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Soil organic matter of forests and climate and atmosphere changes

Bruno Ferry – Thomas Eglin – Antonio Bispo – Étienne Dambrine – Claire Chenu

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INTRODUCTION

Today it is well established that human activities are at the root of an unprecedented rise of the atmospheric levels of CO_2, CH_4 and N_2O, that generate a greenhouse effect that is the main cause of global warming, and is likely to modify the rainfall patterns, with an upwards trend in humid regions and a decrease in dry regions (IPCC, 2013). Another important change, although more on a regional scale, is that human activities are generating nitrogen deposits: ammonia emitted by agriculture and nitrogen oxide produced by the combustion of energy. At the end of the 1990s, the main world regions concerned by these deposits were Europe, the Eastern USA, India and China, and this is set to spread to some of Latin America and Africa in the decades to come (Galloway *et al.*, 2004). On the other hand, nitrogen oxide emissions are currently being reduced in the USA (Templer *et al.*, 2012) and in Europe (de Vries and Posch, 2011), thanks to public policies that are motivated by the desire to reduce ozone formation, which is detrimental to health.

The biogeochemical cycles of terrestrial ecosystems (and the oceans) are affected by these changes and – through various feedback – have the potential to lighten or accentuate these changes in a major way. Over the past 50 years, terrestrial ecosystems have acted as carbon sinks, reducing by around 30% the rise of atmospheric CO_2 generated by the combustion of hydrocarbons. However, there is a risk that this response becomes reduced and eventually reverses itself (Cox *et al.*, 2000).

The soil is at the heart of these global issues due to the fact that it contains at least 3/4 of the carbon globally stocked by terrestrial ecosystems (Eglin *et al.*, 2010) and that it plays a major role in the regulation of carbon and nitrogen cycles. In this way, the dynamic of soil organic matter has become a major question in research on terrestrial ecosystems. This question also interests forest managers, because the organic matter contributes to a large number of soil, physical, chemical and biological properties. In particular, the availability of assimilable nitrogen is a critical factor for fertility in forests.

The aim of this article is to present a summary of knowledge concerning the effects that are already visible – or expected – of climate change on the stock of organic matter in forest soil. Firstly, we will present the methods used to quantify stocks of organic matter. We will then run through the effects of climatic factors (temperature, precipitation and water balance), followed by those of atmospheric composition (CO_2 content, nitrogen deposits, ozone content in the lower atmosphere). Lastly, we will examine the predictions that have been made regarding the change in stocks of soil organic matter based on scenarios for the changes in the atmosphere and the climate.

METHODS FOR STUDYING THE CHANGES IN SOIL ORGANIC STOCKS

Temporal series of soil OM (organic matter) stocks

Soil is a compartment of forest ecosystems that is lacking old observation chronologies. For the atmosphere, direct measurements for greenhouse gas concentrations are provided since 1980, and retrospective measurements on ice cores allow to reconstitute chronologies up to 800,000 years ago. For forests, there have been regular inventories covering the majority of Europe's large forest countries (including France) since the 1960s. For soil, the monitoring networks were established in Europe in the 1990s (RENECOFOR in France), following the dying out of forests attributed to acid rain (Nicolas *et al.*, 2008). However, a densification of these networks and changes to the measurement protocols are required to detect changes in stocks of organic matter (Saby *et al.*, 2008).

Spatial correlations and inference of trends over time

Spatial variations in the climate are classically used to establish correlations with spatial variations in the soil's OM stocks under natural vegetation. These studies can take other environmental factors into account, such as the texture of the soil, rockiness, topography, etc. The relationships obtained give an idea of the long-term effects of climate on the soil OM storage. However, this does not allow us to predict at what speed and according to what trajectory a hypothetical new state of balance will be reached (Smith and Shugart, 1993).

Flow studies: intakes and out-takes of OM in the soil

In order to predict the dynamics of OM in the soil, there is a need to understand the processes that determine it. Under forest, soil OM is essentially formed by transformation and incorporation of dead plant tissue: regular inputs of litterfall and fine roots, and irregular inputs of dead plants. Losses of carbon are mainly the result of microbial respiration in well-drained soil, whilst evacuation in soluble or particulate form may represent a large flow in soils that are periodically waterlogged. In forests going through fires, some of the humus is consumed, whereas coals represent carbon inputs of a special nature, with strong stability over time.

