

FINAL REPORT
Biotic Processes Regulating the Carbon Balance of Desert Ecosystems
DE-FG02-03ER63651

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Summary

Our results from the 10-year elevated atmospheric CO₂ concentration ([CO₂]) study at the Nevada Desert FACE (Free-Air CO₂ Enrichment) Facility (NDFF) indicate that the Mojave Desert is a dynamic ecosystem with the capacity to respond quickly to environmental changes. The Mojave Desert ecosystem is accumulating carbon (C), and over the 10-year experiment, C accumulation was significantly greater under elevated [CO₂] than under ambient, despite great fluctuations in C inputs from year to year and even apparent reversals in which [CO₂] treatment had greater C accumulations. The greater C under elevated [CO₂] after 10 years was due to increased soil organic C and not due to increased shoot or root biomass. As in other deserts, the Mojave Desert is characterized by large amplitude cycles between extreme wet and extreme dry periods, and these cycles have both immediate and long-term effects on ecosystem functions, especially those related to the impacts of elevated [CO₂] on C and N cycling. Our results clearly indicate that vegetation consistently has greater C assimilation rates under elevated [CO₂] when soil moisture is readily available, but enhanced C assimilation occurs only rarely under drought conditions. This pattern of greater photosynthetic enhancements by elevated [CO₂] under wet conditions occurs both between wet and dry years as well as seasonally, i.e. between relatively wet periods in early spring and relatively dry periods later that spring or summer. If soil water availability remains high for extended periods of time, such as occurred during the extremely wet 1998 El Niño event, aboveground net primary productivity (ANPP) is increased by elevated [CO₂]. However, ANPP under elevated [CO₂] is not significantly increased in drought or average precipitation years, even though photosynthesis was increased for a portion of those growing seasons. Furthermore, biomass from increased ANPP does not persist as long-term vegetative biomass in the Mojave Desert but is lost as litter, a portion of which is then incorporated into soil organic C. Our results also indicate that some of the increased photosynthates under elevated [CO₂] are allocated to root systems, but the increased allocation is not to increased belowground net primary productivity and not to increased root respiration, but rather to increased rhizosphere deposition. Thus, increased soil organic C observed after 10 years of elevated [CO₂] in the Mojave Desert is due to large pulse inputs from increased litter following extreme wet years coupled with slow but persistent inputs from root exudation during seasonally wet periods. Although the stochastic nature of wet-dry cycles in desert ecosystems makes modeling the impacts of deserts on global C balance difficult, deserts are an important global C sink that cannot be ignored.

Nitrogen (N) cycling at the NDFF also rapidly responded to the elevated [CO₂] treatment, as indicated by changes in leaf N stable isotope content within the first year of the experiment. Progressive nitrogen limitation was not observed at NDFF. Soil microbes at the NDFF are C limited, and increased C assimilation by plants under elevated [CO₂] ultimately increased C supply to soil microbes. Increased microbial activity not only increased rates of N cycling, but also increased the amount of inorganic N available for plant uptake. Increases in both biomass

and richness of the fungal component of soil microbial communities likely were responsible for much of the changes in N cycling and availability. Biological soil crusts, which are a key feature of arid ecosystems worldwide, had decreased abundance of cyanobacteria and mosses under elevated $[\text{CO}_2]$, but functional characteristics were either not affected (reproduction) or slightly increased (N_2 fixation, stress tolerance) under elevated $[\text{CO}_2]$.

Taken together, the FACE study in the Mojave Desert in Nevada indicates a desert ecosystem that has among the largest positive short-term responses to elevated $[\text{CO}_2]$, as predicted by early global change researchers. However, elevated $[\text{CO}_2]$ interacts with precipitation in a synergistic fashion, and the extreme variation in precipitation that characterizes desert ecosystems tends to dampen long-term effects of elevated $[\text{CO}_2]$ on ecosystem processes. Thus, although long-term responses such as C accumulation are limited by drought cycles, C accumulation extrapolated from the Mojave Desert to other arid ecosystems represents a globally significant mechanism for C sequestration that must be considered in global C models.

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Introduction

The carbon (C) balance of terrestrial ecosystems is the greatest unknown in the global C budget, and estimates are often based on residuals of direct atmospheric measurements and well-constrained models of ocean uptake (Houghton 2007, Houghton et al. 2009, Crevoisier et al. 2010). However, the exact magnitude, location, and causes of terrestrial sinks are uncertain (Heimann 2009, Houghton et al. 2009, Crevoisier et al. 2010). Arid ecosystems are significant components of the terrestrial C budget: drylands cover about 47% of the terrestrial land surface (Lal 2004), represent the fifth largest pool of terrestrial soil C (208 – 241 Pg) (Jobbagy and Jackson 2000, Drigo et al. 2008), and are characterized by large increases in net primary productivity in response to changes in resource availability (Smith et al. 1997). Deserts were also predicted to exhibit increased productivity in response to rising atmospheric CO₂ concentration ([CO₂]), perhaps more than any other biome type (Melillo et al. 1993 Nowak et al. 2004a, Smith et al. 2009a). Thus, desert ecosystems may impact the global C balance as [CO₂] increases into the future.

We established the Nevada Desert Free-Air Carbon Enrichment Facility (NDFF) to test the response of an arid ecosystem to elevated [CO₂]. The NDFF consisted of nine plots: three plots exposed to elevated [CO₂] using Free-Air Carbon Enrichment (FACE) technology (i.e., elevated [CO₂] treatment), three plots exposed to ambient [CO₂] with the FACE technology (i.e., ambient [CO₂]), and three plots exposed to ambient [CO₂] without the FACE technology (i.e., non-blower controls). Diameter of each plot was 25 m, but because the outer 1 m annulus of each plot was a buffer area, the effective area for sampling was 23 m in diameter. Experimental increases in [CO₂] began on April 28, 1997, and plots were exposed to the [CO₂] treatments until July 1, 2007.

This Final Report has two major sections and two appendices. The first section, “Major Findings”, succinctly summarizes the most important findings from the NDFF experiment and is organized by major ecosystem processes and components. The second section, “Site and Operations Summary”, summarizes important characteristics of the site, the experimental treatments, data sets obtained, and personnel involved. To keep the Major Findings section succinct, details of findings are presented in Appendices 1 and 2. Appendix 1 contains manuscripts that are in advanced stages of submission as well as short reports that present salient results from individual studies at the NDFF. Appendix 2 contains a comprehensive list of publications that utilized the NDFF for at least a portion of their study. Because the appendices cover many printed pages, they are provided only in electronic form. Finally, we note that although funding to construct, operate, and conduct research at the NDFF came from many different sources, this DOE grant (DE-FG02-03ER63651) provided a large proportion of the NDFF budget to decommission and compile results from the 10-year experiment. Thus, this

Final Report is comprehensive and includes research that was not originally supported by this DOE Grant.

I. Major Findings

1. *Ecosystem carbon*

1.1. *Net ecosystem production*

Significant C accumulation occurred in an intact, undisturbed arid ecosystem following ten years exposure to elevated [CO₂] (Evans et al. Ms#1). Total ecosystem C was 161 g C m⁻² greater under elevated compared to ambient [CO₂] over the 10-year experiment. The observed difference was due solely to differences in soil C; no differences were observed in above- and belowground plant C pools. This experiment provides the first direct measure of enhancements to net ecosystem productivity in arid ecosystems by exposure to [CO₂] levels predicted within the next 40-60 years. Estimates of the spatial extent of aridlands range from 2.65 X 10⁹ (Jobbagy and Jackson 2000) to 4.89 X 10⁹ ha (Lal 2004). Assuming that comparable responses will occur in similar arid ecosystems, we estimate that global enhancements to net ecosystem productivity will range from 0.43 to 0.78 Pg C y⁻¹ if atmospheric [CO₂] continues to increase towards concentrations used in this experiment. This global aridland enhancement of net ecosystem productivity in future atmospheres could therefore account for 5 – 10% of total current emissions of 8.4 Pg y⁻¹ and 18 – 33% of current estimates of total terrestrial uptake of 2.4 Pg y⁻¹.

