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Opinion

Soil carbon sequestration for climate change mitigation: Mineralization kinetics of organic inputs as an overlooked limitation

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Abstract

Over the last few years, the question of whether soil carbon sequestration could contribute significantly to climate change mitigation has been the object of numerous debates. All of these debates so far appear to have entirely overlooked a crucial aspect of the question. It concerns the short-term mineralization kinetics of fresh organic matter added to soils, which is occasionally alluded to in the literature, but is almost always subsumed in a broader modelling context. In the present article, we first summarize what is currently known about the kinetics of mineralization of plant residues added to soils, and about its modelling in the long run. We then argue that in the short run, this microbially-mediated process has important practical consequences that cannot be ignored. Specifically, since at least 90% of plant residues added to soils to increase their carbon content over the long term are mineralized relatively rapidly and are released as CO_2 to the atmosphere, farmers would have to apply to their fields 10 times more organic carbon annually than what they would eventually expect to sequester. Over time, because of a well-known sink saturation effect, the multiplier may even rise significantly above 10, up to a point when no net carbon sequestration takes place any longer. The requirement to add many times more carbon than what one aims to sequester makes it practically impossible to add sufficient amounts of crop residues to soils to have a lasting, non-negligible effect on climate change. Nevertheless, there is no doubt that raising the organic matter content of soils is desirable for other reasons, in particular guaranteeing that soils will be able to keep fulfilling essential functions and services in spite of fast-changing environmental conditions.

Keywords: climate change mitigation, soil carbon modeling, microbial activity, soil functions

Introduction

Amidst eerily orange skies caused by vast wildfires sweeping though California, Greece, and Siberia, unprecedented droughts in many parts of the world, devastating floods in Belgium,

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Germany and the U.S., and ice sheets in Greenland and at the poles disappearing much faster than predicted, the Intergovernmental Panel on Climate Change (IPCC) has recently released the first part of its eagerly awaited 6th Assessment Report. One of its key messages is that it is becoming extremely urgent to take drastic action to prevent global heating from reaching the 1.5C threshold beyond which one should expect irreversible “tipping points” and severe exponential damage to the environment. In the worrisome “race against time” with which we are faced, governments have tended so far to be painfully slow at adopting measures to reduce greenhouse gas emissions, prompting some researchers to devise alternative approaches that currently seem politically or economically more palatable.

In that context, a large body of literature has been devoted in the last 2 decades to the removal of carbon dioxide from the atmosphere via carbon sequestration in soils, in particular through the incorporation of fresh organic matter (e.g., crop residues, green manure). The associated agricultural practices are broadly referred to as “regenerative” or “conservation” agriculture. The economic feasibility of this approach, as well as the extent to which it could remove enough carbon from the atmosphere to have an effect on climate change in the long run, have been the object of intense debates among soil researchers in the last few years (e.g., Powlson et al., 2011; White and Davidson, 2016a,b; Sanderman et al., 2017; van Groeningen et al., 2017; Rumpel et al., 2018; Amundson and Biardeau, 2018, 2019; Poulton et al, 2018; Baveye et al., 2018a; Loisel et al., 2019; Baveye et al., 2020; Amelung et al., 2020; Ranganathan et al., 2020).

A striking feature of these debates, and particularly of those concerning the reaction of farmers toward proposed soil carbon sequestration schemes, is that a crucial aspect of the whole topic appears to have been so far entirely overlooked. This “blind spot” or “untold story” concerns the short-term mineralization kinetics of fresh organic matter added to soils, which is occasionally alluded to in the literature, but almost always in a broader modelling context. However, this aspect has important practical consequences that we shall analyse in detail below, for the very first time as far as we are aware. Before we get to the gist of this article, it is useful to set the stage to first review in some detail the relevant background concerning what is currently known about the mineralization of fresh organic matter, and how this information has been used in models.