The prospect of climate change has for some 25 years now led to a substantial bolstering of research projects into the processes of OM storage in soil and vegetation, with a major focus on their control by environmental factors whose major evolutions are predicted. Entirely new experiments have appeared in forests: FACE (free-air CO_2 enrichment) systems in which CO_2 is diffused within forest stands (Ainsworth and Long, 2005), heating of the soil using buried electrical cables or other processes (Rustad *et al.*, 2001), or partial thoughfall exclusion to simulate droughts (Nepstad *et al.*, 2002). We should note that the effects of an increase in CO_2 can only be studied through experimentation, due to the almost perfect spatial homogeneity of this factor.

Carbon cycle models

Experiments provide contextual elements for an understanding and quantification of the carbon cycle, and models try to use them with a more widespread scope. There are a wide range of models that explicitly integrate processes for the mineralisation of carbon and nitrogen in the soil, which can be classified as a function of the spatio-temporal scales for which they have been designed, from models on soil aggregate scale to global models (Manzoni and Porporato, 2009).

These models serve on the one hand to clarify the understanding that we have of the carbon cycle, and on the other hand to simulate future changes of the carbon cycle by altering some control factors. In this way, predictions of the effects of climate change over the 100 years to come are made by using various scenarios for the future change in global levels of greenhouse gases provided by the Intergovernmental Panel on Climate Change (IPCC). Several series of scenarios have been published in this way (1992, 1996, 2007, 2013), which serve as intake variables for change models in the area of climate, oceans and terrestrial ecosystems.

Models for change in soil carbon storage must also take into account land use changes, evolutions of agronomic or forest practices, and forest ageing or rejuvenation. During the 20th century, these factors have had a global impact on the same scale as the climate changes regarding stocks of SOM, but with spatio-temporal variations that are a lot stronger (Eglin *et al.*, 2010).

EFFECTS OF CLIMATIC FACTORS

Stocks of soil organic matter

Many studies of the spatial distribution of carbon stocks under natural vegetation have revealed positive correlations with rainfall and negative correlations with temperature, either on the global scale (Post *et al.*, 1982 ; Jobbagy and Jackson, 2000) or in more restricted territories, such as the USA (Homann *et al.*, 2007) or France (Martin *et al.*, 2011). This strongly suggests that a hotter or drier climate will decrease the soil carbon stocks. However, although global warming has already occurred in several world regions, with impacts that can already be measured for vegetation (phenology, species distributions), no direct measurement has been able to detect a decrease of soil OM storage that was clearly linked to global warming. Such an OM storage decrease has been observed in the soils of England between 1978 and 2003, and has been partly interpreted as a direct effect of global warming (Bellamy *et al.*, 2005). However, it has subsequently become apparent that the only probing explanatory factor was the land use change (Chapman *et al.*, 2013).

Net primary production

Net primary production (NPP) is the dry mass of organic matter produced annually by the vegetation per unit of surface area. It is limited by a range of ecological factors, whose relative importance varies strongly over space, and more or less over the course of the year. On the global scale, a modelling study states that the major limiting factors for NPP are – by decreasing order of importance – the water balance (52% of surface area of the land), the temperature (31%), radiation from the sun (5%) or other non-climatic factors (12%), such as nutrition or biotic constraints (Churkina and Running, 1998). Still on the global scale, the net primary production of forests can be modelled simply through the combination of an increasing temperature function and an increasing rainfall function from 0 to 2000 to 3000 mm, then slowly decreasing (Del Grosso *et al.*, 2008). It is generally acknowledged that global warming has a positive effect on NPP in boreal and temperate areas, due to the lengthening of the season of vegetation and improved mineralisation of the soil nitrogen. However, global warming also increases evaporation, and consequently the risk of water stress and excess mortality in dry periods. In fact, a slight decrease in global NPP has been recorded during the decade 2000-2009, in relation to an increase in the frequency and severity of dry and/or hot episodes (Zhao and Running, 2010).

Mineralisation of soil organic matter

The temperature and humidity of the soil have positive effects on soil respiration that have been studied for a long time. We consider that in a wide range of values, soil respiration increases exponentially with the temperature (Davidson and Janssens, 2006) and in a linear way with the logarithm of water potential (Orchard and Cook, 1983). It nonetheless remains necessary to strongly refine these relations, for applying them to a broad diversity of ecosystems and to completely new climate changes. Two issues should be better considered: (i) the multiplicity of environmental factors and their interactions and (ii) the general heterogeneity of organic matter.

