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EDITORIAL

Trends and challenges in soil research 2009: linking global climate change to local long-term forest productivity

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Long-term impacts of global climate change (GCC) and local forest management on important biogeochemical cycles of carbon (C) and nutrient cycling in the soil–plant ecosystems are complex and difficult to assess (Oren et al. 2001; Reich et al. 2006; Xu and Chen 2006; Davidson et al. 2007; Chen and Xu 2008; Clark and Tilman 2008; Xu et al. 2008a, b), particularly under gradually and continuously rising atmospheric carbon dioxide concentration [CO_2] and warming in the real world with multiple limiting factors (Hui et al. 2002; Savard et al. 2004; Büntgen et al. 2007; Feeley et al. 2007; Engelbrecht et al. 2007). In this editorial, as a part of the journal editorial series (Förstner and Salomons 2008), we highlight the recent developments and applications of advanced stable isotope, nuclear magnetic resonance (NMR), and biomolecular techniques in an integrated approach with innovative rhizosphere and tree ring methods, for improving our understanding and management of above- and below-ground C and nutrient cycling processes in forest ecosystems, particularly in response to GCC and local management practices as well as mitigation/adaptation strategies. The opportunities and limitations of these techniques for investigating C and nutrient cycling processes in forest ecosystems are discussed, in the context of both short- and long-term impacts on the above- and below-ground processes. Improved understanding and knowledge of environmental fingerprints of the biogeochemical cycles embedded in tree rings can be effectively used to account for long-term forest productivity and C stocks at local, regional, and global scale in response to the future GCC and management options.

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1 Global climate change and forest management

Over the last century, atmospheric [CO_2] has increased globally by nearly 30% and temperature by approximately 0.6°C, and these trends are projected to continue more rapidly (Xu and Chen 2006), particularly with more extreme climatic conditions. The impacts of GCC on future structure, composition, and C and nutrient cycling in forest ecosystems deserve particular attention and further research. Little is known about the impacts of GCC and forest management on plant–soil–microbe interactions. Plant–soil–microbe interactions mainly occur in the rhizosphere, which is defined as the zone of soil that is affected by the root activity of any plant species. The rhizosphere is suggested here as the "hotspot" for plant–soil–microbe interactions—the most chemically and biologically active microsite in soil (Seguin et al. 2004)—and represents a complex integrated ecosystem. The ecology in the underworld, particularly below-ground processes and their interactions with above-ground processes, has been highlighted in the Science (Volume 304, 1613–1637, 11 June 2004). There is growing need for improving the understanding and management of important below-ground processes. Understanding rhizosphere C and nutrient cycling processes in relation to rising [CO_2] and temperature is crucial for predicting the response of forest ecosystems to GCC (Xu and Chen 2006; Hyvönen et al. 2007).

Annual tree ring width measurements can be used to study tree growth indices of different species at scales from years to decades/centuries in seasonally distinguished growth environments, particularly in response to the changing climate and historical episodes (Duquesnay et al. 1998; Penninckx et al. 1999; Saurer et al. 2004; Savard et al. 2004; Büntgen et al. 2007). Together with tree ring growth measurements, tree ring stable isotope (particularly ^{13}C, ^{18}O, and ^{15}N) compositions (Duquesnay et al. 1998; Elhani et al. 2003; Saurer et al. 2004; Savard et al. 2004; Treydte et al. 2006; Helliker and Richter 2008) and element concentrations (Penninckx et al. 1999; Drouet et al. 2005a, b) may be used to reconstruct past, long-term climate change (particularly atmospheric [CO_2], temperature, and rainfall) in different regions of the world. These methods can also be used to assess the impacts of historical episodes (e.g., acid deposition and fertilization) on long-term productivity and biodiversity of forest ecosystems (Horz et al. 2004; Reich et al. 2006; Davidson et al. 2007; Magnani et al. 2007; Clark and Tilman 2008). Hence, these environmental fingerprints of the biogeochemical cycles embedded in tree rings can be effectively used to account for the long-term forest productivity and C stocks at local, regional, and global scale in response to the future GCC and management practices.

2 Rhizosphere study techniques

The quantitative understanding of rhizosphere processes is poor since the rhizosphere is a difficult system to physically sample and manipulate (Xu and Chen 2006). Currently there are two commonly used methodologies to physically separate rhizosphere soil from bulk soil. One is the hand-shaking method (Seguin et al. 2004). The second approach involves direct (in situ) sampling of soil adjacent to roots by thin sectioning and/or placement of different sized mesh materials around roots (Xu and Chen 2006). It is challenging, but necessary to develop sampling techniques and protocols building on the promising hand-shaking method (Seguin et al. 2004), which takes into account the spatial and temporal variability in the rhizosphere of forest ecosystems. In addition, modeling of rhizosphere will be able to upscale the uptake of nutrients to the whole plant scale (Darrah et al. 2006).

