803	597	37	9.9	0.058	0.032	0.066
Gila at Red Rock (GR)	0	7318	486	32	10.9	0.062	0.028	0.059

Corrections for elevation effects on temperature were performed to calculate basin (arithmetic) mean temperature. The study period spanned from 1971 to 2000 when deriving climatology values before die-off. The selection of such a 30-year climatology period is a common practice in climate studies, and such data was available for all the basins. The post die-off period after 2002 was from 2003 to 2007 or 2008, depending on basin streamflow data availability (the number of years used after die-off for each basin is reported in brackets in Fig. 2). When missing temperature and precipitation data were reported, additional climate stations within 15 miles of the study basin were added to fill in the missing values. When annual values are mentioned we refer to water or hydrologic year (October 1st–September 30th of following calendar year).

2.3. Vegetation data

The extent of piñon–juniper woodland and other major vegetation types present in the study area was estimated from the USGS Southwest Regional GAP Analysis Program (USGS National Gap Analysis Program, 2004). The Drought Impacts on Regional Ecosystems Network (DIREnet, 2009) provided detailed maps of the piñon pine die-off extension from 2000 to 2007 derived from the US

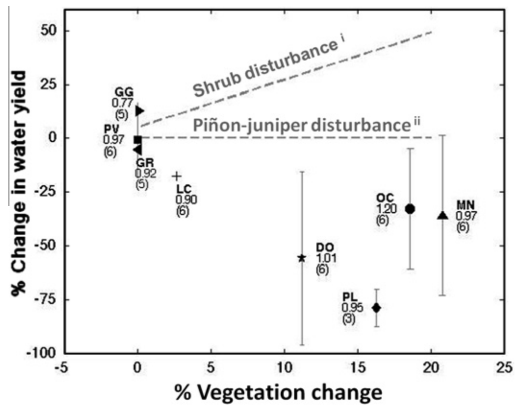

Fig. 2. Change in basin's water yield with fraction of die-off. Decreasing water yield as a function of areal fraction of dead vegetation. The apparent linear trend is significant with $p = 0.03$, $R^2 = 0.57$, $d = 0.65$ and $E = 0.35$, but the change could also follow a more stepwise response (Brown et al., 2005; Zou et al., 2010; Wilcox et al., 2006). The number under the basin initials indicates the ratio of precipitation during the number of years (given in parentheses) after die-off and the average precipitation during 1971–2000. The dashed grey lines represent the literature derived trends of changes in water yield when (i) shrubs (Bosch and Hewlett, 1982) and (ii) piñon–juniper (Hibbert, 1983; Collins and Myrick, 1966; Bosch and Hewlett, 1982) are disturbed by land management.

Forest Service insect & disease aerial survey data. To estimate the percentage of area with a substantial amount of dead piñon trees in each study basin (Table 1), the DIREnet die-off maps were overlaid on the piñon–juniper extension from the 30 m vegetation grid (USGS National Gap Analysis Program, 2004). In response to the drought, mortality of piñon pines was the most widespread and best documented vegetation change in the Four Corner's region (Breshears et al., 2005; USGS National Gap Analysis Program, 2004). Mortality of other species within the region also occurred (USDA, 2002; USGS National Gap Analysis Program, 2004; DIREnet, 2009), but it only affected <5% of the area of any study basin for higher elevation spruce and subalpine fir, when present.

2.4. Statistical analysis of hydrologic change

The ratio between annual streamflow and annual precipitation, or runoff coefficient (RC), provides a measure of a basin's water yield. Long-term RC values, averaged over several years provide a normalization of the inter-annual variability of a basin's response to climate fluctuations. We calculated the change in water yield comparing the reference runoff coefficient during the climatology period (1971–2000) with the runoff coefficient after die-off based on the data available after the hydrologic year 2002 (variable population length shown in brackets in Fig. 2). Time series of runoff coefficient are analyzed using different statistical tests to check for: (i) independence between yearly and seasonal time series before and after die-off; (ii) autocorrelation and time dependence within the RC series; and (iii) presence of temperature or precipitation trends within the climatological record.