To illustrate the first issue, we will cite two examples. The first concerns the action laws used to predict the mineralisation of soil carbon as a function of humidity: they are substantially improved if we take into account soil characteristics such as texture and organic matter levels, whereas the action laws used in the current models for C dynamics are the same irrespective of the soil type (Moyano *et al.*, 2012). The second concerns one-off events that can still be devastating, such as forest fires. It has been estimated that the fires that followed the extreme drought of 1997 in Indonesia emitted the equivalent of 13 to 40% of the global annual emissions by combustion of fossil fuels (Page *et al.*, 2002). However, the fires leave coals with very high biochemical stability in the soil, which in the long term could compensate losses of SOM.

The heterogeneity of organic matter may be described by a high diversity of molecules, residence time, biochemical stability and physical protection. Through the study of an 80 years old bare fallow, Barre *et al.* (2010) reach the evaluation that nearly a quarter of the initial carbon stock may be considered as highly stable (residence time of at least several centuries in the soil). However, the kinetic theory of enzymatic reactions predicts that the mineralisation of this stable carbon will increase more quickly with global warming than that of labile organic matter (Davidson and Janssens, 2006). This prediction has been subject to a debate over the past few years, but today seems to be confirmed by experimentation (Lefevre *et al.*, 2014). This backs up the hypothesis that global warming will eventually lead to positive feedback from terrestrial ecosystems on the greenhouse effect, i.e. terrestrial ecosystems will emit more greenhouse gases than they will absorb.

EFFECTS OF ATMOSPHERIC FACTORS

Net primary production

Experimental rise in atmospheric CO_2 can lead to a strong increase (> 30%) in net primary production of forest stands, but the intensity and durability of this effect is greatly dependent on the soil's richness in nutrients: in poor soils, the fertilising effect of the CO_2 is either short lived (a few years), or non significant (Koerner, 2006). The rise in atmospheric CO_2 especially stimulates the development of fine roots, the production of root exudates and the allocation of carbon to mycorrhizae (Drake *et al.*, 2011), which can be understood as a re-balancing between the potential for acquisition of carbon and soil nutrients. On the contrary, nitrogen fertilisation benefits the development of foliage and the litter production as a priority (Aber *et al.*, 1998).

Today it is widely acknowledged that the major explanatory factor for the increase in temperate and boreal forest productivity over the course of the 20th century (Lloyd, 1999), estimated at +50% in France (Bontemps *et al.*, 2009), lies in nitrogen deposits or in the interaction between these deposits and the increase in CO_2 (Magnani *et al.*, 2007 ; Bontemps *et al.*, 2011 ; Eastaugh *et al.*, 2011). Such an important effect of nitrogen is due to the fact that this element is a major limiting nutrient of plant production in the boreal and temperate regions – whilst it is mainly phosphorous in humid tropical rainforests (Reich and Oleksyn, 2004; Cleveland *et al.*, 2011).

We are however beginning to observe signs that this nitrogen fertilising effect may be saturated in some temperate forests. For example, the growth of firs in the Vosges seems to be strongly correlated with the nitrogen richness of the soil during the 20th century until 1970, and then the correlation disappears (Pinto *et al.*, 2007). Other observations in Switzerland (Braun *et al.*, 2010) and on the East coast of the USA (Crowley *et al.*, 2012) indicate that there is a process of moving from a nitrogen limitation to a phosphorous limitation, which could become widespread during the 21st century (Goll *et al.*, 2012).

Decomposition of OM and carbon stocks

Rise of atmospheric CO_2 has a slightly positive effect on the C/N ratio and the lignin rate of litter, without this leading to a major slowdown in OM decomposition (Norby *et al.*, 2001). On the other hand, the stimulation of the metabolism of fine roots leads to an activation of microflora, which is reflected by a very large increase in soil respiration. This excess mineralisation compensates approximately the increase in OM inputs to the soil; in the end, the rising atmospheric CO_2 does not have any perceptible effect on the carbon storage in the soil (Dieleman *et al.*, 2010). This result must however be put into perspective by the fact that it is based on experiment periods that are relatively short (< 12 years), which means that it does not integrate the increased production of wood. In addition, the densification of the network of fine roots up to a high depth suggests potential for a slow increase in carbon stores (Iversen *et al.*, 2012).

