LETTER

Metagenomic analysis reveals a marked divergence in the structure of belowground microbial communities at elevated CO₂

Zhili He,† Meiying Xu,†‡ Ye Deng,† Sanghoon Kang,† Laurie Kellogg,† Liyou Wu,† Joy D. Van Nostrand,† Sarah E. Hobbie,¶ Peter B. Reich¶ and Jizhong Zhou†

†Institute for Environmental Genomics and Department of Botany and Microbiology, University of Oklahoma, Norman, OK 73019, USA
‡Guangdong Provincial Key Lab of Microbial Culture Collection and Application, Guangdong Institute of Microbiology, Guangzhou 510070, China
¶Department of Ecology, Evolution, and Behavior, University of Minnesota, St Paul, MN 55108, USA

*Correspondence: E-mail: jzhou@ou.edu
†Both contributed equally.

Abstract
Understanding the responses of biological communities to elevated CO₂ (eCO₂) is a central issue in ecology, but little is known about the influence of eCO₂ on the structure and functioning (and consequent feedbacks to plant productivity) of the belowground microbial community. Here, using metagenomic technologies, we showed that 10 years of field exposure of a grassland ecosystem to eCO₂ dramatically altered the structure and functional potential of soil microbial communities. Total microbial and bacterial biomass were significantly increased at eCO₂, but fungal biomass was unaffected. The structure of microbial communities was markedly different between ambient CO₂ (aCO₂) and eCO₂ as indicated by detrended correspondence analysis (DCA) of gene-based pyrosequencing data and functional gene array data. While the abundance of genes involved in decomposing recalcitrant C remained unchanged, those involved in labile C degradation and C and N fixation were significantly increased under eCO₂. Changes in microbial structure were significantly correlated with soil C and N contents and plant productivity. This study provides insights into potential activity of microbial community and associated feedback responses of terrestrial ecosystems to eCO₂.

Keywords
Ecosystem process, elevated CO₂, feedback, free air CO₂ enrichment, GeoChip, global climate change, metagenomics, phospholipid fatty acid, pyrosequencing, soil microbial community.

INTRODUCTION
The global atmospheric concentration of CO₂ has increased by >30% as the industrial revolution as a consequence of fossil fuel combustion and land-use changes (Houghton et al. 2001; Keeling & Whorf 2004). Such an increase will be much more rapid if fossil fuel emissions continue unabated and the terrestrial or oceanic carbon sinks weaken in the future (IPCC 2007). However, a robust prediction of future atmospheric CO₂ concentrations is hampered by uncertainties regarding the responses of the biosphere to eCO₂, especially belowground microbial communities, and the soil C and N cycling processes they mediate (Luo et al. 2006; Reich et al. 2006; van Groenigen et al. 2006; Carney et al. 2007; Gruber & Galloway 2008; Heimann & Reichstein 2008). Although the stimulating effects of eCO₂ on plant growth and primary productivity are well established (Reich et al. 2001; Ainsworth & Long 2005; Luo et al. 2006), its influences on belowground microbial communities are poorly understood and controversial (Walter et al. 2002; Parmesan & Yohe 2003; Heath et al. 2005; Carney et al. 2007; Gruber & Galloway 2008; Heimann & Reichstein 2008; Lesaunder et al. 2008; Austin et al. 2009). There is an active debate on whether eCO₂ leads to soil C loss (i.e. positive feedback to eCO₂) or sequestration (i.e. negative feedback) (Luo et al. 2006; Carney et al. 2007; Heimann & Reichstein 2008). In addition, it is uncertain whether the magnitude of eCO₂ fertilization is generally constrained by co-limitation by N supply (Reich et al. 2006) and/or whether
the stimulation of plant growth and productivity by eCO₂ can be sustained (Zak et al. 2003; Reich et al. 2006) because of progressively increasing N limitation at eCO₂.

As microorganisms mediate important biogeochemical cycles of C, N, phosphorus (P) and sulphur (S), and various metals, a robust prediction of future atmospheric CO₂ requires mechanistic understanding of how eCO₂ affects microbial community composition (van Groenigen et al. 2006; Carney et al. 2007). However, the responses of soil microbial communities to eCO₂ are poorly understood (Gruber & Galloway 2008) and controversial (Carney et al. 2007; Lesaulnier et al. 2008; Austin et al. 2009) because of their extreme complexity and limitations of conventional molecular microbial ecology approaches for characterizing them. Using conventional molecular biology approaches, the diversity and activity of the microbial community in response to eCO₂ has been shown to be increased (Sonnemann & Wolters 2005; Jossi et al. 2006; Lesaulnier et al. 2008), decreased (Horz et al. 2004; Carney et al. 2007), or unchanged (Austin et al. 2009; Loy et al. 2004; Chung et al. 2006; Gruter et al. 2006). The apparent disparity of microbial responses to eCO₂ could be caused partially by real differences among and complexity of various ecosystems, but likely also by differences among the methodologies used, such as terminal restriction fragment length polymorphism (T-RFLP), denaturing gradient gel electrophoresis (DGGE), 16S rRNA gene-based sequencing, enzyme activities, and phospholipid fatty acid (PLFA), which may resolve differences in the soil community caused by eCO₂ to differing degrees.

