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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):

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

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].

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

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:

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

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].

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

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

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[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.

climates. Data on polar climates were not present in the database. This type of classification provides a method of running a descriptive analysis on two broader climatic categories (tropical and temperate) and improves the discriminatory power of the classification trees as sub-climatic classes offered more precise classification.

The texture triangle was used to categorize soil texture when sand, silt and clay concentrations were reported, while the USDA texture triangle was used to estimate the percentage of each soil particle classes.

Additionally, soil data were further grouped into five broader classes as illustrated in Table 2.

2.5. Statistical analysis

All statistical analyses were performed using R 3.0.2 for Windows (32-bit). Principal Component Analysis (PCA) was carried out using the "prcomp" R function. The following variables were included in the analysis of SOC variability: N-fertilizer use, average annual rainfall, average annual temperature, silt + clay mass fractions, C-input and SOC. These variables were selected as (i) they were assumed to be most relevant factors, (ii) they formed a set of variables that encompassed climatic conditions (average annual temperature and rainfall), farm management (N-fertilization and C-input) and soil characteristics (texture and SOC), (iii) they were reported in most of the selected papers. Moreover, the data on yields were added to the variables set, when maize and wheat yields were investigated.

The PCA was used to reveal the structure of the variance in the dataset, and which variables were mostly associated with SOC and yield variability. As the contribution of each variable to the total variance observed in the target variable may vary in different conditions, classification and regression tree (CART) analyses were performed on more homogeneous subsets of the dataset, using the "rpart" function of R for two subsets: 'tropical' (equatorial + arid climates) and 'temperate' (warm temperate + snow climates). CART is a suitable technique to explore the relationship between variables which can be non-linear and characterized by high-order interactions [30]. Using a set of predictor variables which can be continuous or categorical CART analyses the variation of a response variable partitioning the database into more homogeneous groups [31]. The model examines the values of the predictor variables which maximize the quality of the split creating two child nodes [32]. This process is repeated continuously and forms large trees which are ultimately 'pruned' at the point in which the x-error is minimized. As a result the explanatory variables are listed in a hierarchical order in which the explanatory power decreases from the top to the bottom of the tree [32].

Two main CART models were run using the following set of explanatory variables:

Table 2
Soil texture group used for analysis in this study.

Soil texture group used for analysis	Reported soil texture class
Sand/Sandy loam	Sand Sandy Loam Loamy sand
Sandy clay loam	Sandy clay Sandy Clay loam
Silt clay	Silt loam Silt clay Silt clay loam
Loam	Clay loam Loam
Clay	Clay

CART Model SOC:

SOC = f (climate, soil texture, C-input, residue application management, N-fertilizers)

CART Model Crop Yield:

Yield = f (climate, soil texture, SOC, C-input, residue application management, N-fertilizers)

Both PCA and CART analyses on crop yields were run only for maize (n = 179) and wheat (n = 180) as they were the most represented crops in the literature.

3. Results and discussions

3.1. The meta-database

Of the 1072 publications found when searching for "soil organic carbon crop residues" within the reference period (2003-January 2014), only 157 were considered to be pertinent from the relevance of the title and abstract. Many of the papers reviewed presented data on crop residue management within the context of conservation agriculture and no tillage, in which crop residue retention on the soil surface is but one practice within a broader technological package [13] [33] and [34]. Conservation agriculture builds on three basic principles, crop rotations, no-till and permanent soil cover, the latter of which is inherently linked to soil residue management. Consequently, 73 publications were discarded since they presented the aggregate effects of all three principles of Conservation Agriculture technologies on SOC and crops.

Finally, a total of 84 publications were included in the database which translated to a total of 660 observations. The final database embraced a wide range of climatic conditions, farming systems and edaphic characteristics. Observations were obtained from 32 countries covering a large series of average annual temperatures (from 2 to 35 C), average annual precipitations (from 54 to 2000 mm year^{-1}), farming systems (from smallholders African farming systems to North American intensive monoculture), and soil texture classes (from 6 to 99.4% silt and clay contents).

Fig. 1 shows the locations of the studies included in the database. Greater effort has been invested to study the influence of crop residue management on SOC and yields during the last decade in Asia (particularly in India and China), Africa and North America as compared to Latin America, Europe and Oceania. The Asian studies were mainly concentrated in the North Chinese plain and along the Indo Gangetic plains, as these represent two important regions for intensive cereal production [35] and [36]. The unbalanced global distribution of the studies might be a consequence of the choice to restrict the review to the last 10 years of literature.

3.2. Explaining the variability in SOC as a response to crop residue management

The analysis of the database indicated that (i) crop residue removal led to average SOC contents that were 12% (±12%) and 18% (±15%) lower than in soils in which crop residues were retained in temperate and tropical climate respectively and that (ii) a marked variation existed within the compiled cases, as shown in Fig. 2. This agrees with previous studies and confirms that the net change in SOC via crop residue retention is largely site dependent [37–40]. The factors that played a major role in defining SOC variation as a response to crop residue management were: soil type, soil C initial status, climate, land use and management and the time horizon being considered.

