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ENVIRONMENT AND NATURAL RESOURCES MANAGEMENT WORKING PAPER

ENVIRONMENT CLIMATE CHANGE [ENERGY] MONITORING AND ASSESSMENT

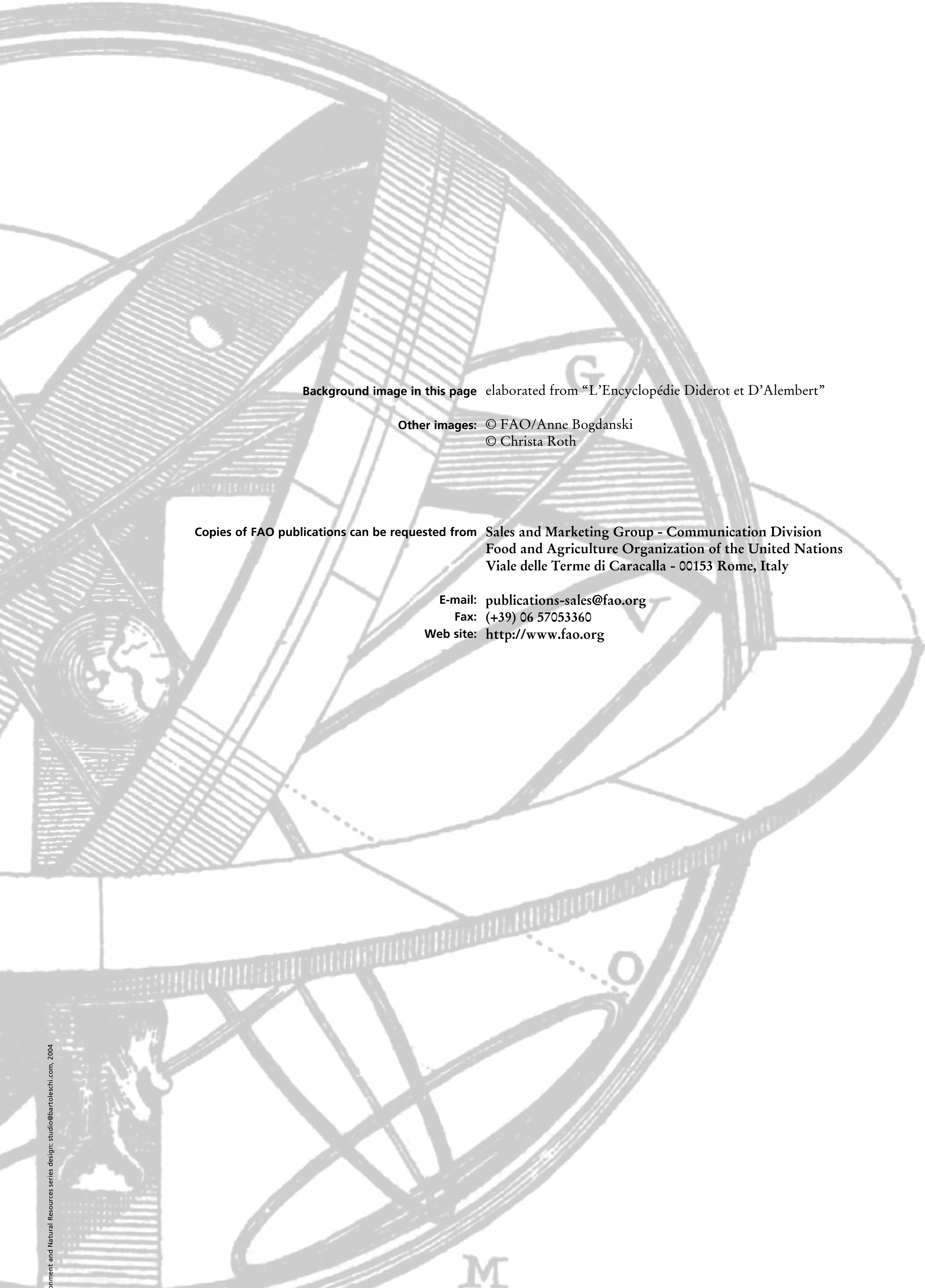
Take it or leave it?