With the recent development and application of large-scale high throughput pyrosequencing-based (Sogin et al. 2006; Huber et al. 2007) and microarray-based (Brodie et al. 2006; He et al. 2007; Zhou et al. 2008; Wang et al. 2009) metagenomics technologies, community-wide spatial and temporal information on microbial community functional structure and potential activity can be rapidly obtained. Although the pyrosequencing-based approach is able to identify new sequences, it suffers from very high sensitivity to random sampling errors, dominant populations and contaminated non-target DNA, whereas the microarray-based approach does not suffer from these limitations (Zhou et al. 2008). Therefore, it will be ideal if both pyrosequencing- and array-based technologies are used in a complementary way. In addition, compared to phylogenetic gene arrays and 16S rRNA gene-based pyrosequencing approaches, functional gene arrays (e.g. GeoChip) are advantageous for detecting specific metabolic functions with quantitative and high-resolution characteristics (He et al. 2007; Zhou et al. 2008). For example, currently available GeoChip 2.0 contains >24 000 probes and covers >10 000 genes in 150 gene families involved in biogeochemical cycling of C, N, P and sulphur, and bioremediation of metals and organic contaminants (He et al. 2007).

In this study, we hypothesize: (1) that microbial community composition and structure will be altered because of both the increased inputs of C to soil and altered chemistry of those inputs under eCO₂ (Dijkstra et al. 2005; Adair et al. 2009), and (2) that various microbial functional groups (e.g. decomposers of recalcitrant C, C fixers, N fixers, denitrifiers) will respond differentially to eCO₂, and in particular we expect that genes related to C and N fixation and labile C degradation will be increased due to changed belowground availabilities of labile C and other resources. To test these hypotheses, integrated metagenomic approaches were used in concert with traditional microbiological approaches, which included GeoChip (He et al. 2007), pyrosequencing (Margulies et al. 2005; Hamady et al. 2008), EcoPlate, and PLFA approaches. This study was conducted in a multifactor free air CO₂ enrichment (FACE) experimental facility, BioCON (Biodiversity, CO₂ and Nitrogen deposition), at the Cedar Creek Ecosystem Science Reserve area in Minnesota (http://www.biocon.umn.edu/). Our analyses indicated that eCO₂ significantly altered the functional structure of soil microbial communities with a significantly increased abundance of genes involved in labile carbon degradation, carbon fixation, nitrogen fixation and phosphorus release, but without a significant change in the abundance of genes involved in recalcitrant C degradation and methane metabolism, and such changes may have significant impacts on soil C and N dynamics. These results have important implications for feedback responses of ecosystems to atmospheric CO₂ and global climate change.

MATERIALS AND METHODS

The following is the summary of methods used in this study. More detailed information is provided in the Data S1.

Site and sampling

This study was conducted within the BioCON experiment site located at the Cedar Creek Ecosystem Science Reserve, MN, USA. The main BioCON field experiment has a total of 296 plots with three treatments: CO₂ (ambient, 368 μmol⁻¹ vs. elevated, 560 μmol⁻¹), N (ambient vs. 4 g N m⁻² per year) and plant diversity (1, 4, 9 or 16 species) (Reich et al. 2001). In this study, soil samples from 24 plots (12 from ambient CO₂, 12 from elevated CO₂, and all with 16 species and ambient N supply) collected in July 2005 and 2007 were analysed.

Plant, soil and microbial biomass analyses

The aboveground and belowground biomass, plant C and N concentrations, soil pH, volumetric soil moisture, total soil C and N concentrations, and in situ net N mineralization and net nitrification were measured as previously described (Reich
et al. 2001, 2006). Microbial biomass (e.g. total, bacterial, fungal) was estimated by PLFA analysis (Chung et al. 2007).

**DNA extraction, purification and quantification**

Soil DNA was extracted by freeze-grinding mechanical lysis as described previously (Zhou et al. 1996). DNA quality was assessed by the ratios of 260 nm/280 nm and 260 nm/230 nm, and final DNA concentrations were quantified with a PicoGreen method.

**454 pyrosequencing and data analysis**

Pyrosequencing of PCR amplicons targeting V4-V5 hyper-variable regions of the 16S rRNA was performed with the 454 FLX Systems (454 Life Sciences, Branford, CT) with a sample tagging approach (Hamady et al. 2008). Details of amplicon preparations, sequencing and data analysis (e.g. classification, OTU identification) are described in the Data S1.