The two-tailed, non-parametric Mann–Whitney U-test (also called Wilcoxon rank-sum test) was used for assessing whether the RC series before and after die-off came from the same distribution. This test, applied recently in another study for detecting changes in annual streamflow (Zhao et al., 2010), was chosen over the *t*-test because our data have a positive skew, which does not comply with the *t*-test normality assumptions. The Mann–Whitney U-test was also used to detect seasonal changes of mean annual precipitation and temperature, as well as changes in the ratio of winter to summer precipitation before and after die-off. We tested for time dependence in the RC time series by computing the autocorrelation functions. We further tested for dependence by means of the method of moments using a split sample Monte Carlo analysis. The expected value of the product and the variance of the sum of two subsets of standardized RCs (10,000 repetitions of the jack knifing procedure) are thus compared to their theoretical values if the subsets contain independent and standardized random variables (0 and 2, respectively). Annual temperature trends during the entire study period have been analysed by using the Mann–Kendall test at a 95% confidence interval.

2.5. Time trend analysis of hydrologic change

Another common method to analyze changes in discharge due to vegetation and climate change is the time trend analysis technique (Zhao et al., 2010). In this approach, a relationship is established between discharge and climatic variables before the basin's vegetation perturbation occurs and is then used to predict the discharge response post-perturbation assuming undisturbed basin conditions. The model accuracy depends on the length of the calibration or pre-perturbation periods (Zhao et al., 2010). This method allows separating the effects of climate variability from the vegetation perturbation on water yield. We use a simple multiple regression model (Eq. (1)) based on the assumption that discharge (Q) is strongly related to annual precipitation (P), and to the available energy, although we used temperature as a proxy for the available energy (Milly and Dunne, 2002; Koster and Suarez, 1999).

$$Q = a + bP + cT \tag{1}$$

where a is an error term, and b and c represent the sensitivity of discharge to precipitation and temperature respectively. The performance of this regression model was assessed using the coefficient of determination (R^2), the modified coefficient of efficiency (E), the modified index of agreement (d), and the mean absolute error (MAE). All these goodness of fit parameters are explained in more detail in Zhao et al. (2010) and Legates and McCabe (1999).

3. Results

3.1. Changes in basin water yield after tree mortality

The low RC values for 2002 (year of die-off), compared to the baseline $RC_{climatology}$ (Table 1) suggest analogous climatological impact of drought in all study basins. For the period 2003–2007/2008 (as noted previously, end date depends on available streamflow data for each basin), the average water yield was only ~50% of the $RC_{climatology}$ in the die-off basins, with a statistically significant decrease of the water yield ($p < 0.10$) in three of four affected basins (Table 1). For that same period, the unaffected basins show no change in water yield (a slight but insignificant increase of 2%). Time series of annual RC from the die-off basins are statistically significantly different from the RC of non-affected basins after 2002 (Mann–Whitney test, z value = 0.009, rank sum = 412, $p = 0.009$, $n_{die\text{-}off} = 23$, $n_{no\ die\text{-}off} = 16$). This suggests a clearly different behaviour for the basins affected by tree die-off compared to the basins where mortality did not occur. Furthermore, the observed average depletion in yield after 2002 in affected die-off basins seems to indicate either a linear trend with the fraction of land affected by tree mortality (Fig. 2; *t*-test: $p = 0.03$, $n = 8$), or a stepwise decrease triggered by certain threshold of vegetation disturbance in the basin (e.g., as discussed by Brown et al., 2005; Zou et al., 2010; Wilcox et al., 2006). The available data are insufficient to differentiate between these two response types. However, if we assume the relationship is linear, a basin in which 20% of its drainage area is affected by piñon pine mortality experiences a reduction of ~50% of its water yield for at least 5 years after die-off.

3.2. Climate variability and vegetation die-off

Independent of changes in vegetation, an increase in temperature, particularly in summer months, is expected to lead to a reduction in discharge through enhanced evapotranspiration by increased soil evaporation and/or increased plant transpiration (except during the hottest periods, when plants may be physiologically constrained), resulting in a depletion of water yield in the basins. Mean annual temperature of all the basins affected by piñon pine mortality after 2002 increased relative to the 1971–2000 average temperature (Table 2), although this increase in temperature was only statistically significant in one of the studied basins: Rio Ojo Caliente (Mann Whitney test, $p = 0.04$, z value = 2.06, rank sum = 160). This increase in temperature and associated changes in vapour pressure deficit (Weiss et al., 2009) may have exacerbated the observed high mortality (e.g. 80% in parts of basin) of the existing piñon pine population in this basin (Breshears et al., 2005; Adams et al., 2009). In the rest of the affected basins the increase in temperature was not significant ($p > 0.05$). Nevertheless, annual temperature over the entire period (1971–2007/2008) shows a significant positive trend in three of the affected basins (OC, PL, DO; Mann Kendall test, $p < 0.01$; not shown). This trend possibly obscures our test of temperature change before and after die-off. Likewise, although both winter and summer temperatures increased, this seasonal increase was not statistically significant.