In forests, nitrogen deposits lead to a substantial decrease in the C/N ratio of the litter produced, which tends to accelerate the initial stages of their decomposition. However, there is a trend towards a reduced soil respiration as an effect of nitrogen deposits, which is all the more marked since the soil is already rich in nitrogen (Janssens *et al.*, 2010). Two explanations are put forward: on the one hand, the addition of nitrogen to a litter that is rich in lignin (highly frequent in forests) would favour the constitution of organic molecules that are resistant to biodegradation; on the other hand, nitrogen inputs would modify the soil microbial community towards more decomposers of labile, energy-rich compounds, and less decomposers of recalcitrant substrates (Janssens *et al.*, 2010).

As nitrogen deposits almost always have a positive effect on net primary production and very often have a negative effect on the mineralisation of carbon in the soil, their average impact on carbon stocks is clearly positive, as has been confirmed by a large number of measures (de Vries *et al.*, 2009).

Soil acidification

In Europe and in North America, the soil acidification caused by the emission of atmospheric pollutants experienced a peak at the start of the 1980s. New regulations have made it possible to substantially reduce industrial emissions of pollutants, especially emissions of SO_2 which were the main agent in the production of acid rain. Nonetheless, these anti-pollution measures have also resulted in a reduction of atmospheric calcium contributions, which partly counterbalanced acid contributions. Initially more diffuse, nitrogen emissions have been less affected. Nitrogen deposits may contribute to the desaturation of soils in Ca^{2+}, Mg^{2+} and K^+ according to 2 large mechanisms: (i) increased leaching of these cations in drainage water due to direct (NH_4^+) or indirect (NO_3^-) causes and (ii) an acceleration in their harvesting by the vegetation under the effect of nitrogen fertilisation, which will lead to a subsequent return or an exporting of these elements by use of biomass (Lucas *et al.*, 2011). Lastly, we should point out that the rise in atmospheric CO_2 leads to a slow yet inexorable trend towards the acidification of soil solutions (Andrews and Schlesinger, 2001).

The result of all these changes in France and elsewhere in Europe is a recent trend towards an increase in soil pH (Riofrio-Dillon *et al.*, 2012 ; Jandl *et al.*, 2012). However, a lot of studies underline the slowness of this restoration, and the persistent vulnerability of a large number of forest stands that have received large sulphur deposits in the past (Akselsson *et al.*, 2013 ; Jonard e*t al.*, 2012). In addition, this trend towards improvement remains dependent on the future evolution of nitrogen deposits and the atmospheric deposits of cations (Lequy *et al.*, 2012).

In China, the acidification of soil is a current problem that is very significant (Hicks *et al.*, 2008). It risks also becoming significant in the decades to come in South America and in South-East Asia (Busch *et al.*, 2001).

Nitrogen and ozone deposits

Nitrogen oxide emissions also favour the formation of ozone in periods of bright sunshine. Ozone has deleterious effects on photosynthesis and growth, which have been well demonstrated by experiments in greenhouses (Skarby *et al.*, 1998), whilst recent outdoor fumigation systems confirm the negative effect of ozone on forest stands growth (Karnosky *et al.*, 2005). On the other hand, the effects of ozone on the soil are still not very well understood (Pregitzer *et al.*, 2006).

SIMULATION OF THE EFFECTS OF GLOBAL CHANGES

General trends

The majority of simulations of changes in soil carbon storage on the global scale – carried out based on the GIEC scenarios – predict a global effect that is more positive than negative for climate change with respect to OM stocks in the soil between now and 2100 (Gottschalk *et al.*, 2012). This is explained by a strong increase in net primary production, due to global warming and fertilisation caused by the CO_2, whilst the increase in mineralisation of the OM caused by global warming is limited by a lower availability of water. This global trend does however hide strong disparities depending on the region and type of vegetation. In this way, forest soil in boreal and temperate regions tends to have a lower OM content, as the predominant effect is that of global warming on decomposition, whereas forest soil in tropical regions is believed to be enriched in OM, the predominant effect being an increase in plant production (Gottschalk *et al.*, 2012). These climate change effects may however be largely counterbalanced by those of changes in land use and plant cover. In temperate and boreal regions, afforestation and ageing of forests should have positive effects on the soil OM storage, whereas in tropical regions, deforestation followed by cultivation will have opposite effects.