**GeoChip analysis**

Two versions of GeoChips were used for this study with GeoChip 2.0 for 22 (11 for each CO$_2$ condition) samples taken in 2005, and GeoChip 3.0 for 24 samples taken in 2007. GeoChip 2.0 contains >24 000 probes covering c. 10 000 gene sequences in 150 gene families (He et al. 2007), while the new version, GeoChip 3.0, contains >27 000 probes and covers c. 57 000 gene sequences in >292 gene families (He et al. 2010). Details for template amplification, labelling and hybridization, image processing and GeoChip data pre-processing are described in the Data S1.

**Statistical analysis**

Pre-processed data (e.g. GeoChip, 454 pyrosequencing, PLFA) were further analysed with different statistical methods: (1) microbial diversity index and response ratio (Luo et al. 2006), (2) DCA of microbial community structure and composition, (3) ANOSIM, adonis, and MRPP analysis of differences of microbial communities, (4) Mantel test and canonical correspondence analysis (CCA) for linking the functional structure of microbial communities to plant or soil variables (Zhou et al. 2008), and (5) partial Mantel test and partial CCA for co-variation analysis of soil and plant variables.

**RESULTS**

**Effects of eCO$_2$ on plant and microbial biomass and soil C and N**

Similar to previous observations in this experiment (Reich et al. 2001, 2004), during the 2005–2007 period (the 9–11th years of this FACE experiment), plant biomass (total, aboveground, belowground) increased significantly ($P < 0.05$) at eCO$_2$ (Fig. 1a). The total ingrowth root production, soil pH, soil moisture and total plant biomass N pool also significantly increased, whereas total plant biomass N concentration significantly decreased (Fig. S1). However, no significant changes were observed for net nitrification, net N mineralization, or the total soil C or N (Fig. S2). Both total microbial and bacterial biomass were significantly increased at eCO$_2$, whereas fungal biomass was unaffected (Fig. 1b), consistent with previous observations (Chung et al. 2007). The results suggest that soil bacterial communities may be stimulated in response to eCO$_2$.

![Figure 1](image-url) **Figure 1** Effects of eCO$_2$ on plant (a) and microbial (b) biomass. Plant aboveground and root (0–20 cm) biomass was the average of six harvests in both June and August of 3 years (2005–2007). Total microbial, bacterial or fungal biomass was the sum of the signature phospholipid fatty acid (PLFA) from 5.0 g soil samples taken in July 2007. All data are presented with mean ± SE (error bars), and the significance of eCO$_2$ on plant and microbial biomass is shown by $P$ values.
Overall responses of soil microbial community to eCO$_2$

To determine the overall response of soil microbial communities to eCO$_2$, the microbial communities at both aCO$_2$ and eCO$_2$ were analysed with (1) functional gene arrays (i.e. GeoChip) (He et al. 2007; He et al. 2010), which measure the functional structure and composition of microbial communities, (2) 16S rRNA gene-based pyrosequencing (Margulies et al. 2005; Hamady et al. 2008), which assesses the phylogenetic composition of microbial communities, and (3) PLFA, which provides information on the abundance and composition of microbial communities (Chung et al. 2007). Although no significant differences were detected in the overall microbial diversity, measured as the number of functional genes or OTUs, Shannon diversity, evenness and dominance (Table S1a), the structure of microbial communities was markedly different between aCO$_2$ and eCO$_2$ as indicated by DCA of GeoChip 3.0 data (Fig. 2a), and 454 pyrosequencing data (Fig. 2b) from 24 soil samples taken in July 2007. GeoChip 2.0 data for 22 samples taken in July 2005 also showed similar results (Fig. S3a), although those two sets of samples were collected in different years and examined with different versions of GeoChip. The gene copy number measured by quantitative real-time PCR was well correlated with the signal intensity detected by GeoChip 2.0 ($r = 0.530$, $P < 0.0001$, $n = 85$) or GeoChip 3.0 ($r = 0.724$, $P = 0.0001$, $n = 91$), indicating that GeoChip hybridization-based detection is quantitative. In addition, DCA of PLFA data showed that most of the samples under eCO$_2$ were separated from those under aCO$_2$, although no clear boundaries could be identified (Fig. S3b). Further analysis of 16S rRNA gene sequences showed the abundance of two phyla significantly changed at eCO$_2$ with one (Crenarchaeota) decreased and one (Verrucomicrobia) increased although the dominant phyla (e.g. Actinobacteria, Proteobacteria, Acidobacteria) did not show altered abundance (Fig. S4a); at the genus level, however, 31 genera from dominant phyla had altered abundances at eCO$_2$ with 18 increasing and 13 decreasing (Fig. S4b).

Three non-parametric multivariate statistical tests, ANOSIM, adonis and MRPP showed significant effects of eCO$_2$ based on the GeoChip 3.0, 454 pyrosequencing (at the species and genus levels), and PLFA analyses of 2007 soil samples, and based on GeoChip 2.0 analysis of 2005 samples (Table 1). Thus, all results indicated that the structure, composition and potential functional activity of microbial communities under eCO$_2$ were significantly different from those under aCO$_2$ at this FACE site. To our knowledge, this is the first comprehensive study at the whole community level to clearly demonstrate the changes in functional structure of microbial communities in response to eCO$_2$.

