100 YEARS Journal of Ecology

British Ecological Society

Journal of Ecology 2015, **103**, 31–43 doi: 10.1111/1365-2745.12335

SPECIAL FEATURE

FOREST RESILIENCE, TIPPING POINTS AND GLOBAL CHANGE PROCESSES

Is drought-induced forest dieback globally increasing?

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Summary

1. Recently, it has been suggested that forest mortality has been generally increasing because of increasing drought and heat stress. But it is unclear if the observations at the investigated forest sites and regions are representative of forests globally and it has not been tested whether forest models are capable of reproducing these observations. We analysed historical climate data and used a dynamic global vegetation model (LPJ-GUESS) to assess (i) Which forests globally might have been affected by drought, (ii) If the field observations are representative for all forests and (iii) If the model can reproduce the reported mortality events.

2. Using two climate data sets and three drought indices, we identified no general global drying trend across all forests, but a large spatial variability. We neither detected a general increase in extreme drought events. A weak drying trend and an increase in extreme drought events were only apparent for forests in already dry climates and the locations or regions for which drought-induced mortality trends have been reported are predominantly in these dry climates.

3. LPJ-GUESS reproduced 66% of the reported mortality events and in 49% of the reported drought-induced mortality events drought was apparent in any of the climatologically derived drought indices. However, only in 30% of the cases simulated increased mortality coincided with drought events.

4. *Synthesis.* Our results indeed suggest that dry forests have been experiencing increasing drought-induced mortality. However, this does not apply to forests in general and the spatial variability has been large. The poor correspondence between the simulated and reported mortality events indicates that models like LPJ-GUESS driven by standard climatologies, and soil input data do not represent drought-induced mortality well. But the poor detection of the reported drought events in our climate indices also suggests that drought stress might not be the main driver of all the reported drought-mortality events.

Key-words: aridity index, climate impacts, drought, dynamic global vegetation model, forest dieback, LPJ-GUESS, palmer drought severity index, plant–climate interactions, tree mortality

Introduction

In the face of global warming, droughts have been projected to become more severe and widespread in future decades (Sheffield & Wood 2008b; Seneviratne *et al.* 2012; Dai 2013). Regionally, there is medium confidence in the intensification of droughts. However, opposing trends also exist, leading overall to low confidence globally (Seneviratne *et al.* 2012). More intense droughts would strongly impact agriculture, the economy, human health and forests (McMichael, Woodruff & Hales 2006; Wang *et al.* 2012; Anderegg, Kane & Anderegg 2013). Forests provide important ecosystem services, are the most productive ecosystem (Beer *et al.* 2010) and are partly responsible for the 'missing sink' in the global carbon cycle (Pan *et al.* 2011). Environmental change can lead to enhanced growth regionally (Fang *et al.* 2014; Keenan *et al.* 2014), but it can also turn forests into a large atmospheric carbon source (Peng *et al.* 2011).

Forest extent and functioning are determined by climate conditions (e.g. Prentice *et al.* 1992) and forest play, via biogeochemical and biogeophysical feedbacks, an important role in the climate system (Bonan 2008). As long as we do not understand the historic impact of changing environmental conditions on forests, we cannot make reliable projections of

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future impacts and feedbacks. Therefore, a recent global review of forest mortality events attributed to drought and heat stress (Allen *et al.* 2010), received much attention (e.g. Sala *et al.* 2010; McDowell *et al.* 2011; Choat *et al.* 2012; Scholes *et al.* 2014). The original observations from 88 forest sites or regions by Allen *et al.* (2010) have been complemented by 44 additional references with increased mortality attributed to drought and heat stress by the IPCC (Scholes *et al.* 2014). We hereafter refer to the combined data as drought-induced mortality events (DIME). However, it has not been assessed whether these field observations are representative of forests globally. Very preliminary results from Steinkamp & Hickler (2013), which were based on a subset of the original sites summarized by Allen *et al.* (2010) and a smaller number of drought indices and analyses compared to the study here, indicate that drought-induced increases in tree mortality might not be as widespread as often stated.

Dynamic global vegetation models (DGVMs, Prentice *et al.* 2007) are widely used to project potential future impacts of climate change on forest distribution and functioning (Scholze *et al.* 2006; Sitch *et al.* 2008; Higgins & Scheiter 2012; Huntingford *et al.* 2013) and, according to these projections, substantial forest dieback might occur in different regions (depending on the climate scenario), which would also feedback on the climate system (Scholze *et al.* 2006; Lenton *et al.* 2008; Scholes *et al.* 2014). Yet, to our knowledge, tree mortality, as simulated by DGVMs or more regional models with similar process representations, has only been evaluated for a small number of sites or restricted regions, often with only limited support for the mortality functions implemented in the models (Bigler & Bugmann 2003; Wunder *et al.* 2008; Wyckoff & Bowers 2010; Manusch *et al.* 2012; Wang *et al.* 2012; Holzwarth *et al.* 2013).

We applied the DGVM LPJ-GUESS (Smith, Prentice & Sykes 2001) driven by two climate data sets and calculated three drought indices to investigate, at the global scale (i) Which forests have been affected by drought, (ii) If the field observations summarized by Allen *et al.* (2010) and Scholes *et al.* (2014) are representative of all forests and (iii) If the LPJ-GUESS model can reproduce the reported mortality events. This work substantially furthers the very preliminary results presented by (Steinkamp & Hickler 2013).

Materials and methods

CLIMATE DATA

We used (i) the CRU TS 3.0 (Mitchell & Jones 2005) monthly data 1901–2006 (hereafter CRU), to generate daily precipitation with a weather generator (Gerten *et al.* 2004) and daily temperature and sunshine hour data by linear interpolation between mean monthly values and (ii) updated spatially downscaled daily reanalysis data 1948–2008 with monthly precipitation sums and monthly temperature averages scaled to match the CRU data (Sheffield, Goteti & Wood 2006 & Sheffield pers. communication; hereafter SHF). Both data sets have a spatial resolution of 0.5° × 0.5°. We used results from the overlapping 59 years (1948–2006) for our analysis.

DROUGHT INDICES

By making use of the LPJ-GUESS hydrology (i) a modified version of the Palmer Drought Severity Index (PDSI; details in the supplementary information, hereafter SI) (Palmer 1965; Alley 1984) was applied, (ii) the soil moisture of the lower soil layer (0.5–1.5 m, SMOIST) simulated by LPJ-GUESS, since the water content of the lower soil layer is an important water source for trees and has been suggested as a good measure of drought (Lakshmi *et al.* 2004) and (iii) the aridity index (AI) as annual precipitation divided by annual potential evapotranspiration (PET) (Middleton & Thomas 1997). The calculation of PET follows Priestley & Taylor (1972) as described in Gerten *et al.* (2004), including the plant physiological water demand, since plant cover influences PET (McDowell *et al.* 2013). The AI for the whole year (AI_{12}), the warmest 3 months (AI_3), as well as the growing season (mean monthly temperatures $T > 5$ °C (Sykes, Prentice & Cramer 1996); AI_{GS}) were analysed. Temperature is implicitly included in the drought indices; therefore, we assume that these indices do not only represent drought stress, but also heat stress. Negative values of the monthly calculated PDSI denote dry conditions. We normalized the PDSI, for statistical evaluation, over time for each model grid cell. Soil moisture is the simulated available relative soil moisture varying between zero (no plant-available water) and 1 (water content at field capacity). Three AI categories were considered here: (i) arid if $AI < 0.65$, (ii) dry if $AI < 1$ (including also arid) and (iii) wet if $AI \geq 1$. Statistical analysis was performed with $\log_{10}(AI)$ since it is approximately log-normally distributed. For these indices, we defined three types of drought: (i) duration of 1 year with 2 standard deviations dryer than during the simulation period, (ii) duration of 3 years with 1.5 standard deviations dryer than during the simulation period and (iii) duration of 5 years with 1 standard deviation dryer than during the simulation period.

