

# COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 11-1					<b>FOR NSF USE ONLY</b>	
<b>NSF 12-524</b>		<b>03/21/12</b>			<b>NSF PROPOSAL NUMBER</b>	
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)						
<b>DEB - Long-Term Ecological Research</b>						
<b>DATE RECEIVED</b>	<b>NUMBER OF COPIES</b>	<b>DIVISION ASSIGNED</b>	<b>FUND CODE</b>	<b>DUNS#</b> (Data Universal Numbering System)	<b>FILE LOCATION</b>	
				<b>555917996</b>		
EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN)		SHOW PREVIOUS AWARD NO. IF THIS IS <input checked="" type="checkbox"/> A RENEWAL <input type="checkbox"/> AN ACCOMPLISHMENT-BASED RENEWAL		IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES <input type="checkbox"/> NO <input checked="" type="checkbox"/> IF YES, LIST ACRONYM(S)		
<b>416007513</b>		<b>0620652</b>				
NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE			ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE			
<b>University of Minnesota-Twin Cities</b>			<b>200 OAK ST SE</b>			
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<b>0023879000</b>						
NAME OF PRIMARY PLACE OF PERF			ADDRESS OF PRIMARY PLACE OF PERF, INCLUDING 9 DIGIT ZIP CODE			
<b>University of Minnesota-Twin Cities</b>			<b>University of Minnesota-Twin Cities</b>			
			<b>2660 Fawn Lake Drive NE</b>			
			<b>Bethel ,MN ,550059718 ,US.</b>			
IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)		<input type="checkbox"/> SMALL BUSINESS <input type="checkbox"/> FOR-PROFIT ORGANIZATION		<input type="checkbox"/> MINORITY BUSINESS <input type="checkbox"/> WOMAN-OWNED BUSINESS		<input type="checkbox"/> IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE
TITLE OF PROPOSED PROJECT <b>LTER: Biodiversity, Multiple Drivers of Environmental Change and Ecosystem Functioning at the Prairie Forest Border</b>						
REQUESTED AMOUNT \$ <b>5,879,701</b>	PROPOSED DURATION (1-60 MONTHS) <b>72</b> months		REQUESTED STARTING DATE <b>01/01/13</b>		SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE	
CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW						
<input type="checkbox"/> BEGINNING INVESTIGATOR (GPG I.G.2)			<input type="checkbox"/> HUMAN SUBJECTS (GPG II.D.7) Human Subjects Assurance Number _____			
<input type="checkbox"/> DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)			Exemption Subsection _____ or IRB App. Date _____			
<input type="checkbox"/> PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)			<input type="checkbox"/> INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)			
<input type="checkbox"/> HISTORIC PLACES (GPG II.C.2.j)			_____			
<input type="checkbox"/> EAGER* (GPG II.D.2) <input type="checkbox"/> RAPID** (GPG II.D.1)			<input type="checkbox"/> HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)			
<input type="checkbox"/> VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date _____						
PHS Animal Welfare Assurance Number _____						
PI/PD DEPARTMENT <b>Dept. of Ecology, Evolution &amp; Behavior</b>		PI/PD POSTAL ADDRESS <b>100 Ecology Building</b>				
PI/PD FAX NUMBER <b>612-624-6777</b>		<b>1987 Upper Buford Circle</b>				
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## BIODIVERSITY, MULTIPLE DRIVERS OF ENVIRONMENTAL CHANGE, AND ECOSYSTEM FUNCTIONING AT THE PRAIRIE FOREST BORDER

The overarching goal of the Cedar Creek Long Term Ecological Research program (CDR) is to **use the interplay of long-term experiments, long-term observations, and theory to gain a mechanistic and predictive understanding of the dynamics and functioning of grassland, savanna, lake, and forest communities and ecosystems**. Patterns observed in long-term experimental and observational studies are used to generate hypotheses of the underlying causative mechanisms, which are tested by integrating and synthesizing studies of population, community, and ecosystem interactions, processes, and feedbacks. CDR science places particular emphasis on the ways in which human-influenced drivers – loss of native biodiversity, shifts in species composition and land use, climate change, elevated CO<sub>2</sub>, nitrogen (N) deposition – impact the structure and functioning of ecosystems.

Long-term experiments provide crucial insights into ecological responses to changes in environmental drivers since responses depend not only on the impacts of drivers on each species, but also on how those drivers influence interactions among species and ecosystem feedbacks. The proposed CDR renewal research will **continue core studies of the ecological impacts of multiple drivers of environmental change** – N deposition, altered biodiversity, elevated CO<sub>2</sub>, climate warming, and disturbance – while **growing and expanding the existing experimental infrastructure at CDR**. Specifically, CDR renewal research will search simultaneously for generality and novel insights by: (1) establishing a new *Forest and Biodiversity Experiment* to examine the importance of tree species diversity for forest ecosystem functioning; (2) overlaying new warming and precipitation manipulations on existing long-term experiments to further understanding of interactions among global change factors; (3) coordinating a long-term manipulation of nutrients and consumers replicated at CDR and five other LTER sites and at ~50 other sites around the world towards achieving general understanding of resource and consumer control of grassland ecosystems; (4) expanding research on the ecology and evolution of urbanizing ecosystems to uncover generalities in the ecosystem impacts of residential development; and (5) establishing new research in aquatic ecosystems to explore the nature of multiple nutrient limitation. The **intellectual merit** of the proposed work at CDR arises from the combination of theoretical and long-term observational and empirical studies that will iteratively provide a more mechanistic and predictive understanding of how ecological systems respond to interacting human-driven environmental changes at multiple biological, spatial, and temporal scales, and how these human-induced changes alter the ability of ecosystems to provide the services that support human health and well-being.

The proposed renewal research will expand CDR's **broader impacts** through the promotion of K-12 teaching, training, and learning; enhancement of infrastructure; creative dissemination of results to the broader public; and advising of government official and agencies. CDR will continue to expand its Schoolyard LTER, a signature professional development program for K-12 teachers and inquiry-based field tours for K-12 students, which has grown six-fold since 2006, reaching more than 6000 teachers and students in 2011. CDR's Schoolyard LTER will continue partnerships to train educators of Native American students and strengthen engagement with urban, underserved schools. For example, this proposal includes funds for a new program to offset transportation costs for schools participating in CDR programs. CDR also will continue training diverse undergraduates from across the country (>200 undergraduate in past 5 years) and will continue to serve as a fundamental resource for graduate and post-doctoral training.

Results from research at CDR will continue to impact both the scientific community through research publications (>200 during the last 6 years) and the broader public through classes, interviews with the media, participation in public forums and advising government officials. The project will *enhance the infrastructure for research and education*. For example, data from experiments at CDR support research well beyond the boundaries of CDR and UMN: ~20% of the papers using CDR data have been written by researchers with no direct connection to CDR. The proposed work will build on this successful data-sharing model by doubling the personnel working on information management in order to speed the delivery and clarity of high-quality, publically accessible data. More broadly, the proposed work will benefit society by increasing understanding of how human activities alter the functioning of the ecosystems on which humans depend. For example, work at CDR has been at the forefront of quantifying the factors that control the ability of ecosystems to provide vital services including the sequestration of atmospheric carbon, removal of nutrients and toxins from groundwater, and the sustainable production of biofuels. The proposed work will expand these efforts by developing partnerships with global experimental networks, increasing research efforts in human-dominated ecosystems, and expanding research into forested and aquatic ecosystems.

## TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.B.2.

	Total No. of Pages	Page No.* (Optional)*
Cover Sheet for Proposal to the National Science Foundation		
Project Summary (not to exceed 1 page)	1	_____
Table of Contents	1	_____
Project Description (Including Results from Prior NSF Support) (not to exceed 15 pages) <b>(Exceed only if allowed by a specific program announcement/solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)</b>	32	_____
References Cited	14	_____
Biographical Sketches (Not to exceed 2 pages each)	10	_____
Budget (Plus up to 3 pages of budget justification)	18	_____
Current and Pending Support	21	_____
Facilities, Equipment and Other Resources	2	_____
Special Information/Supplementary Documents (Data Management Plan, Mentoring Plan and Other Supplementary Documents)	5	_____
Appendix (List below. ) <b>(Include only if allowed by a specific program announcement/ solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)</b>	_____	_____
Appendix Items:		

\*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

## SECTION I. RESULTS FROM PRIOR SUPPORT

**LTER DEB-0620652; Biodiversity, Environmental Change and Ecosystem Functioning at the Prairie-Forest Border; David Tilman, Peter Reich, Sarah Hobbie, Stephen Polasky, Jean Knops, Jeannine Cavender-Bares, Linda Kinkel, Rebecca Montgomery, and Jennifer Powers; 2006-2012.**

Since January 2006, when we submitted our current LTER grant, the Cedar Creek LTER (CDR) team has published 214 papers in peer reviewed journals, including 28 papers in *Ecology or Ecological Monographs*, 17 in *Ecology Letters*, 12 in *Science*, 12 in *PNAS*, and 7 in *Nature*, plus an additional 8 Responses or Replies in *Science*, *Nature*, and *PNAS*. These 214 papers have been cited >8000 times, with three papers cited >500 times each and 15 others cited >100 times each. Several of these papers, including our most highly cited paper (Fargione et al. 2008), were “broader impacts” contributions that synthesized our findings and applied them to issues such as the greenhouse gas impacts of alternative biofuels, or how biodiversity could be used to simultaneously provide goods (such as biofuels) and ecosystem services (carbon sequestration, water purification). Our 214 publications report results from a total of 47 different sets of experiments, with four of these – the biodiversity, nitrogen (N) addition, CO<sub>2</sub> x nitrogen x biodiversity, and litter decomposition experiments – accounting for half of our publications. In addition, CDR data, often downloaded from our website, were used by non-CDR scientists in >40 publications, including 8 papers that have been cited >100 times each. These high-impact papers by non-CDR scientists are mainly multi-site data syntheses or meta-analyses. The papers authored by non-CDR scientists demonstrate the success of our open data model at increasing the impacts of CDR research. The full publication list for CDR is at <http://www.cedarcreek.umn.edu/2006-2012publications/>.

We organize this summary of results from prior support around ten highlighted papers. The first eight papers have provided particularly novel insights into the effects of major drivers of community and ecosystem processes at our site, including global change agents. The last two papers are illustrative of our cross-site research and of the “broader impact” papers that were inspired by our on-site research. In addition to these 10 papers, we present results from many other papers in our discussion of proposed research (Section II) because of their direct relevance to that research.

**1: “Loss of plant species after chronic low-level nitrogen deposition to prairie grasslands” (Clark & Tilman 2008 *Nature*).** This was the first multi-decadal experiment to examine the impacts of chronic N addition at rates as low as 10 kg N ha<sup>-1</sup> y<sup>-1</sup> above ambient atmospheric N deposition, a rate comparable to terrestrial N deposition in many industrialized nations. This chronic low-level N addition rate reduced plant species numbers by 17% relative to controls receiving ambient N deposition. Moreover, plant species numbers were reduced more per unit of added N when N was added at lower rates, showing that chronic, low-level N deposition may have a greater impact on diversity than previously thought (Fig. 1).

**2: “Nitrogen effects on decomposition: a five year experiment in eight temperate sites” (Hobbie 2008 *Ecology*).** Although N deposition often increases primary production, its effect on global soil carbon (C) stores also depends on the impact of N deposition on litter decomposition. Long-term decomposition experiments showed that added N increased initial rates of decomposition, but led to shifts in extracellular enzyme activity that resulted in larger recalcitrant litter pools, slowing decomposition in the long term (Fig. 2) (Hobbie 2005, 2008, Hobbie et al. in revision). These results suggest that elevated atmospheric N deposition should contribute to increased rates of C sequestration, an insight that could only be gained by long-term decomposition studies (Adair et al. 2010).

**3: “Biodiversity and ecosystem stability in a decade-long grassland experiment” (Tilman, Reich & Knops 2006 *Nature*).** This paper tested, and found strong support for, our controversial conjecture (Tilman and Downing 1994) that greater numbers of plant species led to greater year-to-year temporal stability of aboveground net primary production. Ecosystem stability was also positively dependent on root mass, a measure of perenniating biomass. Temporal stability of the ecosystem increased with diversity (Fig. 3), despite a lower temporal stability of individual species, because of both portfolio (statistical averaging) and overyielding effects.

**4: “From selection to complementarity: Shifts in the causes of biodiversity-productivity relationships in a long-term biodiversity experiment” (Fargione, Tilman, Dybzinski, Hille-Ris-Lambers, Clark, Harpole, Knops, Reich & Loreau 2007 *Proc. Roy. Soc. B*).** Using the method of Loreau and Hector (2001), this paper showed that the cause of the increasingly positive effect of biodiversity on plant biomass production shifted from sampling (increased likelihood of the presence of very productive species) to strong complementarity (complementary resource use among species) over time (Fig. 4). Furthermore, complementarity was associated with the joint presence of legumes and C4 grasses.

5: “Nitrogen limitation constrains sustainability of ecosystem response to CO<sub>2</sub>” (Reich, Hobbie, Lee, Ellsworth, West, Tilman, Knops, Naeem & Trost 2006 *Nature*) This paper demonstrated a strong interaction between N supply and the capacity for plant growth rates to increase in response to elevated CO<sub>2</sub> (Fig. 5). In particular, after a transient start-up period, low availability of soil N halved the positive response of plant biomass to elevated CO<sub>2</sub> compared to that observed at higher N supply rates. This provided support for the hypothesis (Hungate et al. 2003) that past predictions of future atmospheric CO<sub>2</sub> concentrations likely overestimated the extent that rising CO<sub>2</sub> would stimulate net primary production and C sequestration across the earth’s terrestrial ecosystems.

6: “Plant species loss decreases arthropod diversity and shifts trophic structure” (Haddad, Crutsinger, Gross, Haarstad, Knops & Tilman 2009 *Ecology Letters*). We sampled arthropods for over a decade in an experiment that manipulated the number of grassland plant species. Herbivore and predator species richness were strongly, positively related to plant species richness. Moreover, there was a threefold increase, from low to high plant species richness, in abundances of predatory and parasitoid arthropods relative to their herbivorous prey. These results demonstrate that, over the long term, the loss of plant diversity can lead to decreased arthropod species richness and an increasingly herbivore-dominated foodweb, thereby potentially impacting ecosystem productivity (Fig. 6).

7: “Elevated CO<sub>2</sub> reduces losses of plant diversity caused by nitrogen deposition” (Reich 2009 *Science*). This paper addressed the interactive effects of rising atmospheric CO<sub>2</sub> concentrations and N deposition on plant diversity in the BioCON experiment. Over 10 years, elevated N reduced species richness by 16% at ambient CO<sub>2</sub> but by just 8% at elevated CO<sub>2</sub> (Fig. 7). This resulted from multiple effects of CO<sub>2</sub> and N on plant traits and soil resources that altered competitive interactions among species. Effects on species richness were the result of the aggregate effects of CO<sub>2</sub> and N on soil water, tissue stoichiometry, and total biomass. As a result, elevated CO<sub>2</sub> helped ameliorate the negative effects of N enrichment on species richness.

8: “Shocks to the system: Community assembly of the oak savanna in a 40-year fire frequency experiment” (Cavender-Bares & Reich 2012 *Ecology*) This paper showed that a major drought of the late 1980s caused temporary shifts in community traits (specific leaf area, leaf N, and leaf length), and that adaptive traits that evolved ~80 mya drove the assembly of communities across the fire gradient (Fig. 8). Functional traits and the sorting of species into contrasting fire regimes revealed a clear signature of phylogenetic conservatism. The article is part of a special issue in *Ecology* initiated by a CDR-led LTER working group.

9: “Productivity is a poor predictor of plant species richness” (Adler et al. 2011 *Science*) This paper used data from the Nutrient Network (NutNet) that comprises >70 grassland sites worldwide, including 6 LTER sites, to ask if there is a hump-shaped dependence of diversity on productivity, which has been a largely untested axiom in ecology for three decades (Al-Mufti et al. 1977). There was no evidence for a consistent dependence of diversity on productivity in this uniquely powerful data set (Fig. 9).

10: “Land clearing and the biofuel carbon debt” (Fargione, Hill, Tilman, Polasky & Hawthorne 2008 *Science*) This paper addressed the potential for various biofuels to provide greenhouse gas (GHG) benefits relative to fossil fuels. Analyses showed that the land clearing associated with production of palm nut for biodiesel, corn for ethanol, soybean for biodiesel, and sugarcane for ethanol resulted in a “carbon debt”, the release of sufficient greenhouse gases such that all the biofuels analyzed would have a worse GHG signature than gasoline or conventional diesel for decades to centuries (Fig. 10). This highlighted paper plus two related “broader impact” CDR papers (Tilman, Hill & Lehman 2006, Hill et al 2006) are the most cited of our recent papers. We presented their results in invited congressional testimony and in media interviews.

Finally, during our current LTER award, the CDR team has obtained other federal, state and foundation grants and awards totaling >\$9 M. This leveraging of our LTER funding has greatly expanded both our on-site research and our ability to use it in cross-site syntheses and projects with broad application to major societal environmental issues.

### Broader Impacts

CDR research has provided **benefits to society** by informing public policy debates around the issues of biofuels and carbon sequestration and advancing understanding of the ecological consequences of global environmental change. CDR has promoted **teaching, training, and learning activities** that foster an ecologically and scientifically literate public (see Section III) through the CDR Schoolyard LTER, which has grown tremendously over the grant period (Fig. 11) and now serves >1900 participants annually, and through environmental education-based recreational opportunities for local residents. A new Artist in

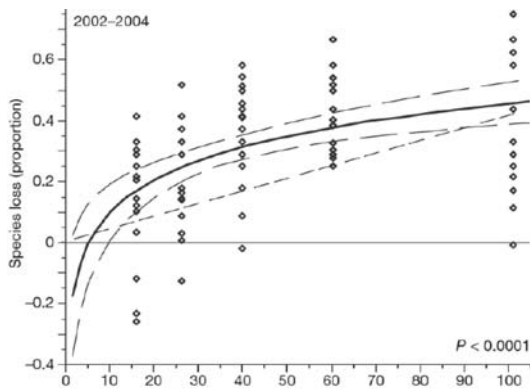
Residency program promotes cross-disciplinary interaction and understanding. Since 2006, CDR contributed to training 36 graduate students and 22 postdocs, as well as 230 undergraduate research interns, who participated in research, often did independent research projects, and attended research and professional development seminars and discussions. **CDR has enhanced infrastructure for research and education** by opening the Lindeman Research and Discovery Center in 2008, providing new laboratory, teaching, meeting, reception and office spaces and hosting our Schoolyard LTER program.

CDR has **broadened the participation of underrepresented groups** by increasing education of and outreach to those groups in our region. In 2011, our K-12 program partnered with the UMN STEM Education Center to host a workshop for secondary teachers of Native American students. Curriculum included ecology presentations and investigations through the lens of climate change and Native American culture. CDR graduate students have participated in Teaching SMART (Science, Math and Research), a volunteer program that connects university graduate students with underserved urban elementary schools. With funding from the State of Minnesota Office of Higher Education, CDR staff developed the *Get Ready!* college-preparedness program, a week-long residential summer science camp for at-risk 10<sup>th</sup> graders focusing on science research methods and ecology studies.

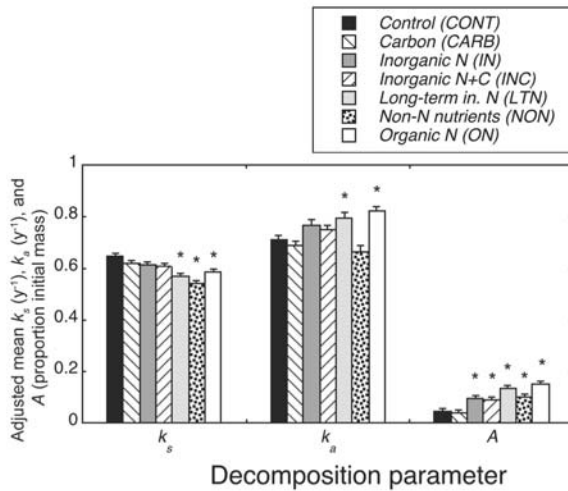
CDR **enhances scientific and technological understanding** through public engagement of PIs and CDR staff with social and traditional media and with government officials and agencies, and by populating the CDR website (>150 hits per day) with data designed to be easily used by scientists, and by the general public via links to Facebook.

Since 2006, CDR researchers were invited twice to present at the NSF LTER Mini-Symposium, aimed at showcasing to Washington the relevance and broader impacts of LTER research. During this award period, CDR research has been featured in 45 newspaper and magazine articles; 37 radio and TV interviews; and 220 invited talks around the world. CDR researchers served on two different subcommittees of the President's Council of Advisors on Science and Technology, MN State Energy Committee, and on the MN Governor's Climate Change Advisory Group. We provided testimony to the US House Agriculture Committee Chair and Staff, the US House and Senate Energy and Natural Resources Committee, the US Senate Environment and Public Works Committee and the US Senate Committee on Agriculture, Nutrition and Forestry, the Minnesota Senate Agriculture Committee, the Minnesota House and Senate Energy and Environment Committees, the Minnesota House Environment & Natural Resources Committee, and the Minnesota House Energy Policy and Finance Committees. We also hosted dignitaries at CDR, including former Vice President Walter Mondale and Prime Minister of Norway Jens Stoltenberg, who came to Cedar Creek to see our global change experiments.

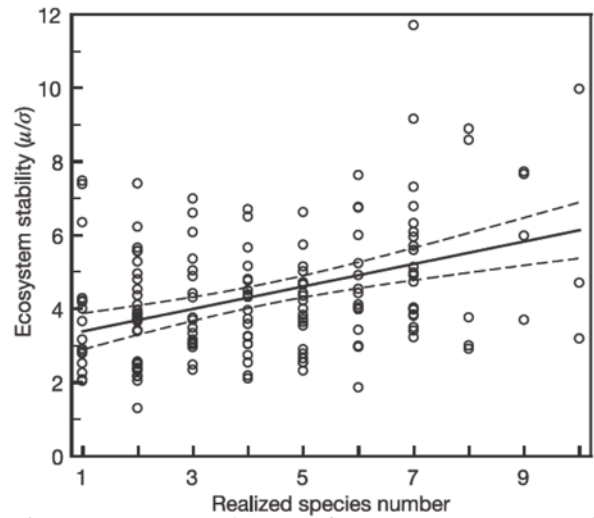
**Results of Supplement Funding.** We received social science and international supplements to our LTER award. Social science supplements expanded our "Twin Cities Household Ecosystem Project" (TCHEP; <http://www.tchep.umn.edu/>), in which we study of the patterns and controls of biogeochemical fluxes through households (the along an urban to exurban gradient extending to CDR (Fig. 12) (Fissore et al. 2011ab, Submitted). TCHEP found that many environmentally significant household activities exhibit disproportionality whereby a small number of households contribute greatly to overall household fluxes. The international supplement funded a German graduate student, Sonya Knapp, who led an international study of human impacts on plant diversity in urban households. S Knapp et al. (2012) demonstrated that urbanization causes homogenization of naturally regenerated yard plant communities. The project applied a new LTER-based phylogenetic database and "TRY" functional trait databases to urban ecology research (Beaulieu et al. 2012). Additional social science supplement funds support ongoing analyses of the social drivers of residential landscape decisions around biodiversity. LTER supplement funds also purchased a new Costech Soil Element Analyzer (housed at co-PI Knops' Ecosystem Analysis Laboratory at UNL) to accommodate larger soil samples, allowing accurate measurement of soil C and a higher throughput of CDR samples. Finally, we received supplement funds to support a History of Science postdoc, Gina Rumore, who conducted oral history interviews with current and former LTER scientists and located and reviewed LTER document archives to explore the historical origins of the LTER network concept. She presented her research at the Columbia History of Science Group Annual Meeting and at the annual meeting of the American Society for Environmental History (ASEH). In March she will take part in a panel discussion at ASEH of uses of environmental history in long-term ecological research.



