A New Generation of Climate-Change Experiments: Events, Not Trends

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A new generation of climate-change experiments: events, not trends

Anke Jentsch[1,2*], Jürgen Kreyling[1,2,3], and Carl Beierkuhnlein[3]

Intensification of weather extremes is currently emerging as one of the most important facets of climate change. Research on extreme events ("event-focused" in contrast to "trend-focused") has increased in recent years and, in 2004, accounted for one-fifth of the experimental climate-change studies published. Numerous examples, ranging from microbiology and soil science to biogeography, demonstrate how extreme weather events can accelerate shifts in species composition and distribution, thereby facilitating changes in ecosystem functioning. However, assessing the importance of extreme events for ecological processes poses a major challenge because of the very nature of such events: their effects are out of proportion to their short duration. We propose that extreme events can be characterized by statistical extremity, timing, and abruptness relative to the life cycles of the organisms affected. To test system response to changing magnitude and frequency of weather events, controlled experiments are useful tools. These experiments provide essential insights for science and for societies that must develop coping strategies for such events. Here, we discuss future research needs for climate-change experiments in ecology. For illustration, we describe an experimental plan showing how to meet the challenge posed by changes in the frequency or magnitude of extreme events.

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Ongoing climate change is considered to be a driving factor for ecosystems in the 21st century (IPCC 2001). Links between climate change and shifts in vegetation have been documented convincingly, mainly by modeling shifts in species distribution patterns and monitoring phenological rhythms (eg Walther *et al.* 2002; Root *et al.* 2003). Field and laboratory experiments have demonstrated the effects of changing climate parameters on vegetation (eg Harte and Shaw 1995; Beerling 1999). Although there is a high degree of uncertainty in the details of climate change, we propose separating the impacts of changes in mean climate values (what we term "trend effects") from those produced by changes in the magnitude or frequency of extreme events ("event effects"). Event-focused research is difficult because the impacts of "extreme weather events" on ecosystems are out of proportion to their short duration. Thus, weather extremes, which are increasing in magnitude and frequency, have serious implications for ecosystems and societies (IPCC 2001; EEA 2004).

Here, we discuss (1) the ecological relevance of extreme events, (2) evidence of intensifying weather extremes in climate change, (3) definition issues with respect to discrete versus gradual processes, and (4) the current state of experimental climate-change research. We conclude by discussing emerging research challenges and laying out an experimental plan to meet them.

In a nutshell:

- Intensification of weather extremes is currently emerging as one of the most important facets of climate change
- Evidence suggests that the frequency and magnitude of extreme weather events is increasing in many regions in response to global climate change
- Extreme events can be distinguished from gradual trends by their statistical extremeness (magnitude) combined with their discreteness (duration) relative to the life span of the organisms in focus
- Experimental research on extreme weather events has increased recently and accounts for one-fifth of the experimental climate change studies published in 2006. Here, we lay out research needs and introduce an experimental plan to meet the challenges posed by extreme events

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■ Ecological importance of extreme weather events

To illustrate the ecological role of extreme weather events, let us consider catastrophic shifts in ecosystems (Scheffer and Carpenter 2003) due to extreme disturbance events that change system characteristics. For example, tropical hurricanes or temperate winter storms are capable of destroying entire forests (Figure 1). However, not all extreme events are so lethal (Turner *et al.* 1998) that they push a system beyond the threshold of dynamic equilibrium, resulting in a novel system trajectory (White and Jentsch 2001). Less severe disturbance events may change competitive interactions among plants and alter successional pathways by reducing the

Figure 1. *Importance of extreme weather events. (a) Winter storm "Lothar" affected large forested areas in Central Europe in December 1999, as did winter storm "Kyrill" in January 2007. In Germany, Lothar blew down about 175 million m^3 of timber, more than twice the amount of the annual silvicultural harvest (69 million m^3) and nearly twice the annual increment (96 million m^3). (b) Severe summer drought in central Europe in August 2003. In Germany, drought primarily affected deciduous trees, resulting in leaf senescence of large forest patches.*

inertia of a system (Jentsch and Beierkuhnlein 2003; Figure 2).

Effects on the dynamics of biotic communities have often been associated with extreme weather events at ecological time scales (for reviews see Easterling *et al.* [2000b] and Parmesan *et al.* [2000]), and with climatic extremes at evolutionary time scales (Gutschick and BassiriRad 2003). Here, we discuss the ecological significance of extreme climatic parameters, using the following as illustrations: (1) minimum temperature, (2) heavy rainfall events, and (3) drought.