The PDSI as well as the soil moisture have a memory effect (autocorrelation) concerning the conditions of previous months and the PDSI also of the same month of several previous years (Guttman 1998). Therefore, short-term strong droughts like the European heat wave in 2003 were hardly visible in the PDSI. After removing the trend and seasonal cycle, a weak autocorrelation was still present in the remaining part, which could not be removed further. Therefore, we used the time series as is, instead of just the trend part for the trend analysis. This results in less significant trends, giving us even more confidence in the results. However, we are aware of potential statistical errors (see SI Fig. E1–E16 for autocorrelation plots).

FIELD OBSERVATIONS OF INCREASED MORTALITY ATTRIBUTED TO DROUGHT AND HEAT STRESS

Of the original locations by Allen *et al.* (2010), we could access the literature for 60 out of their 88 locations. Missing locations were either published as conference abstracts, with insufficient information, in a language, we were unable to translate or the exact date or geographical position was unavailable. Additionally, we used 21 forest mortality events from Scholes *et al.* (2014). *Allen et al.* (2010) sometimes summarize several drought events either in space or time as one 'location'. We treated them separately, together with the sites from Scholes *et al.* (2014), where we could extract the location and years. This resulted in a total of 100 reported drought-induced mortality events (DIME) here with duration from one year to trends over 50 years (Fig. 1). According to a potential natural vegetation (PNV) map (Ramankutty & Foley 1999), 58 locations were in forested ecosystems, 15 are in savanna ecosystems and 29 are in non-forested ecosystems. Based on the CRU/SHF climate 38/42, 59/64, 41/36 locations were in arid, dry and wet regions, respectively, with the

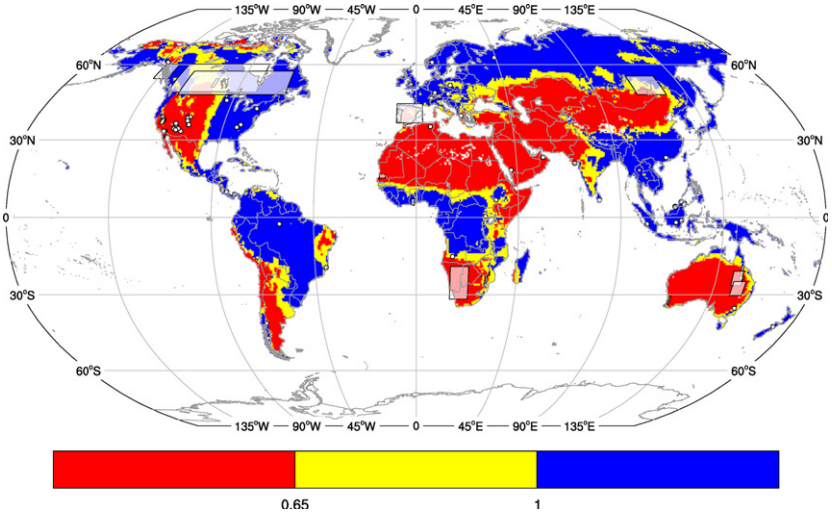

Fig. 1. Mean AI_{12} (1948–2006) with the locations of reported drought-induced mortality events analysed here. Locations are either depicted as dots (single grid cells) or as rectangles covering the whole analysed regions.

multi-annual mean AI_{12}. Of the 58 sites located in forest biomes, which we focus on here, 12/12 are located in arid, 25/29 in dry and 33/29 in wet climate conditions with CRU/SHF, respectively. However, forests are dominantly located in wet climate conditions ($47.2/38.45 \cdot 10^6$ km^2) compared to dry ($10.35/18.97 \cdot 10^6$ km^2) or even arid ($1.92/3.27 \cdot 10^6$ km^2) conditions based on CRU/SHF, respectively, and a PNV map (Ramankutty & Foley 1999).

VEGETATION MODEL DESCRIPTION

The DGVM LPJ-GUESS version 2.1 (Smith, Prentice & Sykes 2001; Ahlström *et al.* 2012) was applied. LPJ-GUESS combines the ecophysiological processes that are very similar to those of the Lund–Potsdam–Jena (LPJ) DGVM (Sitch *et al.* 2003) with hydrological updates from Gerten *et al.* (2004) and more detailed representations of vegetation dynamics and forest mortality, adopting a forest gap model approach similar to the FORSKA model (Prentice *et al.* 1993; Smith, Prentice & Sykes 2001). Tree mortality occurs in LPJ-GUESS as a result of stochastic stand-replacing mortality (representing, e.g. windstorms and pest attacks), fire, low growth efficiency and increasing age (Smith, Prentice & Sykes 2001; Wramneby *et al.* 2008). We only analysed changes in the latter two because these two are directly or indirectly driven by climatic trends and correspond best to the type of mortality events that have been reported for the field sites. Growth-efficiency mortality is influenced by water stress as follows. If the water supply (derived from root-distribution-weighted soil water content and a maximum transpiration rate) is lower than the water demand (associated with optimal non-water-limited photosynthesis rates), stomatal conductance and thereby CO_2 uptake and photosynthesis is reduced in the model, which leads to a reduced net primary production (NPP). Growth efficiency is defined as annual (NPP) in kg(C) m^{-2} divided by leaf area in m^2 using a five-year running average. Mortality is calculated according to equation 1 with $mort_{greff}$ being a running 5-year average. Annual mortality is reaching a maximum of 30% if $greff_{mean}$ is zero. $greff_{min}$ is a specific parameter for the plant functional types (PFT) to distinguish shade-tolerant ($greff_{min}$ = 0.04) and shade-intolerant ($greff_{min}$ = 0.08) PFTs (Hickler *et al.* 2004). PFTs are defined by a set of parameters associated with general traits such as physiognomy (tree or herbaceous), geographical distribution (tropical, temperate, boreal; Sitch *et al.* 2003), shade tolerance (Hickler *et al.* 2004), specific leaf area, physiognomy (tree or grass), phenology (evergreen, raingreen, summergreen) and photosynthesis type (C_3 or C_4), leading to PFTs such as a shade-tolerant temperate summergreen deciduous tree (see Ahlström *et al.* for specific parameters in this version). The age-related mortality can be influenced indirectly by climate change if climate change changes the composition of trees in terms of their maximum non-stressed longevity, which is higher for shade-tolerant trees. However, in our simulation results changes in growth-efficiency mortality dominated the total mortality change. Mortality changes were analysed for all PFTs weighted by their relative cover.