The correlation between SOC and climatic and edaphic factors

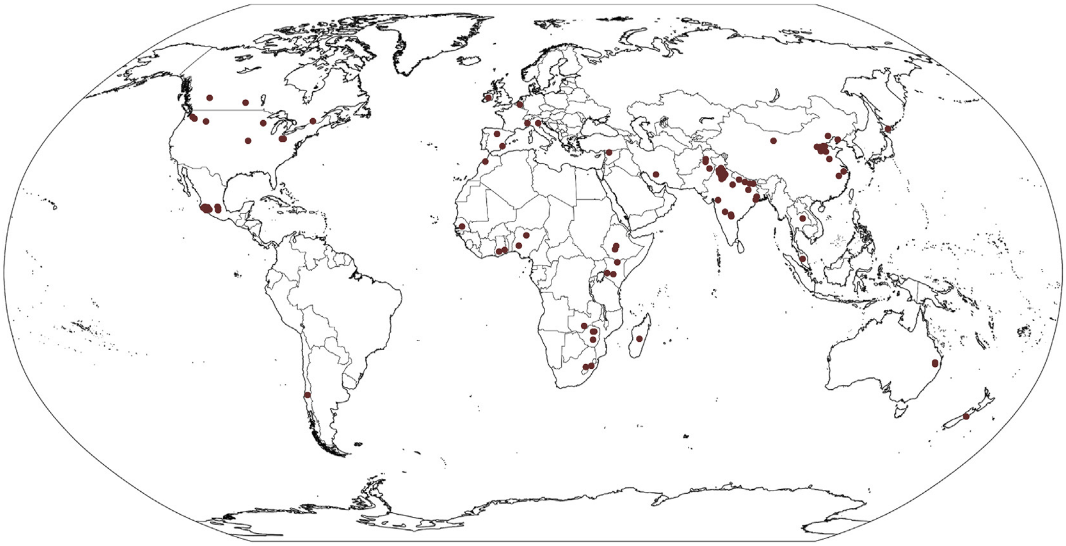

Fig. 1. Location of the studies included in the database (n = 86).

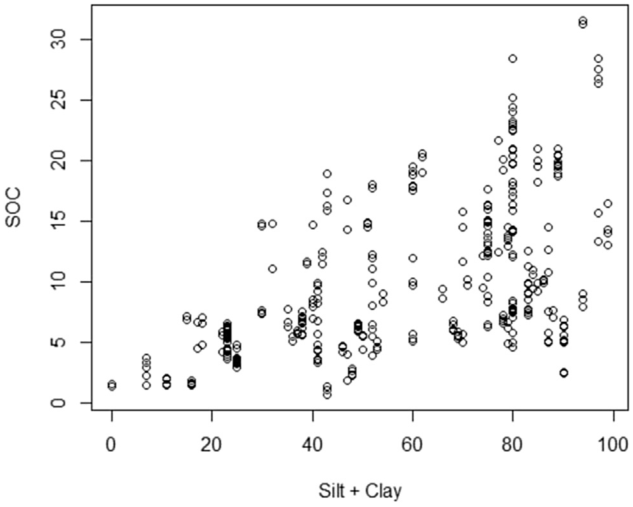

Fig. 2. Variability of SOC concentrations (g kg^{-1}) in relation to silt and clay fractions (%) (n = 411).

was generally weak when considering the entire dataset (i.e., all climates, soil types and farming systems pooled together). As a consequence, the first two principal components (PCs) explained 58% of the variance, and the first four PCs were necessary to account for 87% of it. Similar results were obtained by PCAs for the maize and wheat yield dataset. At this level of analysis, with all observations pooled together the PCA outcomes did not reveal any strong pattern, and further classificatory analyses was deemed necessary. A description of the PCA outcomes (variance explained by PCs and PC loadings) can be found in the Appendix.

The CART analysis showed in Fig. 3 presents a graphical representation of the analyses concerning SOC in tropical climates. CART identified the best predictor and its threshold value able to split the dataset in two sub nodes, while minimizing the x-error, proceeding in the same way to obtain the sub-nodes all along the two main branches [32]. The numbered boxes in Figs. 3–6 indicate the repeated splits of the tree and the associated explanatory variables. The numbered and dark colored boxes indicate the terminal nodes of the tree. The effects of C-Input and crop residue management had less explanatory power on SOC variability than the climate (arid or equatorial) and soil texture (Fig. 3). In tropical regions, the actual C-input rate was crucial to sustain SOC in coarse soils, regardless of the way in which crop residues were applied. In temperate regions, crop residue management seemed to have a greater influence on SOC than soil texture and N-fertilization (Fig. 4).