Increased C accumulation under elevated [CO₂] is ultimately related in part to increased photosynthesis. Plants grown under elevated [CO₂] at the NDDF had photosynthetic rates from 1.3 to 2.0 times greater than those grown under ambient conditions (Section 6.1), and increased aboveground production were observed during wet years (Section 4). Plants grown under elevated [CO₂] also had decreased stomatal conductance to water vapor, although this response was more variable than that of photosynthesis (Section 6.2). Thus, plants grown under elevated [CO₂] increased photosynthesis while decreasing stomatal conductance, enhancing water-use efficiency as well as carbon gain during wet years when net primary production (NPP) was already high.

The observation that above- and belowground biomass were similar between treatments at final harvest (Newingham et al. Ms#3) may at first seem contradictory to enhanced photosynthesis and NPP under elevated [CO₂], but in fact it highlights an important mechanism for the observed increase in soil C. Arid ecosystems are characterized by large, rapid increases in NPP and standing biomass in response to increases in resource availability. The greatest differences in NPP and in annual and perennial growth under elevated [CO₂] at the NDDF occurred when moisture was most available. For example, integrated leaf-level carbon gain was 170 g C m⁻² y⁻¹ and 118 g C m⁻² y⁻¹ greater in wet and dry years under elevated [CO₂], respectively, for the dominant shrub *Larrea tridentata* (Housman et al. 2006). The final harvest at NDDF occurred during a dry summer, which indicates that although growth may be enhanced when moisture is available, the observed peaks in production that occur under elevated [CO₂] cannot be sustained during intervening drought. Hence, additional biomass under elevated [CO₂] is senesced, which increases C inputs into the soil as above- and belowground litter (Koyama et al. Ms#2). High rates of biomass turnover are common in arid ecosystems; Huenneke and Schlesinger (2006) estimated that aboveground biomass can turn over every 1.5 years.

Increased photosynthesis also may increase rhizodeposition, which represents an additional mechanism for increased C inputs under elevated [CO₂]. Plant photosynthates are deposited within rhizosphere microbial communities within 1 h of labeling a leaf with excess ¹³C (Jin and Evans 2010a), highlighting the tight linkage between plant photosynthesis and rhizodeposition in Mojave Desert plants. Field observations of increased mineral-bound soil organic C under elevated [CO₂] is consistent with increased rhizodeposition (Koyama et al. Ms#2). Because overall fine root production and loss are not significantly different between [CO₂] treatments at the NDDF (Section 4.4), root exudation may be a more important determinant of belowground carbon balance than input of fine root litter. Results at the NDDF are analogous to those of Pendall et al. (2004b) in the semiarid shortgrass steppe, where elevated [CO₂] stimulated rhizodeposition more than aboveground production.

1.2. Net ecosystem exchange

Although C accumulation occurred over the 10-year NDDF experiment, C accumulation was neither constant nor always greater under elevated [CO₂]. Net ecosystem exchange (NEE) of both ambient and elevated [CO₂] treatments were positive during 2004 (Jasoni et al. 2005) and 2005 (Arnone and Jasoni, unpublished data), which indicated that the Mojave Desert is accumulating C under current and future atmospheric [CO₂] conditions. However, NEE data indicated that ambient [CO₂] plots were accumulating C at a greater rate than elevated [CO₂] plots, which is contrary to the overall pattern of increased C under elevated [CO₂] from the detailed harvest data at the end of the experiment (Section 1.1). Although accurate NEE measurements in desert ecosystems are difficult to obtain (Wohlfahrt et al. 2009, 2013), NEE data indicate that C flux in the Mojave Desert is an extremely dynamic process that possibly changes in both magnitude and relative effects of [CO₂], depending on precipitation.

1.3. Soil CO₂ flux

Soil CO₂ efflux under elevated and ambient [CO₂] were measured using static soil respiration cuvettes drawing a continuous stream of air of which CO₂ concentrations were measured every 6 minutes using infra-red gas analyzers. Cuvettes were positioned in three microsites (under the canopy of the evergreen shrub *Larrea tridentata*, under the canopy of the deciduous shrub *Ambrosia dumosa*, and in the interspace area among perennial plants). Soil CO₂ flux was spatially and temporally variable (Nowak et al Rep#2), with highest fluxes during spring – early summer and under plant canopies, especially from soil under the evergreen shrub *L. tridentata*. Elevated [CO₂] increased soil respiration rates, although the extent of the increase varied over time and among different microsites (Nowak et al. Rep#2, Billings et al. 2004). Soil CO₂ flux responded rapidly and positively to rain in both field observations (Nowak et al. Rep#2) and modeling studies (Shen et al. 2009). Soil CO₂ flux in the Mojave Desert differed from that in other arid ecosystems by having lower magnitude rates, greater sensitivity to temperature, and sensitivity only to current soil moisture conditions (Cable et al. 2011). These results suggest that increases in C assimilation and accumulation due to elevated [CO₂] may be partially offset by increased CO₂ effluxes from increased soil respiration in a Mojave Desert ecosystem.

2. *Ecosystem nitrogen pools and fluxes*

Total ecosystem nitrogen (N) was significantly greater under elevated [CO₂] across all community microsites, and total ecosystem N was 25 g N m⁻² greater under elevated compared to ambient [CO₂] (Evans et al. Ms#1). This greater ecosystem nitrogen must result from increased nitrogen inputs into the ecosystem or from greater retention of nitrogen through decreases in volatilization, nitrification, or denitrification. The primary sources of nitrogen input at the NDDF are nitrogen fixation by higher plants and by biological soil crusts. Increased rates of heterotrophic N₂ fixation occurred under elevated [CO₂] (Billings et al. 2003a, Schaeffer et al. 2007), but increased N₂ fixation rates were not great enough to solely account for the observed differences between treatments (Koyama et al. Ms#2). Although rates of N input in arid ecosystems are thought to be balanced by similar rates of gaseous loss (Peterjohn and Schlesinger 1990), elevated [CO₂] has the potential to increase total ecosystem N over time by increasing rates of N retention by plants and microbes, thereby decreasing rates of gaseous loss (Schaeffer et al. 2003, Sondergerger et al. Ms#8). This hypothesis has been supported by experimentation: volatilization is the primary source of N loss in the Mojave Desert (Billings et al. 2002a, McCalley and Sparks 2008, 2009), and C addition as labile C (McCalley and Sparks 2008) or under elevated [CO₂] (Schaeffer et al. 2003) greatly decreases gaseous N emissions.

The progressive nitrogen limitation hypothesis predicts that nitrogen limitations to NPP will increase as ecosystems accumulate C (Luo et al. 2004), but progressive nitrogen limitation has not been observed at the NDDF. Results from [CO₂] enhancement and direct C additions demonstrate that microbial activity at the NDDF is limited by available C (Schaeffer et al. 2003, 2007), and increased C inputs regardless of the C source accelerated rates of soil nitrogen transformations, thus increasing rates of nitrogen mineralization and inorganic N availability (Billings et al. 2002a, 2004, Jin and Evans 2007, Jin et al. 2011). Soil organic matter in arid ecosystems is composed largely of recalcitrant substrates (Billings and Evans 2004) that resist microbial breakdown. Increased litter and rhizodeposition under elevated [CO₂] increased overall fungal biomass and diversity (Jin and Evans 2010a, Nguyen et al. 2011), and these fungi are better able to utilize recalcitrant substrates. Concurrent with this increase in fungal abundance and diversity is an increase in the diversity of substrates used by the microbial community as well as in activities of enzymes involved in N and C cycling (Jin and Evans 2007, Jin et al. 2011), which may further increase gross rates of nitrogen production in the soil.

