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Research paper

How does crop residue removal affect soil organic carbon and yield? A hierarchical analysis of management and environmental factors

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ABSTRACT

The current advancement of the bioenergy sector along with the need for sustainable agricultural systems call for context-specific crop residue management options – implying variable degrees of removal – across climatic regions, soil types and farming systems around the world. A large database ($n = 660$) on the effects of crop residue management on soil organic carbon (SOC) and crop yields was compiled from studies published in the last decade and analyzed using descriptive and multivariate statistics and data mining techniques. Removing crop residues from the field led to average SOC contents that were 12 and 18% lower than in soils in which crop residues were retained, in temperate and tropical climates respectively. The dataset showed a wide variability as a result of the wide range of biophysical and management factors affecting net changes in SOC. In tropical climates the effect of crop residue management on SOC was subject to local climate and soil texture. In these regions the addition of C via crop residues was crucial in sustaining SOC especially in coarse textured soils. Yields increased following residue retention in tropical soils, while low SOC corresponded with lower crop production in temperate areas. Our results suggest that crop residue removal is not recommended in tropical soils, particularly in coarse-textured ones, and in SOC-depleted soils in temperate locations. Partial residue removal can be considered in temperate climates when soils are well-endowed in SOC. Future policies must consider the role of residues within different agro-ecosystems in order to advance agriculture and the bio-energy sector sustainably.

1. Introduction

In the last decade, the increased interest in bioenergy and the specific role of crop harvest residues as feedstock has called for carefully designed crop residue management practices in agricultural systems [1]. The use of biomass as feedstock for bioenergy production is seen as an opportunity to strike a balance between (i) producing renewable energy with a reduced impact on food security compared with energy-crop production, (ii) generating alternative income for farmers and (iii) reducing environmental impacts [2,3], and [4]. The appropriate use of crop residues within cropping systems is essential to enhance agricultural and environmental sustainability [5]. Competing claims for crop residues from the bioenergy and agricultural sectors are thus likely to arise. In the case of smallholder agriculture, in particular, the removal of crop residues for bioenergy production may lead to soil degradation, and/or to an increased dependence on external sources of inputs of animal feeds and nutrients [6]. Understanding the impact of crop residue management on soil fertility and crop productivity is therefore, crucial to inform the design of practices and policies aimed to limit the potential trade-off between energy and food production, and ultimately food security goals.

Soil organic carbon (SOC) is considered to be a reliable proxy for soil quality, in terms of its physical, chemical and biological properties, and an informative indicator for sustainable land management [7]. As crop residue addition represents a C-input in the soil C-balance, the management of agricultural residues affects SOC content [8]. The maintenance of optimal SOC content has been identified as a criterion to define a sustainable removal rate of crop residues for energy purposes [9] and [10]. Along with increasing SOC levels, crop residue application was also reported to affect crop production [11], due to its impact on soil structure, water retention, nutrient cycles and biological activity [12]. The importance of crop

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residues is also recognized in the agricultural management system known as conservation agriculture (CA),[1] which promotes permanent soil cover with crop residue mulches [13].

The scientific literature on the impact of crop residue management on both SOC and crop yields provides widely variable, and sometimes ambiguous results across and within agro-ecosystems [14]. Several recent meta-analyses and reviews indicated an overall improvement in soil fertility and crop productivity as a response to crop residue retention [15–17] and [12]. Yet, it was also demonstrated that the actual changes in SOC and crop yields are site-specific, as they depend on biophysical and management conditions [12,14,18–23]. Such a diversity of recommendations suggests that a standard definition of sustainable crop residue management cannot be easily drawn, as this can vary across different sites depending on climatic and edaphic conditions. These studies concluded that there is the need to understand in which areas and under which conditions crop residues should be prioritized for soil fertility maintenance and in which areas their removal could be considered.

We compiled scientific evidence from experimental papers published in the last 10 years (2003–2013[2]) and reanalyzed this information in order to categorize the reported variability in the response of soils and crop yields to crop residue management. This paper aims to provide a preliminary identification of the potential locations, in terms of climatic regions, soil types and farming systems in which crop residue removal can have potentially negative consequences for crop production and soil fertility. It is seen as a crucial step in providing guidance and solid evidence to support stakeholders in outlining sustainable crop residue management systems. This is of particular interest to the bioenergy sector, and the growing bio-economy in general, where residues are assumed to be a freely available resource.