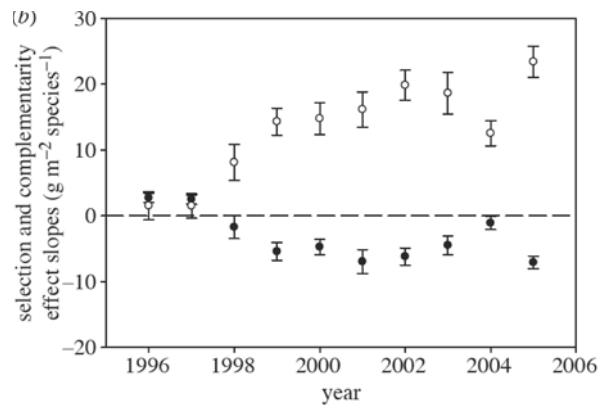
**Figure 1.** Species loss (as proportion of control diversity) after 20 years of chronic N addition versus N input rate (deposition plus N addition;  $\text{kg ha}^{-1} \text{yr}^{-1}$  of N). Plot averages (2002-2004) are fit to a logarithmic curve, with 95% confidence curves shown. Dashed line corresponds to linear interpolation between the mean effect at the highest N addition rate and controls. Per-unit loss of diversity due to N addition is greatest at the lowest addition rates. (Clark & Tilman 2008)



**Figure 2.** Adjusted mean decomposition parameters from fits of single exponential and asymptotic models to data that show faster initial decomposition rates ( $k_s$ ), but larger slowly decomposing pools ( $A$ ) in treatments that include N addition (IN, INC, LTN, ON) in E211.  $k_s$ , single-exponential model decomposition rate;  $k_a$ , asymptotic model decomposition rate;  $A$ , asymptote. Values are adjusted treatment means with SE bars. Asterisks indicate significant Bonferroni-corrected pairwise comparisons within a decomposition parameter of all treatments with the control. (Hobbie et al. in revision)

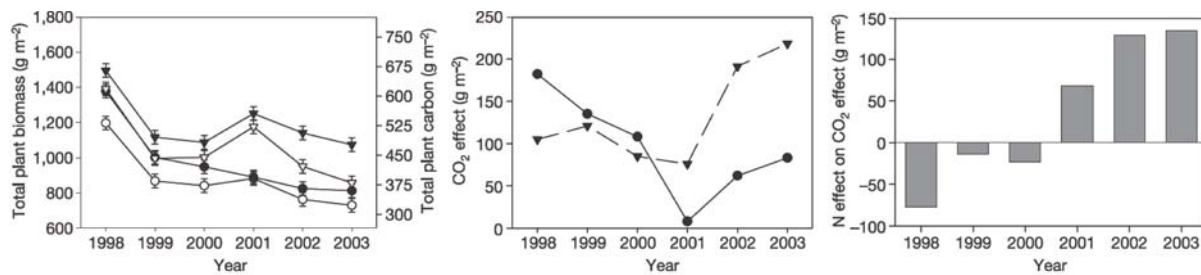


**Figure 3.** Dependence of ecosystem temporal stability (the proportional change in annual biomass production) on realized species number in E120, 1996-2005. Realized species number was calculated for each plot as the smallest number of species which together comprised 90% of the aboveground biomass. Ecosystem stability was positively dependent on realized species number with cutoffs of 90% ( $P < 0.0001$ ; shown), 75% ( $P < 0.0001$ ) and 99% ( $P = 0.002$ ). (Tilman, Reich & Knops, 2006)

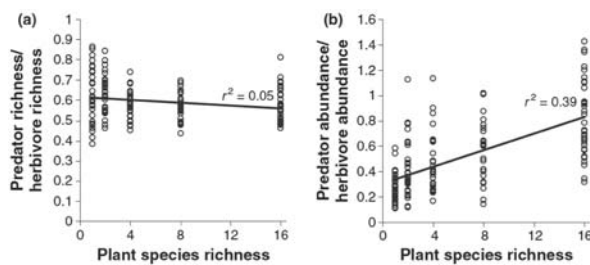


**Figure 4.** Temporal trends in the strength (slope) of sampling effects (also called selection effects) (closed circles) and of complementarity effects (open circles) per species for 1996-2005 in the BigBio experiment. Since the complementarity effect increased more through time than the selection effect decreased, the net effect of plant diversity on productivity (their sum) increased over time. (Fargione et al. 2007)

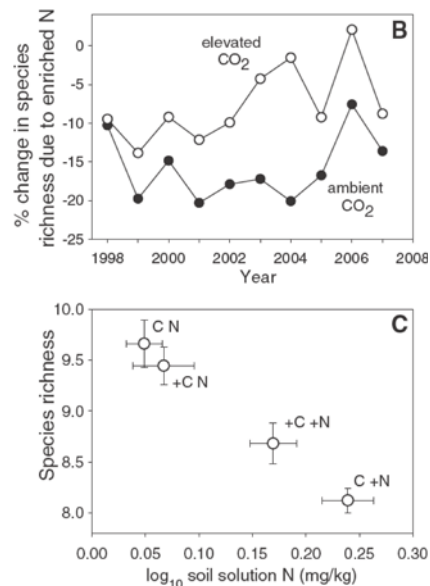




**Figure 5.** The constraining effect of N limitation on the response of total plant biomass to CO<sub>2</sub> over time in E141. (a) Annual mean total plant biomass (above-ground plus 0–20 cm below-ground) and carbon at ambient CO<sub>2</sub> and N (open circles), elevated CO<sub>2</sub> and ambient N (filled circles), ambient CO<sub>2</sub> and enriched N (open triangles), and elevated CO<sub>2</sub> and enriched N (closed triangles), pooled across diversity treatments. (b) The annual effect of CO<sub>2</sub> on total plant biomass (elevated CO<sub>2</sub> biomass - ambient CO<sub>2</sub> biomass) under ambient N (circles) and enriched N (triangles). (c) The annual effect of N availability on the CO<sub>2</sub> biomass effect (triangle – circle). (Reich et al. 2006)

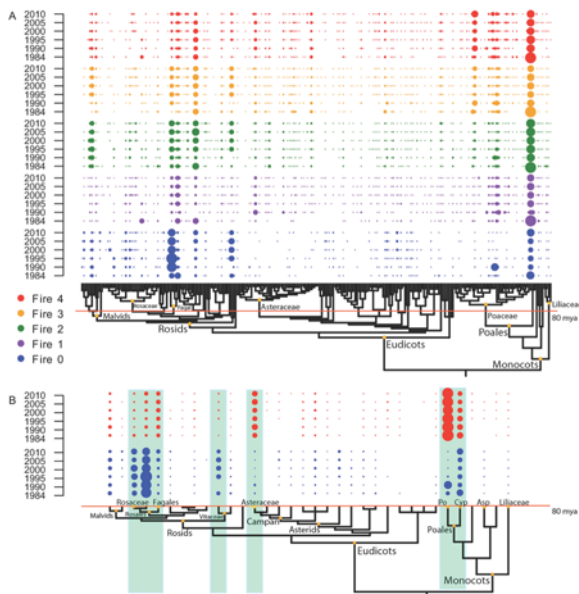


**Figure 6.** Effects of plant species richness on arthropod trophic structure in BigBio, the biodiversity experiment. (a) High plant diversity was associated with a slight decrease in the number of predator and parasitoid species relative to the number of herbivorous species in the arthropod foodwebs, and (b) with a major increase in the abundances of arthropod predators and parasitoids relative to the abundances of herbivores. (Haddad et al., 2009)



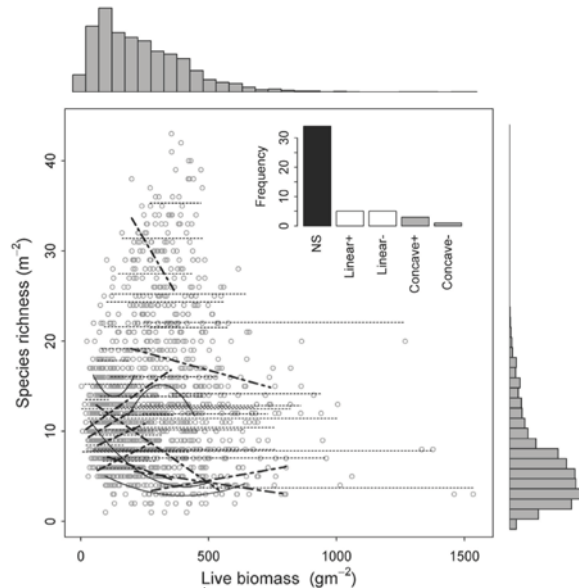
**Figure 7.** (b) Mean change in species richness ( $\pm$ SE) with added N in elevated and ambient CO<sub>2</sub> and (c) relationship between soil solution N (0–20 cm) ( $\pm$ SE) and species richness under ambient and enriched CO<sub>2</sub> and N treatments in BioCON. Elevated CO<sub>2</sub> reduces losses of plant diversity caused by N deposition. (Reich 2006)



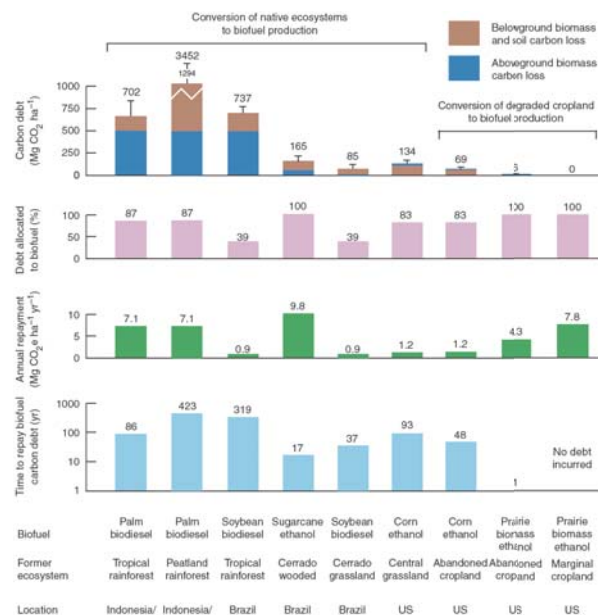


**Figure 8.** The influence of prescribed burning and the 1988 drought on phylogenetic beta diversity in the oak savanna burn experiment from 1984-2010. Circle sizes are proportional to relative abundance. Frequently burned communities (red) had the highest species richness, the most resource-conservative leaf traits, and spanned the greatest number of lineages, but had more close relatives within lineages. Unburned communities (blue) had the lowest diversity and the fewest lineages, but close relatives co-occurred less frequently. Phylogenetic turnover between treatments is greatest ~80 million years ago (red line). (Cavender-Bares & Reich, in press)

**Figure 10.** This figure shows results of a “broader impact” synthesis paper we wrote that was inspired by the relevance of results of BigBio to biomass production for biofuels (Tilman et al. 2006). (a) Carbon debt, including CO<sub>2</sub> emissions from soils and above-ground and belowground biomass resulting from habitat conversion to grow a biofuel crop. (b) Proportion of total carbon debt allocated to biofuel production. (c) Annual life-cycle GHG reduction from biofuels, including displaced fossil fuels and soil carbon storage. (d) Number of years after conversion to biofuel production required for cumulative biofuel GHG reductions, relative to displaced fossil fuels, to repay the biofuel carbon debt. (Fargione et al., 2008)



**Figure 9.** Within-site dependence of plant diversity on productivity (peak live biomass dry weight) across NutNet sites, including the CDR NutNet site. The inset shows the frequencies of relationships that were non-significant (thin dashed lines), linear (thick dashed lines), or concave-up or -down (solid curves). The marginal histograms show the frequency of species richness and peak live biomass across all sites. No “hump shaped” dependence of local diversity on productivity was found within sites, within regions, or across the globe. (Adler et al. 2011)



## SECTION II. PROPOSED RESEARCH

### 1. CONCEPTUAL FRAMEWORK

The overarching goal of the Cedar Creek Long Term Ecological Research program (CDR) is to use the interplay of long-term experiments, long-term observations, and theory to gain a mechanistic and predictive understanding of the dynamics and functioning of our grassland, savanna, lake, and forest communities and ecosystems. For instance, we use patterns observed in our long-term experimental and observational studies to generate hypotheses of the underlying causative mechanisms, and test these hypotheses by integrating and synthesizing studies of population, community, and ecosystem interactions, processes, and feedbacks. The underlying processes that we study include plant ecophysiology, interspecific competition, plant-herbivore interactions, plant-disease interactions, controls of decomposition and nutrient cycling rates, controls of soil C and N stores, and linkages and feedbacks among these and other processes. Our hypothesis generation also occurs in the other direction – from underlying mechanisms to predictions of the resultant ecosystem patterns, with these predictions tested against observational and experimental data.

In this research, we put particular emphasis on the ways in which human-influenced drivers impact ecosystem functioning. Anthropogenic changes are occurring at local to global scales and include alterations in abiotic factors, loss of biodiversity, shifts in species composition, and land use change. Changes in climate, atmospheric CO<sub>2</sub>, atmospheric N deposition and other abiotic factors may have major impacts on ecosystems and the species they contain (Falkowski et al. 2000, Solomon et al. 2007). Biotic changes, such as habitat alteration from land use or land cover changes, loss of diversity, and introduction of novel species, including pests and pathogens, can modify the structure and functioning of ecological communities and ecosystems (Hector and Bagchi 2007, Keesing et al. 2010, Weidenhamer and Callaway 2010, Ellis and Ramankutty 2008). Together, these environmental changes drive fundamental shifts in the resource availability, the range of conditions, and the biological players experienced by and contributing to the composition and functioning of ecological communities and ecosystems (Rockström et al. 2009). A mechanistic understanding of the underlying interactions, linkages, and feedbacks over long time scales would advance fundamental knowledge while also providing society with insights into managing and adapting to these challenges.

Long-term experiments provide crucial insights into ecological responses to changes in environmental drivers since responses depend not only on the direct impacts of drivers on individual species, but also on how the drivers influence both interspecific interactions and cumulative ecosystem feedbacks (A Knapp et al. 2012). Such feedbacks may ultimately dominate the responses, but may be undetectable over shorter time periods. For example, N addition did not lead to detectable increases in soil C sequestration during the first 10 years of an N deposition experiment at CDR (Wedin and Tilman 1996), but after 28 years we now observe progressively greater soil C sequestration at higher rates of N addition (Fornara and Tilman In Review). Similarly, in our biodiversity experiment, there were no detectable effects of increased plant species numbers on soil C and N after 5 years, but after 12 years we found markedly higher rates of soil C and N sequestration at higher plant diversity (Figs. 13-14; Tilman et al. 2006). The resulting increases in soil fertility ultimately led to increasingly higher primary productivity at higher diversity (Fig. 15; Fornara and Tilman 2008, 2009). Here we propose continued sampling and analyses of these and other long-term experiments to detect feedbacks and shifts, and to develop a better understanding of mechanisms over decadal time scales. We also propose to expand the scope of the CDR studies on nutrient drivers to include lacustrine environments.

Long-term studies are also critical to determining if, when, and why perturbations to ecosystems lead to sudden shifts between alternate stable states (i.e., tipping points, Scheffer et al. 2001, Carpenter et al. 2011, Hirota et al. 2011, Staver et al. 2011) or to smooth and readily reversible shifts. For instance, while plant community diversity rebounded 12 years after the cessation of a decade of chronic low-level N addition (Figs. 16; Clark et al. 2009, diversity had not recovered at higher rate of N addition (Fig. 17a), and the original plant community composition had not yet recovered 19 years after cessation. Exotic plant species, especially *Agropyron repens*, that were favored by N addition still dominate (Fig. 17c), species abundances have become increasingly oscillatory, and current analyses suggest a bi-modal community composition distribution, all of which are signatures of systems with alternate stable states (Scheffer et al. 2001, Hirota et al. 2011, but see Hastings and Wysham 2010). Here we propose data collection in many of

our long-term experiments specifically designed to test for the existence and importance of tipping points and alternate stable states in our grassland and savanna ecosystems.

Over the past decade, much research at CDR focused on the effects of biodiversity – specifically the number of species – on various aspects of ecosystem functioning. Our most recent work has shown that the traits and evolutionary history of species also impact how communities assemble (Cavender-Bares et al. 2009, Willis et al. 2010, Cavender-Bares and Reich 2012), respond to global change (Reich 2009), and drive ecosystem function (Fig. 18) (Ollinger et al. 2008, Cornwell et al. 2008, Reich 2012). Information about shared ancestry provides a means to estimate organism functional similarity, because species that have diverged recently from a common ancestor tend to have high functional similarity due to shared genetic background. For this reason, biodiversity metrics that incorporate shared ancestry can provide insights beyond those derived solely from counts of species numbers (e.g., Faith 1994, Webb et al. 2002, Cavender-Bares et al. 2004, Cadotte et al. 2008). Similarly, we have gained additional mechanistic insights into the dynamics and functioning of populations, communities, and ecosystems using approaches that include functional traits, such as  $R^*$  values, root mass, root:shoot ratios, tissue nutrient concentration, life span, and photosynthetic rates. For example, CDR research has demonstrated that plant tissue chemistry (e.g., C:N:P stoichiometry) and resource requirements (i.e.,  $R^*$  values for soil nitrate and light interception) predict the long-term outcomes of interspecific competition (Dybzinski and Tilman 2007), the effects of species on nutrient cycling (Wedin and Tilman 1996, Dijkstra et al. 2006a, Clark et al. 2009, Reich et al. 2001abc, Adair et al. 2009), and decomposition rates (Fig. 18) (Knops et al. 2007, Cornwell et al. 2008, Hobbie 2005, 2008, In Revision, Hernández and Hobbie 2010). New research outlined in this proposal focuses on traits that we hypothesize are important at the ecosystem level and in the delivery of ecosystem services. In studying these traits, we will also investigate the relationships among species diversity, phylogenetic diversity, functional trait diversity, and ecosystem functioning (see Section 3.1.2).

Most ecological experiments are performed within one or a few locations at a single research site, making it difficult to infer the generality of the results (Rockström et al. 2009, Cardinale et al. 2011). In some cases, such as for our long-term N addition (Gross et al. 2000, Suding et al. 2005, Collins et al. 2008, Clark et al. 2009), fire frequency (Moles et al. 2012), litter decomposition (Fig. 18; Cornwell et al. 2008, Sinsabaugh et al. 2008, Adair et al. 2010, Berg et al. 2010, Sinsabaugh 2010, Laliberté et al. In Review), biodiversity (Cardinale et al. 2007, 2009, 2011, Isbell et al. 2011), and CO<sub>2</sub> experiments (Ainsworth and Long 2005, Reich et al. 2006b), CDR data have played prominent roles in meta-analyses that evaluated the breadth and applicability of specific results. However, for many studies at CDR and elsewhere, this has not yet occurred. Here we propose several initiatives to address this issue. For example, CDR data provide a reference point for examining the effects of urbanization and suburbanization on plant community composition and diversity (S Knapp et al. 2012), however the applicability to other metropolitan regions is not yet known. Recent CDR work has begun to quantify regional-scale variation in ecosystem responses to change, including links between land conversion for residential uses, ecological communities, and ecosystem processes (Fig. 12; Chapman and Reich 2007, Fissore et al. 2011ab). Here we propose to extend the regional and global inferences arising from our research in a variety of ways. We will facilitate synthesis of nutrient and herbivore manipulations across the Nutrient Network (NutNet), and we will continue work on the ecology of urbanizing ecosystems on a gradient from CDR to the Minneapolis-St. Paul metropolitan area. We will collaborate with other LTER sites on the effects of warming and changes in precipitation on ecosystem functioning and lead new initiatives within the U. S. National Phenology Network. We will partner in developing trait networks (e.g. TRY, Kattge et al. 2011), and in modeling that will incorporate our findings into larger-scale analyses (e.g., Goll et al. Submitted). These activities will directly address the LTER Network 30 Year Review's goal of achieving regional to continental scale syntheses.

Finally, ecosystems provide services that contribute to human wellbeing (Hooper et al. 2005, Millennium Ecosystem Assessment 2005, Diaz et al. 2006, Kareiva et al. 2011). Among the services that we study are C sequestration, water purification, enhancement of soil fertility, regulation of pests and disease, and primary productivity and its stability. We have found clear links between biodiversity and each of these services (Tilman and Downing 1994, Lehman and Tilman 2000, Naeem et al. 2000, Loreau et al. 2001, Tilman et al. 2001, Tilman et al. 2006, Fornara and Tilman 2008, 2009, Cadotte et al. 2008). Our work also has shown how plant biodiversity can be a tool to provide sustainable sources of biomass for biofuel production, to store sufficient C in previously degraded soils to make these biofuels be C-negative, and to provide much cleaner groundwater compared to corn ethanol (Hill et al. 2006, Tilman et al. 2006, Fargione et al. 2008, 2010). Here we propose further studies of the long-term effects of biodiversity on the provisioning of ecosystem services in grasslands as well as expansion of these studies to forest

ecosystems via a new tree diversity experiment. In addition, we will collaborate across the LTER network to develop curricula on sustainability science that use our results to quantify how environmental change impacts ecosystem services.

## 2. RESEARCH PLAN

Since its inception in 1982, research at CDR has deepened our understanding of the mechanisms and principles that govern the dynamics and functioning of communities and ecosystems. CDR research has contributed to the general understanding of the interactions among abiotic factors, species and feedback effects that control diversity, composition, productivity, decomposition, nutrient dynamics, and stability. We began by focusing on the effects of N (Tilman 1987, Wedin and Tilman 1996), competition (Wedin and Tilman 1992), and disturbance on plant succession (Inouye et al. 1987, Tilman 1985) and on the causes of species coexistence. Next we contributed to the understanding of the community and ecosystem consequences of biodiversity (Tilman and Downing 1994, Tilman et al. 1996, 1997, 2001, 2006, Fornara and Tilman 2008, 2009, Isbell et al. 2011), fire (Reich et al. 2001b, Dijkstra et al. 2006b, Dickie et al. 2009b), N availability (Fig. 2; Hobbie 2005, 2008, in revision), CO<sub>2</sub> concentrations (He et al. 2010, 2012, Deng et al. 2012), and on the interactive effects of biodiversity, elevated N deposition, and elevated CO<sub>2</sub> (Reich et al. 2001a, 2004, 2006ab, Hobbie 2005, 2008, in revision, Reich 2009, Adair et al. 2009, 2011, Antoninka et al. 2011, Eisenhauer et al. 2012).

We propose to build on this legacy of mechanism-seeking iteration among experiments, observations, and theory. We will continue our long-term experimental and observational field studies, but will sample our oldest studies (N addition; N addition x fire; N x N-cessation; N x herbivory; fire frequency in savanna) every third or fifth year, because they are now changing very slowly. This will provide project resources for establishing and sampling new studies that expand our work into forest and aquatic ecosystems. Should unusual circumstance arise, such as drought, an outbreak of major herbivore or disease, etc., we will adjust our sampling to capture the event and its aftermath.

A detailed description of our ongoing and proposed work is presented in below. Here we highlight a few of our new research directions. (1) We propose a new tree diversity experiment (section 3.1.2) that manipulates functional, species, and phylogenetic diversity of communities assembled from the regional tree species pool. This experiment would provide numerous insights into the functioning of our forest ecosystems, and would be globally unique in separating the effects of plant species number and identity, *per se*, from those of functional and phylogenetic diversity and identity. (2) We propose a focused examination of drivers of microbial and insect herbivore and predator abundances, diversity, and feedbacks to plants (section 3.5). (3) We propose to explore short and long term responses of lacustrine communities to changes in nutrient loading coming from the surrounding landscape (section 3.5.3); (4) We propose new analyses, syntheses, and modeling (section 4) of the long-term impacts of experimentally imposed environmental drivers to determine if or when they cause ecosystems to switch between alternate stable states, or show smooth reversible transitions. (5) Finally, we will expand the scope of our work by direct comparison among LTER sites and >50 grassland sites worldwide (as embodied in the Nutrient Network) to better understand how fine-scale processes interact with regional-scale processes to determine variation in ecosystem responses to perturbations of nutrients and consumers (section 3.6.1).

## 3. LONG-TERM STUDIES OF MULTIPLE DRIVERS OF ENVIRONMENTAL CHANGE

We propose using four complementary and interrelated types of experiments and long-term observations to determine the separate and interactive mechanisms whereby multiple drivers of environmental change, particularly the loss of biodiversity, climate change, elevated CO<sub>2</sub>, N deposition, fire, and residential land use, impact the grassland, savanna, forest, and lake ecosystems of CDR. We will synthesize the results of our ongoing work with new experiments, observations, and theory to formulate a more mechanistic and generalizable understanding of the functioning of our grassland, woodland, wetland, and lake ecosystems and their susceptibility to human-caused changes. This long-term perspective and search for underlying mechanisms are of value because global land use changes, often associated with agricultural expansion, is reducing the biodiversity of grassland and forest ecosystems worldwide (Foley et al. 2005) at the same time that changes in atmospheric chemistry, fire regimes, nutrient pollution, and climate are occurring. There are, as yet, few rigorous experiments to determine the long-term effects of changes in these drivers, and especially the interactive effects of multiple drivers, and why and how these effects occur. Our four major types of long-term studies are:

**Section 3.1 – Grassland and Forest Biodiversity Experiments:** These experiments examine how and why changes in species, functional, and (with this proposal) phylogenetic diversity of plants affect foodweb structure and community and ecosystem dynamics and functioning. These include our existing grassland Biodiversity Experiment, ‘BigBio’, established in 1994; BioCON (described in 3.2); and a new forest biodiversity experiment.

**Section 3.2 – Multiple Global Change Factors:** These experiments examine the interactions among multiple environmental drivers. ‘BioCON’, established in 1998, manipulates CO<sub>2</sub>, N deposition, and biodiversity using a split-plot design. WWCON, a water x CO<sub>2</sub> x N experiment nested into BioCON, has ambient or reduced rainfall at all combinations of ambient and enriched CO<sub>2</sub> and N, and will incorporate a warming manipulation in 2012. The Biodiversity and Climate (BAC) experiment, nested within BigBio, has an unwarmed subplot, a subplot warmed ~1.5°C and one warmed ~3°C nested within 1, 4, and 16 species plots. We will add a reduced rainfall treatment in 2012 to create a diversity x warming x water factorial experiment.

**Section 3.3 – Nutrient Addition Experiments:** These experiments examine the community and ecosystem consequences of chronic nutrient loading. In an experiment begun in 1982, we impose various rates of N addition on 369 permanent plots in seven grassland sites. In 1993, one site was modified to become a full factorial N x fire experiment, and another site became a full factorial N cessation or N addition comparison. In 2005, a third site became an N x deer herbivory experiment. Two experiments initiated in 1999 and 2004 have explored N limitation of decomposition. New studies to explore multi-factor responses of aquatic communities are being added in this proposal.

**Section 3.4 – Grassland-Forest Disturbance and Succession Experiments and Long-Term Observations:** In our oldest CDR experiment, begun in 1964, we examine responses of microbial, plant, and ecosystem processes to direct and indirect effects of long-term disturbance by imposing different fire frequencies on larger (3 to 27 ha) naturally established savanna plots. We also are continuing long-term observational studies of the dynamics of plant species and soil C and N in numerous grassland fields, which recently were split in half, with a prescribed burning treatment (burned every other year) imposed on a randomly chosen half of each field.