3. *Ecosystem water*

Numerous studies, including those of desert plants, have shown reduced stomatal conductance under elevated [CO₂]. As a consequence, soil water has been postulated to increase. At the NDDF, soil water was measured in the top 0.2 and 0.5 m of soil with time domain reflectometry and to 1.85 m with a neutron probe (Nowak et al. 2004b). Soil water was measured for most of the duration of the NDDF experiment at each of the three treatments (elevated [CO₂], ambient [CO₂], and non-blower controls). Overall, elevated [CO₂] did not conserve soil water for the desert scrub community in the Mojave Desert. The expected greater soil water under elevated [CO₂] only occurred on a small percentage of dates, whereas soil water was significantly lower under elevated CO₂ on a greater number of dates. Thus, we infer that increased water use from increased primary productivity (and therefore leaf area) under elevated [CO₂] coupled with slightly longer plant growth periods under elevated [CO₂] offset the decreased water use from

reduced stomatal conductance, and hence soil water was not conserved under elevated $[\text{CO}_2]$ in the Mojave Desert, unlike other ecosystems.

4. **Biomass and production**

4.1. *Final harvest standing crop*

Aboveground and belowground perennial plant biomass was harvested in an intact Mojave Desert ecosystem at the end of the ten-year elevated $[\text{CO}_2]$, NDDFF experiment (Newingham et al. Ms#3). We measured community standing biomass, biomass allocation, canopy cover, leaf area index (LAI), carbon and nitrogen content, and C and N isotopic composition of plant tissues for five to eight dominant species. Our results provide the first long-term results of elevated $[\text{CO}_2]$ on biomass components of a desert ecosystem and offer information on understudied Mojave Desert species. In contrast to initial expectations, ten years of elevated $[\text{CO}_2]$ had no significant effect on standing biomass, biomass allocation, canopy cover, and C:N ratios of above- and belowground components. However, elevated $[\text{CO}_2]$ increased short-term responses, including leaf intrinsic water-use efficiency and plot-level LAI. Standing biomass, biomass allocation, canopy cover, and C:N ratios of above- and belowground pools significantly differed among dominant species, but responses to elevated $[\text{CO}_2]$ did not vary among species, photosynthetic pathway (C_3 vs. C_4) or growth form (drought-deciduous shrub vs. evergreen shrub vs. grass). Thus, even though previous and current results show that leaf-level photosynthetic rates, water-use efficiency, LAI, and plant growth all increased during at least a portion of the 10-year experiment, most responses were in wet years and did not lead to sustained increases in community biomass over drought cycles. The lack of sustained biomass responses to elevated $[\text{CO}_2]$ is best explained by inter-annual differences in water availability. Therefore, the high frequency of low precipitation years will likely constrain cumulative biomass responses to elevated $[\text{CO}_2]$ in desert environments.

4.2. *Perennial shoot growth and production*

Perennial plant growth in the Mojave Desert is driven primarily by precipitation and hence water availability. Therefore, we predicted the effects of elevated $[\text{CO}_2]$ on plant growth would depend on precipitation. Indeed, at the beginning of the NDDFF experiment, elevated $[\text{CO}_2]$ increased perennial plant growth by 1.6 to >2.3 fold in a wet year 1998 (2.4 fold increased precipitation over long-term mean) but rarely in subsequent dry (below mean precipitation) years (Smith et al. 2000, Housman et al. 2006). During the second wettest year of the experiment (2005; 1.7 fold increased precipitation), elevated $[\text{CO}_2]$ tended to increase *Larrea tridentata* stem elongation, *Lycium pallidum* long shoot production, and *Pleuraphis rigida* leaf production and stem length; however, these growth increases were not statistically significant (Newingham et al. Ms#5). Litter production during the NDDFF experiment is consistent with these observations: significantly increased litter production under elevated $[\text{CO}_2]$ for *Larrea* only occurred following the wet year 1998 (Nowak et al. Rep#1). Thus, the threshold for significant increases in perennial plant growth with elevated $[\text{CO}_2]$ appear to be rather large for Mojave Desert vegetation.

4.3. *Annual plant growth and production*

Responses of annual plant growth to elevated $[\text{CO}_2]$ in the Mojave Desert are also greatly influenced by precipitation as well as by soil fertility, especially soil N (Smith et al. 2000). During the wet year 1998, a large number of annual plants germinated at the NDDFF during the

winter months. Four species of annuals — *Bromus madritensis* ssp. *rubens*, *Eriogonum trichopes*, *Lepidium lasiocarpum*, and *Vulpia octoflora* — constituted over 70% of the total density of annuals in the plots and so were selected for detailed study. *Bromus* (red brome) is an exotic annual grass that has invaded many areas of the Mojave Desert; the other three taxa are native annuals. Total density of the native annuals was 42% lower but total aboveground biomass was 40% higher at elevated [CO₂] compared to ambient [CO₂], with the net result that individual plants were 2.4 times larger at elevated [CO₂]. For *Bromus*, plant density and biomass increased by 50% and 130%, respectively, at elevated [CO₂], with the net result that individual plants were 53% larger at elevated [CO₂]. *Bromus* also exhibited a 3-fold higher total seed rain at the plot level under elevated [CO₂], and *Bromus* density, biomass, and seed rain were all greater in the high N, fertile microsites under canopies of perennial plants than in the open interspace microsites among perennial plants. Differences in plant density were not due to differences in seed germination or in seed banks but to natural self-thinning between germination and peak biomass. A significant reduction in the energetic cost of aboveground biomass construction under elevated [CO₂] for *Bromus* compared to *Vulpia* may have allowed *Bromus* to grow faster, grow bigger, and ultimately produce more seed (Nagel et al. 2004).

We continued to monitor annual plant production during the NDFP experiment, and most annual species increased in size at elevated compared to ambient [CO₂] when precipitation was sufficient for adequate annual seedling establishment and growth (Smith et al. Ms#6). The extent of increased size varied among annuals, and the increase in total biomass was a function of species-specific changes in allocation to leaf and reproductive structures. Elevated [CO₂] accelerated phenology in the dominant forb and grass species, and seed number per unit leaf area also increased in the wet year. However, at the community level, total annual plant biomass and individual plant reproductive allocation were not enhanced at elevated [CO₂] over the whole 10-year experiment.

