

## Investigating the consequences of climate change under different land-use regimes: a novel experimental infrastructure

MARTIN SCHÄDLER,<sup>1,2,†</sup> FRANCOIS BUSCOT,<sup>1,2,3</sup> STEFAN KLOTZ,<sup>1,2</sup> THOMAS REITZ,<sup>1,3</sup> WALTER DURKA,<sup>1,2</sup>  
 JAN BUMBERGER,<sup>4</sup> INES MERBACH,<sup>1</sup> STEFAN G. MICHALSKI,<sup>1,2</sup> KONRAD KIRSCH,<sup>1</sup> PAUL REMMLER,<sup>2,4</sup>  
 ELKE SCHULZ,<sup>3</sup> AND HARALD AUGE<sup>1,2</sup>

<sup>1</sup>Department of Community Ecology, Helmholtz-Centre for Environmental Research – UFZ, Theodor-Lieser-Street 4, Halle 06120 Germany

<sup>2</sup>German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Deutscher Platz 5e, Leipzig 04103 Germany

<sup>3</sup>Department of Soil Ecology, Helmholtz-Centre for Environmental Research – UFZ, Theodor-Lieser-Street 4, Halle 06120 Germany

<sup>4</sup>Department of Monitoring and Exploration Technologies, Helmholtz-Centre for Environmental Research – UFZ, Permoserstraße 15, Leipzig 04318 Germany

**Citation:** Schädler, M., F. Buscot, S. Klotz, T. Reitz, W. Durka, J. Bumberger, I. Merbach, S. G. Michalski, K. Kirsch, P. Remmler, E. Schulz, and H. Auge. 2019. Investigating the consequences of climate change under different land-use regimes: a novel experimental infrastructure. *Ecosphere* 10(3):e02635. 10.1002/ecs2.2635

**Abstract.** Climate change and land-use change are considered as the most important threats to ecosystems. Both factors can be expected to have interacting influences on ecosystem functions directly and indirectly via changes in biodiversity. Knowledge about these interactions is limited due to a lack of experiments which investigate climate change effects under different land-use scenarios. Among the processes involved in ecosystem responses to global change, in particular, those occurring in soils or related to biotic interactions and microevolution were underinvestigated in previous experiments. Examinations of these relationships require spatial and temporal scales which go beyond those realized in the majority of ecological field experiments. We introduce a new research facility, the Global Change Experimental Facility (GCEF), which was designed to investigate the consequences of a future climate scenario for ecosystem functioning in different land-use types on large field plots (400 m<sup>2</sup>). Climate manipulation is based on projections for the period of 2070–2100 with an increased temperature and a changed precipitation pattern consisting of reduced precipitation in summer and increased precipitation in spring and autumn. We subject five different land-use types (two farming systems, three grasslands), differing in land-use intensity, to ambient and future climatic conditions. The use of automated roofs and side panels to passively increase night temperatures results in an average increase in daily mean temperature by 0.55°C accompanied by a stronger increase in minimum temperatures (up to 1.14°C in average) with longer frost-free periods and an increase in growing degree days by 5.2%. The combined use of mobile roofs and irrigation systems allows the reduction (in summer by ~20%) and increase in rainfall (in spring and autumn by ~10%) according to future scenarios superimposed on the ambient variation in precipitation. The large plot size and the technical configuration allow the establishment of realistic land-use scenarios and long-term observations of responses of ecosystem functions and community dynamics on relevant temporal and spatial scales. Thus, the GCEF provides a well-suited platform for the interdisciplinary research on the consequences of climate change under different land-use scenarios.

**Key words:** agroecosystems; climate change; crop fields; Global Change Experimental Facility (GCEF); grasslands; land-use change; microevolution; rain-out shelter; soil processes; species interactions.

**Received** 5 November 2018; revised 23 January 2019; accepted 25 January 2019. Corresponding Editor: Laureano A. Gherardi.

**Copyright:** © 2019 The Authors. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

† **E-mail:** martin.schaedler@ufz.de

## INTRODUCTION

Climate change and land-use change are major drivers of ecosystem change and affect the ability of ecosystems to deliver essential services to humankind. This global change is accompanied by a loss of biodiversity at different scales (Pereira et al. 2012). Even if intensive land use is currently the major threat for species diversity (Maxwell et al. 2016), it is expected that the climate change-induced loss of species in the future will be substantial (Bellard et al. 2012) and exceed the effects of habitat destruction (Leadley et al. 2010). The importance of diversity and composition of species assemblages for ecological functions has been an area of intense research for decades (Tilman 1999, Hooper et al. 2005, Brose and Hillebrand 2016). The majority of studies have consistently shown that the loss of biodiversity alters the functioning of ecosystems and limits their ability to provide services to humanity (Cardinale et al. 2012, Grimm et al. 2013, Lefcheck et al. 2015). Thus, a significant part of global change effects on ecosystem functions might be attributed to changes in the earth's biodiversity (Mooney et al. 2009, Hautier et al. 2015, Maxwell et al. 2016, Scheffers et al. 2016).

The impacts of climate change can be expected to differ among ecosystems (Flombaum et al. 2017, Gruner et al. 2017) and hence among land-use systems. Franklin et al. (2016) pointed out that the rate of land-use change increased strongly in recent decades with important effects on ecosystems which may mask or modulate the effects of climatic changes. Accordingly, effects of land use on ecosystems have been found to override climate change effects in some cases or show interactive effects in others (Thompson et al. 2011, Benot et al. 2014). Especially in agroecosystems, biodiversity is directly (e.g., by seeding or planting and agrochemicals) and indirectly controlled by increasing land management intensity, suggesting a varying relative importance of other global change factors. Climate and land-use changes can thus be expected to interactively influence biodiversity (Titeux et al. 2016, 2017, Urban et al. 2016). For instance, drought effects on grassland vegetation composition have been found to be dependent on land-use intensity (Vogel et al. 2012, Stampfli et al. 2018). Examining the effects of land use and climate change in

isolation will therefore lead to inaccurate results (De Chazal and Rounsevell 2009). However, both global change drivers have been usually investigated separately and there is a strong need for studies which account for their interactions (De Chazal and Rounsevell 2009, Sirami et al. 2017) and experimentally manipulate climate in different environments (Urban et al. 2016). Moreover, biodiversity effects of land-use change are predominantly investigated in terms of habitat loss while the impact of land-use conversions and differences in management intensity received much less attention (De Chazal and Rounsevell 2009). As a conceptual framework for our experiment, we hypothesize that climate change and land-use change importantly affect ecosystem functions and services by their interacting influence on biodiversity above- and belowground.

Previous climate change experiments, especially those investigating the effects of changed precipitation, were strongly biased toward grasslands, whereas other systems such as arable fields have been underrepresented (Beier et al. 2012). Croplands cover a larger part of the total land area in Europe than grasslands (European Commission 2012), but there is an ongoing conversion of cropland to grassland as well as an increase in land abandonment and extensification (Department for Environment, Food and Rural Affairs 2008, Plieninger et al. 2016) in many parts of Europe. On the other hand, certain areas face an ongoing trend toward intensification of agricultural land use (van der Sluis et al. 2016). Such changes in land-use types and land-use intensity are known to have effects on biodiversity as well as ecosystem functions and services (Uchida and Ushimaru 2014, Gosling et al. 2017). Increasingly acknowledged in this context are soil functions related to nutrient and water cycling, storage of carbon, and other processes. Until now, however, the complex interrelations between soil processes and climate change are only poorly understood, even though there is consensus that soils are strongly affected by changes in land-use type and management intensity (Chang et al. 2016, Smith et al. 2016). Land use may further modify these effects since the conversion of grasslands to arable fields (French et al. 2017) as well as different management practices such as residue management, tillage, fertilization, and crop rotations are important

mediators of soil biodiversity (Oehl et al. 2010, Schnoor et al. 2011, Tsiafouli et al. 2015) and soil functions such as carbon storage (Dendooven et al. 2012, Chang et al. 2016). However, the interaction with soil biota may strongly affect the plant's ability to cope with climate change phenomena such as drought (Mariotte et al. 2017), thereby creating complex biological feedback effects of both global change drivers on ecosystems. Comparative assessments of climatic effects on soil systems of different land-use types are scarce making predictions on the effects of climate change on soil processes difficult. Thus, experimental long-term studies with different land-use types are urgently needed (Lu et al. 2013, Bradford et al. 2016).

Similarly, species interactions aboveground are not only affected by global change but are also important for the ecosystem responses to global change factors. Different trophic levels may be differently affected by environmental change (O'Connor 2009, Rasmann et al. 2014) with conceivable consequences for food web structure. Climatic factors may therefore determine the relative strength of bottom-up vs. top-down control of plant communities (van de Koppel et al. 1996, Kuijper and Bakker 2005). These relationships can be directly linked to climate change effects on different land-use types since such trophic interactions and ecological functions may be integral part of certain forms of land management (Crowder et al. 2010, Birkhofer et al. 2011). For example, under warming, the biological pest control by predators has been shown to be more efficient in organic compared to conventional fields (Murrell and Barton 2017). In turn, plant communities may show opposing responses to warming depending on whether herbivores are present or not (Post and Pedersen 2008, Mooney et al. 2009, Kaarlejarvi et al. 2017), and ecosystem responses to altered precipitation regimes may be reversed on the long run due to interactions within and between trophic levels (Suttle et al. 2007). Therefore, deeper insights into the role of species interactions are fundamental for our understanding of interacting effects of land use and climate change on biodiversity and ecosystems (Urban et al. 2016).

Concepts and models on global change effects on ecosystems often consider species as fixed entities. However, genetic variation within

species can allow evolutionary changes in response to changing environmental conditions and there is increasing evidence that these changes can rapidly occur (Hoffmann and Sgro 2011, Franks et al. 2014) and at time scales relevant for ecological dynamics (Wieneke et al. 2004, Michalski et al. 2010, Kuester et al. 2016, Völler et al. 2017). A recent review of plant responses to climate change revealed that most studies did find phenotypic and/or genetic changes (Franks et al. 2014). However, only a relatively low number of studies tested whether changes were actually adaptive. Thus, the evidence that plants respond to climate change by adaptive evolutionary changes is still limited (Franks et al. 2007, Avolio and Smith 2013). Rapid evolutionary changes further play a role in climate change-driven range expansions by promoting the ability of species to spread and to adapt to novel environments (Lustenhouwer et al. 2018). An important consequence of such microevolutionary responses is that traits such as growth, development, and carbon accumulation of plants as well as the long-term dynamics of populations might fundamentally deviate from what would be expected from scenarios that ignore selection (Schmid et al. 1996, Ward et al. 2000). The opportunities for adaptive evolution, however, will be reduced if rapid environmental change leads to reduced population sizes and, hence, genetic bottlenecks (Lynch and Lande 1993). However, even if genetic variation is present, adaptive evolution may be constrained by antagonistic trait correlations, that is, if selection favors high values of two traits that are negatively correlated (Etterson and Shaw 2001). The incorporation of an evolutionary perspective in climate change research and an understanding of the ability of species to respond to global change are therefore urgently needed (Bailey 2014, Urban et al. 2016).

Given the multitude of mechanisms by which climate change may affect ecosystems, studies on the ecosystem level are necessary for a better understanding of the potential consequences of climate change. Ecosystem-level studies of course require a larger plot size than in many of the previous experiments. First, investigation of many of the critical processes such as species interactions, changes in species interactions, soil processes, and microevolutionary responses requires larger

spatial and temporal scales. Second, destructive sampling of above- and belowground material is necessary for a number of investigations (e.g., for the assessment of soil functions) which introduces disturbances into the system and interferences with other measurements on smaller plots. Third, owing to such destructive sampling, plot size constrains the life expectancy of an experiment (Ehlinger et al. 2006). Fourth, additional manipulative experiments may be required to gain a deeper understanding of the mechanisms behind ecosystem responses. Thus, a larger plot size is needed in order to run such manipulative experiments on small subplots without affecting the remaining plot area. Fifth, large plot size is needed to allow a realistic land management using agricultural machinery or even grazing by livestock.