Mineralization kinetics: Patterns and inherent complexity

The scholarly literature provides a wealth of information concerning the temporal dynamics following the addition to soils of individual inputs of fresh organic residues, comprising a combination of any above-ground residues not removed (e.g., cereal straw), stubble or stover, roots, and root exudates. These residues can result from agricultural practices in the field itself, as well as be derived from plants grown elsewhere. Starting with Jenny (1941), researchers have for decades gathered extensive data on the topic, not only in temperate climates, but also in the tropics and in arid regions (e.g., Hénin and Dupuis, 1945; Smith et al., 1951; Laudelout and Meyer, 1951; Hans and Evans, 1957; Hénin et al., 1959; Jenkinson, 1965, 1971, 1977, 1990; Jenkinson and Ayanaba, 1977; Jenkinson and Rayner, 1977; Gonzalez and Sauerbeck, 1982; Mann, 1986; Blet-Charaudeau et al., 1990; Laudelout, 1993; Poeplau et al., 2011; Soudi et al., 2020; Smith et al., 2020; Wieismer et al., 2020; Bhattacharyya et al., 2021). The method of choice in much of this research has been to label organic matter isotopically with either ^{14}C or ^{13}C, then monitor the progressive decay of a single batch of that material over time after its incorporation into soils. The general picture that emerges from this work, illustrated for temperate-zone soils in Figure 1, is that the largely microbially-mediated mineralization of fresh organic matter added to soils typically exhibits an L-shaped pattern, which can be described mathematically by a first-order kinetic equation, or a set of such equations associated with different classes of organic matter. Overall, if one disregards the somewhat arbitrary split of organic matter into “pools”, the message of Figure 1 is that mineralization tends to be very intense soon after incorporation of organic matter into soils, then progressively slows down until one reaches a stage where little further mineralization occurs, and the organic matter that remains is, if not "sequestered", at least stabilized and no longer accessible to either microorganisms or their exoenzymes (Dungait et al., 2012). This is why the so-called stabilized pool accumulates and accounts for the largest proportion of organic carbon in soil. This model, which is based on observations of mass loss or decay following a single addition of organic residues, does not reveal turnover within the stabilized fraction but it does accurately convey the kinetics of materials associated with different states of decay.

In Fig. 1, this sequence of events is depicted as taking place over a 30-year span. Half of the added organic input is mineralized after a little over a year, 80% is gone after 7 years, and the amount of organic matter remaining after 30 years is only one tenth of that applied. In some cases, even in temperate regions, mineralization occurs much faster. Jenkinson (1990), for example, reported that in the case of a sandy soil in the United Kingdom containing 10.7% clay, left fallow after incorporation of labelled ryegrass residues, 65% of the ryegrass was mineralized within the first 6 months, with only 10% of the ^{14}C label still present after 10 years. Intuitively, one would expect that in regions of the world where mean annual temperatures are higher than in temperate zones and therefore microbial activity is enhanced, mineralization would be even more rapid. Indeed, in a soil in Ibadan (Nigeria) with a mean annual temperature of 26C, Jenkinson (1990) reported that 90% of labelled ryegrass incorporated into the soil decomposed after a mere 5 years.

Aside from soil temperature and hydrology, which clearly influence the rate of mineralization of organic matter, many other factors also exert an effect on the kinetics of the process. Wiesmeier et al. (2019) and Basile-Doelsch et al. (2020) have reviewed some of these additional factors in detail. They include the nature (biodegradability) of organic matter, the partial pressure of oxygen, soil particle size, mineralogy of the soil solid particles, soil pH and the nature of ions in the soil solution, the availability and abundance of N, P, and S, microbial and faunal biodiversity, as well as biotic and abiotic interactions. The latter occur for example in the priming process, when root exudates promote carbon loss by releasing organic compounds from protective association with minerals, or when changes affecting the composition of exchangeable cations on soil colloids influence the retention of organic matter (e.g., Julien and Tessier, 2021; Possinger et al., 2021). Broadly speaking, interactions among factors influencing the kinetics of mineralization of organic matter seem to be the rule (Cotrufo et al., 2015), and the resulting, daunting complexity of the system has so far hindered researchers' attempts to quantify the effect of individual factors (Basile-Doelsch et al., 2020). In order to improve the still relatively high uncertainty associated with predictions of mineralization kinetics, some researchers (see review in Baveye et al., 2018b) have argued that investigations of the mineralization kinetics of fresh organic matter should no longer rely solely, as it did in the past, on bulk (macroscopic) measurements of soil parameters, like their organic matter content, texture, or the density of their microbial population. A key reason for this is the large spatial heterogeneity of soils that exists at the microscale and is now becoming increasingly understood through new imaging techniques (e.g. Baveye et al., 2018b; Bacq-Labreuil et al, 2018; Powlson and Neal, 2021). Evidence suggests that microscale information about the relative spatial distribution of organic matter, mineral complexes, and decomposer organisms must be obtained to understand the kinetics of decay (e.g., Falconer et al., 2012; Portell et al., 2018; Chakrawal et al., 2020; Shi et al., 2021; Mbé et al., 2022). The geometry of the pore space in many soils may be so convoluted as to preclude microorganisms, and even their exoenzymes, access to potential substrates. These insights are increasingly reflected by a new generation of mathematical models that take the microscale heterogeneity of soils explicitly into account when describing the fate of organic matter (e.g., Falconer et al., 2015; Vogel et al., 2015; König et al., 2020; Golparvar et al., 2021; Pot et al., 2022).

