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Points of view

The soil carbon dilemma: Shall we hoard it or use it?

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Abstract

Rapidly rising concentrations of atmospheric CO_2 have prompted a flurry of studies on soils as potential carbon (C) ‘sinks’. Sequestering C in soils is often seen as a ‘win–win’ proposition; it not only removes excess CO_2 from the air, but also improves soils by augmenting organic matter, an energy and nutrient source for biota. But organic matter is most useful, biologically, when it decays. So we face a dilemma: can we both conserve organic matter and profit from its decay? Or must we choose one or the other? In this essay, I contemplate the merits, first of building soil C and then of decaying (losing) it, partly from a historical perspective. I then consider the apparent trade-off between accrual and decay, and reflect on how the dilemma might be resolved or assuaged. These fledgling thoughts, offered mostly to stir more fruitful debate, include: finding ways to increase C inputs to soil; seeking to optimize the timing of decay; and understanding better, from an ecosystem perspective, the flows of C, rather than only the stocks. Carbon sequestration is a sound and worthy goal. But soil organic matter is far more than a potential tank for impounding excess CO_2; it is a relentless flow of C atoms, through a myriad of streams—some fast, some slow—wending their way through the ecosystem, driving biotic processes along the way. Now, when we aim to regain some of the C lost, we may need new ways of thinking about soil C dynamics, and tuning them for the services expected of our ecosystems. This objective, perhaps demanding more biology along with other disciplines, is especially urgent when we contemplate the stresses soon to be imposed by coming global changes.

Keywords: Carbon sequestration; Carbon sinks; Soil organic matter; Decomposition; Global change

1. Introduction

Some three decades ago, Freeman Dyson (1977) mused about building ‘carbon banks’ in the biosphere to control atmospheric CO_2. “[I]f ever the danger of catastrophe from CO_2 accumulation becomes acute”, he said, we might plant more trees or “build up carbon reserves in the form of humus”, thereby withdrawing excess CO_2 from the air.

Since then, worries of impending dangers have indeed escalated. Scientists are increasingly persuaded that swiftly-rising CO_2 may one day induce unpleasant changes to global climates (IPCC, 2001), and governments have begun enacting policies to curb CO_2 increases (UNFCCC, 2005). In response has come a flurry of studies and deliberations about building biological carbon (C) banks. Soil-focused journals, conferences, and symposia, in particular, have been deluged with papers on C ‘sinks’, C ‘sequestration’, C ‘storage’, C ‘stabilization’, and C-storing ‘capacity’. This welcome tide of data is showing how we can manage soils to trap more C, how much we might store, and for how long.

But in our new-found zeal for locking up C, do we overlook a fundamental precept: that organic matter has most benefit, biologically, when it decays? Decades ago, William Albrecht (1938) wrote:

> Attempting to hoard as much organic matter as possible in the soil, like a miser hoarding gold, is not the correct answer. Organic matter functions mainly as it is decayed and destroyed. Its value lies in its dynamic nature.

Was there truth in his assertion? And does it still apply? In this essay, I ponder whether we can, at the same time, both sequester C and see the benefits of higher soil C. Can we both conserve organic matter and profit from its decay? Or does building soil C involve a biological cost, a temporary forfeiture of dividend?

To address these questions, I ponder the merits, first of building soil C and then of its decay (loss). I then examine the apparent paradox that emerges, and proffer some tentative thoughts for resolving it. Though these contemplations may apply more broadly, I focus primarily on cultivated soils, the ones most widely seen as intentional C sinks. And I seek a partly historical perspective, trying to avoid preoccupation

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with present pressures and perhaps unearthing again some insights now buried.

2. Soil organic matter as a C sink

Soil organic matter is the accumulated, decaying debris of biota living on or in the soil. It is vastly heterogeneous, encompassing everything from last hour's root exudate to persistent humified material, millennia old (Amundson, 2001). The largest of the active terrestrial C pools, soil organic matter holds about 1500 Pg C to a depth of 1 m (Eswaran et al., 2000; Jobbágy and Jackson, 2000). Its amount in any place changes over time, depending on photosynthetic C added and the rate of its decay (Fig. 1)(Paustian et al., 1998; Janzen, 2004).

