

Final Report for DOE Project: *Climate Effects on Plant Range Distributions and Community Structure of Pacific Northwest Prairies (DE-FG02-09ER64719)*

Scott Bridgham and Bart Johnson, Principal Investigators

University of Oregon

Summary

Pacific Northwest (PNW) prairies are an imperiled ecosystem that contain a large number of plant species with high fidelity to this habitat. The few remaining high-quality PNW prairies harbor a number of sensitive, rare, and endangered plant species that may be further at-risk with climate change. Thus, PNW prairies are an excellent model system to examine how climate change will affect the distribution of native plant species in grassland sites.

Our experimental objectives were to determine:

- (1) how climate change will affect the range distribution of native plant species,**
- (2) what life history stages (i.e., germination and establishment, growth to maturity, and reproduction) are most sensitive to climate change in a group of key indicator native species,**
- (3) the robustness of current restoration techniques and suites of species to changing climate, and in particular, the relative competitiveness of native species versus exotic invasive species,**
- (4) the effects of climate change on carbon and nutrient cycling and soil-microbial-plant feedbacks.**

We addressed these objectives by experimentally increasing temperature 2.5 to 3.0 °C above ambient with overhead infrared lamps and increasing wet-season precipitation by 20% above ambient in three upland prairie sites in central-western Washington, central-western Oregon, and southwestern Oregon (Fig. 1). Additional precipitation was applied within 2 weeks of when it fell so precipitation intensity was increased, particularly during the winter rainy season but with minimal additions during the summer dry season. Each treatment was replicated five times in 7.1 m² circular plots, for a total of 60 plots across our three sites. Our experimental treatments were consistent with the average predictions of an ensemble of general circulation models that the PNW will warm by 1.8°C in the 2040s and by 3.0°C in the 2080s, and that the current Mediterranean climate will experience an enhanced seasonal precipitation cycle with more rainfall during the normal rainy season and drier conditions in the already dry summer season



Fig. 1. Example of site infrastructure. At each site, we have 20 plots within a large fenced area. Non-heated plots have ‘dummy’ heaters hung to control for any shading effect from the heat lamps, and there is an on-site rain collection surface for the precipitation treatment.

(Mote and Salathé 2010). *These three sites also represent a 520-km natural climate gradient of increasing degree of severity of Mediterranean climate from north to south (Fig. 2). This experimental design of a manipulative climate change experiment embedded within a regional climate gradient provided a robust platform for examining regionally consistent versus site-specific plant and ecosystem responses to climate change.*

We have a paper in press that addresses objectives 1 and 2 during the first full year of treatment implementation in 2011 (Pfeifer-Meister et al. 2013), as well as a more general paper on climate change effects on plant communities in the PNW (Bachelet et al. 2011). We additionally have six manuscripts in various stages of preparation that address the remaining objectives, four of which should be submitted within the next 1-3 months.

Training a diverse group of students was an important priority for this project. We have graduated two M.S. students who have worked on this project (Goklany 2012, Wilson 2012), a Ph.D. student has a planned defense date of winter 2014, and another Ph.D. student who did one of his dissertation chapters on the experiment. Both M.S. students and one of the Ph.D. students are female. Additionally as part of the Summer Program for Undergraduate Research (SPUR) at the University of Oregon, we have had a Native American undergraduate and an Afro-American undergraduate (both female) work on the project full-time during summers, as well as do an independent research project and report on that project to the larger SPUR program. The Native American student is currently attending graduate school in conservation ecology. We have also had three high school students (2 female) work on the project full-time during summers as part of the Apprenticeships in Science and Engineering (ASE) Program. All did independent projects and reported on those projects as part of an ASE banquet.

It took two years to completely build the extensive infrastructure for this experiment, and we ran it from fall 2010 through 2012. A renewal of the project was recommended for funding by the NSF Macrosystems Biology program manager in November 2012, but the proposal was ultimately not funded because of federal budget sequestration. A second renewal is now pending with the Macrosystems Biology program.

Temperature and Soil Moisture

The gradient of increasing intensity of Mediterranean climate from north to south in our three sites is clearly demonstrated by the duration of time with extremely low soil matric potential in the control treatments (Fig. 2). The drying effect of the heating treatment is also clearly evident; however the precipitation treatment had minimal effect at reducing drought stress because most of it was applied during the rainy season, similar to what is predicted to occur in the PNW with future climate change. These differences in soil water availability are central to understanding the plant and soil responses that are described below.

Range-Limited Plant Results (Objectives 1 and 2)

To address climate impacts on species ranges, we seeded 12 native prairie plant species, representing a variety of functional groups, that have their northern range limit within the PNW. We split these species into three 'range groups' (4 species each) based on the ecoregion of their current northern range-limit. At each site, we planted the closest local population of each species (depending on range group this involved moving some species north of their current range) and

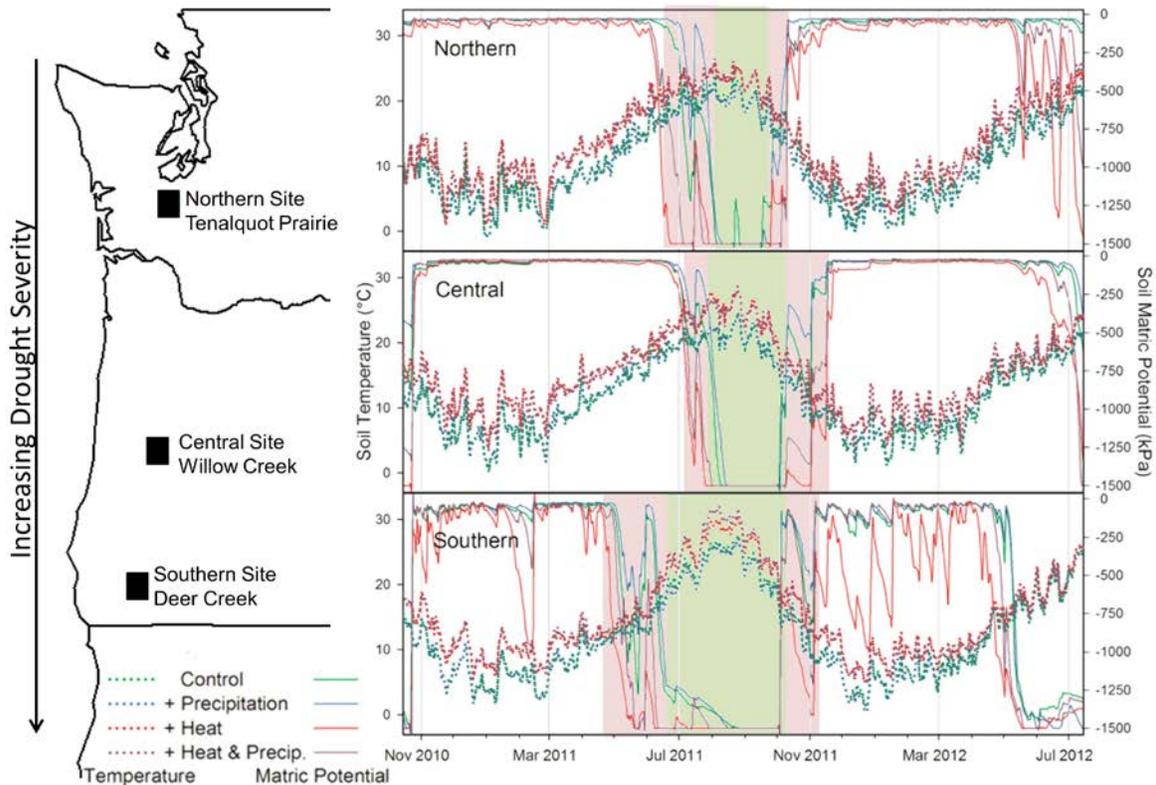


Fig. 2. Soil temperature and matric potential for treatments in the three sites. Green and pink shading represents the drought period in the control and heating treatments, respectively. Soil volumetric water content was converted to soil matric potential using site-specific soil physical characteristics (Saxton and Rawls 2006).

