

# Long-term exposure to elevated CO<sub>2</sub> enhances plant community stability by suppressing dominant plant species in a mixed-grass prairie

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**Climate controls vegetation distribution across the globe, and some vegetation types are more vulnerable to climate change, whereas others are more resistant. Because resistance and resilience can influence ecosystem stability and determine how communities and ecosystems respond to climate change, we need to evaluate the potential for resistance as we predict future ecosystem function. In a mixed-grass prairie in the northern Great Plains, we used a large field experiment to test the effects of elevated CO<sub>2</sub>, warming, and summer irrigation on plant community structure and productivity, linking changes in both to stability in plant community composition and biomass production. We show that the independent effects of CO<sub>2</sub> and warming on community composition and productivity depend on interannual variation in precipitation and that the effects of elevated CO<sub>2</sub> are not limited to water saving because they differ from those of irrigation. We also show that production in this mixed-grass prairie ecosystem is not only relatively resistant to interannual variation in precipitation, but also rendered more stable under elevated CO<sub>2</sub> conditions. This increase in production stability is the result of altered community dominance patterns: Community evenness increases as dominant species decrease in biomass under elevated CO<sub>2</sub>. In many grasslands that serve as rangelands, the economic value of the ecosystem is largely dependent on plant community composition and the relative abundance of key forage species. Thus, our results have implications for how we manage native grasslands in the face of changing climate.**

climate change | elevated carbon dioxide | grassland | community stability | warming

Ecologists have long recognized the importance of climate in shaping plant communities across spatial and temporal scales (1). Together, precipitation and temperature characterize the distribution of terrestrial biomes across the globe. As climate changes, some biomes will be more vulnerable to temperature increase (2) or altered precipitation (3), whereas others will be more resistant (4–6). Ecological stability, the maintenance of community structure and function despite climatic fluctuation or disturbance (7–9), includes two components: resistance [lack of change despite perturbation (9)] and resilience [return to a previous state following a perturbation (10–13)]. Diversity (14) and productivity (11, 15) can both influence community stability (16) and dampen responses to environmental perturbation (5, 9, 17, 18). What remains unclear is how stability and resistance respond to predicted changes in climate.

Multiple climate change factors simultaneously impact plant performance, community structure, and productivity (4, 19, 20). For example, elevated CO<sub>2</sub> can improve water use efficiency and increase plant productivity (21–23), but warming can reduce it, counteracting the positive water-saving effects of elevated CO<sub>2</sub> (24). In addition, plant species and functional groups that differ in photosynthetic pathway often have contrasting responses to elevated CO<sub>2</sub>, warming, and altered precipitation. Furthermore, the effects of individual climate change factors may be additive

(25, 26), subadditive (4, 24, 27), or antagonistic (27, 28). As a result, the performance of a given species or functional group depends on interactions among CO<sub>2</sub>, temperature, and soil characteristics that influence plant water availability at the community level.

Globally, both elevated CO<sub>2</sub> and warming are expected to lead to pronounced changes in vegetation distribution and structure (25, 29, 30). In North American grasslands, warming is expected to promote C<sub>4</sub> dominance, dampening the ability of these areas to show large responses to elevated CO<sub>2</sub> (25). Because responses to climate change differ among individual plant species and depend on community context (31–33), the resultant community dynamics are difficult to predict. In addition, plant responses to climate manipulations can shift over time. Our earlier work in a mixed-grass prairie shows that in the first 3 y of the Prairie Heating and CO<sub>2</sub> Enrichment (PHACE) experiment, both C<sub>3</sub> and C<sub>4</sub> grass production benefited from elevated CO<sub>2</sub> conditions (34). However, long-term studies of CO<sub>2</sub> enrichment show that plant responses can diminish over time (22, 35), including the responses of dominant grass species in our mixed-grass prairie (36). To accurately characterize the trajectory of species responses and predict the interacting impacts of global climate change on plant community structure and function, long-term experiments are necessary.