$$mort_{greff} = \frac{0.3}{1 + \left(\frac{greff_{mean}}{greff_{min}}\right)^5} \qquad \text{(eqn 1)}$$

An increased mortality with low growth was already used by (Botkin, Janak & Wallis 1972), which has been further developed by Pacala, Canham & Silander (1993) and modified for LPJ-GUESS (Smith, Prentice & Sykes 2001). Simulating tree mortality as a function of growth, in a similar way as here, is common in vegetation models (Hawkes 2000; Bugmann 2001; Keane *et al.* 2001). Growth efficiency is influenced by climate in several direct and indirect ways (including competition for light and water). A direct effect of climate is, for example, that PFTs closer to their climatic temperature optimum can have higher growth efficiency. This temperature optimum is different for tropical and non-tropical plants, as they have different optima for photosynthesis and different base respiration rates, the latter being lower for tropical trees (Sitch *et al.* 2003).

The model runs on a daily timestep and output is written on an annual and monthly interval. We used a spin-up time of 1000 years. The first 30 years are used for spin-up. For the CRU climate, they were temperature detrended, whereas for SHF they were just randomly recycled.

Results

HISTORICAL CHANGES IN CLIMATIC DROUGHT

Comparison of drought indices with other drought reconstructions

The global spatial patterns of drying and wettening trends derived here (Fig. 2a–c) corresponded well with previously published patterns (Dai 2010; Sheffield, Wood & Roderick 2012) and all three measures of drought agreed in the spatial pattern. At around 15°N, a clear meridional drying trend,

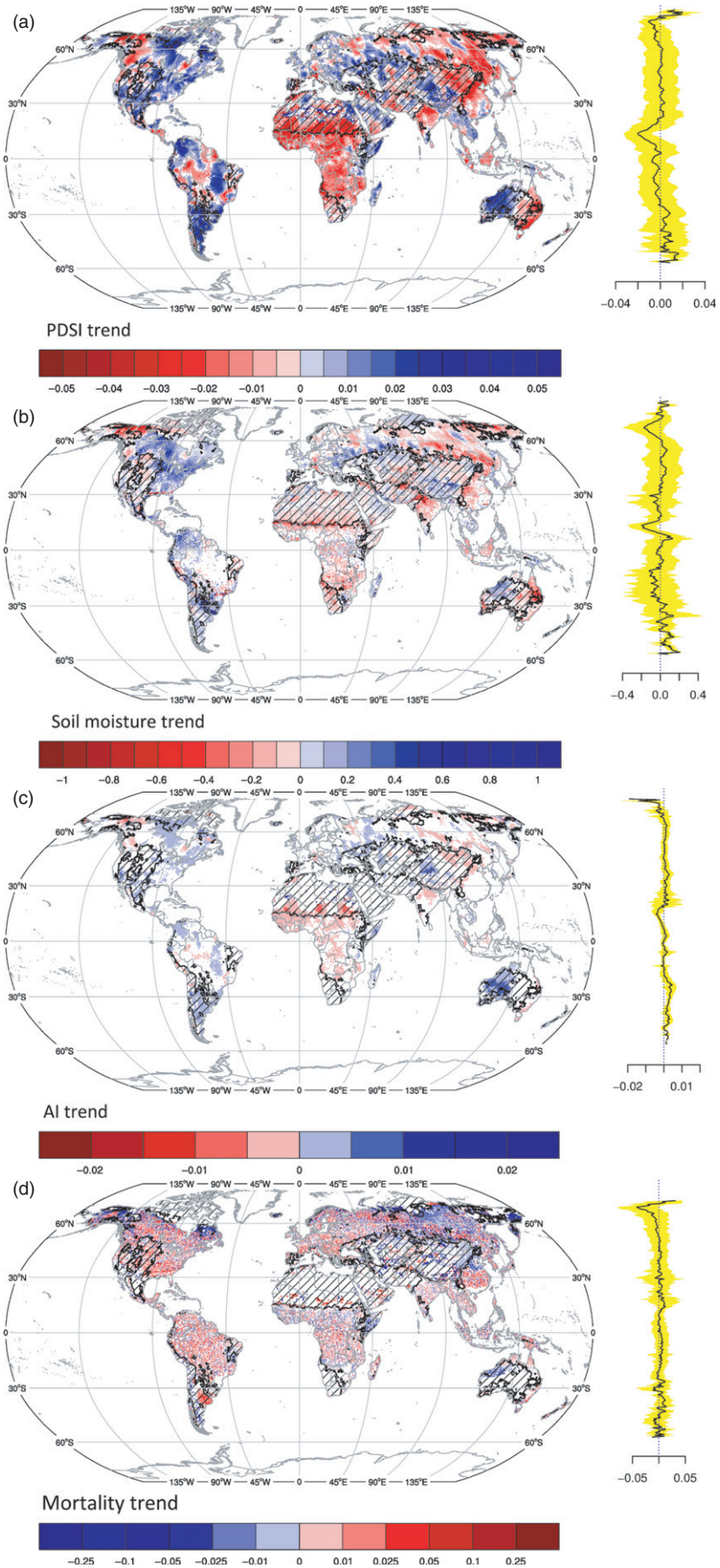

Fig. 2. Significant ($P \leq 0.05$) trends of drought indices (a) normalized PDSI, (b) the soil moisture of the lower soil layer, (c) $\log_{10}(AI_{12})$) and (d) mortality values as change per year from LPJ-GUESS with CRU. For PDSI and AI_{12} values are normalized and for soil moisture and mortality in % per year. A meridional mean (black line), standard deviation (yellow) and zero line (dotted blue) are on the right side. Hashed areas are grassland/steppe, dense/open shrubland, tundra, desert and polar desert/rock/ice based on a PNV map, since trees play only marginal roles in these regions.

dominated by the Sahel, was apparent. North of 75°N, the analyses revealed an additional meridional drying band. South of approx. 20°S wetting trends were dominating (Fig. 2a–c).

A Spearman rank correlation of our PDSI and AI_{12} to growing season PDSI values of the North American Drought Atlas (NADA) with a spatial resolution on 2.5° × 2.5° (Cook *et al.* 1999) and monthly values of the PDSI simulated within the Vegetation/Ecosystem Modelling and Analysis Project (VEMAP) at 0.5° × 0.5° (Kittel *et al.* 2004) mostly gave significant results, whereby SMOIST yielded the weakest correlation (Table 1). Correlation values for AI_{12} were slightly better than for AI_3 and AI_{GS}.

A number of regional drought events, reported in the IPCC (Trenberth *et al.* 2007), are reproduced well by our simulations of AI_{12}, PDSI and SMOIST (SI Figs D1–D8). We choose a rectangular pattern matching the given locations as good as possible. One exception, where droughts were not reproduced, was the Amazon drought in 2005 (SI Fig. D8), which was not apparent in our drought indices. The European summer heat wave was hardly visible in the PDSI and SMOIST simulations, but clearly shown with AI_{12} and even stronger so with AI_3 (SI Fig. D2).