The invasive annual grass *Bromus* had interesting responses to elevated [CO₂] in addition to the very positive growth and seed rain responses at the NDFP during the wet year 1998. Seeds of *Bromus* developed on parents grown in elevated [CO₂] had a larger pericarp surface area, higher C:N ratio, smaller seed reserves, and less total mass than ambient-developed seeds (Huxman et al. 1998), but parental [CO₂] environment did not affect germination percentage or mean germination time. Seedlings from elevated [CO₂] parents had reduced relative growth rate and achieved smaller final mass over the same growth period. Thus, increased seed C:N ratios associated with plants grown under elevated [CO₂] likely affected seed quality (morphology, nutrition) and seedling performance (growth rate, leaf production). Because invasion of *Bromus* is primarily due to its ability to rapidly germinate, increase leaf area, and maintain a relatively high growth rate compared to native annuals and perennials, reductions in seed quality and seedling performance under elevated [CO₂] may temper the very positive growth and seed rain effects observed during the wet year 1998. In addition, cycles of wet and dry years, which are important for how elevated [CO₂] affects perennial plant production (Section 4.2), can also influence annual plant dynamics independent of elevated [CO₂]. Following the wet year 1998, the winter-spring of 1999 was dry, and no annual plants germinated (Smith et al. 2000, Ms#6). Winter rains queued seed germination for the following growing season (the year 2000), but a complete lack of spring rains in 2000 resulted in very high density but little seed production, and *Bromus* largely disappeared from the annual community until 2005, whereas native annuals

continued to germinate and grow during those intervening years. Starting in 2005, *Bromus* again became a major component of the annual plant community and exhibited much higher relative density in the soil seed bank at elevated [CO₂] at the end of the experiment. The conclusion from our observations of annuals in this system is that the effect of elevated [CO₂] will depend on future precipitation – if the climate gets wetter we would expect the exotic *Bromus* to become more dominant in the community, but if it becomes drier we predict that native annuals will have an advantage over the exotic grasses.

4.4. *Fine root growth and production*

Overall, elevated [CO₂] did not significantly affect fine root production, loss, standing crop, turnover, persistence, or depth distribution at the NDFP (Phillips et al. 2006, Ferguson and Nowak 2011). In controlled glasshouse experiments, increased root biomass was only observed for one of three grass species grown from seed (Yoder et al. 2000). Thus, growth and production of fine roots for Mojave Desert species under current ambient [CO₂] appear to be adequate to supply plants with sufficient soil resources, such as water and nutrients, to meet growth demands when grown under elevated [CO₂].

Although the overall [CO₂] effect was not significant, two transitory [CO₂] effects occurred: earlier peaks in fine root production and greater amount of fine root production in shallow soils for the plant community during an above-average precipitation year. These two transitory effect, however, are ecologically important. Growth of both annuals and perennials (Sections 4.2, 4.3) were accelerated under elevated [CO₂] in wet years. Increased C assimilation in these wetter years (Section 6.1) coupled with earlier fine root growth help provide carbon, water, and nutrient resources needed to sustain earlier growth. These transitory [CO₂] effects are related to how elevated [CO₂] interacts with past environmental (e.g., antecedent soil water) and biological (e.g. biological inertia) factors to affect fine-root dynamics (Sonderregger et al. Ms#7). Elevated [CO₂] interacted with antecedent soil moisture to have significantly greater effects on fine-root dynamics during certain phenological periods. With respect to biological inertia, plants under elevated [CO₂] tended to initiate fine-root growth sooner and sustain growth longer, with the net effect of increasing the magnitude of production and mortality cycles. Such interactions are expected to be important for predicting future fine root dynamics, and hence soil carbon pools.

4.5. *Community cover and richness*

We used allometric relationships between canopy volume and biomass to estimate perennial plant biomass at the beginning and end of the ten-year experiment. Additionally, we evaluated the effects of elevated [CO₂] on cover, biomass, species richness, and species diversity. First, elevated [CO₂] did not affect allometric relationships between canopy volume and biomass for 20 perennial species (Vanier et al. Ms#9). Contrary to expectations, cover, biomass, richness, and diversity were not affected by elevated [CO₂] (Newingham et al Ms#4). Over the course of the ten year experiment, all but biomass declined, which may be due to prolonged drought conditions. The proportional representation of *Larrea tridentata* biomass increased in elevated [CO₂] plots from 1997-2007. *Pleuraphis rigida*'s proportional biomass decreased in non-blower and ambient [CO₂] plots and did not change over the ten years in elevated [CO₂] plots.

Also contrary to predictions, C₃ species did not benefit more from elevated [CO₂] than C₄ species. Extended drought, slow growing species, and conservative life history strategies may

explain the lack of strong perennial plant community responses to elevated [CO₂] in this desert ecosystem.

5. *Soil microbes*

5.1. *Soil microbial communities*

Microbial community structure in NDFF soils changed under elevated [CO₂], primarily because of changes in fungal components of the soil microbial community. NDFF soils under elevated [CO₂] had increased fungal biomass, increased richness of fungal communities, and increased abundance of fungi relative to bacteria (Jin et al. 2010a, Jin et al. 2011, Weber et al. 2011) whereas soil bacterial abundance and diversity were not significantly affected (Dunbar et al. 2012). Similar shifts to greater fungi and fewer bacteria was also observed in rhizosphere soil (Nguyen et al. 2011). However, no evidence was found for increase mycorrhizae under elevated [CO₂] (Clark et al. 2009). These shifts in functional composition of soil microbial community likely underlie the observed changes in N cycling at the NDFF (Section 2). These shifts to greater fungal dominance may also influence C accumulation: although increased abundance and diversity of cellulolytic fungi may increase utilization of some recalcitrant soil C, fungi also produce many degradation-resistant organic products that may increase C sequestration in desert soils.

5.2. *Biological soil crust*

Although the soil microbial communities discussed in Section 5.1 are important for soil C and N processes across many ecosystems, biological soil crusts are also important at the NDFF, especially for their effects on heterotrophic N₂ fixation and net ecosystem C exchange. Biological soil crusts are comprised of many different cyanobacteria, algae, fungi, lichens, and bryophytes, and these organisms have different influences on soil characteristics and ecosystem functions. Cyanobacteria in arid ecosystems are important for stabilizing the soil surface, fixing C, and fixing N₂. Quantitative PCR surveys of soils near the end of the NDFF experiment indicated that cyanobacteria biomass decreased under elevated [CO₂] and that this decrease occurred across the majority of cyanobacterial genomes tested (Steven et al. 2012). Decreased cyanobacteria under elevated [CO₂] in desert ecosystems may have deleterious effects, especially on soil stability and N₂ fixation. Mosses, which are important for soil stability and C assimilation, also are slightly smaller under elevated [CO₂] (Brinda et al. 2011). However, smaller mosses under elevated [CO₂] does not lead to decreased sexual or asexual reproduction, presumably because the extra C assimilated under elevated [CO₂] allows smaller mosses to grow as well as the larger mosses under ambient [CO₂]. Furthermore, mosses growing under elevated [CO₂] have greater tolerance to both water (desiccation) and temperature stress (Brinda et al. 2011, Coe et al. 2012). Overall, the effects of elevated [CO₂] on biological soil crust at the NDFF is analogous to what is observed for vegetation: drought conditions adversely affect crust cover and biomass regardless of [CO₂] treatment, although physiological processes benefit by elevated [CO₂] (Wertin et al. 2012).

6. *Physiological responses*

6.1. *Photosynthesis and carbon allocation*

Leaf net assimilation rates consistently have increased under elevated $[\text{CO}_2]$ during relatively wet conditions, regardless of when during the NDDF experiment that measurements were made or what species was measured (Huxman et al. 1998b, 1998c, Hamerlynck et al. 2000a, 2000b, Loik et al. 2000, Taub et al. 2000, Huxman and Smith 2001, Huxman et al. 2001, Hamerlynck et al. 2002, Housman et al. 2003, Naumberg et al. 2003, Ellsworth et al. 2004, Nagel et al. 2004, Naumberg et al. 2004, Aranjuelo et al. 2011). Photosynthetic enhancements with elevated $[\text{CO}_2]$ decrease as soil water availability declines, although the sensitivity to soil water differs among species, with some species such as *Larrea tridentata* maintaining photosynthetic enhancements over a greater range of declining soil water than other species. In annuals, photosynthetic enhancement occurred throughout the developmental cycle in an invasive grass, but only early in the season in a native forb (Huxman & Smith 2001). We suggest two reasons to explain why persistent down-regulation and acclimation of photosynthesis has not been observed at the NDDF. First, maintaining adequate N allocation to leaves helps prevent photosynthetic down regulation in plant species (Ellsworth et al. 2004), and greater N cycling and availability (see Section 2) allows desert species to allocate sufficient N to leaves. Second, desert species such as *Larrea* are able to activate growth earlier and maintain growth longer of both shoots and roots, and these active C sinks reduce the potential for end-product down regulation of photosynthesis (Aranjuelo et al. 2011).