Total annual precipitation before and after die-off did not change significantly (Table 4), except in OC (significant increase in annual precipitation; $p = 0.04$) and GG (significant decrease in annual precipitation; $p = 0.02$). The increase in annual precipitation after tree die-off in OC possibly tempers the change in RC (decrease from 0.183 to 0.123; $p = 0.22$). The significant decrease in annual precipitation in GG (unaffected by piñon pine die-off) did not lead to a significant change in the RC (Table 1). Seasonal precipitation (winter versus summer) did not change in any of the basins (Table 3), despite the increasing trend in temperature. Furthermore, not only the snow line in these basins is above the piñon pine upper ecotone, but also snow accumulation and/or ablation have not changed with die-off (Boon, 2011; Pugh and Small, 2011).

The increase in annual mean temperature compared with the climatological mean is strongly related to the depletion of water yields (Fig. 3, t-test, $R^2 = 0.68$, $n = 6$ and $p = 0.04$; for this analysis we excluded the data from Los Pinos River basin since it has no piñon pine population). We tested whether this increase in temperature, and climate variability in general, could lead to a change in the streamflow. To separate the effects of climate variability from the vegetation perturbation on water yield, we followed a time trend analysis using a multiple linear regression between annual precipitation, temperature and streamflow (Eq. (1)). The multiple linear regression analysis was performed for each basin using annual discharge, precipitation and temperature data for the climatology period before die-off (1971–2000). In general, the regression models show an adequate fit between predictions and observations with highly significant trends ($p < 0.003$), except for OC and PL (Table 2).

From the regression coefficients, we found that streamflow in all the basins showed a positive relationship with precipitation, except for LC. However, the correlation coefficients indicate that in most basins the response to precipitation increase was dampened. This could potentially be due to vegetation, which can effectively utilize an increase in precipitation and associated plant-available water in this semi-arid climate (Huxman et al., 2005). We also observed that most of the basins' streamflow has a negative relationship with temperature, except for PV, which showed no relationship, and MN, which showed a weak positive relationship with temperature (Table 2). We used these regression models to predict each basin's water yield assuming pre-die-off hydrologic response, but using the climate conditions observed after 2002. These two time series of predicted RC (the expected value if die-off would not have occurred but accounting for the warming trend) and the observed RC are statistically significantly different (Mann–Whitney test, z value = 2.69, rank sum = 559, $n = 21$, $p = 0.007$), highlighting the significant effect of die-off in further exacerbating the depletion of water yield in large basins (Fig. 3). Our approach

Table 2
Basin hydrometeorological stations and land cover (% of basin area).

USGS streamflow stations[a]	Climate stations NCDC Coop ID[b]	Elevation range (m)	% Dominant land cover
Mancos River in CO (MN) (USGS 09371000)	Mancos: 055327; Mesa Verde: 055531; Cortez: 051886	1537–4035	45% S039, 8% S036
Rio Ojo Caliente in NM (OC) (USGS 08289000)	El Rito: 292820; Tres Piedras: 299085; Espanola: 293031; Ghost Rch: 293511	1940–3298	41% S036, 20% S038
La Plata River in NM (PL) (USGS 09367500)	Farmington: 293142; Fruitland: 293340; Farmington: 2/4 NE: 293134; Bloomfield 3 SE: 291063	1593–4009	43% S039, 14% S054
Dolores River in CO (DO) (USGS 09171100)	Bedrock: 050581; Paradox: 056315; Uravan: 058560	1500–4332	27% S039, 13% S046
Little Colorado River in AZ (USGS 09402000)	PRISM[c]	830–3850	31% S039, 16% S079, 13.5% S090
Los Pinos River in CO (PV) (USGS 09352900)	Vallecito Dam 058582; Lemmon Dam: 054934	1874–4288	25% S028, 15% S030, 11% S081
Gila River (at Gila) in NM (GG) (USGS 09430500)	MOPEX[d]	1418–3314	55% S036, 22% S039
Gila River (at Redrock) in NM (GR) (USGS 09431500)	MOPEX[d]	1246–3317	42% S036, 19% S112