Towards a decision support tool on sustainable crop residue use

Part 1: Soil management



Food and Agriculture Organization of the United Nations



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ENVIRONMENT CLIMATE CHANGE [ENERGY] MONITORING AND ASSESSMENT

Take it or Leave it? Towards a decision support tool on sustainable crop residue use

Part 1: Soil management

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ACRONYMS

AHI	Apparent Humification Index
BEFS-RA	Bioenergy and Food Security Rapid Appraisal
C	Carbon
CART	Classification and Regression Tree Analysis
EU	European Union
FAO	Food and Agriculture Organization
GHG	Green House Gas Emission
HI	Harvest Index
OM	Organic Matter
N	Nitrogen
PCA	Principal Component Analysis
SOC	Soil Organic Carbon
TSW	total soil weight of the considered layers
WP	Water Productivity

ABSTRACT

In the last decade, the increased interest in bioenergy production and the promotion of sustainable cropping systems have led to the need for improved crop residue management. Additionally, crop residues are historically used for other purposes: as feed and bedding for livestock, substrate for mushroom production and raw material for cooking. The link between crop residue management and food security is therefore evident. Food security consists of four pillars: availability, access, utilization and stability. This study aims at exploring the effect of crop residue management on soil quality and yield, which represent two crucial aspects of the availability pillar of food security. More than 1 000 peer-reviewed journal papers of the past ten years were studied in order to assess whether crop residue application (i) is associated with higher soil organic carbon (SOC), (ii) ameliorates soil structure and (iii) if the change in SOC related to residue application has a positive impact on yields. A database was created containing 90 papers that reported data from a wide range of climate and soils. Overall, SOC decreased by 13 percent when residues were completely removed, but data showed a high level of variability. This suggests that different factors such as soil texture, farm management and climate determine the net change in SOC. The structure of the variance was studied by principal component analysis (PCA) but too many principal components were needed to explain 90 percent of the variance. Therefore, classification and regression tree analysis (CART) was used. The results showed that crop residue addition to soil stabilized SOC in tropical and temperate areas. In tropical climates the effect of crop residue management on SOC was subject to climate and texture. In these climates the addition of C via crop residue was crucial in sustaining SOC especially in coarse soils located in arid areas. In temperate climates crop residue management (both actual rate and application method) appeared to be the main factor in stabilizing SOC concentrations, followed by texture and N-fertilizer. Soil bulk density increased when residues were removed, while the effect of crop residues on soil aggregate could not be determined due to the lack of data. Decreased yields were observed when residues from maize and rice farming systems were removed in both tropical and temperate areas. By contrast, wheat production was less sensitive to residue removal in temperate regions. According to the PCA, yield data on maize and wheat were analysed by CART. In tropical environments, crop residue retention increased grain production but such an increase was not directly influenced by increased SOC. Therefore, it was assumed that the higher yields were related to the enhanced soil water retention, reduced soil losses and ameliorated nutrient pools induced by crop residue application in erratic rainfall environments. In temperate locations low SOC corresponded to lower maize and wheat yields. This paper demonstrates that crop residue management has to be contextualized, suggesting the need for site-specific residue management schemes. In coarse soils located in tropical climates and in SOC-depleted soils located in temperate climates, crop residue removal is not advisable. Building science-based decision support tools can guide stakeholders when considering sustainable crop residue management. This paper presents a first attempt in this direction, though other issues have to be considered to build up a comprehensive decision support tool, such us: competing uses between the diverse sectors, different uses based on the quality of the residues, logistic aspects and the possible re-introduction of by-products obtained from bioenergy generation in agricultural fields.

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CHAPTER 1 INTRODUCTION

The important role of residues in meeting future energy needs has been recognized globally. In fact, residues from the agrifood chains could indeed contribute significantly to providing access to energy and stabilizing a country's energy security. Furthermore, there are strong policy incentives to use agrifood[1] residues in order to reduce greenhouse gas emissions. For example, the European Commission aims to reach a minimum share of 10% renewable energy in every Member State in 2020, and particularly promotes the use of residues within this context (EC, 2009).

However, so far, it is not clear to what extent these residues are actually **available** for energy production or how to **sustainably manage** them. Many scientific publications and policy briefs from all over the world alert to this fact and call for the development of standards and tools which can address this knowledge gap (e.g. Guintoli et al., 2013; Jiang et al., 2012). A central concern within the sustainability debate around the use of residues still remains without an answer: How does the use of crop residues, be it for energy or material applications, **impact food security**?