monitored each successive demographic stage. The 2011 results are in press in Pfeifer-Meister et al. (2013), and the results from 2012 strongly support the first year results (manuscript in prep.).

Under ambient conditions at each site, species planted within their current range had higher recruitment than those outside their range (read horizontally across the panels in Fig. 3), although all species were able to grow at each site. Whether a species was found within or beyond its current range was an important determinant of how it responded to the climate treatments. When species were planted within their current range, increased temperature generally decreased recruitment (read vertically down each panel in Fig. 3). However, when species were moved north of their current range, added heat was neutral for recruitment. These results are consistent with expectations that it may be necessary for species to shift their ranges poleward to remain viable. Surprisingly, we found this result even when species were near their current northern range limit, where one might expect that increased temperatures would be beneficial. This suggests that species' geographic ranges may already be limited by dispersal. In general, precipitation effects on recruitment were minimal. Germination was the most significant hurdle for successful recruitment, and germination and recruitment results were generally the same. In 2012, we grew the 12 range-limited species with and without aboveground competition (~ realized and fundamental niches, respectively), and found similar results without competition (data not shown).

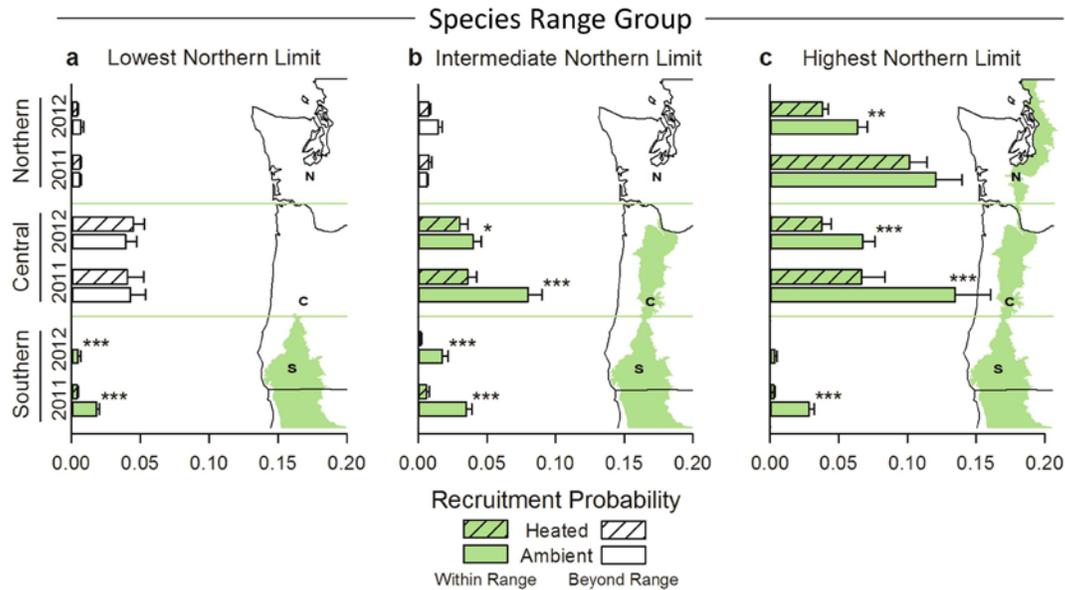


Fig. 3. Recruitment (defined as the probability of germinating and surviving to the end of year one) \pm 1 SE at each experimental site in heated and unheated plots for two years of results (2011 and 2012). Each panel shows a 'range-group' of 4 species defined by the ecoregion of their northern range-limit: (a) Lowest Northern Limit (\sim 41-43°N), (b) Intermediate Northern Limit (\sim 43-46°N), and (c) Highest Northern Limit (\sim 46-50°N). Shaded bars indicate species that were planted within their current range and correspond to shaded ecoregions of inlaid maps. Unshaded bars indicate species that were moved north of their current range. Asterisks indicate significant heating effects within a site.

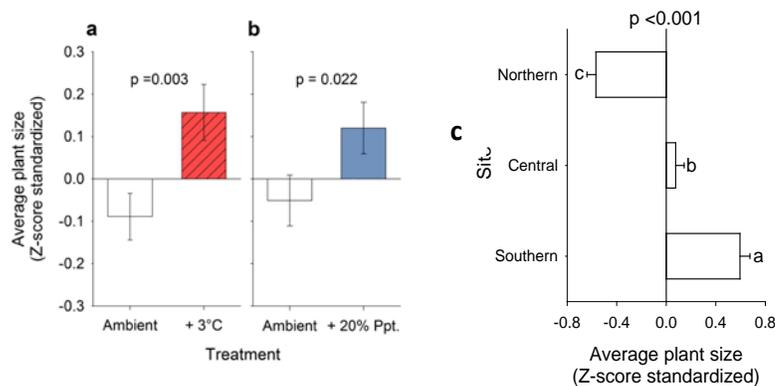


Fig. 4. Mean average plant size (z-score transformed) \pm SE in the (a) unheated and heated plots, (b) ambient precipitation and precipitation addition plots and (c) at each site across all range groups. Results are for 2011 only.

In contrast to recruitment, plant size and seed production were not controlled by a species' current range (range group by treatment interactions $p \geq 0.34$). Instead site and treatment effects were paramount. Surviving plants produced more biomass in heated (Fig. 4a) and precipitation plots (Fig. 4b), and these treatment effects were independent of one another. Seed production (measured for annuals only) was highly correlated with biomass (Pearson correlations: $0.64 \geq r \leq 0.98$) and results were similar to those for biomass. Nutrient availability

was also greater in the heated treatments (see nutrient results below), suggesting that this size response was mediated by an indirect positive effect of warmer temperatures on nutrients. Consistent with this proposed mechanism, both plant size and nutrient availability progressively decreased from south to north, which is a natural nutrient availability gradient (Fig. 4c). A greenhouse experiment with soils from all sites and four plant species verified these soil effects on plant growth were independent of climate (Wilson 2012). So although a species' current range was an important determinant of *whether* a plant could establish, subsequent fitness effects appeared to be controlled by resource availability. This is an excellent example of how embedding a manipulative climate change experiment within a natural climate gradient allows one to decouple site-specific local controls from regionally consistent climatic responses.