Modeling over the long run

Early on in the research on the mineralization of added organic matter, Hénin and Dupuis (1945) initiated a trend to view measured data on the kinetics of mineralization, not so much as useful information in its own right, but more as a stepping stone toward estimating the build-up of soil organic matter over time after many successive yearly additions of fresh organic matter into soils. This perspective made eminent sense in the past. It remains relevant to climate change mitigation and can address farmers' practical concerns. Many farmers wonder whether it is feasible to increase the organic matter content of their soils back to levels present 40 or 50 years ago. They also wonder how much carbon would need to be sequestered to recover soil functions lost due to organic matter depletion and, how those amounts align with carbon farming targets proposed to offset climate change.

In the past, a number of experiments have been carried out to try to answer these kinds of long-term questions. For example, Franzluebbers et al. (2012) summarize graphically various experiments on pasture management in Georgia and Texas and observe that 10 years after conversion of an arable cropping system into perennial grassland —one of the fastest agricultural practices to sequester carbon in soil — the rate of C accumulation down to a depth of 20 cm drops by half, and after 20 years, it is only 0.2 Mg ha^{-1} y^{-1}, i.e., a quarter of its initial value of 0.8 Mg ha^{-1} y^{-1}. After 50 years, the rate is virtually zero, and a new soil equilibrium is reached. Similar observations were made in the Hoosfield Experiment at Rothamsted Research, UK, where a large rate of manure has been applied to one treatment every year since 1852. During the first 20 years, soil organic carbon increased at an average annual rate of 18‰ but by 100 years the rate of increase had declined to almost zero (1-2‰ annually; Poulton et al, 2018). Observations of that nature, which Smith (2016) has described as evidence of "sink saturation", suggest that the potential of soils to sequester additional carbon may only exist for a limited period.

As revealing as this type of data is, the changing climate makes it challenging to extrapolate to the longer term, especially to 70 or 80 years ahead, at the end of the century. In principle, mathematical models of soil organic carbon dynamics may have the capacity to help appreciably in this area, as long as we are able to make them account for all the different factors, many of which are influenced directly by climate change, that affect the short-term dynamics of organic matter mineralization. Over the years, several models of the long-term dynamics of soil organic matter have been developed. These models incorporate kinetic expressions, usually first-order, that encapsulate the dynamics depicted in Figure 1, but integrate its effect over multiple years. Arguably the most popular among them are CENTURY (Parton et al. 1994), C-TOOL (Taghizadeh-Toosi et al., 2014), ICBM (Andrén and Kätterer 1997), ROTH-C (Coleman and Jenkinson, 2005) and YASSO07 (Tuomi et al., 2011). All assume that soil organic matter can be attributed to distinct pools, with different chemical and dynamic properties, though this is recognized as a simplification of reality. The number of these pools is either 3 (C-Tool and ICBM), 5 (RothC and YASSO07), or 8 (Century).

In spite of the fact that they ignore many aspects of the dynamics of organic matter in soils (e.g., the impact of microscale heterogeneity or the biodiversity of the organisms involved), these and similar models have produced useful insights. A particularly telling example is afforded by the very comprehensive analysis carried out recently by Riggers et al. (2021) in the context of German croplands, to determine the extent to which changing climate in decades ahead could affect soil organic carbon stocks. These authors considered 3 different climate change scenarios between 2014 and 2099, as well as a scenario assuming no future climate change. They used 5 distinct methods to estimate organic carbon inputs based on crop yields and crop-specific parameters, and adopted a multi-model ensemble consisting of five different SOC models to predict the organic carbon input required to reach specific SOC stocks in soils at the end of the 21st century. Their simulation results suggest, among other things, that organic carbon input to the soil in 2099 needs to be between 51 and 93% higher than what it is today just to maintain SOC stock levels at their current value. Riggers et al. (2021) conclude that "under climate change increasing SOC stocks is considerabl[y] challenging since projected SOC losses have to be compensated first before SOC build up is possible. This would require unrealistically high OC input increases with drastic changes in agricultural management."