Manipulative field experiments have been proven to be a suitable and informative approach for the assessment of climate change effects in ecosystems (Beier et al. 2012, Smith et al. 2014). Therefore, our aim was to establish an experimental infrastructure consisting of replicated field plots to assess the ecosystem's response to climate change under different land-use scenarios. Thereby, we will provide a platform for the investigation of interactive effects between land-use types and climatic change on ecosystem functions and services at a level intermediate between laboratory and regional monitoring. The aim of the platform is further to explore the ecological consequences of different strategies of land use in order to assess their sustainability under climate change, to develop and validate models, to deduce indicators, and to steer key processes.

Here, we introduce a novel experimental platform—the Global Change Experimental Facility (GCEF) which allows the investigation of interacting effects of land use and climate change. The GCEF uses mobile roofs and side panels to passively increase temperature and—in combination with an irrigation system—precipitation on large field plots. A unique feature of the GCEF is the incorporation of different realistic land-use scenarios ranging from conventional farming (CF) to low-intensity, species-rich, and genetically diverse pastures. This allows the investigation of the role of biodiversity as mediating factor of global change effects. In the following, we will provide detailed information on the experimental

design, the technical implementation, and the functionality and efficiency with regard to climate manipulation.

## MATERIALS AND METHODS

### *Study area*

The field site is part of the field research station of the Helmholtz-Centre for Environmental Research in Bad Lauchstädt near Halle (Saale), Saxony-Anhalt, Germany (51°22'60 N, 11°50'60 E, 118 m a.s.l.). The site is characterized by a sub-continental climate and prevailing West winds. Mean annual precipitation averages at 489 mm (1896–2013) resp. 525 mm (1993–2013) and mean temperature at 8.9°C (1896–2013) resp. 9.7°C (1993–2013). The soil of the study site is a Haplic Chernozem. This highly fertile soil type is typically developed upon carbonatic loess substrate under summer-dry climatic conditions and characterized by a high content of humus down to a depth of more than 40 cm (Altermann et al. 2005). The water-holding capacity of the soil is high and nearly corresponds to the mean annual precipitation in this area. Detailed information on soil chemistry and soil physical properties of the study site can be found in Altermann et al. (2005). The experimental field site is a former arable field with the last crop in 2011. Construction works started in 2012.

### *General layout*

The GCEF is arranged in a split-plot design with climate (ambient vs. future) as main plot factor and land use as subplot factor. We established 10 main plots with a size of 80 × 24 m and randomly assigned them to one of two climate treatments (ambient vs. future). Every main plot was divided into five subplots (16 × 24 m; Appendix S1: Fig. S1) which were randomly assigned to one of five land-use treatments (conventional farming, organic farming, intensively used meadow, extensively used meadow, and extensively used pasture; see below). This results in a total of 50 subplots with five replicates for every climate × land-use treatment combination (Appendix S2: Fig. S1). All plots are equally aligned according to the cardinal directions. Minimum distance between the main plots is 25 m.

To homogenize soil conditions and weed pressure before the start of the experiment and to test for possible differences in plant growing



conditions between the subplots with regard to the assigned treatments, oat was sown on all subplots in April 2013 and harvested in July 2013 as green plants. We measured aboveground plant dry weight, total carbon, and total nitrogen content of plants per subplot using a Vario EL III C/H/N analyzer (Elementar, Hanau, Germany).

#### *General construction, roofs, and side panels*

All subplots were equipped with a tent-like construction consisting of steel framework elements covering the complete ground area of  $16 \times 24$  m (Fig. 1). Along the eastern and western sides of each subplot, seven steel girders were fixed by individual concrete footings to the ground and carry a gable end roof-like construction. All roof girders are equipped with rain water gutters made of translucent plastic sheet to avoid drip off of rain water. The construction has a total height (gable) of 5.50 m. The headroom has a height of 4.50 allowing the use of common agricultural machines.

The construction consists of five  $4.8 \times 12$  m roof segments per subplot. For the subplots with

future climate, these segments are equipped with translucent plastic tarpaulins (93% polyolefin, 7% laminated polyester, 79% direct light transmission, 71% diffused light transmission; type QLS Abri, Svensson, Kinna/Sweden). These tarpaulins are installed as horizontal folding blinds in all roof segments and are automatically unfolded during roof closing. The western and eastern (24 m long) sides of all future climate subplots are equipped with woven plastic tarpaulins (polyethylene, direct light transmission 85%, diffused light transmission 78%; type SHS Woven Clear B3, Novavert Greven/Germany). These tarpaulins are installed as roller blinds and are automatically unrolled during roof closing.

We decided to mimic any possible microclimatic side effects of the construction (Kreyling et al. 2017) on the subplots with ambient climate as far as possible. For this, we installed the same steel constructions without tarpaulins on the subplots with ambient climate. All neighboring subplots are separated from each other by translucent plastic blinds from a depth of  $\sim 50$  cm below-ground to a mean height of  $\sim 50$  cm above-ground.



Fig. 1. Aerial view of the Global Change Experimental Facility (23 May 2013). Picture was taken when oat was grown on all subplots to homogenize soil conditions before the implementation of the treatments. Picture: Tricklabor/Service Drohne.

A rain water reservoir (70 × 20 m, 3.5 m depth) is used to store the rain water which is collected by the roofs. Before re-irrigation, the collected rain water is filtered through seven 1000 L-pool filters filled with sand and activated charcoal. When needed, the filtered water will be used for watering the plots through an irrigation system which is mounted underneath the roofs of all future climate subplots with 40 irrigation nozzles per subplot.

### *Climate manipulation*

The basis for our future climate scenario is projections based on different dynamic regional climate models for the period of 2070–2100 summarized by the regional climate atlas of Germany ([www.regionaler-klimaatlas.de](http://www.regionaler-klimaatlas.de)), which shows how climate change will affect different regions in Germany during the next decades. As guideline for our climate treatment, we used 12 climate simulations under four different emission scenarios with three established regional climate models: COSMO-CLM (Rockel et al. 2008), REMO (Jacob and Podzun 1997), and RCAO (Döscher et al. 2002). Even if these different simulations produce a variety of projections for future climate, there is also a certain consensus regarding some general trends in Central Germany. While the mean temperature is projected to increase over all seasons of the year by about 2°C, the amount of precipitation is projected to change depending on the season with a strong decrease in summer and a slight increase during the rest of the year. However, the magnitude of these projected changes may vary substantially and there is no climate scenario which is more likely than the others. We therefore decided to use the mean values of projections of climate change across the different climate simulations as guideline for our experiment (state December 2013). This yielded a mean projection of precipitation increase of ~10% in spring (March–May) and autumn (September–November) but a decrease of ~20% in summer (June–August).

*Temperature treatment.*—The future increase in daily mean temperatures is often interpreted as a result of increased daily minimum temperatures due to stronger cloudiness and higher greenhouse gas emissions (IPCC 2014). The projected increase in temperature is predicted to be associated with a distinct asymmetry between day

time and night time warming (Harvey 1995, Davy et al. 2017). Several analyses indicate that this narrowing of the daily temperature range is recently continuing in most parts of the world (Easterling et al. 1997, Donat and Alexander 2012).

Passive night time warming is a standard method in climate change experiments and bases on the principle of retaining the higher daytime temperature to increase night temperature (Beier et al. 2004). This is usually done by covering the plots with curtains during the night. This method is considered as relatively inexpensive and associated with minimal disturbances (Aronson and McNulty 2009). In the GCEF, roof segments and the roller blinds at the western and eastern sides of the subplots are automatically operated and close every day at sunset and open at sunrise. At high winds (>7 m/s) and during frosts, the tarpaulins are opened and out of operation to avoid damages. Mikkelsen et al. (2008) demonstrated that there is no passive-warming effect at wind speeds exceeding 6 m/s; therefore, this safety function can be expected to have no consequences for the efficiency of temperature manipulation. Further, temperature for roof operation is measured in the height of 5 m, and therefore, the roofs are still active during the first and last ground frost events of each winter (see *Results*).

*Precipitation treatment.*—Since there is no trend toward heavier rain or drought events predicted for our study area in the future, we decided to offset the projected change in the amount of rain according to season against the ambient precipitation pattern. This requires a continuous adjustment of irrigation and/or roof closing on the subplots with future climate. For this, two different procedures are realized. In spring (1 March–31 May) and in autumn (1 September–30 November), we assessed the amount of precipitation on a weekly basis or immediately after heavy rain from the plots with ambient climate. This value is compared to the amount of rainfall in the future climate plots (which might be already reduced due to night closing of the roofs), and collected rain water is added via the irrigation system to the future climate plots to reach 110% of ambient rainfall. During the summer months (1 June–31 August), the procedure is slightly more complex. During this time, if night closing of roofs results in a reduction in

precipitation of more than 20%, rain water is added to reach 80% of ambient precipitation. In case that precipitation in the future climate subplots is still higher than 80% of ambient rainfall, or if rain is forecasted mainly during the day, a rain sensor is switched on to close the roofs also during rainfall beyond the night time. Roofs are automatically opened 15 min after the end of rain. Again, these adjustments are made at least at a weekly basis or after heavy rain events.

#### Land-use types

Our aim was to use a set of land-use types which also differ with regard to management intensity (intensity and frequency of disturbances, applications of agrochemicals). Further, we aimed to realize characteristic and typical land-use scenarios for Central Europe with their full and typical set of management measures. In Europe, cropland is the second most abundant land cover type (after woodlands) comprising nearly a quarter of the total area followed by grasslands (~20%; European Commission 2012). We therefore decided to use these two land-use types with different levels of management intensity in our experiment.

*Conventional farming.*—This land-use system includes a typical regional crop rotation consisting of a sequence of winter rape, winter wheat, and winter barley. Mineral fertilizers, stem stabilizers, and pesticides are applied as usual in conventional agricultural practice (Appendix S3: Table S1). We started with sowing winter rape in August 2013.

*Organic farming.*—According to the EU regulation for organic agriculture (European Union 2007), only physical weed control instead of herbicides and a restricted use of other pesticides are allowed. Application of mineral N-fertilizers which can be used for CF is not allowed. In the GCEF, nitrogen fertilization is done by the inclusion of legumes every three years in the crop cycle. In two out of three years, the crop cycle for organic farming in the GCEF includes winter wheat and winter barley just as for the CF. In the first and fourth year of this bipartite crop sequence, alfalfa and white clover are included in the crop cycle, respectively. Besides the biological nitrogen fixation by legumes, fertilization is exclusively applied as rock phosphate and patent kali (K-Mg-S) in years with legumes. Weed

control is done through soil cultivation and with spring tine harrows.

*Intensively used meadows.*—The species composition of the intensively used meadows follows the official recommendations of the State Research Centre for Agriculture and Horticulture of the local federal state Saxony-Anhalt for temporary drier sites managed by mowing (Zentrum für Acker- und Pflanzenbau 2012). The recommended seed mixture (RG8) contains 10% (w/w) of early-season cultivars of *Lolium perenne*, 10% of mid-season cultivars of *L. perenne*, 50% of “Festulolium” (*Festuca pratensis* × *Lolium multiflorum*), 20% of *Dactylis glomerata*, and 10% of *Poa pratensis*. Sowing quantity was 30 kg/ha. A moderate mineral NPK fertilization is applied every year at the start of the growing season and after the first, second, and third cut (Appendix S3: Table S1). The grassland was sown in autumn 2013 and mown three times in 2014 (mid of spring, early summer, and early autumn). Beginning with 2015, mowing frequency was increased to four times per year (mid of spring, early summer, late summer, and mid of autumn).