The results so far gave us limited confidence in SMOIST as a drought proxy, although at a local or regional scale soil moisture can serve as a good measure for drought (Lakshmi *et al.* 2004; Granier *et al.* 2007). The low statistical power of SMOIST might partly be explained by the distribution of this variable. In dry regions, the median is located close to zero with a long tail towards 1, whereas in wet regions the median is close to 1, with a long tail towards zero, resulting in a global bimodal distribution of SMOIST. Therefore, we only show results with the other drought measures hereafter.

Drying trends and drought events in forests

On average, forests became slightly drier with respect to PDSI and CRU/SHF, but with large spatial variability (Table 2). However, considering AI_{12}/AI_3/AI_{GS} with CRU/SHF, the calculated average trend indicates a wettening trend. In arid forests, all drought indices with both climate drivers exhibited a drying trend; in dry forests, AI_{GS} was the only index with a wettening trend and in wet forests, the PDSI with CRU/SHF were the only ones with a drying trend. (Table 2).

The PDSI based on the CRU climate gave larger areas with significant drying than with wettening trend, in particular for arid and dry areas (Fig. 3). The AI yielded in less area with significant trends because the sample size is much smaller (annual instead of monthly resolution). Also according to AI_{12} areas affected by a drying trend were larger in already dry areas compared to wet forests (Fig. 3). AI_3 showed a similar pattern as AI_{12}, whereas a slightly larger area with AI_{GS} in dry forests was affected by a wettening trend. With SHF, the pattern was similar but the areas affected by a drying trend were larger. For SHF, the difference between areas affected by drying or wettening was even more distinct (SI Fig. C3).

Overall, the forests affected by extreme drought events, irrespective of overall drying or wettening trends, decreased according to our analyses (Fig. 4) with a stronger trend when using SHF (SI Fig. C4). This overall decline in extreme drought-affected forests was dominated by changes in wet forests. Forests in arid regions showed an increase in extreme drought-affected area according to the PDSI (CRU) and AI_{12} (CRU and SHF); AI_3 (SHF) and PDSI (SHF) gave a decrease in drought-affected area. In dry forests, no significant increase or decrease in extreme drought-affected area was detected.

Table 1. Spearman rank correlation averaged over all grid cells between simulated drought indices and the PDSI from VEMAP (Kittel *et al.* 2004) and NADA (Cook *et al.* 1999). The season is defined from April to October here

		CRU		SHF	
		VEMAP	NADA	VEMAP	NADA
PDSI	Monthly	0.45	–	0.46	–
	Season	0.50	0.57	0.51	0.55
	Annual	0.50	0.61	0.50	0.59
SMOIST	Monthly	0.27	–	0.28	–
	Season	0.44	0.54	0.45	0.50
	Annual	0.44	0.50	0.46	0.46
AI_{12}	Season	0.53	–	0.53	–
	Annual	0.54	0.18	0.54	0.17
AI_3	Season	0.52	–	0.53	–
	Annual	0.50	0.16	0.51	0.16
AI_{GS}	Season	0.49	–	0.50	–
	Annual	0.46	0.17	0.47	0.16

CLIMATIC TRENDS AND SIMULATED MORTALITY AT THE DROUGHT-INDUCED MORTALITY EVENTS

The climatic trends at the forested DIME (according to PNV map by Ramankutty & Foley (1999)) have statistically not been different from these above general trends, both with CRU and SHF (weighted Welch two sample *t*-test). Nevertheless, arid or dry forests were significantly different with respect to the trend at the DIME compared to all arid or dry forests globally, with the reported DIME showing a significantly stronger drying trend (Table 2). The simulated mortality rate for all forests was statistically not different at the locations compared to all forests.

Although our primary focuses are regions dominated by forests, we summarize our findings for all locations in this paragraph, for example including those which are in savanna regions according the PNV map. We checked whether one of our drought indices (with either of the two climate data sets) matches each individual DIME and its end year of the drought event ±5 years. In 49 out of 100 cases, simulated drought events matched the reported DIME (PDSI or AI_{12}) with CRU or SHF (36/37 for CRU/SHF, respectively). Although this was less than 50% of all events per climate data set, it was more than by chance (randomly choosing 1000 times 100 locations and years in forests) for most indices, but not for PDSI in wet and arid forests (Table 3). LPJ-GUESS simulated exceptional mortality (weighted average over all PFTs) for 40/48 of the reported events with CRU/SHF, which also was more than by

Table 2. Averaged significant PDSI, $\log(AI_{12})$, $\log(AI_3)$, $\log(AI_{GS})$ and mortality trends at the 58 forest locations and all simulated grid cells (weighted by area) with CRU/SHF subdivided by AI_{12} and *P*-values of the two sample weighted Welsh *t*-test, where the two samples are trend values at the drought-induced mortality locations and the trends in the corresponding ecosystem for CRU and SHF. Numbers of locations/grid cells in brackets

