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Cropping leads to the loss of soil organic matter: how can we prevent it?

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Soil organic matter (SOM), which associates carbon to key plant nutrients, has been stored in soils for thousands of years and scientists have long recognised its positive impact on key environmental functions such as food production and climate regulation. As soon as a virgin land (forest or grassland) is cultivated, there is a tendency for the soil to lose its SOM and we still largely misunderstand the underlying mechanisms, leading to inappropriate decisions being taken to fight soil, climate and overall ecosystem degradation.

Most likely since the dawn of agriculture, soils converted to croplands have suffered from a continuous, almost inevitable decline in their stock of SOM, which has long been recognized as a major cause of land degradation. Long before farmers began using pesticides, heavy machinery, widespread mineral fertilization and GMOs, scientists such as Swanson and Latshaw (1919), Snyder and Marcille (1941) had published on their observations of systematic declines in SOM through the cultivation of virgin land (forest or meadow) or when livestock was abandoned by farmers. In their writings, these scientists from the early 20th century were only formalizing the observations that crop yields decline during the first 10-15 years following land conversion, associated with increased difficulties in tilling the soil, soil compaction and soil erosion (Hénin and Dupuis, 1945). For instance, using 37 paired sites in Arkansas cropped since the middle of the 19th century, Swanson and Latshaw (1919) showed that after decades of cultivation, losses of soil organic carbon averaged 30% in the 0 to 20 cm soil layer (from 27% under semi-arid to 33% under wet climate) and 6% in the 20-50 cm layer (from 1 to 11%, respectively).

The loss of SOM received too little attention as its role in soil fertility was down played following the work of Dumas and Liebig (1836) who suggested that the air provides most of the “food” for plants. It is only recently that several environmental issues such as soil erosion by water, water and air pollution, climate change and the scarcity of P have put back SOM at the center stage.

Since the loss of SOM has resulted in the emission of large amounts of CO_2 to the atmosphere to cause climate change, it has been suggested that building back SOM would constitute a smart and efficient way to mitigate against land degradation and climate change. This is the aim of the 4p1000 initiative (4 *per 1000 initiative: Soils for Food Security and Climate*) which was launched in Paris in 2015 by the French Ministry of Agriculture. 4p1000 seeks to promote agricultural practices able to increase the carbon stocks of the soil by 4 parts per thousand (i.e. 0.4%) per year, to contribute to offsetting CO_2-C emissions from fossil fuel burning (http://4p1000.org).

As a great physician understands the causes of the disease of its patients, rebuilding the SOM lost from soils requires soil scientists to identify the causes of its loss. Hénin and Snyder in the early 1940s indicated that tillage operations were responsible for the oxidation of SOM. While tillage was the only practice to weed the soil and to prepare the seed bed, it continued to be practiced worldwide until herbicides allowed the possibility to crop without tilling the soil. Direct seeding (or zero tillage) was then born in southern Brazil in the 1960s (Landers, 2001) to address soil water erosion problems that threatened food production and the sustainability of agriculture. Farmers, technicians and researchers then noticed that abandoning tillage led to a significant increase in the organic matter levels of the soil surface, thus confirming the impact of tillage on SOM and with positive feedbacks for rain infiltration and the soil's resistance to water erosion. After gradually conquering the American continent, the practice of zero tillage is now booming in the rest of the world.

More recently, several scientists have noted that in order the assess the benefits of zero tillage for soil carbon storage, the entire soil profile (from its surface to the bedrock or at least to a depth of one meter) needs to be considered (Baker et al., 2007 ; Luo et al., 2010; Liang et al. 2020). These compilations of global results confirm that the abandonment of tillage does indeed lead to an accumulation of carbon in the topsoil but that is compensated by carbon losses in depth. Liang et al. (2020) further indicate that while in well-watered areas in Canada no additional carbon is stored, the semi-arid grasslands of the country accumulate carbon at a rate of 740 kg C ha^{-1} year^{-1}. Ogle et al. (2019) also concluded from 178 global sites that the abandonment of tillage is probably less efficient than other agricultural practices for storing carbon in soils, and that carbon accumulation in the topsoil that limits soil erosion may render the SOM more vulnerable.