In recent centuries, stored C has often declined, at least in cultivated soils. Arable agriculture typically depletes soil C because: it returns less plant litter since a fraction of photosynthetically-fixed C is harvested; it makes organic matter more accessible to biological decay by disrupting soil aggregates and mixing fresh litter into the soil; and it intensifies erosion which displaces C-rich surface soil. In total, cultivated soils have lost some 50 Pg C or more (Paustian et al., 1998; Amundson, 2001; Lal, 2003, 2004a,b; Janzen, 2005). These past losses, now, present the opportunity for future sinks; C sequestration, usually, means re-building past reserves, not adding new ones (Smith, 2004c; Wander and Nissen, 2004).

How much of the lost C can be recovered? Measured rates of soil C accrual, under improved management, are typically a fraction of 1 Mg C $ha^{-1}y^{-1}$, much less (by definition) than net primary productivity on croplands, which has a mean, worldwide, of roughly 3 Mg C $ha^{-1}y^{-1}$ (Goudriaan et al., 2001; Sabine et al., 2004). Globally, as much as 0.4–1.2 Pg C y^{-1} could be stored in agricultural lands (including restored degraded soils), according to Lal (2004b). But such projected values are tentative; we do not know exactly the rates of C accrual under C-conserving practices, nor how widely the practices will be adopted. Such global estimates may be best seen as potential targets, subject to social and economic constraints (Smith, 2004c); some have even called them 'wildly positive' (Schlesinger, 2003). These debates aside, many scientists agree that soil C sinks—indeed all biological sinks—can only, at best, have modest effects on atmospheric CO_2 at this century's end (Amundson, 2001; Royal Society, 2001; Scholes and Noble, 2001; Smith, 2004a,b,c).

Then why the preoccupation with soil C sinks? There are at least two reasons. First, soil C sequestration may be a 'stop gap' measure to help slow the rise of atmospheric CO_2 in coming decades, as societies search for alternatives to burning fossil C. Atmospheric CO_2 is now increasing at about 3 Pg C y^{-1} (IPCC, 2001); even a fraction of a Pg C y^{-1} stored in soils could help slow that increase (Pacala and Socolow, 2004; Lal, 2004b). And secondly, building soil C is meritorious and good even aside from any benefits to the atmosphere. Soil C sequestration is a 'win–win' option, a 'no-regrets' option, because a soil with more organic C, we say, is a better soil, a more productive soil (e.g. Lawes and Gilbert, 1885). So we aim for increased soil C also because it improves our soils (Lal, 2002, 2004b; Wander and Nissen, 2004; Dumanski, 2004).

But now we encounter a disquieting constraint—the benefits of organic matter arise, not from its *accumulation*, but from its *decay*.