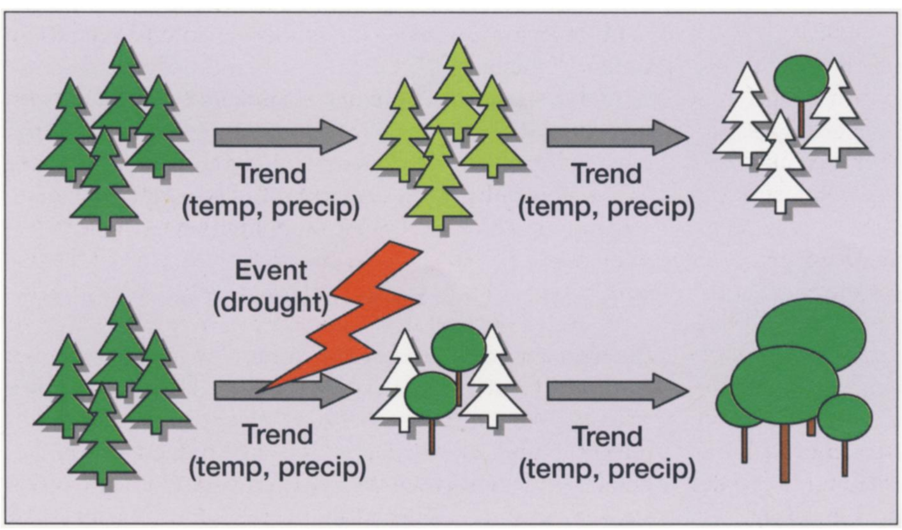

Figure 2. *Extreme events can accelerate system changes by reducing inertia, which is represented in long-lived organisms, competitive balance, or clonal reproduction. Changes in mean values of climate parameters, such as temperature or precipitation, may lead to changing species composition of a given system. The introduction of extreme events can advance this process. Therefore, extreme events can bring systems into novel balance with novel climatic conditions.*

Minimum temperature

Minimum temperature tolerance determines the northern distribution boundaries of tree species; tropical trees suffer cold injuries even at temperatures above 0°C. Deciduous trees in temperate zones tolerate temperatures as low as –30°C, whereas boreal conifers may survive temperatures as low as –70°C or colder without serious damage (Woodward 1987; Larcher 2003). Minimum temperature is clearly one of the most important factors determining species distribution. Woodward (1987) found that minimum temperature effects or cold injuries can be sudden and often lethal. It is noteworthy that processes such as frost hardening in winter change tolerance limits dramatically, and that timing of extreme frost events can be more important than absolute temperature. A decrease in frequency and magnitude of extreme cold temperatures and a lengthening of the growing season are likely to be among the effects of global climate change. Evidence from historical records and model predictions demonstrate that the magnitude of temperature increases under global warming is greater in winter than in other seasons and greater at night than during the day.

Heavy rainfall

In 1992, heavy rainfall events led to extraordinary biomass production by plants in a semi-arid, southwestern part of the US. This increase in forage availability facilitated population booms of deer mice (*Peromyscus maniculatus*). Overcrowding and forage shortage in the following year caused increased rodent activity in human buildings, and this in turn increased the contact between humans and mice, which carry hantavirus. Hantavirus cardiopulmonary syndrome is frequently lethal to humans, and a regional epidemic was observed in the area in 1993. The same chain of events was repeated between 1997 and 1999 (Hjelle and Glass 2000).

Drought

One severe drought that affected northern New Mexico in the 1950s shifted the ecotone between ponderosa pine forest (*Pinus ponderosa*) and piñon–juniper woodland (*Pinus edulis* and *Juniperus monosperma*, respectively) extensively (> 2 km in < 5 yrs; Allen and Breshears 1998). The most striking feature of this example is that the ecotone has remained stable since then, even though climatic conditions returned to those prevalent before the drought.

The importance of extreme events is not yet acknowledged as widely as climatic mean attributes in biogeography and population ecology. Generally, mean values are easy to access, whereas climate data concerning weather extremes that are linked to ecosystems in proper spatial and temporal resolution are rare.