6.2. *Leaf conductance and leaf water use efficiency*

Direct measurements of leaf conductance at the NDDF have shown variable responses to elevated $[\text{CO}_2]$, with some studies finding no or little stomatal closure under elevated $[\text{CO}_2]$ (Hamerlynck et al. 2000b, Huxman and Smith 2001, Aranjuelo et al. 2011) and others finding that stomatal closure was small-to-moderate with high water availability but differences between elevated and ambient $[\text{CO}_2]$ decreased as water availability decreased (Nowak et al. 2001, Hamerlynck et al. 2002, Naumberg et al. 2003). Leaf stomatal characteristics such as stomatal index, stomatal density, and stomatal aperture were not significantly different between leaves from plants grown at ambient and elevated $[\text{CO}_2]$ at the NDDF as well as other FACE sites (Reid et al. 2003).

Deserts have been hypothesized to have among the largest responses to elevated $[\text{CO}_2]$ because anticipated increases in assimilation and decreases in leaf conductance would combine to greatly increase water use efficiency in these water-limited environments (Strain and Bazzaz 1983, Mellilo et al. 1993). Our field observations for assimilation (Section 6.1) and conductance indicate that most species had time periods of increased instantaneous leaf water use efficiency, although these observed increases in water use efficiency were only occasionally due to both increased assimilation and decreased conductance; most often, increased water use efficiency was due primarily to increased assimilation rates. Nonetheless, recent analyses of C stable isotope discrimination from a time series of leaf collections during the entire experiment (Sonderregger et al. Ms#8) as well as from the final plot harvests (Newingham et al. Ms#3) indicate that leaf intrinsic water use efficiency integrated over the time period of leaf construction was significantly increased throughout the experiment and across all species.

6.3. *Root physiology*

In situ measurements of fine root physiology at the NDFP were difficult because of the sparseness of fine roots coupled with the desire to minimize plot disturbance. Extensive measurement of fine root respiration indicated no overall significant effect of elevated [CO₂] (Clark et al. 2010), and controlled-environment glasshouse studies had similar results (Yoder et al. 2000). Root N uptake varied among species in controlled-environment studies, with grass species having no or slightly decreased N uptake rates under elevated [CO₂] (Yoder et al. 2000). In contrast, *L. tridentata* had greater uptake of both organic and inorganic forms of N under elevated [CO₂] (Jin et al. 2010b).

II. Site and Operations Summary

1. Site biological and physical characteristics

1.1 Pretreatment vegetation

Table 1. Number of individual plants in each of the major perennial growth forms recorded in April 1997 at the beginning of the NDFFF experiment for each of the study plots. The last column shows the total number of perennial plants per plot and the total number of perennial plant species per plot. The last row shows the percentages of individual plants that each growth form contributed to the total number of perennial plants averaged over all plots. No treatment mean for any growth form was significantly different from any other. (from Jordan et al. 1999).

Plot number	Evergreen shrubs	Deciduous shrubs	Perennial grasses	Cacti	Perennial forbs	Individuals/ species
CO₂ enriched						
1	35	236	286	3	33	593/19
2	29	117	275	3	84	508/18
3	34	209	425	1	31	700/17
Mean ± SE	33 ± 3	187 ± 62	329 ± 84	2 ± 1	49 ± 29	578 ± 120
Blower controls						
4	46	209	248	2	150	655/20
5	19	85	332	0	20	456/13
6	27	91	270	2	21	411/19
Mean ± SE	31 ± 14	128 ± 70	283 ± 44	1 ± 1	64 ± 75	464 ± 75
Non-blower controls						
7	38	143	374	3	69	627/16
8	29	73	354	0	38	494/13
9	35	132	314	0	21	502/14
Mean ± SE	34 ± 6	116 ± 38	347 ± 31	1 ± 1	42 ± 25	541 ± 76
Overall mean	32 ± 8	144 ± 58	320 ± 57	2 ± 1	52 ± 49	549 ± 98
Percentage	6%	26%	58%	<1%	10%	

1.2 Arrangement of plots

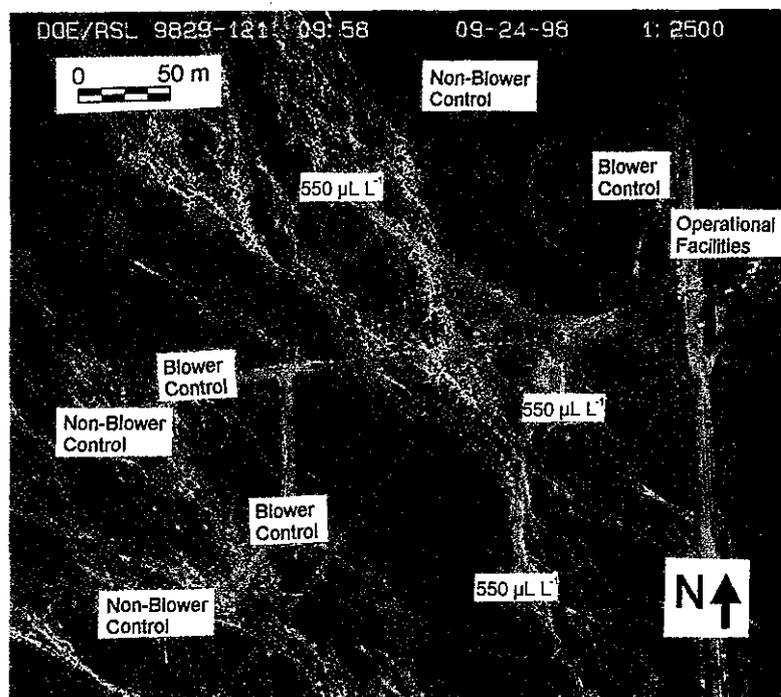


Fig. 1 Aerial photo of Nevada Desert FACE Facility. Octagonal black plenum and aerial access systems are visible at treatment plots and blower control plots. Non-blower control plots are not as clearly delineated, as they lack the black piping, but the walkway system remains clearly visible. (from Jordan et al. 1999)

1.3 Soil analyses

Table 2. Soil texture at 3 soil depth increments for each plot at the NDDF. Soil samples collected from the center of each plot during construction of the center pivot elevated sampling platforms.