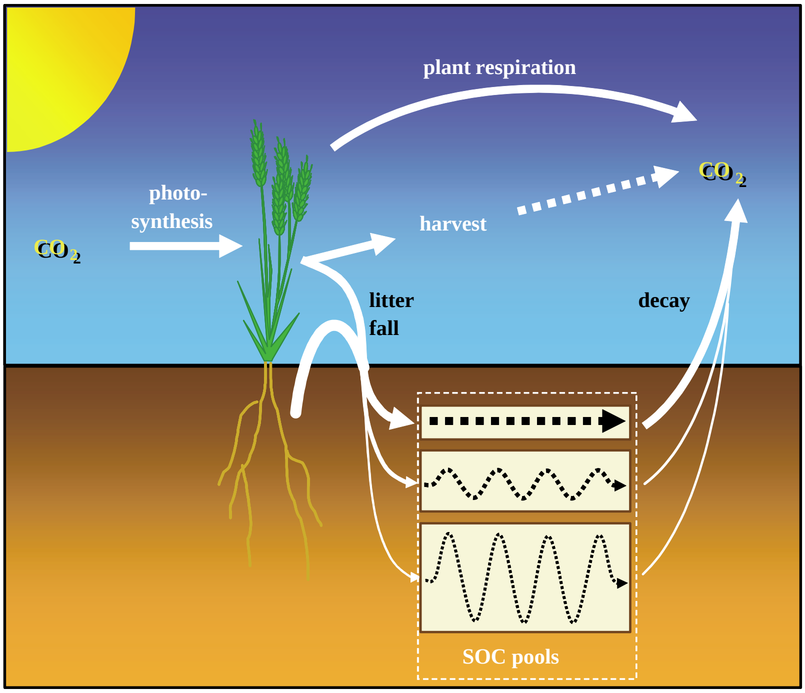

Fig. 1. Illustration of the main stores and flows of C in a cropland, showing three pools of soil C for simplicity, though recognizing that soil C spans a continuum of forms.

3. Soil organic matter as substrate (fuel)

Early in the previous century, scientists studying organic matter focused on its dynamic nature; they saw organic matter as a stream of C and other atoms gradually flowing back to CO_2 and other elementary constituents. Waksman (1936, p. 7) wrote: “Humus is not in a static, but rather in a dynamic, condition, since it is constantly formed from plant and animal residues and is continuously decomposed further by microorganisms.” And Howard (1940) agreed: “Humus in the natural state is dynamic, not static.”

From this vantage, organic matter is fuel for soil’s biological machinery (King, 1907, p. 95; Shutt, 1916); in Albrecht’s (1938) words it is “fuel for bacterial fires in the soil, which operates as a factory producing plant nutrients”. It is in decay that organic matter becomes most useful. “The old agricultural investigators…”, wrote Russell (1926, p. 47), “knew that organic matter must suffer decay or decomposition before it served its proper purpose in the soil: in the language of the eighteenth century, ‘Corruption’ (using the word in its original significance) ‘is the mother of vegetation’ ”. Lipman has been quoted to say: “… humus as such is of no use to plants, it becomes valuable only in so far as it is resolved into the simple compounds carbon dioxide, nitric acid and various mineral salts.” (Woodruff, 1968, p. 153).

The cited views of Lipman and others, admittedly, may be a little narrow. Soil organic matter is more than “fuel”; it has persistent benefits also through physical effects (soil structure, moisture retention) and chemical effects (ion exchange, buffering) (Waksman, 1936; Allison, 1973). But even here, ongoing decay may be helpful or even necessary. For example, soil organic matter helps maintain structure partly through continual turnover (Six et al., 2004). So from a biological standpoint, at least, the benefits of organic matter depend on decay. The words of Hopkins (1910) may still apply: “It is the decay of organic matter, and not the mere presence of it, that gives ‘life’ to the soil”. (Or as Swanson (1914, p. 646) quotes him: “It is not the presence of organic matter which is most important but the decay of organic matter”.)

Implicitly, we still acknowledge the importance of decay as a measure of soil performance, as reflected in the wide use of soil respiration as an indicator of soil ‘quality’ or ‘health’ (Doran and Parkin, 1994; Kennedy and Papendick, 1995; Karlen et al., 1998; Wander and Bollero, 1999; Knoepp et al., 2000). In effect, we are saying: the more the decay, the ‘better’ is the soil; the more active the soil biota, the richer the biological rewards.

But here, now, is the apparent paradox: to build organic C, we may need to stifle respiration (suppress microbial activity). With fixed input of C, we cannot increase soil C reserves without suppressing respiration (decay). And if we constrain microbial activity, are we also squelching the many ecosystem functions delivered by the soil’s teeming hordes?

4. The dilemma

In advocating soil C sequestration, we may be chasing two contradictory aims: storage of organic matter, and also its decay. (Sometimes we even include the two together, in lists of soil quality indices, using both soil C and respiration rate as indicators (Doran and Parkin, 1994.)). We imply that the two are correlated; that when we increase organic matter we also increase nutrient release and biological activity. For example, a superb recent paper concluded that “No tillage and increased cropping intensity improved soil fertility by increasing soil organic matter and potential nutrient supply to crops.” (Wright and Hons, 2005). No doubt similar inferences appear in many papers, mine perhaps among them. But the reason that no-till increases soil organic C (absent differences in erosion or residue inputs) is because it inhibits microbial activity, it slows decomposition (e.g. Lupwayi et al., 1999, 2004), and presumably also nutrient release.

