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SYNTHESIS AND EMERGING IDEAS

Not just a carbon story: uncertainties related to the significance of microbially-produced nitrous oxide during soil carbon sequestration

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Abstract In the last decade, in extensive debates on the potential of soil carbon sequestration to decrease the amount of greenhouse gases (GHGs) emitted by soils, and thereby help mitigate climate change, discussions have centred overwhelmingly on CO_2. Separate research efforts have shown that other greenhouse gases, and in particular N_2O, produced by soil microorganisms, can have a sizeable impact on climate change. At this stage, it is unclear to what extent climate mitigation benefits due to increased soil carbon storage could be offset by N_2O emissions from soils. In the present article, we critically review the relevant primary literature. We conclude that reliable data do not exist at this point to determine whether soil carbon sequestration can help mitigate climate change at all. This is in part because of a lack of recognition in past years of the imperative to measure simultaneously all GHG emissions from soils to cope with their large spatial and temporal heterogeneity, and, also because of ignoring the dynamics of the hydric regime of soils. To resolve this question, a comprehensive, interdisciplinary approach of soil organic matter sequestration is needed, encompassing all the factors that can influence the microbial emission of GHGs.

Keywords Climate change mitigation · Soil carbon storage · Greenhouse gases · Nitrous oxide · Methane · Policy making

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Introduction

Recent monitoring data from around the world (e.g., https://public.wmo.int/) suggest that the past three years, 2023–2025, have been the three warmest years on record. The consolidated three-year average 2023–2025 temperature is 1.48 °C (with a margin of uncertainty of ± 0.13° C) above that in the pre-industrial era. For many years, the value of 1.5 °C has been considered to be a critical threshold, above which, over time, the likelihood of tipping points, leading to irreversible damages, increases substantially (e.g., Armstrong McKay et al. 2022; Möller et al. 2024). Concurrently, various organisations like the National Aeronautics and Space Administration (NASA) in the US, or the World Meteorological organization (https://public.wmo.int/), have reported that carbon dioxide (CO_2), now at a concentration of 430 ppm, has accumulated in the atmosphere faster in the last few years than at any previous time in human history, suggesting that countries are unable to successfully deal with the technical, economic, and social challenges of the key remedial strategy recommended by the Intergovernmental Panel on Climate Change (IPCC), namely the reduction of greenhouse gases (GHGs) emitted from fossil fuel consumption.

Alternative approaches to the mitigation of climate change, which actively remove greenhouse gases (GHGs) from the atmosphere and are therefore sometimes referred to as negative emission technologies (NETs), have appeared to some to be promising. They are being intensively studied, and are in some cases implemented in practice. In that context, it was logical to develop NETs by turning to the management of soils, given the very large stock of organic matter they contain and the fact that soils in North America and Europe have lost a significant portion of their organic matter in the last 70 or so years since the advent of intensive agricultural practices, and sometimes continue to do so even after practices are adopted that have been promoted specifically for their capacity to store more carbon (e.g., Loubet et al. 2026). From that perspective, there is a strong consensus that increasing the organic matter content of soils, regardless of whether or not it helps mitigate climate change, is absolutely crucial for a number of reasons, such as maintaining crop yields or improving the architecture of soils, which would be important under most conditions but are even more so under a changing climate (e.g., Johannes et al. 2017; Baveye et al. 2020; Sauzet et al. 2024).

Three soil-based NETs involve the sequestration of carbon in soils, via the incorporation, respectively, of pyrolyzed organic matter (Woolf et al. 2010; Lin et al. 2015; Smith, 2016; Lehmann et al. 2021), ground silicate rock (Kantola et al. 2017; Lewis et al. 2021), or fresh crop residues (Whitmore et al. 2015; Pellerin et al. 2020; Rumpel et al. 2023a, b; Almaraz et al. 2023). These three NETs have been the object of a large body of literature over the last two decades. Whilst many articles have emphasized the benefits of these NETs, others have argued that their implementation faces significant hurdles (e.g., Schlesinger and Amundson 2019). In particular, the use of pyrolyzed organic matter may in some cases stimulate the emission of N_2O by soils (e.g., Sánchez-García et al. 2014; Kollah et al. 2022), cause shifts in ligninase to cellulase ratios, correlating negatively with soil C sequestration (Feng et al. 2023), and lead to changes in the bulk density of soils, which if they are improperly taken into account, can bias soil carbon sequestration estimates (Sun 2026). In addition, biochars additions often suffer from economics that has already been shown unfavourable (e.g., Bach et al. 2016; Kochanek et al. 2022) and is likely even more so due to the fact that pyrolyzed organic matter does not contribute to the maintenance of soil architecture (Baveye 2023a, b) or to conclusively improving yields (Chaplot et al. 2025). The field application of ground silicate rock is currently facing a series of challenges ranging from health hazards associated with dust exposure (Edwards et al. 2017), risks of soil contamination with toxic traces elements (Dupla et al. 2023), limited social acceptance (O'Sullivan et al. 2025), and the fact that little actual knowledge is currently available on weathering and carbon sequestration rates under field conditions (Fuss et al. 2018; Dupla et al. 2025; Schiedung et al. 2026). Simultaneously, a growing body of literature has identified practical reasons causing the incorporation of fresh plant residues to soils to have only a marginal and temporary effect on the amount of carbon sequestered in soils, and therefore on the amount of CO_2 released by soils to the atmosphere (e.g., White and Davidson 2016a, b; Baveye et al. 2018a, b; Powlson and Neal 2021; Berthelin et al. 2022a, b; Schlesinger 2022; Baveye et al. 2023; Moinet et al. 2023a, b; Powlson and Galdos 2023; Savage 2024; Waring 2024; Man et al. 2025).

In the overwhelming majority of debates that have taken place in the past two decades within the soil science community about these NETs and more broadly about the merits of relying on soils as GHG sinks to mitigate climate change, emphasis has been placed almost entirely on the fate of carbon in soils and on their release of CO_2 to the atmosphere. Researchers have either attempted to measure CO_2 emissions directly, or have tried to quantify them indirectly, based on measuring changes in SOM content over time. This C-centered perspective persists unabated to this day (e.g., Bruni et al. 2022; Georgiou et al. 2025; Chenu et al. 2025, 2026; Coucheney et al. 2025), with some authors stating that "soil is a major terrestrial carbon reservoir, and enhancing its carbon stock is a central strategy to mitigate climate change" (Copard et al. 2025) or that "soil organic carbon has emerged as a crucial component of international climate and environmental policy, serving as both a target for restoration and a lever for mitigation through carbon sequestration" (Chenu et al. 2026). Viewing things from that angle seemed justified initially, e.g., by the figures calculated for France in 2000 by Arrouays et al. (2002), indicating that of the total net GHG emissions in equivalent carbon, the contributions of the different GHGs amounted, respectively, to 69% for CO_2, 16% for N_2O, and 13% for methane. This ranking appears implicitly to have convinced many researchers over the years that a decrease of CO_2 emissions from soils, via sequestration of carbon, would automatically lead to positive results (e.g., Panchal et al. 2022; Rumpel et al. 2023a, b; Almaraz et al. 2023). The heavy emphasis on CO_2, and hence carbon, that ensued is particularly clear in the terminology used in debates about "carbon farming", by which farmers are remunerated to increase the carbon content of their soils and provide credits for industries that exceed regulatory CO_2-emission limits (e.g., Oldfield et al. 2022; Paul et al. 2023; Leifeld 2023; Van der Voort et al. 2023; Dupla et al. 2024), or in the literature on the development of a "carbon–neutral" agriculture (e.g., Oenema 2022).