Climatic factors, such as temperature and rainfall, regulates the activity of the soil biota responsible for SOC degradation, which ultimately explains the overall higher SOC concentration found in the temperate compared with the tropical dataset [41–43]. Soil texture represented an important dividing factor in both climates (Figs. 3 and 4). Texture is an important determinant of the capacity of soils to store C, as higher silt and clay fractions correspond with higher SOC contents (e.g. Ref. [44]). The concentration of silt and clay plays a central role in the SOC dynamics as it (i) promotes the formation of organic–mineral complexes, which chemically stabilize SOC and (ii) influences the physical protection of carbon within soil aggregates [43,45–48]. Furthermore, finer soil particles are associated with higher water retention in soils especially in arid climates. This retention enhances biomass production and ultimately increases the availability of soil C-inputs from roots and aboveground residues [49].

According to CART analysis, rates of about 1.5 and 2.5 t of C ha^{-1} $year^{-1}$ applied via crop residues were needed to maintain SOC in equatorial and arid tropics, respectively (Fig. 3, nodes 3, 4, 5, 10 and 14). Crop residue retention equal or higher than these rates increased SOC by 50% in arid climates (Fig. 3, nodes 3, 4 and 5) while SOC almost doubled in equatorial climates (Fig. 3, nodes 10 and 14). Such C-input thresholds appeared to be reasonable considering the climatic and edaphic conditions that limit SOC stabilization in these climatic areas, but the application of such amounts of C-input seems unrealistic in smallholder tropical farming systems. In fact more than 3 and 5 t ha^{-1} $year^{-1}$ of maize stover would be needed to satisfy such C requirements. In these areas, where biomass productivity is often low and competing uses of residues exist, such residue amounts are rarely available [50,51].

In finer soils located in arid climates the way in which crop residues were applied affected SOC concentration. Although only few observations determined this category (n = 8), mulching increased SOC concentration by 60% as compared with residues

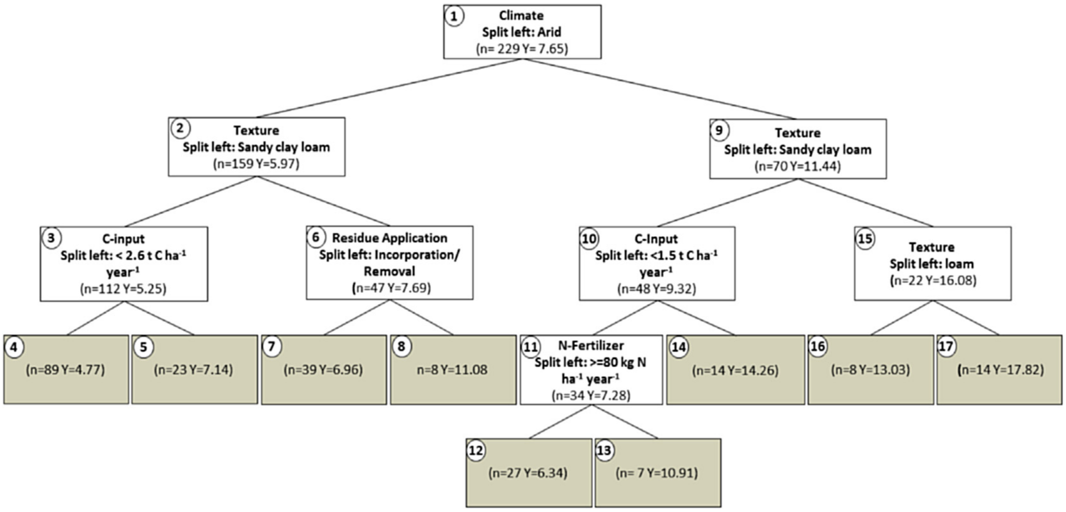

Fig. 3. Regression trees on SOC for tropical environments (n = 229). Y represents average SOC values expressed in g kg^{-1}, dark coloured boxes indicate the terminal nodes of the tree.