We say we want to store more organic C; we say that will make the atmosphere cooler and the soil better. But organic matter is most beneficial, biologically, as it dissipates by microbial activity. With constant C inputs, we cannot both increase soil C and increase microbial activity (Table 1). If we want higher microbial activity, we have to sacrifice soil organic C; if we want to store more C, we must quash microbial activity. So for any patch of land and span of time, we have to choose one—higher soil C or higher respiration (or a compromise between them).

Table 1
An illustration of the relationships between change in stored soil C and nutrient mineralization, microbial activity, and population size of active microbes

	Scenario 1 (Losing C)	Scenario 2 (Steady state)	Scenario 3 (Gaining C)
	Relative rate or size		
Change in stored C	−	0	+
Nutrient mineralization	+*	0	−
Respiration (microbial activity)	●●●**	●●	●
Active microbial population (and perhaps biodiversity?)	●●●**	●●	●

*‘+’ denotes nutrient mineralization > nutrient input in litter; ‘−’ denotes nutrient mineralization < nutrient input in litter; **The more bullet points, the faster the rate or larger the population.

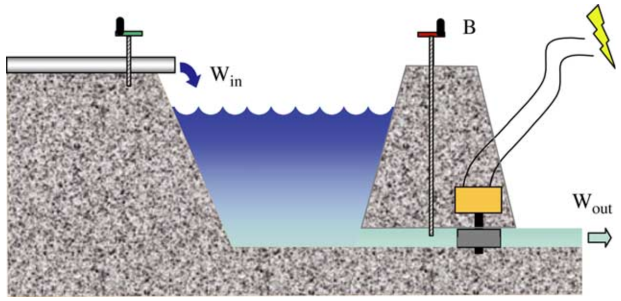

Fig. 2. Illustration of hypothetical hydroelectric plant. If rate of water inflow (W_{in}) is fixed, then opening valve B temporarily increases power generation, but at the expense of water storage. As pressure diminishes, rate of outflow (W_{out}) also declines until $W_{out} = W_{in}$. The amount of water stored can be increased by partially closing valve B, but at the temporary expense of power generation.

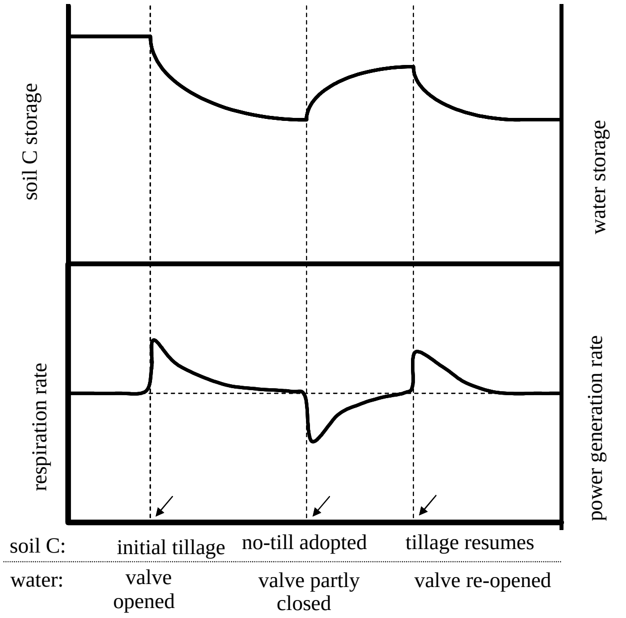

Fig. 3. Conceptual illustration showing the relationship between soil C storage and soil respiration rate (microbial activity), assuming a fixed rate of C input. Also shown (right-hand axis) is the relationship, parallel to that for C, between water storage and rate of electrical power generation in the hypothetical hydroelectric dam described in Fig. 2. (Curves may not be proportional.)