		CRU			SHF		
		Sites	All	*P*	Sites	All	*P*
PDSI	Arid forest (AI < 0.65)	0.006 ± 0.006 (12)	−0.005 ± 0.01 (876)	<0.001	0.0009 ± 0.006 (12)	−0.009 ± 0.01 (1514)	<0.001
	Dry forest (AI < 1)	0.0002 ± 0.01 (25)	−0.005 ± 0.01 (5036)	0.022	−0.003 ± 0.009 (29)	−0.006 ± 0.01 (8767)	0.033
	Wet forest (AI ≥ 1)	−0.002 ± 0.01 (33)	−0.001 ± 0.01 (22111)	0.7	−0.006 ± 0.01 (29)	−0.003 ± 0.01 (18424)	0.14
	All forests	0.0008 ± 0.01 (58)	−0.002 ± 0.01 (27191)	0.42	−0.004 ± 0.009 (58)	−0.004 ± 0.01 (27191)	0.98
AI_{12}	Arid forest (AI < 0.65)	0.001 ± 0.0009 (12)	−0.0003 ± 0.002 (876)	<0.001	0.001 ± 0.0006 (12)	−0.0005 ± 0.002 (1514)	<0.001
	Dry forest (AI < 1)	0.001 ± 0.0006 (25)	−0.0002 ± 0.001 (5036)	0.0096	0.0003 ± 0.001 (29)	−0.0002 ± 0.001 (8767)	0.013
	Wet forest (AI ≥ 1)	−0.0001 ± 0.0007 (33)	0.00006 ± 0.0009 (22111)	0.13	−0.0003 ± 0.0008 (29)	0.000009 ± 0.001 (18424)	0.082
	All forests	0.0001 ± 0.0009 (58)	0.000007 ± 0.001 (27191)	0.44	0.00004 ± 0.001 (58)	−0.00006 ± 0.001 (27191)	0.45
AI_3	Arid forest (AI < 0.65)	0.001 ± 0.0008 (12)	−0.0002 ± 0.002 (876)	<0.001	0.001 ± 0.0005 (12)	−0.0005 ± 0.002 (1514)	<0.001
	Dry forest (AI < 1)	0.0006 ± 0.001 (25)	−0.0001 ± 0.001 (5036)	0.008	0.0008 ± 0.001 (29)	−0.0002 ± 0.001 (8767)	<0.001
	Wet forest (AI ≥ 1)	−0.0002 ± 0.0008 (33)	0.00005 ± 0.001 (22111)	0.059	−0.0005 ± 0.0008 (29)	−0.000004 ± 0.001 (18424)	0.01
	All forests	0.0001 ± 0.001 (58)	0.00001 ± 0.001 (27175)	0.39	0.0002 ± 0.001 (58)	−0.00006 ± 0.001 (27191)	0.21
AI_{GS}	Arid forest (AI < 0.65)	0.002 ± 0.0009 (12)	−0.0001 ± 0.002 (876)	<0.001	0.002 ± 0.0008 (12)	−0.0002 ± 0.002 (1514)	<0.001
	Dry forest (AI < 1)	0.0009 ± 0.001 (25)	0.00006 ± 0.001 (5036)	0.008	0.0009 ± 0.001 (29)	0.000004 ± 0.001 (8767)	<0.001
	Wet forest (AI ≥ 1)	−0.00006 ± 0.001 (33)	0.0001 ± 0.001 (22111)	0.83	−0.0001 ± 0.0009 (29)	0.0001 ± 0.001 (18405)	0.002
	All forests	0.0004 ± 0.001 (58)	0.00009 ± 0.001 (27172)	0.052	0.0004 ± 0.001 (58)	0.00008 ± 0.001 (27172)	0.079
MORT	Arid forest (AI < 0.65)	0.004 ± 0.008 (12)	−0.003 ± 0.01 (743)	0.012	0.009 ± 0.006 (12)	0.00008 ± 0.01 (1344)	<0.001
	Dry forest (AI < 1)	0.004 ± 0.007 (25)	0.0002 ± 0.01 (4613)	0.009	0.004 ± 0.009 (29)	−0.0007 ± 0.01 (8161)	0.012
	Wet forest (AI ≥ 1)	−0.0008 ± 0.01 (32)	0.001 ± 0.01 (20169)	0.31	−0.003 ± 0.01 (29)	−0.002 ± 0.01 (15695)	0.67
	All forests	0.002 ± 0.01 (57)	0.001 ± 0.01 (24782)	0.45	0.0006 ± 0.01 (57)	−0.001 ± 0.01 (23856)	0.2

chance (Table 3). However, only in 15/20/30 (CRU/SHF/any) cases, exceptional mortality was associated with exceptional drought (PDSI or AI_{12}). The DIME showed a trend towards increasing mortality in arid and dry forests, which was significantly stronger than for all arid/dry forests (Table 2).

We explored five mortality events in more detail: the one with the largest spatial extent (not in Table 4) and four with a duration of several decades (Table 4). The largest area with reported drought-induced mortality covered west to mid southern Canada with a doubling of the mortality rate (Hogg, Brandt & Michaellian 2008; Allen *et al.* (2010): A5-20; equivalent to 1813 model grid cells) following a drought in 2001–2002. For this event, the vegetation model simulated a slight, but significant increase in the mortality of 2.75/2.71% in 2002–2004 compared to 2.62 ± 0.11/2.44 ± 0.12% during the whole period with CRU/SHF, respectively. However, no drought was apparent in any of the climate data sets for the year 2000 and 2001 here, but a clear continuous drying trend from 1948 to 2006 (SI Fig. F3). At two African locations (Gonzalez 2001; : Allen *et al.* (2010): A1–4; Foden *et al.* 2007; : Allen *et al.* (2010): A1–8), the vegetation model simulated drying and increased mortality, whereby at the second site, the drying was only apparent in the PDSI with both climate data sets (SI Figs F1–F2). At two locations in western U.S. (Van Mantgem *et al.* 2009; : Allen *et al.* (2010): A5–23; Hennon & Shaw 1997; Allen *et al.* (2010): A5–27), the vegetation model simulated no consistent trends. Van Mantgem *et al.* (2009) concluded that warming and the resulting

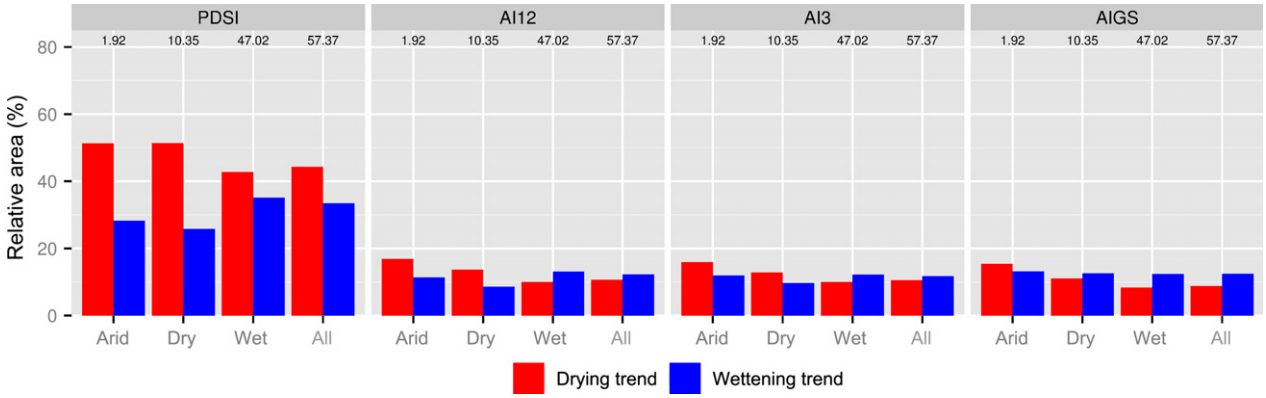

Fig. 3. Relative forest area in each ecosystem type and with different AI_{12} thresholds (arid: $AI_{12} < 0.65$; dry: $AI_{12} < 1$; wet: $AI_{12} \geq 1$) with significant drying (red) or wettening (blue) trends. Numbers above the columns are absolute areas in 10^6 km^2.