Aside from the enormous C-centered literature extolling soil carbon sequestration as a "win–win" or even "win–win-win" solution to climate change, a separate and comparatively smaller body of publications has consistently pointed out the practical significance of, and the need to have more information about, other GHGs, beside CO_2, emitted by soils (e.g., Schlesinger 2010; Ma et al. 2012; Imer et al. (2013); Crutzen et al. 2016; Halvorson et al. 2016; Muñoz and Zornoza 2017; McDaniel et al. 2017; Cha-un et al. 2017; Xia et al. 2018; Muhammad et al. 2019; Meier et al. 2020; Davies et al. 2021; Wong et al. 2023; Du et al. 2023). A particularly significant article in this context appears to be that of Li et al. (2005), who carried out computer simulations using the heavily-tested biogeochemical model DNDC (Li et al. 1992a, b, 1994). They simulated 20-year management scenarios involving both conventional tillage and no-till in fields in Iowa (U.S.A.), Hebei (China), and Bavaria (Germany). Their conclusion is that N_2O emissions would offset respectively 75, 103, and 308% of the climate change mitigating benefits of carbon sequestration in these three different situations. These model predictions have been confirmed by subsequent experimental and modelling work. Liu and Greaver (2009), for example, found that although N additions to soils increased the global terrestrial C sink, reduction in CO_2 emission could be significantly offset (to the tune of 53–76%) by stimulation of global CH_4 and N_2O emissions from multiple ecosystems. Haas et al. (2022), in another modelling study, concluded that "climate change will further intensify the effect of residue return on soil N_2O emissions, which on the long run will override the positive effects of increased soil C sequestration on the net GHG balance of arable cropping systems."

The separate literatures dealing respectively with carbon sequestration and N_20 emissions seem to rarely overlap. The C-centered literature on the benefits of soil carbon sequestration appears to frequently bypass articles that hold a conflicting perspective. Out of 20 groups of authors presenting national perspectives in the often-cited article of Minasny et al. (2017) on the 4-per-mil initiative, only 2 mention the emission of N_2O by soils as a possible offset to the benefits derived from soil carbon sequestration. The comprehensive review of the field by Amelung et al. (2020) briefly mentions Li et al.'s (2005) prediction that N_2O emissions could offset the climate change mitigating effect of soil carbon sequestration, but, in spite of that, the abstract of this article starts with the clear message that "sustainable soil carbon sequestration practices need to be rapidly scaled up and implemented to contribute to climate change mitigation". Likewise, Guenet et al. (2021) also cite Li et al. (2005) but do not discuss their conclusions in any detail. Nevertheless, this article by Guenet et al. (2021), which has been heavily cited since its publication, purports to address directly the extent to which various agricultural management practices meant to increase soil organic carbon (SOC) stocks could concomitantly lead to increases in N_2O emissions that could offset the climate change benefit of sequestering carbon. Their conclusion, based on a review of 13 published meta-analyses, is that "the climate mitigation induced by increased SOC storage is generally overestimated if associated N_2O emissions are not considered but, with the exception of reduced tillage, is never fully offset."

Since this article by Guenet et al. (2021) seems to have acquired a pivotal role in the justification of the exclusively C-centered narrative in the last couple of years, it would appear warranted to revisit their analysis. Another reason for doing so is that it is not clear at this stage to what extent their conclusions, based on previous meta-analyses, are still valid. In the last couple of years, two decades after problems were identified in applications of the method (e.g., Eysenck 1984, 1994), concerns have been raised about the quality of many published meta-analyses (e.g., Baveye 2024; 2025a, b), to such an extent that increasing numbers of scholarly journals in a wide range of disciplines are now adopting measures to make sure that future meta-analyses meet appropriate standards. In soil science, Fohrafellner et al. (2023) recently published a thorough assessment of 31 meta-analyses focused on the effects of different management practices on SOC contents. They concluded that out of these 31 meta-analyses, only one met almost all the quality criteria they identified for such endeavours. Notably, several of the 13 meta-analyses reviewed by Guenet et al. (2021) were among those assessed by Fohrahfellner et al. (2023). They satisfied fewer than half of these authors' quality criteria. More broadly, none of the 13 meta-analyses reviewed by Guenet et al. (2021) checked for publication bias in the body of literature they looked at, and only 2 carried out any kind of weighing of effect sizes with the inverse of the variance, casting significant doubt on the soundness of conclusions that could be derived from them.

In this general context, we decided to return to the primary sources reviewed by the various meta-analyses considered by Guenet et al. (2021), and analyse them in detail, without carrying out a new meta-analysis, which at this stage does not appear to be theoretically sound given the unbalanced state of the literature. Our primary objective was to assess what we actually know from local, small-scale field measurements involving only soil (and no above-ground plant contributions), about the extent to which the production of other GHGs than CO_2, and in particular N_2O, by soil microorganisms can offset the climate change benefit of sequestering carbon in soils. In the section immediately following this introduction, we discuss how the traditional perspective on the fundamental interdependence between the dynamics of C and N in soils is modified by research carried out in the last decade on the nitrogen nutrition of plants and the impact of rainfall patterns on the dynamics of both C and N dynamics. On that basis, we argue that measurements of CO_2 and N_2O emissions from soils should imperatively occur simultaneously on the same soil samples or at the same locations in the field, and should include parallel characterizations of microscale hydric properties of the soils. In the subsequent section, we show that primary sources used in the meta-analyses reviewed by Guenet et al. (2021) downplayed the interdependence of C and N dynamics, the practical significance of the spatial heterogeneity of soils, and the importance of their hydric regime. Finally, in the last section, we draw what appears to be the only logical conclusion from the preceding analysis and we try to outline future experimental and theoretical research efforts needed to get a more precise picture than is currently available of the extent to which non-CO_2 GHG emissions from soils are likely to affect the alleged potential of soil carbon sequestration to mitigate climate change, regardless of which of the NETs mentioned above is adopted in practice.

Carbon and nitrogen fates in plant-soil systems: intimately connected and strongly influenced by rainfall

Over the last decades, researchers have studied in great detail the many processes involved in the cycles of C and N in soils, and in their interactions. Progress continues to be made, unabated, in this area, as illustrated for example by the recent article of Yeung et al. (2025), which sheds light on the different mechanisms by which N enrichment in soils triggers diverse responses of different soil organic carbon pools. Nevertheless, many aspects of the complexity associated with the C and N cycles are reasonably well understood at this stage, as illustrated graphically in Fig. 1. It is also generally acknowledged that the net effect of all the processes depicted in this figure depends largely on climate as well as on soil type and management, and is therefore very difficult to predict a priori.

A key feature of Fig. 1 is that as the focal point of the soil C cycle on the left, one does not find a "C pool", but a SOM one, containing both organic C and organic N. Indeed, even though a lot of attention is devoted to carbon sequestration in soils these days, one should never forget that what is "sequestered" or at least stabilized in soils is not C but really SOM, even on mineral surfaces. The stabilized mineral-associated organic matter (MAOM) often has a significantly lower C:N ratio than plant materials, and thus N is sequestered as well. In industrial agricultural settings, this likely means that there will be an increased need for synthetic N fertilizers, and the C accounting costs of this increased fertilizer (production, deployment, gaseous release) should be added into the overall GHG balance sheet (Schlesinger 1999, 2022).