*Extensively used meadow and extensively used pasture.*—1. *Species selection.*—We aimed to establish highly species-rich grasslands from the regional species pool to facilitate ecological and genetic reactions to the experimental changed precipitation and temperature regimes. Thus, the species selection for the extensively used meadow (EM) and pasture followed four main criteria:

1. Species selected are typical for mesotrophic and mesophilous to dry meadows and pastures as well as for steppe grasslands of the dry region of Central Germany which are present in Arrhenatherion, Cynosurion, Festucion valesiaca, and Cirsio-Brachypodium communities (Schubert et al. 2009).
2. The species selected cover a broader variety of potential niches with respect to temperature and moisture conditions, as indicated by the respective indicator values (Appendix S4: Table S1).
3. Species selected present all main life and growth forms of grasslands in Germany such as annuals, biennials, and perennial herbs (including legumes and perennial grasses).
4. High species richness was achieved by selection of 56 species (14 grass species, 10



legumes, and 32 other herbs) that are a representative selection of the regional species pool.

Seed sowing densities are given in Appendix S4: Table S1.

2. *Genetic variation within plant populations.*— We aimed to establish genetically highly diverse populations originating from natural source populations. Exceptionally, seed propagated for restoration was used from a local producer of certified regional seeds. As regional adaptation is common among Central-European grassland species (Weissshuhn et al. 2012, Bucharova et al. 2017, Durka et al. 2017), seeds should originate from a regional gene pool. Therefore, seeds were collected in a total of 69 grassland sites, at distances between 6 and 210 km (mean 42 km) from the experimental site. Most sampling sites were located in the region Central German Lowlands comprising seed transfer zone No. 5 and 20 of the German regional seed source system (Bucharova et al. 2018). Only five sites were located in adjacent seed zones. Finally, for each of the 56 species, between 1 and 6 source populations were available (average: 2.8). Species sown at high densities ( $\geq 30$  seeds/m<sup>2</sup>: 3.4 source populations, see Appendix S4: Table S1) were on average collected from more source sites than low-density species ( $\leq 20$  seeds/m<sup>2</sup>: 2.3 source populations).

To assess the genetic diversity within and among source populations and to assess the representation of source sites in GCEF subplots after the establishment phase, we identified anonymous molecular genetic markers (AFLP) in a subset of six species. Analyses showed that source populations were significantly genetically differentiated from each other and that GCEF populations are representing a mixture of available gene pools (A. M. Madaj, S.G. Michalski, and W. Durka, *in preparation*), providing a broad basis for future microevolution in response to experimental treatments.

3. *Management.*— Management of the extensively used grasslands is intended to represent strategies for sustainable grassland management with maintenance of biodiversity. In the EM, mowing takes place two times per year (mid- to late spring and mid of summer). In the establishment phase in 2014, one first mowing was applied to repress establishing arable weeds

(topping). Beginning with 2015, the EM was managed by two cuts every year (mid- to late spring, mid of summer). No further management measures are applied.

Management of the extensively used pasture (EP) was the same like for the EM until the end of 2014. In the mid of summer 2015, the first grazing event was conducted. In 2016, grazing took place two times in early summer and early autumn. Beginning with 2017, sheep are allowed to graze three times per year (early spring, mid- to late spring, and mid of summer). The lower grazing intensity at the beginning of the experiment was applied to allow all grassland species to establish despite selective grazing and trampling pressure. Grazing is conducted as short-time high-intensity grazing events (managed intensive rotational grazing, mob grazing) with a group of ~20 sheep (German black-headed mutton sheep) grazing on each EP-subplot for 24 h. This kind of grazing management is considered to have advantages from the economic (more uniform seasonal forage production and potentially higher forage yield and quality) and ecological point of view (less soil erosion, maintenance of grassland species richness; Launchbaugh et al. 2006) and is recommended for nature conservation purposes (Landesamt für Landwirtschaft, Umwelt und ländliche Räume 2010).

#### *Assessment of initial soil conditions*

In order to assess soil characteristics before implementing the treatments, we performed a grid-cell soil sampling after oat harvesting. The core area (15 × 12 m) of each subplot (see *Climate Measurements*) was divided into nine sub-subplots (5 × 4 m). For each of these sub-subplots, composite soil samples were obtained by pooling 30 soil cores with 12 mm diameter from two soil layers (0–15 cm and 15–30 cm depth). For the deeper soil layers (30–50, 50–100, 100–150, and 150–200 cm), three soil cores (18 mm diameter for the first meter and 8 mm diameter for the second meter) taken at a diagonal transect on each subplot were pooled. Before disassembling the cores into the four depths, the soil cores were used for surveying the thickness of the different soil layers (Chernozem, mixed horizon, loess, and till). For all depths, total amounts of carbon and nitrogen, stable C and N isotopes, carbonate content, and



pH were measured. For the two upper soil layers (0–15 and 15–30 cm), in addition, labile C and N pools as well as available phosphorus were quantified. For the uppermost soil layer, microbial biomass carbon was determined. Total carbon and nitrogen were determined by dry combustion using a Vario EL III C/H/N analyzer (Elementar). Carbonate concentration was determined by conversion into CO<sub>2</sub>, water, and CaCl<sub>2</sub> by 4 mol/L HCl. The liberated amount of carbon dioxide was measured volumetrically with a Scheibler apparatus. Hot water-extractable C and N, which represents the labile C and N pools, were determined from 10 g of air-dried soils according to Schulz (2002). Mineral N fractions, that is, ammonium and nitrate, were extracted with 1 mol/L KCl (1:4 w/v) from 10 g soil by shaking for 1.5 h and measured using a flow injection analyzer (FIAstar 5000; Foss GmbH, Rellingen, Germany). Plant-available P was extracted from fresh soil with double lactate (1:50 w/v, pH: 3.6, 1.5 h) and quantified colorimetrically using the molybdenum blue method (Murphy and Riley 1962). Microbial biomass carbon was estimated using 20 g dry equivalent of field-moist soil from the CO<sub>2</sub> response after addition of 0.8 g of a glucose/talcum mixture (1:1.5 w/w) according to Anderson and Domsch (1978). Bulk soil densities were determined using soil cores (5 cm diameter) from each subplot in the ploughed (20–25 cm) and unploughed (40–45 cm) topsoil according to ISO 17892-2.

### *Climate measurements*

To avoid edge effects, all measurements are restricted to a core area of 15 × 12 m within each subplot, resulting in buffer zones of 2 m to each of the side panels and 4.50 m to the open (gable) sides of the subplots. In this core area, several smaller subunits are devoted to different regular assessments of ecosystem and population responses to the treatments and manipulative experiments.

For the measurement of microclimate parameters and other parameters, a high scalable ad-hoc wireless sensor network has been employed as central component of the experimental platform. This adaptive process-oriented approach can be used for the continuous modification, extension, and improvement of the sensor network itself. It eliminates the circumstance of a complex wiring

and the sensor nodes can, for example, in management measures are taken out easily.

The ultra-low power continuous self-organizing mesh multi-hop network uses bidirectional protocol capability with a 6LoWPAN wireless application, complies the IEEE 802.15.4 communication standard, and operates within the 2.4 GHz band (Götze et al. 2013). All network nodes are time synchronized with each other and there is a local memory on each node for data redundancy, which can hold data for a few days. To enable effective multi-hop data communication in the sensor network, router nodes are mounted on each steel construction for redundancy. The power is supplied to all measuring nodes by means of batteries, only the routers are powered by the local power grid. The high-scaled wireless sensor network consists of about 300 network nodes (including routers) and has been in continuous operation for about three years. The network nodes (AT-ANY2400-1 with Atmega1281V Microcontroller and AT86RF231 receiver; A.N. Solutions GmbH, Dresden, Germany) use sensors (Appendix S5: Table S1) with a digital interface (I2C or RS485) or converted the analog signals with the implemented A/D converter and use a TinyOS operation system. The sensors as well as the network nodes are mounted on tripods on each plot or block. Data from the sensor network are collected with a gateway device and transmitted to a SQL database via a network connection and can be visualized and processed online. The gateway device (works with an embedded Linux system) has been integrated to serve as an embedded logger and access point to data from the sensor network. Dedicated services visualize both the status of the network and the measurement data, which allows the sensor network to be monitored remotely and can be used for control of the GCEF entire system.

## RESULTS

### *Soil conditions*

The study site has a Chernozem topsoil layer (A<sub>xh</sub>) with an average thickness of 47 ± 7 cm, followed by a mixed horizon (e<sub>l</sub>C+A<sub>xh</sub>) of 18 ± 4 cm (means ± standard deviation). The A<sub>xh</sub> horizon is most relevant for plant growth and showed a total variation between 33 and

61 cm depth with one considerable outlier of 81 cm in one subplot. The parent material loess is found at average depths of 65 cm and has a thickness of  $65 \pm 7$  cm. In deeper depths of  $130 \pm 7$  cm, till layers were observed, which were in most cases clearly separated from the loess layer by a thin stone layer. Bulk soil density was  $1.31 \pm 0.11$  g/cm<sup>3</sup> and  $1.33 \pm 0.11$  g/cm<sup>3</sup> in the ploughed (20–25 cm) and unploughed (40–45 cm) topsoil. Soil chemical properties are given in Appendix S6: Table S1.

The oat harvest in summer 2013 before the start of the experimental treatments on all experimental subplots was used to test for possible effects of soil conditions on plant growth with regard to the assigned but not yet implemented treatments. We did not find any significant effects on dry weight (climate:  $F_{1,8} = 1.43$ ,  $P > 0.05$ ; land use:  $F_{4,32} = 1.42$ ,  $P > 0.05$ ; interaction:  $F_{4,32} = 0.53$ ,  $P > 0.05$ ) or moisture content of oat (climate treatment:  $F_{1,8} = 2.86$ ,  $P > 0.05$ ; land use:  $F_{4,32} = 0.57$ ,  $P > 0.05$ ; interaction:  $F_{4,32} = 0.67$ ,  $P > 0.05$ ). The same conclusion can be drawn with regard to nitrogen content (climate:  $F_{1,8} = 0.43$ ,  $P > 0.05$ ; land use:  $F_{4,32} = 1.83$ ,  $P > 0.05$ ; interaction:  $F_{4,32} = 2.23$ ,  $P > 0.05$ ), carbon content (climate:  $F_{1,8} = 0.21$ ,  $P > 0.05$ ; land use:  $F_{4,32} = 0.68$ ,  $P > 0.05$ ; interaction:  $F_{4,32} = 0.94$ ,  $P > 0.05$ ), or C/N-ratio (climate:  $F_{1,8} = 0.48$ ,  $P > 0.05$ ; land use:  $F_{4,32} = 1.40$ ,  $P > 0.05$ ; interaction:  $F_{4,32} = 1.72$ ,  $P > 0.05$ ).

#### Climate treatment

The roofing phase was initiated on 25 February 2015 as well as on 23 March 2016 and terminated on 11 December 2015 as well as on 23 November 2016 after consideration of the respective weather forecasts. Roofs were active 79.2% (2015) and 82.0% of the night time, and interruptions were due to frost (9.3% in 2015 and 8.2% in 2016) and strong wind (11.5% in 2015 and 9.8% in 2016) during these roofing phases. Interruptions of roof closing were more common during the early spring and late autumn (Appendix S7: Fig. S1).

We were able to alter the precipitation regime on the plots according to targeted values of our future climate scenario. In 2015, precipitation was increased by 9.3% and 8.1% in spring and autumn, respectively, but decreased by 20.1% during the summer months. In 2016, spring and autumn precipitation was increased by 13.6%

and 9.2%, whereas summer precipitation was decreased by 19.3%. Since precipitation is generally higher during the summer months, increased precipitation in spring and autumn could not alleviate the effect of summer reduction resulting in a decrease in annual precipitation by 7.4% in 2015 and 4.8% in 2016. The temporal pattern of precipitation across the two seasons was similar for the ambient and future climate treatment (Fig. 2).