While, at present, the increasing interest in crop residues for energetic and material uses is mainly seen in industrialized countries like Germany, the Netherlands, or the United States, projections already point to the future need of sourcing such biomass from abroad to complement national production capacities (e.g. FNR, 2012). Especially less industrialized countries whose economies are based on the agricultural sector are likely to profit from such opportunities, however only and if sustainability standards are duly met, and current residue uses are taken into account. Livelihood and food security considerations should be given first priority. The link between food security and sustainable residue management is particularly evident when highlighting the interdependence of soil organic carbon, crop yields and food availability - which constitutes the core of this publication as laid out hereafter.

1.1 DEFINITIONS: WHAT IS A RESIDUE?

One might easily believe that residues are widely available. Residues are often seen as being equal to waste. However, many types of residues are valuable resources much sought after - and not just for energy production. Residues offer several alternative functions and as a result, often possess various competing uses (Table 1). Depending on whether they have or do not have a use, residues are often referred to as "co-products" or as "waste". Residues can be classified in

1 The term agrifood residues concerns both primary and secondary residues from value food chains based on crop, livestock, fish and forest products. This report focuses on primary crop residues.

a number of ways: i) by origin such as agriculture or forestry; ii) by commodity group such as cereals, fruits, or industry; iii) by geographical location such as national, regional or rural; iv) by physical status such as solid, slurry or liquid; v) by type (common properties, common main component) such as meals and press cake or starchy and cellulosic; vi) by category such as primary, secondary and tertiary or vii) by end use (see Table 1).

Relevant literature often refers to and defines residues according to the three categories "primary", "secondary" and "tertiary" residues (e.g. GEA, 2012; Lecher, 2008). Primary residues refer to unprocessed residues from agriculture and forestry such as straw or fallen branches; secondary residues come from the processing industry also covering agricultural and forestry residues, e.g. bagasse or wood chips; tertiary residues constitute different types of municipal waste. The latter two are less relevant for this study as they are not often used for soil management and will therefore not be addressed at this stage. Other definitions are briefly presented hereafter (Box 1); however one needs to be aware that there are no internationally nor even regionally agreed definitions of the terms "residue", "waste" or "co-product".

1.2 CURRENT USES AND BARRIERS TO CROP RESIDUE USE

Hasty actions and unsound decisions regarding the future use of residues for the sake of bioenergy production and GHG emission reductions might have significant negative environmental and socio-economic consequences (Lal 2006a, Lal 2006b, Blanco-Canqui & Lal 2007). Primary crop residues have several important ecosystem functions and provide a wealth of ecosystem services to both humankind and the environment that go far beyond the provision of bioenergy and carbon storage for the sake of reducing GHG emissions (Table 1). Regulating services are provided when residues are left on the soil, contributing to agricultural productivity, to adaptation to climate change and variability and climate change mitigation. More particularly, they prevent soil erosion, reduce soil water evaporation, help increasing rain water infiltration and capturing precipitation from snow, deliver essential nutrients, and constitute an important source for soil carbon, a media for soil-life, a habitat for micro- and macro-organisms, and a tool for weed management. The protection of the soil resource entails savings on external inputs such as fertilizers and soil amendments, concomitantly lowering the need for external energy consumption.

Furthermore, residues provide a large variety of provisioning services with a significant financial value. They are used for animal feed production and bedding, as construction material, and as feedstock for the paper, chemical and pharmaceutical industries. Especially in parts of the family farming sector where both livestock and crop production is practiced, the use of residues for energy is likely to compete with the availability of residues for soil management and for animal feed. As a result, this and other competing uses for residues are likely to determine the profitability of residue use for energy, as each current use already has a financial value.

Box 1. Definitions of the term "Residue" as opposed to "Waste" and "Co-product".

The Food and Agriculture Organization of the United Nations does not have one common, internationally agreed definition for agrifood, crop or wood residues, co-products or waste. Definitions vary by authors and publications. Preston (1986), for instance, in a FAO publication, states that "crop residues are invariably fibrous, of low digestibility and low in nitrogen. They are produced on the farm and therefore widely spread geographically. On small farms in developing countries they form the principal feed of ruminant livestock during the dry seasons." Preston further explains that "agro-industrial by-products result from the processing of crops such as oilseeds, sugar cane, sisal, citrus, pineapple and bananas; or the slaughter and processing of livestock and fish. They are geographically restricted to the factory sites, are usually marketed and frequently exported to earn foreign exchange. They are rich in protein (oilseeds and meals of animal origin) or sugar (molasses, citrus and pineapple pulps) and occasionally in starch (reject bananas, cassava peels) and usually low in fibre. Exceptions are sugar cane bagasse, palm-press fibre, coffee pulp and cocoa pods."