Most of the aspects of the C and N cycles have been clear to researchers for several decades, and are routinely covered in depth in most soil chemistry or biogeochemistry textbooks. On a couple of aspects that are directly relevant to GHG emissions, however, significant progress has been achieved only recently. The first aspect concerns the impact of plants on the fate of C and N in soils. In Fig. 1, as in the original version of this diagram in Guenet et al. (2021), plants, although centrally located, seem to play a secondary, almost passive role. However, the perspective in this respect has evolved rapidly in recent years. Research over the last decade has shown that plants are actively influencing the C and N cycles in the soil surrounding their roots. Acquisition of N by plants through mineral N absorption from soils is highly regulated by plant growth capacity and synchronized with acquisition of C by plants through photosynthesis (Lemaire et al. 2008; Briat et al. 2020). Moreover, the plants themselves influence dynamic processes related to nitrogen in soils via interactions with microbial communities that are present in the rhizosphere (Briat et al. 2020). Progress has been made recently in terms of the dynamic analysis of the soil microbiome (Stringlis et al. 2018), the influence of root exudates (Akhami et al., 2023; Garcia Arredondo et al.

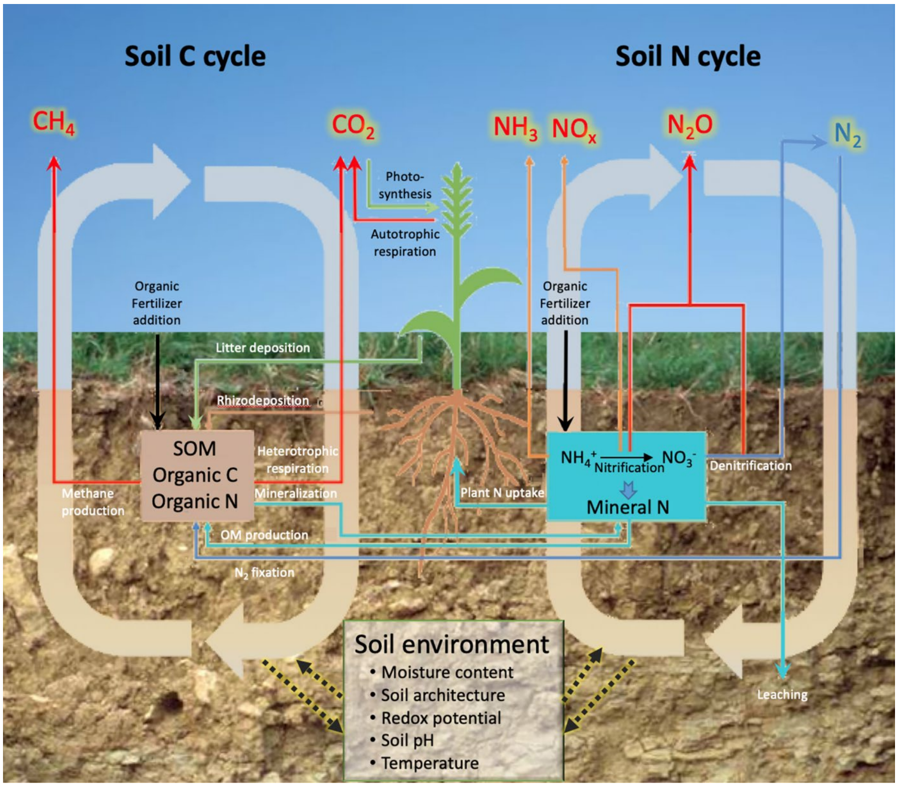


Fig. 1 Schematic representation of the interconnectedness of the carbon and nitrogen cycles in soils. (Modified from Guenet et al. (2021)). The location of the subcomponents relative to the whole is arbitrary and for illustrative purpose. One could for example locate centrally the soil organic matter box, since it participates in both cycles

2024; Rötzer et al. 2026), and the role of soil microbe communities in making nutrients available to plants (Jacoby et al. 2017; Garcia and Kao-Kniffin 2018). As a consequence, soil N availability can no longer be considered solely as a property of the external medium to which plants adapt passively, but should be viewed as resulting from the functioning of the whole plant-soil-living organisms ecosystem (see Fig. 2).

The classical paradigm for plant N nutrition was based on the assumption that the mineralization of the soil organic N was the bottleneck restricting N supply to plants (Balesdent et al. 1988). According to this paradigm soil mineral N supply was considered as decoupled from plant N demand. The revised paradigm illustrated in Fig. 2 is now based on a large series of results showing the capacity of the plant to modify most N fluxes from soils (Finlay et al. 2020; Henneron et al. 2020; Grandy et al. 2022, 2024). This new paradigm has been recently developed by using the concept of synchrony between plant demand and soil supply to design sustainable agrosystems (Fontaine et al. 2023). These authors put forward that asynchrony between soil N supply and plant N demand in agrosystems is the cause of most nutrient losses, greenhouse gas emissions, and reliance on synthetic fertilizers. Therefore, the accumulation of NO_3^- in soil and its residence time, the two parameters to consider in order to predict the extent of N_2O emissions, are under the control of *both* soil and vegetation. This observation is pertinent to the debate on whether one should consider both soil and plants when trying to measure GHGs emissions.

Another aspect of the complex interactions of the C and N cycles in soils, which has attracted a sizeable amount of attention in recent years, is related to the strong influence that soil moisture has on the emission of GHGs to the atmosphere. Years ago already, several authors pointed out that the amount of moisture that is present in soils, regardless of its dynamics, seems to influence the rate of their gaseous emissions (e.g., Letey et al. 1980; Aulakh et al. 1983; Linn and Doran 1984; Aulakh and Doran 1990). Modeling work in recent years attempted to take this effect of soil moisture into account (e.g., Wang et al. 2020; Hao et al. 2025). Other parameters have also been

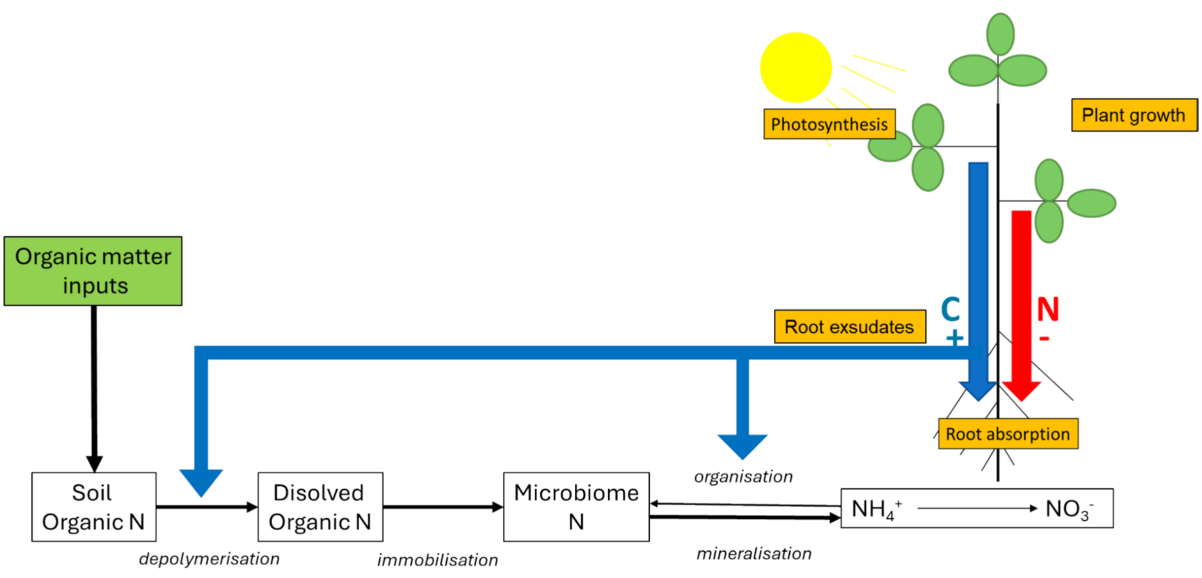


Fig. 2 Schematic representation of plant-soil microbiome interactions for control of N dynamics in soil. Mineral N absorption by plant depends of soil N supply in NH_4^+ and $NO_3.^-$ and is retro-controlled by (i) a positive C signal from shoot associated to photosynthesis; and (ii) a negative N signal from shoot associated to plant N satiety. These two signals leading to control plant N uptake according to plant N demand for growth (Briat et al. 2020). By feeding soil microbe communities with highly available C by root exudates, plants have the capacity to accelerate the depolymerization process considered as the limiting step for the mineralization of soil organic matter, and at the same time to stimulate the reorganization of mineral N forms into microbial N (Fontaine et al. 2023)