Grasslands in the northern Great Plains are experiencing rapid climate change, with average annual temperatures increasing by 2.6 °C over the last century and winter and spring temperatures increasing more rapidly than summer temperatures (37). Grasslands

## Significance

**Evaluating ecological responses to climate change is essential to predict ecosystem function under future climate scenarios. In a mixed-grass prairie, we use a multifactor field experiment to show that the effects of elevated CO<sub>2</sub> and warming on plant community structure and productivity depend on interannual variation in precipitation. We also show that shifts in plant dominance patterns driven by elevated CO<sub>2</sub> in a mixed-grass prairie ecosystem promoted biomass and compositional stability and resistance to interannual variation in precipitation. The economic value of grasslands is largely dependent on the relative abundance of key forage species. Thus, our results have implications for how we manage native grasslands in the face of changing climate.**

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**Table 3. Results from a two-way permutational analysis of the main and interactive effects of warming, elevated CO<sub>2</sub>, and year on plant community composition, presenting the pseudo *F* ratio and permuted *P* values within years 2007–2013**

| Source                | Year (precipitation) |       |                |      |            |      |            |      |            |      |            |      |            |      |            |      |
|-----------------------|----------------------|-------|----------------|------|------------|------|------------|------|------------|------|------------|------|------------|------|------------|------|
|                       | 2006 (dry)           |       | 2007 (average) |      | 2008 (dry) |      | 2009 (wet) |      | 2010 (wet) |      | 2011 (wet) |      | 2012 (dry) |      | 2013 (dry) |      |
|                       | F                    | P     | F              | P    | F          | P    | F          | P    | F          | P    | F          | P    | F          | P    | F          | P    |
| Whole community       |                      |       |                |      |            |      |            |      |            |      |            |      |            |      |            |      |
| +CO <sub>2</sub>      | 2.7                  | 0.005 | 1.9            | 0.03 | 2.4        | 0.02 | 1.5        | 0.15 | 1.5        | 0.2  | 1.4        | 0.2  | 2.1        | 0.03 | 0.8        | 0.7  |
| +T                    |                      |       | 2.4            | 0.03 | 1.4        | 0.2  | 2.1        | 0.03 | 1.7        | 0.08 | 1.9        | 0.05 | 2.2        | 0.02 | 2.5        | 0.01 |
| +T × CO <sub>2</sub>  |                      |       | 0.5            | 0.9  | 0.5        | 0.9  | 0.8        | 0.7  | 1.1        | 0.4  | 1.2        | 0.3  | 1.2        | 0.3  | 1.9        | 0.05 |
| Water                 |                      |       | 1.5            | 0.2  | 2          | 0.03 | 2.2        | 0.2  | 1.3        | 0.3  | 1.3        | 0.2  | 1.1        | 0.3  | 2          | 0.03 |
| Subdominant community |                      |       |                |      |            |      |            |      |            |      |            |      |            |      |            |      |
| +CO <sub>2</sub>      | 1.2                  | 0.3   | 0.7            | 0.7  | 1.1        | 0.4  | 1          | 0.5  | 1.1        | 0.4  | 0.6        | 0.8  | 1.5        | 0.2  | 0.3        | 1    |
| +T                    |                      |       | 2.3            | 0.07 | 1.4        | 0.2  | 2.9        | 0.01 | 2.7        | 0.02 | 1.4        | 0.2  | 2.4        | 0.03 | 3          | 0.01 |
| +T × CO <sub>2</sub>  |                      |       | 0.3            | 0.9  | 0.3        | 0.9  | 0.7        | 0.7  | 1          | 0.5  | 0.5        | 0.8  | 1.1        | 0.4  | 2.1        | 0.04 |
| Water                 |                      |       | 0.8            | 0.6  | 1.2        | 0.3  | 2          | 0.05 | 1.4        | 0.2  | 1          | 0.5  | 1.7        | 0.1  | 1.8        | 0.08 |

+CO<sub>2</sub>, elevated CO<sub>2</sub>; +T, warming. In 2006, only the elevated CO<sub>2</sub> treatment was in place. The effects of irrigation were evaluated separately because the irrigation additions were not crossed with the other treatments. Significant treatment effects at the  $\alpha < 0.05$  are bold. Growing season precipitation (relative to the 30-y site mean) is noted.

over time, whereas subdominant biomass remained stable or slightly increased. Summer irrigation increased soil water content to nearly the same level as in the elevated CO<sub>2</sub> treatments (50) but had no overall effect on the dominant:subdominant biomass ratio across time (ANCOVA  $F = 1.2$ ,  $P = 0.3$ ), suggesting that the effects of elevated CO<sub>2</sub> were not similar to those of irrigation. There was a marginally significant positive effect of warming on the dominant:subdominant biomass (ANCOVA  $F = 3.2$ ,  $P = 0.07$ ; Fig. 1).