S028: Rocky Mountain Subalpine Dry-Mesic Spruce-Fir Forest and Woodland; S030: Rocky Mountain Subalpine Mesic Spruce-Fir Forest and Woodland; S036: Ponderosa Pine woodland; S038: Southern Rocky Mountain Piñon–Juniper Woodland; S039: Colorado Plateau Piñon–Juniper Woodland; S046: Rocky Mountain Gambel Oak-Mixed Montane Shrubland; S054: Inter-mountain Basins Big Sagebrush Shrubland; S079 Inter-Mountain Basins Semi-Desert Shrub Steppe; S081: Rocky Mountain Dry Tundra; S1 12: Madrean Pinyon–Juniper; Woodland; S090 Inter-Mountain Basins Semi-Desert Grassland. Only the fraction of vegetation above 10% has been reported with the exception of MN.

[a] http://waterdata.usgs.gov/nwis/rt.
[b] http://lwf.ncdc.noaa.gov/oa/climate/stationlocator.html.
[c] http://www.prism.oregonstate.edu/.
[d] http://www.nws.noaa.gov/oh/mopex/mo_datasets.htm.

Table 3
Multiple linear regression analysis relating annual temperature, precipitation and streamflow.

	Multiple linear regression							Annual temperature variations		
	Slope with precipitation (mm/mm)	Slope with temperature (mm/°C)	E	d	RMSE (mm)	R^2	p value[a,b]	T_{climat} (°C)	$T_{>2002}$[b] (°C)	Change in mean temperature (°C)
MN	0.17	0.1	0.40	0.67	14.9	0.63	2.4×10^{-6}	9.3	9.8	0.5
OC	0.15	−17.1	0.22	0.49	26.4	0.35	3.2×10^{-3}	9.5	9.9	0.4
PL	0.13	−4.8	0.23	0.51	14.7	0.36	2.2×10^{-3}	11.3	11.7	0.4
DO	0.32	−23.5	0.40	0.66	31.4	0.56	3.7×10^{-5}	11.7	12.3	0.6
LC	-5×10^{-4}	0.9	0	0.17	3.1	0.03	6.2×10^{-1}	10.4	11.2	0.7
PV	0.79	23.9	0.55	0.75	74.9	0.77	2.7×10^{-9}	5.6	6.4	0.8
GG	0.12	−3.1	0.47	0.71	13.3	0.67	2.6×10^{-7}	10.0	9.8	−0.1
GR	0.13	−5.9	0.40	0.67	14.2	0.61	3.5×10^{-6}	10.93	10.8	−0.1

[a] p Values using t-test, n_1 = 30, years of precipitation, temperature and discharge data for the climatology period 1971–2000.
[b] The number of records after the die-off hydrologic year 2002 depend on data availability and is shown in Fig. 2.

Table 4
Annual and seasonal changes in precipitation (P).

	Mean P before	Mean P after	p-Value	$P_{summer}/P_{annual} - P_{winter}/P_{annual}$ (%)		p-Value$_{summer}$	p-Value$_{winter}$
				Before die-off	After die-off		
MN	480	467	0.75	0.46–0.54	0.47–0.53	0.98	0.85
OC	323	389	0.04	0.62–0.38	0.58–0.42	0.62	0.62
PL	218	187	0.78	0.53–0.47	0.50–0.50	0.70	0.70
DO	316	339	0.62	0.51–0.49	0.49–0.51	0.72	0.94
PV	705	682	0.75	0.49–0.51	0.48–0.52	0.88	0.88
GG	597	456	0.02	0.57–0.43	0.59–0.41	0.76	0.76
GR	486	446	0.46	0.59–0.41	0.59–0.41	0.98	0.98

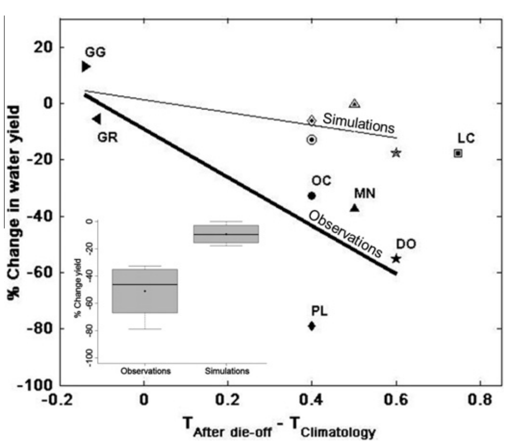

Fig. 3. Change in basin water yield and temperature. The black symbols show the decreasing water yield as a function of increasing temperature after die-off (*Observations*) compared to the climatology. The black and white symbols show results after removing the die-off effect (*Simulations*). (Inset) Mean percentage decrease in water yield in die-off affected basins, given 0.5 °C warming using the observed trend (*Observations*) and without considering the die-off effect (*Simulations*). The dot in the box plot represents the mean, the black segment the median, the limits of the box one standard deviation and the whiskers the range of the data.