Reforestation and conversion of croplands to grassland would certainly rebuild lost SOM (Guo et al. 2021) but food production would be lost or displaced elsewhere. Amongst the practices allowing production of grains to continue, while restoring lost soil carbon, cover crops are often cited with to our knowledge only two meta-studies involving sites all over the world existing on the subject (Poeplau and Don, 2015; Abdalla et al., 2019). Poeplau and Don (2015) who considered the topsoil (0-5 to 0-30cm) indicate that the average SOC increase was 0.35 tonne ha^{-1} yr^{-1} but among the 37 sites, the overall median was as low as 0.1 tonne ha^{-1} yr^{-1} and 13 sites showed a decrease in carbon stocks. Abdalla et al. (2019) found a mean value of 0.54 tonne ha^{-1} yr^{-1} but 8 sites out of 43 had very low values since between -0.1 and 0.03 tonne ha^{-1} yr^{-1}.

If tillage, the absence of cover crops but also the use of pesticides, mineral fertilizers and heavy machinery (that were absent in croplands experiencing significant losses of soil C in the late 19th century) do not fully explain soil carbon losses, are there other contributing factors?

One often overlooked factor is the massive exports of nutrients by cultivated plants. Studies such as by Chatzav et al. (2010) indicate that winter wheat when yielding 7 tonnes per ha and per year of grains (world average) export per hundred years 2.9 tonnes ha^{-1} of P, 3.3 tonnes ha^{-1} of K, 0.26 tonnes ha^{-1} of Ca and 0.9 tonnes ha^{-1} of Mg. For equivalent area and growing duration, P exports by wheat grains are 153 times higher than a clearcut of deciduous forest (1.6 tonne ha^{-1} yr^{-1}) and 34 times higher than the meat produced on an average grassland (400 kg per ha^{-1} yr^{-1}). K exports are, respectively, 18 and 23 times higher and exports are 19 and 90 times higher for Mg (Table 1).

Table. Biomass production and nutrient exports by different land use: winter wheat vs natural vegetation (forest, grassland). (computed from Johnson and Todd, 1987 and Chatzav et al. 2010)

Land use	**Biomass**	**P**	**K**	**Ca**	**Mg**
	Tonne ha^{-1} 100 yr^{-1}	--------------- kg ha^{-1} 100 yr^{-1} --------------			
Forest (wood)	160	19	185	1250	47
Grassland (meat)	40	86	145.2	1.8	10
Wheat (grain)	700	2900	3300	260	900
Grain/wood	***4***	***153***	***18***	***0***	***19***
Grain/meat	***18***	***34***	***23***	***144***	***90***

To find these quantities of nutrients, plants solicit bacteria (by secreting exudates sometimes called “dissolved” or “liquid carbon” *via* their roots) to degrade SOM, the only reservoir of easily assimilated nutrients in the soil. Indeed, past research studies such as by Kallenbach et al. (2016) have pointed to the recruitment by plants of soil bacteria that mineralize phospholipids, nucleic acids and other phosphorus bound organic molecules from SOM to feed plants in P but leading to the loss of SOM and carbon release to the atmosphere.

So how can the trend of SOM destruction be reversed?

Early 20th century researchers and practitioners knew the virtues of decomposed manure (which provides essential nutrients without acidifying the soil) and clover, which draws nutrients from the atmosphere and the deep layers of soils and rocks, to accumulate them in the topsoil. Kirkby et al. tell us in their 2014 work that SOM is formed rather than lost when organic inputs to the soil meet the nutrient ratios found in soil bacteria, the source of SOM. Because crop residues such as wheat straws are far too rich in carbon for the needs of bacteria, in order to avoid “priming” (Fontaine et al., 2007), and the associated loss of SOM in the process of straw decomposition, one tonne of wheat straw should be supplemented with the addition of 5 kg of N, 2 kg of P and 1.4 kg of S. Using C isotopes in four soils with differing clay content, these authors showed that conversion of straw into new SOM increased by up to three-fold by supplementing crop residues with nutrients. In addition, Poeplau et al. (2016) in a long-term trial pointed to enhanced SOM formation with increasing nutrient availability.

Contrasts in nutrient availability or nutrient balance in the soil are likely to explain the observed differences in efficiency to increase SOM of approaches such as reduced tillage or cover cropping, with the situations experiencing SOM losses potentially resulting from nutrient deficiencies or imbalances. Improving fertilization during crop cycles to avoid SOM loss linked to nutritional imbalances, by adding manure, by adding to crop residues fertilizer combos such as of the 20-10-5-10 type, by using cover crops supplemented with balanced fertilization, or by lessening nutrient losses due to soil erosion, will help to deliver soil- and climate-smart agronomic practices, which will allow SOM to be rebuilt. Maintaining various nutrient balances through fertilization might also enhance the ability of the historical approaches to build SOM which calls for long-term field trials under different environments, worldwide, where impact of cover cropping, tillage suppression, crop type or rotation on SOM are investigated for different soil nutrient status.

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