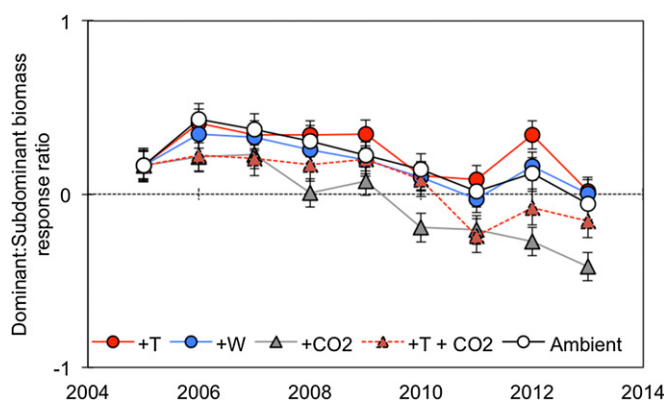
Across the entire plant community, elevated CO<sub>2</sub> and, to a lesser extent, irrigation significantly influenced community composition in dry years, and warming significantly influenced community composition in wet years. However, subdominant plant community composition responded largely to warming (Table 3). The marginally significant effect of irrigation on subdominant community composition in the wet year 2009 could be explained by the late-summer timing of irrigation relative to the timing of precipitation (Table 1). Overall shifts in plant community composition across the 8-y study (Table S1) were mostly driven by changes in the biomass of five species: *B. gracilis* (a C<sub>4</sub> graminoid); the C<sub>3</sub> graminoids *Hesperostipa comata*, *P. smithii*, and *Koeleria macrantha*; and the subshrub *Artemisia frigida* (40% average dissimilarity between 2005 and 2013), with an increase in *A. frigida* and *K. cristata* biomass and a decrease in the other species. Together, CO<sub>2</sub> and warming independently led to divergence in plant community composition, with dominant and subdominant components of the plant community differing in their responses (Table S1). These differential responses reduced community dominance and promoted community evenness and diversity (Fig. S2).

**Community Stability Under Climate Change.** Compositional and biomass stability (i.e., productivity) varied among treatments ( $F_{4,7} = 9.4$ ,  $P < 0.0001$  and  $F_{4,24} = 3.5$ ,  $P = 0.03$ , respectively). Elevated CO<sub>2</sub>, especially in combination with warming, influenced annual plant compositional change (i.e., plot turnover; Fig. 2), maintaining low annual plot turnover for most of the 8-y CO<sub>2</sub> enrichment experiment and conferring compositional stability across time. Similarly, biomass stability was highest in irrigated and elevated CO<sub>2</sub> plots and lowest in ambient and heated plots (Fig. 3). High stability in elevated CO<sub>2</sub> and irrigated plots indicates that productivity remained unchanged across wet and dry years, whereas productivity in ambient and warmed plots was more variable, decreasing in dry years and increasing in wet years (34). Furthermore, the slopes of the relationship between mean

aboveground biomass and temporal SD across the 8-y study varied among the PHACE treatments ( $F_{4,24} = 3.7$ ,  $P = 0.03$ ), and productivity was more sensitive to variation in climate (evidenced by high SD) under ambient conditions than in plots under elevated CO<sub>2</sub> (Fig. 3). Community biomass stability in our study was unrelated to species richness or diversity, but positively related to species evenness ( $F = 6.7$ ,  $P = 0.02$ ; Fig. S2), illustrating the importance of the subdominant community in stabilizing plant productivity across dry years. Together, our results illustrate that elevated CO<sub>2</sub> increases community biomass stability in the face of interannual shifts in precipitation, overcoming the negative effects of warming by increasing plant community evenness.