shown to have an effect on GHG emissions, like the geometry and connectivity of pores (Rabot et al. 2015a, b), the location of particulate organic matter in the pore space (Kravchenko et al. 2017, 2018), and the positioning of microorganisms relative to POM (Schlüter et al. 2019). In this context, Rohe et al. (2021) and Ortega-Ramírez et al. (2023) have shown that to describe reasonably well the emission of N_2O from soils, it is necessary to involve descriptors accounting for the fact that the propensity of "hot-spots" of microbial activity in POM to turn anoxic depends on the distance to air-filled pores.

Nevertheless, one could argue that the most interesting findings with respect to the effect of soil moisture is that N_2O emissions are highly dependent on a process that tends to be generally ignored (e.g., in the review of Hao et al. 2025), namely the fast dynamics that is associated with rainfall events. That phenomenon is not entirely new. Waksman and Starkey (1923) and Birch (1958) showed experimentally that the rewetting of soils that were previously dried produced a sudden release of CO_2 by the soils. This process, known as the "Birch" effect but more appropriately referred to as the "Waksman-Starkey-Birch" effect (as suggested by Steve Blazewicz, personal communication, 2025), is currently researched intensively (e.g., Qiu et al. 2022; Singh et al. 2023; Guo et al. 2024; Min et al. 2026), along with the effect of pore connectivity on the emission of CO_2 (e.g., Coucheney et al. 2025). Similarly, for N_2O, Rabot et al. (2014; 2015a, b; 2016), showed that the hydric history of soils strongly affects emissions. These authors carried out laboratory experiments on undisturbed soil columns, in which they varied the intensity and rate of soil drying under non-steady-state to control the bottom boundary condition. Three treatments of stepwise drying were applied across the range 0 to -100 cm pressure head in two wetting–drying cycles. Two types of N_2O peaks of the same order of magnitude were observed. A first peak appeared within 2 d after rewetting and was thought to be related to microbial processes. The second type of peak was sudden and occurred on average 1.6 h after the change in hydric regime, coinciding with a steep decline in the soil matric potential. The authors were unable to definitively determine the exact origin of the released N_2O, whether it resulted from previously entrapped gaseous N_2O or dissolved N_2O released from the soil solution. The intensity of the peak of N_2O emission during the soil drying was however correlated with the amount of water drained, indicating a link with the connectivity of the air-filled pore space. The sudden peak may occur when a continuous air-filled pathway suddenly connects a region of high production of N_2O with the soil surface. However, aside from this physical process, the air-filled space may also provide aeration to the soil and thereby, as observed by Blagodatsky et al. (2006) in batch and continuous cultures, stimulate the activity of heterotrophic nitrifiers and the production by them of N_2O.

Regardless of the exact cause, either physical or microbiological, of these sudden peaks of N_2O emission, their existence implies that one needs to exercise great care when monitoring the release of N_2O by soils, in order to capture all the relevant events, a conclusion also reached by Friedl et al. (2022). Because of the Waksman-Starkey-Birch effect, careful monitoring of the hydric condition of soils is required as well to appropriately schedule measurements of the emission of CO_2.

Concurrent measurements of GHG emissions from soils are essential

The intimate connections that exist between the C- and N cycles in soils, as depicted schematically in Fig. 1, suggest that to get accurate assessments of the extent to which the addition of fresh organic matter to a soil indeed results in a CO_2 sink, which would have a positive impact on climate change, one needs to know not only how much carbon stays in the soil over time, but also how much of the other GHGs beside CO_2 are emitted.

This measurement of emitted GHGs can in principle be carried out at a number of different spatial scales. Beside traditional "chamber-based" methods, which consist of collecting gases in chambers positioned at the soil surface at given locations in a field, one can also adopt complementary techniques involving, e.g., eddy covariance (EC), applicable to larger scales, from area of a few square meters to entire ecosystems. The EC method is based on the fact that surface fluxes are mixed via turbulence into the near-surface atmosphere. Consequently, EC measurements can be carried out at some distance above the surface, providing accurate and spatially-integrated flux density estimates (Egster and Merbold 2015). However, because of the distance above the soil surface at which it operates, the EC method is affected by meteorological conditions, in particular wind force and direction, and its "footprint" (the area that actually influences the measurement) shifts spatially over time. The point is often made that the interpretation of the data this and other large-scale methods produce in terms strictly of the soil GHG fluxes is further complicated or even becomes impossible if the soil is covered by vegetation, because the methods are not able to separate fluxes from the soil surface and from above-ground vegetation (e.g., Myklebust et al. 2008; Pavelka et al. 2018). However, even though it might sound reasonable to try to eliminate the effect of plants when one wants to study the emission of GHGs by soils, plants still exert an influence on the measurements through their roots, as explained above. The key reason why the kind of local measurement obtainable with the small chamber method is preferable under some conditions than large-scale eddy covariance measurements is that small-scale measurements are needed to understand, at a fine scale, which soil characteristics and agricultural practices are most conducive to GHG emissions from soils. Hence, methods based on small chambers continue to be used extensively when one tries to understand how physical, chemical, and biological processes occurring in soils influence their emission of GHGs (e.g., Thalasso et al. 2023; Pullens et al. 2023).

To alleviate the technical difficulties associated with the use of these small-chamber-based methods to measure simultaneously the emission of different GHGs, one might be tempted to simply measure the component of the C cycle, including the emission of CO_2, at one location, and the components of the N cycle, including the emission of N_2O, at another location nearby (see, e.g., Apostolakis et al. 2026). However, as various researchers have evinced, microbial activity in the topsoil is characterized by a sizeable spatial heterogeneity at small scale (e.g., Parkin 1987, 1993), and concomitantly, the physical and chemical properties of soils also exhibit significant small-scale spatial variability (e.g., Sisson and Wierenga 1981; Vauclin et al. 1982; Mallarino 1996). Even if one takes soil samples a few centimeters apart, the history of faunal activity or root growth in them may be sufficiently distinct to cause emissions of GHGs in the samples to be different than if these emissions had been measured in a single sample. In this respect, experimental results suggest that the presence of earthworms in soils can have a large effect on the amount of N_2O that is emitted, in a few cases at least by reportedly stimulating emissions locally by as much as 50.8% (e.g., Lubbers et al. 2011, 2013). Hence, the optimal and most accurate solution to monitor GHG emissions is to measure them concurrently on unique samples.