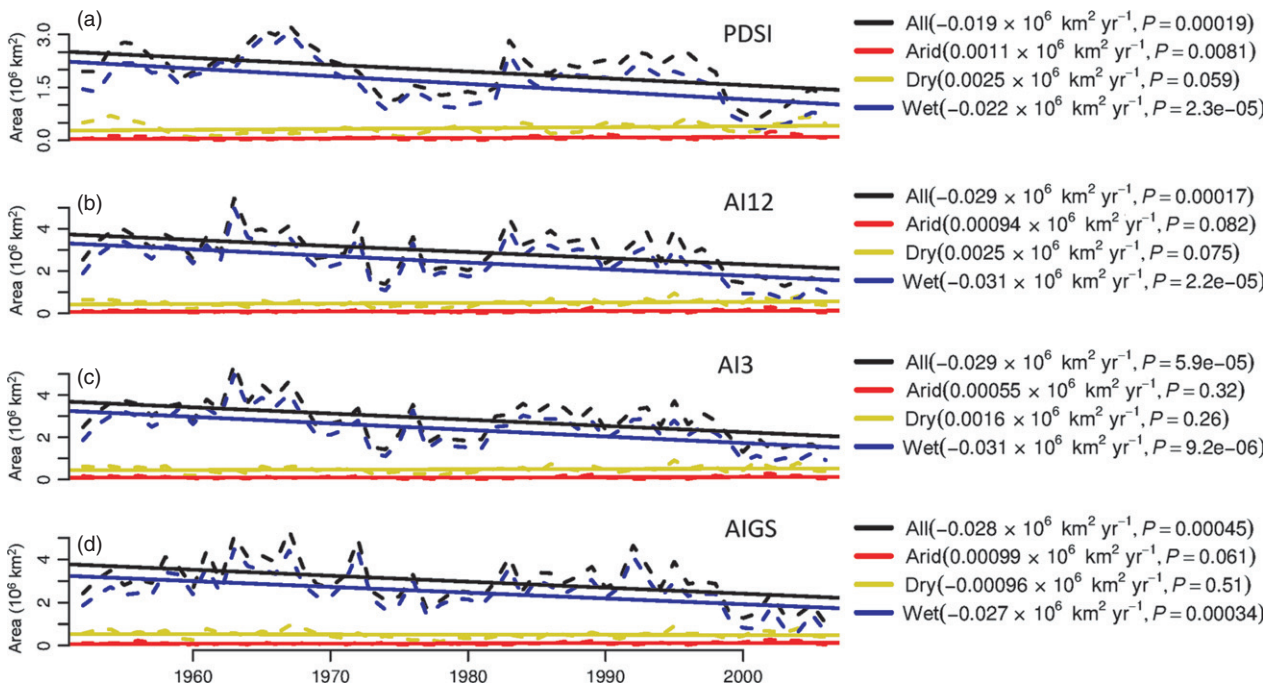

Fig. 4. Forest area affected by any of the 3 defined types of droughts each year (dashed line) and linear trend (solid line) for (a) PDSI, (b) AI_12, (c) AI_3 and (d) AI_GS. The slope and *P*-value are given in the legend, filtered by AI_{12} (arid: $AI_{12} < 0.65$, dry: $AI_{12} < 1$, wet: $AI_{12} \geq 1$).

Table 3. Number of matching drought and mortality events (*N*) in forests classified by AI_{12}. N_{total} is the number of model grid points for each vegetation/climate class. Percentages in brackets are the fraction of randomly choosing 1000 times *N* locations and years out of N_{total} grid points, where less or equal to N exceptional drought/mortality events occurred

			AI			
	N (N_{total})	PDSI	GS	3	12	MORT
Arid forests (AI < 0.65)	12 (876)	1 (46.6%)	0 (52.4%)	2 (98%)	5 (100%)	7 (99%)
Dry forests (AI < 1)	25 (5036)	6 (95.7%)	4 (96.3%)	7 (99.9%)	9 (100%)	15 (99.9%)
Wet forests (AI ≥ 1)	33 (22111)	6 (93.1%)	12 (100%)	12 (100%)	11 (100%)	11 (74.9%)
All forests	58 (27191)	12 (98.7%)	16 (100%)	19 (100%)	20 (100%)	26 (99.3)
Global	100 (59191)	20 (99.2%)	30 (100%)	30 (100%)	31 (100%)	40 (99%)

increase of the climatic water deficit likely was an important factor contributing to the increase of tree mortality in western USA since the 1960s. Our analyses instead gave a wettening trend with the PDSI and CRU/SHF, but no significant trends with AI_{12} and mortality for this location (SI Fig. F4). In western Canada Hennon & Shaw (1997), we simulated a wettening trend with the PDSI and CRU, as well as with AI_{12} and SHF; otherwise, the trend of the remaining drought indices and mortality rate were not significant (SI Fig. F5).

GLOBAL SIMULATED TREE MORTALITY

The spatial pattern of mortality trends varied at a much finer spatial scale (Fig. 2d) with no clear global mean trend for forests globally (Table 2). At high latitudes, where temperature rather than water availability constrains forest growth, the changes in both directions were the largest (Fig. 4c). However, moisture availability was indeed a main driver of the tree mortality according to LPJ-GUESS in dry areas, confirming the sensitivity of forests in these areas to increasing droughts (Fig. 5). Meridionally drier conditions coincided with higher simulated mortality between 15°N–45°N and 15°S–30°S, respectively. In the wet tropics, no clear meridional dependence of mortality on either drought or temperature was simulated. All forests show an increase in the area affected by extreme drought events over the studied period (Fig. 5). However, this trend is not significant for dry forests and in arid forests, we even calculate a decreasing trend in area affected by extreme droughts.

Discussion

HISTORICAL CHANGES IN DROUGHT SEVERITY

Estimating drought levels from climate data is challenging because different drought measures can yield quite different results (e.g. Sheffield, Wood & Roderick 2012). Therefore, we have compared our drought reconstructions to other independent reconstructions. The spatial patterns of wettening and drying presented here correspond well with those inferred by Dai (2010) and Sheffield, Wood & Roderick (2012). The reconstructed changes through time are consistent with those derived by NADA and VEMAP (Table 1). Furthermore, we were able, with only one exception, to reproduce most reported major climatological historical drought events (SI Figs D1–D8). These comparisons give us high confidence in our drought calculations. In the case of the Amazon drought in 2005, which was not reproduced, the low number of weather stations in this region might lead to climatic input data of relatively poor quality.

According to our results, there has not been a drying trend or an increase in extreme drought events across all forest globally (Figs 4 and C4). This conclusion is in line with global analyses from Sheffield & Wood (2008a) and Sheffield, Wood & Roderick (2012), who have not found strong changes in drought severity and extent since 1950. However, our analyses suggest that forests in already dry or arid regions are very likely to have been affected by drying, independent from the applied drought measure and climate data set (Figs 3 and C3).

HOW WELL DO THE DROUGHT-INDUCED MORTALITY EVENTS REPRESENT FORESTS IN GENERAL?

The DIME are not evenly distributed over all forests globally. For large areas in particular in Russia (i.e. for most of the boreal taiga), no drought-mortality events have been reported, which might simply reflect that they have not been investigated in these not heavily used forests. (Fig. 1) The DIME tend to be in more arid regions compared to the global distribution of forests, in particular for dry and arid

Table 4. Trends (significant trends ($P < 0.05$) in bold) of simulated drought indices and mortality for four observed long-term drought-induced mortality events from the literature. SMOIST and MORT trends are in % per year, PDSI is in standard deviations per year and AI is in $\log_{10}$(AI) per year. Location names are from Allen *et al.* (2010)

	A1–4		A1–8		A5–23		A5–27	
	CRU	SHF	CRU	SHF	CRU	SHF	CRU	SHF
PDSI	**−0.024**	**−0.026**	**−0.0081**	**−0.016**	**0.007**	**0.0041**	**0.0043**	−0.00054
AI_{GS}	**−0.0038**	**−0.004**	−0.00037	−0.00098	**0.0028**	**0.0029**	0.00076	−0.000079
AI_3	**−0.0038**	**−0.004**	−0.00033	0.0009	0.0017	0.0018	−0.00019	**−0.0015**
AI_{12}	**−0.0038**	**−0.004**	−0.00038	−0.00098	0.0018	0.0018	−0.00014	**−0.0014**
MORT	**0.0051**	**0.0092**	0.00045	**0.0015**	0.00032	0.0017	−0.0031	**−0.0078**