**Section 3.5 – Biotic Interactions and Feedbacks:** These experiments examine the long-term feedbacks between plant diversity, microbes, invertebrates, and vertebrates and the effects of these feedbacks on grassland species abundances, productivity, and decomposition. In two experiments established in 2008, we independently reduce different components of the consumer foodweb via insecticide, foliar and soil fungicide, and vertebrate fences.

### *3.1. Grassland and Forest Biodiversity Experiments*

#### **3.1.1. Cedar Creek Biodiversity Experiment**

The Cedar Creek Biodiversity Experiment (BigBio), E120, determines effects of grassland plant species numbers and composition on foodweb, community, and ecosystem dynamics and functioning. The fully randomized design manipulates plant species number – 1, 2, 4, 8, or 16 perennial grassland species – in 152 plots, each 9 m x 9 m. The species planted in a plot were randomly chosen from a pool of 18 species (C4 grasses, C3 grasses, legumes, other forbs). Planted in 1994, it has been sampled annually since 1996.

**Key Results:** The CDR Biodiversity Experiment has provided insights into the effects of plant community composition and diversity on responses as diverse as plant productivity and stability (Figs. 3, 4 & 15), soil microbial composition and diversity, foliar fungal abundances, arthropods (>500 species sampled and identified), soil C and N, nutrient leaching, and invasion ecology.

Recent findings include: (1) Long-term ecosystem feedbacks had surprisingly strong effects on productivity. Initially, 16 species plots had ~70% greater productivity than monocultures. After 15 years, this diversity effect has increased to 240% (Fig. 15), partly due to the accumulation of soil N (Fig. 19b) and C (Fig. 13) in high-diversity plots, which led to higher N mineralization rates (Fig. 19a). Soil C and N increased from a feedback between root production and decomposition when C4 grasses and legumes were both present (Fig. 14; Fornara and Tilman 2008, 2010).

(2) Niche plasticity also contributed to higher productivity at higher diversity. Plant species shifted the depth distributions of their roots when in competition, causing higher-diversity communities to exploit a greater soil volume and to be more productive (Mueller et al. In Prep).

(3) Plant diversity strongly impacted year-to-year stability of plant productivity (Fig. 3) and arthropod foodweb compositional stability (Haddad et al. 2011). The arthropod composition in high diversity plots shifted toward higher abundances of predatory and parasitoid species relative to herbivorous species (Fig. 6; Haddad et al. 2009). Similarly, foliar fungal infections were less severe in higher-diversity plots (Mitchell et al. 2002). These results suggest that diversity-dependent shifts in the abundances of natural enemies might also contribute to the greater productivity of higher-diversity plots. Plant diversity also affected the diversity of soil fungi via changes in resource levels (Waldrop et al. 2006).

(4) Analyses of the species significantly associated with increased provisioning of each of many different ecosystem services showed that species contributed differently to various services, which meant that many more species, in total, were needed to provide multiple services than needed to provide a single service (Zavaleta et al. 2010, Isbell et al. 2011). Two services – sequestration of soil C and increases in soil fertility caused by increased levels of soil total N – were highly dependent on plant diversity (Tilman et al. 2006, Dybzinski et al. 2008, Fornara and Tilman 2008, 2009).

(5) Plant composition and diversity had complex impacts on soil microbial communities. Bacterial diversity associated with the rhizospheres of individual host plant species was often dependent on plant diversity (Schlatter et al. In Prep), with the number of Actinobacterial species (operational taxonomic units based on 454 sequencing) associated with the rhizosphere of a dominant perennial grass, *Andropogon gerardii*, increasing from 130 in its monocultures to 170 in high diversity plots (Bakker et al. Submitted). Microbial antagonistic activity against fungal plant pathogens declined with increasing plant diversity. Prokaryotic diversity and composition were also significantly associated with soil characteristics, suggesting that the plant effects on rhizosphere microbes is mediated partly through plant effects on soil nutrient availability (Bakker et al. Submitted, Schlatter et al. In Prep).

(6) Metrics of phylogenetic diversity that used the summed phylogenetic distances between species often were better predictors of ecosystem productivity than species number (Cadotte et al. 2009, 2011), showing that phylogenetic history influences ecosystem functioning.

(7) In addition, many non-CDR researchers used data from the CDR Biodiversity Experiment, obtained via our website, in their papers, including Cadotte et al. (2008), Biondini (2007), Fox and Harpole (2008), Cadotte et al. (2011), Lin et al. (2011), Lopez-Villalta (2008), Cardinale et al. (2007; 2009; 2011) and Flynn et al. (2011).

**Future Research:** This experiment, now in its 17<sup>th</sup> year, is still highly productive, resulting in 43 peer-reviewed papers during the current grant. We propose continuing our annual sampling of primary productivity and plant species abundances, and periodic sampling of soil properties, heterotroph communities, and other parameters. Among the questions that we will address in future research are:

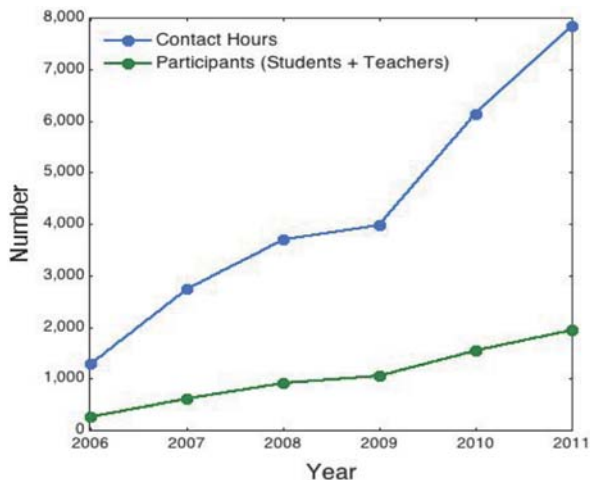
(1) Why did the impact of plant diversity on primary productivity increase so much from 1996 to 2005 and then slow during the past 5 years? Might productivity in low diversity plots slowly increase, and eventually catch up with that of high diversity plots?

(2) What are the long-term prospects for high diversity plantings to serve as C sinks, and what role might herbivory play, since many herbivores preferentially feed on legumes? Can high diversity plant mixtures accrue more soil C and N than occurs in nearby native grassland ecosystems?

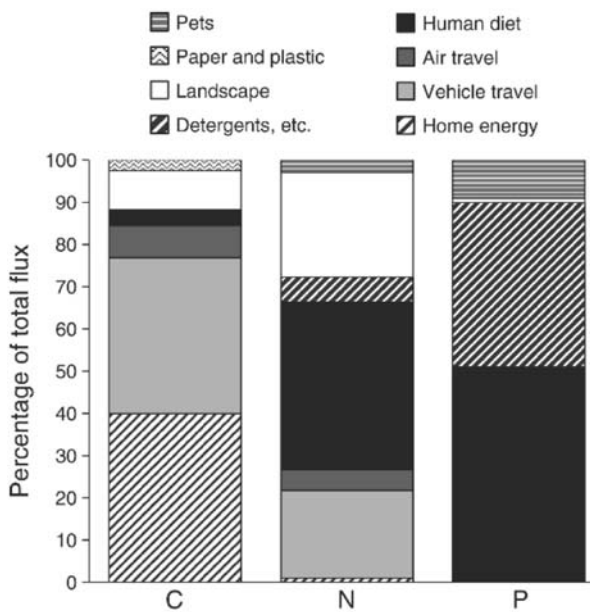
(3) What are the quantitative dependences of various ecosystem services on plant species composition and diversity? We will explicitly quantify such services as improved ground water quality, provisioning of predatory and parasitoid insects of importance for the control of agricultural pests, provisioning of pollinators of agricultural relevance, reductions in the diversity and prevalence of agriculturally important pathogens, and the ability of high diversity buffer strips to capture sediment in surface runoff and remove excess nutrients and other agrichemicals. We also estimate the economic values of these and other ecosystem services.

(4) Finally, we note that the CDR Biodiversity Experiment, the oldest and best replicated large-plot biodiversity experiment in the world, has become an important resource for many non-CDR researchers who visit CDR to sample the experiment to address their own novel questions (Zak et al. 2003, Haddad et al. 2009, 2011; P Vanderkoornhuyse, Universite de Rennes). We actively encourage and continually seek such outside collaborations and independent research initiatives.

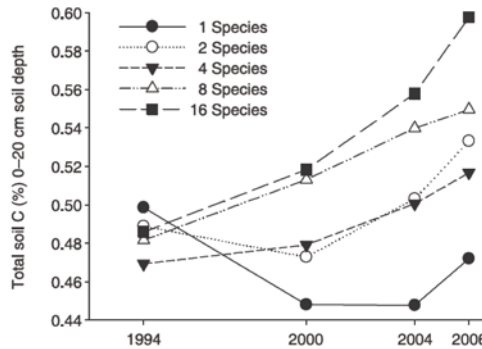




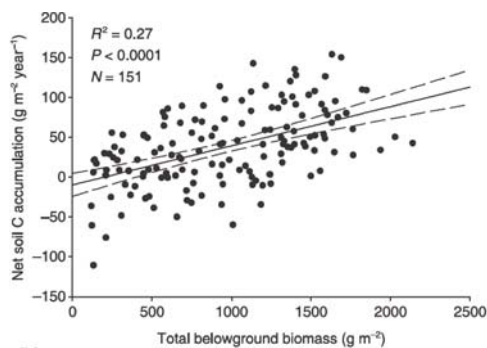
**Figure 11.** Growth in the CDR Schoolyard LTER Program 2006-2012, showing the increase in number of contact hours and participants (teachers and students).



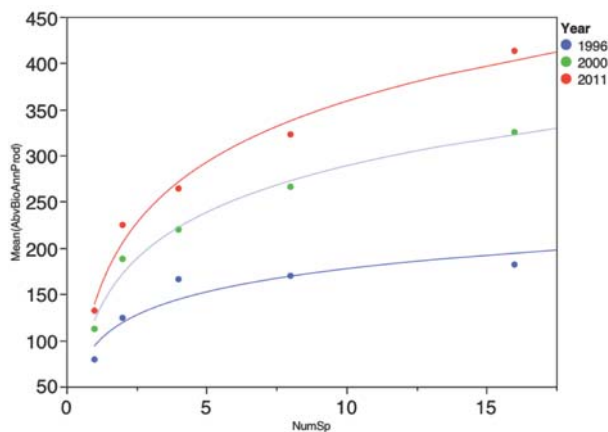
**Figure 12.** Relative contributions of household activities to total household-caused fluxes of C, N and P as estimated from our TCHEP survey data. All total and component fluxes had skewed distributions, suggesting that policies targeting households with disproportionately high fluxes could be efficient at reducing pollution (e.g., 20% of households contributed 75% of air travel emissions and 40% of motor vehicle emissions). (Fissore 2011)



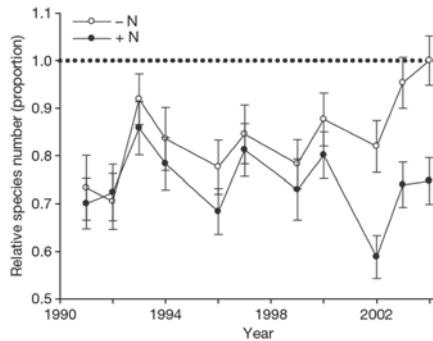
**Figure 13.** Soil C dynamics in BigBio. During the 12-year period analyzed, soil C declined in monoculture plots but increased at higher diversity, with the greatest increase in 16 species plots. (Fornara and Tilman, 2008)



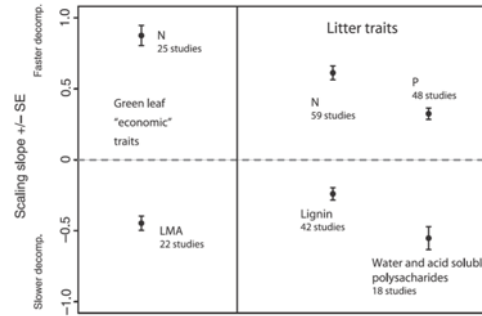
**Figure 14.** Annual net soil C accumulation in BigBio (0-60 cm depth; 1994 to 2006) was strongly dependent on total below-ground plant biomass, which is greatest in the 16 species treatment. The highest rates of net soil C sequestration are  $>1 \text{ t ha}^{-1} \text{ yr}^{-1}$ . Dashed lines are 95% confidence intervals. (Fornara and Tilman, 2008)



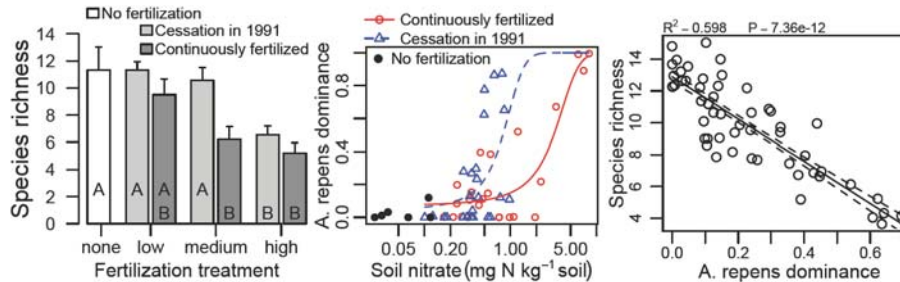
**Figure 15.** Aboveground plant biomass versus plant diversity treatment in E120 plots in 1996, 2000, and 2011. Note the large increases through time in productivity of the most diverse plots. (Reich et al., in review)



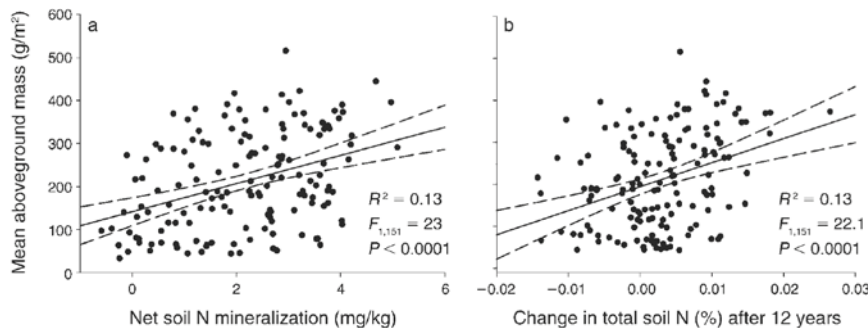
**Figure 16.** After 12 years of cessation, plant diversity of plots no longer receiving N (“-N”) recovered to the levels of unfertilized control plots, but diversity did not recover in the plots the continued to be fertilized (“+N”). The diversity measure shown is (species number in a treatment)/(species number in unfertilized control plots). (Clark & Tilman 2008)



**Figure 18.** Meta-analysis of the dependence of decomposition rate ( $k$ ) on green leaf or litter traits and based on studies across the world, including E145 at CDR. The slopes of correlations between the log-transformed decomposition rate ( $k$ ) and each log-transformed trait (litter N, leaf N and P, leaf mass per unit area (LMA), litter lignin and polysaccharide contents). ANCOVA found each of the six traits significant at  $P < 0.01$ . (Cornwell et al. 2008)



**Figure 17.** (a) Species richness (number of species  $0.3 \text{ m}^2$ ) versus N addition in 2011. While some plots received continuous N addition (1982-2011; dark gray bars), N addition was ceased in 1991 in other plots (light gray). After three decades, plots were either species rich (no N addition, or cessation of low and medium rates of N addition) or species poor (high N addition and cessation of high N addition). Treatments significantly differed (ANOVA;  $F_{6,47}=7.38$ ,  $P<0.0001$ ); different letters indicate  $P<0.05$  for Tukey contrasts. (b) *Agropyron repens*, an exotic perennial, exhibited hysteresis as it shifted between these rarity or abundance in response to changes in soil nitrate (in  $\log_{10}$  scale). (c) High abundance of *Agropyron repens* was associated with low diversity of native plant species. (Isbell et al., in prep)



**Figure 19.** Plant diversity treatments caused changes in soil total C and N content, and in N mineralization rates (Fornara and Tilman 2009). Plant productivity was significantly positively correlated with (a) N mineralization and (b) the change in total soil N over the first 12 years of the BigBio experiment.

### 3.1.2. FAB – Forests And Biodiversity

We propose a new forest biodiversity experiment (FAB), focused on trees of our region, that will allow analysis of the same wide diversity of plant, soil, decomposer, food web, and ecosystem responses that we have studied in our grassland experiments but also allow exploration of novel questions regarding the effects of functional and phylogenetic diversity on ecosystem processes. Due to the long lag between planting tree seedlings and determining effects of tree composition and diversity on ecosystem functioning, very few experiments elucidate the role of biodiversity in the functioning of forest ecosystems. The few existing forest diversity experiments tend to be limited in terms of plot size and/or species number (but see Hector et al. 2003). The long-term nature of the proposed experiment, our experience with large-scale biodiversity experiments, and especially the major insights that FAB is likely to provide make it highly suited to the long-term research mission of CDR. Indeed it would be nearly impossible to fund such a necessarily long-term experiment with non-LTER funding programs.

FAB is designed to unravel effects of three forms of biological diversity: species richness (SR), functional diversity (FD), and phylogenetic diversity (PD). We define FD (*sensu* Laliberté and Legendre 2010) as the representation of multiple traits of leaves, roots, seeds, and the whole organism that are correlated with species positions along gradients of resource supply, growth, and decomposition (Wright et al. 2004, Freschet et al. 2011). PD is the representation of evolutionary lineages measured as the genetic distances between species (Cavender-Bares et al. 2009). While PD and FD are often correlated (Cadotte et al. 2009), convergent evolution and adaptive differentiation can decouple them (Cavender-Bares et al. 2004, Graham and Parra 2012, Swenson et al. 2012, Eaton et al. 2012). When functional traits that drive specific ecosystem functions are not phylogenetically conserved, PD and FD may give contrasting predictions. SR, PD, and FD are not independent, and we posit that PD may help explain SR effects (Cadotte et al. 2009), and FD may help explain both PD and SR effects. A valuable and unique contribution of the FAB design is its explicit ability to test for PD and FD effects when SR is held constant; so direct contrast of PD and FD effects can be made independent of SR. Thus FAB is designed to examine the separate and combined effects of all three components of diversity and, in addition to testing in forests all the hypotheses explored in grasslands with BigBio, also test the following hypotheses:

**(H1)** PD, FD, and SR will all contribute to increased productivity, stability, and diversity of other trophic levels (herbivores, predators, parasitoids, soil microbes, soil flora and fauna) as well as to greater soil C sequestration. **(H2)** Because PD incorporates both the number of species and measurement of their evolutionary divergence, PD will explain more of the variation in ecosystem productivity and stability than SR. Similarly, among-species FD will explain more variation in these ecosystem functions than SR or PD. **(H3)** Plant assemblages of similar SR but comprised of increasingly divergent PD or FD will show increasing divergence in ecosystem functions. **(H4)** Species with functional traits not yet present in a plot will more easily invade than species with traits similar to the established species.

The FAB single species plots will allow us to test hypotheses about the importance of plant functional traits in influencing ecosystem properties (e.g., NPP, soil C, N mineralization) and plant-associated microbial communities. For example, we expect that plant species that increase concentrations of polyvalent soil cations (e.g., because of unique base cation chemistry or because of effects on soil acidity that influence Al and Fe solubility) will promote soil C stabilization through mineral-organic matter interactions and the formation of microaggregates that protect soil C from decomposition.

**Design:** The experiment will have two density levels, each with 180 plots. Low density plots will be 22.5 x 22.5 m and high density will be 5.5 m x 5.5 m. Richness levels will be 1, 3, 6 and 12 species, drawn from a pool of 20 tree species that occur in or near CDR (Fig. 20). Plots will be assigned to random locations within 10 blocks across the 17-ha experiment providing high statistical power. Prior to planting, soil and plots will be prepared similarly to our long-term grassland biodiversity experiment; replicated soil cores at sequential depths to 1.5 m will be sampled and analyzed for C, N, P, K, Ca, Mg, and other elements; pH; bulk density; microbial processes; and  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ . The difference in  $\delta^{13}\text{C}$  between C4-grassland soils and C3 trees will likely provide us a powerful tool to determine composition and diversity effects on soil C turnover. A portion of each soil sample will be air-dried and archived, and another portion cryo-archived for long-term comparisons and genetic analyses of microbial communities.

In low density plots, tree seedlings will be planted in a square grid of 13 x 13 seedlings spaced 1.7 m apart. Within each plot, all species will be planted at equal densities, with each individual assigned a random location in the grid. Three monoculture plots will be planted for each of the 20 tree species (60 total). There will be 50, 50, and 20 plots planted within the 3, 6, and 12 SR levels, respectively.

A classic species diversity experiment (124 total plots) will be formed from the 60 monoculture, and a subset of the other plots (22 3-SR, 22 6-SR, and 20 12-SR plots) by randomly drawing the species mixture of each 3, 6 and 12 species plot.

To provide a strong test of the effects of PD and FD, we will use the remaining 28 plots at each of the 3 and 6 SR levels to ensure that a much wider range of PD and FD combinations are planted than can be achieved by random species draws. These additional plots will allow us to detect and separate effects of SR, PD, and FD. We base this approach on simulations of 22 random draws of species compositions that show predominately mid-range values of PD and FD for either the 3 or 6 species treatments. Calculations of PD of every possible species composition for 3 and 6 SR levels allow us to rank the compositions from lowest to highest PD, and to divide PD into three equal-sized groups. Calculations of FD permit ranking compositions from low to high FD within each of these PD groups. From the low and high groups, we will randomly choose 7 compositions for each of the four possible combinations of low or high PD X low or high FD, and do so for both the 3- and the 6-SR levels. Our simulations show that this provides the broad coverage of PD and FD combinations in both the 3- and 6-SR treatments that are needed for a powerful test of the joint effects of SR, PD, and FD. We will not manipulate PD and FD within the 12-SR plots because our calculations show that both are constrained to be high at this SR level.

The high density plots will be established within the same 10 blocks as the low density plots (Fig. 20). In particular, within each block there will be a randomly placed 45 m x 22.5 m sub-block that contains 18 high-planting-density 5.5 x 5.5 m plots, with trees at a 0.55 m spacing (total of 180 plots). Higher tree density will cause more rapid canopy closure, and interactions among neighboring plants to occur sooner, allowing detection of treatment effects earlier than in the low-density plots. The treatments within each block, as well as the location of the sub-blocks within each, will be assigned randomly.

In the first two years, we will mow or otherwise weed periodically between the rows of tree seedlings to reduce competition from grasses and forbs. We will replace seedlings that die during that period. For a subset of individuals, we will annually measure height, stem diameter, crown diameter, and assess insect and pathogen damage. More extensive sampling will begin in the 3<sup>rd</sup> or 4<sup>th</sup> field seasons for the high density treatment, and in the 5<sup>th</sup> or 6<sup>th</sup> field season for the low-density treatment. We will make FAB part of the TreeDiv network of forest biodiversity experiments ([www.treedivnet.ugent.be](http://www.treedivnet.ugent.be)).

### **3.2. Multiple Global Change Experiments**

#### **3.2.1. BioCON – CO<sub>2</sub>, Nitrogen, and Biodiversity**

Many ecosystems around the world are experiencing simultaneous increases in atmospheric CO<sub>2</sub> levels and N deposition, and decreases in biodiversity. The potential importance of these aspects of global environmental change, coupled with a lack of understanding of their interactions (Vitousek 1994), led us to develop the long-term BioCON experiment, which addresses the direct and interactive effects on grassland ecosystems of elevated CO<sub>2</sub>, added N, and varying plant diversity, including shifts in both richness and composition (e.g., Reich et al. 2001ac, 2004, 2006ab). The BioCON project addresses basic scientific questions about coupled biogeochemical cycles, biodiversity, and other issues while also providing information relevant to society about the implications of these global change variables.

BioCON focuses on 4 key questions: (1) Do CO<sub>2</sub> and N interact at physiological, whole plant, multi-trophic, community and/or biogeochemical scales, on short- and long-term time horizons? (2) Do plant species and/or functional group diversity and composition influence responses to CO<sub>2</sub> and N? (3) Are there linear or non-linear temporal changes in effects of treatments on individual, community, or ecosystem metrics? (4) What mechanisms (physiological, biotic interaction, biogeochemical, etc.) explain the patterns observed in addressing questions 1-3? In other words, how does the integration of plant, consumer, mutualist, and decomposer interactions at multiple temporal scales lead to the responses observed at tissue to ecosystem scales across various time scales?

The BioCON experiment (E141) directly manipulates plant species numbers (1, 4, 9, or 16 perennial grassland species randomly chosen from a pool of 16 species, planted as seed in 1997), soil N availability (ambient soil vs. ambient soil + 4 g N m<sup>-2</sup> yr<sup>-1</sup>), and atmospheric CO<sub>2</sub> concentrations (ambient vs. +180 ppm, beginning in 1998) in a well-replicated split-plot experiment. It includes 296 individual plots, each 2 m x 2 m, in six 20-m diameter rings, three exposed to ambient CO<sub>2</sub> and three to elevated CO<sub>2</sub> using free-air CO<sub>2</sub> enrichment. Additional fully factorial experiments (many plots serve multiple experiments) include tests of species composition (in monoculture) x CO<sub>2</sub> x N (n=128 plots, Reich et al. 2001c),

functional group composition  $\times$  CO<sub>2</sub>  $\times$  N (n=176, Reich et al. 2004), species richness  $\times$  CO<sub>2</sub>  $\times$  N at a standard functional group richness (n=176), and functional group richness  $\times$  CO<sub>2</sub>  $\times$  N controlling for species richness (n=123).