## Discussion

Our 8-y study included years with substantial climate variation, and plant biomass production varied twofold between the wettest



**Fig. 1.** The effects of the PHACE climate-change treatments on the dominant:subdominant biomass response ratio, calculated as the ratio of dominant species *P. smithii* and *B. gracilis* to the subdominant species across time. Elevated CO<sub>2</sub> treatments were initiated in 2006 and warming and summer irrigation in 2007. +T indicates warmed plots, +W indicates irrigated plots, +CO<sub>2</sub> indicates plots under elevated CO<sub>2</sub>, and +T+CO<sub>2</sub> indicates plots under both warming and elevated CO<sub>2</sub>. Biomass is represented as the least-square means of the ANCOVA model that accounts for baseline differences in biomass in 2005. Error bars are  $\pm 1$  SEM ( $n = 5$  per treatment). A shift to greater abundance of dominant species is indicated by +1, and a shift to greater abundance of subdominant species is indicated by -1.



a positive relationship between stability and species richness or diversity (15, 24, 26), but biomass stability in our study was only positively associated with species evenness, further illustrating the importance of the subdominant community in stabilizing plant productivity across dry years. The relationship between community evenness and biomass stability was especially strong in the plots representative of future climate conditions (namely, plots that received both elevated CO<sub>2</sub> and warming treatments).

Globally, grasslands cover up to 1/3 of the terrestrial surface and provide important ecosystem services, including carbon sequestration and forage for livestock. Over the past two centuries, many grasslands across the globe have been transformed by agriculture, grazing, fire, and invasive species. Anthropogenic influences are expected to intensify to keep pace with a growing global population that relies heavily on grassland production. In addition to land use, climate impacts most aspects of grassland function (51, 58). In rangelands, the economic value of livestock operations relies on stable production of key forage grass species (45, 59). Others have noted that the dominant species in our plots, *P. smithii* and *B. gracilis*, as well as the subdominants *H. comata*, *C. eleocharis*, *A. frigida*, *S. coccinea*, and *K. macrantha*, are relatively drought- and disturbance-tolerant (60–63), and our findings generally agree. Although the dominance patterns in ambient mixed-grass prairie plots shifted slightly over the 8-y study, the transition from *P. smithii*- and *B. gracilis*-dominated communities to the subdominants occurred gradually. Despite the general shift in dominance in ambient plots, overall plant community biomass and composition remained relatively stable, but rendered more stable under elevated CO<sub>2</sub>. As climate becomes increasingly variable (30, 64), with longer and more pronounced droughts in the future, elevated CO<sub>2</sub> appears to further stabilize this mixed-grass prairie community against shifts in precipitation. Thus, our results suggest that production can be maintained under elevated CO<sub>2</sub> conditions, but with subdominant plant species contributing more to total production and perhaps increasing in dominance. Such shifts in species composition can have important implications for rangeland quality and should be considered in future management plans for mixed-grass prairie ecosystems.

## Methods

The PHACE experiment was initiated in 2005 at the U.S. Department of Agriculture High Plains Grasslands Research Station, located west of Cheyenne, WY (41° 11' N latitude, 104° 54' W longitude). The vegetation at PHACE is a northern mixed-grass prairie and is dominated by C<sub>3</sub> graminoids. C<sub>4</sub> grasses make up 25% of the plant community, and 20% of the plant community consists of sedges, forbs, and small shrubs. Annual precipitation at the site averages 384 mm; mean winter air temperature is –2.5 °C, and mean summer air temperature is 17.5 °C. The site was regularly grazed since 1974, but was fenced to prevent livestock grazing in 2005. The soil at the site is a fine-loamy, mixed, mesic Aridic Argisols, pH 7.9. In the north side of the site, the soil is Ascalon series, and the south side soil is Altvan series; as a result of these soil type differences, we blocked the experimental units by soil type and included block as a random effect in the models. In 2005, 25 circular 3.4-m-diameter plots were established with a 60-cm-deep impermeable barrier to prevent lateral inflow. Elevated atmospheric CO<sub>2</sub> was applied starting in 2006 and accomplished by using mini-FACE (The Free Air CO<sub>2</sub> Enrichment) technology [ambient CO<sub>2</sub> ~385 parts per million by volume (ppmv) and elevated CO<sub>2</sub> 600 ± 40 ppmv (65)], using 3.3-m FACE rings. A differential daytime/nighttime warming (1.5/3 °C) treatment was applied by using infrared heaters (66) in full factorial design, with five replicates for each of the four combinations (ambient, +CO<sub>2</sub> and ambient temperature; ambient CO<sub>2</sub> and + temperature; +CO<sub>2</sub> and ambient temperature; and + CO<sub>2</sub> + temperature). Elevated CO<sub>2</sub> treatments were initiated in early spring of 2006, and warming and summer irrigation were started in the spring of 2007. All plots were irrigated by hand in 2006 to facilitate establishment of an associated experiment (20 mm × eight irrigation dates, the equivalent of 160 mm of additional growing-season precipitation). Beginning in 2007, plots were irrigated to match the water saving under elevated CO<sub>2</sub> treatments, receiving an equivalent of 18 mm of precipitation with each irrigation × five irrigation dates in 2007, the equivalent of 90 mm of additional