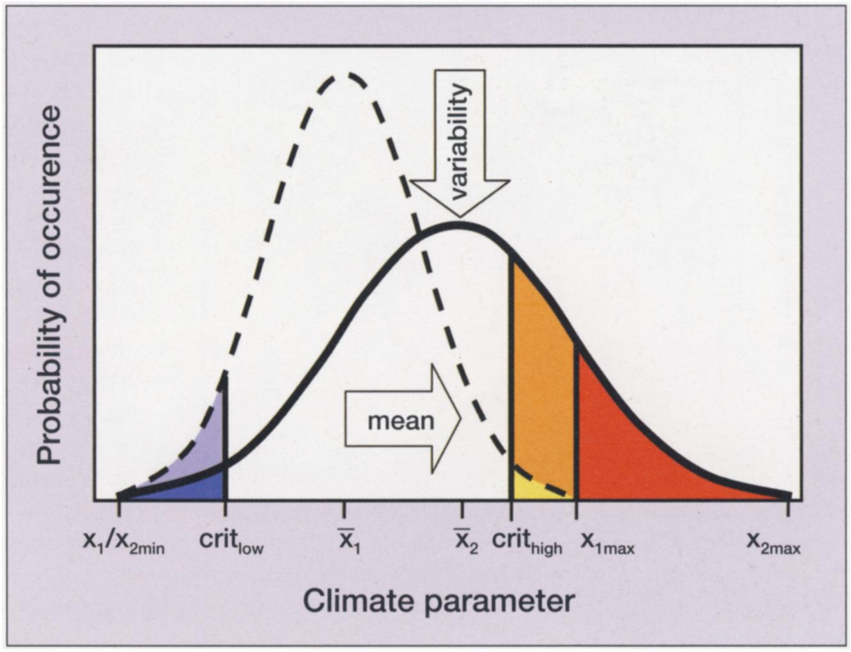

Figure 3. *Expected changes in the probability of occurrence of extreme weather events under climate change for any given climate parameter (eg precipitation, temperature). From scenario A (dotted line; eg today) to scenario B (solid line; eg year 2050), mean value ($\bar{x}_1$ to $\bar{x}_2$) and overall variability (standard deviation or width of the curve) increase. The probability of situations exceeding critical thresholds ($crit_{low}$ and $crit_{high}$) changes dramatically; for example, $crit_{high}$ shifts from including only the yellow area to including the whole orange and red area. Unprecedented extremes occur (red area) as novel maxima are reached (x_{1max} to x_{2max}). On the other hand, current minima become less probable (light blue to dark blue). All alterations stress the increasing significance of extreme events with gradual shifts of climatic parameters. Note that the overall pattern will prevail, even if other probability distributions are appropriate. Adapted from Meehl* et al. *(2000).*

Weather extremes in climate change

The current scientific debate surrounding climate change (IPCC 2001) focuses on which climatic parameters are changing and how these will vary on regional spatial scales. With respect to shifts in intensity and frequency of extreme events, three types of evidence dominate scientific activity: observations, models, and theoretical considerations.

Observation of intensifying weather extremes based on time series seems to be the most straightforward approach to monitoring changes. However, several difficulties arise because extreme-value statistics in time series require historical datasets with reliable and precise measurements of extremes. Currently, weather stations are not evenly distributed across the globe, and only a few countries fulfill the conditions necessary to carry out extreme-value statistics for their biogeographical region (Easterling *et al.* 2000a). Standard routines to detect outliers may even eliminate very rare, real events, such as the 2003 heat wave in Central Europe, from climatological time series (Schar *et al.* 2004). Nevertheless, there are numerous studies observing changes in extremes: for instance, increased frequency of heavy precipitation events since 1920 in the US (Karl *et al.* 1995; Kunkel 2003), centennial increases in frequency of heavy precipitation events (10%–30%) in Switzerland (Schmidli and Frei 2005), and increases in duration of extremely wet conditions in winter (Schonwiese *et al.* 2003) and of unusually dry periods in summer (Beck *et al.* 2001) in Europe. The European heat wave of 2003 has convincingly been associated with anthropogenically forced global warming (Schar and Jendritzky 2004). Record-breaking temperature events are reported to be on the increase worldwide (Benestad 2004). With regard to hurricanes, there is considerable debate in the climatological community as to whether climate change will lead to a change in intensity of these events (Emanuel 2005).

Predictive modeling is a powerful tool for identifying upcoming developments. Some 15 years ago, the General Circulation Model (GCM) approach predicted an increase in the variability of precipitation events (eg Mearns *et al.* 1990). Unfortunately, GCMs do not provide specific information about regional changes of extreme events, and modeling at ecologically meaningful spatial scales is just beginning. As regional climatic models are developed, changes in the frequency and intensity of extreme weather events are predicted for several parts of the world. They predict substantial regional differences, and even shifts in opposite directions and diverging developments in, for example, frequency of heavy precipitation events in North America (Easterling *et al.* 2000b; Milly *et al.* 2005), frequency and duration of heat waves and heavy rainfall events during summer in southern Europe, and frequency and duration of heat waves during winter in North Africa (Sanchez *et al.* 2004). Studies generally predict increasing frequency of heavy rainfall for Central Europe (Christensen and Christensen 2003), the UK, and Bangladesh (Palmer and

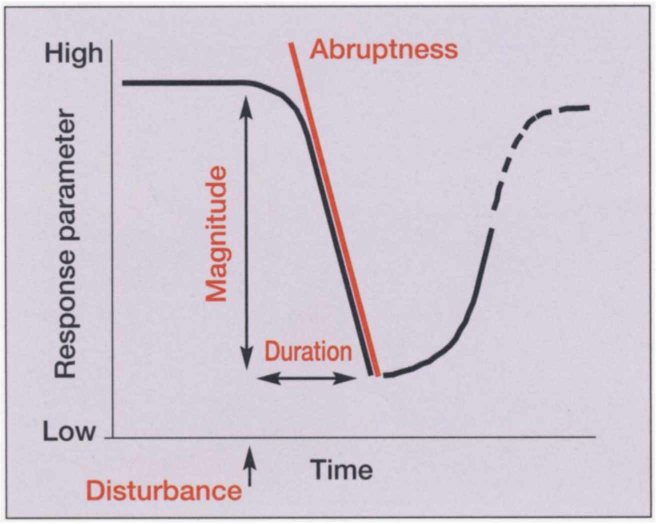

Figure 4. *Test of a discrete event: abruptness. The abruptness of an event is a function of magnitude over duration. Note that magnitude of the disturbance event refers to its effect on the parameter studied, such as destruction of biomass. Duration of the disturbance event is to be perceived relative to the life span of the organisms studied (White and Jentsch 2001).*

Raisanen 2002), as well as increasing intensity (Raisanen and Joelsson 2001). Enhanced summer droughts are expected for southern Europe and central North America (Seneviratne *et al.* 2002). The variability of summer temperatures in Central Europe may in fact increase by more than 100% (Schar *et al.* 2004).