**Key Results:** BioCON is a highly productive experiment that led to 44 peer-reviewed papers during our current award. Its most novel element is the simultaneous, long-term manipulation of and examination of effects of multiple global change drivers on ecosystem processes ranging from plant physiology to plant and soil communities to ecosystem biogeochemistry. BioCON is to our knowledge one of only three studies in the world capable of providing long-term evidence on joint effects of CO<sub>2</sub> and N on biodiversity and ecosystem function, and the only experiment involving either CO<sub>2</sub> or N and biodiversity. Here we highlight its two most important findings of the past 6 years.

(1) CO<sub>2</sub> and N interact non-additively in influencing plant biodiversity (Fig. 7; Reich 2009). Over 10 years, elevated N reduced species richness by 16% at ambient CO<sub>2</sub> but by just 8% at elevated CO<sub>2</sub>. This resulted from multiple effects of CO<sub>2</sub> and N on plant traits and soil resources that altered competitive interactions among species. Results of this study have important implications for natural ecosystems under global change, because they demonstrated that altered CO<sub>2</sub> and N regimes had significant, interactive, persistent impacts on species diversity resulting from direct, but mostly indirect effects on plant and ecosystem processes. The sensitivity of plant diversity to factors that themselves were sensitive to CO<sub>2</sub> and N suggests that predicting responses of biodiversity at local scales may be challenging, as responses to multiple global change drivers may not be generally predictable from the responses to each alone.

(2) Nitrogen limitation of plant growth, which is common worldwide, constrains biomass responses to CO<sub>2</sub> over the long-term (Reich et al. 2006ab, Reich and Hobbie In Prep) (Fig. 5). In 2007, the Intergovernmental Panel on Climate Change (IPCC) stated that the largest uncertainty in the global C cycle – and hence a key to predicting future climate change – involves the size of the so-called CO<sub>2</sub> fertilization effect. Although photosynthesis and plant productivity generally increase with rising CO<sub>2</sub> levels in most plant communities, whether this response will decelerate or "saturate" is not known, and hence we lack the ability to predict the fraction of future global C emissions that terrestrial ecosystems acquire and store. The long-term constraint on the CO<sub>2</sub> fertilization effect due to natural N limitation confirms a key criticism (Hungate et al. 2003) of earlier IPCC efforts.

Overall BioCON provides a platform for examining the myriad processes that contribute to interactions such as described above. For instance, the long-term interacting effect of CO<sub>2</sub> and N on biomass and biodiversity occur despite a lack of CO<sub>2</sub>  $\times$  N interaction on photosynthesis (Lee et al. 2011) and likely result from complex effects of species identity and diversity, along with CO<sub>2</sub> and N, on belowground communities and processes (e.g., Dijkstra et al. 2006a, 2007, West et al. 2006, He et al. 2010, 2012, Chung et al. 2007, 2009, Adair et al. 2009, 2011, Reich 2009, Antoninka et al. 2011, Schnitzer et al. 2011, Reid et al. 2012, Deng et al. 2012; Fig. 21). Collectively, these findings have important implications globally. For instance, because of N limitation and biodiversity losses, global estimates of potential C sequestration in the face of rising CO<sub>2</sub> may be currently considerably over-estimated. If this is true, atmospheric CO<sub>2</sub> concentrations (and associated global temperatures) may increase more quickly than anticipated. BioCON data have been important in broader analyses, syntheses, and meta-analyses of biodiversity, N, and CO<sub>2</sub> effects (Reich et al. 2006b, Isbell et al. 2011, Schnitzer et al. 2011) and development of global databases (Kattge et al. 2011). In addition, a team of non-CDR researchers used results of CDR decomposition studies (data downloaded from our website) in analyzing the effects of plant biodiversity on decomposition rates (Srivastava et al. 2009).

**Future Research:** Because the responses to CO<sub>2</sub>, N, and diversity have been highly dynamic temporally (Reich et al. 2006a, Reich and Hobbie In Prep), this experiment will continue providing valuable insights into the interactive effects of multiple global change factors. As one of the longest running multiple global change factor open-air experiments in the world, the results will be among the best available for showing the long-term impacts of such drivers on population, community, and ecosystem responses. Thus, we propose continued annual measurement of many plant, soil, community, and ecosystem variables across all 370 plots each year.

In addition, we will expand analyses of soil communities and trophic interactions, including their response to global change, and impacts on ecosystem structure and function, building on early and ongoing work at BioCON (e.g. Chung et al. 2009, He et al. 2010, 2012, Deng et al. 2012, Eisenhauer et al. 2012, Weisenhorn submitted, Weisenhorn et al. In Prep). This will include use of molecular tools to characterize both bulk soils and the rhizosphere microbiome (e.g., functional gene arrays, 454

pyrosequencing, and 16S ribotyping) in collaboration with research groups led by J. Zhou (Oklahoma), J. Dangel (U. North Carolina), and C. Henry (Argonne National Laboratory). It will also include a comprehensive plan to improve the mechanistic understanding of soil multitrophic interactions in shaping the relationship between producer diversity and ecosystem functioning under varying CO<sub>2</sub> and N conditions. This collaborative project will be led by N. Eisenhauer (Technische Universität Darmstadt, Germany), and it comprises several complementary subprojects, including experimental tests of the significance of positive and negative soil feedback effects across biodiversity, CO<sub>2</sub>, and N combinations.

### 3.2.2. WWCON – Warming, Water, CO<sub>2</sub>, and Nitrogen

Global change-related shifts in temperature, precipitation, atmospheric CO<sub>2</sub>, and N deposition will each likely impact terrestrial ecosystem processes, however the effects of each global change element alone may be influenced by other global change factors, via antagonistic and synergistic impacts and by indirect effects on soil resources and soil biota that modulate subsequent ecosystem responses. Yet, considerable uncertainty exists regarding the direction, magnitude, and ubiquity of such interactions, posing a significant challenge for predicting ecosystem feedbacks to multiple global change drivers. In 2007, we began a 5-year sub-experiment examining interactions of CO<sub>2</sub>, N and water availability. The water manipulation (ambient and -45% rainfall, achieved via temporary, portable rainout shelters) was added to the ongoing CO<sub>2</sub> x N treatments that began in 1998. The objective of a new BioCON research subexperiment is to incorporate experimental warming into the ongoing grassland manipulation of precipitation, CO<sub>2</sub>, and N to elucidate their interactive effects on long-term ecosystem response. The WWCON experiment is thus designed to determine the direct and interactive effects of warming, water, CO<sub>2</sub> and N on the productivity, biogeochemical cycling, and dynamics of plant and soil communities in a perennial grassland ecosystem. WWCON uses 48 plots from BioCON, all originally planted with 9 species in 1998.

**Key results:** Results to date of the water manipulation include a near total elimination of the CO<sub>2</sub> effect on productivity when both water and N are limited (Reich et al. Submitted) and complex pathways by which the resource treatments directly and indirectly drive trophic networks belowground (Eisenhauer et al. 2012). These include both direct effects of CO<sub>2</sub> and N on the abundance and diversity of soil animals, as well as indirect effects mediated by changes in other abiotic and biotic components of the soil environment (Fig. 22).

**Future research:** The new warming manipulation (3°C) will be added in 2012, resulting in a CO<sub>2</sub> x N x water x temperature factorial experiment. The study is largely funded through a grant from the NSF Ecosystems program, but will be available as a platform for LTER-related investigations, e.g., by undergraduates, graduate students, and post-docs, just as the core BioCON experiment has been. It will test the overarching hypothesis that global change drivers interact, such that responses will not simply be additive. Unlike interactions of CO<sub>2</sub>, N, and water, for which multiple limitation theory provides a relatively simple conceptual framework, experimental warming will induce different responses during cool vs. warm, or wet vs. dry, times during the growing season, with myriad possible pathways for interactions. For all four of the treatments, interactions will be influenced by the effects of drivers on the availability of soil resources and on soil biota, and by weather in each specific growing season. Warming will be imposed on a subset of species-rich plots in BioCON, to achieve a 2 x 2 x 2 x 2 factorial manipulation of temperature (ambient and +3°C), growing season precipitation (ambient and -45% rainfall, achieved via temporary rainout shelters), CO<sub>2</sub> (ambient and +180 ppm, achieved via FACE technology), and N (ambient and +4 g N m<sup>-2</sup> y<sup>-1</sup>).

Simultaneous soil and vegetation warming will be achieved by synchronized deployment of infrared heat lamps that warm aboveground plant structures, and a network of low-profile, buried electric pins that concurrently warm the soil to 0.75 m deep. Integrated microprocessor-based feedback control will maintain a fixed temperature differential (+3°C) between warmed and ambient control plots. We have successfully deployed similar technology in an experiment in the southern boreal forest in northern Minnesota (Reich et al. submitted, <http://forestecology.cfans.umn.edu/B4WARMED.html>). The new study will determine the interactive effects of these four global change factors on a suite of responses including: plant physiology, NPP, phenology, symbiotic N fixation, soil N availability, soil CO<sub>2</sub> flux, soil food webs, as well as the soil microenvironment. This project will provide one of the few empirical datasets describing the interactive effects of multiple important human-caused global change factors on terrestrial ecosystem processes, thereby enhancing mechanistic understanding of the ecological impacts of global change and informing models that aim to predict biotic feedbacks to such change.



### 3.2.3. BAC – Biodiversity, Warming, and Water

The Biodiversity and Climate (BAC) experiment is designed to determine the direct and interactive effects of plant richness, plant community composition, temperature, and water on the productivity; C and N dynamics; stability; and plant, microbe, and insect species dynamics and abundances in CDR grassland ecosystems. BAC uses 32 plots from Big Bio: 14 monoculture plots (one randomly chosen replicate for each of the 14 species that became well established in monoculture); 9 plots planted to 4 species (randomly chosen from 4-species plots planted with various combinations of these 14 species); and 9 plots planted to 16 species (randomly chosen from all 16-species plots containing these 14 species). Plant species are from 4 different functional groups (C3 grasses, C4 grasses, legumes, and non-legume forbs). Each of the 32 BAC plots originally contained three 3 m x 2.5 m subplots: a subplot warmed with a 1500-watt infrared heat lamp that elevates soil temperatures by ~3°C on average, a 700-watt lamp that elevates soil temperatures ~1.5°C on average, and an unwarmed control plot.

In 2007, before any treatments were imposed, we sampled vegetation (species abundances, root mass, species diversity, aboveground plant biomass production) and soils (air dried and archived for C and N; fresh soils archived at -40°C for analyses of soil microbial communities). Lamps were installed and tested in summer and autumn of 2008 and have been in continuous operation from March 1 through November 30 each year since then. Soil temperatures (3 locations per subplot) are recorded continuously (~5 minutes between readings) in all subplots. Soil moisture (0-10 cm depth) is measured at >10 sites per subplot at weekly intervals, and at 2 sites per subplot at 5 depth intervals (0-20, 20-40, 40-60, 60-80 & 80-100 cm) every third week. Starting in 2012, humidity and air temperature will be measured at 2 locations within each subplot every 5 minutes throughout each growing season.

In spring 2012 we will add water as a new treatment to create a Biodiversity x Warming x Water experiment. Unlike the WWCON experiment, which is performed at one level of diversity, BAC will allow tests of the interactive effects of diversity, warming, and water availability. Thus, each BAC plot will have a factorial combination of [ambient temperature; or +3°C] x [ambient rainfall; or a 40% decrease in precipitation via movable rainout shelters]. About half the cost for BAC is covered by a grant from the Legislative-Citizen Commission on Minnesota Resources.

**Key Results:** The first three years of this experiment included a hot, dry (2009), a cool, wet (2010), and a warm, wet (2011) growing season. In all three years, warming had strong impacts on phenology, advancing all phases we monitored, especially flowering (Whittington et al. In Prep). Warming and plant diversity each had strong positive impacts on aboveground plant community biomass production, with a positive diversity x warming interaction in the cool, wet year (Cowles et al. In Prep). However, a strong positive early growing season diversity x warming interaction in 2010 (as observed via weekly Normalized Differential Vegetation Index (NDVI) measurements in each subplot) had dissipated by August (based on both NDVI and clipped plant mass measurements). Finally, by 2011, both warming treatments had caused significant reductions in plant species numbers in all subplots compared to 2009, but no decline had occurred in unwarmed control plots (Tilman et al. In Prep). In general, we could readily detect effects of the 3°C warming on measured responses, but detected effects of the 1.5°C treatment only on plant species number. We also have used BAC results to examine responses of consumers to temperature. Grass species differ in quality for aphid reproduction, but aphid reproductive rate is generally depressed in C3 grasses under elevated temperature (Schmidt et al. In Prep).

**Future Research:** We will continue annual sampling in all subplots of primary productivity and plant species abundances; weekly measures of soil moisture and NDVI; hourly measurements of soil temperature, air temperature and humidity; and arthropod community composition and diversity from D-Vac samples from each plot each year. The results of the first three years of this experiment strongly suggest that the ecological impacts of elevated temperature depend on rainfall and possibly also on biodiversity. The proposed water manipulation to be implemented in 2012 will provide a direct test of this possibility.

### 3.3. Nutrient Addition

Humans are releasing biologically available N, a major limiting resource in terrestrial ecosystems, at high rates around the globe (e.g., Galloway et al. 1995, Howarth et al. 1996, Smil 1997, Vitousek et al. 1997, Holland et al. 1999). In addition, human land use is accelerating the movement of nutrients from terrestrial to aquatic ecosystems. Beginning in 1982, we established several closely related N addition experiments to determine the effects of this enhanced N supply on competitive interactions, plant-

herbivore interactions, and C and N cycling in CDR ecosystems. One of these (E001) consisted of 207 plots, each 4 m x 4 m, located in three successional grassland fields and in a savanna prairie opening. Another (E002) was essentially identical to E001, and consisted of 162 plots in the three successional fields, but on sites that had been disturbed by agricultural disking in spring of 1982. Treatments were a control, addition of all nutrients except N, and addition of all nutrients plus N, with N added at 1 of 7 rates (Tilman 1987). From 1982 through 2005 plots were annually sampled for aboveground biomass (sorted to species) and litter, and periodically for extractable soil  $\text{NH}_4$  and  $\text{NO}_3$ , belowground biomass, insect abundances, mycorrhizal fungi, small mammals, and microbial biomass. In 2006, the sampling frequency in most fields was reduced to approximately once every three years because the pace of change had slowed. In addition, three experiments, each with 54 plots, received N treatments starting in 1982, but now differ as noted below:

**3.3.1. N Cessation (E097):** To determine the dynamics of recovery after cessation of N addition, N addition was halted in 3 plots per treatment randomly chosen from among the 6 total replicates per treatment in one of the 7 N addition sites in 1993.

**3.3.2. N and Fire (E098):** Similarly, to determine how the effects of N addition depend on litter accumulation and other factors related to fire suppression, at a different site 3 randomly chosen replicates of each N treatment have been burned and 3 have been unburned each spring beginning in 1993. All continue receiving N addition.

**3.3.3. N and Deer Herbivory (E172):** Deer, a major mammalian herbivore at CDR, significantly impact CDR grasslands (also see section 3.5). In autumn of 2004, in another site, 3 randomly chosen N treatment plots per treatment were assigned to be fenced to exclude deer and the other 3 were open to deer. All continue to receive N.

**3.3.4. N and other nutrients:** Two experiments (E145, E211) were established in 8 different grassland and forest sites in 1998 and in 3 sites in 2004, respectively, to elucidate the nature of N limitation of decomposition processes and litter and soil microbial communities. In 2007, we also added an experiment composed of 60 plots to examine the effects of N (3-levels) on productivity, decomposition, and composition are mediated by its interactions with phosphorus (P), potassium (K), and micronutrients. This experiment is the Cedar Creek node of the Nutrient Network experiment (see Section 3.6.1 for detailed description).

**Key Results:** (1) Using data from the first 25 years of the N addition experiment, Clark and Tilman (2008) found that chronic low-level N addition ( $10 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ) reduced plant species numbers by 17% relative to controls receiving ambient N deposition (Fig. 1). Moreover, species numbers were reduced more per unit of added N at lower addition rates, suggesting that chronic, low-level N deposition may have a greater impact on diversity than previously thought. Clark et al. (2009) found that net N mineralization rates remained elevated in plots that had ceased receiving N 12 years earlier. Although these grassland ecosystems had not retained a high portion of the deposited N, the effects of this N retention were surprisingly long-lasting.

(2) Because soils are the largest active terrestrial sink of C, the potential effects of elevated N deposition on soil C stores is of great interest. Earlier CDR work suggested that N deposition did not impact soil C stores (Wedin and Tilman 1996). However, we have recently found that 27-years of chronic N addition to prairie grasslands strongly increased the C sequestration in mineral soils (Fornara and Tilman In Review). A key mechanism was an N-induced increase in root mass accumulation with a shift to C3 grasses, which despite their lower N-retention ability still acted as important soil C sinks. Because C3 grass species often invade grasslands receiving high rates of N deposition, it is critical to understand whether soil C sequestration also occurs across other regions worldwide. The NutNet experiment (3.6.1) will be used to address this global question.

(3) We have also explored N effects on decomposition (Fig. 2). In a range of forested and grassland sites, both substrate N and externally supplied N accelerated the initial decomposition rate (Fig. 2) (Hobbie 2005, 2008, In Revision), whereas later in decomposition, litter and externally supplied N slowed decomposition. This shift in the effects of N on decomposition rates through time can only be elucidated through long-term experiments and has been little considered by ecosystem models. It corresponded to changes in the effects of N on extracellular enzymes: N increased activity of polysaccharide-degrading enzymes early in decomposition, but depressed lignin-degrading enzyme activity later in decomposition (Hobbie et al. In Revision). Other related work on decomposition includes a global synthesis in which we were involved (Parton et al. 2007), an analysis of the litter decomposition rates that suggested that plant

traits were a predominant controller of these rates worldwide (Cornwell et al. 2008), studies of the effects of fire (Hernandez and Hobbie 2008), of fire and herbivory (Kay et al. 2008), of N (Keeler et al. 2009), and of photodegradation (Brandt et al. 2010) on decomposition.

(4) Other work in E001 and E002 examined the correlates and controls of plant species loss after N deposition (Cleland et al. 2008; Collins et al. 2008), and the effects of N addition on soil microorganisms, including mycorrhizal fungi (Bradley et al. 2006, Lee et al. 2006, Davelos-Baines et al. 2007, Egerton-Warburton et al. 2007, Johnson et al. 2008, Schlatter et al. 2010), among other questions (Chalcraft et al. 2008, Polasky et al. 2011, Clark et al. 2007, Knops et al. 2010).

(5) In 2011, work in the CDR-NutNet plots demonstrated increased rust infection of grasses with N addition; in contrast, fungal infection severity did not respond to addition of either P or K (Lacroix et al. In Prep). Earlier work demonstrated an increase in viral infection with P, not N addition (Borer et al. 2010). The differing nutrient limitations of these pathogen groups suggest a testable mechanism for maintaining viral and fungal coinfection. Further, work in the CDR-NutNet plots shows that N addition increases aphid reproduction, whereas P addition reduces aphid population growth rate (Schmidt et al. In Prep). Factorial addition of N, P, and K in the CDR-NutNet plots leads to higher plant biomass only when N is one of the nutrients, supporting earlier findings at CDR. In contrast, nutrient addition steadily reduces plant diversity with increasing number of nutrients, regardless of the identity of the nutrient (Borer et al. In Prep).

(6) Several groups of non-CDR researchers have used the long-term data from our N experiments in various publications, including those by Hillebrand et al. (2007), Elser et al. (2007), LeBauer et al. (2008), Xia and Wan (2008) and Wang et al. (2010), who obtained the data and metadata from our web site. Others non-CDR researchers collected soils from our experiments for new microbial community analyses, including Bates et al. (2010), Ramirez et al. (2010), and Fierer et al. (2011).

**Future Research:** As already discussed, the chronic N addition experiments provide an excellent opportunity to test for multiple stable equilibria or tipping points. Regular and novel data collection and analyses will be focused on these issues and their relevance to conservation and management needs. CDR-NutNet sampling will include a focus on consumer community responses to nutrient combinations, including fungal rusts and endophytes, viruses, and insects, as well as on decomposition processes and soil carbon sequestration. We are also examining whether functional traits associated with nutrient use are phylogenetically conserved and correlated with species-level responses to N addition.

### 3.3.5. Scale-Dependent Nutrient Interactions among Lacustrine Communities

We propose expanding our exploration of the effects of interacting global change factors to aquatic systems. The Cedar Creek Ecosystem Science Reserve includes four lakes (Cedar Bog, Fish, Beckman, and Ice) as well as the creek itself that have been little studied since the famous work done in Cedar Bog Lake by Raymond Lindeman (Sterner 2012). We propose to initiate long-term studies to determine how nutrient retention vs. export in the uplands affects downslope aquatic communities. Experimental work will focus on stoichiometry and patterns of nutrient limitation at different observational scales. Many experimental studies at the bottle to mesocosm scale point to multiple nutrient limitation (Elser et al. 2007) whereas whole-lake studies and biogeochemical logic used by Redfield (1958), Schindler (1977) and others argue that P alone ultimately controls trophic status (Schindler et al. 2008). Feedback loops involving such processes as N fixation and denitrification require sufficient time and the existence of particular physical conditions. Therefore, there are mechanistic reasons to expect a discontinuity of limiting factors at different observational scales (Sterner 2008). Sterner et al. 2008 referred to this as the “biogeochemical mosaic hypothesis” (Fig. 23). Our proposed work will test the hypothesis that with increasing spatial and temporal scale, interactions among limiting nutrients diminish and single factor limitation is increasingly prevalent. We will test this hypothesis at CDR by observations of nutrient limitation at two observational scales. In addition, close cooperation with the Nutrient Network (see Section 3.6.1) will likely catalyze the formation of a similar community of scholars studying nutrient limitation in aquatic systems.

**Future Research:** Field sampling of aquatic habitats will be performed every 2-3 weeks during the 3-month summer season. Standard limnological parameters (temperature, oxygen, pH, salinity, chlorophyll, as well as dissolved and particulate C, N, and P pools) will be measured. Groundwater sampling will also be performed and nutrients measured. Small-scale experimental work will consist of bioassay, nutrient addition studies using closed transparent containers containing filtered / diluted plankton in a full factorial addition of P, N, and Si. The diluted bioassay design minimizes effects of

herbivores and helps avoid bottle effects. Responses will be measured by chlorophyll and by several rapid community-based analyses including particle counting which provides detailed information on size structure and by use of a FlowCAM to pull out the dynamics of morphologically distinct species from the community (Poulton and Martin 2010). A subset of treatments will also be examined microscopically. These studies will give us foundational information on the role of different nutrients in plankton dynamics over time in these lakes and will be performed in years one and two. We anticipate that, like most aquatic environments, more than one limiting substance will be found to play some role in the dynamics in experiments at this scale. Given the information to be obtained in years one and two, one of the CDR lakes will be chosen for establishing a set of limnocorrals (*in situ* mesocosms) to be constructed with wooden rafts and polyethylene walls. Some will be closed at the bottom and others will be open to the sediments. Again, factorial nutrient addition experiments will be performed to test the central hypothesis that the larger the observational scale and the more heterogeneous the conditions examined the less prevalent multiple nutrient limitation will be. We expect that this work will lead to future experimental studies at the whole-lake scale.

### 3.4. Woodland-Grassland Ecology, Interaction, and Dynamics

Past work at CDR and elsewhere has demonstrated an overriding influence of fire frequency in maintaining prairie openings and oak savanna at the prairie-forest border (Peterson and Reich 2001, Reich et al. 2001b). Fire regimes harm some types of species while favoring others and drive light and nutrient dynamics, which in turn drive community functional attributes and diversity levels (Peterson and Reich 2001, Willis et al. 2010, Cavender-Bares and Reich 2012). Ultimately, fire frequency interacts with climate, N deposition, land use, and biotic invasion to determine the outcomes of tree-grass interactions and the dynamics of vegetation at ecotones such as the prairie-forest border in Minnesota (Frelich and Reich 2010).

Our work focuses on two long-term studies as well as short-term manipulations nested within or separate from those experiments. First, we study a prescribed burning experiment (E015 begun in 1984 and expanded to E133) composed of 29 landscape units (3 to 27 ha) that had been protected from fire from about 1900 to 1964. Fire treatments (prescribed spring ground fires) range from complete fire protection to near-annual burning, spanning the range of pre-settlement fire frequencies along the forest-prairie border. Permanent sampling plots (50 x 75 m) were established in 12 burn units in 1984, and in 17 more by 1995.

Second, we study an old-field chronosequence (Inouye et al. 1987, E014) established in 1983 and consisting of 100 permanent plots in each of 21 successional fields with time since abandonment spanning 7 decades. We have sampled plots every 5 or 6 years for herbaceous species composition and cover and soil C and N. In addition, in 14 of these fields, 4 permanent plots per field are sampled annually for aboveground biomasses of all plant species. Fields are periodically sampled for arthropods (e.g., Siemann et al. 1999ab). In 2008 each of these 14 fields was divided in half, and one half randomly chosen for periodic prescribed burning (a fire every other year). We anticipate that the burned half will continue succession to prairie grassland while the unburned half will become white pine stands if seed sources are nearby, or will otherwise undergo extremely slow succession to oaks.