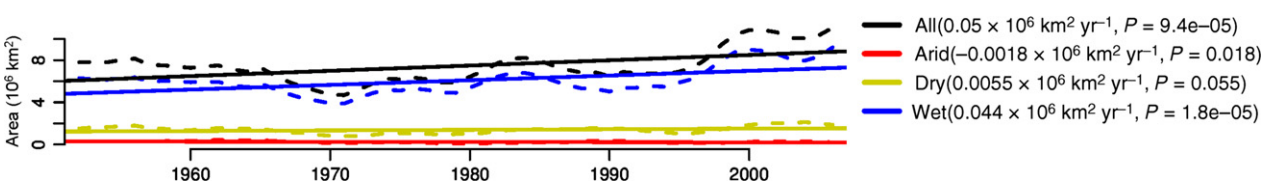

Fig. 5. Forest area affected by any of the 3 defined types of exceptional mortality events each year (dashed line) and linear trend (solid line). The slope and *P*-value are given in the legend, filtered by AI12 (arid: AI12 < 0.65, dry: AI12 < 1, wet: AI12 ≥ 1).

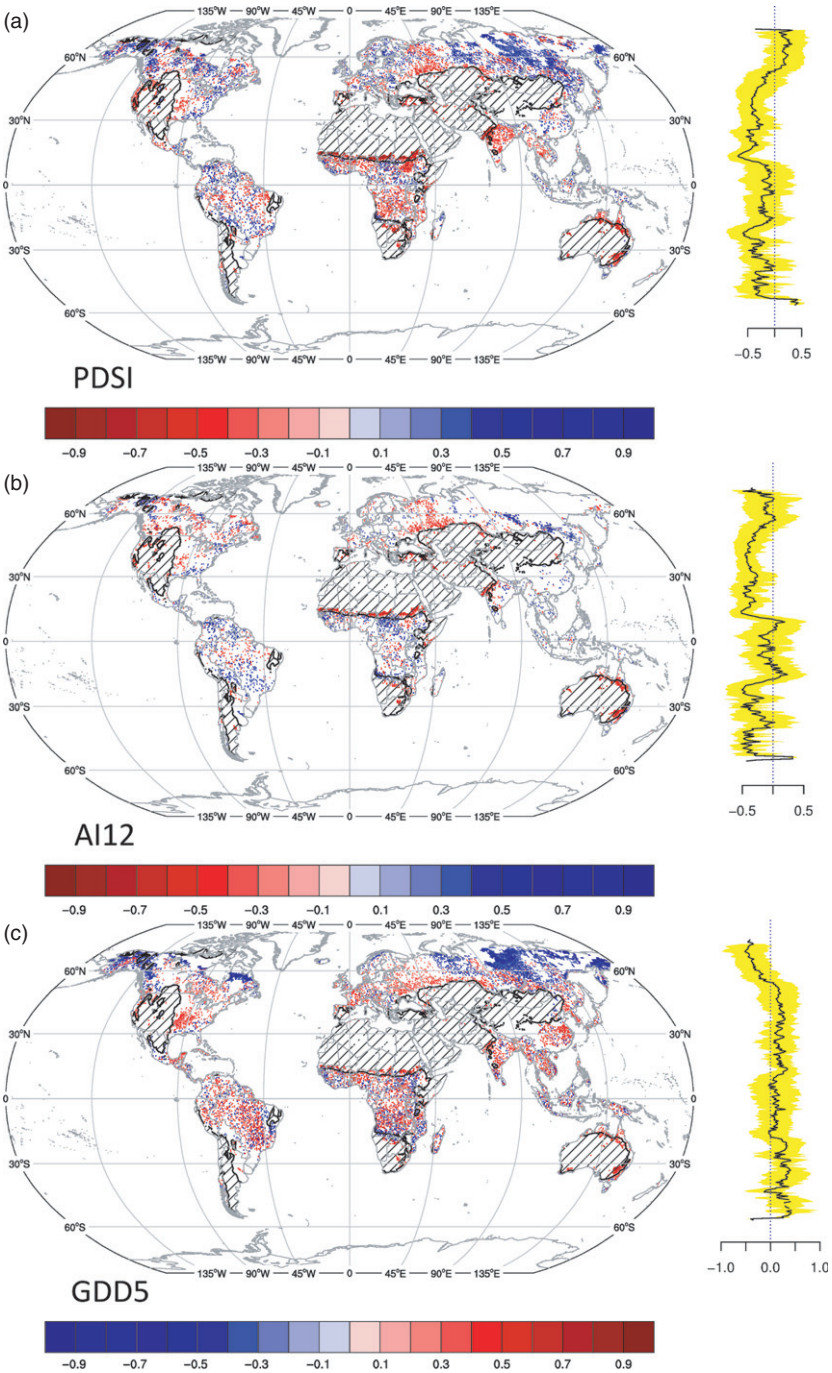

Fig. 6. Spearman rank correlation ρ between (a) PDSI, (b) AI_{12} and (c) growing degree days (GDD5) and mortality based on CRU with a meridional mean (black line), standard deviation (yellow) and zero line (dotted blue). Hashed areas are arid ($AI_{12} < 0.65$). Insignificant correlations ($P \geq 0.05$) as well as non-forested vegetation types are white.

regions and many locations are even in areas classified as savannas in the PNV data set that we used. Therefore, they are not fully representative of all forests. Forests in general have probably suffered less from drought-induced mortality than concluded by Allen *et al.* (2010). This is in line with Scholes *et al.* (2014), who stated that there only was 'low confidence' that warming and changes in precipitation are increasing in a wide range of forest ecosystems. However, the climatic trends at the DIME in forest regions according to the PNV map are not statistically different from those averaged over all DIME, implying that the climatic bias of the sites for which increased mortality has been reported is not very strong.

SIMULATED DROUGHT-INDUCED MORTALITY

Globally, the simulated changes in tree mortality were not clearly related to changes in water availability (Fig. 2), which reflects that water availability is not the only driver of tree growth (Nemani *et al.* 2003), vigour and mortality. In many northern areas, simulated mortality rates declined over time with climate warming (Fig. 2d), which is consistent with widespread greening in the high northern latitudes during the last 20 years of the last century (Lucht *et al.* 2002; Piao *et al.* 2011). However, in boreal forests, pests and fire are major drivers of tree mortality (e.g. Kurz *et al.* 2008). Forest pests were not included in the model and fire effects were not analy-

sed because fires were not the primary reason for the increases in tree mortality reported in the study by Allen *et al.* (2010) and Scholes *et al.* (2014). But, according to the vegetation model, drought is an important driver of tree mortality in already dry or arid forests (Fig. 4), suggesting that increasing drought severity indeed might have caused increasing tree mortality in many already dry forest areas, although the area affected by extreme mortality did not change significantly in our simulations (Fig. 5).