The theoretical line of evidence is independent of the problems associated with adequate datasets and meaningful spatial scales. Considering a given probability distribution of occurrence for any climatic parameter, changes in mean values as well as increased variance in amplitude will inevitably lead to more frequent and more intense extreme events at one tail of the distribution (Meehl *et al.* 2000; Figure 3). It should be noted that extremes at the minimum of a given parameter will virtually disappear when mean values increase, whereas historically unprecedented intensities arise at the maximum, so that biota will face novel events and habitat conditions. Statistically, evidence of changing mean values is easier to handle than evidence of intensifying extreme values. Many examples of shifting means are available (IPCC 2001). For the standard Gaussian distribution, an increase in the mean by one standard deviation makes an event with a former probability of occurrence of 1% 9.2 times more probable. A doubling of CO_2 is likely to produce changes of greater than one standard deviation in both precipitation and temperature. Intuitively, an increase in rainfall severity, for example, is probable. This is because a warmer atmosphere contains more latent energy (Kunkel 2003). For almost normally distributed parameters – such as temperature – changes in variance might not be climatically relevant, although statistically sound. In contrast, for clearly non-normally distributed parameters – such as precipitation – changes in variance are predicted to increase significantly (IPCC 2001). Overall, evidence suggests that weather extremes are changing.

Terrestrial ecosystems across the globe are adapted to regional climate dynamics. Shifts in vegetation or ecosystems across large spatial and long temporal scales represent gradual changes in climate. In contrast, instead of only transiently affecting the dynamics of ecosystems at the local scale, we propose that discrete events of novel extreme magnitude and frequency can have long-term ecological significance and drive ecosystems beyond stability and resilience.

Accordingly, the debate about climate change has expanded from an analysis of trends to an interest in extreme events. Thus, we now aim to clarify the "event" character of climatic processes and to quantify their "extremeness".

■ Event versus trend, extreme versus average

For decades, ecology has regarded mean values as powerful indicators of climatic site conditions. Short-term deviations were regarded as extraordinary and non-representative measurements. However, there is a smooth transition between discrete events and gradual trends of shifting means; any clear-cut distinction depends on the temporal resolution. Changes in annual precipitation are generally perceived as shifting means or trends, whereas changes in the duration of the longest drought period represent shifts in the intensity of extreme events.

For ecological investigations, we argue that a discrete event is distinguished from a continuous process by its abruptness, no matter whether the event is recurrent, expected, or normal (White and Jentsch 2001). Abruptness of an event is a function of magnitude over duration (Figure 4), which is best described relative to the life cycles of the organisms of interest or to the successional speed of the ecosystems in which they occur (Jentsch 2006). Using such relative currency to express abruptness allows comparison among organisms with different life spans. Using it to express frequency allows comparison among ecosystems of differing productivity.

The distinction between "event" and "trend" is therefore an issue of hierarchy. Event-based ecological research deals with several orders of magnitude in the life spans of response communities. The life cycles of individuals are nested within the dynamics of populations. Likewise, climatic events are nested within climatic trends, from annual to decadal or even millenial scales.

Extremeness of events can be determined by statistical extremity with respect to a historical reference period (eg extraordinary deviation from the median of probability distributions; Gumbel 1958; Reiss and Thomas 1997). Extremeness can be chosen in terms of a probable recurrence interval. The 100-year event – sometimes referred to as the 1% event, since there is a 1% chance of occurrence in any given year – is widely used in disciplines as