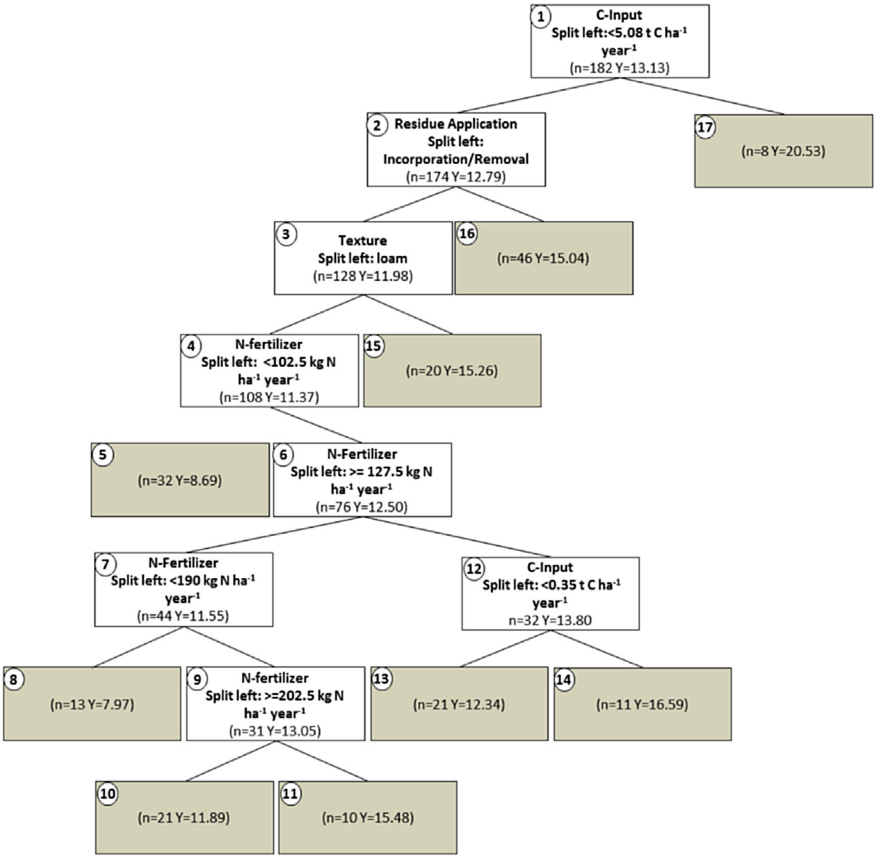

Fig. 4. Regression trees on SOC for temperate environments (n = 182). Y represents average SOC values expressed in g kg^{-1}, dark coloured boxes indicate the terminal nodes of the tree.

incorporation or removal (Fig. 3, nodes 2 and 16).

In many tropical agro-ecosystems, soils have low levels of organic carbon as a result of (i) high mineralization rates stimulated by elevated soil temperature and faunal activity (i.e. termites), (ii) generally lower biomass production by crops due to a range of limiting factors and (iii) coarse texture [45]. In such contexts, crop residue have multiple functions: (i) it represents a source of organic C to soil, (ii) it is an effective mean to reduce SOC losses induced by wind or water erosion, and (iii) especially when applied as mulch, it mitigates soil temperature which in turn reduces organic matter decomposition [52].

In temperate areas the application of large amounts of crop residues (more than 5 t of C ha^{-1} year^{-1}, which translates to about 10 t of crop residue ha^{-1} year^{-1}) was associated with higher SOC

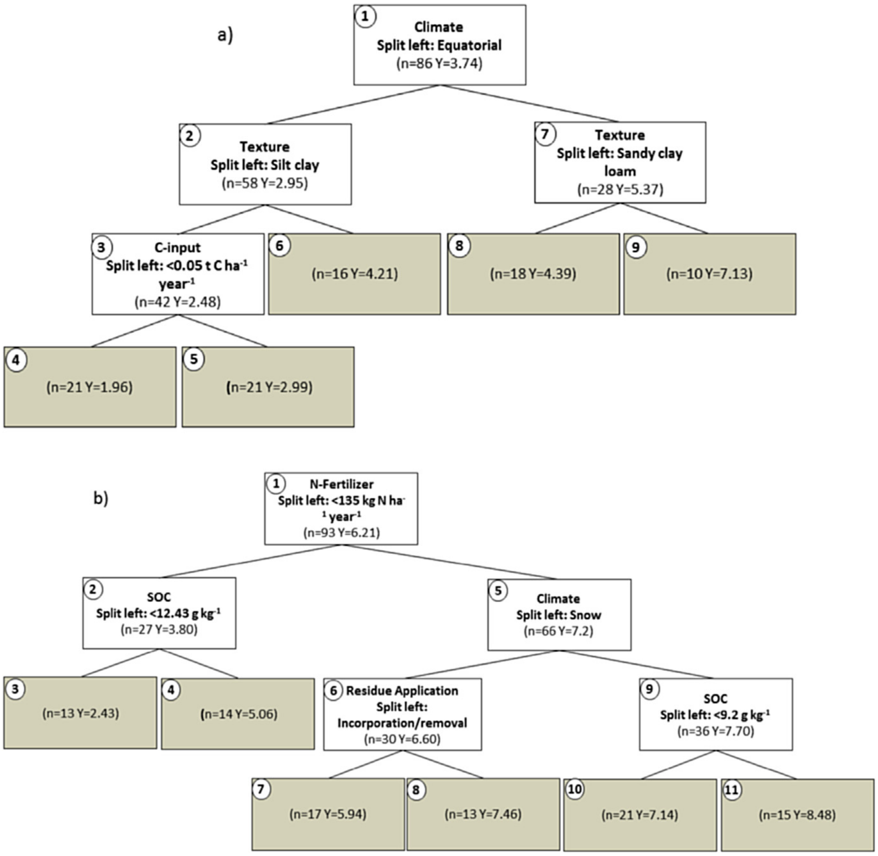

Fig. 5. a) Regression trees for maize yields in tropical environments (n = 86); b) Regression trees for maize yields in temperate environments (n = 93). In both graphs, Y represents average grain yields (t ha^{-1} $year^{-1}$) and dark coloured boxes indicate the terminal nodes of the tree.