Plot	Treatment	Depth	% sand (>62.5 µm)	% silt		% clay (<3 µm)	Texture class
				(15 µm)	(3 µm)		
1	Elevated	0-30	87.1	7.3	3.0	2.6	Sand /Loamy sand
		30-50	89.1	5.5	2.8	2.6	Sand
		50-100	89.6	4.9	2.9	2.7	Sand
2	Elevated	0-30	83.2	7.1	5.0	4.6	Loamy sand
		30-50	84.3	6.1	4.9	4.8	Loamy sand
		50-100	92.5	2.6	2.7	2.2	Sand
3	Elevated	0-30	85.9	7.4	3.6	3.1	Loamy sand
		30-50	85.2	6.7	4.3	3.8	Loamy sand
		50-100	91.6	3.2	2.6	2.5	Sand
4	Ambient	0-30	89.4	4.5	3.0	3.0	Sand
		30-50	94.0	1.9	1.9	2.1	Sand
		50-100	88.3	5.1	3.4	3.2	Sand
5	Ambient	0-30	81.6	9.2	4.9	4.3	Loamy sand
		30-50	81.5	9.1	5.5	4.0	Loamy sand
		50-100	78.0	11.8	5.7	4.5	Loamy sand
6	Ambient	0-30	83.5	7.0	5.0	4.5	Loamy sand / sandy loam
		30-50	84.6	6.6	4.7	4.0	Loamy sand
		50-100	84.5	7.4	4.4	3.7	Loamy sand
7	Non-blower	0-30	79.1	9.4	6.0	5.6	Loamy sand / sandy loam
		30-50	83.0	7.2	5.4	4.4	Loamy sand
		50-100	91.8	3.4	2.5	2.2	Sand
8	Non-blower	0-30	76.0	12.0	6.4	5.6	Loamy sand / sandy loam
		30-50	91.2	2.4	2.9	3.4	Sand
		50-100	84.9	7.2	4.4	3.6	Loamy sand/Sand
9	Non-blower	0-30	81.3	10.4	4.4	3.8	Loamy sand
		30-50	89.2	3.6	3.5	3.7	Sand
		50-100	86.4	4.1	4.2	5.4	Sand/Loamy sand

Table 3. Percentage rock by volume in the top 1 m of soil for each plot at the NDDF. Soil samples were collected during the root and soil destructive harvests at the end of the NDDF experiment.

Plot	Treatment	% rock
1	Elevated	47.8
2		46.0
3		50.2
4	Ambient	51.1
5		34.8
6		39.9
7	Non-blower	44.9
8		44.9
9		44.9

1.4 *Weather data*

Table 4. Total annual precipitation, mean annual temperature, mean minimum (December) and mean maximum (July) temperature at the NDFP for each hydrologic year (October 1 - September 30) over the ten year experimental period (1997-2007). The experiment commenced April 1997 and continued through June 2007. Note total annual precipitation for 2006-2007 only includes natural precipitation through June 2007, as well as an irrigation event on March 21, 2007.

Hydrologic Year	Total Annual Precipitation mm	Mean Annual Temperature °C	Mean Low Temperature °C (December)	Mean High Temperature °C (July)
1996-1997	151	15.6	-1.6	36.8
1997-1998	328	13.3	-5.2	37.4
1998-1999	107	13.8	-6.6	35.4
1999-2000	98	16.5	-5.4	38.3
2000-2001	102	15.8	-5.9	36.5
2001-2002	47	15.9	-4.3	39.9
2002-2003	149	16.2	-4.6	40.1
2003-2004	123	15.5	-4.6	37.5
2004-2005	242	15.1	-3.6	39.9
2005-2006	113	16.1	-5.0	39.5
2006-2007	65*	Na	-6.0	na
Average	146	15.4	-4.8	38.1

* Includes irrigation event on 3/21/2007

2. CO₂ control and treatments

Table 5. Performance metrics of the NDFFF CO₂ treatments from 1997 to 2007. The column “% Fumigation Scheduled” is the percentage of time that the FACE system was operating when air temperature was above and wind speed was below their respective thresholds (Note: daytime solar altitude threshold added November 2006). “[CO₂] During Fumigation” is the average CO₂ concentration in ppm (± standard deviation) during the time periods when the fumigation system was operating. “% Fumigation Total” is the percentage of all time that the FACE system was fumigating. “[CO₂] Total” is the average CO₂ concentration in ppm (± standard deviation) during all time periods. “Ambient Air [CO₂]” is the average CO₂ concentration of ambient air in ppm (± standard deviation).

Notes:

* Results for 2007 are for the period before 1 July 2007 when fumigation ended.

** Results for 1997 are for the period after 28 April 1997 when fumigation was initiated.

Year	% Fumigation Scheduled	[CO ₂] During Fumigation	% Fumigation Total	[CO ₂] Total	Ambient Air [CO ₂]
2007*	99.8	549.3 ± 37.7	47.3	463.6 ± 84.8	379.0 ± 5.1
2006	99.7	550.2 ± 34.2	76.5	510.4 ± 74.6	376.0 ± 6.7
2005	98.1	550.2 ± 32.8	81.7	520.7 ± 63.2	376.0 ± 7.4
2004	99.2	549.7 ± 31.6	81.5	518.2 ± 63.6	373.1 ± 6.6
2003	98.4	549.7 ± 31.3	80.6	517.2 ± 62.5	369.4 ± 6.7
2002	98.8	550.2 ± 30.4	78.1	512.3 ± 66.7	367.3 ± 8.8
2001	98.8	550.3 ± 32.2	81.2	517.5 ± 64.7	380.5 ± 10.8
2000	99.5	550.6 ± 34.7	82.0	519.2 ± 64.9	381.3 ± 13.7
1999	99.8	550.1 ± 33.7	79.3	514.8 ± 65.5	378.1 ± 11.8
1998	98.6	550.0 ± 33.8	78.1	513.9 ± 63.8	377.7 ± 10.9
1997**	98.7	550.1 ± 34.9	78.8	512.2 ± 72.5	371.2 ± 9.7

3. Data sets

Table 6. List of major data sets that were collected at the NDFF. At the time of this final report preparation, most of the data sets have been centrally archived and are available to the scientific community.

Ecosystem Component	Years	Ecosystem Component	Years
Environmental		Soil measurements	
Temperature	97-08	Particle size and texture	97
Precipitation	96-06	Texture	97
Net radiation	97-08	Inorganic N	98-09
Water/CO ₂ flux	97-08	Bulk density	00
Soil heat flux	97-08	Potential mineralization	02
Soil WC (TDR)	97-05	Labile and recalcitrant N	02
Soil WC (Neutron Probe)	99-08	Crust δ ¹³ C and δ ¹⁵ N	99-01
Soil temperature	99-01		
Plant measurements		Final harvest	
Diurnal gas exchange (5 species)	98-05	Perennial cover by species	
Water potential (5 species)		Perennial biomass by species	
98-05		Perennial C,N, δ ¹³ C, δ ¹⁵ N for some species	
Shoot growth (5 species)	98-02	Crust cover	
Annual biomass and density	98-05	Crust C,N, δ ¹³ C, δ ¹⁵ N	
Leaf δ ¹³ C and δ ¹⁵ N	98-04	Soil mass to 1m	
Litter biomass	98-08	Soil C, N, δ ¹³ C, δ ¹⁵ N to 1m	
Litter chemistry	00	Root biomass, C, N, δ ¹³ C, δ ¹⁵ N by species	
Fine root turnover, standing crop	98,99,03-07		
Root respiration	01-06		
Ecosystem gas exchange			
Soil respiration - continuous	03-05		
Soil respiration - seasonal	99-01		
Potential denitrification	99-01		
Volatilization	99-01		
N ₂ O	99-01		
Crust N ₂ fixation	99-01		

4. Personnel

Numerous internal (Nevada-lead grant recipients) and external researchers, staff and students were supported throughout the lifespan of NDFF (1996-2012) by several research grants from DOE, NSF, TECO, USGS and individual universities. In addition, several university classes and tour groups benefitted from visits to observe research being conducted at NDFF. Table 7 below summarizes the number of people supporting research at NDFF and visiting NDFF throughout its history. Early data for the years 1997-2002 are not readily available for each year, but a summary for that 5-year time period was extracted from a previous report. In some instances, a single researcher had two or more grants, and therefore the total number of principle investigators (PIs) and co-principle investigators (Co-PIs) may include multiple counts for the same person to better reflect the amount of research being conducted. The total number of PIs and Co-PIs but counting each person only once regardless of number of grants is provided in parentheses.