**Key Results:** During the current award we have advanced understanding of processes underpinning the dynamics of tree-grass ecosystems, as well as the mechanisms that operate at different scales to create such patterns. (1) We have examined the impact of fire, vegetation, and plant-insect interactions on biogeochemical cycling (Laungani and Knops 2009ab, Dijkstra et al. 2006ab, Kay et al. 2007, 2008, and Hobbie 2010, Knops and Bradley 2009) and plant, bird, and mutualist communities (Chapman and Reich 2007, Peterson et al. 2007, Peterson and Reich 2008, Dickie et al. 2005, 2007, 2009a), as well as the interactive role of plant-mutualist interactions (Dickie et al. 2007) and tree-shrub interactions (Pelc et al. 2011) on the dynamics of the plant community.

(2) We have found that phylogenetic relatedness corresponds with spatial scale and environmental variation and species responses to fire in the savanna burn treatments (Willis et al. 2010, Cavender-Bares and Reich 2012). These studies show that traits influencing patterns of phylogenetic beta-diversity along a gradient of fire frequency may have originated as long as 80 million years ago (Fig. 8).

(3) At a broader scale, we examined impacts of gradual versus sharp borders across prairie-forest ecotones at a regional scale (Danz et al. 2011) and examined how differing hydraulic plumbing influences

species distributions (Savage and Cavender-Bares 2012) as well as drought resistance and resilience of trees (Savage et al. 2009, Savage and Cavender-Bares 2011) within and across biomes, further contributing to theory regarding network models of metabolic scaling (McCulloh et al. 2010).

(4) In the old fields, soils lost up to ~80% of C due to agriculture and after abandonment have slowly regained C, at about  $340 \text{ kg C ha}^{-1} \text{ y}^{-1}$  (Knops & Bradley 2009), with the rate of C accumulation seemingly controlled by atmospheric N deposition and legume N fixation (Knops and Tilman 2000). Because atmospheric N deposition has increased in the last 50 years, and other factors such as temperature, rainfall, growing season length, and legume abundance also have changed, past rates of C accumulation might not apply to the future. We are addressing this by resampling soils and vegetation every six years in a total of 2100 plots across 21 old fields, and are examining how these changes correspond with vegetation and climate.

(5) Invasion of grasslands by woody species has consequences for ecosystem processes, because woody species often have different productivity (Reich et al. 2001b), detrital chemistry (Dijkstra et al. 2006a), soil C stocks (Jackson et al. 2002), nutrient dynamics (Dijkstra et al. 2006a), mycorrhizal and other soil microbial associations (Dickie et al. 2005, 2009b). As a result, wood invasion can redistribute N from the soil into biomass, with corresponding large ecosystem C changes (Fig. 24; Laungani and Knops 2009ab). Surprisingly, pine invasion in recent decades (*Pinus strobus*, Dovčiak et al. 2005) has had little effects on soil pH, or C and N cycling (Hobbie et al. In Prep, Laungani and Knops 2012), although pines accumulate two times more N in biomass than do the grasslands they invade (Laungani and Knops 2009ab).

**Future Research:** We will continue CDR's longest running experiment by applying the burning treatments across the grassland-savanna-woodland mosaic and in the 14 successional fields. We will use the long time series in the oak savanna system and the successional fields to examine resiliency to perturbation, resistance to invasion, impact of initial soil and vegetation conditions on dynamics and composition, and the role of evolutionary history in invasion resistance. We will also use these long-term studies to determine if our ecosystems show the multiple equilibria recently reported for grassland-savanna-forest ecosystems elsewhere (Staver et al. 2011). We anticipate that the high frequency burn sites, which have the highest phylogenetic diversity, may be more resistant to invasion by exotics than the unburned communities, which have the lowest phylogenetic diversity. In addition, we hypothesize that burned communities will have greater resilience to perturbation from major climatic events, such as prolonged drought, than unburned communities in which species are less adapted to disturbance.

### 3.5. Interactions and feedbacks: Resources, Plants, Herbivores, Predators and Parasitoids

#### 3.5.1. Interactive Effects of Pathogens, Herbivores, and Plant Diversity

Past work at CDR has shown that disease and insect herbivory are reduced in high-diversity plant communities (Mitchell et al. 2003, Haddad et al. 2011, Schnitzer et al. 2011), and that their lower abundances may contribute to the higher productivity observed at higher plant diversity. However, such short-term studies cannot address the possibility of long-term feedbacks between plant composition, plant diversity, microbial diversity, pathogens, and herbivores. To explore such feedbacks, we established two experiments (E244 and E245) in 2008 that use insecticides, fungicides, and fences to manipulate the presence of insects, soil fungi, foliar fungi, or vertebrate herbivores. The first experiment (E244) is nested within 32 BigBio plots (E120, section 3.1.1) such that the fungicide and insecticide treatments are crossed with plant community diversity. The second experiment (E245) is conducted in an old field and has an additional treatment (unfenced, or fenced to exclude vertebrate herbivores). In both experiments, we apply treatments and measure NDVI weekly to bi-weekly throughout the growing season in all plots. We annually harvest biomass of each plant species, determine plant species diversity, and sample root biomass in all 253 experimental plots.

These experiments test three hypotheses. (H1) Herbivore and microbe-induced reductions in productivity will be smaller in high-diversity than low-diversity plant communities (Mitchell et al. 2003, Schnitzer et al. 2011, Hillebrand et al. 2007). (H2) Exclusion of any consumer group reduces plant diversity, increases dominance of competitive species, and increases total aboveground herbaceous biomass (Hillebrand et al. 2007, Gruner et al. 2008, Schnitzer et al. 2011). (H3) Reduced fungal load leads to later leaf senescence and greater aboveground and seed biomass (Battelsen et al. 2001, Bryson et al. 2000, Wise and Mueller 2011, Wu and von Tiedemann 2001).

**Key Results:** Counter to H2, plant diversity in the old field plots (E245) was higher in fungicide- and insecticide-treated plant communities after three years of treatment. Vertebrates had no effect on plant diversity, again counter to H2. While consumers did not alter plot-scale productivity in the old fields (Borer et al. In Prep), reduced fungal loads in the BigBio experiment (plots E244) led to increased plant productivity, with the greatest effects occurring in high-diversity plant communities (Kinkel et al. In Prep), in contrast to H1. Finally, foliar fungicides led to more rapid early-season increases in plant biomass and delayed senescence as predicted by H2 (Montgomery et al. In Prep).

**Future Research:** The first years of this experiment have shown that altered consumer compositions impact both plant diversity and productivity, but have not revealed if the plant changes are transient, nor if the changes in plant productivity and diversity may themselves impacts other aspects of the functioning of these systems. Therefore, we will continue to gather the data needed to test our original hypotheses.

We also will explore long-term feedbacks between consumers and plants and the effects of these feedbacks on community and ecosystem function. A growing body of evidence is showing important short- and long-term feedbacks between plant composition, productivity, and decomposition and vertebrates (Duffy 2002), invertebrates (Eisenhauer et al. 2011), and microbial heterotrophs (Diez et al. 2010, Kardol et al. 2007, Kulmatiski et al. 2008). We will use our experiment to examine two major areas in which feedbacks may be important in controlling ecosystem processes. First, our early result that productivity is independent of foodweb composition in natural plant communities (E245) but elevated with removal of fungi in the controlled BigBio communities (E244) suggests that feedbacks between foliar fungi and plant composition may be critical for understanding productivity in natural grasslands. In addition, while productivity was not altered in the early years of the experiment, long-term feedbacks between consumers and plant production could arise via positive feedbacks in which enemy removal leads to increased productivity, increasing soil nutrients and C. Alternatively negative feedbacks may arise because simplified foodwebs, particularly if lacking soil decomposers, lead to long-term accumulation of litter, reducing N mineralization and ground-level light, leading to a long-term reduction in diversity and productivity.

### 3.5.2. Interactive Effects of Deer, Fire and Nitrogen

Many ecosystems are experiencing changes in multiple drivers of ecosystem composition and functioning. Our experiment manipulating deer, fire, and N focuses on three important drivers of ecosystem change for our region. Specifically, in 2000 we began a long-term experiment to examine impacts of these three drivers in an area with rapid establishment by *Pinus strobus* (white pine) in a late successional grassland. This full factorial experiment, with 4 replicates of each combination, manipulates N (0 or 3 g m<sup>-2</sup> yr<sup>-1</sup>), fire (none or every 4 years), and deer (fenced or open to deer), for a total of 32 plots, each 20 m x 20 m (E153). Because effects of these factors emerge slowly, we sample these plots at 5 year intervals. We hypothesize that the response of this ecosystem to the combined effects of fire, N, and deer herbivory will depend on how abundances of pine and perennial grassland species respond to the different combinations of the drivers. We hypothesized that warm-season grasses would increase with and encourage fire, resist herbivores, and inhibit woody plant invasion (Davis et al. 1998, Inouye et al. 1994); that cool-season plants would be favored by N deposition (Tilman 1987) but be fire-intolerant and palatable to herbivores; that legumes tolerate fire but decrease with herbivory and N deposition; and finally, that establishing woody plants, especially white pine, would be fire-intolerant and more susceptible to herbivory. We are measuring treatment effects on the composition and diversity of plants and consumers (insects, small mammals, lizards) as well as plant and soil C and N.

**Key Results:** By 2010, dense white pine sapling stands had developed in the absence of fire, the C-3 perennial grass *Poa pratensis* had increased in the presence of fire and N fertilization, and the C-4 perennial grass *Schizachyrium scoparium* dominated plots with fire but no N addition. By 2010 N fertilization had significantly increased gross ammonification and ammonium immobilization, but this was independent of the other treatments.

**Future Research:** Because the experimental treatments have now established the three different vegetation types described above, in the next six years, we will determine how soil C and N sequestration and dynamics are controlled by deer, fire, and N deposition, and their long-term interactive effects on vegetation.



### 3.6. Regional and Cross-site Research and Synthesis

In keeping with the growing emphasis of the LTER network on cross-site research and with the recommendations of the 30-year review report, we propose strong CDR involvement in some nascent or ongoing cross-site initiatives. Specifically, we aim to (1) provide a formal home for the data analysis, synthesis, and management of the ongoing Nutrient Network experiment (NutNet) within CDR; (2) participate in an ongoing study of the influence of urbanization on ecological structure and function throughout cities of the US by serving as a natural reference site for this work; and (3) lead initiatives and participate in ongoing research as part of the National Phenology Network. Below we describe each of these cross-site efforts.

#### 3.6.1. Nutrient Network – Nutrients and Consumers

The Nutrient Network ([nutnet.umn.edu](http://nutnet.umn.edu)), now in its fifth year, is a collaborative experimental network established to understand the long-term consequences of global-scale changes in climate, nutrient inputs, and food web structure for grassland diversity and ecosystem functioning. Over 90 scientists conduct a standard set of observations and manipulations at ~70 herbaceous plant-dominated sites on five continents to develop a global perspective on the effects of multiple nutrients and herbivory on plant productivity and diversity. Sites span a wide range of short-statured vegetation types and environmental conditions and include six LTER sites (CDR, SEV, SGS, KNZ, HJA, NWT). 39 sites are conducting stand-alone experiments within a randomized-block design with 5 m x 5 m plots and 3 replicate blocks per site. The Multiple-Nutrient Experiment is a factorial addition of three nutrient treatments (N, P, and K + micronutrients). The Consumer x Nutrient Experiment (at 33 sites) is a full factorial manipulation of nutrients (Control or All Nutrients) and consumers (Control or Fenced). The 180 cm fences are designed to exclude aboveground mammalian vertebrates, including deer; small, climbing, or subterranean animals may potentially access plots. Annual data collected in all plots includes aboveground live and dead plant biomass and species and growth form composition.

Here we propose to strengthen the LTER – NutNet partnership. CDR hosts one of the first NutNet sites and is in an advantageous position to support NutNet activities. CDR PIs Borer and Seabloom are the lead PIs of NutNet and several other CDR investigators are contributing to NutNet (Cavender-Bares, Hobbie, Kinkel, and Knops). Borer and Seabloom also host annual NutNet scientific meetings at UMN, and NutNet data are hosted on Minnesota Supercomputer Institute servers. NutNet also benefits CDR – and the LTER Network – by providing a global context for site-scale research on diversity, nutrients, consumers, and ecosystem processes. In addition, the highly standardized NutNet data can help in calibrating and synthesizing long-term datasets across LTER sites.

**Key results:** To date, NutNet data have been the basis for cross-site syntheses on the drivers of plant diversity and invader abundance (Cadotte et al. 2010, Adler et al. 2011, Firn et al. 2011), analyses that have demonstrated the insights that this unique dataset can provide. For example, NutNet data revealed no globally consistent relationship between site or plot-scale productivity and plant diversity (Fig. 9; Adler et al. 2011). Similarly, they revealed that exotic species had similar abundances in their native and invaded ranges, suggesting that the same species traits or interactions controlled species abundance in invaded ranges as in home ranges (Firn et al. 2011).

**Future Research:** With five years of data in hand, the NutNet is poised to make major contributions to ecology; there are currently 15 manuscripts in preparation. We propose to support the centralized coordination, data syntheses, and data management that are essential for this network to gain insights into the global drivers of species distributions and ecosystem processes. For example, we will use the increasingly long-term and rich NutNet data set to examine the global relationships between grassland vertebrates, grassland productivity and nutrient cycling (Borer et al. In Prep) and the regional variation and contingencies in the susceptibility of communities to invasion. We also are using these data to assess global patterns – and suggest potential drivers – of nutrient limitation of decomposition (Hobbie et al. In Prep).

We also propose to pursue NutNet-wide experiments. We are currently using CDR funds to evaluate the role of nutrient inputs and herbivory in decomposition of a standard substrate (pin oak leaf litter, *Quercus ellipsoidalis*) at 36 NutNet sites. Over 7000 litter bags were deployed in treatment plots in 2010, to be collected over seven years (2011-2017). We also propose to use NetNet to seek global-scale insights into the factors controlling soil organic matter via density fractionations, long-term incubations, and chemical oxidation at a subset of North American NutNet sites that have a range of precipitation (MAP),

temperature (MAT), soils, atmospheric N deposition, and aboveground biomass. To determine site and treatment effects on soil C pools, we will aerobically incubate soils from 210 plots at 22°C in the dark at field capacity to measure CO<sub>2</sub> evolution, density fractionation, and oxidation with H<sub>2</sub>O<sub>2</sub> (Jagadamma and Lal 2010).

### 3.6.2. Urbanization Effects on Ecosystem Structure and Function

The landscape surrounding CDR is changing rapidly, as agricultural lands are replaced by low-density residential land use at the fringes of the Twin Cities of Minneapolis and St. Paul. In a series of related projects, we have been examining the influence of residential development on ecological structure and function.

**Key Results:** (1) Soil C levels in a 100-year chronosequence of residential lawns of 40 houses surrounding CDR was highly variable and nonlinearly related to age of development (King et al. In Prep). Soil C accumulated in the top 40 cm at a rate of 68 g C m<sup>-2</sup> yr<sup>-1</sup>, comparable to rates measured in lawns in Colorado and California and more than double rates measured in the CDR old-field chronosequence (Knops and Bradley 2009), likely because of lawn management.

(2) Using CDR Social Science Supplement funds, we extended the Twin Cities Household Ecosystem Project to the exurban region surrounding CDR ([www.tchep.umn.edu](http://www.tchep.umn.edu)). Among households, fluxes of C, N, and P were highly variable and often skewed, with a small number of households disproportionately contributing to total fluxes across all households (Fissore et al. 2011, In Press). Carbon fluxes were dominated by home energy use, motor vehicle travel, and air travel; N fluxes by human diet, fossil fuel emissions, and lawn fertilizer; and P fluxes by human diet, detergents, and pet diet. Both social and biophysical factors contributed to patterns of household biogeochemical fluxes (Fissore et al. 2011, Nelson et al. In Prep): greater household income was associated with greater household C fluxes, while less easily quantifiable factors like values, norms, and attitudes also influenced specific behaviors such as maintaining a lawn.

(3) We used CDR International Supplement funds to enlist the collaboration of a German graduate student to compare phylogenetic diversity and functional trait composition of spontaneously occurring (not planted) species in privately managed yards change along a gradient of housing density in the Twin Cities and between yards and CDR (S Knapp et al. 2012). Yards had more spontaneously occurring plant species per hectare in urban than in exurban regions, but phylogenetic diversity and functional composition did not change with housing density. In contrast, in comparison to natural areas, yard plant species were more closely related to each other, causing phylogenetic homogenization within yards, and were functionally distinct, being more often short-lived, self-compatible, and having higher specific leaf area than species of CDR. The total plant diversity per hectare in household yards increased with household wealth and education and decreased with higher use of fertilizer (Cavender-Bares et al. 2012) indicating an important role for human choices in driving biodiversity in human-dominated landscapes.

**Future Research:** We recently received funding along with investigators in Boston, Miami, Phoenix, Los Angeles, and Baltimore (including CAP, PIE, BES, and FCE LTER sites) from the NSF Macrosystems Biology program (Peter Groffman, PI) to test the hypothesis that maintenance of similar management practices among cities leads to homogenization in ecological structure and functions relevant to ecosystem C and N dynamics, with potential continental scale implications. Further, we suggest that understanding the nature and extent of urban homogenization will provide the conceptual basis, data, and methodologies for scaling the effects of urban land use change from local to continental scales. CDR will be one of the natural “reference” areas for the Twin Cities, providing measures of plant diversity and soil properties. Further, phylogenetic analyses piloted at CDR (S Knapp et al. 2012) will form the basis for comparative analyses across all cities.

### 3.6.3. National Phenology Network

Phenology, the timing of seasonal biological events such as budburst, blossom dates, bird migration and insect development, can influence species interactions (e.g. pollination, herbivory, food availability); provides a biological measure of changes in growing season length in seasonal terrestrial ecosystems; and influences species range limits. Both plant and animal phenology seem to be changing more in recent decades than at any time during the previous 1200 years (Primack et al. 2009). In 2009 we began measurement of phenology in grasses and forbs across several core long-term experiments that manipulate environmental drivers (e.g., BioCON, BAC). Moreover, as part of our cross-site research, CDR collects plant phenological observations for the USA-National Phenology Network (NPN);

<http://www.usanpn.org/>). As an ecotonal site, the species we monitor span several regions. One of our PIs, Montgomery, is liaison for the LTER Network to the USA-NPN.

**Future Research:** We currently lack knowledge of variation in phenology among individuals within a population. Such variation is the basis for adaptive responses to climate change. Interspecific phenological differences could impact interspecific interactions. However, sampling phenology on a large number of individuals at a site or in a region is difficult because of the considerable time and effort necessary for human observers to collect data. We are currently using CDR as a site to test the power of high resolution (sub-meter spatial resolution; up to daily temporal resolution) aerial imagery to follow phenology of individual trees from satellites.

#### 4. SYNTHETIC RESEARCH

Synthesis has been a hallmark of CDR since its founding. As in the past, the development, testing and refinement of concepts and theory are central features of the research and synthesis that we propose. Here we highlight three of these additional synthesis activities. The first activity aims to take full advantage of our numerous long-term observational and experimental studies by using comparisons, contrasts and syntheses of combinations of them to seek a more general understanding of population, community, and ecosystem processes, especially their responses to multiple driving variables and their interactions. The second synthetic activity seeks the underlying causes of such general patterns by using species traits and phylogenetic history to explore the potential roles of interspecific tradeoffs and the drivers of community assembly, composition, diversity, and ecosystem functioning, and positions CDR as a leader in the development of global trait databases. The third uses our specific site-based results to better understand the provision of ecosystem services that contribute to human well-being and how the manipulation of ecosystems changes the provision of services.

##### 4.1. Cross-Experiment Syntheses

The 16 core CDR experimental and observational studies (see Supplement: Electronically Available Datasets), which are the long-term, ongoing projects that have occupied much of the efforts of our team and in which we have invested much of our funding over the past decades, are now sufficiently long-term and data rich to provide a major opportunity for cross-study synthesis. This potential is increased by numerous other shorter-term studies that PIs, graduate students, post-doctoral researchers, and visiting researchers have performed during the past three decades, often with their own funding and often with only one or a few years of observations.

**Key Results.** Our efforts at cross-experiment synthesis at CDR are nascent, but exciting. For instance, we recently have formally compared our two long-term biodiversity experiments (Reich et al. Submitted). We found that in both BigBio and BioCON, diversity effects on productivity not only have grown stronger over the years (Fig. 15), but have become progressively less saturating, and thus more linear. In other words, differences in species richness between the second highest levels (8 or 9 planted species) and the highest (16 planted species) were lacking or modest early on but have grown larger with time. In both experiments these changes were likely due to increasingly positive effects of highly diverse assemblages on N availability.

Although these two biodiversity experiments have revealed multiple effects of biodiversity on ecosystems (e.g., Tilman et al. 2001, Reich et al. 2001a), the importance of biodiversity relative to other factors and drivers has been the subject of far-ranging and insightful dialogues (Wardle and Jonsson 2010, Duffy 2009), and questioned by observational studies that suggested that ecosystem productivity was either independent of diversity (Adler et al. 2011) or more dependent on soil fertility than on diversity (Grace et al. 2007). To address this issue, we synthesized results of 12 CDR long-term experiments that have quantified the absolute and relative effects on productivity of biodiversity, N addition, N cessation, drought, water addition, CO<sub>2</sub>, fire, and herbivory (Fig. 25; Tilman et al. In Revision). We found that ecologically relevant decreases in grassland plant diversity influenced productivity at least as much as ecologically relevant changes in nitrogen, water, CO<sub>2</sub>, herbivores, drought, or fire. Moreover, effects of biodiversity on productivity increased through time, while those of other factors either declined (N addition) or remained unchanged (all others), showing that biodiversity became an increasingly dominant driver of ecosystem productivity through time. These results suggest that observational studies and short-term experiments may underestimate the relative influence of biodiversity on productivity, and

that the loss of biodiversity may have at least as great an impact on ecosystem functioning as other anthropogenic drivers of environmental change.

Because our experiments are highly replicated and long-term, our cross-experiment syntheses can bring surprising power to the analyses. For instance, the 12 long-term grassland experiments we analyzed had >7700 relevant productivity measurements. Moreover, because our observational and experimental studies are conducted at a single site with similar sandy soils, the same climate, and species from the same regional species pool, our on-site syntheses control for many factors that could potentially confounding cross-site analyses. As such, we feel that they are an excellent complement to cross-site syntheses.

**Future Research.** We are particularly excited to use our numerous multi-factor experiments to explore both the direct and interactive effects of multiple drivers of environmental change. For instance, we propose synthesizing results of our N x herbivory experiment, N x fire experiment, water x CO<sub>2</sub> x N x warming experiment, and fire x N x herbivory experiment to determine the direct effects of each factor and their interactive effects on plant diversity. We will also compare these results to the dependence of plant diversity on these variables in our grassland chronosequence and savanna prescribed burning studies. We will use the studies mentioned above plus BAC and BioCON to determine the direct and interactive effects of multiple drivers on soil C and N stores and soil nitrate levels. Similarly, we can use this suite of CDR experiments to synthesize the direct and interactive effects of multiple drivers on soil microbial communities as described by microbial sequence datasets that are increasingly being collected by multiple researchers at CDR. We also propose examining the extent to which plant responses to global change factors across these core experiments are phylogenetically conserved.

#### *4.2. A Synthesis of Tradeoffs, Scaling, Phylogenetic History and Community Assembly*

Plant traits influence how plants interact with their abiotic and biotic environments and are shaped by phylogenetic histories. Traits influence whole-plant function, biotic interactions, and plant-environment interactions, and thus, in combination with nutrient dynamics, disturbance, and foodweb interactions, the dynamics, structure, and function of ecosystems. Patterns of trait variation and trait correlations within and among habitats are related to environmental and trade-off axes, and can be considered plant strategies of resource capture and tolerance (Reich et al. 1997, 2003b, Wright et al. 2004). A perspective that appropriately integrates multiple plant traits can provide a mechanistic underpinning for the processes that drive community dynamics.

**Key Results:** At CDR, we have studied ecosystem structure and function, community dynamics, trophic interactions, and plant traits (e.g., Tilman and Downing 1994, Tilman 1996, Reich et al. 2003b, 2006b, 2007, 2010, Lehman and Tilman 2001, Wright et al. 2004, 2005ab, Tilman et al. 2006, Kattge et al. 2011, Willis et al. 2010, Cavender-Bares and Reich, 2012, Savage et al. 2009, Haddad et al. 2002, 2009, 2011, Savage and Cavender-Bares 2011, 2012, Moles et al. 2012). During the current LTER project period, our participation in synthetic trait and scaling studies has led to improved understanding of (1) scaling of leaf and root traits in relation to species strategies, soils, and climate (Shipley et al. 2006, Cavender-Bares et al. 2006, Reich et al. 2007, Ordóñez et al. 2009, Reich et al. 2010, Han et al. 2011, Kattge et al. 2011, Swenson et al. 2012, van Ommen Kloeke et al. 2011, Yuan et al. 2011), (2) respiration across space, tissue types, plant types, taxonomy, climate and size (Reich et al. 2006c, Wright et al. 2006, Makarieva et al. 2008, Reich et al. 2008), (3) global patterns of plant  $\delta^{15}\text{N}$  (Craine et al. 2009), (4) major controls on litter decomposition and soil extracellular enzyme activity (Fig. 18; Cornwell et al. 2008, Sinsabaugh et al. 2008, Berg et al. 2010, Sinsabaugh 2010), (5) mechanisms of C isotope fractionation (Cernusak et al. 2009), (6) tissue size and morphological scaling (Milla and Reich 2007, Niklas et al. 2007, Milla et al. 2008), (7) the relationship of traits to community assembly processes and hence patterns of diversity (Harpole and Tilman 2006, Peterson and Reich 2008, Reich 2009, Willis et al. 2010, Moles et al. 2011), and (8) scaling from leaf to ecosystem scales (Ollinger et al. 2008, McMurtrie et al. 2008, Savage et al. 2010, Reich 2012).