As compartment models are improved in years ahead and new, more mechanistic types of model emerge, future simulations are likely to include aspects that so far have not been taken into account, like the effect of erosion on the long-term dynamics of soil carbon stocks. One of the consistent predictions climate modelers have made over the last decade is that climate change will result in less frequent but more intense rainfall events in many parts of the world (e.g., Trenberth et al., 2003; Baveye et al., 2020, and references cited therein). This will undoubtedly affect the amount of erosion of soils, not only as a result of heavy downpours during rainfall events, but also via the effect of winds during dry spells between them (e.g., Nearing et al., 2004; Morán-Ordóñez et al., 2020). The effect that enhanced erosion will have on soil carbon stocks remains a matter of continued debate, yet will need to be included at some stage in future simulations like those of Riggers et al. (2021).

Practical challenges in the short run

There is no doubt that the research on the *long-term* modeling of the evolution of soil carbon stocks and soil carbon sequestration should and will continue in years to come. Among other reasons, decision-makers need to assess whether soils will be able in 20 or 50 years to satisfactorily fulfill a number of their current functions, e.g., the storage of water to make it available to plants, or the recharge of aquifers (e.g., Baveye et al., 2020). If, because of a weakened architecture due to a depleted carbon stock, soils will not be able to absorb the more intense rains that may become routine in a decade or two, plans need to be made immediately to build bigger retention dams or redesign bridges to cope with potential flash floods. Many of these building projects require years or even decades to complete.

The focus on long-term trends predicted with computer models has unfortunately led researchers to overlook realities that will pose significant challenges to farmers who are asked to participate in carbon capture schemes. These challenges stem from the short-run mineralization kinetics exhibited in Figure 1, which ultimately raises a number of very practical issues. Clearly, if we expect farmers to sequester an amount x of carbon in their soil, for example the 0.4% yearly increment that is targeted by the "4 per 1000" initiative, they need to add ten times that amount of C in some way. Specifically, to eventually sequester 0.5 tons/ha of carbon in his/her soil via the addition of a single supply of fresh organic matter, a farmer has to add 10 times that amount, or 5 tons/ha, knowing that 90% of the carbon this added organic matter contains will be used by perpetually hungry microorganisms and will be released relatively rapidly to the atmosphere! In other words, instead of talking to farmers about a "4 per 1000" target, one should really present it to them as a "40 per 1000" one, since they would have to increase the carbon input every year by that amount, in order to effectively increase the amount of soil carbon eventually sequestered by 0.4% annually. This proposition is entirely unrealistic practically, and not just because it would be impossible to come up with enough crop residues to meet the demand, but also because the nitrogen requirement that this would create would be unmanageable. Van Groeningen et al. (2017) estimated that to sequester in agricultural soils the 1200 Tg C yr^{-1} called for globally by the "4 per 1000" initiative would require 100 Tg N yr^{-1}, which is much larger than the rate of ~30 Tg N yr^{-1} at which nitrogen is considered to accumulate in global cropland residues. If we reflect in terms not of the amount of carbon that eventually gets sequestered but of the quantity that needs to be added to soil annually, the latter would be of the order of 12,000 Tg C yr^{-1} to meet the same targeted sequestration. The amount of nitrogen that would be involved would likely be less than 10 times the figure suggested by Van Groeningen et al. (2017), but it would still be many more times that in current cropland residues globally!

The discussion so far has been based on a simplified model that uses a ratio of 10:1 between the amount of carbon added to soil in fresh organic matter to the carbon eventually sequestered in the soil, in line with Figure 1. Evidence however tends to suggest that this value of 10 may be conservative, and that the real ratio is likely to change upward over time. Indeed, the capacity of a soil to sequester carbon has been shown to decrease over time and to effectively vanish at the stage of "sink saturation" (e.g., Franzluebbers et al., 2012; White and Davidson, 2016a; Smith, 2016; Baveye et al., 2018b; Poulton et al., 2018). Beyond the stage of saturation, since soil carbon sequestration is reversible (Smith, 2012), it is necessary to keep adding plant residues to soils to maintain the benefits associated with the level of carbon sequestration that has been achieved. Further research is needed to assess how graphs like that of Figure 1 change over time as one gets closer to the "sink saturation" point, but it seems logical to assume that the ratio of added to sequestered carbon rises significantly above 10 within a few years, rendering any "soil carbon sequestration for climate mitigation" scheme even less feasible in practice over the long-term than the above calculations indicate. The fact that Jenkinson (1990) observed in a sandy soil in the U.K. mineralization kinetics much faster than that depicted in Fig. 1 may have been due in part to this sink saturation process. Further research will be needed to understand it more fully.