(Fig. 4, nodes 1, 2 and 17). This may be reasonable considering the low degradation rate and the extremely high threshold of C-input. However, it should be noted that (i) few observations (n = 8) fall under this category and (ii) this does not necessarily imply that C-Input is overall the main determinant for SOC, but rather it proposes that massive crop residue applications were associated with sensibly higher SOC levels. A study carried out in three sites in Ohio confirmed these findings. The authors reported that the amount of residues left on the soil surface was significantly related with SOC, but the net change in SOC depended on site specific characteristics [40]. These results suggest that in SOC-depleted soils, large crop residue application can be a valuable practice to increase the SOC concentration. This is consistent with Zhao et al. [18], which reported that the sustainable removal rate of crop residue was the lowest (or equal to zero) in Australian agricultural lands with low initial SOC content. Conversely, in soils well-endowed in SOC, higher amounts of residues could be sustainably harvested.

Additionally, mulching appeared to be effective in increasing SOC at a C-input application rate lower than 5 t of C ha^{-1} $year^{-1}$. Overall, mulched soils showed SOC average concentration of about 15.0 g kg^{-1} (Fig. 4, node 16), whereas in the case of residue removal or incorporation SOC levels was on average about 11.9 g kg^{-1} (Fig. 4, node 3).

Previous studies reported higher SOC when residues were left on the soil surface compared with un-mulched soils, both in temperate and tropical climates [40,53–56]. In temperate areas this can be particularly valid in erosion prone sites, where mulching forms a physical barrier against SOC losses [40,57]. Also, the higher SOC concentration found in mulched tropical soils (Fig. 3, node 8) may be related with the capacity of the mulch layer to decrease soil temperature, hence, moderating soil organic matter decomposition [45,59]. However, from the other meta-analyses existing on the topic, it is still unclear whether mulch or incorporation has a higher influence on SOC dynamics. Liu et al. [15] reported a slightly higher effect on SOC when residues were incorporated than when kept as mulch, whereas Virto et al. [17] indicated C-input to be the main factor explaining 30% of the variance in SOC stocks, irrespective of the way in which crop residues were retained.

Following climate and texture, N-fertilizer use appeared to be an additional factor which influenced SOC in tropical areas (Fig. 3). Whereas, in temperate regions, the effect of N-fertilizer use was not as significant as the effect of crop residue management (both application method and actual rate) and texture (Fig. 4). In both climatic areas results from CART analyses were not entirely consistent. In fact, in some nodes higher N-fertilizations were associated with higher SOC concentrations (Fig. 3, nodes 5, 6, 8, 9) while in others N-application seemed to have a negative influence on SOC (Fig. 3, nodes 12 and 13; Fig. 3, nodes 10, 11, 7 and 12). The role of N in increasing SOC is related with the increase in above- (and secondarily below-) ground biomass. This seems to suggest that the results observed depend on the actual N-rate applied and on the initial N availability in the soil [60–64]. When the N is available in the soil, any additional units of N have little effect on biomass production and ultimately on SOC. Conversely, in N-limited systems, N-application increases biomass production significantly. This translates into larger amounts of crop residues produced, which increase the amount of C to the soil [60]. Therefore, the lack of consistency in the results displayed in Fig. 3 can be caused not only by the uneven sample size of the two categories, but also by a difference in the initial soil N-pool between the studies considered.

