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Review

Knowledge gaps in soil carbon and nitrogen interactions – From molecular to global scale

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ABSTRACT

The objective of this review was to identify, address and rank knowledge gaps in our understanding of five major soil C and N interactions across a range of scales – from molecular to global. The studied five soil C and N interactions are: i) N controls on the soil emissions of greenhouse gases, ii) plant utilisation of organic N, iii) impact of rhizosphere priming on C and N cycling, iv) impact of black N on the stabilisation of soil organic matter (SOM) and v) representation of fractions of SOM in simulation models. We ranked the identified knowledge gaps according to the importance we attached to them for functional descriptions of soil–climate interactions at the global scale, for instance in general circulation models (GCMs). Both the direct and indirect influences on soil–climate interactions were included.

We found that the level of understanding declined as the scale increased from molecular to global for four of the five topics. By contrast, the knowledge level for SOM simulation models appeared to be highest when considered at the ecosystem scale. The largest discrepancy between knowledge level and importance was found at the global modelling scale. We concluded that a reliable quantification of greenhouse gas emissions at the ecosystem scale is of utmost importance for improving soil–climate representation in GCMs. We see as key questions the identification of the role of different N species for the temperature sensitivity of SOM decomposition rates and its consequences for plant available N.

1. Introduction

A large percentage of the Earth's active carbon (C) is found in soil organic matter (SOM) and its cycling rate is strongly linked to nitrogen (N) availability. It was recognised already in the 1990s, that N availability is the main governing factor controlling soil C response to climate change in N-limited ecosystems (Diaz et al., 1993; Ineson et al., 1996). This understanding has been emphasised through a number of research programmes studying interactions between the C and N balances in ecosystems, using both the present climate and simulated climate change conditions e.g. the Climex (Dise and Jenkins, 1995), Nitrex (Wright et al., 1995), Canif (Schulze, 2000) and Nitro-Europe (NitroEurope, 2006) programmes. Appreciation of the importance of soil C and N interactions for predicting the impacts of climate change has certainly increased, but we still lack a full understanding and quantification of the drivers (Hu et al., 2001; Hyvönen et al., 2007).

To date, the interactions between soil C and N are not adequately represented in general circulation models (GCMs) despite the

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importance attached to these interactions by the majority of soil and ecosystem scientists (Thornton et al., 2007). In 2000, some first attempts were made to incorporate soil feedback responses into GCMs (Cox et al., 2000) and these models are now considered too simplistic (Davidson and Janssens, 2006). It is possible that the influence of soil C and N interactions may to a certain extent be implicitly captured in the production and respiration predictions from GCMs for the recent past and present situations, assuming greenhouse gas fluxes are accurately quantified. However, this certainly does not mean that current representations are sufficient to accurately predict future greenhouse gas fluxes, together with their impact on the climate system. Future scenarios generated from GCMs may have significant biases if soil C and N interactions are being modified due to global change. Moreover, there is a growing body of literature suggesting that these interactions will change in response to a variety of factors, such as increased carbon dioxide (CO_2) fertilisation, land use and management as well as changing precipitation and temperature regimes. The challenge is to incorporate realistic aspects of the interactions between ecosystem/biome N status and trace gas emissions in coupled GCMs. Although the majority of basic knowledge is present in the literature, uncertainties still remain.

Bouma (2005) distinguished major kinds of knowledge gaps hampering progress in research: i) 'We know what we don't know', ii) 'We don't know what we know', and iii) 'We don't know what we don't know yet' (Bouma, 2005; pp. 73). The first kind is the most tractable one, and here we attempt to identify some of the key scientific issues falling under this heading since awareness of such knowledge gaps is a convenient starting point for progress in scientific understanding. The second type of knowledge gap is less tractable and may cause some degree of frustration. For example, there is still no standard way of measuring such a seemingly simple process as litter decomposition; even the results of the long-standing mesh bags techniques are difficult to interpret. So, for something even as seemingly straightforward as monitoring litter decomposition, we actually 'don't know what we know'. The third type of knowledge gap is the most problematic one. Science abounds with examples of falsely inherited wisdom or total ignorance of extremely important processes. For example, until the mid-1990s, the uptake of organic N by plants was assumed to be negligible. Consequently research focussed entirely on inorganic N and therefore, descriptions of N cycling in models often lack this entire pathway (Schimel and Bennett, 2004). We have identified five major knowledge gaps relating to soil C and N interactions relevant for soil–climate interactions.