The term "Wood residue" is defined within FAOSTAT (n. d.) Forest Product Definitions as a secondary residue, namely as "the volume of roundwood that is left over after the production of forest products in the forest processing industry (i.e. forest processing residues) and that has not been reduced to chips or particles. It includes sawmill rejects, slabs, edgings and trimmings, veneer log cores, veneer rejects, sawdust, residues from carpentry and joinery production and agglomerated products such as logs, briquettes, pellets or similar forms." However, the definition excludes primary residues and their products from the forest sector such as "wood chips made either directly in the forest from roundwood or made from residues (i.e. already counted as pulpwood, round and split or wood chips and particles)."

The European Commission, in its Fuel Quality Directive, advises to interpret terms "Residue" "Waste" and "Co-product in line with the sustainability objectives of the Directive without giving a standard definition. A communication from the Commission on the practical implementation of the EU biofuels and bioliquids sustainability scheme sheds more light on this issue and refers to "waste" as "any substance or object which the holder discards or intends or is required to discard" (EC, 2010). The term "by-product", on the other hand, as defined by the European Waste Directive, refers to "a substance or object, resulting from a production process, the primary aim of which is not the production of that item" (EC, 2007). By contrast, the term "residue" is described as "agricultural, aquaculture, fisheries and forestry residues, and processing residues" (EC, 2010). The EC source further explains that a "processing residue is a substance that is not the end product(s) that a production process directly seeks to produce … it is not a primary aim of the production process and the process has not been deliberately modified to produce it" (EC, 2010).

TABLE 1.

CROP RESIDUES BY ECOSYSTEM SERVICE AND END USE

ECOSYSTEM SERVICE	End-Use
Regulating services	*Examples*
	Carbon sequestration and maintenance of soil structure
	Management of nutrients/soil fertility
	Protection of soil organisms
	Water conservation/holding capacity and drought resistance
	Balance of soil temperature
	Decreased soil erosion
Provisioning services	*Examples*
Feed	Direct use
	Upgrading (physical, chemical, microbial)
	Ensilage
	Microbial biomass
Fertilizer	Direct use
	Compost
	Biochar
Energy	Heat
	Steam
	Bioelectricity
	Liquid biofuels
Construction materials	Boards, panels, bricks
Paper pulp	Paper, paperboard, packaging materials
Chemicals	Organic acids such as citric acid or lactic acid
	Polysaccharides
	Plastics

Adding to the problems that might arise with competitive functions, the use of residues for energy production in general might be hindered by further constraints going along with different quantitative and qualitative aspects inherent in residue use. In order to make energy production from residues a viable option, one needs to answer many cross-cutting questions, combining the knowledge of several disciplines, such as agricultural science, biology, chemistry, engineering and logistics: Are sufficient quantities of the residue feedstock available for cost-effective bioenergy production? Can residues be easily collected, or are they widely scattered throughout the region? Are they bulky? Are they prone to perish quickly? Are the logistics necessary for residue collection and handling in place? Are the logistics technically and financially feasible? What are the opportunity costs involved in such an operation? Is the necessary labour force available?

1.3 RESIDUE AVAILABILITY

To date, assessments regarding residue availability are often very broad and only give a very rough indication of how much energy could theoretically be available from residues in a given country or region. However, for the design of *detailed* biomass use strategies **at**

national level, e.g. for the development of national policy, these rough estimates are often insufficient. When comparing different estimates, one can see that a lack of good data and uncertainties regarding basic assumptions have led to a wide range of differing results. Accordingly, the methodologies to undertake these assessments vary widely, depending on factors such as the design of the study boundaries and the choice of possible parameters (see also table 2 below for examples of assessments on crop residue availability).

For example, according to Smeets et al. (2007) the energy content of potentially harvestable residues from both crop and wood residues, both from harvesting and processing activities, as well as other lingo-cellulosic wastes, ranges from 76 to 96 EJ globally in the year 2050. Assuming that only a quarter of this is realistically recoverable (Berndes et al. 2003) and that all residues are exclusively used for energy production, they could provide roughly 5 percent of the world's energy consumption[2].