Night closing of the roofs and side panels resulted in a consistent increase in air temperatures during the nights (Fig. 3). This resulted in a remarkably similar increase in the mean daily temperature of 0.55°C in a height of 5 cm and 0.24°C in a height of 70 cm in both years during the times in which the roof closing was active (Table 1, Fig. 4A, B). The daily minimum temperatures (Fig. 4C, D) showed a stronger increase in the warming treatment compared to the daily maximum temperatures (Table 1, Fig. 4E, F). Especially in a height of 70 cm over soil surface, there was no significant effect of roof closing on maximum air temperature. There was also a trend toward higher temperatures during the winter months in which the roofs are inactive. Especially, the daily minimum temperatures were slightly but significantly increased during winter months (Table 1).

Close to the soil surface, the mean minimum temperature dropped below 0°C in autumn 2015 at 2 October in the ambient climate plots but only at 12 October in the future climate plots. Last sub-zero temperatures of this winter were recorded at 29 April for the plots with future climate and at 3 May 2016 for ambient subplots. This resulted in a two-week longer frost-free period on the future climate plots in winter 2015/2016. During this period, we recorded 87 d with temperatures below 0°C on subplots with future climate vs. 93 d for the subplots with ambient climate (based on the mean minimum temperature). In autumn 2016, first sub-zero minimum temperature was recorded at 23 October for both treatments. The potential for plant growth was assessed as growing degree days (GDD) assuming thresholds of 5°C and 30°C for plant growth (Beier et al. 2004). Across the two years, we found an increase in GDD by 5.2% in warmed plots (5015.4 GDD) compared to ambient plots (4767.8 GDD).

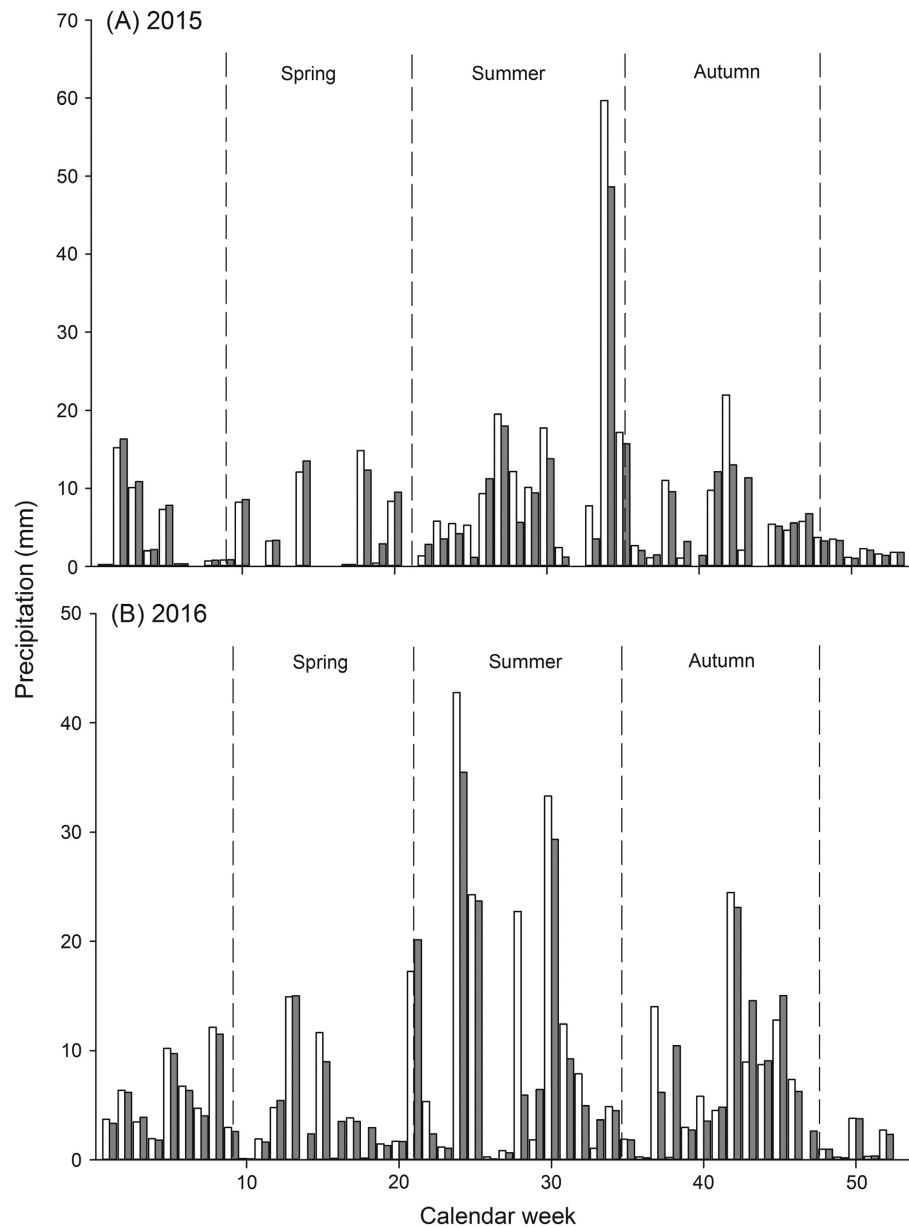


Fig. 2. Weekly amounts of ambient and manipulated precipitation on experimental plots in two experimental years: (A) 2015 and (B) 2016. White bars are ambient climate, gray bars are future climate.

The increase in temperature due to night closing of the roofs was also detectable within the soil (Table 1, Fig. 5). However, in contrast to air temperatures, the increase in soil temperature was not only obvious during the night but also peaked during the day around noon near the soil surface and in the afternoon hours deeper in the soil (Appendix S8: Fig. S1). Therefore, the mean

increase in temperature was often found to be more pronounced in the soil, especially at higher depth ( $-15$  cm), than for air temperatures (Table 1). This increase in soil temperature during the hours with intensive insolation can be explained by the lower vegetation cover on the subplots with future and should therefore be interpreted as feedback effect which further



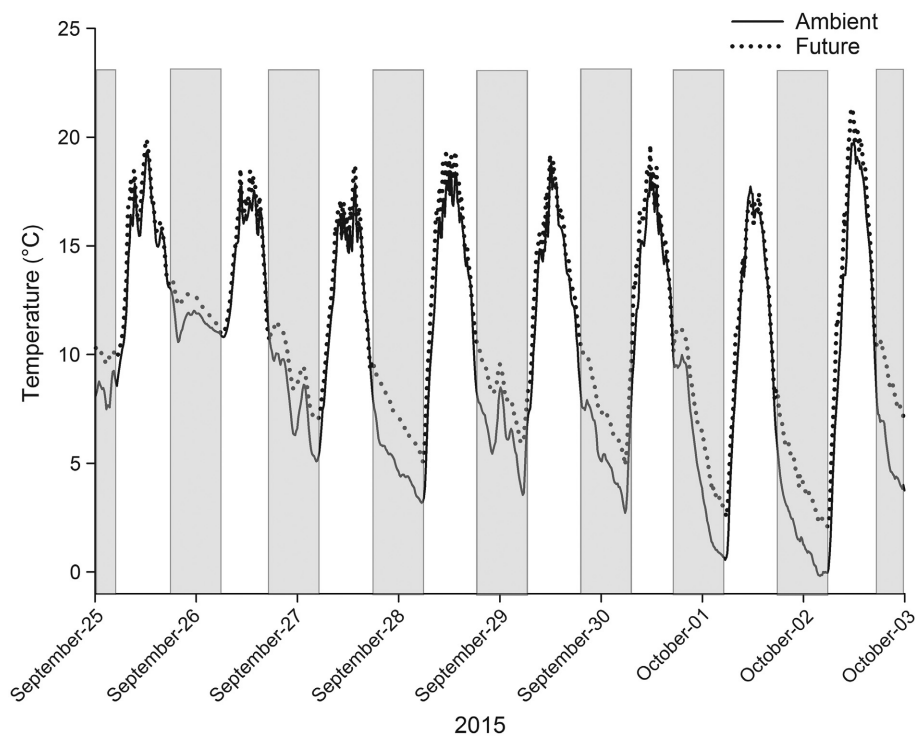


Fig. 3. Mean air temperatures (5 cm above soil surface) on plots with intensively managed meadows during one exemplary week in autumn 2015. Gray areas indicate the nightly periods of roof closing.

Table 1. Average deviation of daily mean, minimum, and maximum temperatures on plots with future climate compared to plots with ambient climate during times with and without nightly roof closing at different heights and depths in the intensively used meadows ( $\pm$ standard error).

Period	1 June 2015–11 December 2015	12 December 2015–23 March 2016	24 March 2016–22 November 2016	23 November 2016–31 December 2016
Climatic variable	Roofs active	Roofs inactive	Roofs active	Roofs inactive
Daily mean temperature (air)				
5 cm	<b>+0.55° ± 0.03°C</b>	+0.01° ± 0.01°C	<b>+0.55° ± 0.03°C</b>	<b>+0.08° ± 0.03°C</b>
70 cm	<b>+0.24° ± 0.01°C</b>	<b>+0.09° ± 0.01°C</b>	<b>+0.24° ± 0.01°C</b>	<b>+0.09° ± 0.01°C</b>
Daily minimum temperature (air)				
5 cm	<b>+0.95° ± 0.06°C</b>	<b>+0.04° ± 0.01°C</b>	<b>+1.14° ± 0.06°C</b>	<b>+0.11° ± 0.04°C</b>
70 cm	<b>+0.56° ± 0.03°C</b>	<b>+0.17° ± 0.01°C</b>	<b>+0.58° ± 0.03°C</b>	<b>+0.11° ± 0.02°C</b>
Daily maximum temperature (air)				
5 cm	<b>+0.43° ± 0.06°C</b>	+0.03° ± 0.02°C	<b>+0.24° ± 0.03°C</b>	+0.04° ± 0.03°C
70 cm	-0.02° ± 0.02°C	+0.02° ± 0.01°C	-0.02° ± 0.02°C	<b>+0.05° ± 0.02°C</b>
Daily mean temperature (soil)				
1 cm	<b>+0.65° ± 0.02°C</b>	<b>+0.11° ± 0.01°C</b>	<b>+0.44° ± 0.02°C</b>	<b>+0.31° ± 0.03°C</b>
15 cm	<b>+0.53° ± 0.02°C</b>	<b>+0.07° ± 0.01°C</b>	<b>+0.48° ± 0.02°C</b>	<b>+0.23° ± 0.02°C</b>

Notes: In 2015, roofs were active since the end of February, but sound air temperature data are available since June for technical reasons. Values different from zero (*t* test,  $P < 0.05$ ) are given in bold.

favors soil warming. Moreover, this lower vegetation cover had also consequences for soil temperatures in phases during which the roofs were inactive. As a result, we could observe a stronger

soil warming during the day especially in the upper soil horizon due to higher exposure of soil surface to direct insolation on plots with lower vegetation cover, whereas during the night, the