growing-season precipitation. From 2008 to 2011, irrigated plots received an equivalent of 21 mm of precipitation three times during the growing season (equivalent to 63 mm of additional precipitation), and in the dry year of 2012, 65 mm of water was added four times during the growing season (equivalent to 260 mm). In 2013, 24 mm was added before harvest. The site, experimental setup, and treatment performance are described in detail in ref. 34. Annual aboveground production was clipped by species to the crown in 12 subplots of 625 cm<sup>2</sup> in each experimental plot, alternating the location of the clipped area each year. Vegetation was harvested in late July, at the time of peak biomass. All harvested material was sorted to species, dried for 3 d at 55 °C, and weighed. We used species-specific relative biomass in all subsequent statistical analyses.

**Analyses: Plant Community Productivity and Composition.** To examine the effects of the climate-change treatments over time on plant community composition, we used a two-way permutational analysis of variance (PERMANOVA) on the Bray Curtis similarity index of square-root transformed species-specific relative biomass, with year, elevated CO<sub>2</sub>, and warming as the fixed effects in one model, block as a random effect, and year and irrigation in a separate model because the treatment application was not fully factorial (warming and elevated CO<sub>2</sub> were not crossed with irrigations). The same main effects were tested within each year, with the effects of elevated CO<sub>2</sub> only in 2006 because it was the only treatment in place. The PERMANOVA analysis was complimented with permutational multivariate analysis of dispersion (PERMDISP), a multivariate analysis of dispersion that calculates the centroid of each treatment in multivariate space and calculates the distance of each plot within the treatment from the treatment centroid. We found no significant PERMDISP differences within treatments, indicating that the PERMANOVA results show significant differences among treatments that are not the result of dispersion differences within treatments. A similarity percentage (SIMPER) analysis was performed to quantify the contribution of individual species to compositional differences among treatments and years. The PERMANOVA, PERMDISP, and SIMPER analyses were conducted for the whole community and the subdominant community separately; for the latter, we removed the two dominant species, *P. smithii* and *B. gracilis*, and recalculated the relative biomass of the remaining species. Principle coordinates analysis (PCO) ordination was performed to visualize whole plot composition in a 2D space. The multivariate community analyses PCO, PERMANOVA, and SIMPER analyses were performed by using PRIMER (Version 1.0.3; Plymouth Marine Laboratory).

The multivariate analyses were complimented with a series of univariate analyses. We calculated a biomass response ratio by taking the difference between dominant and subdominant biomass and dividing it by the sum of dominant and subdominant biomass. Changes in the ratio of dominant (*B. gracilis* and *P. smithii*) to subdominant species biomass over time were analyzed by using an ANCOVA, with block as a random effect, plot number nested within treatment, treatment effects and their interaction as well as their interactions with year, and 2005 biomass and its interaction with year included as covariates to account for differences in starting conditions among plots. Least-square means from the ANCOVA model were plotted to illustrate the effects of the climate-change treatments on the biomass response ratio instead of raw biomass measures because ANCOVA model least-square means account for differences in biomass between plots at the start of the experiment.

