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Evidences of plants' impact on land degradation and climate change: An urgent call for new multidisciplinary research

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1 **Evidences of plants' impact on land** 2 **degradation and climate change: an** 3 **urgent call for new multidisciplinary** 4 **research.**

5
6 **Atmospheric carbon has been stored in soils for thousands of years in the form of**
7 **organic matter which associates carbon to key plant nutrients. Recent analysis reveals**
8 **that when facing nutrient deficiency, plants decompose soil organic matter to mine**
9 **nutrients and carbon is released into the atmosphere which causes land degradation and**
10 **climate change.**

11
12 Soils have lost enormous amounts of organic carbon due to agriculture because of the
13 conversion of natural ecosystems to cropland and more recently as a result of agriculture
14 intensification. Several compilations of individual studies performed by for instance Guo and
15 Gifford (2002) have estimated the soil organic carbon (SOC) losses from the 0-0.3 m soil
16 layer to amount 42% of initial stocks from native forest and 59% from grasslands. Globally,
17 the resulting annual carbon losses from agricultural soils are estimated to be ~12% of human
18 induced total emissions

19
20 Because soils have lost large amounts of carbon consecutive to changes in their use it is
21 assumed that carbon recovery in soils may occur if appropriate management is taken. Several
22 world initiatives such as the “4 per 1000 initiative: *Soils for Food Security and Climate*”, also
23 known as “4 per mille” (which was launched by the French Ministry of Agriculture in 2015 in
24 preparation for the Paris climate conference of the United Nations Framework Convention on

25 Climate Change, UNFCCC) thus aim at promoting land management practices to increasing
26 soil organic carbon (SOC) stocks. The 4P1000 suggests that, if the rate of C sequestration by
27 4 per mille or 0.4% per year was achieved for all soils globally to a depth of 40 cm, the C
28 removed from the atmosphere would equal annual CO₂-C emissions from fossil fuels of 8.9
29 Gt and thus halting the annual increase in CO₂ in the atmosphere while sustaining soil quality
30 and food production (<http://4p1000.org>).

31

32 Initiatives such as the 4P1000 have proposed several shifts in cropland management to store
33 back the lost SOC. As tillage was assumed to be responsible for most of the decrease of soil
34 carbon because of aggregate breakdown that renders organic matter accessible to
35 decomposers such as bacteria, tillage abandonment was long suggested as a credible “nature-
36 based” solution to store back the lost SOC (Lal, 2004). Nevertheless, as early as 2007, Baker
37 et al. in a compilation of existing data worldwide indicated that the carbon accumulation
38 observed in the topsoil (0-0.3m) was in most cases compensated by losses in the subsoil (0.3-
39 1m), which was further confirmed by the meta-papers by Luo et al., (2010), Ogle et al. (2019)
40 and Liang et al. (2020). The implantation of cover-crops or catch crops to compensate the
41 short growing cycles of cash crops has proven to almost systematically yield SOC stock
42 recovery by an average $0.32 \pm 0.08 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ (Poepflau and Don, 2015 from 139
43 experiments worldwide considering the 0-20cm layer). However, while 102 experiments
44 exhibited an annual SOC increase between 0 and $1 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$, thirteen sites, mostly from
45 tilled soils in the tropics, pointed to a SOC stock depletion.