Our results suggest that future climate change will decrease the ability of prairie species to persist in their current range because a negative effect of increased temperature on recruitment generally outweighed its positive effect on growth and seed production (Objectives 1 and 2). This negative effect of warming was observed even at the coolest edge of species' current ranges. However, when moved beyond their current range, the net effect of increased temperature was no longer negative because of a neutral effect on recruitment and a positive effect on growth and seed production. These responses were generally consistent across 12 species in a variety of plant functional groups, suggesting they may be widespread among prairie species.

Plant Community Responses (Objective 3)

Plant cover generally increased from north to south in both 2011 and 2012, and was also generally significantly increased by heating (Fig. 5). As discussed below, these results reflected the inherent greater nutrient availability across the sites (southern >> central > northern) and the effect of warming increasing nitrogen and phosphorus availability.

Despite the fact that all sites were originally vegetated with primarily perennial introduced grasses and subsequently were seeded with the same diverse mix of native species, plant community composition quickly diverged based upon regional position on the gradient and the heating treatment. By 2012, the number of introduced annuals and overall introduced species increased dramatically from north to south (annual cover approximately tripled at each step in the gradient) and with heating within a site (Fig. 6). Species richness (and also

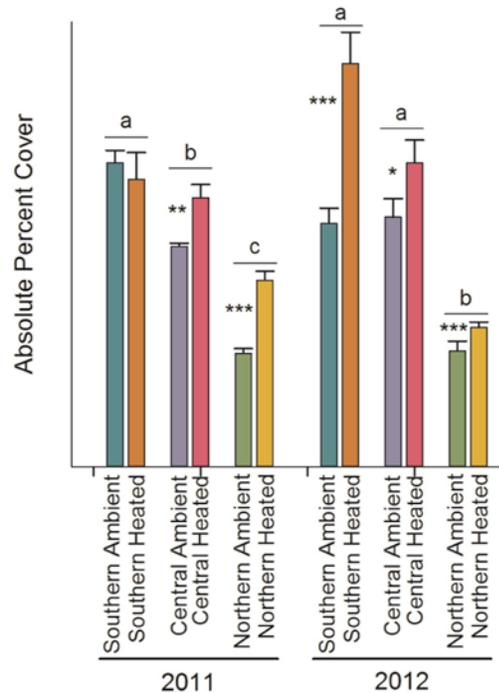


Fig. 5. Percent cover in 2011 and 2012. Small letters indicate significant difference among sites within years; asterisks indicate significant heating affects.

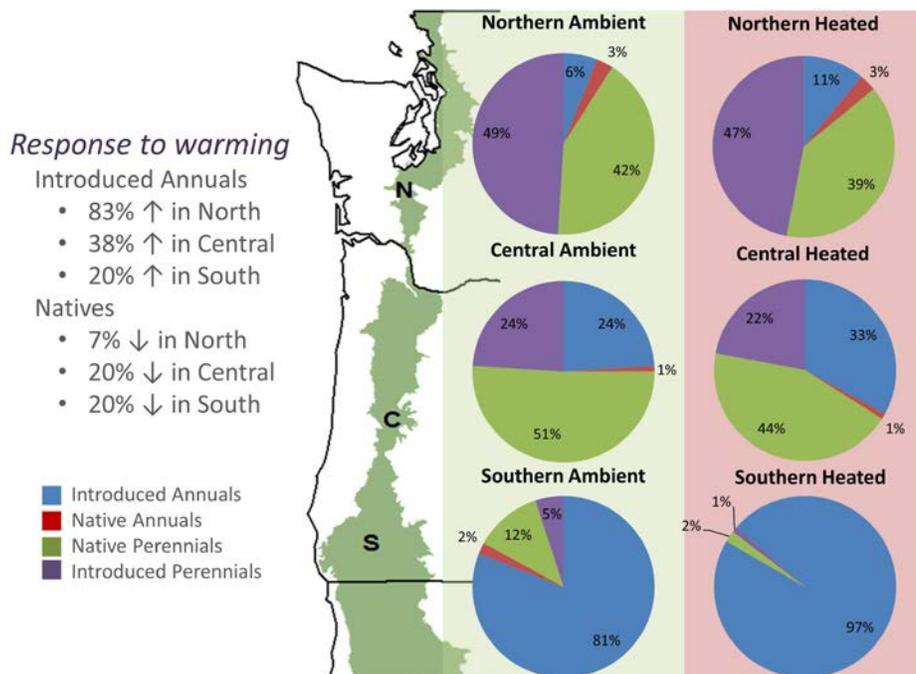


Fig. 6. Percentage of plant functional groups in 2012 in the ambient and heated treatments at each site.

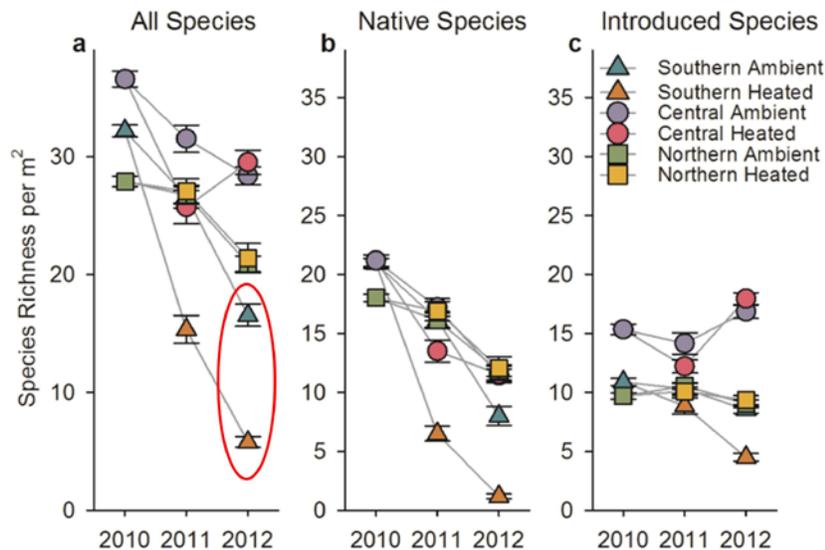


Fig. 7. Species richness in 2010 (pre-treatment), 2011 (year 1), and 2012 (year 2). Red ellipse in panel A emphasizes the dramatic loss in richness in the southern site over time, particular in the heated treatment.

diversity, not shown) decreased from north to south, with warming, and through successional time (Fig. 7a). These trends were primarily driven by native species (Fig. 7b), and the number of introduced species in some cases even increased over time (Fig. 7c). The largest loss of species richness over time and with heating occurred in the southern site with its more severe Mediterranean climate.

These effects are demonstrated dramatically in a Nonmetric Multidimensional Scaling (NMDS) of community structure that explained 97% of the variance in the first two axes (Fig. 8). The x-axis largely describes the regional climate gradient, and the second axis describes successional time. Heating moved the communities further to the upper left in the NMDS, largely driven by the increasing dominance of introduced annual grasses, reflecting more severe Mediterranean climatic conditions.