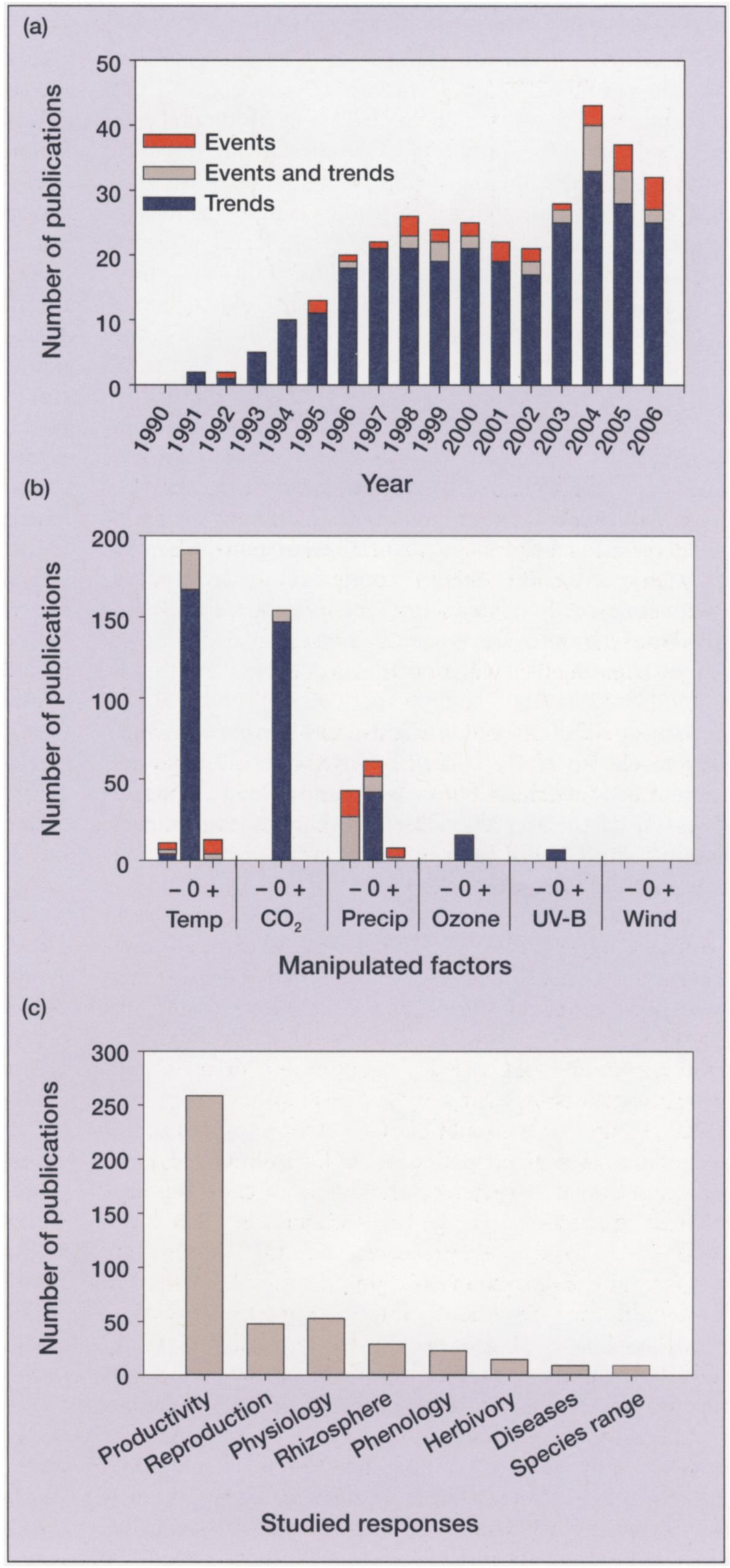

***Figure 5.** Trend and event research in climate-change experiments. (a) Temporal development of the number of publications on trends versus events. (b) Manipulated climate factors, distinguished by mean value (0), low extreme value (–), and high extreme value (+) of the observed distribution tail (eg precipitation with drought and heavy rain). (c) Studied effects. Note that the term "growth" includes biomass gain, cover, and other measures of above-ground biomass production. "Rhizosphere" includes both root and mycorrhizal measures. All diagrams are based on analysis of 364 peer-reviewed papers. See text for information about literature search and distinction between trend and event.*

disparate as hydrology and economics. However, an adequate time scale for analysis is especially crucial. Statistical extremes over longer time scales, not affecting single organisms or populations but possibly altering species evolution, may also be influential (Overpeck *et al.* 2003). We propose choosing the temporal resolution of the data in relation to the organisms studied.

In predicting extreme events in future climatic scenarios, we are faced with two different qualities of extremeness: (1) an increase in the probability of occurrence of a maximum or minimum of a given climatic parameter (frequency of event), such as a particular temperature, and (2) a novel crossing of the observed minimum or maximum of a climatic parameter (magnitude of event), such as length of drought period. In this context, the extremeness of an event is described independently of its effects on organisms. Taking together extreme value theory and discreteness of events, we are able to distinguish between shifts in mean trends and alterations in the occurrence, frequency, and magnitude of extreme events. However, further problems arise when we consider ecosystems with numerous communities and organisms displaying a diverse array of life spans, differences between appropriate time scales for individuals and populations, the rareness of adequate datasets, especially for tropical countries (Easterling *et al.* 2000b), and statistical extremes that change considerably over time (Luterbacher *et al.* 2004). Nevertheless, the use of rough estimates to study the ecological effects of extreme events experimentally is more promising than waiting for confirmed regional forecasts, which will soon become outdated.

Extreme events in experimental climate-change research

Experiments enable us to perform analyses of causation, whereas adequate controls are often missing in field observations of naturally occurring extreme weather events. In addition, experimental simulations are a useful tool to test the effects of forecasted extremes that have not yet occurred. Here, we focus on controlled field experiments in ecological climate-change research.