Consider a simple analogy: a hydro-electric plant, driven by water from a small reservoir (Fig. 2). The amount of water in the reservoir is controlled by two things: the rate of water entering from the inlet, and the rate of water flowing past the turbines and escaping from the reservoir. If the rate of inflow is fixed, the manager controls the level of water in the reservoir by adjusting outflow: open the valve more and the rate of water outflow (and power generation) increases (Fig. 3). But only temporarily—as the water storage is depleted, and head diminishes, the rate of outflow again declines approaching that of the inflow, but now with lower water storage. Restrict the outflow again, and the water level will increase until the increasing pressure eventually results in outflows as high as the inflow, restoring the rate of power generation. The options are clear: to increase water stored in the reservoir, the manager needs to sacrifice temporarily the rate of power generation. Conversely, the manager can temporarily increase the rate of power generation, but only at the cost of reduced water storage.

The same principle applies also to managing C in agricultural lands (Fig. 3). If the amount of C entering the soil as plant litter is fixed, the manager can create conditions to stimulate decay, benefiting from that higher decomposition through higher fertility and microbial activity, but at a cost to amount of C stored (this is what we did historically). Or the manager can effectively increase the amount stored, but only by suppressing decay—and at a cost to energy, nutrients, and other functions derived from decay (this is what we hope to do).

There is a difference, then, between *having* high soil C and *building* high C. *Having* high soil C gives the manager the potential to tap into the reserve of accumulated energy, and temporarily, at least, derive enhanced returns from its decomposition. *Building* high C, however, involves a cost. So when we say that increasing soil organic matter benefits soil performance, we may not be quite right—the benefits accrue only when we have stopped building; during the phase of C increase, we may, in fact, have diminished soil quality.

To use another analogy: it is nice to have a large bank account, but to build a large bank account on a fixed income requires temporary suppression of outflow. The end result affords potential spending; but building that potential requires, sadly, that spending be curtailed.

5. Resolving the dilemma?

How might the apparent conflict between C sequestration and C decay be assuaged or even used to advantage? Here are a few preliminary thoughts, intended mainly to foster deeper debate from which may spring insights more robust than these.

5.1. Find ways to increase C inputs

There is a way out of the paradox: increasing the amount of C entering the soil. Until now, I have assumed a fixed amount of C entering the soil; but if we add more C, then we can both increase decay and augment the C stored. To extend the earlier analogy: we can increase the rate of water inflow into our reservoir (Fig. 2). In the long run, the average outflow from the reservoir must equal the average rate of inflow (assuming no other losses). In time scales beyond decades, beyond the short-term fluctuations induced by management, the average rate of soil C decay must almost equal the rate of C added to the soil. So adding more C, always enhances the benefits from decomposition of added C.

The amount of C inputs to land is a product of two factors:

$$C_{\mathrm{i}} = \mathrm{NPP} \times f_{\mathrm{r}}$$

Where C_{i}, annual C added to soil (Mg C ha^{-1}); NPP, net primary productivity (Mg C ha^{-1}); f_{r}, fraction of NPP returned to soil.

Thus C inputs can be enhanced by increasing photosynthesis (NPP) or by increasing the proportion of NPP added to soil (f_{r}). But increasing C inputs may not be easy. Although, 20th century plant breeders and agronomists achieved stunning increases in crop yields, some of those came, not from higher photosynthesis, but from allocating more C to harvestable plant fractions (Smil, 2000). According to Evans (1997): “Empirical selection for yield has not enhanced photosynthetic capacity to date… [G]iven the prolonged and intense natural selection pressures already endured by photosynthesis, we cannot be optimistic that photosynthetic efficiency will be increased significantly in the next few decades. … Further increase in the harvest index will be limited and, so far, the maximum rates of photosynthesis and crop growth have not been improved genetically.” In effect, therefore, higher crop yields have come, at least partly, by *reducing* ‘f_{r}’, allocating a smaller fraction of C to soil.