**Analyses: Ecosystem Stability.** We assessed the effects of the PHACE climate-change treatments on stability using two approaches. To assess community compositional stability, we first quantified community compositional dissimilarity, taking the inverse of the square-root-transformed Bray Curtis similarity index on the sample × species matrix and calculating the annual percentage of community turnover per plot. Small changes in community composition within a plot from year to year represent greater community stability than larger shifts. The effects of the climate-change treatments on indices of community composition for each year were examined by using an ANOVA, with elevated CO<sub>2</sub> and warming as the main effects and block as a random effect, and followed with Tukey–Kramer post hoc comparisons. A separate one-way ANOVA was used to look at the effect of elevated CO<sub>2</sub> in 2006 and irrigation between 2007 and 2012. To assess temporal biomass stability, *S*, we calculated the mean plot productivity per treatment across the study ( $\mu$ ) and divided by the temporal SD over the same time period ( $\sigma$ ) (17). Log-transformed temporal biomass stabilities were compared among treatments by using a one-way ANOVA, with post hoc Tukey–Kramer comparisons to distinguish treatment differences. All univariate analyses were performed by using JMP (Version 10.0; SAS Institute).

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- Whittaker RH (1975) *Communities and Ecosystems* (Macmillan, New York).
- Walker MD, et al. (2006) Plant community responses to experimental warming across the tundra biome. *Proc Natl Acad Sci USA* 103(5):1342–1346.
- Knapp AK, et al. (2008) Consequences of more extreme precipitation regimes for terrestrial ecosystems. *Bioscience* 58(9):811–821.
- Dukes JS, et al. (2005) Responses of grassland production to single and multiple global environmental changes. *PLoS Biol* 3(10):e319.
- Hudson JMG, Henry GHR (2010) High Arctic plant community resists 15 years of experimental warming. *J Ecol* 98(5):1035–1041.
- Kardol P, et al. (2010) Climate change effects on plant biomass alter dominance patterns and community evenness in an experimental old-field ecosystem. *Glob Change Biol* 16(12):2676–2687.
- Holling CS (1973) Resilience and stability of ecological systems. *Annu Rev Ecol Syst* 4:1–23.
- Walker BH, Noy-Meir I (1982) *Aspects of the Stability and Resilience of Savanna Ecosystems*, eds Huntley B, Walker BH (Springer, Berlin).
- Lepš J, Osbornová-Kosinová J, Rejmanek M (1982) Community stability, complexity and species life history strategies. *Vegetatio* 50:53–63.
- Halpern CB (1988) Early successional pathways and the resistance and resilience of forest communities. *Ecology* 69:1703–1715.
- Tilman D, Downing JA (1994) Biodiversity and stability in grasslands. *Nature* 367:363–365.
- Gunderson LH (2000) Ecological resilience - in theory and application. *Annu Rev Ecol Syst* 31:425–439.
- Allison SD, Martiny JB (2008) Colloquium paper: Resistance, resilience, and redundancy in microbial communities. *Proc Natl Acad Sci USA* 105(Suppl 1):11512–11519.
- Van Ruijven J, Berendse F (2010) Diversity enhances community recovery, but not resistance, after drought. *J Ecol* 98(1):81–86.
- Post E (2013) Erosion of community diversity and stability by herbivore removal under warming. *Proc Biol Sci* 280(1757):20122722.
- Tilman D, et al. (2001) Diversity and productivity in a long-term grassland experiment. *Science* 294(5543):843–845.
- Tilman D, Reich PB, Knops JMH (2006) Biodiversity and ecosystem stability in a decade-long grassland experiment. *Nature* 441(7093):629–632.
- Belote RTR, Jones RHR, Wieboldt TTF (2012) Compositional stability and diversity of vascular plant communities following logging disturbance in Appalachian forests. *Ecol Appl* 22(2):502–516.
- Sala OE, et al. (2000) Global biodiversity scenarios for the year 2100. *Science* 287(5459):1770–1774.