In that regard, contrastedly, not only do the meta-analyses reviewed by Guenet et al. (2021) not deal with concurrent measurements of carbon sequestration and N_2O emission in the same samples, but they do not even deal with data gathered in the same geographical areas or in similar soil types. Of the 13 meta-analyses reviewed by Guenet et al. (2021), only two involve primary literature sources that refer to both CO_2 and N_2O emissions. Kim et al. (2016) compiled the results contained in two separate sets of articles: 56 articles dealing with net rates of change of carbon stocks in agroforestry systems (from which one can estimate CO_2 emissions), and another, distinct set of 15 publications dealing with CH_4 and N_2O emissions *in other agroforestry systems*. In some of the primary sources compiled by Abdalla et al. (2019), N_2O emissions were measured directly, whereas in others they were indirectly estimated from N leaching data. CO_2 emissions were never measured but were always estimated indirectly. In all 11 other meta-analyses reviewed by Guenet et al. (2021), the primary sources related either to CO_2 emissions (Feliciano et al. 2017; Cardinael et al. 2018; Poeplau and Don 2015; Vicente-Vicente et al. 2016; Virto et al. 2012; Du et al. 2017; Meurer et al. 2018; Maillard and Angers 2014)), or to N_2O emissions (Mei et al. 2018; Kessel et al. 2013; Skinner et al. 2014) *but never to both simultaneously*. In the literature on the practice of meta-analyses, this mixing of data that are not directly related to each other is considered to cause what is referred to as the "apples and oranges" problem (e.g., Eysenck 1984; Sharpe 1997; Baveye 2024). Under these conditions, it would seem entirely reasonable to contend that the conclusion reached by Guenet et al. (2021) that "the climate mitigation induced by increased SOC storage is generally overestimated if associated N_2O emissions are not considered, but, with the exception of reduced tillage, is never fully offset" is questionable. Indeed, since the primary data on which this statement is based relate to processes occurring separately in entirely different soils, there is no real possibility to realistically compare and contrast the emissions of the various GHGs by individual soils.

Experimentally, it is not straightforward at all to carry out the concurrent measurements of all parameters needed to assess to what extent the benefits of carbon sequestration in soils may be offset by the emission of other GHGs, like N_2O and CH_4. On the carbon side, one needs to measure enough parameters to be able to calculate a mass balance in both a control plot and in a treatment receiving crop residues. One possible set of measurements could include carbon added, carbon drained, and emitted CO_2 or CH_4 over time. Another set would consist of initial carbon added, carbon left in the soil over time, and emitted CO_2 or CH_4 or carbon drained over time. On the nitrogen side, if one neglects in first approximation the fate of the N contained in the drainage water, one needs to measure over time, at a minimum, how much N_2O is emitted. *At present, no existing data set that we are aware of satisfies these requirements.* In other words, the claim that the incorporation of fresh organic matter, like crop residues, to soils can, at least partly, mitigate climate change is not backed at all by experimental data of any kind. It is entirely possible that so much N_2O, for example, is emitted by soils after addition of fresh organic matter that the net effect on climate change be one of worsening rather than mitigation. The fact that N_2O has a Global Warming Potential (GWP) 298 times that of CO_2 makes this scenario all the more plausible. Yet, it is also possible that some approaches to the management of N inputs in soils could result in a lowering of the total GHG emissions from soils, which would have a positive mitigating effect on climate change. The truth of the matter is that at this point we do not know one way or the other, whether the effect of sequestering organic matter in soils (and therefore both C and N) has a net positive or negative effect on climate mitigation.

The design of future experiments can take advantage of previous research

Given the entire lack of reliable data on simultaneous emissions of all GHGs by soils and on carbon accumulation in them, it seems obvious to recommend carrying out field or laboratory experiments to secure the information needed to determine to what extent soil carbon sequestration can help mitigate climate change. In this context, useful guidance for the design of suitable measurement protocols can perhaps be gleaned from a number of articles that, over the years, have attempted to measure, concurrently, the emissions of CO_2 and N_2O from soils. The direct monitoring of gases evolved from soils has historically presented sizeable challenges to experimentalists (e.g., Jury et al. 1982; Hutchinson and Livingston 1993; Conen and Smith 1998), but nevertheless, several groups of researchers, in the 1980s and 1990s, managed to overcome the hurdles by effectively "trapping" gas fluxes. They developed automated techniques to measure concurrently, at the same spot, the emission of several GHGs, in particular CO_2 and N_2O, either in the field (e.g., Lotfield et al. 1992; Brumme and Beese 1992; Smith et al. 1995; Thomson et al. 1997; Butterbach-Bahl et al. 1998, 2013; Scott et al. 1999; Hutchinson and Livingston 2001; Savage and Davidson 2003; Parkin and Venterea 2010; Laville et al. 2011) or in the laboratory, using samples brought there to that effect (e.g., Thomson et al. 1997). For example, the design with which Lotfield et al. (1992) and Brumme and Beese (1992) came up more than 30 years ago (Fig. 3a) presents the advantage that it involves two chambers; a central one where measurements are made, and an outer one that serves as a buffer zone to the one-dimensional flux of the gas in the soil under the central chamber. One occasionally-mentioned downside of the retractable lid, actioned by an electric motor, is that it is sensitive to strong winds when in an upward position. Another design (Fig. 3b), due to Scott et al. (1999) is far less affected by wind, but it does not involve dual chambers.

Using these and several other gas sampling devices, various researchers over the last 30 years have measured concurrently the emissions of CO_2, N_2O, and sometimes NO and NH_3 as well (e.g., Laville et al. 2011; Ma et al. 2012; Trost et al., 2013; Savage et al. 2014; McDaniel et al. 2017; Delon et al. 2017; Yang et al., 2020; Gillespie et al. 2023, 2024) in a wide range of soils and climatic conditions. The body of literature in this regard has been reviewed in detail by Xu et al. (2008), Chen et al. (2013), and Muhammad et al. (2019). Among them, Xu et al. (2008), considered 47 primary sources that did not mention any field application of fertilizers during the measurement year or in previous ones. The 18 and 41 studies reviewed, respectively, by Chen et al. (2013)

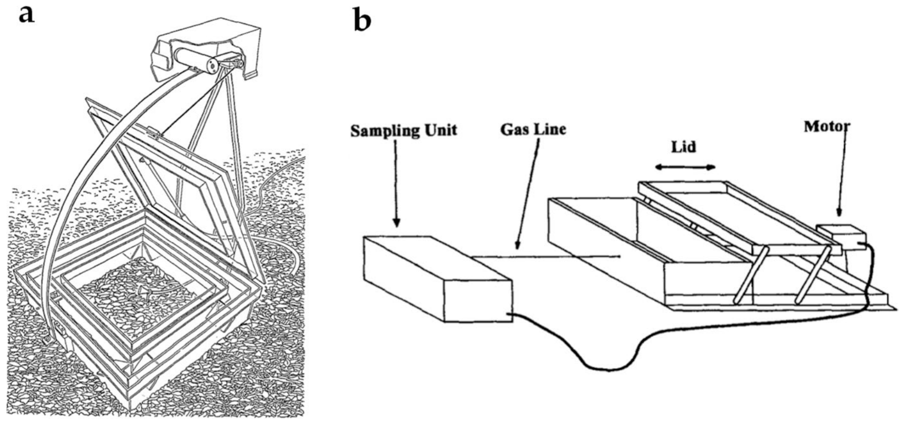


Fig. 3 **a** Double-wall chamber with motor-driven lid (Lotfield et al., 1992). **b** Automated sampling system developed by Scott et al. (1999). The auto-chamber is shown on the right with the lid in the open position. (Schematics reproduced with permission)

and Muhammad et al. (2019) had no such restriction. These authors all observed a positive, linear correlation between CO_2 and N_2O emissions from soils, even though the underlying data tended to be somewhat scattered. In addition, Muhammad et al. (2019) found inverse curvilinear correlations between CO_2 and N_2O emissions and the C/N ratio of plant residues incorporated in the soils under different agricultural practices. When they tried to relate the emissions of CO_2 and N_2O to the annual air temperature or annual precipitation, they observed scattered clouds of points with no statistically meaningful trend (Muhammad et al. 2019, Fig. 6).