Limits of the current models and prospects for improvement

We should emphasise that these trends are subject to high levels of uncertainty, which arise from (i) emission scenarios, (ii) the absence of global scenarios for intake variables as important as nitrogen deposits or the production of ground level ozone, (iii) uncertainties regarding climate models, in particular in order to predict rainfall patterns (Falloon *et al.*, 2011), (iv) simplifications that are still excessive for terrestrial models, in particular when taking into account interactions between factors.

The introduction of scenarios for nitrogen deposits only exists at the moment for local studies, whereas in principle it is one of the factors that is most favourable to the OM enriching of OM in forest soil (Dijkstra *et al.*, 2009). This positive effect has for example been demonstrated in the forests of Central Europe, where it more than compensates the effect of climate change by horizon 2050 (Tatarinov *et al.*, 2011).

Among the interactions between factors that complicate the modelling of their effects on Soil OM stocks, two are of particular importance. Firstly, any warming accelerates the mineralisation of nitrogen in the soil, and consequently has similar effects to the nitrogen deposits (Dieleman *et al.*, 2012). Secondly, an atmosphere that is richer in CO_2 improves the water use efficiency of vegetation, since the opening of leaf stomata regulates both the absorption of CO_2 and the loss of water at the same time. However, this link is strongly dependent on the species (Gagen *et al.*, 2011).

CONCLUSIONS

Up to now, it has not been demonstrated that there is any substantial variation in the quantity of organic matter stored in forest soils that can be said to be clearly attributable to climate and atmospheric change. However, global warming is expected to lead to a fall in these stocks in temperate and boreal forests over the coming century, but the predictions for the models are still marred by a high degree of uncertainty. A major bias in carbon models on the global scale is the failure to take into account nitrogen deposits, which appear to be the environmental change that is the most favourable to an increase in stocks of organic matter in forest soils, via 3 mechanisms: (i) increasing net primary production, (ii) a shift in microbial communities to the detriment of specialist micro-organisms in the lysis of recalcitrant substrats, (iii) the formation of organic molecules that are rich in nitrogen and resistant to biodegradation. The positive effect of nitrogen deposits on net primary production seems however to become weaker in some places, and a gradual shift from N-limited to P-limited nutrition is expected in boreal and temperate forests, whereas tropical forests are already mainly P-limited. Nitrogen enrichment can also aggravate the leaching of exchangeable cations (Ca, Mg, K) in soils that are naturally acidic, even though anti-pollution measures in Europe and the USA have strongly reduced sulphur emissions, which are the main anthropogenic factor in acidification. Lastly, the abundance of nitrogen oxides encourages ozone formation, which also reduces primary production.

Experiments into air CO_2 enrichment have yet to prove any effect on soil OM storage, but we can expect in the long term that the positive effects for lignin production and for the allocation of carbon in roots will favour the carbon enrichment of the soil.

Beyond stocks of organic matter, which are important for a large number of physical, chemical and biological properties of soil, we can see that climate and atmospheric changes have strong effects on the relative abundance of the nutrients that are required for the growth and health of forests: between N, P, K, Mg and Ca, the cards are being reshuffled.

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SOIL ORGANIC MATTER OF FORESTS AND CLIMATE AND ATMOSPHERE CHANGES (Abstract)

Soil organic matter is the largest carbon reservoir of the terrestrial ecosystems and is a main driver of soil fertility. Its evolution driven by climate and atmosphere changes is a main issue in the medium and the long term, on a global scale and on a local scale. We present a literature synthesis on this topic, focused on forest SOM. The main study methods are the comparisons of soil inventories, the interpretation of spatial correlations with climate into temporal trends, the monitoring of the inputs and outputs of soil carbon in forest as well as in laboratory, and a diversity of models that link the knowledge's and foresee the evolutions of SOMs. The results confirm that a decrease in SOM content is to be expected sooner or later in the boreal and temperate forests, due to the global warming. However, nitrogen deposition has a positive effect on SOM storage, which is not yet included in the carbon models at a global scale. In addition, the free air carbon dioxide experiments (FACE) could not detect any change in SOM storage up to now, but it is likely that positive effects will occur later. Qualitatively, nitrogen deposition and warming are reducing the limitation of fertility by nitrogen, and it is expected that phosphorus limitation will become relatively more important.