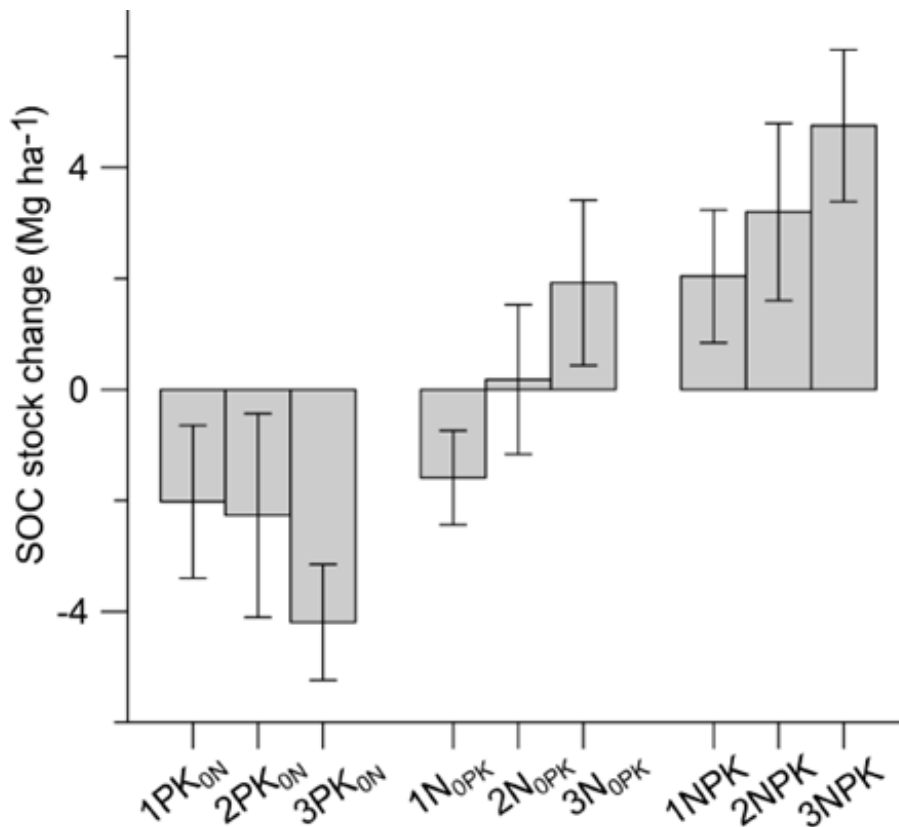
46

47 Contrary to no-tillage and cover-cropping, excess fertilisation (i.e fertilization above crop
48 requirements for a targeted grain yield) either in inorganic or organic forms proved to enhance
49 SOC stocks in all cases. The two longest running agricultural experiments (>150 years)

50 worldwide in the US (Moron plots) and in England (Rothamsted) showed that annual
51 farmyard manure (FYM) applications at 35 tons fresh material per hectare (~3.2 t organic C
52 $\text{ha}^{-1}\text{yr}^{-1}$; 220 kg N $\text{ha}^{-1}\text{yr}^{-1}$; 140 kg P $\text{ha}^{-1}\text{yr}^{-1}$; 175 kg K $\text{ha}^{-1}\text{yr}^{-1}$) induced soil carbon increases
53 of between 1.8 and 4.3% per year for the entire soil profile for the first 20 years followed by
54 increases of 0.7% for 40-60 years (Poulton et al. 2018). Applying straw residues to the soil
55 surface was also shown to increase SOC stocks at 10 per mille yr^{-1} when applied at a rate of
56 12 ton $\text{ha}^{-1} \text{yr}^{-1}$. Similarly, excess N, P, K inorganic fertilisation at for instance the Swedish
57 long-term soil fertility experiments (> 45 years) shows enhanced SOC stocks by a maximum
58 of 4 ton C ha^{-1} or 0.09 ± 0.07 ton $\text{ha}^{-1} \text{yr}^{-1}$ or $0.16\pm 0.12\%$ yr^{-1} (Poeplau et al. 2016) (Figure 1).

59

60 In contrast, the same Swedish long-term soil fertility experiments revealed that unbalanced
61 fertilization induces a decrease in SOC stocks. When P and K was applied without N, SOC
62 stocks surprisingly decreased to a maximum of 0.072 ton C $\text{ha}^{-1} \text{yr}^{-1}$ or 2.3 per mill yr^{-1} . These
63 authors linked the SOC losses to stimulated microbial activity and stated that the “*reasons for*
64 *that remained unclear*”.



65

66 Fig 1. Changes in SOC stocks as function of N, P, K fertilization: 1PK_{0N} (P and K at plant
 67 requirements rates and zero N); 2PK_{0N} (P and K at two times plant requirements rates and
 68 zero N), ...). From Poeplau et al. (2016).

69

70 So, what may be the reason for a SOC stock decrease under nutrient imbalance? In contrast,
 71 what could be the reason for a SOC increase under conditions of nutrient excess?

72

73 Because of a staggering enhancement of the yield of main crops, decades of agriculture
 74 intensification have exported enormous amounts of nutrients (N, P, K but also S, Ca, Mg, Fe,
 75 Cl, Mn, Zn, Cu, B, Mo), largely more than the soil and the underlying rocks can provide
 76 (Burghlea et al. 2015) and farmers only systematically apply N, P, K and S. From the data by
 77 Chatzav et al. (2010), modern wheat cultivars when producing 7 tons per ha yr⁻¹ of grain
 78 (world average) export through grains, an average 3.3 ton ha⁻¹ 100 yr⁻¹ of K, P (2.9), Mg (0.9),

79 Ca (0.26) and 28 kg ha⁻¹100 yr⁻¹ of Zinc. This is respectively 6.4, 4.9, 4.8, 6.6 and 4.7 times
80 higher than grain exports by wild Emmer wheat (1 ton ha⁻¹ yr⁻¹).