A piece of research that, strangely, is not mentioned in any of these reviews and yet appears to be highly relevant is that of Scott et al. (1999). Using the automated sampling device depicted in Fig. 3b, these authors monitored CO_2 and N_2O emissions for 48 d, in a grass sward in Scotland, starting 5 d after the application of sewage sludge. The measurement frequency was adjusted to sample emitted gases every 4 h (chamber closed for six 1-h periods per day) when fluxes were expected to be high. At other times, the frequency could be reduced to every 8 h (chamber closed during three 1-h periods per day).

At various times during the experiment, rain fell on the field site (Fig. 4, top graph), sometimes heavily. N_2O emissions responded strongly to rainfall events, in accordance with the observations of Laville et al. (2011) and Rabot et al. (2014, 2015a, b). After a rainfall, one expects the soil to drain and eventually reach a moisture content where enough of the pore space is air-filled and connected to the surface for the trapped N_2O to escape and be emitted to the atmosphere. Often (but not systematically), in Scott et al.'s (1999) experiment, large fluxes tended to follow periods of high precipitation, with smaller fluxes occurring during periods of dry weather. Sometimes, the response to a rain event seemed to manifest in just a few hours, like on days 31 and 47. At other times, the response appeared to be delayed, or even to be lacking, as on day 28. That may mean that the frequency of the automated sampling system (1 h of sampling e4 or 8 h) may not have been high enough to catch what Rabot et al. (2014) have observed to be the sudden flux of emitted N_2O when the soil, as it dries, reaches the gas percolation threshold, at which enough of the gas-filled pore space is connected to the atmosphere. From that perspective, some of the key peaks may be missing from the N_2O emission graph of Fig. 4 In that context, it is relevant that, in parallel with their automated measurements, Scott et al. (1999) also carried out a small number of punctual, manual measurements, which, for N_2O, missed most of the peaks obtained with the automated system.

By contrast with the N_2O results, CO_2 emissions seemed to respond closely to soil temperature changes associated with net radiation fluctuations, and little to rainfall. Again, this may have been a result of the sampling frequency, which was too low to detect CO_2 peaks due to the Waksman-Starkey-Birch effect, upon rewetting of the soil after periods of drying. The start of some of the rainfall events in Fig. 4 appears to be associated with relative peaks in CO_2 evolution. However, there is no assurance that the peaks were correctly measured in their entirety.

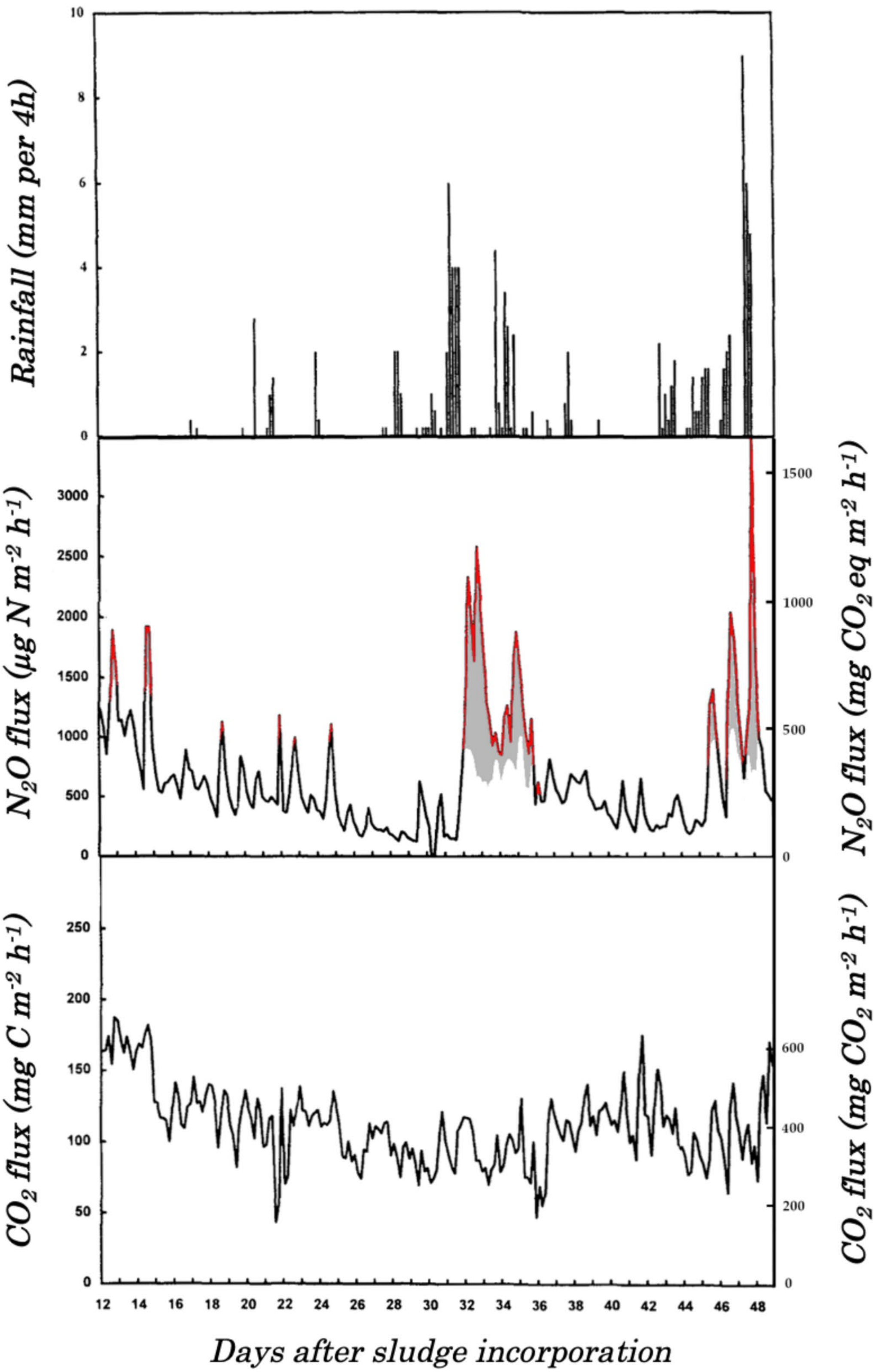
Nevertheless, the graph of Fig. 4 suggests that the emitted N_2O flux may be commensurate with that of CO_2. Over the duration of their experiment, Scott et al. (1999) found that 3619 kg of CO_2 ha^{-1} were emitted by the soil, versus 2800 kg of equivalent CO_2 ha^{-1} for the emissions of N_2O. In other words, the N_2O flux from the soil amounted to at least 77% of that of CO_2, in terms of global warming potential, and may conceivably have been even higher with a different sampling frequency, able to capture all the peaks in N_2O emission. And this is without accounting for additional concurrent emissions of CH_4, which may have further tilted the GHG balance. Had Scott et al. (1999) chosen to monitor CO_2 and N_2O emissions over a shorter timeframe, they may very well have ended up with the conclusion that the incorporation of organic matter in their soil resulted in a response dominated by N_2O rather than by CO_2. Indeed, if they had focused on the few days immediately following the heavy rainfalls on days 31 and 47, they would have recorded N_2O fluxes exceeding those of CO_2 in terms of global warming potential. Apparently unaware of the earlier work of Scott et al. (1999), Laville et al. (2011) also carried out concurrent field measurements of several GHGs, including N_2O, at a higher temporal frequency (16 measurements per day) and obtained results that are similar to Scott et al.'s (1999) in many respects. However, it is not entirely clear either in this case whether or not they were able to capture the sudden release of N_2O as the soil dried after rainfall events.