Our results are strongly suggestive of a wider biogeographic pattern in plant functional group composition. There is a general observation that grasslands in California tend to be dominated by annual introduced grasses, whereas further north they are dominated by perennial grasses (with southern OR being somewhat intermediate). Our results suggest that this pattern is at least partly due to the increasingly severe Mediterranean climate from north to south in Pacific Coast grasslands, and that climate change will make more northern grasslands become increasingly dominated by annual introduced grasses, similar to their southern counterparts. Also, overall warming appears to decrease plant diversity, and particularly the diversity of native species. Given the high biodiversity value of grasslands in the PNW and their imperiled status, this finding has important consequences. In contrast, the precipitation treatment had few significant effects on the plant communities. Our results may also be extrapolatable to other Mediterranean grassland ecosystems, which are biodiversity hot spots. These results are in final revision before submission for publication.

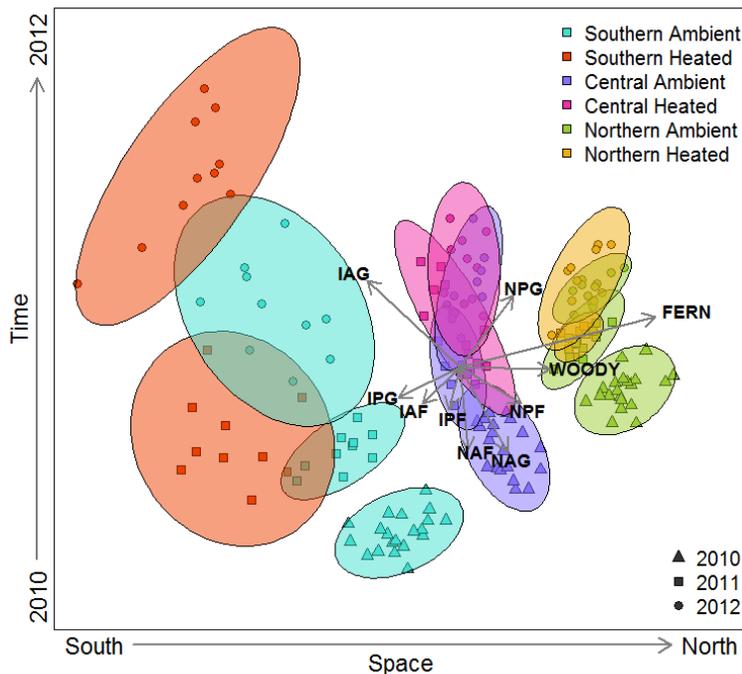


Fig. 8. Nonmetric Multidimensional Scaling (NMDS) of plant cover in all climate treatments, sites, and years. Ellipses are included for visual differentiation of groups. Vectors are the average species loadings for each functional group (N: native, I: Introduced, A: annual, P: perennial, G: graminoid, F: forb). Note that the y-axis predominantly represents change over time and the x-axis represents change over space, with warming shifting communities up (enhanced succession) and left (further south).

Ecosystem Results (Objective 4)

Nutrient Availability. We used anion and cation exchange resins to seasonally measure the availability of numerous soil chemical constituents (NO_3 , NH_4 , P, Ca, Mg, K, Fe, Mn, Cu, Zn, B, S, Pb, Cd) in the plots. The southern site has much higher total N (mostly driven by NO_3) and P availability, the central site has intermediate N and P availability, and the northern site has low N and P availability (Fig. 9). This primary reflects the different parent materials from which the soils were derived (base-rich alluvium in the southern site; sandstone, siltstone, and tuffaceous materials in the central site; sandy glacial outwash and volcanic ash in the northern site). Thus, our climate gradient is also a nutrient-availability gradient. One could view this as a confounding variable in our experimental design, but it is virtually impossible to find three widely dispersed sites with exactly the same soils. Moreover, we view this as an opportunity to determine how consistent climate responses are across a diverse set of regional grassland sites.

Heating generally increased N and P availability when it had a significant main effect, with minimal effects of added precipitation (Fig. 9). Thus despite large differences among sites in N and P availability due to differences in soils and large seasonal variability, a relatively straight-forward picture of higher temperatures enhancing nutrient availability occurred, with minimal effects due to changing precipitation.

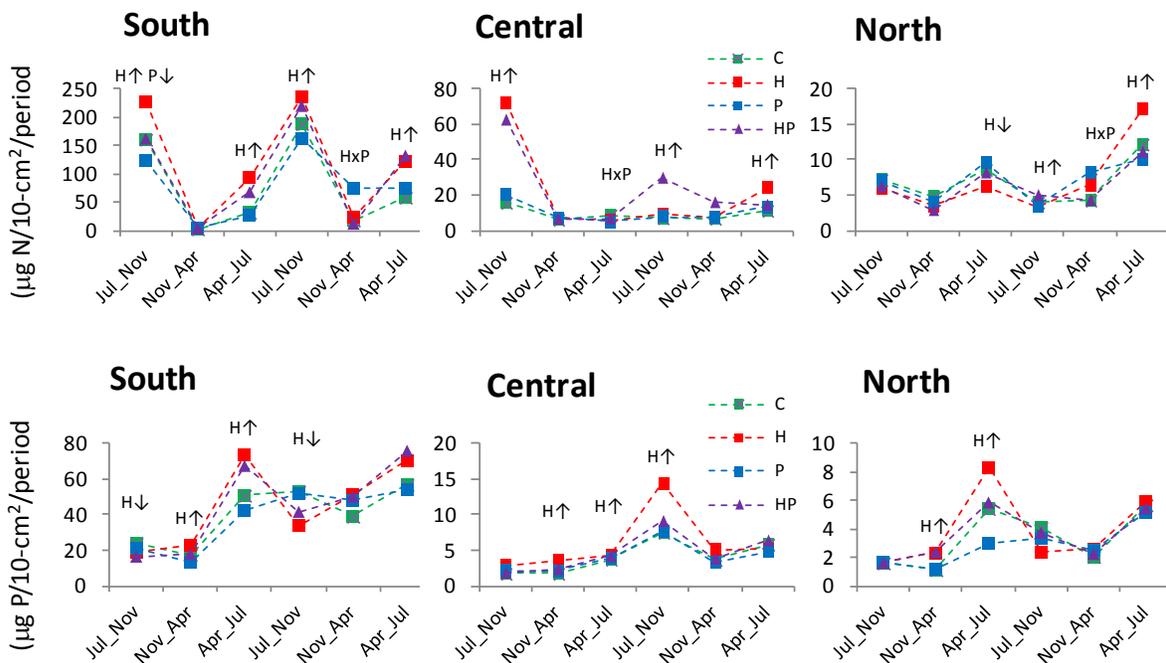


Fig. 9. Total inorganic nitrogen (top) and phosphorus (bottom) availability determined with cation and anion exchange resins at each site in control (C), heated (H), precipitation (P), and heat + precipitation (HP) plots. Letters with arrows indicate significant main effects of H and P during a particular time period. Note differences in scales on the y-axes.