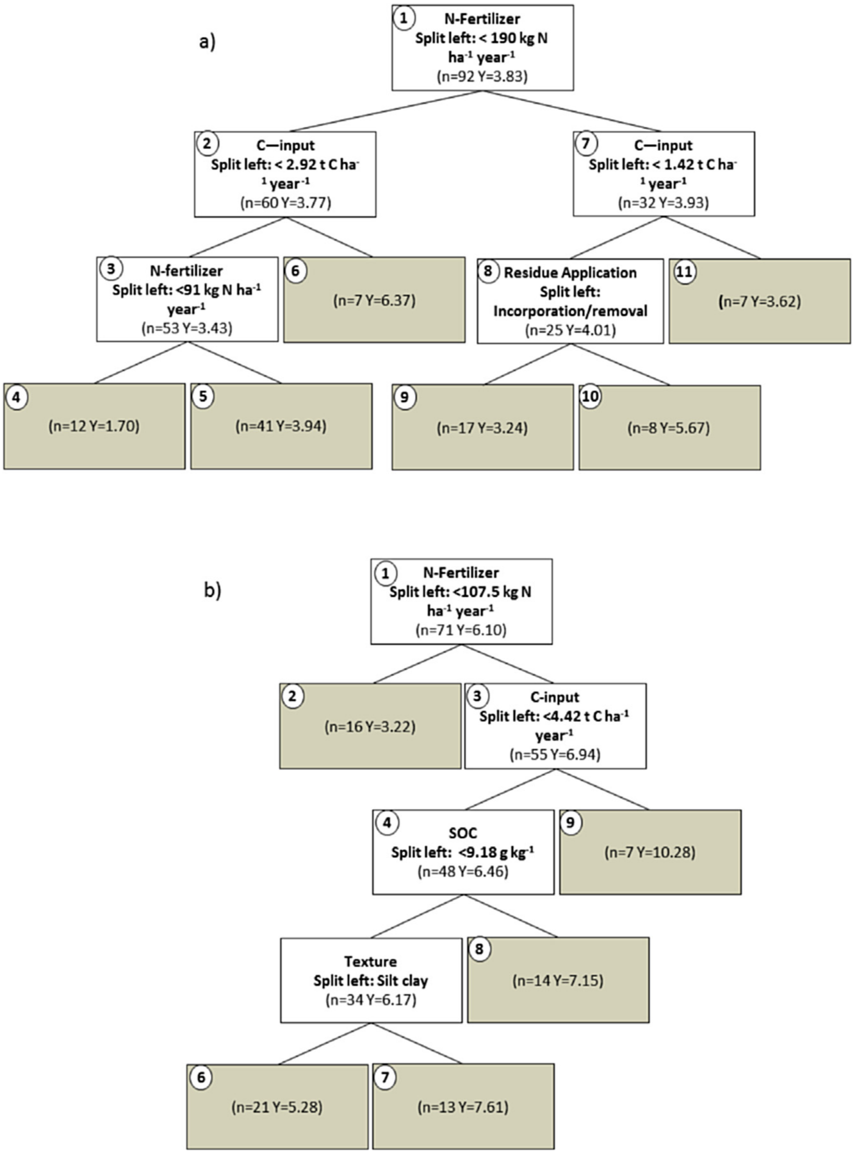

Fig. 6. a) Regression trees for wheat yields in tropical environments (n = 92); b) Regression trees for wheat yields in temperate environments (n = 71). In both graphs, Y represents average grain yields (t ha^{-1} $year^{-1}$) and dark coloured boxes indicate the terminal nodes of the tree.

3.3. *Explaining the variability in maize yields as a response to crop residue management*

Maize production was sensitive to crop residue management, to a variable extent across climatic areas. In the tropics, crop residue removal resulted in severe overall yield losses, as grain production decreased by 25% (±25%). In temperate areas, maize yields were less sensible to residue management as yields dropped by 9% (±1%) following residue removal.

In the tropics, maize yield variability was less associated with crop residue management than with variability in soil texture and climate (Fig. 5a, nodes 1, 2 and 7). Particularly in tropical maize growing regions the variation in seasonal rainfall represents a major factor responsible for yield fluctuations [22]. This ultimately can explain the wide variability found in the database, and the fact that climate was the first splitting criterion for yield variability the CART analysis [22,65,66]. In such conditions, soil water retention was crucial in determining yields, and soil hydrological properties are influenced by soil texture [67] with finer soils able to retain more water than coarse soils. In fine-textured soils located in the tropics maize yields were about 62 and 70% higher in equatorial and arid areas, respectively (Fig. 5a, nodes 3, 6, 8 and 9).

Following the effects of climate and soil texture, the amount of organic C-inputs played an essential role in determining maize yield in tropical environments (Fig. 5a, nodes 4 and 5). Minimum C additions via crop residues (50 kg ha^{-1} $year^{-1}$ of C which roughly translates into about 100 kg of crop residues ha^{-1} $year^{-1}$) can sensibly increase maize productivity in coarse soils. Abdourhamane Toure et al. [68] indicated the same amount of millet stalks to be effective in reducing wind erosion by a factor of four in a desert equatorial sandy soil located in Niger. In this environment, wind erosion represents a loss in terms of SOC and nutrients, which ultimately affects yields [69]. Relatively small amounts of mulch cover (1.5 t ha^{-1} $year^{-1}$) were reported to increase maize production also in a silt loam soil, located in a steppe equatorial Mexican location. Here, residue cover reduced evaporative water losses and increased soil water storage (through increased infiltration and reduced runoff), thereby enhancing maize yields [70].

Unexpectedly, C-input or residue retention did not appear to be among the main maize yield determinants in arid climates (Fig. 5a). The smaller data set available (n = 28) for these locations might have hampered the analysis, but one possible explanation resides also in the low crop productivity. In such environments, the availability of crop residue biomass may be insufficient to bring the desired effects on water storage.