3 Microbiological methods

Soil microbial properties such as biologically regulated nitrogen (N) transformations, microbial biomass C, N, and phosphorus (P), respiration, metabolic quotient, and enzyme activity can be very sensitive to GCC and forest management (Xu and Chen 2006; Chen and Xu 2008; Huang et al. 2008a, b, c; Pan et al. 2008; Xu et al. 2008a, b). However, information about the impacts of GCC and forest management on soil microbial properties is rather limited (Chen et al. 2004; Chen and Xu 2006; Burton et al. 2007a, b; Zhao et al. 2007; He et al. 2008a, b). Conventional culture-dependent methods have been used for the measurement of soil microbial composition for more than a hundred years. Nevertheless, only 0.1–1% of soil microorganisms are accessible by these approaches.

4 Biomolecular techniques

Recent advances in biomolecular techniques make it possible to apply culture-independent and DNA/RNA nuclear acid-based techniques to analyze the targeted sequences of bacterial or fungal DNA directly extracted from soil (He et al. 2005a, b, 2006; Bastias et al. 2006a, b; Xu and Chen 2006; Bastias et al. 2007; Ge et al. 2008a, b; He et al. 2008a; Zhang and Xu 2008; Zheng et al. 2008). The determination of 16S ribosomal RNA (rRNA) genes and 18S rRNA genes has proved most useful for investigating the diversity and composition of bacteria and fungi, respectively, since these molecules are composed of highly conserved regions and also of regions with considerable sequence variation. The applications of microbial functional genes (e.g., *pmoA* and *amoA*) have greatly improved our understanding of the abundance and composition of specific groups (e.g., methanotrophs and ammonia oxidizers) of microorganisms involving in the biogeochemical cycling (Leininger et al. 2006; He et al. 2007; Shen et al. 2008; Zheng et al. 2008).

5 Stable isotope and NMR techniques

Stable isotope techniques are considered as a critical component in the studies of GCC (e.g., elevated [CO_2]) and forest management on soil C and N dynamics (Blumfield et al. 2004; Xu and Chen 2006; Chen and Xu 2008; Huang et al. 2008b; Pan et al. 2008). Stable isotope techniques have been found to be a very powerful tool for advancing the understanding of important C and N cycling processes in terrestrial ecosystems (Xu et al. 1993a, b; Guinto et al. 2000; Pu et al. 2001, 2002; Blumfield et al. 2004; Pu et al. 2005; Huang et al. 2008b; Pan et al. 2008). Recent applications of stable isotope techniques to soil biological studies have resulted in significant advances in the understanding of soil microbial processes regulating the C and N cycling in terrestrial ecosystems. It is very exciting to see the combined use of stable isotope and biomolecular techniques in recent studies (Xu and Chen 2006), which have identified specific microorganisms that are actively involved in particular metabolic processes.

NMR techniques have been increasingly used in soil science, geochemistry, and environmental science (Mathers et al. 2000; Mao et al. 2002; Blumfield et al. 2004; Chen et al. 2004; Johnson et al. 2005; Xu and Chen 2006; Chen and Xu 2008). In particular, ^{13}C NMR has been widely used to improve the understanding of soil organic matter (SOM) quality and composition in relation to terrestrial C and N cycling processes. Natural abundance ^{15}N cross-polarization/magic angle spinning NMR spectra of SOM have been obtained by Knicker et al. (1993), indicating that almost all signal intensity is in the chemical shift region assigned to peptide/amide N. In the first application of ^{14}N NMR to soil humic acid (HA) studies, Mao et al. (2002) have discovered the surprising existence of nitrate-N in soil HA, with the HA nitrate-N closely related to soil N availability and rather responsive to ecosystem management. The advanced NMR techniques need to be assessed for their potential in improving the understanding of rhizosphere C and nutrient cycling, particularly when combined with stable isotope and biomolecular techniques (Knicker 2002).