Take-home message

Much of the literature on soil carbon sequestration over the last 20 years, and especially in the last 6 years, since the COP 21 meeting, has suggested that, via this "silver bullet", the agricultural sector could have a significant role to play in the mitigation of climate change. This perspective ignores the fact that most of the organic matter added to soils in order to increase the amount of carbon that is sequestered is quickly mineralized by soil organisms and returned to the atmosphere as CO_2. Back-of-the-envelope calculations that take this process into account show readily that farmers cannot practically come up with the large amount of fresh organic plant residues that would be needed on a yearly basis for soil carbon sequestration in arable agricultural soils to make a substantial contribution to mitigating climate change.

In that context, since it is not reasonable to ask of soil carbon sequestration to compensate all of the greenhouse gas emissions of other anthropogenic sectors, it is wise to scale down the expectation of what agriculture can practically achieve in years to come in relation with climate change mitigation. A still daunting, but perhaps more realistic objective in that respect might be for agriculture to become a zero emitter of greenhouse gases. This would require interdisciplinary research scrutinizing many aspects of agriculture jointly, not just what happens to organic matter in soils. Concomitantly, one should also ensure that soils will be sufficiently resilient to adapt to a rapidly changing climate in the near future, and still be able to fulfill their essential functions, on which humanity depends crucially. Based on what we know at this stage, this means that we need to make sure that the organic matter content of all agricultural and forest soils, including degraded ones, are restored to a suitable level. Since many of the very complex processes involved still remain poorly understood, further basic research is needed to make progress in this respect in a timely fashion. In terms of communication efforts in which the soil science community should engage in the near future, probably the most urgent, given the rate at which climate change is predicted to occur, is to let policymakers know in no uncertain terms that carbon sequestration in soils as a "silver bullet" to significantly mitigate climate change is off the table, and that they should focus on other possible avenues to halt climate change, like transitioning promptly to renewable forms of energy. In addition, we need to help farmers and land users determine what they can do relatively rapidly to make soils more resilient to the changes ahead, in particular the sizeable shifts of rainfall patterns that are forecasted, so that soils can keep providing essential services to human populations.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflict of interest.

Data Availability Statement

No new data were generated during the writing of this article.

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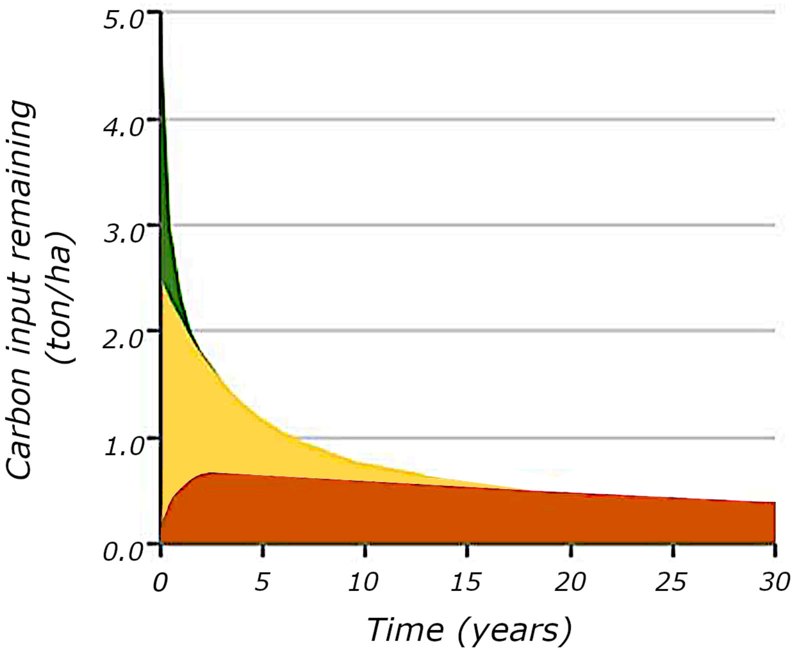
Figure captions

Figure 1: Illustration of the fate of plant organic inputs into a soil (single input event, here 5 t Cha^{-1}). The numerical values are representative of the 0–30 cm layer of temperate soils. In this diagram, the mineralization kinetics is arbitrarily divided into three phases: fast, intermediate and slow. Organic matter can be divided into three corresponding pools, the size of which is represented in the figure by the coloured areas. (Modified from Pellerin et al., 2020; Basile-Doelsch et al., 2020).



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