In temperate climates, N-application was the main determinant of maize yields (Fig. 5b, node 1). SOC appeared to be an additional important factor in defining maize production in these areas (Fig. 5b). At N-application rates lower than 135 kg of N ha^{-1} $year^{-1}$, the maize yield was on average twice as high when soils had a SOC concentration that was greater than 12.4 g kg^{-1}, than in soils with a lower SOC content (Fig. 5b, nodes 3 and 4). A similar trend was observed in more intensive systems (N-rate ≥ 135 kg N ha^{-1} $year^{-1}$) located in warm temperate regions. In this case, average maize yields were 8.48 t ha^{-1} $year^{-1}$in soils with a SOC concentration greater than 9 g kg^{-1}, while yields dropped to 7.14 t ha^{-1} $year^{-1}$ in soils with lower SOC content (Fig. 5b, nodes 10 and 11). However, these cut-off points (9 and 12.4 g kg^{-1}) were considerably low [71] and [72]. The increased yields related with higher SOC concentrations is associated with the capacity of SOC to provide a wide range of benefits for crop production and ecosystem stability including: (i) improved water and nutrients retention, (ii) appropriate soil structure, (iii) higher soil biodiversity, (iv) enhanced yield response to fertilizers and (v) protection from sediment losses [73–75].

Mulching was associated with greater maize yields in snow climates at high N-fertilization rates with grain yield increasing from about 6 to 7.5 t ha^{-1} $year^{-1}$ (Fig. 5b, nodes 7 and 8). Although mulch can maintain the topsoil excessively wet hampering seeds germination [11,76], crop residues are often left on the soil surface in order to trap snow thereby increasing soil water retention. In turns the higher water availability improves the efficiency of fertilizers which stabilizes plant growth and production [77].

3.4. Explaining the variability in wheat yields as a response to crop residue management

Wheat yields were on average 9% (±13%) lower when crop residues were removed in tropical climates. Contrarily, in temperate climates grain yields were almost not affected by crop residue management; yield differences following crop residue removal were on average only −1.5% (±5%).

These results are consistent with the results reported from studies in Ireland [78] and Pakistan [79]. No effect of crop residues on wheat yields was reported in the Irish site, where average annual precipitation was 940 mm $year^{-1}$ and average temperature 9.5 °C. In the Pakistani case, which received on average 380–550 mm $year^{-1}$ and where average temperature was 22.7 °C [80], yields increased by 30% as a response to crop residue retention in the field.

Analyzing the wheat yield database with CART it appeared that organic C-inputs via crop residue application were important yield determinants immediately after N-fertilization in tropical wheat production (Fig. 6a, nodes 2 and 7). The combination of N-input (lower than 190 kg of N ha^{-1} $year^{-1}$) and crop residue retention led to the highest wheat yields in the tropics (Fig. 6a, node 6). Although this category was based on only 7 observations, coupling N-fertilization with organic amendments has been shown to be extremely effective at increasing yields, especially in tropical soils where mineral fertilisers are often ineffective in the absence of organic matter [81–83]. Crop residue retention ameliorates physical and biological soil fertility, while fertilizers guarantee immediate nutrient availability minimizing the risk of N-immobilization [81]. At even higher N application rates (more than 190 kg of N ha^{-1} $year^{-1}$), the amount of C-inputs applied followed by the method of crop residues application became important determinants of wheat yields (Fig. 6a, node 8). However, extremely high N-rate and C-input on average did not result in greater yields (Fig. 6a, node 11). When smaller amounts of crop residues were applied, mulching led to the highest wheat yield (Fig. 6a, nodes 9 and 10), possibly due to improvements in soil water dynamics. In addition, data on mulching and especially on crop residue incorporation or removal showed wide variability, likely due to a relatively small number of observations (Fig. 6a, nodes 9 and 10).

In temperate regions wheat yield was affected by N-fertilizers, C-Input and SOC concentration. Low SOC concentrations (lower than 9 g kg^{-1}) appeared to be a limiting factor for wheat production when N-fertilization was higher than 107 kg of N ha^{-1} $year^{-1}$ and at C-input application lower than 4.42 t C ha^{-1} $year^{-1}$ (Fig. 6b). Therefore, at low N-applications N was clearly the factor that limited wheat yields. Once the N availability increased through N fertilizer application the role of SOC on soil biological, chemical and physical fertility became an important yield determinant.

3.5. Limitations of the study

A large metadatabase on the effects of crop residue management on SOC and yields was compiled in order to embrace a wide diversity of biophysical and management conditions worldwide. Data on soil structure (bulk density and aggregate stability) were also collected. However, the small number of observations and the differences in the methods used to assess soil aggregation did not allow any further analyses. Lack of consistency was also found when gathering reported SOC data, such as differences in sampling depths, units and timing. This calls for a standardization of sampling methods and the format of data reporting in the literature.