6 Tree ring technique

Most terrestrial ecosystem studies (Oren et al. 2001; Reich et al. 2006; Xu and Chen 2006; Hyvönen et al. 2007; Piao et al. 2008) on GCC impacts have been undertaken over short periods (<10 years) with one or two factors of contrasting treatments (e.g., with and without N additions) and large step increases (e.g., ambient [CO_2] 350 ppm and elevated [CO_2] 700 ppm). These would be very different from the real world with gradually rising [CO_2] and warming as well as changing rainfall patterns in the context of atmospheric deposition over periods from decades to centuries, particularly for forest ecosystems (Duquesnay et al. 1998; Saurer et al. 2004; Drouet et al. 2005b; Büntgen et al. 2007; Feeley et al. 2007). Tree ring growth (Duquesnay et al. 1998; Penninckx et al. 1999; Saurer et al. 2004; Savard et al. 2004; Büntgen et al. 2007), stable isotope composition (Duquesnay et al. 1998; Elhani et al. 2003; Saurer et al. 2004; Savard et al. 2004; Treydte et al. 2006; Helliker and Richter 2008), and element concentration (Penninckx et al. 1999; Drouet et al. 2005a, b) over decades or centuries can provide exciting opportunities to investigate the impacts of GCC and historical episodes (e.g., acid deposition and prescribed burning or wild fires) on important biogeochemical cycles of C and nutrients (Xu and Chen 2006; Gruber and Galloway 2008; Heimann and Reichstein 2008), underpinning the long-term tree growth and water-use efficiency (WUE) as well as biodiversity of forest ecosystems (Saurer et al. 2004; Savard et al. 2004; Büntgen et al. 2007; Engelbrecht et al. 2007; Clark and Tilman 2008). However, this type of research approach is not without significant problems and requires complementary short-term laboratory and field experiments to help tease out the complex interactions among multiple factors of gradual GCC (Duquesnay et al. 1998; Hui et al. 2002; Saurer et al. 2004; Büntgen et al. 2007; Feeley et al. 2007) and historical episodes (Savard et al. 2004; Magnani et al. 2007; Clark and Tilman 2008). While rising [CO_2] and atmospheric warming are well-recognized GCC phenomena (Davidson and Janssens 2006; Xu and Chen 2006), their long-term impacts on biogeochemical cycles, ecosystem productivity, and biodiversity can differ with locations and species/ecosystems (Horz et al. 2004; Davidson and Janssens 2006; Büntgen et al. 2007; Feeley et al. 2007; Hyvönen et al. 2007) as well as historical episodes (Savard et al. 2004; Magnani et al. 2007; Clark and Tilman 2008), in the context of local rainfall, temperature, atmospheric deposition/air pollution, and soil fertility.

In addition, rising [CO_2] is expected to result in increased plant photosynthesis and reduced stomatal conductance, hence higher plant WUE and $\delta^{13}C$ (Duquesnay et al. 1998; Prasolova et al. 2000, 2001; Xu et al. 2000; Saurer et al. 2004; Long et al. 2006; Hyvönen et al. 2007), but this can be counteracted by decreasing plant photosynthesis and $\delta^{13}C$ due to acid deposition (Savard et al. 2004) and decreasing atmospheric $\delta^{13}C$ from increasing fossil CO_2 emissions (Keeling et al. 1979), respectively. Plant WUE and growth can be increased by elevated [CO_2] and N availability (Oren et al. 2001; Prasolova and Xu 2003; Xu et al. 2003; Prasolova et al. 2005; Long et al. 2006; Reich et al. 2006; Hyvönen et al. 2007; Magnani et al. 2007; Huang et al. 2008d, e, f), at least in the short term, but their long-term levels may be counteracted by age-related biologically declining trends (Duquesnay et al. 1998; Penninckx et al. 1999) and progressive nutrient limitations (Oren et al. 2001; Drouet et al. 2005a, b; Long et al. 2006; Reich et al. 2006; Hyvönen et al. 2007). The mobility of elements (Penninckx et al. 1999; Elhani et al. 2003; Drouet et al. 2005a, b; e.g., N) between adjacent tree rings and differences in stable isotope composition between components (Duquesnay et al. 1998; Elhani et al. 2003; Saurer et al. 2004; Treydte et al. 2006) of tree ring material (e.g., cellulose against whole tree ring material) can also pose problems in interpreting these ring data, with increasing margins of error. Furthermore, there are limited long-term records of local atmospheric [CO_2], temperature, rainfall, and acid deposition for many parts of the world and either re-constructed or global averages of these parameters would need to be used from ice core (Mayewski and Whitlow 1996; Etheridge et al. 1998) and tree ring data (Keeling et al. 1979; Duquesnay et al. 1998; Saurer et al. 2004; Treydte et al. 2006; Büntgen et al. 2007) for assessing the long-term impact of gradual GCC and historical episodes. These would need to be calibrated and tested by well-controlled and focused studies as well as sophisticated mathematical and ecosystem modeling across the diversified regions of the world.

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