SIMULATED AND REPORTED DROUGHT AND MORTALITY EVENTS FROM FIELD SITES

Even though our drought reconstructions match most reported climatological major drought events well, we could not detect drought events or trends for all DIME and we simulated drought events and associated increases in tree mortality for less than half of the field sites. Either the gridded climatologies are in many cases not able to capture more local drought events, or drought might not be the main driver of all reported forest mortality events. Furthermore, the vegetation model might not be able to simulate drought-induced mortality well.

Gridded climate data sets have always spatially varying quality because the number of weather stations varies geographically. Furthermore, local microclimates and soil conditions can be crucial drivers of forest mortality (e.g. Peterken & Mountford 1996) and have not been considered here. This might be the reason why some local mortality events could not be reproduced. However, also for some of the DIME with large spatial extent (e.g. western Canada and western U.S.), we could not detect a clear drought signal. We think that studies on tree mortality generally should be accompanied by more vigorous analyses of potential climatic drives, also using a variety of drought indicators. In this respect, forest researchers and climatologists should work closer together.

THE STATE OF MORTALITY MODELLING

Forest mortality is a complex process and the result of interactions between direct climatic effects on tree physiology, management and disturbances, such as wind, fire and insect pests (Franklin, Shugart & Harmon 1987; Manion 1991; Kurz *et al.* 2008), which are poorly or not at all represented in vegetation or forests model (Allen *et al.* 2010). Most DGVMs and forest models use a similar approach as LPJ-GUESS for simulating tree mortality (Keane *et al.* 2001) and growth in general seems to be a good predictor for tree mortality (Wyckoff & Bowers 2010; Holzwarth *et al.* 2013). However, many studies have shown that such models have difficulty reproducing observed tree mortality (Wunder *et al.* 2008; Wang *et al.* 2012; McDowell *et al.* 2013; Powell *et al.* 2013), which has been attributed to the fact that we lack a good mechanistic understanding of the physiological mechanisms underlying tree mortality (Wang *et al.* 2012). Powell *et al.* (2013) even concluded that our understanding and representation of mechanisms underlying drought-induced forest mortality in the tropics are inadequate for ecosystem modelling. The representation of stomatal conductance, the hydraulic system, respiration and carbon starvation and appropriate mortality thresholds are all important processes for model predictions and have large uncertainty. Hydraulic failure is not represented explicitly by most DGVMs (Hickler *et al.* 2006; McDowell *et al.* 2011), but also models that are physiologically more advanced have difficulties with simulating the interdependence of carbon starvation and hydraulic failure and interactions with biotic attacks (McDowell *et al.* 2013). Another caveat is that different tree provenances are highly adapted to the prevailing climate, for example, in terms of their base respiration rates and drought tolerance (e.g. Bolte *et al.* 2009) which is not captured by PFTs with fixed parameters. Physiological effects of increasing atmospheric CO_2 (fertilization and reduced stomatal conductance) and nitrogen deposition are often believed to reduce the negative effects of droughts (Wang *et al.* 2012). Potential CO_2 effects are now included in many vegetation models, but these are heavily debated and highly uncertain. An increasing number of models also include a nitrogen cycle (Zaehle *et al.* 2014) but most studies have addressed the effects on growth, not mortality. Finally, access to deep water in the soil is important in many water-limited forests (in particular with highly seasonal or winter rain) and poorly represented in most vegetation models. This is probably the reason why different versions of LPJ underestimate evapotranspiration at some Mediterranean forest sites (Gerten *et al.* 2004; Hickler *et al.* 2006).

Conclusions

We could not identify a general drying trend or an increase in extreme drought events in forests globally, but already dry forests, seem to be affected by decreasing water availability and increasing frequency of droughts. However, the trends are not very strong and the spatial variability is large. As our drought reconstructions are consistent with other estimates of major drought events, we are confident that they are generally accurate. The forested DIME are predominantly in already dry forests and not fully representative of global forests and the vegetation model results generally confirm that forest mortality in these areas is sensitive to drought. Nevertheless, the poor correspondence of the reconstructed drought events with those reported by Allen *et al.* (2010) cast some doubt on the conclusion by Allen *et al.* (2010) and Scholes *et al.* (2014) that all reported mortality events have been primarily driven by climatological drought and heat stress. However, in some cases, where the spatial extent of the reported drought event was small, local soil conditions and microclimate might be important drivers, which are not captured in global gridded climatologies and the available soil data. We think that, in studies of drought and heat-induced forest mortality, more effort should be devoted to also measuring or analysing potential environmental drivers, in particular, climatological drought, microclimate if the event covers a small area and soil conditions. This would be crucial for attribution, which often has been proved to be difficult. Good estimates of the environmental drivers are also crucial for testing vegetation models.

Vegetation models such as DGVMs have been widely used for climate impact research and gave in some cases dramatic forest mortality in the future, with substantial feedbacks on the climate system. Yet, these models have hardly been tested against observations of forest or tree mortality. This is clearly a bottleneck for climate impact research. We have no proof yet that the projected changes in mortality are generally realistic. We present a first such test against observations from a large number of sites across the globe. The results are not very encouraging. The reasons for this are manifold, including the complex nature of forest mortality, which is physiologically not fully understood and, hence, necessarily not fully captured in vegetation models. However, large uncertainty also arises from the environmental input data and access to deep soil water. Close collaboration between researchers working with forest field observations and experiments, vegetation modellers, climatologists and soil scientists will be necessary to improve our understanding of drought and heat-induced forest mortality and the predictive power of climate impact models. Different hypotheses concerning the physiological mechanisms driving forest mortality (such as hydraulic failure versus carbon starvation) should be implemented in vegetation models, which then should be tested against observations and experiments. In the case of DGVMs, data from multiple sites will be necessary to establish the general applicability of these models. Much of the necessary data is emerging right now, yet not in standardized large open-access data bases, which would be ideal. Site-scale vegetation models have also started to include more mechanistic representations of the processes supposedly driving drought and heat-induced mortality, such as hydraulic failure, which could also be implemented in DGVMs. Hydraulic traits, as well as other potentially relevant traits, have become increasingly available via the global TRY plant trait data base (Kattge *et al.* 2011). Thus, we should be fully equipped to improve the state of forest mortality modelling in the coming years.

Acknowledgements

We thank Dominique Bachelet and Wendy Peterman for putting the data set on DataBasin.org, Justin Sheffield for providing his climate driver and our colleagues (Matthew Forrest, Bob O'Hara, Allan Spessa, Christian Werner) for discussions. J.S. and T.H. acknowledge support from the research funding program 'LOEWE-Landesoffensive zur Entwicklung Wissenschaftlich-ökonomischer Exzellenz' of Hesse's Ministry of Higher Education.

Data accessibility

Drought-mortality data available from figshare: http://dx.doi.org/10.6084/m9.figshare.1108108 and PDSI module for LPJ-GUESS from Zenodo: http://dx.doi.org/10.5281/zenodo.11843

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Received 18 July 2014; accepted 6 October 2014
Handling Editor: David Gibson

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Supplementary Material.