Aside from this, the results depicted in Fig. 4 provide insight concerning an idea that, if proven correct, would simplify greatly the assessment of GHG emissions by soils and the calculation of carbon credits. This idea, emanating from the results obtained by several researchers, is that there is a simple linear correlation between the emissions of CO_2 and N_2O from soils. Figure 4 shows that this is not what happens when the measurement time frame includes rain events. Indeed, the trend that N_2O emissions are low when CO_2 emissions are low, and that as a rule, the former represent only a tiny fraction of the latter (e.g., Xu et al. 2008; Chen et al., 2013), appear to break down entirely when one considers the peaks of N_2O emission following rainfall events. The very sizeable N_2O peak on days 32–33 in Fig. 4 is associated with one of the lowest CO_2 emissions during the entire monitoring. Likewise, the very large, literally off-the-chart N_2O peak at day 48 is associated with a CO_2 emission rate that is large but not exceptionally so.

These various comments concerning the results of Scott et al. (1999) suggest that it is crucial to take into account the chronology of hydrological events when trying to assess the practical significance of N_2O emissions from a given soil relative to those of CO_2. Unfortunately, the field studies of Scott et al. (1999) and Laville et al. (2011) appear to be the only ones to date where proper attention was devoted to this aspect. When, exceptionally, the primary sources reviewed by Xu et al. (2008), Chen et al. (2013), and Muhammad et al. (2019) mention rain, it is often in terms of annual precipitation statistics, not with respect to particular rainfall events. The air-filled porosity at the time of sampling is mentioned in several primary sources, but it is viewed statically, not in a dynamic context, and never in terms of how close to, or far from, it is to the percolation threshold at which according to Rabot et al. (2014), one could expect a strong, sudden release of previously trapped N_2O. Again, because of the Waksman-Starkey-Birch effect, the same could be said about the emissions of CO_2 (see discussion in Coucheney et al. 2025).

Take-home message and future prospects

The unavoidable conclusion of the preceding critical review of the relevant literature is that, at this stage, as a result of the lack of attention to the extreme spatial heterogeneity of soils and to the temporal aspect of their hydric regime, many of the field and laboratory observations made in the past of the emission of GHGs by soils may be somewhat questionable. *Practically, this means that, at present, there are no reliable, simultaneous field measurements of how much of the different GHGs are emitted by soils at specific locations, over timeframes long enough to include the drying process immediately following rainfall events, and sudden releases of N_2O by soils that may be associated with this process, in experiments that involved a control treatment and in which the extent of carbon sequestration was systematically monitored.* Because of this lack of data, it is therefore impossible to assert at this stage, as some authors have done in recent years, that the CO_2 sink associated with the sequestration of carbon in soils is not compensated by the emissions of other GHGs (e.g., N_2O, CH_4). For all we know, total emissions of GHGs from soils in which one attempts to store more carbon could have a negative impact on climate change. Given this uncertainty,


Rainfall (mm per 4h)
N2O flux (µg N m-2 h-1)
N2O flux (mg CO2 eq m-2 h-1)
CO2 flux (mg C m-2 h-1)
CO2 flux (mg CO2 m-2 h-1)
Days after sludge incorporation

◂**Fig. 4** Temporal evolution of the emission of CO_2 and N_2O following the incorporation of sewage sludge in a grass sward in Scotland and record of the rainfall pattern at the site. The fluxes expressed in terms of masses of C or N were transformed into masses of CO_2 and N_2O by accounting for the molecular weights of these compounds. The N_2O flux was further transformed into a mass of CO_2 equivalent through the use of the Global Warming Potential for a 100-year timescale (GWP100). Several values are in use for this coefficient. We used the value of 298 adopted by the European Union (https://ec.europa.eu/eurostat). The portions of the curves in red and the grey parts of the graph related to N_2O (center panel) correspond to times when the N_2O fluxes exceeded the CO_2 ones in terms of global warming potential. (Graph modified from Scott et al. 1999)

decision-makers would do well not to rely on soil carbon sequestration to mitigate climate change, and to focus on sounder strategies, like the transition to renewable forms of energy.

In this context, it is important to stress, as we have done consistently throughout this article, that its scope is restricted to the soil component of agroecosystems. This focus is very useful since it allows one to address the question of how modifications of soil properties by different management practices can affect the microbial population responsible for the production of the GHGs emitted by soils, and the release of the GHGs themselves to the atmosphere. From a broader perspective, it may still be true that adding fresh organic residues to soils may have a positive effect on climate change. The practice is known to produce several agroecosystem co-benefits (higher water and nutrient retention capacity, stabilization of soil architecture with a reduction in susceptibility to crusting, compaction and erosion, etc.), which not only make soils more resilient to the effects of climate change and therefore should definitely be encouraged (e.g., Johannes et al. 2017; Baveye et al. 2020; Berthelin et al. 2022a, b) but are also likely to affect the growth of plants. This in turn could influence soil processes via a number of feedback mechanisms, e.g. albedo effects. Therefore, to evaluate fully the effect of increases in the carbon content of soils on climate change, one would have to work at a larger scale, which presents a whole set of significant challenges. Some of them are related to the spatial heterogeneity of soils and of microclimatic conditions, which complicates the mechanistic explanation of experimental observations and their modelling. There are also challenges in terms of measurements, since the eddy covariance technique, often adopted to quantify the emission of GHGs, unfortunately suffers from a number of drawbacks, as discussed earlier. One solution in that context would be to return to the work of Galle et al. (1994) and Smith et al. (1994, 1995), who designed large chambers, 50–60 m^2 in area, that offer a way to overcome small-scale spatial variability and include plants. New designs for such large chambers would have to allow rainfall to penetrate between measurements, as in the case of the smaller chambers (Fig. 3). Clearly, a lot more research is needed in that context, not just in temperate zone environments, as has been overwhelmingly the focus to date, but in others as well, e.g., in paddy rice cultivation or in thawing permafrosts, where CH_4 emissions might be particularly significant.

Regardless of which perspective is adopted, either solely focused on soils at small spatial scale or encompassing both soils and plants at a broader scale, it seems clear at this point that a focus solely on carbon would not provide reliable information on how to manage soils so that they can have a beneficial effect on climate change. Given the close connections between the dynamics of carbon and nitrogen in soils, it seems that paying attention to both simultaneously might be a far more fruitful avenue for progress. Two decades ago already, Robertson (1999), Robertson et al. (2000), and Robertson and Grace (2004), advocated that the best bet for soil management practices to have an effect on climate change is not through increasing the carbon content of soils, as overwhelmingly assumed, but by managing better the use of nitrogen in agriculture and thereby reducing the emission of N_2O. At the very least, nitrogen management should definitely be part of the picture, as suggested by Haas et al. (2022) when they write that "strategies to promote enhanced C sequestration in agricultural soils need to go hand in hand with improvements in N management for N_2O mitigation." At this juncture, this may be a perspective worth adopting again as a working hypothesis, to counterbalance to some extent the disproportionate emphasis placed so far on carbon.