![Figure 2 Detrended correspondence analysis (DCA) of GeoChip 3.0 data (a) and 454. pyrosequencing data (b) showing that eCO$_2$ significantly affected the soil microbial community composition and functional structure. The normalized signal intensity data for 5001 detected functional gene sequences or the relative abundance of all detected OTUs (3777) in at least three of 12 samples were used for DCA. Non-filled circles are for aCO$_2$ samples, and filled circles for eCO$_2$ samples. Details for GeoChip 3.0, 454 pyrosequencing and associated analyses were described in Data S1. For both datasets, the effects of eCO$_2$ on the soil microbial community composition and structure appeared to be well separated by the first axis.](image)

Effects of eCO$_2$ on functional genes

To obtain more mechanistic insights into how eCO$_2$ affects functional processes of microbial communities, GeoChip 3.0 (He et al. 2010) data from 2007 samples were further examined by focusing on important biogeochemical processes, especially genes involved in C, N, P and S cycling. Among a total of 1503 detected functional genes involved in C, N, P and S cycling, a considerable portion (39%) of them were only detected under either aCO$_2$ (14%) or eCO$_2$.
All three tests are non-parametric multivariate analyses based on dissimilarities among samples. More detailed information is available in Data depends on the internal variability of the data.

**Table 1** Significance tests of the effects of CO$_2$ on the overall microbial community structure with three different statistical approaches

<table>
<thead>
<tr>
<th>Statistical approaches</th>
<th>GeoChip</th>
<th>454 pyro-sequencing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2005</td>
<td>2007</td>
</tr>
<tr>
<td>N</td>
<td>1212</td>
<td>5001</td>
</tr>
<tr>
<td>ANOSIM*</td>
<td>R</td>
<td>0.514</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>Adonis†</td>
<td>F</td>
<td>7.132</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>Mrpp‡</td>
<td>δ</td>
<td>27.1</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>$&lt;0.001$</td>
</tr>
</tbody>
</table>

*Analysis of similarities ANOSIM.
†Non-parametric multivariate analysis of variance (MANOVA) with the adonis function.
‡A nonparametric procedure that does not depend on assumptions such as normally distributed data or homogeneous variances, but rather depends on the internal variability of the data.

All three tests are non-parametric multivariate analyses based on dissimilarities among samples. More detailed information is available in Data S1.

(25%) (Table S1b), indicating that the functional characteristics of the microbial community were significantly altered by eCO$_2$. Several biogeochemically important functional genes were substantially changed. For example, five pathways for autotrophic CO$_2$ fixation have been identified so far (Berg et al. 2007), and GeoChip 3.0 contains probes for the genes encoding CO$_2$ fixation enzymes from four pathways: ribulose-1, 5-bisphosphate carboxylase/oxygenase (Rubisco) for the Calvin cycle, carbon monoxide dehydrogenase (CODH) for the reductive acetyl-CoA pathway, propionyl-CoA/acetyl-CoA carboxylase (PCC/ACC) for the 3-hydroxypropionate/malyl-CoA cycle and ATP citrate lyase (AcEb) for the reductive acetyl-CoA pathway. The PCC/ACC and Rubisco pathways were identified to be dominant in the BioCON grassland ecosystems, whereas the AcEb pathway was not detected. A total of 79, 46 and 17 probes were detected for Pcc/Acc, Rubisco and CODH pathways, respectively, and they had significantly higher signal intensities under eCO$_2$ than aCO$_2$ (Fig. 3a). All four forms of Rubisco genes were detected, but most of them belonged to Form I, a major form for CO$_2$ fixation. Although the significant increase in the abundance of C fixation genes under eCO$_2$ may potentially lead to more C fixation in soil, further studies are needed to determine the rates and extent of C fixation stimulated, and the impacts of the fixed C on the overall soil C dynamics in this ecosystem.

Elevated CO$_2$ either increased or had no effect on C degradation genes. Most C degradation genes whose abundance significantly ($P < 0.05$) increased under eCO$_2$ were those involved in the degradation of relatively labile C (e.g. starch, hemicelluloses, cellulose and simple aromatics), including those encoding amylase, glucoamylase, pullulanase, arabinofuranosidase and endoglucanase. The abundance of genes involved in the degradation of recalcitrant C (e.g. lignin) was largely unchanged by eCO$_2$, including those encoding lignin peroxidase, manganese peroxidase, glyoxyl oxidase, and phenol oxidase (Fig. 3b). The results suggest that eCO$_2$ might not significantly stimulate recalcitrant C degradation.