Increasing the flow of C into soils may soon become even more challenging because of growing competition for fixed C. For example, industrial interests are increasingly eyeing crop 'wastes' as feedstocks for bio-fuel (Jenny, 1980). Some have even proposed dumping agricultural residues into oceans as a way of sequestering C (Metzger et al., 2002).

So the dilemma, in theory, can be resolved easily by returning more plant litter to soil, directly or in manures. But can we hope for large increases in C returned to soil, given rising demands for harvested C?

5.2. Find ways to optimize the timing of decay

Organic matter may give highest benefit when it decays. But the rewards of that decay are higher at some times than at others. For example, high rates of decay during a fallow period or after senescence of plant growth may be wasteful. Can we better manage the annual balance between C accumulation and decay, by how we select our crops, time the tillage, manage residues, apply manures, irrigate the land? Can we hasten decay when it has most benefit and suppress it when it has least? (Returning to our analogy: can we adjust water outflow in accordance with fluctuating power demands?) And, maybe more daringly, can we better manage the long-term C balance, over periods of years and decades? For example, is there merit in long-term cycles of accumulation and decay, encouraging accumulation for some years, then reaping the benefits, for a time, of the decay of that accumulation?

A fruitful research objective, in recent years, has been learning how to sequester C into recalcitrant soil 'fractions' that will protect the C against the scrabbling biota that seek to use it (Six et al., 2002; Krull et al., 2003; Goh, 2004). Perhaps now we should also ask whether it is possible to encourage a suite of fractions, some that retain the C, others that are available to microbial populations in synchrony with biological demands for energy and nutrients. Do we really want only more cast-iron C?

5.3. Study flows (not only stocks) of C

Westman (1977) suggested that "To date, those concerned with quantifying and evaluating benefits of natural ecosystems to [humanity] have largely focused on the standing stocks of nature rather than the flows." Does that apply also to our studies of soil C? Has our preoccupation now with 'sinks' and 'sequestration' and 'capacity' over-emphasized soils as 'tanks' for C? Have we been more intent on measuring how much C is there and where it resides, than in seeing how C atoms stream through the soil and what happens to them along the way? Maybe what is needed is more study of process than of structure, more study of dynamics than of capacity, more focus on dC/dt than merely on C. By definition, this means more devoted study of the agents of C turnover—the populations of microbes and fauna which derive their energy from the burning of the organic matter fuel (Waksman, 1936, p. xi). And it may mean studying them alongside other disciplines, and at ecosystem levels (Coleman et al., 2004, p. 294).

The aim of soil C studies then might be, not merely to maximize the amount of C stored, but to find a balance between amounts held in reserve and amounts used for microbial activity, a balance between amount hoarded for future use and the amount burned for immediate benefit. "Agriculture must always be balanced.", said Howard (1940, p. 25). "If we speed up growth we must accelerate decay. If, on the other hand, the soil's reserves are squandered, crop production ceases to be good farming: it becomes something very different. The farmer is transformed into a bandit."

From this perspective, more is not always better: C gain is not always good, C loss is not always bad. It is not just a question of C gain or C loss; what counts is whether the balance between amount stored and amount used is tuned for the 'services' expected of the ecosystem in question. Finding that optimum balance for all our ecosystems in diverse conditions might be a promising research objective. And seeking ways of managing our lands toward that balance might be another.

These objectives might become especially urgent in the face of pressures and stresses imposed upon our ecosystems with coming global changes. Soils may grow warmer, litter inputs may change as CO_2 increases, land use may intensify as billions more of us compete for food and space. Conserving our ecosystems and wisely extracting from them the services we need will, assuredly, depend on our understanding better the biological flows of C through our soils.

6. Closing thoughts

For much of the history of arable agriculture, soil C reserves have been declining. Much of what we know about organic matter was learned during that period of loss. But now that we are in a period of soil C recovery (a laudable aim!), what we inferred about organic matter's benefits may not all apply. The benefits of organic matter during a period of accrual, when biological activity and decay rates might need to be suppressed, may deserve new ways of studying C flows. Almost certainly, these new approaches will have to look more closely at the biotic populations that shuffle the C atoms about in the soil, rather than merely counting how many atoms are stored.

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