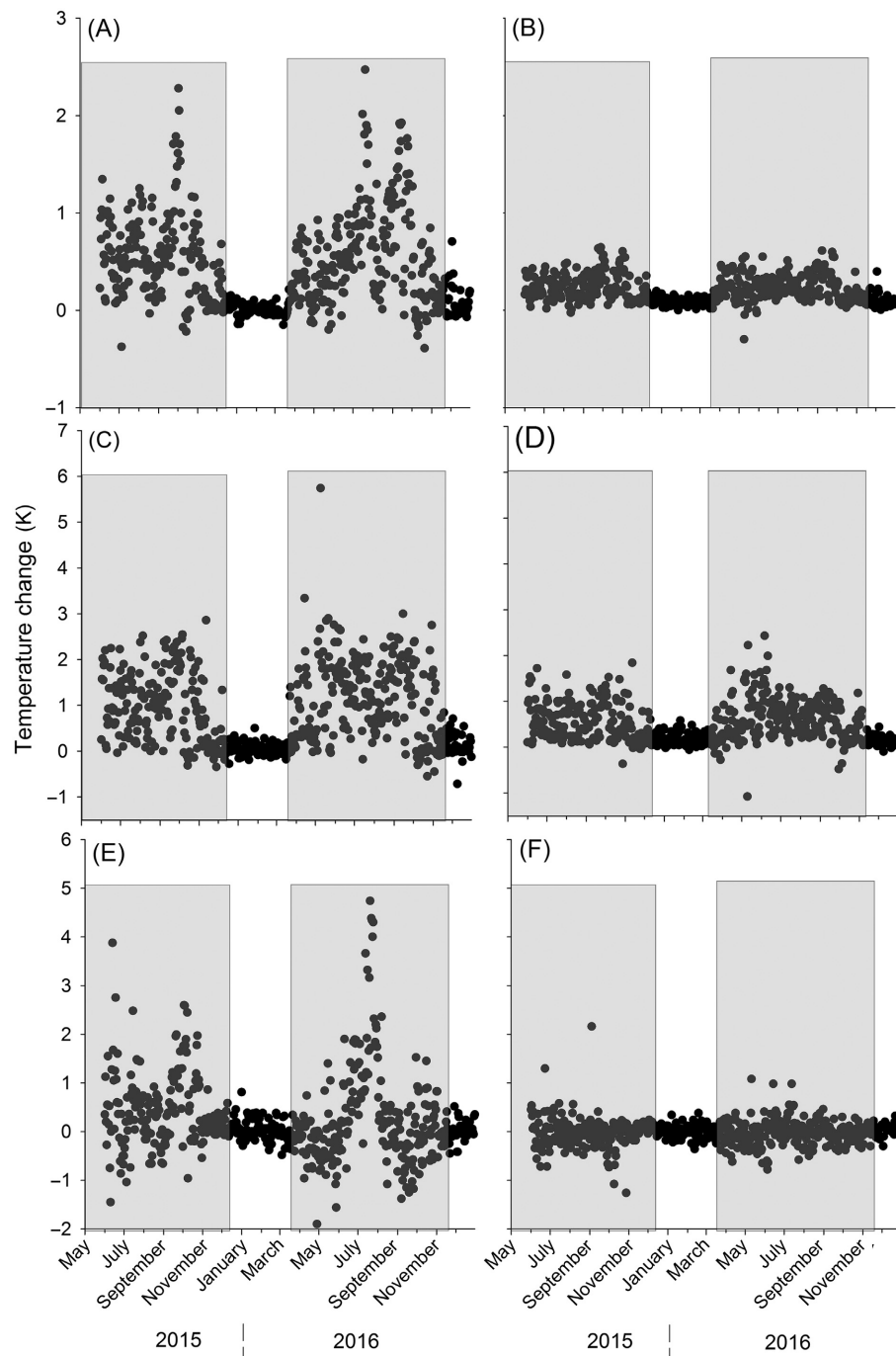


Fig. 4. Average change in daily mean air temperature (A, B), daily minimum temperature (C, D), and daily maximum temperature (E, F) recorded 5 cm (A, C, E) and 70 cm above soil surface (B, D, F) on plots with future climate relative to plots with ambient conditions, across all land-use types. Gray areas indicate times of the years in which the roofs were active.

soil temperature dropped below the values in the control plots due to stronger heat emission (Appendix S9: Fig. S1). Nevertheless, in sum, this caused higher soil temperatures even in winter with strongest effects at the end of 2016 (Table 1), when also differences in the proportion of bare soil between plots with ambient and future climate were highest (Appendix S10: Fig. S1). This further explains the trend toward higher air temperatures during the winter months.

## DISCUSSION

The investigation of the effects of climate change on the functioning of ecosystems under different land-use scenarios requires experimental approaches which combine realistic scenarios of both future climate and common land-use practices. There is increasing awareness of the eminent role of interactive effects of global changes factors on grasslands and other agroecosystems (Wu et al. 2011). Thus, the last decades have seen an increase in manipulation experiments which alter either one or several climatic factors, sometimes in conjunction with management options such as mowing and grazing (White et al. 2012). However, there is still a lack of studies which comparatively investigate

climate change effects depending on complete and realistic land-use scenarios, including the typical set of management and cultivation measures (e.g., quality and quantity of fertilization, species compositions resp. crop rotations, etc.). The GCEF was designed and established to close this gap and to serve as a long-term experimental platform to study ecosystem responses to climate change under different common land-use scenarios.

The modulation of the ambient climatic conditions according to a future scenario in the GCEF maintains the intra- and inter-annual climatic variability of temperature and precipitation. This approach mimics the realistic situation that there will be warmer as well as colder years in the future and that despite a trend to dryer summers; some of the future summers will be even wetter than some of them today. Our approach of a continuous modulation of ambient amounts of precipitation pattern was successful in maintaining the general natural rainfall pattern. Knapp et al. (2017) consider this as imperative for precipitation experiments since wet and dry years often show typical patterns regarding duration, number, and seasonality of rain events, and changing these patterns can be seen as “hidden treatment” for ecosystem responses.

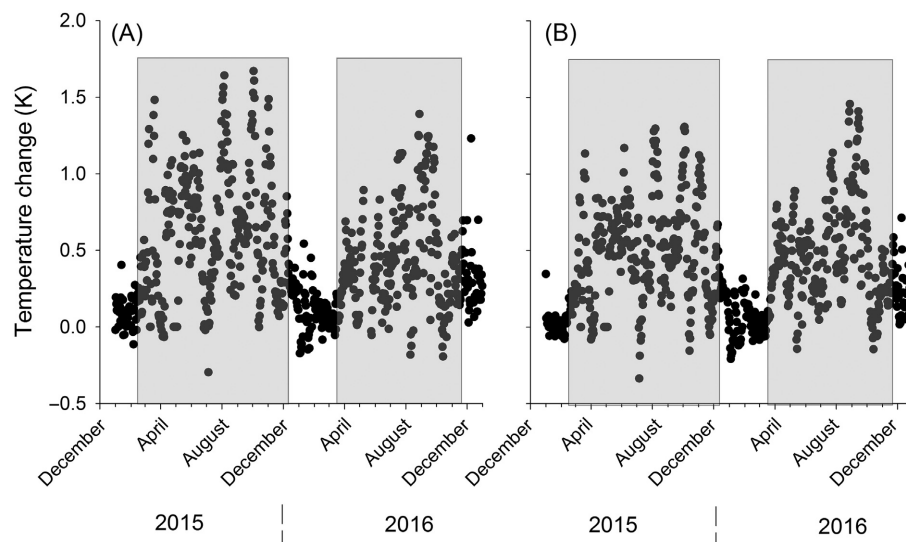


Fig. 5. Average change in soil temperatures at a depth of (A) 1 cm and (B) 15 cm in response to roof closing on plots with future climate relative to plots with ambient conditions, across all land-use types. Gray areas indicate times of the years in which the roofs were active.



The continuous monitoring of the amount of natural precipitation together with the quick adjustments via rain-controlled sensors for roof closing and the irrigation system allowed a relatively precise manipulation according to the proposed scenario without important changes in the within-seasonal precipitation patterns. Most precipitation experiments are designed to either reduce or increase the total amount of annual rainfall (Knapp et al. 2017). In contrast, the GCEF allows the consideration of seasonally differing projections of precipitation patterns by a combined use of mobile roofs and irrigation systems. Depending on the distribution of the amounts of rain across the specific year, the seasonal manipulation might lead to reduced or increased total annual precipitation. In our region of Central Germany, average rainfall is highest during the summer months and therefore a decrease in summer precipitation will usually lead to a moderate reduction in total annual precipitation despite increased precipitation in spring and autumn. The seasonal timing of water availability has been shown to be a crucial determinant of the effects on above- and belowground productivity in grasslands, and thus, on local scales, the predictive power of mean annual precipitation for productivity may be low (Denton et al. 2017). Shifts in the seasonal timing of droughts are expected to be common in the future, and many models predict reduced rain during the summer months but increased precipitation during the rest of the year in large parts of Europe (Christensen et al. 2007). The combined use of mobile roofs and irrigation system allows the manipulation of this seasonal precipitation pattern according to these scenarios. The mobile roofs of the GCEF are mainly operating during the night, and roof closing via rain sensor during the day to further reduce summer precipitation is not very often necessary. Further, since roofs automatically close upon rain and automatically open 15 min after the rain, possible microclimatic side effects are minimized compared to experiments which use fixed roof constructions during longer periods (Kundel et al. 2018).

In our experiment, passive night warming causes an increase in daily mean temperatures mainly as a result of the increase in (nightly) minimum temperatures and can be seen as favorable option to implement passive temperature

increase in larger-scale ecological experiments. This is in accordance with projections of future climatic conditions and further reflects the trend across past decades (Easterling et al. 1997, Donat and Alexander 2012). Considering the different mechanisms of daily temperature variations might be essential since the relative importance of minimum temperatures vs. maximum temperatures might change depending on environmental conditions (Shen et al. 2016). Speights et al. (2017) pointed out that only few studies explicitly addressed the effects of night time warming and decreased daily temperature variation, but this might have potentially important consequences for plant growth (Dhakhwa and Campbell 1998, Cheesman and Winter 2013) and phenology (Rossi and Isabel 2017) as well as implications for the productivity of crop plants (García et al. 2015). Further, diurnal temperature variations have been shown to affect insect ecology and behavior (Vangansbeke et al. 2015, Speights et al. 2017). This might also have practical implications for pest control since in contrast to the often predicted increased probability of pest outbreaks with higher daily mean temperatures in the future (Taylor et al. 2018), pest species might be detrimentally affected by night time warming (Zhao et al. 2014). This is complicated by potentially strong effects of daily temperature variations on trophic interactions between insect populations (Stoks et al. 2017) and the resulting top-down effects on vegetation (Barton and Schmitz 2018). Moreover, the effects of climate change on predator–prey interactions and pest control have been shown to differ between differentially managed agricultural systems (Murrell and Barton 2017).

Passive night time warming usually imposes only modest increases in mean temperature in climate change experiments (Beier et al. 2004). In our experiment, the number of days with frost was reduced on our plots with future climate, whereby the potential for plant growth was increased. The observed increase in GDD by 5.2% lies within the range observed in passive-warming experiments along a European gradient from Spain (no change) to Northern European sites (+9–12%; Beier et al. 2004). These variable effects on the length of growing season indicate that with decreasing latitude, temperature is a less limiting factor of plant growth. However,

even for more temperate regions, there is no simple relationship between an increase in temperature and productivity. In contrast, in drought-prone areas, even a rather modest temperature increase by 1°C may lead to considerable reductions in crop yields (Pinke and Lovei 2017). Thus, a reduced precipitation may counteract potentially favorable temperature conditions for plant growth, calling for experimental approaches which consider both factors of climate change. The warming effect of our manipulation was also detectable in different soil depths and is, in contrast to air warming, sustained throughout the year. This effect has also been found in other experiments using passive night time warming (Mikkelsen et al. 2008). At least in our experiment, this effect can be attributed to the lower vegetation cover in plots with future climate causing a higher direct solar radiation of the soil surface. As a consequence, soil temperature is increased also during the day, especially in the afternoon. We consider this increase in soil temperature due to lower vegetation cover and consequently stronger insolation as a realistic mechanism under future climatic conditions.