i) *To what extent does N control the soil emissions of the greenhouse gases CO_2, CH_4 and N_2O?*
ii) *To what extent do plants utilise organic N?*
iii) *To what extent does rhizosphere priming affect C and N cycling?*
iv) *How does black N affect SOM stability?*
v) *How could different fractions of SOM be adequately represented in models at various scales?*

Several of these questions are hybrids of the first and second types of knowledge gaps. We know that processes, such as priming by roots, are potentially important; however, we cannot yet advise the GCM modellers whether these processes need to be represented in global models or how this could be achieved. We also know that N controls greenhouse gas emissions, but still, we cannot fully assess how strong these interactions are, and although there are studies quantifying these effects locally, it is difficult to generalise to a global scale.

The objective of this study was to identify, address and rank the knowledge gaps in the five topics on soil C and N interactions at molecular, organism, ecosystem and global scale. The ecosystem scale is here defined as field and forest stand scale. We ranked the knowledge gaps identified according to the importance we attached to them for functional description of soil–climate interactions at the global scale, for instance in GCMs. Both direct influences on soil–climate interactions and indirect influences through plant N availability were considered and how these influences might change with climate change.

An attempt was made to identify the governing factors at specific scales, i.e. what do we know, or what do we not know. We also discuss possible effects of climate change on the controlling factors, and what needs to be considered when moving between scales. Upscaling is an important and recurring issue throughout these discussions and, wherever possible, estimation has been made of where the uncertainties are, both regarding structural uncertainty due to lack of understanding of processes and uncertainty due to data quality and aggregation. For instance, what are the possible consequences of upscaling short-term experiments at microorganism scale to long-term global trends or those of aggregated data derived at different scales?

2. Knowledge gaps in five topics of soil C and N interactions

2.1. To what extent does N control the soil emissions of the greenhouse gases CO_2, CH_4 and N_2O?

There is a long-standing awareness of the importance of soil management as a central element in the sustainability or collapse of human societies at local and regional scales (Russell, 1973; Diamond, 2005). However, the full realisation of the importance of soils in maintaining atmospheric concentrations of greenhouse gases at the global scale first entered mainstream thinking as the 21st Century approached. The assessments of the Intergovernmental Panel on Climate Change (IPCC, 1995) and the incorporation of soil feedbacks into coupled GCMs (Cox et al., 2000) clearly demonstrated the developing concepts of the major role played by soils in climate feedback processes. Indeed, it is from soils that some of the greatest climate destabilising feedbacks can be expected (Heimann and Reichstein, 2008). The increases in atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are of major importance when considering future climates. All three of these gases have a substantial part of their cycling, either production, consumption or storage, associated with soils and here we consider relevant knowledge across a number of scales and how N interacts with these transfers.

At the *molecular scale* there is considerable fundamental knowledge, gained largely from laboratory studies investigating the underlying reactions associated with the production and consumption of these three important trace gases. Undoubtedly, new pathways and reactions will be discovered. Of the three greenhouse gases mentioned above, CO_2 is one of the most frequently measured and more fully understood gas emitted from soils. Biological oxidation of energy-rich molecules in soils results in the uptake of oxygen, with a concomitant release of CO_2, a process termed soil respiration (Russell, 1905). The major components of this net flux are normally the combined respiratory activities of soil micro-organisms, such as bacteria and fungi, in the bulk soil (heterotrophic) and those from plant roots (autotrophic) (see Gloser and Tesarova, 1978; Högberg and Read, 2006; Heinemeyer et al., 2007). The contributions from heterotrophs and autotrophs to soil respiration are probably comparable in magnitude (Högberg et al., 2002). Behind the measured net CO_2 fluxes are numerous processes of CO_2 production and consumption, both biotic and abiotic.

Identifying, understanding and quantifying these processes is crucial, as we seek to find new ways to sequester increasing amounts of C from the atmosphere. The underlying biochemistry behind the biotic production of CO_2 in soils is highly conserved, and