A substantial number (147) of genes involved in N$_2$ fixation (nifH) were detected, and the abundance of the detected nifH genes was significantly higher ($P < 0.05$) under eCO$_2$ than aCO$_2$ (Fig. 4). Among four defined clusters of nifH genes, only Cluster I showed a significant ($P < 0.05$) difference between aCO$_2$ and eCO$_2$, and most of the detected Cluster I genes were closely related to known organisms, such as *Rhizobium*, *Azospirillum* and *Bradyrhizobium* species. Cluster I contains nifH sequences from both free-living and symbiotic N$_2$-fixing microorganisms. In addition, most abundant nifH genes detected were from uncultured microorganisms (Fig. 4 and Fig. S5). The results indicate that eCO$_2$ may stimulate microbial N$_2$-fixation, but our understanding of N$_2$-fixing microorganisms and microbial N$_2$ fixation mechanisms may be very limited. No significant differences in the total signal intensity were observed for other N cycling genes except for nirS (Fig. 4 and Fig. S5).

GeoChip 3.0 targets three enzymes involved in P utilization, exopolysphhatase (Ppx) for inorganic polyphosphate degradation, polyphosphate kinase (Ppk) for polyphosphate biosynthesis in prokaryotes, and phytase for phytate degradation. While no significant differences of signal intensity were observed for Ppk and phytase genes, the total signal intensity of Ppx genes was significantly increased at eCO$_2$ at $P < 0.1$ (Fig. S6a), suggesting a possible increase in the degradation of polyphosphates and the availability of inorganic P under eCO$_2$. 

© 2010 Blackwell Publishing Ltd/CNRS
GeoChip 3.0 also has three enzymes involved in methane cycling, the alpha-subunit of methyl coenzyme M reductase (mcrA) for methane production, and particulate methane monooxygenase (pmoA) and methane monooxygenase (mmoX) for methane consumption. No significant differences in signal intensities were observed for mcrA or pmoA, but no probes for mmoX were detected at aCO2 and very weak signals at eCO2 (Fig. S6b), suggesting that eCO2 may have little impact on methane cycling processes at this site.

**Linking microbial community structure to soil properties and plant variables**

Mantel tests and CCA were performed to assess the relationships between microbial community structure and soil properties and plant variables. As using many unrelated individual variables could mask the signature of any significant variables in Mantel tests and redundant variables would generate inefficient CCA models, BIO-ENV and CCA-based variance inflation factor (VIF) were performed to identify common sets of soil and plant variables important to the microbial community structure (Table 2 and Table S2). Both simple and partial Mantel tests revealed that the selected soil variables were positively correlated with the microbial community structure based on all detected genes, or subsets of the genes involved in C fixation, labile C degradation, or N2 fixation (P < 0.05 or 0.01) (Table 2). Significant correlations at P = 0.1 were also observed between these soil variables and the genes involved in recalcitrant C degradation, dissimilatory nitrate reduction to ammonium, phosphorus release and denitrification (Table 2). The correlations between the selected soil variables and N2 fixing microorganisms were also supported by CCA (Table S2). In addition, significant correlations at P = 0.1 were observed between the selected plant biomass variables and subsets of functional genes, especially the genes involved in the N cycling (Table 2). These results suggested that the microbial community functional struc-
Figure 4 The relative changes of the detected genes involved in N cycling at eCO2. The signal intensity for each gene detected was normalized by all detected gene sequences using the mean. The percentage of a functional gene in a bracket was the sum of the signal intensity of all detected gene sequences of this gene divided by the grand sum of the signal intensity of the detected N cycling genes, and weighted by the fold change of the signal intensity of this gene at eCO2 to that at aCO2. For each functional gene, colours mean that this gene had a higher (red) or lower (blue) signal intensity at eCO2 than at aCO2 with significance at P < 0.05 (**). Gray-coloured genes were not targeted by this GeoChip, or not detected in those samples. It remains unknown if nosZ homologues exist in nitrifiers. Details for each gene and its involved functional process are shown in Fig. S6.

Discussion

Although eCO2 significantly affects plant growth and primary productivity via an increase in photosynthesis, little is known about the influence of eCO2 on the structure and potential activity of the belowground microbial community. As microorganisms mediate important biogeochemical processes, such as C, N, P and S cycling, they are expected to play important roles in influencing future atmospheric CO2, so understanding their response to elevated atmospheric CO2 is critical. In this study, using functional gene-based GeoChip, 16S rRNA gene-based pyrosequencing, and PLFA analysis we showed that 10 years of field exposure of a grassland ecosystem to eCO2 dramatically altered the structure and potential function of soil microbial communities. At eCO2, an increase in plant biomass (Reich et al. 2006) and belowground carbon inputs (Adair et al. 2009), and associated microenvironmental changes, such as greater soil moisture (Reich 2009), stimulated microbial, especially bacterial growth, which led to significant changes in the structure and activity of soil microbial communities. Statistical analyses showed that the changes in the microbial community structure were significantly correlated with soil C and N contents and weakly with plant productivity. These results will be important for understanding the responses of microbial communities to elevated CO2 and their potential consequences.