We conducted a literature study, searching the ISI Web of Science for ["climate change" or "climatic change"] and "experiment*" and ["vegetation" or "plant*"]. In December 2006, this search yielded about 2300 published papers. From these, only original studies on the response of plants to experimentally manipulated climate parameters were selected, giving 364 studies. These were separated into research focusing on "events" and research focusing on shifts in mean "trends". The results show that experimental climate-change research has existed since the 1990s (Figure 5a). Within this field, event-focused research has increased and, in 2006, accounted for one-fifth of the experimental climate-change studies published. Generally, trend-based climate-change research has focused primarily on elevated temperature and enhanced CO_2 (Figure 5b) and produced crucial knowledge about the effects on biomass production (Figure 5c), which is one of the most essential ecosystem processes. However, only a few studies reported on other response parameters or compared both events and trends, thus allowing us to rate effects against each other.

One experiment comparing effects of events and trends manipulated rainfall timing (periodicity) and rainfall amount in a tall-grass prairie in Kansas (for experimental design, see Fay *et al.* [2000]). Redistribution of the total rainfall amount into fewer but more intense discrete events resulted in a reduction of aboveground net primary productivity (ANPP) and increased root to shoot ratios. Such responses are found to be highly species specific, leading to changes in competitive abilities. Increased variability in rainfall generated stronger reactions than a reduction of 30% in rainfall quantity without alteration of the timing of rainfall inputs (Fay *et al.* 2003). Interestingly, ANPP is not related to mean soil water content, but to temporal variability in soil water (Knapp *et al.* 2002).

Another field experiment carried out in four European countries (Beier *et al.* 2004) tested the effects of extreme drought events and increased nighttime temperature as a trend in heath systems. Here, drought decreases aboveground biomass and flowering, whereas the effect of warming depends on overall soil moisture status, leading to enhanced productivity in more humid sites (ie UK, Netherlands) and to reduced productivity in drier sites (ie Spain; Penuelas *et al.* 2004).

Overall, event-based experiments have identified ecosystem responses capable of changing structure and composition of various communities (Table 1). Therefore, interferences of ecosystem functions and services are to be expected. Obviously, timing of events has crucial implications; periods of accelerated growth and reproduction are most susceptible (eg Koc 2001).

Research needs and experimental plan

Understanding the factors governing the response of biodiversity to extreme weather events will increase our abil-

Table 1. Key findings of experiments manipulating weather events[1]

Observed effect	*Manipulation*	*Sources*
Reduced aboveground productivity	Drought	Borghetti *et al.* 1998; Gordon *et al.* 1999; Sternberg *et al.* 1999; Grime *et al.* 2000; Koc 2001; Llorens *et al.* 2002; Filella *et al.* 2004; Gorissen *et al.* 2004; Llorens *et al.* 2004; Penuelas *et al.* 2004b; Kahmen *et al.* 2005; Le Roux *et al.* 2005; Erice *et al.* 2006
	Rain and drought[2]	Fay *et al.* 2000; Fay *et al.* 2002; Knapp *et al.* 2002; Fay *et al.* 2003
	Frost	Weih and Karlsson 2002; Martin and Ogden 2005; Oksanen *et al.* 2005
	Heat	Marchand *et al.* 2005; Musil *et al.* 2005; Marchand *et al.* 2006
	Drought and heat	Roden and Ball 1996; Ferris *et al.* 1998; Hamerlynck *et al.* 2000; Shah and Paulsen 2003; Xu and Zhou 2005
Reduced belowground productivity	Drought	BassiriRad and Caldwell 1992; Beier *et al.* 1995; Asseng *et al.* 1998
	Rain	Martin and Ogden 2005
Altered species compensation	Drought	Grime *et al.* 2000; Buckland *et al.* 2001; Koc 2001; Lloret *et al.* 2004; Schwinning *et al.* 2005
	Rain	Sternberg *et al.* 1999; Gillespie and Loik 2004
	Rain and drought	Knapp *et al.* 2002; Bates *et al.* 2005; English *et al.* 2005
	Heat	White *et al.* 2000, 2001
Reduced reproductive success	Drought	Fox *et al.* 1999; Gordon *et al.* 1999; Lloret *et al.* 2004; Morecroft *et al.* 2004; Penuelas *et al.* 2004b; Llorens and Penuelas 2005; Lloret *et al.* 2005; Schwinning *et al.* 2005
	Rain	Germaine and McPherson 1998; de Luis *et al.* 2005
	Drought and heat	Shah and Paulsen 2003
	Heat	Liu *et al.* 2006
Altered phenology	Drought	Llorens and Penuelas 2005
	Rain and drought	Fay *et al.* 2000; Penuelas *et al.* 2004a

[1]Table is based on 46 peer-reviewed publications. Bibliography is available in WebPanel 1.
[2]Rain and drought comprise manipulations of rainfall variability with intensified rainfall events as well as increased drought intensities.