The analysis of the dataset concerning SOC and yields was extensive and robust from a quantitative perspective, but it was quite superficial when it came to identifying the processes behind the soil mechanisms that underpin crop yield variability. This was also evident from the outcome of the PCAs, both of SOC and crop yields. At this level of analysis, with the high variation that characterized our dataset due to climatic, management and topographic variability, it was not possible to draw strong conclusions on the deterministic relationships between crop residue management, soil fertility management and crop production. The dataset also suffered from an unbalanced global distribution of the studies, with a large proportion of data coming from specific regions (i.e. Northeast China and Punjab). Despite the robust statistical analyses, this should be taken into account when considering the results of this study.

An additional source of lack of accuracy in the estimates presented was the use of average values for the harvest index or the concentration of carbon in residues, as these parameters may vary according to management and ecological characteristics [84] and [85]. Furthermore, the quantification of C-inputs to soil considered only the aerial plant biomass – straw or stover – while C-inputs from below ground biomass – roots – was not considered. The publications that measured SOC originating from root biomass using ^{13}C techniques, reported that C inputs from below ground biomass can be substantial [49,64,84,86–88].

4. Conclusion

The analysis of a large dataset on quantitative effects of crop residue management on crop yields and soil organic carbon, compiled after having carefully screened more than 1000 published studies, led to the following conclusions:

- The different magnitude at which crop residue retention affected SOC and crop yields confirmed the need for site-specific management of crop residues;
- In the tropics, particularly in coarse soils located in arid areas, crop residue removal is not recommended, as this will decrease soil fertility (Fig. 3) and negatively impact crop yields (Figs. 5a and 6a);
- In temperate areas, crop residue removal should be avoided in soils that are depleted or show inherently low levels of C and nutrients (Fig. 4). In these soils large crop residue application may be effective at increasing SOC.

Further studies at finer scales of analysis are necessary to establish deterministic relationships between crop residue management, soil quality and crop yields. Yet, this study presents preliminary guidelines for context-specific recommendations on crop residue management and related policies. These findings are of high relevance for the bioenergy sector where the use of residues for energy generation is assumed *to have no impact* on food security, as compared to bioenergy production from food and energy crops. However, this study demonstrated that inefficient crop residue management can also have adverse effects on land productivity and hence on long-term food security. Therefore, the use of crop residues must not be considered as a broad avenue to achieve sustainable bioenergy production. Effective agricultural and bioenergy management cannot neglect the functional role of crop residues in agro-ecosystems. Future bioenergy policies must therefore consider ecological constraints to residue use, in order to advance sustainable agricultural and the bioenergy sector.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2015.07.022.

Appendix

Table A.1
Standard deviation, proportion of variance and cumulative proportion of the six PCs from the PCA of the SOC data.

	PC1	PC2	PC3	PC4	PC5	PC6
Standard deviation	1.4445	1.1931	0.9680	0.68363	0.55633	0.55633
Proportion of variance	0.3478	0.2373	0.1562	0.1293	0.07789	0.05158
Cumulative proportion	0.3478	0.5850	0.7412	0.8705	0.94842	1.00000

Table A.2
Loadings of the extracted components from the PCA of the SOC data.

	PC1	PC2
Silt + Clay	−0.4747409	0.30587022
N-Fertilization	−0.4793547	−0.33510784
C-Input	−0.2834071	−0.15274499
SOC	−0.2935698	0.60381886
Temperature	0.5694520	−0.05121624
Rainfall	0.2325119	0.63529111

Table A.3
Standard deviation, proportion of variance and cumulative proportion of the PCs from the PCA of the maize yields data.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Standard deviation	1.7598	1.2938	0.9736	0.8609	0.53372	0.48906	0.1268
Proportion of variance	0.4424	0.2391	0.1354	0.1059	0.04069	0.03417	0.0023
Cumulative proportion	0.4424	0.6815	0.817	0.9228	0.96353	0.9977	1

Table A.4
Loadings of each of the extracted components from the PCA of the maize yields data.

	PC1	PC2
Silt + Clay	−0.1614548	−0.5418
N-Fertilization	−0.4621568	−0.264
C-Input	−0.3045704	−0.2298
SOC	0.3287946	−0.4881
Yield	−0.3480551	−0.41
Temperature	0.4721631	−0.1797
Rainfall	0.4641057	−0.3811

Table A.5
Standard deviation, proportion of variance and cumulative proportion of the PCs from the PCA of the wheat yields data.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Standard deviation	1.6689	1.2508	0.9256	0.8255	0.7146	0.6600	0.4067
Proportion of variance	0.3979	0.2235	0.1224	0.0973	0.0729	0.0622	0.0236
Cumulative proportion	0.3979	0.6214	0.7438	0.8411	0.9141	0.9763	1.0000

Table A.6
Loadings of the extracted components from the PCA of the wheat yields data.

	PC1	PC2
Rainfall	0.0291660	−0.599823
Temperature	−0.4963635	0.333342
Silt + Clay	−0.5133541	−0.109947
N-Fertilization	0.3797623	0.399392
SOC	−0.2822617	−0.390718
C-Input	0.2720567	0.405881
Yield	0.4374175	0.200227

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