As an example of this latter work, evidence across sites, including CDR, shows strong regulation of C flux by key traits at scales from minutes to years, and from leaves to ecosystems (Fig. 26). Additionally, we have found phylogenetic constraints on traits of species that influence community composition across gradients of fire frequency (Cavender-Bares and Reich 2012), light availability (Willis et al. 2010), and hydrology (Savage et al. 2009, Savage and Cavender-Bares 2011, Savage and Cavender-Bares 2012). The integration of traits and phylogenetic history may better reveal the processes involved in community assembly (Cavender-Bares et al. 2009) and ecosystem function (Cadotte et al. 2009).

**Future Research:** We propose to work toward a synthesis of evolutionary, community, and ecosystem ecology, to better understand the mechanistic links between biodiversity – in its multiple forms – and ecosystem stability, productivity, and ecosystem services in our grassland, savanna and forest ecosystems. The result of this research may be a deeper understanding of how to sustain and restore ecosystem services in the face of global change. We propose studying functional traits through the TRY Global Plant Data Initiative (Kattge et al. 2011), a consortium of collaborators who have contributed ~3 million trait entries for ~70,000 species. We have begun collaborating with the Max Planck Institute for Biogeochemistry (Jena, Germany) to further develop dynamic global vegetation models and with the NESCENT Project (led by A. Zanne, W. Cornwell) to examine the evolutionary history of trait diversification. Finally, we are working with researchers using several ecosystem and earth system models (e.g., G'Day, PnET, JSBACH, CLM CABLE) to incorporate trait-based approaches and other knowledge gained in the CDR research in such modeling studies.

#### *4.3. Valuing Ecosystem Services – A Synthesis of Ecological and Economic Perspectives*

Our research on N deposition, elevated CO<sub>2</sub>, changes in biodiversity, temperature, water availability, and fire frequency mimics ways that anthropogenic changes are altering ecosystem services, such as the provision of clean water, sequestration of atmospheric C, and regeneration of soil fertility (Millennium Ecosystem Assessment 2005, Daily 1997). By synthesizing our results with economic theory of valuation, we are striving to complete the causal loop between societal activities, the functioning of natural and human dominated ecosystems, and the delivery of services to society. Such information on direct economic costs and benefits and those mediated through alteration of ecosystem functioning could help society make more efficient choices (NRC 1999, 2005, Millennium Ecosystem Assessment 2005, Daily et al. 2009, TEEB 2010).

**Key Results:** Both our on-site results (Tilman et al. 2001, Tilman et al. 2006, Polasky et al. 2011) and syntheses across a variety of ecosystems (Tallis and Polasky 2009, Kareiva et al. 2011) show that ecosystem structure and function impact ecosystem services. We have linked ecological and economic approaches to value ecosystem services either in terms of monetary measures or measures of human well-being (Polasky and Segerson 2009, Kareiva et al. 2011). We have found that some current activities are sub-optimal, or, in economic terminology, are far from what has been called a “tradeoff frontier.” For example, society could achieve higher yields, higher profits, and lower greenhouse gas emissions by agricultural practices that use land and fertilizer more efficiently (Foley et al. 2011, Tilman et al. 2011). In another analysis, the economic valuation of water quality and C sequestration shifted the ranking of preferred land uses in Minnesota. Agricultural expansion was preferred when water quality and C sequestration were not considered. Scenarios that limited agricultural expansion or promoted conservation were preferred when these factors were taken into account (Polasky et al. 2011). Other work has explored the tradeoffs and synergies among provisioning of marketed commodities, biodiversity conservation and ecosystem services (Polasky et al. 2008, Nelson et al. 2008, Nelson et al. 2009), and the greenhouse gas impacts associated with biofuel production (Hill et al. 2006, 2009, Fargione 2008). This work has shown how policy, market forces and Payments for Ecosystem Services (PES) can drive land-use change and affect biodiversity and ecosystem services (Radeloff et al. in press, Lewis et al. 2011, Kinzig et al. 2011).

**Future Research:** We propose using results from the BioCON and BigBio experiments and their derivatives to quantify the economic value of grassland biodiversity for biomass, water quality, below-ground C storage, and their insurance value (temporal stability). Second, we propose using the mechanisms uncovered by our CDR research to develop a model of ecosystem services that links physical materials (e.g., nutrients, sediment, or biomass), biota (e.g., plants and their diversity, pests, pathogens), and energy flow. We would then test the predictions of the model at our site and in our region.

### **SECTION III. EDUCATION AND OUTREACH ACTIVITIES**

**Promoting teaching, training, and learning.** Our vision for the Cedar Creek Schoolyard-LTER (sLTER) program is to serve as an inspiring catalyst and outstanding resource for improving science education throughout our K-12 community. Our goals are to help K-12 students and teachers better understand scientific principles and processes, such as data collection, data analysis, critical thinking, and application of science to real-world contexts; and to help students and teachers build their understanding of biological and ecological concepts through hands-on field-based studies and direct exposure to LTER

research and data. The primary objective of our programs is to provide students with an inquiry-based way to learn about the natural world. Cedar Creek's Managing Director, Dr. Jeffrey Corney, and Education Coordinator Ms. Mary Spivey, are actively involved at the LTER Network level and with other national STEM initiatives, with Corney serving on the Schoolyard LTER Leadership Committee as well as ESA's Education Committee, and Spivey collaborating with fellow LTER education coordinators and active with NSTA and Minnesota based STEM organizations. Cedar Creek also has forged a strong partnership with the University of Minnesota's College of Education, collaborating on K-12 professional development programs funded by NASA and the State of Minnesota.

The centerpiece of our program is professional development of K-12 teachers through training in inquiry-based learning that addresses state science standards. We also provide field and inquiry based activities for visiting K-12 school groups. Our programs have grown immensely (Fig. 11). In 2011, we hosted 1,943 students, and teachers participated in programs for 7,830 contact hours representing a 625% increase from 2006. From 2006-2011 we served 6,155 teachers and students via 26,420 contact hours.

Over the past six years, CDR has served as the major field site and training venue for 41 graduate students (PhD and MSc) and 23 post-doctoral scholars. CDR serves undergraduate education both as a field trip destination for regional college and university courses (>1000 students/year for >3000 contact hours) and through a vibrant summer intern and REU program (>40 students/year). The summer undergraduate research intern program attracts students from across the nation to engage with project PIs, post-docs, and graduate students in project design, implementation, data analysis, and interpretation. Interns also conduct independent research, participate in a weekly research seminar series, an annual research symposium, and career development discussions. The field season begins with a symposium at which PIs, post-docs, and graduate students present their research and interns find potential mentors for independent projects, and ends with interns presenting their research results at an intern symposium.

We offer informal education through outreach programs and tours, which had a 325% increase in participants from 2006 to 2011. Notable activities included the Citizen Scientist Field Day and the Redheaded Woodpecker Recovery project, a partnership between CDR, Audubon and bird enthusiasts.

Catalyzed by a workshop at the 2006 LTER All Scientists Meeting and funded by the National Center for Ecological Analysis and Synthesis (Cavender-Bares and Polasky, PIs), we developed a *Sustainability Science Distributed Graduate Seminar*. An interdisciplinary, inter-institutional team developed a hybrid classroom/internet approach for teaching sustainability science. The effort brought together diverse faculty and student expertise and perspectives from across the continent, providing a pedagogic foundation for this emerging discipline. In its first phase, the group developed links between biodiversity and sustainability (Cavender-Bares et al. 2012); it then addressed the challenges of sustainable economic development across contrasting biophysical, institutional, and cultural contexts. Seminar participants will present their findings in a symposium of the 2012 EcoSummit on Restoring the Planet's Ecosystem Services.

**Future plans for education and outreach.** We will expand our work with under-served students, continue our professional development programs for K-12 teachers, and develop skill-building science projects that can be directly transferred to classrooms and schoolyards. In particular, we will increase participation by underrepresented student groups at CDR by subsidizing transportation costs for schools that serve underrepresented populations and cannot afford transportation to CDR. Activities will focus on strengthening the connections between teachers, students, and researchers at Cedar Creek and the extended LTER community in order to support LTER's mission to "deepen the understanding of long-term ecological research and Earth's ecosystems by future generations of ecologists and educators." We also will enhance outreach via our website to provide teachers and students access to LTER databases modified for K-12 activities. We propose hiring an education field assistant to work directly with teachers and students both at Cedar Creek and in the classroom, providing field instruction and assistance with curriculum development and program assessment. Each year we fill this position with a highly qualified undergraduate student who seeks a career in ecology education and outreach, thus training and mentoring a future teacher who in turn helps provide instruction to our K-12 audience.

#### SECTION IV. RESPONSES TO MID-TERM SITE REVIEW

We appreciate the comments, concerns and insights provided by the mid-term review. As described below, we have already addressed many concerns, and will address others during this renewal.



*Concern: Multi-trophic Interactions and Belowground Processes* – We have developed collaborations with scholars with expertise in multi-trophic-level interactions and above and below ground interactions. In addition, two recent hires by UMN's Department of Ecology, Evolution, and Behavior, Drs. Elizabeth Borer and Eric Seabloom, add expertise in disease ecology and top-down versus bottom-up effects to our team. They are studying insect herbivory and disease in BigBio and BAC, the Enemy Removal Experiment, and NutNet, which they lead. We now collaborate with microbial ecologists to use genomics to examine the influence of environmental change on microbial community structure and function: N Fierer, Colorado University (Bates et al. 2010, Ramirez et al. 2010, Fierer et al. 2011); P Vanderkoornhuyse, Universite de Rennes (with whom we are collaborators on a funded French ANRF grant for CDR microbial research); J Zhou, University of Oklahoma (He et al. 2010, 2012, Deng et al. 2012); C Henry, Argonne National Laboratory; and T Schmidt, Michigan State University. These interactions will continue during our renewal. We also collaborate with N Haddad (North Carolina State University) on the dynamics of arthropod communities (Haddad et al. 2009, 2011).

*Concern: Climate Responses in BAC* – In response to concerns that BAC lacked sufficient measurement of the physical impacts of warming, we installed three temperature sensors in the soils of each of the 96 subplots and record temperatures every 5 minutes. We sample surface soil moisture weekly (0 – 10 cm at each of 10 sites within each subplot) and deeper soil moisture via TDR (0-100 cm in 20 cm increments at 2 sites per plot) every 3<sup>rd</sup> week. Starting with the 2012 field season we will measure air temperature and humidity every 5 minutes at heights of 5 cm and 25 cm in each subplot.

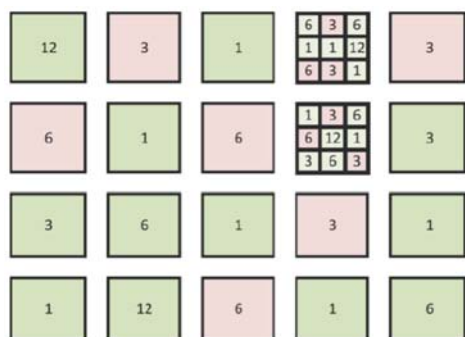
*Concern: Network Participation* – Since the mid-term review, more members of our team participate in network-wide initiatives and efforts. Hobbie continued to serve on the LTER Executive Board through 2010. Cavender-Bares was a member of the 2009 LTER All-Scientists Meeting program committee, which inspired her to develop the distributed graduate seminar focused on sustainability that has involved the CAP, FCE and HFR LTERs and other institutions. She is also co-PI with Hobbie on a new cross-site investigation of urban ecosystems. Montgomery is the CDR representative to the LTER Network Climate Committee, the LTER liaison to the National Phenology Network, and co-PI on the new WWCON proposal (with Reich and Hobbie). This renewal will formalize CDR's connection to the cross-site Nutrient Network experiment. We will continue to promote junior CDR researchers in site-based initiatives, LTER Network-level activities, and cross-site initiatives as opportunities arise.

*Information Management and Technology.* "...Toward that end, the team recognized a significant need to provide him with additional support and help so the CDR can continue to catch up with the other LTER sites in the IM area..." – We request funds in this renewal for a new FTE to assist our Information Manager with data collection from faculty, graduate students, and post-docs, data documentation and website development.

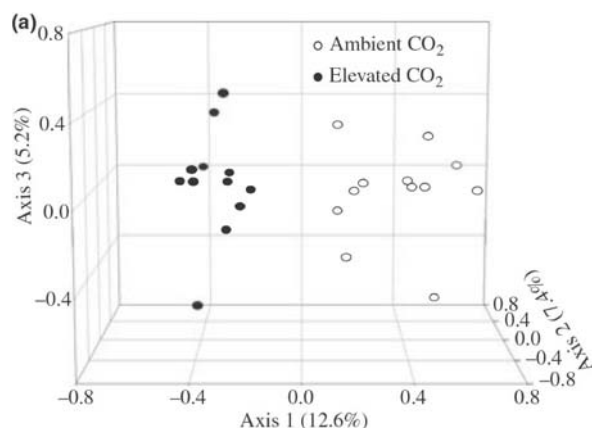
*Site Management/Administration.* "...mechanisms be formalized that can facilitate leadership development, including leadership and project administration experience. In addition, it was apparent to the review team that more resource availability to the CDR junior faculty would go a long way toward helping them more fully integrate into the project and further the breadth and connectivity of research." – Our allocation of grant funds to PIs is based on the CDR projects in which each individual is involved and the costs of proposed research. Our renewal proposal allocates much more project support to our younger members than did the current proposal precisely because of how involved the younger team members have become in CDR research.

*Research Facility.* "...the university not rely solely on the LTER program for its monetary support but rather codify the relationship between the station, LTER and the university." – Cedar Creek's Operating Budget (\$500K) is now covered entirely by the College of Biological Sciences (CBS) as a State Allocation Operations & Maintenance fund. Further, CBS allocated a total of \$800K for our recently constructed lab and housing facilities and for our Lawrence Laboratory renovations, scheduled for completion by Summer 2012.

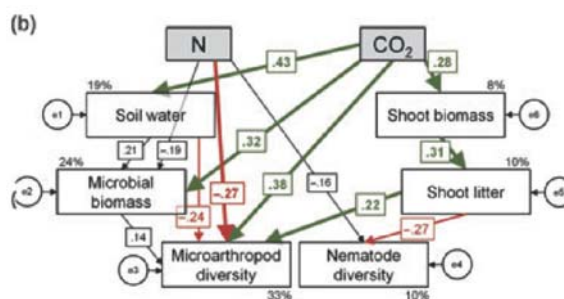
*Site Education and Outreach.* "Finally, providing ongoing, stable support for the coordinator is highly recommended." – The Education Coordinator, Mary Spivey, is now employed full time with direct university support. Thus, funds requested here would hire program assistants to help with education and outreach and would provide travel funds for students from underserved schools.



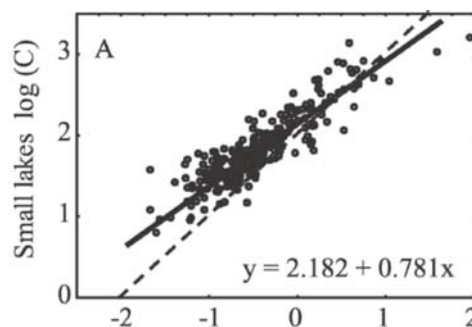
**Figure 20.** A sample of one block in the experimental design to be used in the Forests and Biodiversity (“FAB”) experiment. Random assemblages of 20 CDR tree species will be grown in 180 low tree density (large squares) and 180 high tree density (small squares) plots at species richness levels of 1, 3, 6 and 12. Plots will be randomly assigned a location in one of 10 blocks. Each block will contain 18 large plots and a subplot containing 18 small plots. Green squares indicate random species assemblages of a given diversity level. Light red squares indicate assemblages with 1 of 4 possible combinations of PD and FD at the 3 and 6 species diversity levels. See main text for more details.



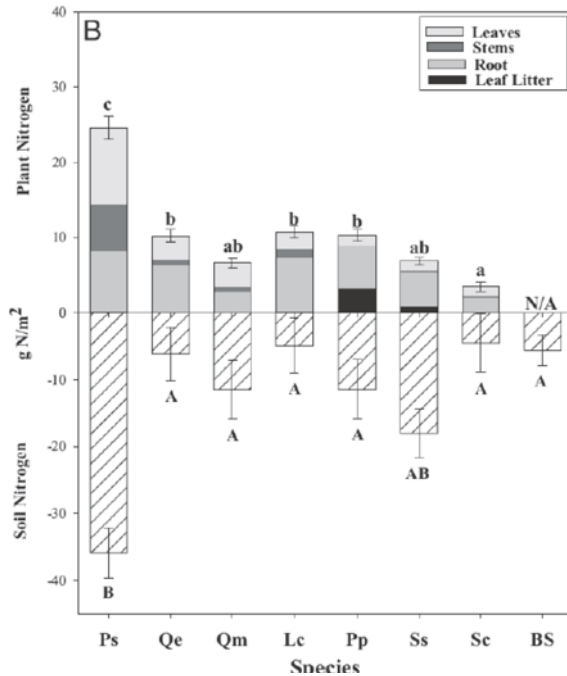
**Figure 21.** Detrended correspondence analysis (DCA) of Geochip 3.0 functional gene data showed that elevated CO<sub>2</sub> significantly affected soil microbial community composition and functional structure in E141. Of the 1503 detected functional genes involved in C, N, P and S cycling, 25% of these were only detected under elevated CO<sub>2</sub> conditions, while another 14% were detected only in the control. (He et al. 2010)



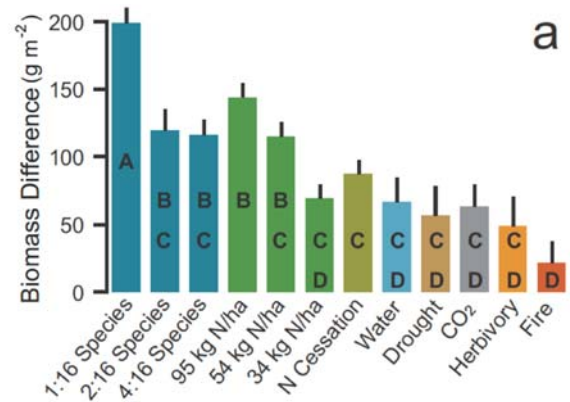
**Figure 22.** Structural equation models of global change effects on soil biota. Causal influences of elevated N and CO<sub>2</sub> (exogenous variables) on soil water content, shoot biomass productivity, shoot litter, microbial biomass, and taxa richness of soil microarthropods and nematodes (endogenous variables). Numbers on arrows are standardized path coefficients. Green/red(+/-) bold arrows have significant standardized path coefficients ( $P<0.05$ ), regular green or red arrows ( $0.05<P<0.1$ ), black arrows indicate non significant path coefficients ( $P>0.1$ ). Circles indicate error terms (e1–e7). Percentages are variance explained by the model ( $R^2$ ). (Eisenhauer et al. 2012)



**Figure 23.** Scale dependent stoichiometry in small lakes from around the world. As indicated by the slope less than one, seston stoichiometry at the whole small-lake scale (dots,  $n = 281$  lakes) deviates significantly from the Redfield 106:1 proportionality (dashed line), which is a good representation of the relationship between seston C and seston P at larger observational scale, taking in multiple aquatic habitats including fresh and saline waters. Similar differences in the coupling of elements across scales are seen with other element ratios and in other habitats in fresh and saline waters, a difference which has been hypothesized to result from the inclusion of greater environmental heterogeneity. (Sternner 2008; Sternner et al. 2008)

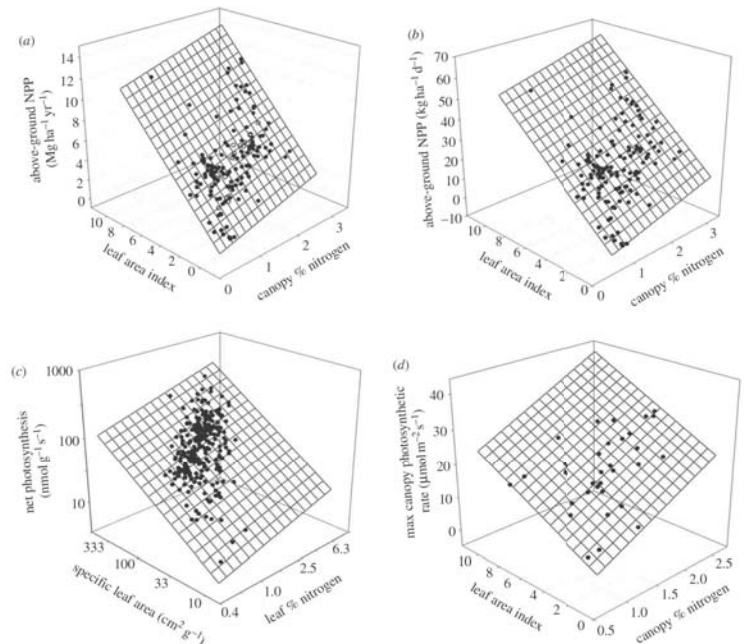


**Figure 24.** Increase in plant N and decrease in surface soil N under each species over 6 years (0-10cm). No species differences were found in lower depths. Letters represent significant differences across sp. using ANOVA and post hoc Tukey tests ( $P < 0.05$ ). Ps, *Pinus strobus*; Qe, *Quercus ellipsoidalis*; Qm, *Q. macrocarpa*; Lc, *Lespedeza capitata*; Pp, *Poa praetensis*; Ss, *Schizachyrium scoparium*; Sc, *Solidago canadensis*; BS, bare soil. (Laungani & Knops 2009)



**Figure 25.** Each bar shows the mean difference in aboveground living plant biomass between two treatments, or between a treatment and its control, based on long-term results of 12 different CDR experiments that manipulated from 1 to 3 of the variables shown. Lines at top of bars are SE. This figure summarizes results of more than 7700 measurements of aboveground living plant biomass in various plots and years. (Tilman et al. in review)

**Figure 26.** Relationship of (a,b) ANPP to leaf area and nitrogen content, and (c,d) photosynthetic capacity to leaf area and canopy nitrogen content across 128 forest sites, including CCESR. Stand-scale productivity is shown to be a function of the capacity to harvest light (LAI) and to biochemically fix carbon (%N). LAI and canopy %N explain greater than 75% of variation in ANPP. (Reich 2012)



## DATA AND INFORMATION MANAGEMENT

The primary goals of data management at CDR are (1) to assure long-term availability of high quality data, and (2) to enhance and promote research by facilitating data access for researchers and other data users globally. The effectiveness of our strategies is evidenced by the continued use of the long-term data from CDR for research, education and outreach. During the current award, data from CDR have been a critical part of more than 200 papers, many of which have become seminal in the field of ecology (See Results of Prior). More importantly, the openness and accessibility of CDR data has expanded the impact of LTER-funded work by providing researchers with little or no direct connection to CDR with unrestricted access to the unique, long-term data. For example, we have identified ~40 papers published in the past 6 years that did not include any CDR PI's. These publications, coauthored by over 110 different researchers, are strong indicator of our success at providing unique and valuable data to the research community at large. Furthermore, many of these papers are having large impacts on our field; 35% have been cited at least 10 times per year and 17% at least 20 times per year.

Here we propose to expand and improve our information management (IM) model. Most notably, we propose hiring a second data manager who would assist both CDR researchers and non-CDR researchers working at the Cedar Creek Ecosystem Science Reserve (CCESR) in rapid integration of new data into our online public datasets. We also will embark on several major upgrades of our IM infrastructure. In the following, we provide a detailed overview of our Information Management strategy and how it ensures data security and accessibility, and we outline future activities.

IM at CDR is integrated throughout the site's research, education, and outreach programs, and the IM team is involved in the full life cycle of research projects – from data acquisition, storage, and retrieval to data analysis and publication. This involvement is essential in ensuring that data are collected and documented in a standardized manner, rigorous standards of quality control are followed, and the resultant information is available to researchers as quickly as possible. Our full life-cycle approach to IM includes the maintenance of extensive systems for automated data collection and backup. Funneling data through our centralized collection system allows us to assure the quality, on- and off-site automated backup, and availability of data to the research community. This approach was started for core LTER-funded projects, and is available and is being adopted by most other projects at CCESR.

**Infrastructure.** CDR has developed a cooperative relationship with the Minnesota Supercomputing Institute (MSI), which maintains web and database servers for CDR use, allowing the IM team to focus on IM activities rather than system administration. MSI performs weekly maintenance and backups of all data systems. In addition to MSI's servers, CDR maintains two 4TB data servers used for additional long-term backups of site data and daily backups of all on-site computers. Our on-site resources include a T1 line managed by the University of MN (UMN), wireless connectivity across the main campus of CCESR, and open computer labs for data capture from instrumentation, data entry, and data quality checking.

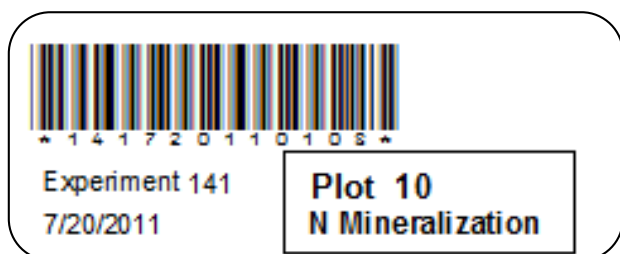
**Data Acquisition and Quality Control.** CDR employs automated systems for most of its data acquisition. We develop project-specific database systems for lab and handheld field computers greatly reducing human error and simplifying the QA/QC process. These systems are designed with scalability, usability, and continuity in mind using common, commercially available software whenever possible (Figure 1).