Many different technical approaches are available to increase temperature in field experiments, each associated with certain drawbacks and benefits. Active warming by infrared heaters has been criticized for producing ecophysiological side effects in plants and for the rather non-uniform warming effect on experimental plots (Kimball 2005). Similarly, soil heating cables are causing non-realistic temperature gradients in soil and other artifacts (Mchale and Mitchell 1996). Moreover, this technique would be not appropriate for our experiment due to regular soil cultivation in the crop fields. In general, active warming techniques are highly energy-consuming approaches and therefore also not feasible for field experiments with many large plots for economic reasons. In contrast, open-top chambers are a technically simple and easy to set up passive-warming approach which is especially suited for investigations in remote areas and for high replication. However, it is only suitable for rather short-statured vegetation and smaller plots, even if combined approaches with heating systems partly compensate for these drawbacks (Sun et al. 2013). Mobile roofs have therefore become a standard method for

increasing (night) temperatures on experimental plots since they exert a minimum of side effects (Beier et al. 2004, Aronson and McNulty 2009). These roofs are usually made of plastics, and their efficiency can be increased by materials reflecting the infrared radiation (Mikkelsen et al. 2008). Such materials are not available for larger plots like in the GCEF, and we therefore decided to equip the plots with two side panels to increase the warming effect without creating a greenhouse-like environment during the night. We consider the automatic operation of roofs as important to avoid unwanted side effects since daytime shading by permanent roofs has been shown to cause cooling effects (Gundersen et al. 1998). Nevertheless, the majority of experiments still use permanent rain-out shelters which further have several other unwanted microclimatic side effects (Kreyling et al. 2017). However, a technical drawback of the GCEF and many other infrastructures is that operation during the winter months is limited or even impossible during times of frequent freezing events what might affect ecosystem responses to the climate change treatment (Sanders-DeMott and Templer 2017). Especially, the manipulation of the different types of precipitation during wintertime is technically challenging.

Soil conditions are known to react slowly to environmental changes, and microevolutionary processes necessarily have to be observed over several generations. Further, ecosystems are suggested to show complex transient responses to climate change involving a temporal hierarchy of responses (Smith et al. 2009). For these reasons, the GCEF is planned to run for at least 15 yr, but we consider a time span of 20–25 yr as desirable and feasible. The relatively large size of the experimental plots (400 m<sup>2</sup>) has a number of advantages for the long-term research on ecosystem and community responses in the GCEF. First, it allows the establishment of a relatively large buffer zone around the inner plot for research purposes. Second, long-term series of several measurements have to be to some extent necessarily destructive. For instance, the assessment of soil chemical and physical parameters, root biomass, and community structure of belowground biota causes soil disturbances which might affect the surrounding soil and vegetation. The large plot size allows us to organize

a basic measurement program for soil traits without interferences with other experimental manipulations or measurement on these plots. Of course, this problem is more relevant for the grasslands, whereas in the crop fields, these effects can be considered as negligible due to regular soil cultivation. Nevertheless, it is our philosophy to keep such disturbances as low as possible and to use taken soil and plant samples for as many different assessments as possible. Further, from each sample, deep-frozen as well as dried subsamples of plant and soil material are stored in an archive for future research projects. Third, complete land-use scenarios can be realized including particular crop rotations or species combinations, the corresponding application of agrochemicals, and the use of usual agricultural machinery and equipment what would not be possible on a small plot size. For this, the experimental field station in Bad Lauchstädt gives the optimal frame conditions since the necessary equipment is available. We are aware that prioritizing larger spatial and temporal scales as well as multiple factor levels and replication also has drawbacks regarding the inclusion of other important global change factors into the design. For instance, the increase in atmospheric CO<sub>2</sub> levels is regarded as an important factor of global change, but its experimental implication is technically and budgetary challenging and therefore usually associated with smaller plot sizes and/or low replication (McLeod and Long 1999). In order to design the experiment according to our central research question—how land use and climate change interactively influence ecosystem functions—we therefore disregarded atmospheric CO<sub>2</sub> concentration.

Climate changes will have profound impacts on ecosystem dynamics and ecosystem services, and are themselves dependent on mitigation technologies influencing present land-use systems. Sound management and policy intervention can restore ecosystems and safeguard their sustainable use. For that reason, basic information is needed on the functioning of ecosystems and on the influences of climate and land-use change as complex pressures on ecosystem services. Manipulative experiments are essential for the assessment of ecological key processes which trigger ecosystem transformations (Beier et al. 2012, Reichstein et al. 2013). Climate change and

land use, however, are interrelated in many different ways including feedbacks between them (Feddema et al. 2005, Foley et al. 2005). To complicate things, different scenarios of climate change can be linked to projected changes in land-use patterns, for example, the percentage area used for food production and croplands (Schröter et al. 2005, Schmitz et al. 2014). Adaptation strategies to climate change will therefore not only include short-term adjustments (e.g., changes in crop species and management activities) but also include changes in the allocation of land to different land-use systems (Olesen and Bindi 2002). A large part of our current knowledge is based on scenarios and modeling approaches. However, field experiments manipulating the complex influence of land use and climate change on ecosystems are urgently needed to better understand and quantify the underlying processes, to develop and validate models, to deduce indicators, to develop strategies for sustainable land use, and to steer key processes. For this, modeling based on experimental data greatly contributes to the understanding of key processes and allows upscaling to spatial and temporal scales not covered by our experimental approach. In the framework of the GCEF, a number of modeling approaches have been initialized addressing research questions from the community to the landscape level. For instance, vegetation and soil data are used for the regionally transferable parametrization of process-based vegetation models (e.g., GRASSMIND, see Taubert et al. 2012) coupled with soil models (e.g., CANDY, see Franko et al. 1995) and to deduce management options for maintaining high biodiversity and reducing leaching in grasslands.

The vast majority of global change experiments, however, is not only conducted in different biomes and land-use systems but also under different regional settings and employing different methodologies (Smith 2011, Knapp et al. 2017) what makes the assessment of key processes difficult. One approach to deal with this issue is to set up coordinated distributed experiment (CDEs). Coordinated distributed experiments are characterized by rather simple and low-cost experimental set-ups which allow the comparison of a high number of experimental sites on a more global perspective (Fraser et al. 2013, Borer et al. 2014, Knapp et al. 2017). While



these CDEs are usually designed to examine the responses of one land-use type across a geographical gradient, our approach in the GCEF investigates the responses of different ecosystems under specific regional and experimental settings. Furthermore, there is an increasing awareness of the importance of extremes and non-linear behavior in relationships between climate change and ecosystem responses (Kreyling et al. 2014, Kayler et al. 2015, Damgaard et al. 2018). Gradient approaches are therefore a valuable tool in particular in the research on extreme events and tipping points (de Boeck 2018). We therefore consider them as a supplementary approach in addition to scenario-based experiments such as the GCEF. According to the tripartite trade-off between realism, generality, and precision in experimental ecology (Levins 1966, Morin 1998), we consider the GCEF as an important step toward realism and as complementary to other approaches targeting rather generality (CDEs, gradient approaches) and precision (e.g., climate chambers), together resulting in a better understanding of general patterns of ecosystem responses to global change.

## ACKNOWLEDGMENTS

We appreciate the Helmholtz Association, the Federal Ministry of Education and Research, the State Ministry of Science and Economy of Saxony-Anhalt, and the State Ministry for Higher Education, Research and the Arts Saxony to fund the Global Change Experimental Facility (GCEF) project. We also appreciate the staff of the Bad Lauchstädt Experimental Research Station for their work in maintaining the plots and infrastructures of the GCEF. The GCEF greatly benefited and benefits from fruitful discussion with Martin Hänsel (Bioland e.V./Germany) and the GCEF-Advisory Board: Nina Buchmann (Zurich/Switzerland), Stephan Hättenschwiler (Montpellier/France), Ingrid Kögel-Knabner (Munich/Germany), Jørgen Eivind Olesen (Tjele/Denmark), Jacques Roy (Montpellier/France), and Bernhard Schmid (Zurich/Switzerland).

## LITERATURE CITED

- Altermann, M., J. Rinklebe, I. Merbach, M. Körschens, U. Langer, and B. Hofmann. 2005. Chernozem – Soil of the year 2005. *Journal of Plant Nutrition and Soil Science* 168:725–740.
- Anderson, J. P. E., and K. H. Domsch. 1978. A physiological method for the quantitative measurement of microbial biomass in soil. *Soil Biology and Biochemistry* 11:215–221.
- Aronson, E. L., and S. G. McNulty. 2009. Appropriate experimental ecosystem warming methods by ecosystem, objective, and practicality. *Agricultural and Forest Meteorology* 149:1791–1799.
- Avolio, M. L., and M. D. Smith. 2013. Mechanisms of selection: Phenotypic differences among genotypes explain patterns of selection in a dominant species. *Ecology* 94:953–965.
- Bailey, J. K. 2014. Incorporating eco-evolutionary dynamics into global change research. *Functional Ecology* 28:3–4.
- Barton, B. T., and O. J. Schmitz. 2018. Opposite effects of daytime and nighttime warming on top-down control of plant diversity. *Ecology* 99:13–20.
- Beier, C., et al. 2004. Novel approaches to study climate change effects on terrestrial ecosystems in the field: drought and passive nighttime warming. *Ecosystems* 7:583–597.
- Beier, C., et al. 2012. Precipitation manipulation experiments – challenges and recommendations for the future. *Ecology Letters* 15:899–911.
- Bellard, C., C. Bertelsmeier, P. Leadley, W. Thuiller, and F. Courchamp. 2012. Impacts of climate change on the future of biodiversity. *Ecology Letters* 15:365–377.
- Benot, M. L., P. Saccone, E. Pautrat, R. Vicente, M. P. Colace, K. Grigulis, J. C. Clément, and S. Lavorel. 2014. Stronger short-term effects of mowing than extreme summer weather on a subalpine grassland. *Ecosystems* 17:458–472.
- Birkhofer, K., A. Fliessbach, D. H. Wise, and S. Scheu. 2011. Arthropod food webs in organic and conventional wheat farming systems of an agricultural long-term experiment: a stable isotope approach. *Agricultural and Forest Entomology* 13:197–204.
- Borer, E. T., W. S. Harpole, P. B. Adler, E. M. Lind, J. L. Orrock, E. W. Seabloom, and M. D. Smith. 2014. Finding generality in ecology: a model for globally distributed experiments. *Methods in Ecology and Evolution* 5:65–73.
- Bradford, M. A., W. R. Wieder, G. B. Bonan, N. Fierer, P. A. Raymond, and T. W. Crowther. 2016. Managing uncertainty in soil carbon feedbacks to climate change. *Nature Climate Change* 6:751–758.
- Brose, U., and H. Hillebrand. 2016. Biodiversity and ecosystem functioning in dynamic landscapes. *Philosophical Transactions of the Royal Society B: Biological Sciences* 371:20150267.
- Bucharova, A., O. Bossdorf, N. Hölzel, J. Kollmann, R. Prasse, and W. Durka. 2018. Mix and match! Regional admixture provenancing strikes a balance among different seed-sourcing strategies for