- Bloor JMG, Pichon P, Falcimagne R, Leadley P, Soussana J-F (2010) Effects of warming, summer drought, and CO<sub>2</sub> enrichment on aboveground biomass production, flowering phenology, and community structure in an upland grassland ecosystem. *Ecosystems* 13(1):888–900.
- Morgan JA, et al. (2004) CO<sub>2</sub> enhances productivity, alters species composition, and reduces digestibility of shortgrass steppe vegetation. *Ecol Appl* 14(1):208–219.
- Ainsworth EAE, Long SP (2005) What have we learned from 15 years of free-air CO<sub>2</sub> enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO<sub>2</sub>. *New Phytol* 165(2):351–371.
- Blumenthal DM, et al. (2013) Invasive forb benefits from water savings by native plants and carbon fertilization under elevated CO<sub>2</sub> and warming. *New Phytol* 200(4):1156–1165.
- Cantarel AAM, Bloor JMG, Soussana J-F (2012) Four years of simulated climate change reduces above-ground productivity and alters functional diversity in a grassland ecosystem. *J Veg Sci* 24(1):113–126.
- Cramer W, et al. (2001) Global response of terrestrial ecosystem structure and function to CO<sub>2</sub> and climate change. *Glob Change Biol* 7(4):357–373.
- Zavaleta ESE, Shaw MRM, Chiariello NRN, Mooney HAH, Field CBC (2003) Additive effects of simulated climate changes, elevated CO<sub>2</sub>, and nitrogen deposition on grassland diversity. *Proc Natl Acad Sci USA* 100(13):7650–7654.
- Albert KR, et al. (2011) Effects of elevated CO<sub>2</sub>, warming and drought episodes on plant carbon uptake in a temperate heath ecosystem are controlled by soil water status. *Plant Cell Environ* 34(7):1207–1222.
- Williams AL, et al. (2007) Warming and free-air CO<sub>2</sub> enrichment alter demographics in four co-occurring grassland species. *New Phytol* 176(2):365–374.
- Ehleringer JR, Cerling TE, Helliker BR (1997) C<sub>4</sub> photosynthesis, atmospheric CO<sub>2</sub>, and climate. *Oecologia* 112(3):285–299.
- Polly HW, et al. (2013) Climate change and North American rangelands: Trends, projections, and implications. *Rangeland Ecol Manag* 66(5):493–511.
- Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421(6918):37–42.
- Tylanakis JM, Didham RK, Bascompte J, Wardle DA (2008) Global change and species interactions in terrestrial ecosystems. *Ecol Lett* 11(12):1351–1363.
- Zavaleta E, et al. (2003) Grassland responses to three years of elevated temperature, CO<sub>2</sub>, precipitation, and N deposition. *Ecol Monogr* 73(4):585–604.
- Morgan JA, et al. (2011) C<sub>4</sub> grasses prosper as carbon dioxide eliminates desiccation in warmed semi-arid grassland. *Nature* 476(7359):202–205.
- Rogers A, Humphries SW (2000) A mechanistic evaluation of photosynthetic acclimation at elevated CO<sub>2</sub>. *Glob Change Biol* 6(8):1005–1011.
- Morgan JA, Hunt HW, Monz CA (1994) Consequences of growth at two carbon dioxide concentrations and two temperatures for leaf gas exchange in *Paspopyrum smithii* (C<sub>3</sub>) and *Bouteloua gracilis* (C<sub>4</sub>). *Plant Cell Environ* 17(9):1023–1033.
- Kunkel KE, et al. (2013) 2013: Regional climate trends and scenarios for the U.S. national climate assessment. Part 4. Climate of the U.S. Great Plains. *NOAA Technical Report NESDIS* 142-143:82.
- Huxman TE, et al. (2004) Convergence across biomes to a common rain-use efficiency. *Nature* 429(6992):651–654.
- Easterling DR, et al. (2000) Climate extremes: Observations, modeling, and impacts. *Science* 289(5487):2068–2074.
- Allan RP, Soden BJ (2008) Atmospheric warming and the amplification of precipitation extremes. *Science* 321(5895):1481–1484.
- Groisman PY, Knight RW (2008) Prolonged dry episodes over the conterminous United States: New tendencies emerging during the last 40 years. *J Clim* 21:1850–1862.
- McDonald RI, Girvetz EH (2013) Two challenges for U.S. irrigation due to climate change: Increasing irrigated area in wet states and increasing irrigation rates in dry states. *PLoS ONE* 8(6):e65589.