The extensive use of barcodes (Figure 2) to track virtually all plant and soil samples and related chemical or physical analyses has helped eliminate data entry, sample labeling, and sample misplacement errors. Moreover, the automated data collection system resident on all CDR computers allows continuous backup of data to central servers, minimizing the danger of data loss and allowing us to run our quality control procedures to rapidly check data. Data generated through devices with integrated data loggers are annotated with unique identification codes, downloaded to local computers, and synchronized with the central databases at MSI. These types of data are generated by our weather station and other instruments, such as light meters, soil CO<sub>2</sub> flux meters, and TDR soil moisture devices.

**Figure 1.** Example of a Cedar Creek database from a handheld computer

Initials	Old Field	Transect	Plot	Species	% Cover	Notes	Date_Time
JJ	4	G1	3	Sorghastrum nutans	10		8/2/2011 7:54:26 AM
JJ	4	G1	3	Erigeron canadensis	12		8/2/2011 7:56:14 AM

**Figure 2.** Example of a barcode, used, in this case to identify a soil sample used in measurement of nitrogen mineralization



Data and metadata not captured and processed through automated systems are submitted for archiving and distribution to the information manager. A sample format for submissions is available to researchers online at <http://www.cedarcreek.umn.edu/research/procedures/dataprotocols/>. CDR and UMN have made the capture of all data gathered by all researchers at CCESR a top priority. This includes CDR and non-CDR investigators and aims to increase data synthesis and collaboration. While non-CDR investigators at CCESR are encouraged to use CDR data management practices, we also host and archive non-standard data in the CDR long-term archive. For example, the CDR IM team is formally supporting data archiving for two related NSF projects, the Twin Cities Household Ecosystem Project (TCHEP), funded by the NSF Dynamics of Coupled Human and Natural Systems program (data undergoing QA/QC), and a study of ecological homogenization among urban lawns, funded by the NSF Macrosystems Biology program (data yet to be collected).

**Dataset Management and Archiving.** All data, metadata, publication, and site personnel information are stored in a single Oracle relational database, which serves as the backbone for CDR's data archiving and distribution systems, personnel records, and publication catalog. Data are organized by CDR experiment number and data type, and are internally associated with publication and researcher information. We have created a web-based database interface using PHP. The database and interface are specifically designed using best practices standards developed by the LTER IM community for the Ecological Metadata Language (EML), keywords, and units. This simplifies the creation of EML documents for the LTER data catalog. In 2011, CDR developed a versioning system to track changes to any data or metadata. This allows us to generate data packages with data and metadata as it was on any given date.

CDR employs multiple data backup procedures to ensure protection from catastrophic data loss. The central database hosted by MSI is mirrored to a remote location on a daily basis, with weekly and monthly full tape backups stored off site. All on-site computers at CDR are backed up to a local data server, which is in turn mirrored to an offsite server. Annually, all data files, along with a copy of our web server directories and text file versions of all database tables, are copied to portable media and stored in fire safes at two different remote locations.



CDR also employs multiple strategies to ensure the long-term accessibility and usability of our data and metadata as the computing and software environment evolves over time. Data archive files are created in a simple, tab delimited format containing all data and metadata, including methods, attribute information, and personnel information. This format is designed to be easily imported into future databases or other data systems, as well as being printable in a format easily read by optical character recognition or human users. Archive files are created individually via automated scripts immediately upon entry into the relational database. On a biannual basis, automated scripts generate a complete set of archive files for all datasets in the database. CDR also archives a tab delimited text file for each table in our relational database, again via automated scripting on a biannual basis. All archive files are stored on several servers and on backup media that are stored offsite.

CDR's metadata system uses standardized units and keywords, as developed by LTER IM working groups. These standards are designed to facilitate data discovery locally, within the LTER network, and globally. We also maintain GIS data, including bounding coordinates for experiments, cover type and soil type layers, and facilities information. These files are stored on local servers and integrated into the relational database where appropriate. As with all CDR data, GIS information is protected with multiple backup systems.

**Data Access.** CDR has adopted the LTER General Data Use Agreement. Data is time-stamped within the database, and automated systems make data publicly available within two years of collection, or earlier with researcher approval. Samples of datasets and associated metadata are available without a login requirement at <http://www.cedarcreek.umn.edu/research/data>. CDR requires users to register with our authentication system (which assists in finding publications that use CDR data) and agree to our data ethics policy (<http://www.cedarcreek.umn.edu/research/data/htmldata.php>) prior to accessing datasets. Data and metadata is available as HTML, downloadable text files, or as EML with data inline. Data and metadata files are generated dynamically on request from our Oracle database through a PHP based web interface.

All CDR datasets are registered in the LTER Metacat data catalog (<http://metacat.lternet.edu/>). Access to data through Metacat is managed through the LTER Network Office (LNO) Data Access Server (DAS). CDR has adopted use of the DAS to help facilitate cross-site data synthesis by allowing users access to data from multiple participating LTER sites from a central catalog using a single user account.

**Integration with Site Science, Education, and Outreach.** CDR's information management team is available to researchers throughout the investigation process, providing background data, advising on statistical design of experiments, creating data acquisition methods, establishing metadata standards, ensuring data quality, and providing data analysis. Researchers are encouraged to meet with the IM team on a regular basis as systems are continually evaluated.

CDR's IM team also works closely with education and outreach personnel. Datasets and analysis techniques are cooperatively designed for visiting students and on-site teacher training. CDR's web site is used to communicate current research and findings to a variety of audiences. Our image archives, containing more than 10,000 photos with associated information, of plants, birds, mammals, and especially insects (<http://www.cedarcreek.umn.edu/insects/albumframes/orderframe.html>) have proven to be a valuable resource for the public.

CDR's website serves as its main portal for researchers, educators, students, and the public to access CDR's data, image archives, and research information. In December of 2011, we began employing Google Analytics to track the use of our web resources. Web use data supports better informed decisions when prioritizing areas for future web development. In the first 50 days of tracking, our website had 5705 unique visitors from 127 countries, who on average viewed 3.7 pages. The most accessed areas of our website are our data distribution system and our insect photo archive.

**LTER Network Activity.** CDR has been dedicated to network level IM activities through participation in meetings, network committees, and working groups. In 2010, our information manager, Dan Bahaiddin, was elected to serve on the IM executive committee. Subsequently, he has met regularly with the committee throughout 2011. Bahaiddin has served on the EML Best Practices working group. He is also a member of the Data Management Server "Tiger Team", advising the LNO on the development of the PASTA data distribution system specified in the NIS. Bahaiddin is also a member of the LTER-LNO 2012 All Science Meeting planning group.

**Future Activities.** We propose personnel changes that will double the staffing for IM activities and increase the daily interactions between CDR researchers and IM staff. Currently, a single employee (Bahauddin) has the responsibility for the bulk of our IM activities. The addition of the new IM position will significantly increase the speed that data are available to both on-site and off-site researchers and to the public, and will also better assure that all data gathered at CCESR, including data by non-CDR researchers, become accessible via our data archives. These changes will improve the already successful IM program at CDR.

We anticipate some major infrastructure changes in coming years. Our T1 internet connection is scheduled to be upgraded to fiber, providing 100 Mbps, by the end of 2012. This will allow major improvements in our ability to deliver large datasets to off-site storage, improve our ability to teleconference, and provide a backbone for future data needs. When this upgrade is complete, we will switch our phone systems to VOIP, integrating it into the UMN system. By the end of 2013, we will extend wireless service to some of the remote housing and research buildings at CCESR, as well as to the BioCON and Big Biodiversity field sites, allowing for current data collection systems to stream data, as well as opening opportunities for future research.

We are beginning the conversion of our website to a Drupal content management system. Doing so allows us to utilize the developer expertise of the University of MN's College of Biological Sciences, which has committed itself to providing Drupal support for our site. The LTER Drupal Environmental Information Management System (<http://im.lternet.edu/projects/DEIMS>) working group is developing cross-site Drupal tools. We anticipate being able to participate in future development, as well as integrating developed tools into our local systems, when this conversion is complete by the end of 2012.

With more than 10,000 images related to CDR research available online, organization and discovery of images can be a challenge. We propose creation of a searchable index encompassing all of our image archives. This index will support a new initiative in which high resolution photographs of CDR's extensive insect collection (~5000 insect species collected on-site) are currently being created through collaboration with the UMN's Entomology Department. These images, likely to number >20,000, will be associated with species and collection metadata in a relational database and presented on our website by the end of 2014.

We will develop new, improved systems for tracking the status of datasets, from the planning stages through publication. This system will aid in, and encourage, the submission of metadata in a timely manner, and will better ensure that data are archived and made publically available in accordance with LTER standards. To facilitate continued improvement and expansion of our IM systems and procedures, we will establish small focus groups to test ease of data access, clarity of metadata, and discovery and usability of datasets as a part of an annual assessment program. These focus groups will consist of a cross-section of our data users. We will develop questionnaires to track problems and progress over time.



## POSTDOCTORAL MENTORING PLAN

While the current proposal requests funds for a single postdoctoral researcher to work on the Nutrient Network research (Section 3.6.1 of Project Description), it is likely that other postdoctoral researchers may be employed at CDR during the period of this grant. We will adhere to the principals in this mentoring plan for all LTER postdoctoral scholars, although the current text is aimed specifically at the Nutrient Network postdoc supervised by PI's Borer and Seabloom. Our goal is to provide our postdoctoral scholars with the training and mentoring needed to meet their professional goals. To do this, we ensure that there are clear lines of communication between the postdoctoral researcher, their supervisors, other members of the lab, and the larger research community. Finally, we ensure that each postdoc takes advantage of University training in ethics and conduct.

In the current professional climate, postdoctoral scholars need to consider the full range of career options, including academia, industry, nonprofit, and governmental; effective mentoring is essential to their success. We provide career counseling for postdoctoral scholars that includes these different career tracks. In addition, a critical component of any position hired at the doctoral level includes preparation of effective grant proposals. To do this, we provide examples of our proposals, and in some cases, include the postdoctoral scholars in writing proposal if appropriate. Similarly, research positions hired at the doctoral level come with the expectation of dissemination of original work as both publications and presentations. All postdoctoral scholars will be expected to be lead author on at least one (preferably several) publications each year stemming from research associated with this grant. The PIs will provide discussion, feedback, and assistance in this process, and will provide funds for the postdoc to present work at least one scientific conference.

Communication is a critical component of effective mentoring, and the PIs will facilitate communication with the postdoctoral scholars in a variety of ways. First, all lab members (undergraduates, graduate students, postdoctoral scholars, and visitors) participate in a group meeting every two weeks. The primary focus of these meetings is to provide feedback on research and to share new statistical, modeling, or laboratory techniques. In addition, each lab member makes a longer presentation to get feedback on both presentation skills and on the research itself. Second, while PIs are always available for ad hoc meetings, we meet individually with the postdoctoral scholars in the alternate weeks to discuss project plans and findings, provide feedback, and to maintain close contact with the progress and needs of the postdoctoral scholars. We also initiate discussions about how to work toward professional goals, including gaining teaching and scientific presentation experience, mentoring undergraduates, developing a strong job application packet, becoming a member of the local scientific community, and strategies for working with collaborators from a diversity of backgrounds. Performance reviews will be provided and discussed annually.

University of Minnesota researchers are expected to exemplify the highest standards of integrity and ethical conduct and are required to have training in the responsible conduct of research. UMN postdoctoral researchers must complete training in key concepts and best practices of research integrity, including topics such as History and Values Relating to Research and Scholarship; Social Responsibility & Reporting Misconduct; and Authorship, Plagiarism & Peer Review, Fiscal Responsibilities; Intellectual Property; Conflict of Interest ([www.research.umn.edu/first/EdReqs.htm](http://www.research.umn.edu/first/EdReqs.htm)); and Research Data Management. UMN additionally provides and tracks annual continuing education in research ethics. Finally, postdoctoral fellows are encouraged to join the UMN Postdoctoral Association ([blog.lib.umn.edu/pda/pda/](http://blog.lib.umn.edu/pda/pda/)) for access to a wide variety of resources for postdoctoral scholars, covering issues from employment to professional development and university life, as well as meaningful networking opportunities across the UMN campus.

## Supplement: Electronically Available Datasets

Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
<b>e001: Long-Term Nitrogen Deposition: Epopilation, Community, and Ecosystem Consequences (Core)</b>			
nbe001	Plant aboveground biomass carbon/nitrogen	2009 (1 year)	
ple001	Plant aboveground biomass data (sorted to species)	1982-2011 (30 years)	21
lpe001	Percent light penetration	1982-2004 (11 years)	
rbe001	Root biomass data	1987-2002 (15 years)	8
nre001	Root carbon/nitrogen data	2009 (1 year)	
mse001	Small mammal abundance	1982-1985 (4 years)	1
cae001	Soil Calcium	1982 (1 year)	1
care001	Soil carbon	1982-2009 (5 years)	
mge001	Soil magnesium	1982 (1 year)	2
nohe001	Soil nitrate and ammonium	1985-2009 (14 years)	2
ne001	Soil nitrogen	1982-2009 (5 years)	5
phe001	Soil phosphorous	1982-2010 (10 years)	
ke001	Soil potassium	1982 (1 year)	
<b>e002: Long-Term Nitrogen Deposition During Grassland Succession (Core)</b>			
ple002	Plant aboveground biomass data (sorted to species)	1982-2011 (24 years)	9
nle002	Litter carbon/nitrogen data	2009 (1 year)	
lpe002	Percent light penetration	1982-1990 (9 years)	
rbe002	Root biomass data	1988-1992 (4 years)	2
nre002	Root carbon nitrogen data	2009 (1 year)	
mse002	Small mammal abundance	1982-1985 (4 years)	
cae002	Soil Calcium	1982 (1 year)	
care002	Soil carbon	1982-2011 (6 years)	1
mge002	Soil magnesium	1982 (1 year)	
nohe002	Soil nitrate and ammonium	1985-2009 (7 years)	4
ne002	Soil nitrogen	1982-2011 (6 years)	1
pe002	Soil phosphorous	1982 (1 year)	
phe002	Soil pH	1982-1990 (5 years)	
ke002	Soil potassium	1982 (1 year)	
<b>e012: Effect of Fire Frequency on Grassland Vegetation and Soils (Core)</b>			
ple012	Plant aboveground biomass data (sorted to species)	1983-2010 (5 years)	5
lpe012	Percent light penetration	1987-1990 (3 years)	1
pce012	Plant species percent cover data	1905-2000 (2 years)	3
nohe012	Soil nitrate and ammonium	1987 (1 year)	3

Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
<b>e014: Successional Dynamics on a Resampled Chronosequence (Core)</b>			
ghe014	Grasshopper cage data	1989-2004 (16 years)	
hte014	Maximum plant height along transects	1984 (1 year)	
mre014	Nitrogen mineralization rate	1986 (1 year)	1
lpe014	Percent light penetration	1984-1989 (2 years)	
pce014	Plant species percent cover data	1983-2011 (7 years)	7
she014	Shrub data	2006 (1 year)	
mse014	Small mammal abundance	1983-1993 (4 years)	
care014	Soil carbon	1983-2007 (5 years)	
ne014	Soil nitrogen	1983-2007 (5 years)	2
ome014	Soil organic matter	1983 (1 year)	4
sphe014	Soil pH	1983 (1 year)	1
phe014	Soil phosphorous	1983 (1 year)	2
<b>e054: Old-Field Chronosequence: Plant Productivity (Core)</b>			
ple054	Plant aboveground biomass data (sorted to species)	1988-2011 (24 years)	6
nohe054	Soil nitrate and ammonium	1991 (1 year)	
<b>e080: Meterologic Measurements at Cedar Creek Natural History Area (Core)</b>			
ftsne080	Daily precipitation from Fort Snelling near MPLS airport	1836-1993	
dclime080	Daily climate summary	1962-2012	
clime080	Hourly climate data	1988-2012 (25 years)	22
<b>e084: Water table Dynamics at Cedar Creek (Core)</b>			
gwe084	Depth to water table (<80 sites; ~6 measurements/yr)	1989-2011 (23 years)	2
<b>e097: Nitrogen Addition and Dynamics of Recovery from Cessation of N Addition (Core)</b>			
ple097	Plant aboveground biomass data (sorted to species)	1982-2011 (23 years)	
nle097	Litter carbon/nitrogen data	2009 (1 year)	
lpe097	Percent light penetration	1982-1990 (9 years)	
rbe097	Root biomass data	1988-1992 (4 years)	
nre097	Root carbon nitrogen data	2009 (1 year)	
mse097	Small mammal abundance	1982-1985 (4 years)	
cae097	Soil Calcium	1982 (1 year)	
care002	Soil carbon	1982-2011 (6 years)	
mge002	Soil magnesium	1982 (1 year)	
nohe002	Soil nitrate and ammonium	1985-2009 (7 years)	

Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
ne002	Soil nitrogen	1982-2011 (6 years)	
pe097	Soil phosphorous	1982 (1 year)	
phe097	Soil pH	1982-1990 (5 years)	
ke097	Soil potassium	1982 (1 year)	
<b>e098: Fire X Nitrogen: Interactive Effects in a Prairie-Like Grassland (Core)</b>			
ple098	Plant aboveground biomass data (sorted to species)	1982-2011 (24 years)	
nle098	Litter carbon/nitrogen data	2009 (1 year)	
lpe098	Percent light penetration	1982-1990 (9 years)	
rbe098	Root biomass data	1988-1992 (4 years)	
nre098	Root carbon nitrogen data	2009 (1 year)	
mse098	Small mammal abundance	1982-1985 (4 years)	
cae098	Soil Calcium	1982 (1 year)	
care002	Soil carbon	1982-2011 (6 years)	
mge002	Soil magnesium	1982 (1 year)	
nohe002	Soil nitrate and ammonium	1985-2009 (7 years)	
ne002	Soil nitrogen	1982-2011 (6 years)	
pe098	Soil phosphorous	1982 (1 year)	
phe098	Soil pH	1982-2001 (6 years)	
<b>e120: Biodiversity II: Effects of Plant Biodiversity on Population and Ecosystem Processes (Core)</b>			
nbe120	Plant aboveground biomass carbon/nitrogen	1996-2006 (7 years)	2
ple120	Plant aboveground biomass data (sorted to species)	2001-2011 (11 years)	22
aage120	Insect abundance collected by sweepnet	1996-2006 (11 years)	4
invre120	Invasion strip root biomass	2002 (1 year)	2
invne120	Invasion strip soil nitrogen	2002 (1 year)	
lpe120	Percent light penetration	1996-2000 (5 years)	
pce120	Plant species percent cover data	1996-2000 (5 years)	1
aafe120	Plant traits	2008 (1 year)	
rbe120	Root biomass data	1997-2010 (8 years)	1
nre120	Root carbon/nitrogen data	1997-2006 (6 years)	
care120	Soil carbon	1994-2006 (7 years)	
nohe120	Soil nitrate and ammonium	1996-2007 (8 years)	5
ne120	Soil nitrogen	1994-2006 (7 years)	1
<b>e133: Effect of Burning patterns on Vegetation in the Fish Lake Burn Compartments (Core)</b>			
herbe133	Herb Survey	1984-2010 (6 years)	4
lite133	Litter biomass	1995-2005 (10 years)	1
lpe133	Percent light penetration	2000-2010 (2 year)	2

Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
ple133	Plant aboveground biomass data (sorted to species)	1999-2002 (4 years)	5
dse133	Plant density	1984 (1 year)	1
aafe133	Plant traits	2005 (1 year)	
rbe133	Root biomass data	1999-2006 (8 years)	4
rie133	Root ingrowth biomass	1999-2005 (7 years)	2
sape133	Sapling survey	2000-2010 (3 years)	2
shrube133	Shrub Survey	1984-2010 (5 years)	5
bde133	Soil bulk density	1995 (1 year)	3
cae133	Soil Calcium	2002 (1 year)	2
care133	Soil carbon	1984 (1 year)	2
scfe133	Soil carbon flux	1999-2002 (4 years)	2
mge133	Soil magnesium	2002 (1 year)	2
hoe133	Soil moisture	1999-2002 (4 years)	4
ne133	Soil nitrogen	1984 (1 year)	1
sphe133	Soil pH	1984 (1 year)	1
ke133	Soil potassium	2002 (1 year)	2
nae133	Soil sodium	2002 (1 year)	2
tree133	Tree survey	1984-2010 (5 years)	2
<b>e141: BioCON : Biodiversity, Elevated CO2, and N Enrichment (Core)</b>			
nbe141	Plant aboveground biomass carbon/nitrogen	1998-2008 (11 years)	8
ple141	Plant aboveground biomass data (sorted to species)	1998-2010 (13 years)	32
lye141	Lysimeter data	2003-2005 (3 years)	2
nie141	N15 isotope in plants	1999-2000 (2 years)	1
mre141	Nitrogen mineralization rate	1998-2010 (13 years)	5
lpe141	Percent light penetration	1998-2010 (13 years)	5
phoe141	Photosynthesis (A max, etc.)	1998-2008 (6 years)	8
pce141	Plant species percent cover data	1998-2010 (13 years)	8
sachmie141	Reproduction data for Achillea millefolium	2002 (1 year)	3
samocae141	Reproduction data for Amorpha canescens	2006-2010 (5 years)	2
sasctue141	Reproduction data for Asclepias tuberosa	2007-2010 (4 years)	2
sgrasse141	Reproduction data for grasses	2002-2010 (7 years)	2
slescae141	Reproduction data for Lespedeza capitata	2001-2010 (10 years)	1
sluppee141	Reproduction data for Lupinus perennis	2001-2010 (9 years)	1
spetvie141	Reproduction data for Petalostemum villosum	2006-2010 (5 years)	1
ssolrie141	Reproduction data for Solidago rigida	2001-2010 (7 years)	2
roote141	Root biomass data	1998-2010 (13 years)	1
nre141	Root carbon/nitrogen data	1998-2006 (9 years)	8
rie141	Root ingrowth biomass	1998-2010 (13 years)	2
swe141	Seed weight	2001-2002 (2 years)	1

Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
care141	Soil carbon	1997-2002 (2 years)	4
nhe141	Soil ammonium	1998-2002 (5 years)	12
bde141	Soil bulk density	2003-2004 (2 years)	6
scfe141	Soil carbon flux	1998-2010 (13 years)	4
hoe141	Soil moisture	1998-2010 (13 years)	5
nohe141	Soil nitrate and ammonium	1998-2002 (5 years)	8
ne141	Soil nitrogen	1997-2002 (2 years)	3
sphe141	Soil pH	1999-2010 (12 years)	5
slae141	Specific Leaf Area	2001 (1 year)	4
<b>e172: Herbivory by Nitrogen Interactive Effects on Community and Ecosystem Processes and Dynamics (Core)</b>			
ple172	Aboveground biomass data (sorted to species)	1982-2011 (30 years)	
lpe172	Percent light penetration	1982-2004 (11 years)	
nbe172	Plant aboveground biomass carbon/nitrogen	2009 (1 year)	
rbe172	Root biomass data	1987-2002 (15 years)	
nre172	Root carbon/nitrogen data	2009 (1 year)	
mse172	Small mammal abundance	1982-1985 (4 years)	
cae172	Soil Calcium	1982 (1 year)	
care172	Soil carbon	1982-2009 (5 years)	
mge172	Soil magnesium	1982 (1 year)	
nohe172	Soil nitrate and ammonium	1985-2009 (14 years)	
ne172	Soil nitrogen	1982-2009 (5 years)	
phe172	Soil phosphorous	1982-2010 (10 years)	
ke172	Soil potassium	1982 (1 year)	
<b>e244: Natural enemies, plant diversity and plant community composition (Core)</b>			
ndvie244	Plant aboveground biomass estimated by Normalized Difference Vegetation Index	2009-2011 (3 years)	
ple244	Plant aboveground biomass data (sorted to species)	2007-2010 (4 years)	
pce244	Plant species percent cover data	2008-2011 (4 years)	2
roote244	Root biomass data	2010 (1 year)	2
<b>e245: The influence of natural enemies on plant community composition and productivity (Core)</b>			
ple245	Plant aboveground biomass data (sorted to species)	2008-2010 (3 years)	3
pce245	Plant species percent cover data	2008-2011 (4 years)	2
roote245	Root biomass data	2010 (1 year)	2
<b>e249: BAC: Biodiversity and Climate (Core)</b>			
ple249	Plant aboveground biomass data (sorted to species)	2007-2011 (4 years)	2

Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
ndvie249	Plant aboveground biomass estimated by Normalized Difference Vegetation Index	2009-2011 (3 years)	2
roote249	Root biomass data	2009-2010 (2 years)	
tdre249	Soil moisture (TDR)	2009-2011 (3 years)	
temoe249	Soil temperature	2009-2011 (3 years)	
e003: Effects of Various Nutrients and Water on Vegetation			
ple003	Plant aboveground biomass data (sorted to species)	1982-1991 (6 years)	
lpe003	Percent light penetration	1982-1990 (6 years)	
msce003	Small mammal scatter counts	1985 (1 year)	
nhe003	Soil ammonium	1988 (1 year)	
noe003	Soil nitrate	1988 (1 year)	
nohe003	Soil nitrate and ammonium	1991 (1 year)	
ne003	Soil nitrogen	1982 (1 year)	
phe003	Soil phosphorous	1982-1985 (2 years)	
pe003	Soil phosphorous	1982 (1 year)	
tce003	Soil trace metals	1984 (1 year)	
e005: Effect of Herbivores on Vegetation Treated with Different N Levels and the Effect of N Addition on Herbivore Populations.			
ple005	Plant aboveground biomass data (sorted to species)	1982-1985 (2 years)	
lpe005	Percent light penetration	1985 (1 year)	
e007: Effects of Deer on Growth and Establishment of Woody Vegetation in Old Fields			
dre007	Deer browse	1991 (1 year)	
ne007	Soil nitrogen	1983 (1 year)	
tre007	Tree data	1985 (1 year)	
e008: Effect of N Addition on Vegetation with Mammalian Herbivory			
ple008	Plant aboveground biomass data (sorted to species)	1983-1986 (3 years)	
avne008	Average soil nitrogen	1985 (1 year)	
gme008	Gopher mounds	1983-1985 (3 years)	
hce008	Grasshopper data	1983 (1 year)	
hse008	Grasshopper individual characteristics	1984 (1 year)	
lpe008	Percent light penetration	1983-1986 (2 years)	
mse008	Small mammal abundance	1983 (1 year)	
nhe008	Soil ammonium	1986 (1 year)	
noe008	Soil nitrate	1986 (1 year)	
ne008	Soil nitrogen	1983-1985 (2 years)	



Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
<b>e009: Effect of N Addition on Vegetation With Mammalian Herbivory Initially on Disked Ground</b>			
ple009	Plant aboveground biomass data (sorted to species)	1983-1985 (2 years)	
gme009	Gopher mounds	1983-1985 (3 years)	
hce009	Grasshopper data	1983 (1 year)	
hse009	Grasshopper individual characteristics	1984 (1 year)	
lpe009	Percent light penetration	1983 (1 year)	
mse009	Small mammal abundance	1983 (1 year)	
ne009	Soil nitrogen	1983 (1 year)	
<b>e010: Herbivore Effects on a Large, Unmanipulated Area</b>			
ple010	Plant aboveground biomass data (sorted to species)	1983-1986 (3 years)	
gme010	Gopher mounds	1983-1985 (3 years)	
hce010	Grasshopper data	1983 (1 year)	
hse010	Grasshopper individual characteristics	1984 (1 year)	
lpe010	Percent light penetration	1983-1986 (2 years)	
mse010	Small mammal abundance	1983 (1 year)	
ne010	Soil nitrogen	1983 (1 year)	
<b>e011: Effects of Nitrogen on Vegetation Under Herbivore Pressure</b>			
ple011	Plant aboveground biomass data (sorted to species)	1984-1992 (5 years)	
avne011	Average soil nitrogen	1985 (1 year)	
gme011	Gopher mounds	1983-1984 (2 years)	
hce011	Grasshopper data	1983 (1 year)	
hse011	Grasshopper individual characteristics	1984 (1 year)	
ne011	Soil nitrogen	1985 (1 year)	
<b>e023: The Seasonal Effects of Nitrogen Addition in the Spring on Vegetation at Differing Times of the Growing Season</b>			
ple023	Plant aboveground biomass data (sorted to species)	1985 (1 year)	
<b>e024: The Effect of Nitrogen Addition and Different pH Levels on Microorganism Populations</b>			
ple024	Plant aboveground biomass data (sorted to species)	1987-1989 (2 years)	
lpe024	Percent light penetration	1987-1990 (3 years)	
nhe024	Soil ammonium	1987 (1 year)	
noe024	Soil nitrate	1987 (1 year)	
phe024	Soil phosphorous	1987-1991 (3 years)	

Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
<b>e025: The Effects of Adding Different Levels of Nitrogen at Different Times During the Growing Season</b>			
ple025	Plant aboveground biomass data (sorted to species)	1985-1988 (4 years)	
<b>e026: Traits: Competition and Resource Reduction for Five Grass Species Grown in Monoculture and Competition in Soils with Different Nitrogen Availabilities</b>			
ple026	Plant aboveground biomass data (sorted to species)	1992-1993 (2 years)	1
fde026	Available light at soil surface	1987-1988 (2 years)	
htlte026	Percent light penetration and maximum plant height	1986 (1 year)	
pce026	Plant species percent cover data	1989 (1 year)	
sexe026	Reproductive output	1988 (1 year)	
rbe026	Root biomass data	1986 (1 year)	
swe026	Seed weight	1985 (1 year)	
nohe026	Soil nitrate and ammonium	1989-1993 (5 years)	
ne026	Soil nitrogen	1985 (1 year)	
wee026	Weed biomass	1994 (1 year)	
<b>e038: Schizachyrium scoparium Nutrient Uptake Profiles</b>			
mbe038	Microbial nitrogen	1987 (1 year)	
nhe038	Soil ammonium	1987 (1 year)	
noe038	Soil nitrate	1987 (1 year)	
<b>e042: Traits: Biomass Allocation Trends in Old Field in Relation to Gradients of Succesional Age and Soil Nitrogen</b>			
ple042	Plant aboveground biomass data (sorted to species)	1987 (1 year)	
rppe042	Plant biomass allocation	1987 (1 year)	2
tne042	Plant tissue nitrogen	1987 (1 year)	
rbe042	Root biomass data	1987 (1 year)	
nhe042	Soil ammonium	1987 (1 year)	
noe042	Soil nitrate	1987 (1 year)	
<b>e052: Interactive Effects of Fertility and Disturbance on Plant Community Diversity and Structure</b>			
ple052	Plant aboveground biomass data	1988-1994 (7 years)	
hve052	Full harvest data	1990-1991 (2 years)	
lfe052	Leaf length data	1990-1991 (2 years)	
hte052	Maximum plant height along transects	1990 (1 year)	
lpe052	Percent light penetration	1990-1998 (3 years)	
pce052	Plant species percent cover data	1998 (1 year)	
rbe052	Root biomass data	1988-1994 (7 years)	
cde052	Seedling condition	1990 (1 year)	

Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
sde052	Seedling data	1991 (1 year)	
sge052	Seedling growth	1991 (1 year)	
sse052	Seedling leaf length	1991 (1 year)	
loce052	Seedling planting information	1990 (1 year)	
rbse052	Seedling root biomass	1990 (1 year)	
nohe052	Soil nitrate and ammonium	1989-1992 (3 years)	
ne052	Soil nitrogen	1988-1998 (2 years)	
phe052	Soil phosphorous	2001 (1 year)	
<b>e053: Components of Plant Competition Along an Experimental Gradient of Nitrogen Availability</b>			
lpe053	Percent light penetration	1988 (1 year)	
nohe053	Soil nitrate and ammonium	1988 (1 year)	
<b>e055: Plant Competition Under Different Nitrogen Levels:A Garden Experiment</b>			
ple055	Plant aboveground biomass data (sorted to species)	1989-1999 (7 years)	
lpe055	Percent light penetration	1989-1999 (4 years)	
pce055	Plant species percent cover data	2002 (1 year)	
reproe055	Reproductive biomass	1989-1993 (3 years)	
rbe055	Root biomass data	1992-2002 (4 years)	
roote055	Root biomass data	1989-1993 (4 years)	
nohe055	Soil nitrate and ammonium	1989-2002 (7 years)	
<b>e060: Vegetation Phenology and Grasshopper Competition</b>			
ple060	Plant aboveground biomass data (sorted to species)	1989 (1 year)	
ghe060	Grasshopper cage data	1989-1990 (2 years)	
<b>e061: Effect of Bird Predation on Grasshopper and Plant Communities</b>			
ple061	Plant aboveground biomass data (sorted to species)	1989-2003 (10 years)	
ghe061	Grasshopper cage data	1989-1990 (2 years)	
nohe061	Soil nitrate and ammonium	1991-1998 (4 years)	
<b>e062: Selective Herbivory and Plant Allocation</b>			
ple062	Plant aboveground biomass data (sorted to species)	1989 (1 year)	
<b>e064: Effects of Deer and Pocket Gophers on Vegetation and Soils</b>			
tne064	Plant tissue nitrogen	1989 (1 year)	
she064	Shrub data	1991 (1 year)	
nohe064	Soil nitrate and ammonium	1991 (1 year)	

Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
<b>e065: Forest Deer Enclosures Near the Cornea Cabin</b>			
tre065	Tree data	1989 (1 year)	
<b>e066: Seed Size and Establishment</b>			
hte066	Maximum plant height along transects	1990 (1 year)	
pce066	Plant species percent cover data	1990 (1 year)	
<b>e069: Tree Competition Garden</b>			
nbe069	Plant aboveground biomass carbon/nitrogen	1996-1997 (2 years)	
ple069	Plant aboveground biomass data (sorted to species)	1993-1997 (3 years)	
rbe069	Root biomass data	1996-1997 (2 years)	
nre069	Root carbon/nitrogen data	1996-1997 (2 years)	
bde069	Soil bulk density	1997 (1 year)	
nohe069	Soil nitrate and ammonium	1990-1996 (5 years)	
ne069	Soil nitrogen	1996-1997 (2 years)	
<b>e070: Legume Competition Garden</b>			
nbe070	Plant aboveground biomass carbon/nitrogen	1998 (1 year)	
ple070	Plant aboveground biomass data (sorted to species)	1992-1998 (3 years)	
rbe070	Root biomass data	1992-1998 (2 years)	
nre070	Root carbon/nitrogen data	1998 (1 year)	
bde070	Soil bulk density	1998 (1 year)	
nohe070	Soil nitrate and ammonium	1990-1998 (4 years)	
ne070	Soil nitrogen	1998 (1 year)	
wee070	Weed biomass	1994 (1 year)	
<b>e071: Mechanisms of Grasshopper-Plant Interactions</b>			
ple071	Plant aboveground biomass data (sorted to species)	1991 (1 year)	
ghe071	Grasshopper cage data	1991 (1 year)	
nohe071	Soil nitrate and ammonium	1991-1992 (2 years)	
<b>e077: Long-Term Grasshopper-Plant Interactions</b>			
nohe077	Soil nitrate and ammonium	1991-1992 (2 years)	
<b>e079: Distribution of Wetland Plant Species in Relation to the Level of the Water Table</b>			
pce079	Plant species percent cover data	1988-1989 (2 years)	

Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
<b>e081: Atmospheric Deposition-Wet and Dry at Cedar Creek</b>			
ate081	Atmospheric deposition and precipitation	1984-2011 (16 years)	
<b>e085: Plant Colonization and Species Diversity in an Old Field</b>			
pce085	Plant species percent cover data	1990-1998 (6 years)	
sde085	Seedling data	1992 (1 year)	
nohe085	Soil nitrate and ammonium	1994 (1 year)	
<b>e086: The Diversity and Abundance of Prairie Plant Communities</b>			
lpe086	Percent light penetration	1991 (1 year)	
pce086	Plant species percent cover data	1990-1991 (2 years)	
fle086	Reproductive output--number of flowering heads	1991 (1 year)	
<b>e088: Litter Quality and Landscape Controls of Decomposition</b>			
nohe088	Soil nitrate and ammonium	1991 (1 year)	
<b>e090: Grasshopper removals</b>			
ple090	Plant aboveground biomass data (sorted to species)	1991 (1 year)	
nohe090	Soil nitrate and ammonium	1991-1992 (2 years)	
<b>e091: The Effect of Seed Addition on Biodiversity in an Oak Savanna</b>			
mpce091	Mean percent cover--average of 2 survey groups	1993 (1 year)	
pce091	Plant species percent cover data	1991-1998 (5 years)	
sdle091	Seedling density	1992 (1 year)	
nohe091	Soil nitrate and ammonium	1994 (1 year)	
<b>e093: Soil Heterogeneity and Plant Diversity in an Oak Savanna</b>			
lpe093	Percent light penetration	2004 (1 year)	1
pce093	Plant species percent cover data	1991-2004 (7 years)	2
sdle093	Seedling density	1992-2004 (2 years)	
nohe093	Soil nitrate and ammonium	1991-1994 (2 years)	2
<b>e099: Total C and N Storage Along Wetland-Upland Gradients</b>			
nohe099	Soil nitrate and ammonium	1992 (1 year)	

Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
<b>e107: Soil Heterogeneity With Disturbance</b>			
fle107	Reproductive output--number of flowering heads	1991 (1 year)	
<b>e108: Soil Disturbance Gradient</b>			
lpe108	Percent light penetration	1991 (1 year)	
pce108	Plant species percent cover data	1990 (1 year)	
fle108	Reproductive output--number of flowering heads	1991 (1 year)	
<b>e111: Multiple Traits of Multiple Plant Species Measured in Monoculture Gardens</b>			
nbe111	Plant aboveground biomass carbon/nitrogen	1997 (1 year)	2
ple111	Plant aboveground biomass data (sorted to species)	1997 (1 year)	1
nre111	Root carbon/nitrogen data	1997 (1 year)	
nohe111	Soil nitrate and ammonium	1997 (1 year)	
<b>e112: Seedling Addition Experiment in Field D</b>			
lpe112	Percent light penetration	2004 (1 year)	1
psae112	Plant species inventory	1996 (1 year)	1
<b>e113: Seed Addition in Lawrence Strips</b>			
pce113	Plant species percent cover data	1994-1998 (4 years)	
<b>e115: Addition of Schizachyrium scoparium Seeds to the Lawrence Strips</b>			
pce115	Plant species percent cover data	1994-1998 (2 years)	2
<b>e122: Trophic Structure: Insect Species Diversity, Abundance and Body Size</b>			
inscadunde122	Abundance and Body size of Insects Collected	1992 (1 year)	4
araspee122	Arachnida species (spiders) abundance	1992 (1 year)	
colspee122	Coleoptera species abundance	1992 (1 year)	
dipsee122	Diptera species abundance	1992 (1 year)	1
forespee122	Formicidae species (ants) abundance	1992 (1 year)	
hemspee122	Hemiptera species abundance	1992 (1 year)	1
homspee122	Homoptera species abundance	1992 (1 year)	1
hymspsee122	Hymenoptera species abundance	1992 (1 year)	
insctrape122	Insects caught in pitfall traps	1992 (1 year)	
lepspsee122	Lepidoptera species abundance	1992 (1 year)	
miscspsee122	Miscellaneous insect species abundance	1992 (1 year)	1
ortspsee122	Orthoptera species abundance	1992 (1 year)	1

Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
<b>e123: The Small Biodiversity Experiment</b>			
nbe123	Plant aboveground biomass carbon/nitrogen	1996-1998 (3 years)	2
ple123	Plant aboveground biomass data (sorted to species)	1996-2005 (8 years)	4
nle123	Litter carbon/nitrogen data	1998 (1 year)	1
lpe123	Percent light penetration	1996-1999 (3 years)	2
pce123	Plant species percent cover data	1995-2005 (7 years)	2
rbe123	Root biomass data	1997-2004 (4 years)	3
nre123	Root carbon/nitrogen data	1996-1998 (3 years)	2
nohe123	Soil nitrate and ammonium	1997-2005 (5 years)	2
nme123	Soil nitrate, ammonium, moisture and nitrogen mineralization	1996 (1 year)	2
ne123	Soil nitrogen	1996-1998 (2 years)	4
<b>e145h: Effects of Nitrogen Fertilization on Litter and Soil Decomposition</b>			
cze145h	Extracellular enzyme	2005 (1 year)	
ldnde145h	Litter Decomposition and Nitrogen Dynamics	2005 (1 year)	1
<b>e153: Interactive Effects of Deer, Fire and Nitrogen</b>			
ple153	Plant aboveground biomass data (sorted to species)	2002-2009 (3 years)	5
arce153	Arthropod collection	2003-2004 (2 years)	1
psae153	Plant species inventory	2001-2005 (2 years)	1
pce153	Plant species percent cover data	2001-2005 (3 years)	2
roote153	Root biomass data	2002-2005 (2 years)	5
skte153	Skink trapping	2004 (1 year)	2
mse153	Small mammal abundance	2003-2005 (3 years)	2
bde153	Soil bulk density	2002 (1 year)	4
tre153	Tree data	2001-2005 (5 years)	1
<b>e169: Causes of change in ectomycorrhizal communities</b>			
abae169	Belowground fungal community presence in savanna and oak forest	2002 (1 year)	
aaze169	Sporocarp count aboveground fungal communities in savanna and oak forest	1998-2002 (3 years)	
<b>E199: Arabidopsis BioCON Evolutionary Study</b>			
aaaje199	Arabidopsis Tolerance to herbivory	2006 (1 year)	
aaxe199	Lespedeza herbivory Census	2004-2005 (2 years)	
aake199	Lupinus Transgenerational Effects	2006 (1 year)	



Dataset ID	Title	Range of Years (# years with data)	2011 Downloads by Outside Researchers
aaie199	Phenology, growth, and fitness of Arabidopsis under ambient and elevated CO2	2005 (1 year)	
aahe199	Phenology, growth, and fitness of Arabidopsis under ambient and elevated CO2 and in the presence/absence of competitors	2006 (1 year)	
aale199	Poa Transgenerational Effects	2006 (1 year)	
aame199	Schizachyrium Transgenerational Effects	2006 (1 year)	
<b>e211: Nitrogen limitation in decomposition</b>			
aaae211	Decomposition Model Parameters	2005 (1 year)	
aabe211	Initial Substrate Chemistry	2005 (1 year)	
aade211	O horizon extracellular enzyme activity	2009 (1 year)	
aace211	Substrate mass, nitrogen, extracellular enzyme, and microbial biomass and stoichiometry dynamics	2005-2008 (4 years)	
<b>e219: The role of photodegradation in surface litter decomposition in grasslands along UV-B gradient</b>			
aane219	UV Litter Decomposition	2006-2008 (3 years)	
<b>e234: An evolutionary perspective on functional diversity in co-occurring willow(salix) species</b>			
aase234	Willow photoprotection	2007 (1 year)	
<b>e238: Investigating patterns of habitat specialization in fifteen co-occurring willow and poplar species</b>			
aave238	Field plots	2008 (1 year)	
aare238	Greenhouse Traits	2009 (1 year)	
aawe238	Greenhouse Traits	2009 (1 year)	
aaue238	Phylogenetic samples	2010 (1 year)	
aaqe238	Plot abundances	2008 (1 year)	
aate238	Willow drought	2007 (1 year)	
aape238	Willow hydraulics	2008 (1 year)	
aaqe238	Willow predrought	2006 (1 year)	
<b>e248: The Effect of Nitrogen Addition and Irrigation in High Diveristy Prairies</b>			
ple248	Plant aboveground biomass data (sorted to species)	2007-2009 (3 years)	4
pce248	Plant species percent cover data	2007-2010 (4 years)	1
roote248	Root biomass data	2010 (1 year)	
<b>e268: Phenology, the timing of biological events such as bud break, plant flowering times and bird migration</b>			
aaye268	National Phenology Network tree phenology	2009-2011 (3 years)	

## MANAGEMENT OF CDR AND CCESR

The Cedar Creek LTER project (CDR) performs its research within a highly diverse mosaic of grassland, savanna, hardwood and mixed forest, boreal forest, bog, wetland, lake and stream ecosystems that make up the 22 km<sup>2</sup> of the Cedar Creek Ecosystem Science Reserve (CCESR). Although CDR and CCESR have their own missions, funding sources and personnel, they are highly interdependent and have grown in tandem during the past three decades. The current LTER grant period, for instance, saw construction of a Science and Outreach Center at CCESR that is now providing immensely better facilities for CDR research, education, and outreach activities. We also completed construction of additional housing facilities (three new multi-suite homes, each with 5 bedrooms) for use by visiting scientists, graduate students, post-doctoral researchers, and undergraduate research interns.

The management of the facilities and habitats of CCESR is performed by the staff of CCESR under the authority of the Dean of the College of Biological Sciences of the University of Minnesota. CCESR is overseen by a full-time, on-site Manager and Associate Director, Dr. Jeff Corney. Dr. Corney manages and coordinates all issues and budgets related to CCESR facilities and their use for research, education, outreach, and community relations. Dr. Corney also chairs the CCESR Research Review Committee that evaluates all proposals for research done at CCESR and leads the Summer Research Intern program. Dr. Corney reports to David Tilman, the faculty Director of CCESR, a position appointed by the Dean of the College of Biological Sciences. The staff and facilities of CCESR, funded by the University of Minnesota, provide many types of support that are vital to the success of our LTER, as discussed in the Facilities section of this proposal.

### *Leadership Transition at the CDR LTER Project*

David Tilman has led the CDR LTER for the past 30 years, since its inception in 1982. Starting with this renewal, we will adopt a new leadership structure in which lead-PI duties are split between two co-equal Lead PIs. This change will increase the intellectual and administrative diversity in the leadership role, lower the administrative burden on the leaders, mentor more junior personnel into leadership positions, and smooth the transition towards Tilman's eventual retirement from CDR leadership. We adopted this strategy after discussions with numerous other LTER sites convinced us that it was the best of the alternative models being practiced.

Our leadership plan is one of gradual transitions. Starting with this renewal award, the Lead PIs will be David Tilman and Eric Seabloom. At the start of the fourth year of the renewal award, Sarah Hobbie will replace David Tilman as one of the Lead PIs (she is not able to assume CDR leadership sooner than that because she is committed to a 3-year term directing the Ecology, Evolution and Behavior graduate program). The order and timing of these transitions are based on the consensus of those directly involved (Hobbie, Seabloom, and Tilman) and the rest of the LTER scientists. After finishing his term as one of the Lead PIs, Tilman will remain as active a researcher as ever; he is fully dedicated to the long-term success of CDR and proposed this leadership transition to assure the long-term creativity and vitality of our LTER.

During this leadership transition, we will maintain the long-standing philosophies of our LTER. We have learned that maintaining open, honest, yet respectful communication among all researchers, as well as intellectual diversity, are central to our success. We have assembled a young, dynamic, creative, and dedicated team of researchers at CDR. Just as we can look back on the past three decades of CDR research, so, too, has our team planned the research we propose here with an eye on the long-term contributions that our LTER site can make to science and society in the decades to come.

### *Management of the CDR LTER Project*

Among other duties, the Lead PIs will share responsibility for supervising CDR staff; tracking CDR budgets, publications, and other products and contributions from the CDR; preparing the Annual Report for NSF; organizing the Summer Field Day, meetings of the CDR Executive Committee, and meetings of PIs and staff during the field season. They will coordinate the monthly on-campus CDR science discussions during the academic year. They will represent CDR at the National LTER Science Council meetings and one of them will serve on the LTER Executive Board. One of the two other senior PIs will

lead the annual winter Science Synthesis Workshop and the other will lead the summer Science Symposium.

The Lead PIs will receive advice and guidance from the CDR Executive Committee (the lead PIs plus Sarah Hobbie, Elizabeth Borer, and Peter Reich for Years 1-3; and Peter Reich, Elizabeth Borer and David Tilman for Years 4-6). The Executive Committee meets at least twice each year to discuss and reach consensus on all matters related to the project, focusing especially on strategic issues related to science, personnel, and their responsibilities and budgets. The Manager and Associate Director of CCESR (Corney) serves as an ex officio member of the committee. As has been our tradition, the Co-Lead PIs will manage based on the consensus of the CDR Executive Committee with possible rare exceptions. Other researchers at CDR will continue to have ample opportunity for involvement in management of CDR, e.g., at frequent meetings (e.g., those mentioned in the previous paragraph) focused on science, and especially on opportunities for new experiments, syntheses, and cooperation. These discussions have generated many of our best ideas, and will remain the heart of our team management plan.

We have found that CDR research projects run most efficiently when managed by small groups of PIs who are more closely tied to each project. To reflect this approach, budgets are allocated based on input from the all research PIs, but the day-to-day management of each project is based on the decisions of the smaller subset of PIs dedicated to each project. In addition to the research project budgets, there is a budget managed by the Lead PIs that covers general support for research at CDR and non-research activities such as education and outreach. Our proposed budget reflects the allocations made to support the research plans formulated by our full team. We recognize that new ideas and opportunities will arise that we will also want to pursue. Major new ideas would, of course, require new grants. However, as our CDR-funded science evolves, we will change, as a team, how we allocate our time and resources in ways that maintain commitment to long-term research and allow us to take advantage of the most exciting new opportunities that our long-term studies reveal.

#### *Participation of Other Scientists*

We strongly believe that intellectual diversity increases scientific creativity and productivity. We openly encourage non-project scientists to pursue their interests at CCESR and to join in and use CDR research as a basis for their own work. We have found that such interactions can be particularly beneficial when the other scientists have skills and/or ideas that differ from those already at CCESR. During the current LTER, more than a dozen other senior scholars have worked with the CDR team, with about half of these individuals being faculty at other institutions. In particular, Nick Haddad (University of North Carolina), Don Zak (University of Michigan), Dave Ellsworth (University of Western Sydney), Nancy Johnson (Northern Arizona University), Tali Lee (University of Wisconsin- Eau Claire), Michael Russelle (ARS), Ross McMurtrie (University of New South Wales), Jizhong Zhou (University of Oklahoma), Noah Fierer (Colorado University), Adam Kay (University of St. Thomas), Mark Davis (Macalester College), and Philippe Vandenkoornhuyse (University of Rennes, Rennes, France) have worked with us, as have the following University of Minnesota faculty: Peter Tiffin (plant evolution), Ruth Shaw (community genetics), and David McLaughlin (fungal biology). In addition, it is worth noting that some of these individuals have now 'joined the team' and have funding allocated to them in this proposal. For example, Elizabeth Borer and Eric Seabloom started work at CDR in 2007 and are now involved directly in research and management of CDR after moving to UMN in 2010.

A large number of scientists from around the world actively use the long-term data sets that we gather; about 20% of the papers published with CDR data do not have CDR PIs as authors. Many of these scientists have never visited Cedar Creek nor seen the experiments about which they are writing. Because they would benefit from such a visit, and because we would benefit from learning their thoughts and ideas, we are proposing holding an annual summer site visit to which we would invite all of our extended data synthesizers and analysts. We believe that such a meeting could spark important new analyses, suggest critical new data that to collect, expand the impact of our various experimental and observational studies, and encourage our data users to become actively engaged in their own on-site research at Cedar Creek.