Chronic eCO2-induced increases in plant biomass, root exudation and soil moisture may stimulate soil microbial biomass. Previous studies at the BioCON site showed that both aboveground and belowground plant biomass significantly increased at eCO2 (Reich et al. 2001; Reich 2009), and were associated with increased carbon inputs into soil (Adair et al. 2009). Under long-term eCO2 soil moisture is also consistently increased (Reich 2009). Collectively, these shifts in resources and microenvironment enhance the microbial biomass and activity, as shown both in the current paper and previously (Dijkstra et al. 2005; Chung et al. 2007). Another study conducted in a FACE experiment at Rhinelander, WI, USA suggested no significant changes in the relative abundance or composition of fungi measured by PLFA and DGGE, respectively (Chung et al. 2006). Consistent with those previous studies, this study showed that bacterial biomass significantly increased at eCO2, but fungal biomass was unchanged. However, fungal biomass significantly increased in a chaparral ecosystem at eCO2 (Lipson et al. 2005), and the relative abundance of fungi was higher in a scrub-oak ecosystem at eCO2 than at aCO2 (Carney et al. 2007). This disparity among studies may be caused by the different ecosystems studied, although no patterns emerge that would allow us to speculate on what might cause such differences.

An issue relevant to our study and many other FACE studies is whether the initial abrupt increase in atmospheric CO2 influences microbial communities. Klironomos et al. (2005) compared the effects of both abrupt and gradual increase in atmospheric CO2 on a mycorrhizal fungal community, and showed that an abrupt CO2 rise resulted in an immediate decline in fungal species richness and a significant increase in mycorrhizal functional activity with stronger effects than a gradual CO2 rise (Klironomos et al. 2005). Whether such effects translate to our study or other field studies is unknown.

Although it is impossible to fully answer, it will be important to understand whether it is the stimulation of microbial biomass at eCO2 that leads to significant alterations in the structure of microbial communities. With increased organic matter inputs into soil, soil microbes are expected to respond rapidly to the greater availability of substrates. Such increased organic matter inputs may activate the growth of previously dormant microorganisms that are able to degrade such substrates, or increase the
growth rate of active microorganisms that were previously at a low abundance like r-strategists, which grow quickly and specifically degrade freshly input organic matter, and disappear after it is consumed (Fontaine et al. 2004). However, K-strategists, which are soil organic matter decomposers, may compete with r-strategists for the freshly input organic matter by increasing their growth and decomposition rates (Fontaine et al. 2004). The dynamics and competition of r- and K-strategists are expected to affect the structure and function of soil microbial communities. Indeed, the soil microbial community structure significantly changed at eCO$_2$. This was demonstrated by DCA of the abundance of functional genes, 16S rRNA genes and microbial abundance and composition measured by GeoChip, 454 pyrosequencing and PLFA, respectively. In addition, changes in the structure and potential activity of soil microbial communities at eCO$_2$ were reflected in a significant increase in the abundance of many functional genes, such as those involved in labile C degradation, rbcL for CO$_2$ fixation and nifH for N$_2$ fixation. Those changes may have occurred because of changes in the dynamics of active microbial populations stimulated by increased organic matter input at eCO$_2$. For example, the soil microbial community may change from oligotrophic regimes to copiotrophic regimes at eCO$_2$. All results suggest that eCO$_2$ drives a marked divergence in the structure and functional activity of soil microbial communities, and which microbial populations are stimulated by eCO$_2$ may be important to further understand if such changes lead to soil C sequestration or C loss.

Another question is whether the change in the microbial compositional structure affects community-level functional processes, especially soil C and N dynamics. Previous studies have shown inconsistent responses of soil C to eCO$_2$. For example, one meta-analysis showed a 5.6% increase in soil C over 2–9 years of exposure to eCO$_2$ (Jastrow et al. 2005), which may lead to a negative feedback to increased global C emissions (Houghton et al. 1999). In contrast, other studies showed a significant C loss at eCO$_2$, suggesting a positive feedback to globally increased CO$_2$ (Fontaine et al. 2004; Carney et al. 2007; Heimann & Reichstein 2008). A recent meta-analysis showed that elevated CO$_2$ generally increased net soil C accumulation when N fertilizer was added, but not under low N conditions (Hungate et al. 2009), consistent with findings in BioCON (Adair et al. 2009). Our GeoChip data showed a significant increase in the abundance of genes involved in degradation of labile substrates with rapid turnover times. Thus, eCO$_2$ may lead to an increase in soil microbial respiration such that elevated inputs of C are readily consumed by stimulated microbial populations (e.g. r-strategists) (Adair et al. 2009), resulting in little significant impact on soil C stocks. More importantly, the abundance of genes involved in recalcitrant C degradation did not significantly change at eCO$_2$, indicating that the soil C storage may remain unaffected in the long term. Thus, our

Table 2 The relationships of microbial community functional structure to soil C and N dynamics and aboveground plant characteristics revealed by partial Mantel test