Plant Biomass and Net Primary Productivity (NPP). We also examined seasonal effects on green plant canopy biomass with a handheld instrument to measure canopy reflectance as Normalized Difference Vegetation Index (NDVI). As with nutrient availability, we observed a strong seasonal interaction between the climatic gradient and the treatments for NDVI. For

example, heating increased NDVI in winter in all sites (Fig. 10). However, heating decreased NDVI in the dry season, and this effect occurred earlier in the spring in the southern site and progressively later in the central and northern sites. Thus, we again observed a regionally consistent climate effect driven by the greater degree of seasonal moisture stress as one moves from north to south in the PNW.

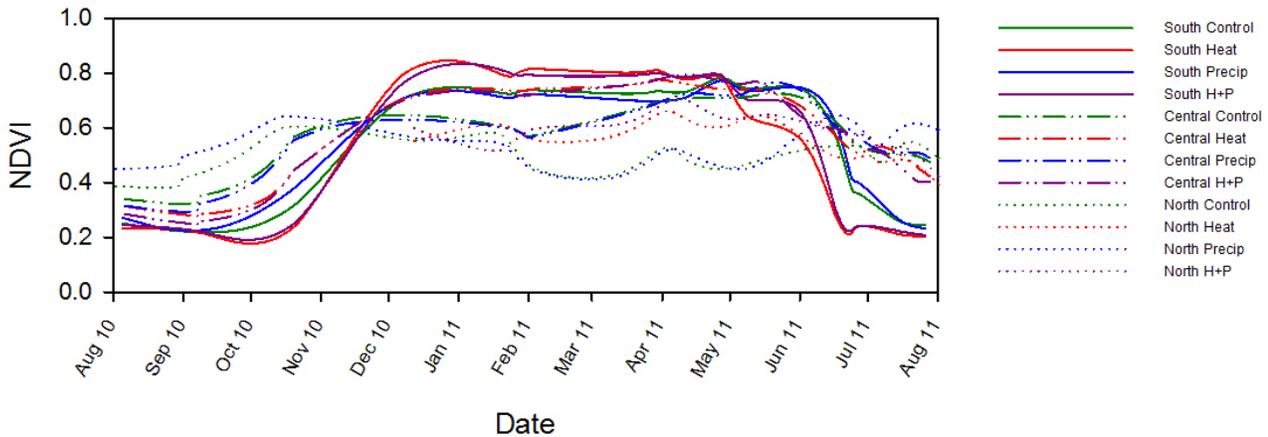


Fig. 10. Normalized Difference Vegetation Index (NDVI) as a measure of green biomass in each of the treatments in the three sites for a 1 year period beginning Aug. 10, 2010. The northern site did not have heating begun until Oct. 27, 2010.

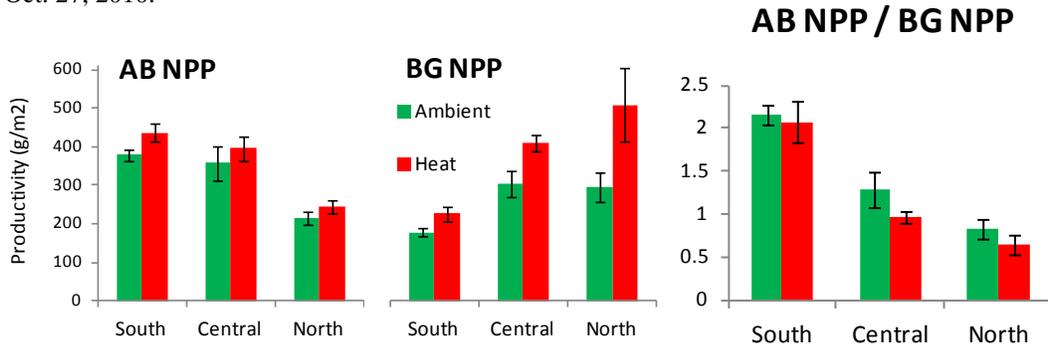


Fig. 11. Aboveground (AB NPP) and belowground (BG NPP) net primary production and the ratio of these two variables in the heated and ambient plots at the three sites.

These results were corroborated with aboveground NPP in 2011, with the lowest NPP in the northern site (Fig. 11). However, the southern site had the lowest belowground NPP, so there were overall small differences in total NPP among sites. The progressive decrease in allocation to aboveground vegetation as one moves from southern Oregon to Washington was likely due to site-level differences in nutrient availability (Fig. 9). However, we observed positive heating effects on both aboveground and belowground NPP that were consistent among sites, indicating that this response was driven solely by climate.

Soil Carbon Dynamics. A Ph.D. student (Lorien Reynolds) extensively studied soil carbon dynamics in our plots, and here we focus on the soil respiration response, which is in a manuscript that is nearly ready for submission for publication. We again observed large