Figure 6. *Event-focused climate-change experiment (EVENT) testing the effects of drought, heavy rain, and altered freeze–thaw cycles on biodiversity at Bayreuth University, Germany. Location is 49°55'19" N, 11°34'55" E; mean annual temperature = 7.8°C; mean annual precipitation = 709 mm. Soil consists of drained sandy loam, homogenized prior to planting in spring 2005. C/N ratio = 15.4–20.2; pH = 5.5.*

ity to predict the future behavior of ecosystems. This is one of the next great challenges in the life and environmental sciences. So far, gradual climatic trends such as global warming and increasing levels of CO_2 have been studied in much more detail than have alterations in sudden events. Thus, there is a lack of knowledge on how extreme weather events affect biodiversity and ecosystem functioning. Here, we discuss emerging research challenges. Aside from general frontiers in ecology, experimental research on extreme weather events needs to address five additional issues: (1) timing of events, (2) ecological memory, induced tolerance, and time lags in response, (3) hidden players (sensu Thompson *et al.* 2001), (4) quality of local climate data, including past records and future model predictions, and (5) a historical control. After discussing these emerging issues, we lay out the experimental design of a new event-focused climate-change experiment in Bayreuth, Germany, as an illustration of how we can meet some of the challenges.

Appropriate timing of manipulations is a sensitive experimental issue, which needs to take into account various underlying ecological rhythms: (1) interaction with different stages in the development of natural or artificial plant communities, including critical thresholds in ages of individuals and in the process of community assembly; (2) interactions with natural event regimes or with critical thresholds of gradual, sometimes hidden trends in environmental parameters; and (3) interactions with periodic pulses of productivity, such as yearly seasons or "bad and good years". These long-term dynamics may produce resource reserves or buffers, which in turn modify the short-term performance of species in response to extreme events. Experiments have to either exclude or explicitly tackle some of this variation in order to test for particular effects. A simple experiment would profit from equally-aged artificial communities and a temporal design of manipulations specified by annual season.

The concept of "ecological memory" and the idea of "disturbance-induced community tolerance" point to the crucial role of history in climate-change experiments. To date, there is no clear understanding of the speed or time lag with which biotic communities of different taxa can evolve or respond when subjected to sudden environmental change. Thus, an experimental design of extreme weather events would profit from manipulations that are recurrent and abrupt within the life spans of responding organisms. Data acquisition should be capable of capturing metapopulation dynamics in time.

Hidden players (sensu Thompson *et al.* 2001), such as microbes, fungi, and soil invertebrates, undoubtedly contribute to community performance in response to extreme weather events and to the complexity of system functioning at different scales. Thus, an experimental study would profit from interdisciplinary cooperation and from using aggregated information, such as the construct of functional groups across guilds, based on traits such as nitrogen fixation. This could also reveal the relative importance of redundancy versus complementarity for functional stability under new extremes.

For sound manipulation of extreme climatic events in the field, local climate data, including past weather