2. Materials and methods

2.1. Selection of the study

A literature survey on soil organic carbon (SOC) in relation to crop residue management was carried out using the on-line Scopus-Elsevier database (http://www.scopus.com). Principally, all studies containing the key words "soil organic carbon crop residues" from the past ten years (January 2014–2003) were examined. As most studies reported SOC stocks in the topsoil (0–15 or 0–30 cm), we excluded all references or data points below these depths in order to avoid sampling biases. Further, we excluded studies that (i) did not report comparisons between treatments with residues applied and residues removed, (ii) presented results from simulation model elaborations and (iii) literature reviews or meta-analyses. Additionally, within each study, data regarding treatments in which C-input other than crop residues (i.e. compost, manure) were applied were also excluded from the analysis.

2.2. Soil organic carbon (SOC)

The variable chosen for comparative analysis was the concentration of organic carbon in the top layer of the soil (at depths of 0–15 and 0–30 cm as reported in the source study), assessed through oxidative analysis, and expressed in g kg^{-1} of dry soil. When SOC was reported in equivalent soil masses, total weight of the considered soil layers (TSW) was calculated using soil bulk density. SOC concentration was obtained by Equation (1):

$$\mathrm{SOC}\left(\mathrm{g\ kg^{-1}}\right) = \mathrm{SOC}\left(\mathrm{t\ ha^{-1}}\right)\Big/\mathrm{TSW}\left(\mathrm{t\ ha^{-1}}\right)*1000 \quad (1)$$

Studies reporting SOC content and not showing bulk density data were excluded from the SOC analysis. In the few cases when soil organic matter (OM) percentage was reported, SOC was calculated by Equation (2) [24].

$$\mathrm{SOC}\left(\mathrm{g\ kg^{-1}}\right) = \mathrm{OM}(\%)/1.72*10 \quad (2)$$

2.3. Amount of residues applied and C-input

Not all the publications that were consulted reported the C concentration of the residues that were applied annually. When this information was not provided, the total C-input was calculated as:

$$\mathrm{C\ input}\left(\mathrm{t\ ha^{-1}year^{-1}}\right) = \mathrm{Crop\ residue\ applied}\left(\mathrm{t\ ha^{-1}year^{-1}}\right) *\mathrm{C\ concentration}(\%) \quad (3)$$

C concentration was assumed to be 42.5% for maize and the other cereals, respectively, if these values were not explicitly reported in the studies [25] and [26]. In the only case in which the amount of residues was not reported [27] this amount was calculated using the harvest index (HI) and the crop yield (at crop harvest) adjusted to zero moisture. The HI were extracted from the CropSyst model [28].

$$\mathrm{Crop\ residue\ applied}\left(\mathrm{t\ ha^{-1}year^{-1}}\right) = \frac{(1-\mathrm{HI})*\mathrm{Y}\ \left(\mathrm{t\ ha^{-1}year^{-1}}\right)}{\mathrm{HI}} \quad (4)$$

Table 1 shows the HI and C-concentration values used for such calculations.

2.4. Pedoclimatic data

Climates were classified according to the Köppen-Geiger classification updated by Kottek et al. [29]. This classification distinguishes between five main climates: Equatorial, Arid, Warm Temperate, Snow and Polar. In the context of this study, two main climate categories were defined, thereby grouping these five climates. Tropical climates included arid and equatorial climates while temperate climates comprised warm temperate and snow

Table 1
Harvest Index (HI) and C residues concentration (C) used in the study for different crops.

Crop	HI	C (%)
Maize	0.475	42.65
Wheat	0.475	42.50
Sorghum	0.475	42.50
Rice	0.475	42.50
Barley	0.450	42.50

[1] FAO defines Conservation Agriculture as an approach to manage agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. Specifically, Conservation Agriculture is characterized by the following three principles, (i) minimum soil disturbance, (ii) permanent organic soil cover and (iii) diversified crop rotations. (http://www.fao.org/ag/ca/).

[2] The 10-year period was selected for the basis of this study as more than 72% of the publications (since 1971) relating to the topic of interest were published during this timeframe.