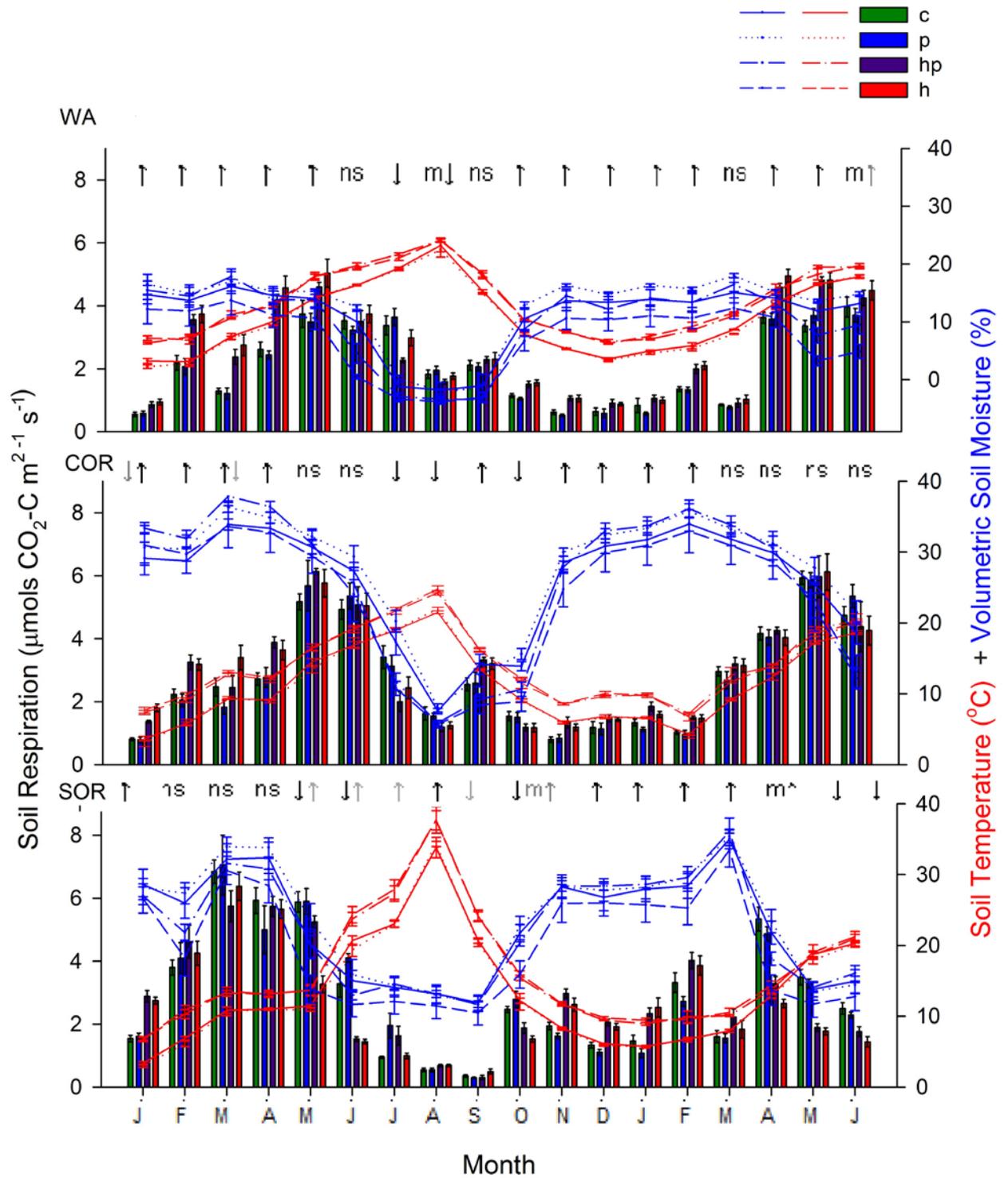


Fig. 12. Soil respiration (bars), soil moisture (blue lines) and temperature (red lines) by treatment for each site in control (c), heat (h), precipitation (p), and heat + precipitation (hp) treatments. Arrows indicate significant and non-significant (ns) heat (black; m=marginal) and precipitation (grey) effects. WA=Washington, COR=Central Oregon, SOR=Southern Oregon.

interactions between the Mediterranean climate gradient and the effect of the climate treatments on soil respiration. In general, the effect of the warming on soil respiration tracked soil moisture availability (Fig. 12), with warming increasing soil respiration when soil moisture was high or increasing, and either decreasing soil respiration or having no effect when soil moisture was decreasing or low. The number of months with positive responses to warming also increased from southern Oregon to Washington, consistent with decreasing drought intensity and soil moisture limitation. Again, there were relatively few significant soil respiration responses to the precipitation treatment.

The response of annual soil respiration to heating was also greater further northwards where soil moisture is less limiting (Fig. 13; $p = 0.001$). Heating did not affect soil respiration in southern Oregon, it caused a marginally significant increase in soil respiration in central Oregon in both 2011 and 2012, and it significantly increased soil respiration in Washington in both years. Soil respiration also increased marginally in southern Oregon due to the precipitation treatment in 2011, consistent with its position at the dry end of the moisture gradient.

We examined a range of models that incorporate both the effects of temperature and soil moisture on soil respiration, and we found no model adequately captured the complicated seasonal controls over soil respiration across the climate gradient and treatments. These findings support those of Falloon et al. (2011), who demonstrated that current earth system models inadequately capture the interactive controls of soil moisture and temperature on soil respiration, particularly in drier ecosystems.

A growing literature indicates that increasing moisture-limitation may offset soil respiration response to warming (e.g., Schindlbacher et al. 2012, Suseela et al. 2012). To our knowledge, ours is the first study to document this with a manipulative warming-precipitation study done at a regional scale, which provides much stronger evidence than either single site studies or models. The consequences may be that currently projected estimates for ecosystem carbon loss are overestimated if soil moisture becomes limiting.

Plant-Microbial Interactions. A master's student (Hannah Wilson) examined mycorrhizal colonization rates in the roots of four species in the control and heat treatments at each site (Wilson 2012). She observed a negative effect of heating on mycorrhizal colonization that was consistent across plant species and sites. This manuscript is in the process of being prepared for publication.

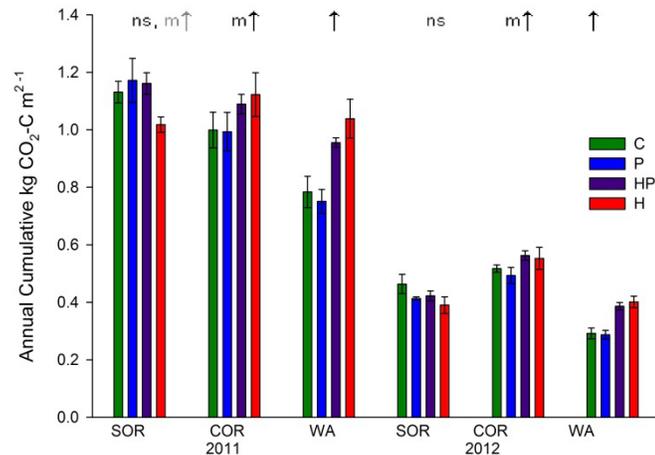


Fig. 13. Annual cumulative CO₂-C respired for 2011 (January-December) and 2012 (January-June). Arrows indicate significant, nonsignificant (ns) and marginally significant (m) effects. Black = heat, grey = precipitation.

A Ph.D. student, Roo Vandegrift, examined the effects of the treatments on colonization of a leaf endophyte (*Epichloë*), mycorrhizae, and dark septate root endophytes on several grasses. Both leaf endophytes and mycorrhizae are thought to be generally have a symbiotic relationship with plants, whereas the effects of dark septate root endophytes on plants is uncertain. Mr. Vandegrift's main finds are that (i) *Epichloë* modulates the host's response to the environment, as well as other symbionts' response to the environment, and (ii) the overall effect on the host is the result of the integration of the effects of the total consortium of symbionts.

Other Plant Responses

Plant Physiology Effects. Another master's student (Maya Goklany) examined heating and precipitation effects on the photosynthesis and water dynamics of four grass species in the central Oregon site only because of the very labor-intensive nature of these measurements (Goklany 2012). Ms. Goklany found climate treatments effects on a number of plant physiological variables, although these effects varied by plant species, season, and time of day. She related treatment effects on plant size and reproduction to the direct effects on plant physiology and the indirect effects on plant cover (and thus competition) and soil nutrient availability using structural equation modeling. A manuscript from this research is currently being prepared for publication.

Conclusions

Objective 1: How will climate change affect the range distribution of native plant species?

Recruitment of plant species within their ranges was negatively impacted by increased temperatures, but for species planted north of their current range, increased temperature was neutral. However, for surviving plants climate treatments and site-specific factors (e.g., nutrient availability) were the strongest predictors of plant growth and seed set. When recruitment and plant growth are considered together, increased temperatures are negative within a species current range but beyond this range they become positive. Our results underscore the importance of including plant vital rates into models that are examining climate change effects on plant ranges, but this is rarely done (with niche-based models being the norm) and there is little data to parameterize demographic plant models.

Objective 2: What life history stages are most sensitive to climate change in a group of key indicator native species?

Germination was the most critical stage for plant response across all sites and climate treatments.