It might be advantageous in that context to add the reduced emission of GHGs to the list of objectives that the research on improved nitrogen management in soils is currently pursuing. At the moment, a significant effort focuses on understanding better the demand of plants for nitrogen, and on making sure that mineral nitrogen fertilizers are not added in quantities exceeding the needs of crops (e.g., Lemaire and Gastal 2018; Briat et al. 2020; Lemaire et al. 2021, 2025; Ciampitti et al. 2022). In soils where, historically, mineral nitrogen fertilizer inputs have been high and where a substantial amount of SOM-associated nitrogen is present, another emphasis of present research is to study how soil microorganisms, possibly stimulated by root exudates, can extract from the soil matrix not just nitrogen but also other nutrients (P, K, micro elements) that it contains, and make them available to crops (e.g., Amadou et al. 2021; Dakora and Phillips 2002; Raymond et al. 2021; Grandy et al. 2022, 2024). This research, in and of itself, already has a likely impact on climate change. Indeed, by easing the dependence of agriculture toward mineral nitrogen fertilizers in parts of the world (e.g., Europe and China) where agricultural soils have been traditionally over-fertilized, one would decrease substantially the amount of fossil fuel currently used for the production of mineral nitrogen fertilizers via the energy-intensive Haber–Bosch process, and for their transport to the point of use.

Beyond that, any decrease in the quantities of mineral nitrogen fertilizers applied to agricultural fields would also have a large impact, at least after a while (Van Meter et al. 2016), on the contamination of groundwater resources and surface waters with nitrates. Over the last decades, nitrate has been worldwide the primary nonpoint source pollutant of groundwater, lakes, and rivers, in large measure because a large portion of applied mineral nitrogen fertilizers are not used by crops but end up either leaching in soils or being carried away by runoff at the soil surface (e.g., Burri et al. 2019; Richa et al. 2022). These losses of nitrogen from agricultural fields contribute to the eutrophication of lakes and rivers, and ultimately to the existence of occasionally enormous dead zones at the mouth of rivers around the world (Baveye 2015). In terms of human health, the fact that large amounts of nitrate reach groundwater resources can lead to significant problems in parts of the world where pre-treatment of drinking water is not routine. Consumption of water contaminated by excessive levels of nitrate can lead to increased risk of birth defects, blue baby syndrome in infants, and stomach cancer in adults (e.g., Rahman et al. 2021; Levintal et al. 2023). To prevent the further spread of this growing problem, many countries around the world have put regulations in place to safeguard human health (Kim et al. 2019; Musacchio et al. 2021; Yu et al. 2022), however most experts (e.g., Badeenezhad et al. 2021) agree that the best way to resolve the issue in the long run is to encourage farmers to manage nitrogen fertilization better. To that end, the link between optimal nitrogen use and climate change mitigation might constitute an attractive carrot, because its effects are expected to be more immediately noticeable than impacts of soil nitrogen management on nitrate concentrations in aquifers.

Clearly, to make progress in that direction, further research is needed on the combined dynamics of carbon and nitrogen in soils. It seems obvious that work should initially focus on getting better and more extensive data on the respective emissions of CO_2 and N_2O by soils. Dynamic laboratory experiments on soil columns can be started immediately to get a better grasp of the balance of C and N for soils subjected to different additions of organic residues and different hydric regimes. Some of the research should also be carried out in the field. Intuitively, one would think that 2 or 3 decades after the development of automated sampling systems by Lotfield et al. (1992), Brumme and Beese (1992), and Scott et al. (1999) and at a time when we routinely send highly sophisticated "Rovers" to sample Martian soils, it should nowadays be possible to design even better sampling systems, involving improved detection technologies for all GHGs simultaneously and allowing sudden peaks in the emission of CO_2, N_2O and, as the case may be, CH_4 to be detected. Some work has been carried out in recent years on the development of new chamber-based systems (e.g., Baral et al. 2017; Thalasso et al. 2023; Pullens et al. 2023), but one could argue that further improvements are still needed, particularly in terms of making measurements better responsive to rainfall events, or, through the use of larger chambers, in order to encompass both soils and several plants.

Once better data become available, it would be useful to develop a new generation of models of GHG emissions. Li et al. (2005), Palmer et al. (2017), Bos et al. (2017), Lugato et al. (2018), and Haas et al. (2022) demonstrated the interest that models might present in this general area. However, the models they used, like most "biogeochemical" models currently available, are still considered deficient in a number of ways (e.g., Baveye 2023a, b; Manzoni and Schimel

2024). Following in this respect a combination of the modeling efforts of Haas et al. 2022) and Rabot et al. (2015a, b), and taking advantage of the significant progress achieved in recent years in the modeling of microscale processes in soils (Baveye et al. 2018a, b; Pot et al. 2022a, b), one could develop new models that would provide guidance on which agricultural practices may lower N_2O and CH_4 emissions and therefore on when and where carbon sequestration in soils may provide benefits for climate change mitigation. Zhang et al. (2025) have carried out this type of modelling recently to describe quantitatively the emission of methane from rice paddy fields. The very recent, and particularly interesting modeling effort of Rötzer et al. (2026), which definitely represents a step in the right direction, could be extended to take into account soil moisture changes resulting from rainfall events.

At this juncture, since the next few steps needed to make progress in this general area seem self-evident, one might wonder why they have not yet been taken. A possible explanation is that the extreme reductionism that, we would argue, has historically characterized a lot of the research in soil science, has led some soil chemists working on the fate of soil organic matter to focus solely on carbon, while other soil chemists, as well as soil fertility specialists, zeroed in on their side exclusively on either nitrogen, potassium, or phosphorus. In some situations, these different soil chemists worked in geographically separate centers, and rarely had reasons or programmatic opportunities to interact. Neither, in many cases, did they have a chance or feel compelled by their institutions to routinely rub elbows or compare notes with soil microbiologists or soil physicists, who could have provided valuable insight on their experiments and questioned some of their conceptual viewpoints.

In that context, the key message of the present article implies clearly that a drastic change of attitude in soil science is needed. We should stop considering that the potential of soils to mitigate climate change is solely a carbon story, exclusively within the purview of soil chemists or biogeochemists who focus on carbon. The potential of soils to contribute to climate change mitigation should be addressed by a much wider constituency, including specialists of other GHGs beside CO_2, soil physicists and hydrologists, soil microbiologists and soil fauna specialists, not to forget computational modelers, who can help with the development of predictive models. All these researchers will have to work intimately together in order to finally generate the kind of experimental data and theoretical/modeling advances we need to make progress. In other words, what is called for is a truly interdisciplinary approach to soil science. This is not a new idea. Various researchers have already been trying to foster interdisciplinary research in soil science over the last few decades (e.g., Wagenet et al. 1992; Smith et al. 2003; Baveye and Wander 2019; Chaplot 2021; Baveye et al. 2018a, b, 2020, 2024). But the need for it seems more pressing now than ever, as humanity faces increasingly urgent challenges, in which soils play important roles.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Furthermore, to the extent that he is no longer actively seeking funding for his own research related to the modelling of soils, the author also adheres to the broader concept of conflict of interest described in (Baveye 2023a, b) and has no vested interest in the conclusions reached in the present article.

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