- ecological restoration. *Conservation Genetics*. <https://doi.org/10.1007/s10592-018-1067-6>
- Bucharova, A., S. G. Michalski, J. M. Hermann, K. Heveling, W. Durka, N. Hölzel, J. Kollmann, and O. Bossdorf. 2017. Genetic differentiation and regional adaptation among seed origins used for grassland restoration: lessons from a multi-species transplant experiment. *Journal of Applied Ecology* 54:127–136.
- Cardinale, B. J., et al. 2012. Biodiversity loss and its impact on humanity. *Nature* 486:59–67.
- Chang, J. F., P. Ciais, N. Viovy, N. Vuichard, M. Herrero, P. Havlik, X. Wang, B. Sultan, and J. F. Sossana. 2016. Effect of climate change, CO<sub>2</sub> trends, nitrogen addition, and land-cover and management intensity changes on the carbon balance of European grasslands. *Global Change Biology* 22:338–350.
- Cheesman, A. W., and K. Winter. 2013. Elevated nighttime temperatures increase growth in seedlings of two tropical pioneer tree species. *New Phytologist* 197:1185–1192.
- Christensen, J. H., et al. 2007. Regional climate projections. Pages 486–940 in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. *Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, New York, USA.
- Crowder, D. W., T. D. Northfield, M. R. Strand, and W. E. Snyder. 2010. Organic agriculture promotes evenness and natural pest control. *Nature* 466:109–112.
- Damgaard, C., M. Holmstrup, I. Kappel Schmidt, C. Beier, and K. Steenberg Larsen. 2018. On the problems of using linear models in ecological manipulation experiments: lessons learned from a climate experiment. *Ecosphere* 9:e02322.
- Davy, R., I. Esau, A. Chernokulsky, S. Outten, and S. Zilitinkevich. 2017. Diurnal asymmetry to the observed global warming. *International Journal of Climatology* 37:79–93.
- De Boeck, H. J., et al. 2018. Global change experiments: challenges and opportunities. *BioScience* 65:922–931.
- De Chazal, J., and M. D. A. Rounsevell. 2009. Land-use and climate change within assessments of biodiversity change: a review. *Global Environmental Change* 19:306–315.
- Dendooven, L., L. Patiño-Zúñiga, N. Verhulst, M. Luna-Guido, R. Marsch, and B. Govaerts. 2012. Global warming potential of agricultural systems with contrasting tillage and residue management in the central highlands of Mexico. *Agriculture, Ecosystems and Environment* 152:50–58.
- Denton, E. M., J. D. Dietrich, M. D. Smith, and A. K. Knapp. 2017. Drought timing differentially affects above- and belowground productivity in a mesic grassland. *Plant Ecology* 218:317–328.
- Department for Environment, Food and Rural Affairs. 2008. Change in the area and distribution of set-aside in England: January 2008 update. DEFRA Agricultural Change and Environment Observatory Research Report No. 10. Department for Environment, Food and Rural Affairs, London, UK.
- Dhakhwa, G. B., and C. L. Campbell. 1998. Potential effects of differential day-night warming in global climate change on crop production. *Climatic Change* 40:647–667.
- Donat, M. G., and L. V. Alexander. 2012. The shifting probability distribution of global daytime and night-time temperatures. *Geophysical Research Letters* 39:L14707.
- Döscher, R., U. Willén, C. Jones, A. Rutgersson, H. E. M. Meier, U. Hansson, and L. P. Graham. 2002. The development of the regional coupled ocean-atmosphere model RCAO. *Boreal Environment Research* 7:183–192.
- Durka, W., S. G. Michalski, K. W. Berendzen, O. Bossdorf, A. Bucharova, J. M. Hermann, N. Hölzel, and J. Kollmann. 2017. Genetic differentiation within multiple common grassland plants supports seed transfer zones for ecological restoration. *Journal of Applied Ecology* 54:116–126.
- Easterling, D. R., et al. 1997. Maximum and minimum temperature trends for the globe. *Science* 277:364–367.
- Ehleringer, J., R. Birsey, R. Ceulemans, J. Melillo, J. Nösberger, W. Oechel, and S. Trumbore. 2006. Report of the BERAC subcommittee reviewing the FACE and OTC elevated CO<sub>2</sub> projects in DOE. [http://www.sc.doe.gov/ober/berac/FACE\\_2006\\_report.pdf](http://www.sc.doe.gov/ober/berac/FACE_2006_report.pdf)
- Etterson, J. R., and R. G. Shaw. 2001. Constraint to adaptive evolution in response to global warming. *Science* 294:151–154.
- European Commission. 2012. Europe in figures. Eurostat yearbook 2012. Publications Office of the European Union, Luxembourg City, Luxembourg.
- European Union. 2007. Council regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing regulation (EEC) No 2092/91. Official Journal of the European Union L189/1-23, Luxembourg.
- Feddema, J. J., K. W. Oleson, G. B. Bonan, L. O. Mearns, L. E. Buja, G. A. Meehl, and W. M. Washington. 2005. The importance of land-cover change in simulating future climates. *Science* 310:1674–1678.

- Flombaum, P., L. Yahdjian, and O. E. Sala. 2017. Global-change drivers of ecosystem functioning modulated by natural variability and saturating responses. *Global Change Biology* 23:503–511.
- Foley, J. A., et al. 2005. Global consequences of land use. *Science* 309:570–574.
- Franklin, J., J. M. Serra-Diaz, A. D. Syphard, and H. M. Regan. 2016. Global change and terrestrial plant community dynamics. *Proceedings of the National Academy of Sciences USA* 113:3725–3734.
- Franko, U., B. Oelschlägel, and S. Schenk. 1995. Simulation of temperature-, water- and nitrogen dynamics using the model CANDY. *Ecological Modelling* 81:213–222.
- Franks, S. J., S. Sim, and A. E. Weis. 2007. Rapid evolution of flowering time by an annual plant in response to a climate fluctuation. *Proceedings of the National Academy of Sciences USA* 104:1278–1282.
- Franks, S. J., J. J. Weber, and S. N. Aitken. 2014. Evolutionary and plastic responses to climate change in terrestrial plant populations. *Evolutionary Applications* 7:123–139.
- Fraser, L. H., et al. 2013. Coordinated distributed experiments: an emerging tool for testing global hypotheses in ecology and environmental science. *Frontiers in Ecology and the Environment* 11:147–155.
- French, K. E., A. Tkacz, and L. A. Turnbull. 2017. Conversion of grassland to arable decreases microbial diversity and alters community composition. *Applied Soil Ecology* 110:43–52.
- García, G. A., M. F. Dreccer, D. J. Miralles, and R. A. Serrago. 2015. High night temperatures during grain number determination reduce wheat and barley grain yield: a field study. *Global Change Biology* 21:4153–4164.
- Gosling, P., C. Van Der Gast, and G. D. Bending. 2017. Converting highly productive arable cropland in Europe to grassland: -a poor candidate for carbon sequestration. *Scientific Reports* 7:12.
- Götze, M., W. Kattanek, R. Peukert, E. Chervakova, H. Töpfer, P. Dietrich, and J. Bumberger. 2013. A flexible service and communication gateway for monitoring applications. Pages 1–5 in *Institute of Electrical and Electronics Engineers*, editor. *Proceedings of the 21st International Conference on Software, Telecommunications and Computer Networks. SoftCOM 2013, Split, Croatia*.
- Grimm, N. B., et al. 2013. The impacts of climate change on ecosystem structure and function. *Frontiers in Ecology and the Environment* 11:474–482.
- Gruner, D. S., M. E. S. Bracken, S. A. Berger, B. K. Eriksson, L. Gamfeldt, B. Matthiessen, S. Moorthi, U. Sommer, and H. Hillebrand. 2017. Effects of experimental warming on biodiversity depend on ecosystem type and local species composition. *Oikos* 126:8–17.
- Gundersen, P., A. W. Boxman, N. Lamersdorf, F. Moldan, and B. R. Andersen. 1998. Experimental manipulation of forest ecosystems: lessons from large roof experiments. *Forest Ecology and Management* 101:339–352.
- Harvey, L. D. D. 1995. Warm days, hot nights. *Nature* 377:15–16.
- Hautier, Y., D. Tilman, and F. Isbell. 2015. Anthropogenic environmental changes affect ecosystem stability via biodiversity. *Science* 348:336–340.
- Hoffmann, A. A., and C. M. Sgro. 2011. Climate change and evolutionary adaptation. *Nature* 470:479–485.
- Hooper, D. U., et al. 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecological Monographs* 75:3–35.
- IPCC. 2014. Climate change 2014: synthesis report. In R. K. Pachauri and L. A. Meyer, editors. *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland.
- Jacob, D., and R. Podzun. 1997. Sensitivity studies with the regional climate model REMO. *Meteorology and Atmospheric Physics* 63:119–129.
- Kaarlejarvi, E., A. Eskelinen, and J. Olofsson. 2017. Herbivores rescue diversity in warming tundra by modulating trait-dependent species losses and gains. *Nature Communications* 8:419.
- Kayler, Z. E., H. J. de Boeck, S. Fatichi, J. M. Grünzweig, L. Merbold, C. Beier, N. McDowell, and J. S. Dukes. 2015. Experiments to confront the environmental extremes of climate change. *Frontiers in Ecology and Evolution* 13:219–225.
- Kimball, B. A. 2005. Theory and performance of an infrared heater for ecosystem warming. *Global Change Biology* 11:2041–2056.
- Knapp, A. K., et al. 2017. Pushing precipitation to the extremes in distributed experiments: recommendations for simulating wet and dry years. *Global Change Biology* 23:1774–1782.
- Kreyling, J., M. A. S. Arfin Khan, F. Sultana, W. Babel, C. Beierkuhnlein, T. Foken, J. Walter, and A. Jentsch. 2017. Drought effects in climate change manipulation experiments: quantifying the influence of ambient weather conditions and rain-out shelter artifacts. *Ecosystems* 20:301–315.
- Kreyling, J., A. Jentsch, and C. Beier. 2014. Beyond realism in climate change experiments: Gradient approaches identify thresholds and tipping points. *Ecology Letters* 17:125 e1.
- Kuester, A., A. Wilson, S. M. Chang, and R. S. Baucom. 2016. A resurrection experiment finds evidence of



- both reduced genetic diversity and potential adaptive evolution in the agricultural weed *Ipomoea purpurea*. *Molecular Ecology* 25:4508–4520.
- Kuijper, D. P. J., and J. P. Bakker. 2005. Top-down control of small herbivores on salt-marsh vegetation along a productivity gradient. *Ecology* 86:914–923.
- Kundel, D., S. Meyer, H. Birkhofer, A. Fließbach, P. Mäder, S. Scheu, M. van Kleunen, and K. Birkhofer. 2018. Design and manual to construct rainout-shelters for climate change experiments in agroecosystems. *Frontiers in Environmental Science* 6:14.
- Landesamt für Landwirtschaft, Umwelt und ländliche Räume. 2010. Beweidung von Offen- und Halboffenbiotopen. Eine adäquate Pflegemethode unter besonderer Berücksichtigung der FFH-Lebensraumtypen und Arten. Schriftenreihe des Landesamtes für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein 18:1–30.
- Launchbaugh, K. L., R. J. Daines, and J. W. Walker. 2006. Targeted grazing: a natural approach to vegetation management and landscape enhancement. American Sheep Industry Association, Centennial, Colorado, USA.
- Leadley, P., H. M. Pereira, R. Alkemade, J. F. Fernandez-Manjarres, V. Proenca, J. P. W. Scharlemann, and M. J. Walpole. 2010. Biodiversity scenarios: projections of 21st century change in biodiversity and associated ecosystem services. Secretariat of the Convention on Biological Diversity, Montreal, Québec, Canada.
- Lefcheck, J. S., J. E. K. Byrnes, F. Isbell, L. Gamfeldt, J. N. Griffin, N. Eisenhauer, M. J. S. Hensel, A. Hector, B. J. Cardinale, and J. E. Duffy. 2015. Biodiversity enhances ecosystem multifunctionality across trophic levels and habitats. *Nature Communications* 6:6936.
- Levins, R. 1966. The strategy of model building in population biology. *American Scientist* 54:421–431.
- Lu, M., X. Zhou, Q. Yang, H. Li, Y. Luo, C. Fang, J. Chen, X. Yang, and B. Li. 2013. Responses of ecosystem carbon cycle to experimental warming: a meta-analysis. *Ecology* 94:726–738.
- Lustenhouwer, N., R. A. Wilschut, J. L. Williams, W. H. van der Putten, and J. M. Levine. 2018. Rapid evolution of phenology during range expansion with recent climate change. *Global Change Biology* 24:e534–e544.
- Lynch, M., and R. Lande. 1993. Evolution and extinction in response to environmental change. Pages 234–250 in P. M. Kareiva, J. G. Kingsolver, and R. B. Huey, editors. *Biotic interactions and global change*. Sinauer Associates, Sunderland, Massachusetts, USA.
- Mariotte, P., A. Canarini, and F. A. Dijkstra. 2017. Stoichiometric N:P flexibility and mycorrhizal symbiosis favour plant resistance against drought. *Journal of Ecology* 105:958–967.
- Maxwell, S., R. A. Fuller, T. M. Brooks, and J. E. M. Watson. 2016. The ravages of guns, nets and bulldozers. *Nature* 536:143–145.
- Mchale, P. J., and M. J. Mitchell. 1996. Disturbance effects on soil solution chemistry due to heating cable installation. *Biology and Fertility of Soils* 22:40–44.
- McLeod, A. R., and S. P. Long. 1999. Free-air carbon enrichment (FACE) in global change research: a review. *Advances in Ecological Research* 28:1–56.
- Michalski, S. G., W. Durka, A. Jentsch, J. Kreyling, S. Pompe, O. Schweiger, E. Willner, and C. Beierkuhnlein. 2010. Evidence for genetic differentiation and divergent selection in an autotetraploid forage grass (*Arrhenatherum elatius*). *Theoretical and Applied Genetics* 120:1151–1162.
- Mikkelsen, T. N., et al. 2008. Experimental design of multifactor climate change experiments with elevated CO<sub>2</sub>, warming and drought: the CLIMAITE project. *Functional Ecology* 22:185–195.
- Mooney, H., A. Larigauderie, M. Cesario, T. Elmquist, O. Hoegh-Guldberg, S. Lavorel, G. M. Mace, M. Palmer, R. Scholes, and T. Yahara. 2009. Biodiversity, climate change, and ecosystem services. *Current Opinion in Environmental Sustainability* 1:46–54.
- Morin, P. J. 1998. Realism, precision and generality in experimental tests of ecological theory. Pages 50–70 in W. J. Reserits and J. Bernardo, editors. *Issues and perspectives in experimental ecology*. Oxford University Press, Oxford, UK.
- Murphy, J., and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta* 27:31–36.
- Murrell, E. G., and B. T. Barton. 2017. Warming alters prey density and biological control in conventional and organic agricultural systems. *Integrative and Comparative Biology* 57:121–133.
- O'Connor, M. I. 2009. Warming strengthens an herbivore-plant interaction. *Ecology* 90:388–398.
- Oehl, F., E. Laczko, A. Bogenrieder, K. Stahr, R. Bosch, M. van der Heijden, and E. Sieverding. 2010. Soil type and land use intensity determine the composition of arbuscular mycorrhizal fungal communities. *Soil Biology and Biochemistry* 42:724–738.
- Olesen, J. E., and M. Bindi. 2002. Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy* 16:239–262.