Table 7. The total number of research personnel and visitors at NDFFF are summarized below for the period 1997-2002 and for each year individually after 2002. In the PI and Co-PI columns, the total number for each grant is listed first and in parentheses, the total but counting each PI or Co-PI only once is listed. The total number of people working at or visiting NDFFF is provided in the final column (each person only counted one time).

<i>Year</i>	<i>PIs</i>	<i>Co-PIs</i>	<i>Staff</i>	<i>PostDocs</i>	<i>Grad Students</i>	<i>Students</i>	<i>Visitors</i>	<i>Total</i>
1997-2002	19 (15)	30 (16)	12	13	16	59	78	209
2003	9 (8)	12 (7)	7	5	10	10	88	135
2004	12 (11)	15 (10)	7	4	11	10	59	112
2005	16 (14)	18 (11)	16	5	12	13	27	98
2006	13 (10)	17 (11)	11	3	7	4	121	167
2007	12 (10)	14 (11)	6	3	5	7	42	84
2008	3	5	6	3	3	4	21	45
2009	2	5	3	3	2	14	21	50
2010	1	5	2	2	0	11	5	26
2011	1	5	2	1	0	1	8	18
2012	1	5	1	0	0	0	6	13

5. *Site decommissioning*

NDFFF decommissioning has been completed according to the plan prepared for and approved by the National Nuclear Security Administration (NNSA) personnel overseeing the real estate operations permit (REOP) and infrastructure efforts for NDFFF. The key NDFFF decommissioning activities included: dismantling, separation and storage of equipment and materials that were in good condition and could be used for other FACE efforts; identification and removal of all other good condition materials to UNR, UNLV and DRI; and removal of all other materials to the NNSS landfill or scrap metal recyclers. Materials were sorted by the NDFFF Operations Manager based on his knowledge of the equipment age, condition and potential usefulness for other projects. Other efforts related to NDFFF decommissioning during this time period included: meeting all NNSA security, safety and training requirements for continued operation on the Nevada National Security Site (NNSS, formerly the Nevada Test Site); development and NNSA approval of a NDFFF decommissioning plan; renewal of the NDFFF REOP; mandated documentation of NDFFF material history; completion of radiological surveys prior to material removal; and implementation of NDFFF plot restoration. The following sections address the completion of these goals.

5.1 *Site disposition*

As described in the decommissioning plan approved by NNSA some of the NDFFF infrastructure will remain in place permanently and some will remain in place until it is determined that the materials/equipment will not be needed for future research. The items that will remain permanently in place include: buried power, cable and CO₂ gas lines; the concrete center pivot for each plot; the NDFFF trailer, garage and cargo container used for storage. The items that will remain in place for the near term include: the CO₂ tank and vaporizers; the sampling platform

and a portion of the steel track for platform movement; and research infrastructure that is still maintained within the unharvested portion of each plot. Maintaining the NDFF REOP and preserving the unharvested portion of each plot indefinitely into the future will ensure the area is protected for any potential research, sampling and analysis.

5.2 Equipment and materials disposition

Prior to the removal of materials from NDFF, the NNSA Site Monitoring Services Office (RadOps) performed a random radiological survey of NDFF equipment and materials to ensure that project related items at NDFF had not been exposed to radioactive contamination. This is a mandatory requirement for all materials being removed from the NNSS regardless of location and use history. The history of each group/category of materials was documented and provided to Site Monitoring Services prior to the survey. The radiological survey confirmed that all NDFF materials had not experienced radioactive contamination and that the materials could be removed from the NNSS and disposed of as appropriate. The documented history along with the results of the radiological survey provided the necessary documentation to ensure that all materials were safe and posed no public health hazard.

A subset of materials that had been reserved for potential future use by BNL were either shipped to BNL or sold to the University of Western Sydney (USW) for use at their EucFACE facility. At the request of BNL, arrangements were made to ship all of the fiber optic communication boxes to BNL for use as spares at the Duke and Rhinelander FACE sites. We received permission from DOE OBER personnel (Dr. Mike Kuperberg and the DOE Contract Office) to sell this equipment and the purchase price covered the personnel, travel and shipping costs. Items sold to USW included CO₂ delivery system hardware for all rings (Kurz valves, flow sensors, DuTec I/O plexers and modules) plus some miscellaneous smaller items.

Some of the sensors and hardware have been moved to the University of Nevada, Reno (UNR), University of Nevada, Las Vegas (UNLV) and the Desert Research Institute (DRI) for other federally funded research projects. The sensors and hardware included items such as the LI-COR 6262/6252 IRGAs (two to each institution), Climatronix wind sensors, and miscellaneous office furniture, tools and supplies.

All other materials that will not remain in place at NDFF have either been transported to the NNSA approved landfill on the NNSS (four roll-off dump trailer loads) or to a local metal recycling facility (one roll-off dump trailer and a flatbed trailer load). A few office and miscellaneous construction supplies remain in the NDFF trailer and garage for potential future research. All of the NDFF decommissioning under this grant has been completed.

Literature Cited

Note: If a literature citation is not listed below, then the literature cited represents work that was done at the NDDFF, and hence is found in Appendices 1 and 2.

- Crevoisier C, Sweeney C, et al. (2010) Regional US carbon sinks from three-dimensional atmospheric CO₂ sampling. *Proceedings of the National Academy of Sciences of the United States of America* 107(43):18348-18353.
- Drigo B, Kowalchuk GA, et al. (2008) Climate change goes underground: effects of elevated atmospheric CO₂ on microbial community structure and activities in the rhizosphere. *Biology and Fertility of Soils* 44:667-679.
- Heimann M (2009) Searching out the sinks. *Nature Geoscience* 2:3-4.
- Houghton RA (2007) Balancing the global carbon budget. *Annual Review of Earth and Planetary Sciences* 35:313-347.
- Houghton RA, Hall F, et al. (2009) Importance of biomass in the global carbon cycle. *Journal of Geophysical Research-Biogeosciences* 114.
- Huenneke LF, Schlesinger WH (2006) Patterns of net primary production in Chihuahuan desert ecosystems. pp 232-46 *In:* Havstad KM, Huenneke L, Schlesinger WH, editors. *Structure and Function of a Chihuahuan Desert Ecosystem: The Jornada Basin Long-Term Ecological Research Site*. Oxford University Press, New York.
- Jobbagy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications* 10:423-436.
- Lal R (2004) Carbon sequestration in dryland ecosystems. *Environmental Management* 33:528-544.
- Luo Y, Su B, et al. (2004) Progressive nitrogen limitation of ecosystem responses to rising atmospheric carbon dioxide. *Bioscience* 54:731-739.
- McCalley CK, Sparks JP (2008) Controls over nitric oxide and ammonia emissions from Mojave Desert soils. *Oecologia* 156:871-881.
- McCalley CK, Sparks JP (2009) Abiotic gas formation drives nitrogen loss from a desert ecosystem. *Science* 326(5954):837-840.
- Melillo JM, McGuire AD, Kicklighter DW, Moore B III, Vorosmarty CJ, Schloss AL (1993) Global climate change and terrestrial net primary production. *Nature* 363:234-240.
- Pendall E, Mosier AR, et al. (2004) Rhizodeposition stimulated by elevated CO₂ in a semiarid grassland. *New Phytologist* 162:447-458.
- Peterjohn WT, Schlesinger WH (1990) Nitrogen loss from deserts in the southwestern United States. *Biogeochemistry* 10:67-79.
- Smith SD, Monson RK, Anderson JE (1997) *Physiological Ecology of North American Desert Plants*. Springer, 286 p.
- Strain BR, Bazzaz FA (1983) Terrestrial plant communities. pp 177-222 *In:* Lemon E. (ed) *CO₂ and plants: the response of plants to rising levels of carbon dioxide*. AAAS Symp 84. AAAS, Washington DC.