- Asner GP, Elmore AJ, Olander LP, Martin RE, Harris AT (2004) Grazing systems, ecosystem responses, and global change. *Annu Rev Environ Resour* 29:261–299.
- Heisler-White JL, Blair JM, Kelly EF, Harmony K, Knapp AK (2009) Contingent productivity responses to more extreme rainfall regimes across a grassland biome. *Glob Change Biol* 15(12):2894–2904.
- Biondini ME, Patton BD, Nyren PE (1998) Grazing intensity and ecosystem processes in a northern mixed-grass prairie, USA. *Ecol Appl* 8(2):469–479.
- Leakey ADB (2009) Rising atmospheric carbon dioxide concentration and the future of C<sub>4</sub> crops for food and fuel. *Proc Roy Soc B-Biol Sci* 276(1666):2333–2343.
- Smith MDM, Knapp AKA, Collins SLS (2009) A framework for assessing ecosystem dynamics in response to chronic resource alterations induced by global change. *Ecology* 90(12):3279–3289.
- Belote R, Weltzin J, Norby R (2004) Response of an understory plant community to elevated [CO<sub>2</sub>] depends on differential responses of dominant invasive species and is mediated by soil water availability. *New Phytol* 161(3):827–835.
- Barton BT, Beckerman AP, Schmitz OJ (2009) Climate warming strengthens indirect interactions in an old-field food web. *Ecology* 90(9):2346–2351.
- Pendall E, et al. (2013) Warming reduces carbon losses from grassland exposed to elevated atmospheric carbon dioxide. *PLoS ONE* 8(8):e71921.
- Knapp AK, Smith MD (2001) Variation among biomes in temporal dynamics of aboveground primary production. *Science* 291(5503):481–484.
- Thébault A, Mariotte P, Lortie CJ, MacDougall AS (2014) Land management trumps the effects of climate change and elevated CO<sub>2</sub> on grassland functioning. *J Ecol* 102(4):896–904.
- Mariotte P (2014) Do subordinate species punch above their weight? Evidence from above- and below-ground. *New Phytol* 203(1):16–21.
- Yang H, et al. (2010) Community structure and composition in response to climate change in a temperate steppe. *Glob Change Biol* 17(1):452–465.
- Whittaker RH (1965) Dominance and diversity in land plant communities: Numerical relations of species express the importance of competition in community function and evolution. *Science* 147(3655):250–260.
- Grime JP (1998) Benefits of plant diversity to ecosystems: Immediate, filter and founder effects. *J Ecol* 86(6):902–910.
- Suding KN, et al. (2005) Functional- and abundance-based mechanisms explain diversity loss due to N fertilization. *Proc Natl Acad Sci USA* 102(12):4387–4392.
- Hovenden MJ, Newton PCD, Wills KE (2014) Seasonal not annual rainfall determines grassland biomass response to carbon dioxide. *Nature* 511(7511):583–586.
- Dunn BH, et al. (2010) Long-term production and profitability from grazing cattle in the northern mixed grass prairie. *Rangeland Ecol Manag* 63(2):233–242.
- Milchunas D, Schulz K, Shaw R (1999) Plant community responses to disturbance by mechanized military maneuvers. *J Environ Qual* 28(28):1533–1547.
- Frank DA, McNaughton SJ (1991) Stability increases with diversity in plant communities: Empirical evidence from the 1988 Yellowstone drought. *Oikos* 62(3):360–362.
- Epstein HE, Lauenroth WK, Burke IC, Coffin DP (1998) Regional productivities of plant species in the Great Plains of the United States. *Plant Ecol* 134(2):173–195.
- Craine JM, et al. (2012) Global diversity of drought tolerance and grassland climate-change resilience. *Nature Clim Change* 3(1):1–5.
- Hsu JS, Adler PB (2014) Anticipating changes in variability of grassland production due to increases in interannual precipitation variability. *Ecosphere* 5(5):art58.
- Miglietta F, Lanini M, Bindi M, Magliulo V (1997) Free air CO<sub>2</sub> enrichment of potato (*Solanum tuberosum*, L.): Design and performance of the CO<sub>2</sub>-fumigation system. *Glob Change Biol* 3(5):417–427.
- Kimball BA, et al. (2008) Infrared heater arrays for warming ecosystem field plots. *Glob Change Biol* 14(2):309–320.