separates the effects of a warming climate and the associated tree mortality allowing us to investigate which driver of hydrologic response dominates. Based on this analysis an increase of 0.5 °C results in a depletion of only ~10% of annual water yield (Fig. 3, *Simulations trend*), whereas the observed decrease including tree mortality amounts to a depletion of ~50% of annual water yield (Fig. 3, *Observations trend*).

3.3. Die-off and runoff generation

Runoff generation curves (cumulative streamflow versus cumulative precipitation), Fig. 4a and b) also suggest a change in the dominant runoff mechanism at the basin scale. Hydrologic response at the midst of the drought (with below average precipitation and high temperatures) was similar for all study basins, namely, as expected, a sharp increase in discharge after minor early precipitation events or during spring snowmelt (Fig. 4a and b, thick red lines). The year after die-off (Fig. 4a, thick blue lines), the response from the control basins (basins that did not experience any die-off) falls back within the 5th and 95th percentile responses observed during the 1971–2000 period. Conversely, for basins with tree die-off the runoff generation curve shifts strongly to the right, suggesting a delay of runoff generation in the basin (Fig. 4b). Responses from 2002 to 2003 were compared to 2 years from the period 1971–2000 with similar annual mean temperature and total volume and distribution of annual precipitation (thin lines in Fig. 4a and b). To quantify the difference between basin response before and after piñon pine mortality, we computed the fraction of total annual precipitation at the time when half of the annual discharge was generated. In the control basin, there was a very small difference between the before die-off years response and the post drought response (Fig. 4c). However, in affected basins this difference is much larger. This suggests that depleted subsurface water storage in aquifers and soils does not seem to be the driver of the reduced water yield, as this depletion during the preceding drought can safely be assumed to have had similar effects in the affected and in the non-affected catchments. To determine whether changes in rainfall intensity might have caused the post-die-off shift in die-off basins, we compared the probability density functions of daily precipitation before and after die-off for both basins (the control and the die-off). The analysis showed only a small change in the probability of rainfall amounts smaller

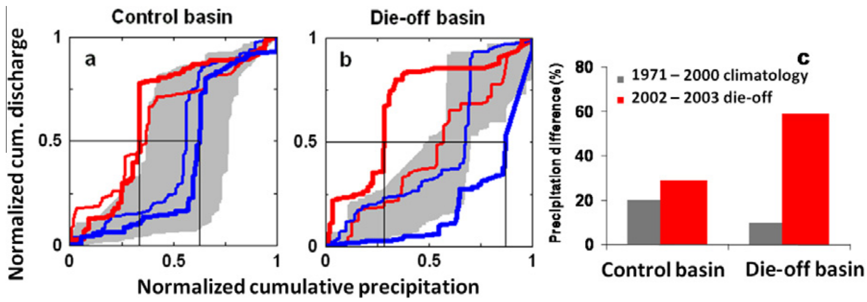

Fig. 4. Basin hydrological response to die-off. Streamflow generation curves for (a) control basin (PV; see Table 2) and (b) die-off basin with the highest fraction of die-off (MN). Thick red lines for the peak die-off year (2002), and thick blue lines for the year following die-off (2003). The thin lines represent streamflow responses during 1 year of the climatological period (1971–2000) with similar annual temperature and total precipitation (including seasonal distribution): the thin red line shows streamflow generation curve for a year similar to the die-off year (2002) and the thin blue line for a year similar to the post die-off year (2003). The shaded area shows the streamflow generation curves during 1971–2000 (climatology) within the 5th and 95th percentiles. (c) Difference in fraction of annual precipitation needed to generate half of the yearly discharge, for the observed change during the die-off event (red) relative to the observed change during two consecutive years from the climatology with similar volume and distribution of precipitation as during the die-off event (grey). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

than 1 mm/day (results not shown), an amount that generally does not produce runoff in these semi-arid basins.