Objective 3: How will climate change affect the robustness of current restoration techniques and suites of species to changing climate, and in particular, the relative competitiveness of native species versus exotic invasive species?

Warming altered plant community composition, decreased diversity, and increased total cover, with warmed northern communities over time becoming more like ambient communities further south. In particular, warming increased the cover of annual introduced species, suggesting that the observed biogeographic pattern of increasing invasion by this plant functional group in US West Coast prairies as one moves further south is at least in part due to climate. Our results suggest that with the projected increase in drought severity with climate change, Pacific

Northwest prairies may face an increase of invasion by annuals, similar to what has been observed in California, resulting in novel species assemblages and shifts in functional composition, which in turn may alter ecosystem function.

Objective 4: What are the effects of climate change on carbon and nutrient cycling and soil-microbial-plant feedbacks?

Heating generally increased nutrient availability and plant productivity across all sites.

The seasonality of soil respiration responses to heating were strongly dependent on the Mediterranean climate gradient in the PNW, with heating responses being generally positive during periods of adequate soil moisture and becoming neutral to negative during periods of low soil moisture. The asynchrony between temperature and precipitation may make soils less sensitive to warming.

Other general findings:

Precipitation effects were minimal for all measured responses indicating the importance of increased temperatures in driving biotic responses to climate change in Mediterranean ecosystems. However, substantially increased precipitation during the dry season would almost certainly have profound effects, but the opposite is predicted by current climate change models for the PNW.

A manipulative climate change experiment embedded within a natural climate gradient provides unique insights into the degree to which biotic responses to climate change are regionally consistent and site-dependent. Perhaps surprisingly, most climatic effects that we observed were either consistent in the three sites or could be readily interpreted in terms of the gradient of increasing intensity of the Mediterranean climate from north to south.

Publications from this Project to Date

- Bachelet, D., B. R. Johnson, S. D. Bridgham, P. V. Dunn, H. E. Anderson, and B. M. Rogers. 2011. Climate change impacts on Western Pacific Northwest prairies and savannas. *Northwest Science* 85:411-429. (<http://www.bioone.org/doi/full/10.3955/046.085.0224>)
- Goklany, M. E. 2012. To Escape, Avoid, or Tolerate: Physiological Responses of Perennial Grasses to Experiment Climate Change. Master's thesis, University of Oregon, Eugene, OR.
- Wilson, H. E. 2012. Climate change effects on arbuscular mycorrhizal fungi and prairie plants along a Mediterranean climate gradient. Master's thesis, University of Oregon, Eugene, OR.
- Pfeifer-Meister, L., S. D. Bridgham, T. Tomaszewski, C. J. Little, L. L. Reynolds, M. E. Goklany, and B. R. Johnson. 2013. Pushing the limit: Experimental evidence of climate effects on plant range distributions. *Ecology*: in press.

Manuscripts in Preparation (most to be submitted within 1-3 months)

- Pfeifer-Meister, L., S. D. Bridgham, L. L. Reynolds, M. E. Goklany, C. J. Little, H. E. Wilson, and B. R. Johnston. Consistent shifts in community composition and diversity in response to experimental climate manipulations across a latitudinal gradient in Pacific Northwest prairies. Target journal *Ecology Letters*.

- Pfeifer-Meister, L., S. D. Bridgham, L. L. Reynolds, M. E. Goklany, C. J. Little, H. E. Wilson, and B. R. Johnston. Climate effects on native plant range distributions in Pacific Northwest prairies. Target journal Nature Climate Change.
- Reynolds, L. L., L. Pfeifer-Meister, B. R. Johnson, and S. D. Bridgham. Soil respiration response to climate change in Pacific Northwest prairies is mediated by a regional Mediterranean climate gradient. Target journal Climate Change Biology.
- Goklany, M. E., B. R. Johnson, L. Pfeifer-Meister, and S. D. Bridgham. To escape, avoid, or tolerate: Physiological responses of perennial grasses to experimental climate change. Target journal New Phytologist.
- Wilson, H. E., B. R. Johnson, B. J. M. Bohannon, L. Pfeifer-Meister, R. C. Mueller, and S. D. Bridgham. Climate change effects on arbuscular mycorrhizal fungi and prairie plants along a Mediterranean climate gradient. Target journal New Phytologist.
- Bridgham, S. D., L. Pfeifer-Meister, L. L. Reynolds, M. E. Goklany, C. J. Little, H. E. Wilson, and B. R. Johnson. Climate effects on plant productivity, biomass, and nutrient availability on Pacific Northwest prairies across a Mediterranean climate gradient. Target journal Climate Change Biology.

Presentations from this Project

- Bridgham, S. D. and B. Johnson. 2009. Climate effects on plant range distributions in (and the restoration of) prairies. Department of Energy, Program for Ecosystem Research Investigators Workshop, Washington, DC, Nov. 17-18.
- Bridgham, S. D. and B. Johnson. 2009. Climate change effects on plant range distribution in (and the restoration of) prairies. Web seminar to The Nature Conservancy personnel in Washington and Oregon. March 12, 2010.
- Bridgham, S. D. Experimental determination of climate change effects on native prairies in the Pacific Northwest. Public talk at Deer Creek Center, Selma, OR, April 8, 2010.
- Bridgham S., B. Johnson., L. Pfeifer-Meister, T. Tomaszewski, L. Reynolds, and M. Goklany. 2010. How will climate change affect the range distributions of native prairie plants and the viability of restored prairies in the Pacific Northwest? 2010 Pacific NW Climate Science Conference, June 15-16, Portland, Oregon.
- Bridgham, S. D., B. Johnson, T. Tomaszewski, L. Pfeifer-Meister, M. Goklany, L. Reynolds, and H. Wilson. 2011. Poster: Temperature and Precipitation Effects on Plant Range Distributions, Community Structure, and Ecosystem Function across a Natural Climate Gradient in Prairie Ecosystems. Invited participant in workshop on How Do We Improve Earth System Models: Integrating Earth System Models, Ecosystem Models, Experiments and Long-Term Data, organized by Integrated Network for Terrestrial Ecosystem Research on Feedbacks to the Atmosphere and Climate (INTERFACE), Feb. 28-Mar. 3, Captiva Island, FL.
- Goklanay, M., B. Johnson, L. Pfeifer-Meister, T. Tomaszewski, and S. Bridgham. 2011. How climate change affect the physiology and productivity of perennial grasses in Pacific Northwest prairies? Ecological Society of America, Aug. 7-12, Austin, TX.
- Bridgham, S. D., L. Pfeifer-Meister, T. Tomaszewski, L. Reynolds, M. Goklany, H. Wilson, and B. R. Johnson. 2011. Climate impacts on terrestrial ecosystems and managed resources. Pacific Northwest Climate Science Conference, Sept. 13-14, Seattle, WA.
- Pfeifer-Meister, L., B. R. Johnson, T. Tomaszewski, M. Goklany, L. Reynolds, H. Wilson, and S. D. Bridgham. 2011. Natural and experimental climatic effects on native plant range