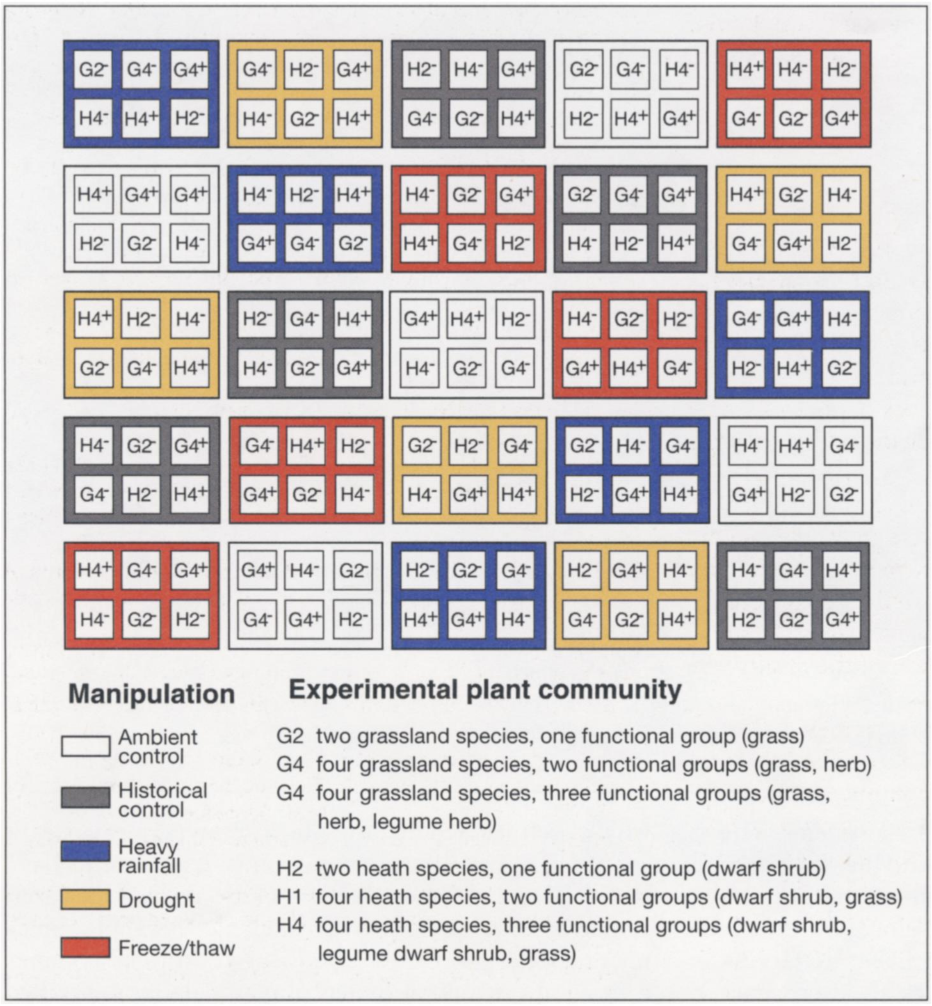

Figure 7. *Design of the EVENT experiment. The manipulations consist of recurrent 100-year extreme events: (1) drought, (2) heavy rain, (3) consecutive freeze–thaw cycles, (4) ambient control, (5) historical control. The experimental plant communities represent different levels of functional and species diversity. n = 5 for each factorial combination, summing up to 150 plots of 2 m x 2 m.*

records and future model predictions, are needed. Historical analyses can be carried out by means of extreme value theory; future climatic projections should be calculated according to one of the approved global-change scenarios. A delicate problem may be imposed by natural extreme weather conditions during the course of the study. We therefore suggest generating historical mean climatic conditions as an additional control to ambient conditions. This second control allows for conclusive results in case of extraordinary weather conditions during the years of experimental manipulation, such as the extreme European precipitation events in summer 2002, the extreme drought in summer 2003, or the extreme heat wave in summer 2006.

This list of research needs is by no means comprehensive and could be supplemented by many other experiments, such as, for example, the comparison of effects on artificially versus naturally grown communities, on species-rich versus species-poor communities, on different ecosystems or systems in different climatic zones (to date, very few studies have been conducted in the tropics), or on a range of other parameters.

We have recently initiated a new two-factorial field experiment in central Europe (EVENT), designed to test the effects of extreme weather events and plant diversity on performance of individual plant species in experimental communities (Figure 6 and 7). In the EVENT experiment, manipulations consist of recurrent 100-year extreme events, namely drought, heavy rain, and consecutive freeze–thaw cycles. We use rain-out shelters, portable irrigation systems, and buried heating wires. To avoid confounding effects of natural extreme events during the course of the experiment, we use two kinds of controls: ambient and historically-based. The first control represents ambient conditions, the second represents the mean weekly amount of precipitation over the past 30 years. The historical control is realized using rain-out shelters, in which precipitation is artificially added. For each parameter, Gumbel I distributions were fitted to the annual extremes and 100-year recurrence events were calculated (Gumbel 1958). Additional manipulations of future climatic projections are based on data developed by the Max Planck Institute for Meteorology, according to a global change scenario (IPPC 2001). The experimental plant communities (n = 5 for each factorial combination, summing up to 150 plots of 2 m x 2 m) consist of planted, equally-aged grassland and heath communities, representing different species richness levels (two or four species), different species compositions (six species combinations taken from a pool of 10 common species in each manipulation), different growth forms (perennial forbs, perennial grasses, or dwarf shrubs), and different abilities to fix atmospheric nitrogen (non-legume or legume). Species used are widespread in Central Europe and are of fundamental importance for agriculture and nature conservation (*Agrostis stolonifera*, *Arrhenatherum elatius*, *Calluna vulgaris*, *Deschampsia flexuosa*, *Genista tinctoria*, *Geranium pratense*, *Holcus lanatus*, *Lotus corniculatus*, *Plantago lanceolata*, and *Vaccinium myrtillus*). Current research activities stem from disciplines as disparate as community ecology, population biology, plant physiology, root ecology, invasion biology, soil fauna, microbiology, genomics, gas exchange analysis, hydrology, and micrometeorology.

Conclusions

We urgently need to advance research on extreme events and their consequences by collecting evidence on their effects from long-term observations and experimental studies in various ecosystems and on various time and magnitude scales. So far, the conceptual distinction between changing mean trends and modified event regimes has not been adequately acknowledged. The characteristics of a process can only be defined in relation to the organisms or systems being studied, and the extremeness only by statistics linked to the occurrences of the process itself. It is essential to take into account information on historical or projected extremes of simulated events (ie relative magnitude compared to mean conditions) though this is lacking in many event-based experiments. Otherwise, the predictive power of the results will be limited.

Event-based research on weather extremes will contribute substantially to the debate as to whether local weather extremes are relevant to the public and political community at large spatial scales and with long-term ecological impacts. Collaborative scientific efforts will contribute to our understanding of the role of biodiversity in the performance and resilience of vital ecosystem processes, goods, and services in the face of extreme climatic events.

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