4. Discussion

Our study is one of a few to evaluate post-die-off hydrologic responses in large catchments (Bethlahmy, 1974, 1975; Beudert et al., 2007; Somor, 2010; Somor et al., in preparation) and the first to do so under the emerging conditions of warmer temperatures both during and following drought in a semiarid region. Our results document a significant decrease of streamflow over at least 5 years following regional-scale die-off in semiarid southwestern USA (Breshears et al., 2005). Notably, several of the different assessments we conducted indicate that climate variability seems to explain only a small part of the observed change in the hydrologic regime after the die-off. We investigated whether significant changes in annual and seasonal precipitation and temperature could explain the observed decrease in water yield. Changes in seasonal temperature could affect precipitation type (snow versus rain in winter months) and evapotranspiration rates (in summer months). However, none of the affected basins show a significant decrease in precipitation after die-off when compared with the 30-year climatology period 1971–2000. There was also no indication of significant changes in the fraction summer versus winter precipitation in these basins. Even though all basins experienced increasing temperatures over the last 40 years, there was only a significant increase in temperature before and after die-off in one of the study basins (Rio Ojo Caliente, where 100% of the piñon pine population died). The rising trend in temperature is also present in winter, but the change was not significant, diminishing the probability that there was an abrupt change in the type of precipitation. When the effects of climate warming were separated from the effects of tree mortality (using time trend analysis), our results showed that vegetation change rather than the increase in temperature was the main driver of hydrologic response in the study basins.

The substantial reduction in water yield in the affected basins is potentially counterintuitive, especially when considering streamflow response to tree harvest in more mesic settings. However, note that water yield did increase in some cases at catchment scales for some piñon–juniper ecosystems in response to thinning (removing branches and placing them on the ground) and harvest in association with increased understorey cover (Tausch and Hood, 2007; Jacobs and Gatewood, 1999). On a related note at larger scales, a lack of increase in streamflow was attributed to increased transpiration of the herbaceous undergrowth (Zou et al., 2010). Notably, a similar increase in understory cover was observed following the drought-induced die-off and this increase was reflected in regional scale "greenness" (NDVI; Rich et al., 2008; Kane et al., 2011). This response may have been due to release of understory vegetation from competition with woody overstory species and/or increases in near-ground solar radiation input below the tree canopies after die-off (Royer et al., 2010), the latter of which also increased regionally (Royer et al., 2010). These changes in the near-ground microclimate and understory would very likely have reduced overland flow by reducing the connectivity among bare patches (Davenport et al., 1998; Wilcox et al., 2003; Urgeghe et al., 2010). This is the most plausible explanation for the observed decrease in streamflow in the basins with the most mortality. In addition, the increased near-ground solar radiation could result in greater water losses to soil evaporation (Royer et al., 2010). Although the majority of streamflow in these basins is thought to be generated from higher elevation locations, note that there was little (<5%) to no change in other vegetation types, so the streamflow response appears to be most directly due to the changes in cover in the piñon–juniper woodlands. Other related studies are needed to further assess the mechanisms of decreased streamflow in more detail and the degree to which this response might be typical of what might occur in semiarid systems undergoing future tree die-off.

In conclusion, our study highlights a potentially counter-intuitive and indirect climate impact on hydrology mediated through vegetation change. Many watershed studies focus on direct responses in water yield following vegetation change but our study highlights the need for more empirical studies that consider ecohydrological responses to climate change and variability that are mediated through vegetation change. Because tree mortality is occurring extensively and appears associated with warming temperatures, and is projected to increase substantially in the future (IPCC, 2007; Allen et al., 2010; van Mantgem et al., 2009; Adams et al., 2009), additional consideration of such potential indirect effects of climate on hydrology is warranted. In this study we show that these rapid vegetation changes have a larger effect on water availability than previously observed in semi-arid environments. These rapid landscape changes have not been considered historically in watershed management, thereby rendering our ability to assess climate change impacts on water resources inadequate (CCSP, 2008; Milly et al., 2008). It is therefore critical to better understand how ecohydrological systems respond to such abrupt perturbations (Wilcox et al., 2006; Jones et al., 2009), given the expected increases in forest mortality in response to climate-change type droughts that are accompanied by warmer temperatures (Breshears et al., 2005; Adams et al., 2009; Barnett et al., 2008).

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