81

82 Past research has shown that when facing nutrient deficiencies or imbalances (which may
83 occur during the whole growing cycle or only part of it), plants have the ability to recruit soil
84 microbiota to help meeting their needs. In the case of P, plants exudate specific sugars to
85 recruit organisms belonging to the genera *Penicillium* and *Aspergillus* which possess ability to
86 bring insoluble soil inorganic phosphates into soluble forms by secreting acids that lower the
87 pH to as low as 3 thus inducing the dissolution of bound forms of phosphate. The
88 mineralization in the soil of most organic phosphorous compounds is carried out by means of
89 phosphatase enzymes that mineralize phospholipids, nucleid acids and other phosphorus
90 bound organic molecules. Since carbon is being stored in soils in the form of organic matter
91 where it is linked with plant nutrients (N, P, K but also S, Ca, Mg, Fe, Cl, Mn, Zn, Cu, B, Mo)
92 any nutrient deficiency in the soil is likely to induce its mining by plants into organic matter
93 thus leading to organic matter decomposition and C releases to the atmosphere.

94 Such a process of nutrient mining is probably exacerbated in modern crop cultivars due to a
95 shrinked rooting system as compared to ancient crop cultivars (Mathew et al., 2020) which
96 limits their ability to acquire nutrients deep into soil profiles where rock weathering occurs.

97 In reverse, when nutrients are in excess in the soil, plants have shown great ability in
98 recruiting microbes to store them in the form of organic matter (Kallenbach et al. 2016) to be
99 further accessible during periods of “famine” rather than being lost to water bodies and
100 ultimately to oceans due to leaching.

101

102 This is to fill the gap between their needs and what is readily available in the soil (a naturally
103 nutrient scare media) that plants have developed great ability to decompose or build organic

104 matter through the feeding of specific soil bacteria. The cultivation of “nutrient thirsty”
105 modern crop cultivars for the last 60 to 70 years has been a game changer which accelerated
106 nutrient mining in organic matter to fill the gap between the amount of nutrients readily
107 available into the soil (naturally or as a result of fertilization) and plant needs.

108 The loss of organic matter induced a direct release of carbon to the atmosphere. In turn, as
109 organic matter is key for soil chemical, biological and physical fertility (Reeves, 1997) the
110 decrease in organic matter content, whose magnitude differs between soil types, climates and
111 management, most likely explains the general yield decrease of main crops since the 90s
112 despite the increase in their yield potential as for instance Dawe et al., (2000) have shown for
113 rice production in Asia.

114

115 As a matter of fact storing more carbon into soils and maintaining it long-term to mitigate
116 against climate change and for sustainable agriculture and ecosystem functioning won't be
117 assessed without a proper understanding of the plants-soils interactions. Here we show that
118 improved nutrient fertilization might halt the current decrease in soil carbon stocks and land
119 degradation worldwide. In contrast, the initially most promising management techniques such
120 as tillage abandonment or inorganic fertilization that have so far largely failed to recover the
121 lost SOC, might prove to be successful under improved nutrient management. This is what
122 tend to show several studies performed under dry climates where soils are less prone to be
123 leached and most likely to be nutrient-rich as compared to soil under wet climates such as by
124 Liang et al. (2020) in Canada that points to a positive impact of tillage abandonment on SOC
125 stocks in drylands only.

126

127 There are several recent policy developments that might be harmful to soil carbon as they are
128 likely to potentiate plants mining of nutrients and thus organic matter destruction. Recent

129 legislations limiting the supply of fertilizers to reasonable targeted grain yields (*vs* excess N
130 fertilization as a cost-effective form of insurance against yield loss from N limitation during
131 favourable years), the widespread adoption of organic agriculture by large scale farms with
132 little if no N, P, K fertilization, the systematic implementation of catch crops constitute as
133 many drivers likely to accelerate nutrient mining into soils by plants and thus the decrease of
134 soil carbon stocks. Plants are “superorganisms” and we should better rely on them rather than
135 on us to solve Earth’s land and climate degradation problems. To help them “do the job”, we
136 urgently need to improve our understanding of the role of plants on organic matter dynamics
137 and the main controls. For this end, soil, rock, and crop scientists should collaborate more
138 closely to define crop and/or crop rotations requirements in all nutrients for a given soil and
139 geologic condition to maintain the current levels of organic matter or to increase them, which
140 calls for long-term experimental trials and innovative technologies. In the meantime, solving
141 our crucial land degradation and climate problems calls to (1) rethink the cascading process
142 from the gathering of scientific evidences to action at large scale through policy definition;
143 and (2) “*go back into the wild*”, i.e. crop ancient and nutrient unthirsty crop cultivars.

144

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