<table>
<thead>
<tr>
<th>In association with: Controlling for: Functional category</th>
<th>Gene no.</th>
<th>Soil*</th>
<th>Plant†</th>
<th>Soil*</th>
</tr>
</thead>
<tbody>
<tr>
<td>All detected</td>
<td>5001</td>
<td>0.312</td>
<td>0.027</td>
<td>0.146</td>
</tr>
<tr>
<td>C cycle</td>
<td>576</td>
<td>0.351</td>
<td>0.014</td>
<td>0.134</td>
</tr>
<tr>
<td>C fixation</td>
<td>147</td>
<td>0.480</td>
<td>&lt;0.001</td>
<td>0.184</td>
</tr>
<tr>
<td>Labile C degradation</td>
<td>259</td>
<td>0.296</td>
<td>0.005</td>
<td>0.126</td>
</tr>
<tr>
<td>Recalcitrant C degradation</td>
<td>127</td>
<td>0.193</td>
<td>0.068</td>
<td>0.020</td>
</tr>
<tr>
<td>N cycle</td>
<td>548</td>
<td>0.239</td>
<td>0.063</td>
<td>0.149</td>
</tr>
<tr>
<td>N$_2$ fixation</td>
<td>147</td>
<td>0.320</td>
<td>0.005</td>
<td>0.166</td>
</tr>
<tr>
<td>Nitrification</td>
<td>54</td>
<td>0.036</td>
<td>0.343</td>
<td>0.104</td>
</tr>
<tr>
<td>Denitrification</td>
<td>277</td>
<td>0.173</td>
<td>0.119</td>
<td>0.148</td>
</tr>
<tr>
<td>N reduction to NH$_4^+$</td>
<td>55</td>
<td>0.202</td>
<td>0.064</td>
<td>0.068</td>
</tr>
<tr>
<td>N mineralization</td>
<td>62</td>
<td>0.095</td>
<td>0.176</td>
<td>0.069</td>
</tr>
<tr>
<td>Phosphorous utilization</td>
<td>74</td>
<td>0.197</td>
<td>0.069</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Note: *Selected soil variables: percentages of soil C and N at the depth of 0–10 and/or 10–20 cm and soil pH.
†Selected plant variables: biomass of Andropogon gerardi (C4), Bouteloua gracilis (C4) and Lupinus perennis (Legume), belowground plant C and N (%), and species count. Soil and plant variables were selected by the BIO-ENV procedure.
results are consistent with recent conclusions that eCO$_2$ has little effect on soil C storage (Hungate et al. 2009).

Whether the change observed in the microbial community structure has significant effects on N dynamics is also a central issue for the long-term sustainability of eCO$_2$ stimulation due to both the progressive nitrogen limitation effect and to co-limitation by CO$_2$ and N that can constrain the eCO$_2$ response when N availability is low (Reich et al. 2006). A previous BioCON study showed that N$_2$-fixing legume species responded to a greater extent than non-fixing forbs to eCO$_2$, and that eCO$_2$ stimulated symbiotic N$_2$ fixation, resulting in an increased amount of N derived from the atmosphere (Lee et al. 2003), and other studies also observed that microbial N$_2$ fixation increased under eCO$_2$ (Luo et al. 2006; van Groenigen et al. 2006). Consistently, a significant increase in the abundance of nifH genes for N$_2$ fixation, and nirS genes for denitrification was observed at eCO$_2$ in this study although net nitrification, net N mineralization, and the total soil N content were not significantly changed. Therefore, eCO$_2$ may affect the overall soil N budget via increased N fixation or denitrification in this grassland ecosystem, although the linkage between increased gene abundances and system-level process rates requires further study.

There are several additional related reasons why we might not see a difference in total soil C and N, net nitrification, or net N mineralization at eCO$_2$ despite significant changes in potential microbial function. The pool size of total soil C and N may be too large and heterogeneous relative to the eCO$_2$ effect to be detectable at present. Although a significant increase in C and N metabolic processes may occur, the net accumulation or consumption of soil C or N may be still very small relative to the total soil C and N pool, making it difficult to detect a difference until more time has passed (Smith 2004). With respect to net N mineralization, it is possible that impacts on mineralization of changes in stoichiometry (C:N ratios of roots and soil solution) may be offset by increased soil moisture in eCO$_2$, which was observed for the same plots in this study and a previous study (Reich 2009).

As suggested above, the effects of microbial structure and potential activity on ecosystem functions are in part controlled by environmental factors, such as soil moisture and pH. Indeed, multivariate statistical analyses showed that many functional genes were significantly correlated with soil variables. For example, the abundance of all detected genes, and genes involved in C fixation, labile C degradation, or/N$_2$ fixation was significantly ($P < 0.05$), positively correlated with soil variables (e.g. moisture, pH), which indicates that environmental variables other than the amount and stoichiometry of plant inputs, could be important in shaping the microbial community. In addition, significant correlations among different functional genes were observed. The results indicate that soil characteristics, such as moisture and pH (which themselves are influenced by eCO$_2$) may mediate the effects of eCO$_2$ on the structure and function of microbial communities.