APPENDIX 1: Manuscripts and Reports

Below is a list of manuscripts and reports for the NDFF. This list includes manuscripts that are *in press*, accepted for publication, submitted for publication, and in preparation for publication. In addition, reports are included that summarize data and results that we anticipate will become portions of publications, but manuscripts are not sufficiently developed at this time. Electronic versions of each manuscript and report are included on the CD-ROM that accompanies this Final Report. Manuscripts and reports are listed in separate categories by lead author.

Manuscripts

1. Evans RD, Koyama A, Sonderegger DL, Charlet TN, Newingham BA, Fenstermaker LF, Harlow B, Ogle K, Smith SD, Nowak RS. Whole-ecosystem exposure to elevated CO₂ increases total ecosystem C in the Mojave Desert. *Nature* (in preparation).
2. Koyama A, Sonderegger DL, Evans RD. Mechanism of soil organic carbon and nitrogen accumulation in a Mojave Desert ecosystem after 10 years exposure to elevated carbon dioxide. *Ecological Monographs* (in preparation).
3. Newingham BA, Vanier CH, Charlet TN, Ogle K, Smith SD, Nowak RS. No cumulative effect of ten years of elevated CO₂ on perennial plant biomass components in the Mojave Desert. *Global Change Biology* (submitted).
4. Newingham BA, Vanier CH, Kelly LJ, Charlet TN, Smith SD. Plant community responses over ten years of elevated CO₂ in the Mojave Desert. *Ecology* (in preparation).
5. Newingham BA, Vanier CH, Smith SD. Elevated CO₂ does not affect seasonal growth and reproduction of three species in the Mojave Desert. *Oikos* (in preparation).
6. Smith SD, Charlet TN, Abella SR, Zitzer SF, Vanier CH, Huxman TE. Long-term response of a Mojave Desert winter-annual plant community to a whole ecosystem atmospheric CO₂ manipulation (FACE). *Ecology* (in preparation).
7. Sonderegger DL, Ogle K, Evans RD, Ferguson SD, Nowak RS. Temporal dynamics of fine roots under long-term exposure to elevated CO₂ in the Mojave Desert. *New Phytologist* (accepted).
8. Sonderegger DL, Billings SA, Jin V, Koyama A, Nowak RS, Ogle K, Evans RD. Leaf $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ as temporal integrators of biogeochemical processes at the Mojave Desert FACE experiment. *Oecologia* (in preparation).
9. Vanier CH, Newingham BA, Smith SD. Carbon dioxide enrichment does not alter mass:volume allometry of desert perennials. *Ecological Archives* (in preparation)

Reports

1. Nowak RS, de Soyza AG, Zitzer SF. Report: Elevated Atmospheric CO₂ effects on litter production at the Nevada Desert FACE Facility. *We plan to combine these litter*

production results with the full set of shoot growth data into a manuscript that examines annual shoot production and their subsequent senescence into litter during the 10-year experiment. We expect to use hierarchical Bayesian techniques to model effects of weather and elevated [CO₂] on these complementary data sets, i.e. how Mojave Desert plants grow shoots under different weather and [CO₂], and then how shoots are senesced and enter the litter pool. Authors for this manuscript will include Newingham and Ogle.

2. Nowak RS, Ogle K, de Soyza AG, Wells CE. Report: Elevated atmospheric CO₂ increases CO₂ efflux from soil in a Mojave Desert ecosystem. *This report highlights major findings from our measurements of soil CO₂ flux at the NDDF. Although increased soil CO₂ efflux under elevated [CO₂] is apparent from traditional data analyses, soil respiration is a complex process that is very dynamic in this ecosystem. Furthermore, elevated [CO₂] appears to interact with other factors in the environment, especially water availability. Based on our success in teasing out additional mechanistic effects from fine root dynamics using hierarchical Bayesian techniques, we initiated a series of Bayesian models to analyze the soil respiration data. To date the Bayesian approach has been promising, but additional analyses are needed.*

APPENDIX 2: Nevada Desert FACE Facility Peer-reviewed Publications

Below is a comprehensive list of all peer-reviewed publications for the NDDFF. Electronic versions of each publication are included on the CD-ROM that accompanies this Final Report. Publications are organized by year of publication.

2013

Wohlfahrt G, Widmoser P (2013) Can an energy balance model provide additional constraints on how to close the energy imbalance? *Agricultural and Forest Meteorology* 169:85-91.

2012

Coe KK, Belnap J, Grote EE, Sparks JP (2012) Physiological ecology of the desert biocrust moss *Syntrichia caninervis* following ten years exposure to elevated CO₂: evidence for enhanced photosynthetic thermotolerance. *Physiologia Plantarum* 144:346-356.

Dunbar J, SA Eichorst, LV Gallegos-Graves, S Silva, G Xie, NW Hengartner, RD Evans, BA Hungate, RB Jackson, JP Megonigal, CW Schadt, R Vilgalys, DR Zak, CR Kuske (2012) Common bacterial responses in six ecosystems exposed to ten years of elevated atmospheric carbon dioxide. *Environmental Microbiology* 14: 1145-1158.

Housman DC, Killingbeck KT, Evans RD, Charlet TN, Smith SD (2012) Foliar nutrient resorption in two Mojave Desert shrubs exposed to Free-Air CO₂ Enrichment (FACE). *Journal of Arid Environments* 78:26-32.

Steven B., Gallegos-Graves L, Yeager CM, Belnap J, Evans RD, Kuske CR (2012) Dryland biological soil crust cyanobacteria show unexpected decreases in abundance under long-term elevated CO₂. *Environmental Microbiology* 14:3247-3258.

Wertin TM, Phillips AL, Reed SC, Belnap J (2012) Elevated CO₂ did not mitigate the effect of a short-term drought on biological soil crusts. *Biology and Fertility of Soils* 48:797-805.

2011

Aranjuelo I, Ebbets AL, Evans RD, Tissue DT, Nogues S, van Gestel N, Ebbert V, Adams, WW III, Nowak RS, Smith SD. (2011). Photosynthetic and carbon allocation responses after long-term exposure to elevated [CO₂] in two Mojave Desert shrubs. *Oecologia* 167:339-354.

Brinda JC, Fernando C and Stark LR (2011) Ecology of bryophytes in Mojave Desert biological soil crusts: effects of elevated CO₂ on sex expression, stress tolerance, and productivity in the moss *Syntrichia caninervis* Mitt. Pages 169-189 in Tuba Z, Slack N, Stark L (eds.), *Bryophyte Ecology and Climate Change*. Cambridge University Press.

Cable JM, Ogle K, Lucas RW, Huxman TE, Loik ME, Smith SD, Tissue DT, Ewers BE, Pendall E, Welker JM, Charlet TN, Cleary M, Griffith A, Nowak RS, Rogers M, Steltzer H, Sullivan PF, van Gestel NC (2011). The temperature responses of soil respiration in deserts: a seven desert synthesis. *Biogeochemistry* DOI 10.1007/s10533-010-9448-z.

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