- distributions in the Pacific Northwest. Pacific Northwest Climate Science Conference, Sept. 13-14, Seattle, WA.
- Wilson, H., B. Johnson, and S. Bridgham. 2011. Increased experimental heating decreases arbuscular mycorrhizal abundance across a latitudinal gradient in annual prairie forbs. Pacific Northwest Climate Science Conference, Sept. 13-14, Seattle, WA.
- Reynolds, L., B. Johnson, L. Pfeifer-Meister, T. Tomaszewski, and S. Bridgham. 2011. The response of soil respiration to simulated climate change along a latitudinal climate gradient in Pacific Northwest prairies. Pacific Northwest Climate Science Conference, Sept. 13-14, Seattle, WA.
- Bridgham, S. D., L. Pfeifer-Meister, T. Tomaszewski, M. E. Goklany, L. L. Reynolds, C. J. Little, and Bart R. Johnson. 2012. Pushing limits: Altered temperature and precipitation differentially affect plant species inside and beyond their current ranges. Poster presented at the U.S. DOE Terrestrial Ecosystem Science Principal Investigators Meeting, Washington, DC, Apr. 23-24.
- Reynolds, L. L., B. R. Johnson, L. Pfeifer-Meister, T. Tomaszewski, and S. D. Bridgham. 2012. Response of soil respiration to experimental warming and increased precipitation intensity depends upon a latitudinal climate gradient in Pacific Northwest grasslands. Poster presented at the U.S. DOE Terrestrial Ecosystem Science Principal Investigators Meeting, Washington, DC, Apr. 23-24.
- Vandegrift, A. W. B. A. Roy, L. E. Pfeifer-Meister, T. E. Tomaszewski, B. R. Johnson, and S. D. Bridgham. 2012. Climate change and *Epichloë* endophyte infection influences arbuscular mycorrhizal colonization rates in grasses. Annual Meeting of the Ecological Society of America, Portland, OR, Aug. 5-10.
- Wilson, H. E. B. R. Johnson, R. C. Mueller, L. Pfeifer-Meister, T. Tomaszewski, B. J. M. Bohannon, and S. D. Bridgham. 2012. Experimental warming across a natural climate gradient reverses soil nutrient effects on arbuscular mycorrhizal abundance in prairie plants. Annual Meeting of the Ecological Society of America, Portland, OR, Aug. 5-10.
- Pfeifer-Meister, L., S. D. Bridgham, T. Tomaszewski, M. E. Goklany, L. L. Reynolds, C. J. Little, and B. R. Johnson. 2012. Pushing Limits: Altered temperature and precipitation differentially affect plant species inside and outside their current ranges. Annual Meeting of the Ecological Society of America, Portland, OR, Aug. 5-10.
- Reynolds, L. L., B. R. Johnson, L. Pfeifer-Meister, T. E. Tomaszewski, and S. D. Bridgham. 2012. Response of soil efflux to experimental warming and increased precipitation intensity depends upon latitudinal climate gradient in Pacific Northwest grasslands. Annual Meeting of the Ecological Society of America, Portland, OR, Aug. 5-10.
- Tomaszewski, T., B. R. Johnson, L. Pfeifer-Meister, M. E. Goklany, L. L. Reynolds, H. E. Wilson, and S. D. Bridgham. 2012. Site-dependent versus regionally consistent effects of increased temperature and precipitation on plant community composition, productivity, and soil nutrient availability in restored Pacific Northwest prairies. Annual Meeting of the Ecological Society of America, Portland, OR, Aug. 5-10.
- Pfeifer-Meister, L., S. D. Bridgham, T. Tomaszewski, L. Reynolds, M. E. Goklany, C. J. Little, H. E. Wilson. 2013. Climate change impacts on biodiversity in Pacific Northwest prairies: Shifts in plant range distributions and functional group composition. Annual meeting of the Northwest Science Association and Cascadia Prairie-Oak Partnership, Portland, OR, March 20-23.

- Pfeifer-Meister, L., S. D. Bridgham, T. Tomaszewski, M. E. Goklany, L. L. Reynolds, C. J. Little, and B. R. Johnson. 2013. Pushing the limit: Experimental evidence of climate effects on plant range distributions. Dept. of Energy Terrestrial Ecosystem/Subsurface Biogeochemical Research Joint Investigators Meeting, Potomac, MD, May 13-15, 2013.
- Pfeifer-Meister, L., S. D. Bridgham, T. Tomaszewski, L. L. Reynolds, M. E. Goklany, C. J. Little, H. E. Wilson, and B. R. Johnson. 2013. Consistent shifts in the community composition and diversity in response to experimental climate manipulations across a latitudinal gradient in Pacific Northwest prairies. Dept. of Energy Terrestrial Ecosystem/Subsurface Biogeochemical Research Joint Investigators Meeting, Potomac, MD, May 13-15, 2013.
- Reynolds, L. L., B. R. Johnson, L. Pfeifer-Meister, T. Tomaszewski, and S.D. Bridgham. 2013. Response of soil respiration to experimental warming and increased precipitation intensity depends upon a latitudinal climate gradient in Pacific Northwest grasslands. Dept. of Energy Terrestrial Ecosystem/Subsurface Biogeochemical Research Joint Investigators Meeting, Potomac, MD, May 13-15, 2013.

References

- Bachelet, D., B. R. Johnson, S. D. Bridgham, P. V. Dunn, H. E. Anderson, and B. M. Rogers. 2011. Climate change impacts on western Pacific northwest prairies and savannas. *Northwest Science* 85:411-429.
- Falloon, P., C. D. Jones, M. Ades, and K. Paul. 2011. Direct soil moisture controls of future global soil carbon changes: An important source of uncertainty. *Global Biogeochemical Cycles* 25:GB3010.
- Goklany, M. E. 2012. To Escape, Avoid, or Tolerate: Physiological Responses of Perennial Grasses to Experiment Climate Change. University of Oregon, Eugene, OR.
- Mote, P. W. and E. P. Salathé. 2010. Future climate in the Pacific Northwest. *Climatic Change* 102:29-50.
- Pfeifer-Meister, L., S. D. Bridgham, T. Tomaszewski, C. J. Little, L. L. Reynolds, M. E. Goklany, and B. R. Johnson. 2013. Pushing the limit: Experimental evidence of climate effects on plant range distributions. *Ecology*:in press.
- Saxton, K. E. and W. J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society of America Journal* 70:1569.
- Schindlbacher, A., S. Wunderlich, W. Borken, B. Kitzler, S. Zechmeister-Boltenstern, and R. Jandl. 2012. Soil respiration under climate change: prolonged summer drought offsets soil warming effects. *Global Change Biology* 18:2270-2279.
- Suseela, V., R. T. Conant, M. D. Wallenstein, and J. S. Dukes. 2012. Effects of soil moisture on the temperature sensitivity of heterotrophic respiration vary seasonally in an old-field climate change experiment. *Global Change Biology* 18:336-348.
- Wilson, H. E. 2012. Climate change effects on arbuscular mycorrhizal fungi and prairie plants along a Mediterranean climate gradient. Master's thesis. University of Oregon, Eugene, OR.