- Pereira, H. M., L. M. Navarro, and I. S. Martins. 2012. Global biodiversity change: the bad, the good, and the unknown. *Annual Review of Environment and Resources* 37:25–50.
- Pinke, Z., and G. L. Lovei. 2017. Increasing temperature cuts back crop yields in Hungary over the last 90 years. *Global Change Biology* 23:5426–5435.
- Plieninger, T., H. Draux, N. Fagerholm, C. Bieling, M. Bürgi, T. Kizos, T. Kümmerle, J. Primdahl, and P. H. Verburg. 2016. The driving forces of landscape change in Europe: a systematic review of the evidence. *Land Use Policy* 57:204–214.
- Post, E., and C. Pedersen. 2008. Opposing plant community responses to warming with and without herbivores. *Proceedings of the National Academy of Sciences of the United States of America* 105:12353–12358.
- Rasmann, S., L. Pellissier, E. Defossez, H. Jactel, and G. Kunstler. 2014. Climate-driven change in plant-insect interactions along elevation gradients. *Functional Ecology* 28:46–54.
- Reichstein, M., et al. 2013. Climate extremes and the carbon cycle. *Nature* 500:287–295.
- Rockel, B., A. Will, and A. Hense. 2008. The regional climate model COSMO-CLM (CCLM). *Meteorologische Zeitschrift* 17:347–348.
- Rossi, S., and N. Isabel. 2017. Bud break responds more strongly to daytime than night-time temperature under asymmetric experimental warming. *Global Change Biology* 23:446–454.
- Sanders-DeMott, R., and P. H. Templer. 2017. What about winter? Integrating the missing season into climate change experiments in seasonally snow covered ecosystems. *Methods in Ecology and Evolution* 8:1183–1191.
- Scheffers, B. R., et al. 2016. The broad footprint of climate change from genes to biomes to people. *Science* 354:7671.
- Schmid, B., A. Birrer, and C. Lavigne. 1996. Genetic variation in the response of plant populations to elevated CO<sub>2</sub> in a nutrient-poor calcareous grassland. Pages 31–50 *in* C. Körner and F. Bazzaz, editors. *Carbon dioxide, populations, and communities*. Academic Press, San Diego, California, USA.
- Schmitz, C., et al. 2014. Land-use change trajectories up to 2050: insights from a global agro-economic model comparison. *Agricultural Economics* 45:69–84.
- Schnoor, T. K., Y. Lekberg, S. Rosendahl, and P. A. Olson. 2011. Mechanical soil disturbance as a determinant of arbuscular mycorrhizal fungal communities in semi-natural grassland. *Mycorrhiza* 21:211–220.
- Schröter, D., et al. 2005. Ecosystem service supply and vulnerability to global change in Europe. *Science* 310:1333–1337.
- Schubert, R., R. Hilbig, and S. Klotz. 2009. *Bestimmungsbuch der Pflanzengesellschaften Deutschlands*. Spektrum Akademischer Verlag, Heidelberg, Germany.
- Schulz, E. 2002. Influence of extreme management on decomposable soil organic matter pool. *Archives of Agronomy and Soil Science* 48:101–105.
- Shen, M., S. Piao, X. Chen, S. An, Y. H. Fu, S. Wang, N. Cong, and I. A. Janssens. 2016. Strong impacts of daily minimum temperature on the green-up date and summer greenness of the Tibetan Plateau. *Global Change Biology* 22:3057–3066.
- Sirami, C., P. Caplat, S. Popy, A. Clamens, R. Arlettas, F. Jiguet, L. Brotons, and J. L. Martin. 2017. Impacts of global change on species distributions: obstacles and solutions to integrate climate and land use. *Global Ecology and Biogeography* 26:385–394.
- Smith, M. D. 2011. An ecological perspective on extreme climatic events: a synthetic definition and framework to guide future research. *Journal of Ecology* 99:656–663.
- Smith, M. D., A. K. Knapp, and S. L. Collins. 2009. A framework for assessing ecosystem dynamics in response to chronic resource alterations induced by global change. *Ecology* 90:3279–3289.
- Smith, N. G., et al. 2014. Toward a better integration of biological data from precipitation manipulation experiments into Earth system models. *Reviews of Geophysics* 52:412–434.
- Smith, P., et al. 2016. Global change pressures on soils from land use and management. *Global Change Biology* 22:1008–1028.
- Speights, C. J., J. P. Harmon, and B. T. Barton. 2017. Contrasting the potential effects of daytime versus nighttime warming on insects. *Current Opinion in Insect Science* 23:1–6.
- Stampfli, A., J. M. G. Bloor, M. Fischer, and M. Zeiter. 2018. High land-use intensity exacerbates shifts in grassland vegetation composition after severe experimental drought. *Global Change Biology* 24:2021–2034.
- Stoks, R., J. Verheyen, M. van Dievel, and N. Tuzun. 2017. Daily temperature variation and extreme high temperatures drive performance and biotic interactions in a warming world. *Current Opinion in Insect Science* 23:35–42.
- Sun, S. Q., L. Peng, G. X. Wang, Y. H. Wu, J. Zhou, H. J. Bing, D. Yu, and J. Luo. 2013. An improved open-top chamber warming system for global change research. *Silva Fennica* 47:1–11.
- Suttle, K. B., M. A. Thomsen, and M. E. Power. 2007. Species interactions reverse grassland responses to changing climate. *Science* 315:640–642.

- Taubert, F., K. Frank, and A. Huth. 2012. A review of grassland models in the biofuel context. *Ecological Modelling* 245:84–93.
- Taylor, R. A. J., D. A. Herms, J. Cardina, and R. H. Moore. 2018. Climate change and pest management: unanticipated consequences of trophic dislocation. *Agronomy* 8:7.
- Thompson, J. R., D. R. Foster, R. Scheller, and D. Kittridge. 2011. The influence of land use and climate change on forest biomass and composition in Massachusetts, USA. *Ecological Applications* 21:2425–2444.
- Tilman, D. 1999. The ecological consequences of changes in biodiversity: a search for general principles. *Ecology* 80:1455–1474.
- Titeux, N., K. Henle, J. B. Mihoub, A. Regos, R. Geijzendorffer, W. Cramer, P. H. Verburg, and L. Brotons. 2016. Biodiversity scenarios neglect future land-use changes. *Global Change Biology* 22:2505–2515.
- Titeux, N., K. Henle, J. B. Mihoub, A. Regos, I. R. Geijzendorffer, W. Cramer, P. H. Verburg, and L. Brotons. 2017. Global scenarios for biodiversity need to better integrate climate and land use change. *Diversity and Distributions* 23:1231–1234.
- Tsiafouli, M. A., et al. 2015. Intensive agriculture reduces soil biodiversity across Europe. *Global Change Biology* 21:973–985.
- Uchida, K., and A. Ushimaru. 2014. Biodiversity declines due to abandonment and intensification of agricultural lands: patterns and mechanisms. *Ecological Monographs* 84:637–658.
- Urban, M. C., et al. 2016. Improving the forecast for biodiversity under climate change. *Science* 353: aad8466.
- van de Koppel, J., J. Huisman, R. van der Wal, and H. Olff. 1996. Patterns of herbivory along a productivity gradient: an empirical and theoretical investigation. *Ecology* 77:736–745.
- van der Sluis, T., B. Pedroli, S. B. P. Kristensen, G. L. Cosor, and E. Pavlis. 2016. Changing land use intensity in Europe – Recent processes in selected case studies. *Land Use Policy* 57:777–785.
- Vangansbeke, D., J. Audenaert, D. T. Nguyen, R. Verhoeven, B. Gobin, L. Tirry, and P. De Clercq. 2015. Diurnal temperature variations affect development of a herbivorous arthropod pest and its predators. *PLoS ONE* 10:e0124898.
- Vogel, A., M. Scherer-Lorenzen, and A. Weigelt. 2012. Grassland resistance and resilience after drought depends on management intensity and species richness. *PLoS ONE* 7:e36992.
- Völler, E., O. Bossdorf, D. Prati, and H. Auge. 2017. Evolutionary responses to land use in eight common grassland plants. *Journal of Ecology* 105: 1290–1297.
- Ward, J. K., J. Antonovics, R. B. Thomas, and B. R. Strain. 2000. Is atmospheric CO<sub>2</sub> a selective agent on model C3 annuals? *Oecologia* 123:330–341.
- Weissshuhn, K., D. Prati, M. Fischer, and H. Auge. 2012. Regional adaptation improves the performance of grassland plant communities. *Basic and Applied Ecology* 13:551–559.
- White, S. R., C. N. Carlyle, L. H. Fraser, and J. F. Cahill. 2012. Climate change experiments in temperate grasslands: synthesis and future directions. *Biology Letters* 8:484–487.
- Wieneke, S., R. Brandl, D. Prati, J. Stöcklin, C. Körner, and H. Auge. 2004. Genetic variation and implications for microevolution in response to elevated CO<sub>2</sub> in the perennial herb *Sanguisorba minor* Scop. *Global Change Biology* 10:1389–1401.
- Wu, Z., P. Dijkstra, G. W. Koch, J. Peñuelas, and B. A. Hungate. 2011. Responses of terrestrial ecosystems to temperature and precipitation change: a meta-analysis of experimental manipulation. *Global Change Biology* 17:927–942.
- Zentrum für Acker- und Pflanzenbau. 2012. Mischungs- und Sortenempfehlungen Grünland – Empfehlungen und Hinweise. State Agency for Agriculture and Horticulture Saxony-Anhalt, Bernburg, Germany.
- Zhao, F., W. Zhang, A. A. Hoffmann, and C. S. Ma. 2014. Night warming on hot days produces novel impacts on development, survival and reproduction in a small arthropod. *Journal of Animal Ecology* 83:769–778.

## SUPPORTING INFORMATION

Additional Supporting Information may be found online at: <http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2635/full>