This study combines metagenomic technologies (e.g. GeoChip, Pyrosequencing) with traditional methods (e.g. PLFA, EcoPlate) to provide an integrative study of soil microbial communities exposed to eCO$_2$. GeoChip-based data especially provide large scale quantitative information on various biogeochemically important microbial functional groups, thus making it possible to link the functional structure of microbial communities with ecosystem processes. In addition, 16S rRNA gene-based pyrosequencing data provide phylogenetic information about the phylogenetic structure and composition of microbial communities. Such datasets provide an integrative approach for reliable detection of microbial structure, composition and functional activity and linking those microbial properties to ecosystem functioning, such as soil C and N dynamics.

The issues addressed in our study are important to the collective understanding of the feedback responses of terrestrial ecosystems to eCO$_2$ and to modelling-based projections of future atmospheric CO$_2$ concentrations. It is obvious that the impacts of eCO$_2$ on soil C and N dynamics and the feedbacks of ecosystems to eCO$_2$ will depend on which groups of microorganisms, and what activities and interactions, are stimulated by the increased C influx to soil. We found that eCO$_2$ significantly altered microbial community structure and composition and elicitd the up-regulation of functional genes involved in labile C decomposition, C and N fixation and phosphorus utilization, whereas those involved in decomposing recalcitrant C were unchanged. Such shifts in microbial community structure and function could potentially modify the direction and magnitude of ecosystem regulation of the rate of increase in atmospheric CO$_2$ concentrations. In addition, current ecosystem modelling efforts largely treat the soil microbial component of the terrestrial biosphere as a single pool (Allison & Martiny 2008) — that is, they ignore the details of microbial communities and typically assume that changes in biogeochemical responses can be predicted from simple assumptions about system behaviour regardless of changes in the identity and abundance of the microbial community. This ‘black box’ assumption may be valid only if microbial composition is resistant, resilient and/or functionally redundant to disturbance (Allison & Martiny 2008). Our study revealed major shifts in the overall structure of soil microbial communities under eCO$_2$, indicating that microbial community structure is not resistant to disturbance in general (Allison & Martiny 2008). Although the current state of global C, N and climate model science and of soil microbiology science are not
sufficiently advanced to incorporate soil communities as anything but a ‘black box’ in elemental and climate modelling, more realistically linked global C, N and climate models must be developed to holistically incorporate microbial community structure and composition, at least at the levels of microbial groups with distinct functions, for more accurate and reliable predictions.

ACKNOWLEDGEMENTS

This work is supported by the United States Department of Agriculture (Project 2007-35319-18305) through NSF-USDA Microbial Observatories Program, by the National Science Foundation under Grant Numbers DEB-0716587 and DEB-0620652 as well as the DEB-0322057, DEB-0080382, DEB-0218039, DEB-0219104, DEB-0217631, DEB-0716587 BioComplexity, LTER and LTREB projects, the DOE Program for Ecosystem Research, and the Minnesota Environment and Natural Resources Trust Fund. The GeoChips and associated computational pipelines used in this study were supported by the Genomics:GTL program through the Virtual Institute of Microbial Stress and Survival (VIMSS; http://vimss.ibl.gov), and Environmental Remediation Science Program, as well as by the Oklahoma Bioenergy Center (OBC) and the Oklahoma Applied Research Support (OARS), Oklahoma Center for the Advancement of Science and Technology (OCAST), the State of Oklahoma.

REFERENCES


SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article.

**Figure S1** Effects of elevated CO\(_2\) on plant biomass, total plant N pool, total plant biomass N concentration, and soil pH and moisture.

**Figure S2** Effects of elevated CO\(_2\) on soil C and N dynamics.

**Figure S3** DCA analyses of GeoChip 2.0 and PLFA data.

**Figure S4** The abundance of 16S rRNA gene sequences at the phylum level at aCO\(_2\) and cCO\(_2\) and the significantly changed genera under eCO\(_2\).

**Figure S5** Normalized average signal intensity of the significantly changed nifH genes and other top 10 abundant nifH sequences detected by GeoChip 3.0.

**Figure S6** Normalized average signal intensity of detected key gene families involved in the N cycling under both CO\(_2\) conditions.

**Figure S7** The normalized average signal intensity of the detected key functional genes involved in P cycling (A), methane production and oxidation (B) under ambient CO\(_2\) and elevated CO\(_2\).

**Table S1** Overall microbial community diversity and the number of detected genes involved in carbon, nitrogen, phosphorus, and sulfur cycling under ambient CO\(_2\) and elevated CO\(_2\).

**Table S2** Simple Mantel tests and partial CCA analyses of correlations between key functional gene categories and environmental and plant variables.
Data S1 Materials and methods.

As a service to our authors and readers, this journal provides supporting information supplied by the authors. Such materials are peer-reviewed and may be re-organized for online delivery, but are not copy-edited or typeset. Technical support issues arising from supporting information (other than missing files) should be addressed to the authors.

Editor, John Klironomos
Manuscript received 28 December 2009
Manuscript accepted 4 January 2010