More recent studies are not as optimistic and assume a lower extraction rate of residues of about ten percent taking into account competing uses like fodder, fertilizer or domestic cooking fuel needs. For instance, Eisentraut (2010) in a publication by the International Energy Agency shows, based on FAOSTAT data from 2007 and eight country studies, that around 120 billion lge (4.0 EJ) of BTL (Biomass to Liquid) diesel or lignocellulosic ethanol and up to 172 billion lge (5.7 EJ) of bio-SNG (Synthetic Natural Gas) could be produced. The author (Eisentraut, 2010) further points to the necessity to obtain a better understanding of material flows to ensure the sustainable use of residues. He also suggests more detailed residue specific studies to assess the economic feasibility of collecting and preprocessing agricultural and forestry residues.

This issue is especially important at the **local level**, where concrete bioenergy projects are developed and implemented. Site-specific characteristics such as soil parameters and climatic conditions as well as the current use of residues at a specific location are essential factors required to build a more realistic picture of residue availability. In turn, the results of such local studies can help to refine national estimates. Omitting the inclusion of only one or two important parameters may cause misleading results and might bear the risk of largely overestimating (or underestimating) the real potential of residue use. This can be particularly critical when such estimates lead to wrong decisions taken on the ground. Relevant stakeholders, be it investors or small-scale farmers, might be faced with unwelcome surprises.

However, the availability of such studies is very limited. Global meta-analysis do not contextualize the information provided (Liu et al., 2014), and data from local studies hardly exist. To date, it is therefore impossible to draw a clear picture of how to handle residue management at the local level.

2 In 2006, the global primary energy consumption was estimated to be 472EJ (IEA, 2006).

TABLE 2.

Average amount of available crop residues for bioenergy production by regional coverage.

REGIONAL COVERAGE	TYPE OF CROP	AVERAGE AMOUNT OF CROP RESIDUES (DRY T/YR)	AVERAGE ENERGY (IN EJ/YR)	NAME OF METHODOLOGY USED	PARAMETERS CONSIDERED	REFERENCE
China	All	506 million	7.4	GIS based approach to determine availability and distribution of crop residues	Total amount (incl. sustainable removal rates), spatial and temporal distribution, transportation costs	Jiang, D., Zhuang, D., Fu, J., Huang, Y., Wen, K. (2012). Bioenergy potential from crop residues in China: Availability and distribution. Renewable and Sustainable Energy Reviews 16 (2012) 1377– 1382.
EUa	All	258 million		-	Total amount (incl, sustainable removal rates and competing uses)	Scarlat N, Martinov M, Dallemand J-F. Assessment of the availability of agricultural crop residues in the European Union: Potential and limitation for bioenergy use. Waste Manage 2010;30:1889–97.
EUb	Cereal straw	21.4 million	0.13	Low indirect impact methodology	Theoretical potential (availability), sustainable potential (sustainable removal rates), low indirect land use change potential (current non-bioenergy uses)	Spöttle, M., Alberici, S., Toop, G., Peters, D., Gamba, L., Ping, S., van Steen, H., & Bellefleur, D. 2013. Low ILUC potential of wastes and residues for biofuels Straw, forestry residues, UCO, corn cobs. Utrecht, The Netherlands, Ecofys. 168pp.
Germany	Cereal straw	8 – 13 million	0.112 – 0.186	Process to determine the sustainable potential of cereal straw	Cereal production area, species relevant grain-straw ratio, straw recovery rate, use of straw for animal feed, sustainable soil use, extra use for material applications	Zeller, V., Weiser, C., Hennenberg, K., Reinicke, F., Schaubach, K., Thrän, D., Vetter, A., Wagner, B. (2011). Basisinformationen für eine nachhaltige Nutzung landwirtschaftlicher Reststoffe zur Bioenergiebereitstellung. Schriftenreihe des BMU-Förderprogramms „Energetische Biomassenutzung". Leipzig, Germany, DBFZ. 28pp.
India	Crop residues	234 million	4.15 EJ	Surplus residue potential	Residue potential after excluding competing uses such as cattle feed, animal bedding, heating and cooking fuel, and organic fertilizer	Hiloidhari, M., Das, D., & Baruah, D. C. (2014). Bioenergy potential from crop residue biomass in India. Renewable and Sustainable Energy Reviews, 32, 504–512.
US	Corn stover	100 million		Corn Stover Supply Model	Stover production, stover feed demand, farm, transport and storage costs, stover supply to industry	Gallagher, P., and Baumes, H. 2012. Biomass Supply From Corn Residues: Estimates and Critical Review of Procedures. Agricultural Economic Report Number 847. USDA, Washington DC, USA.

a All 27 EU member states as defined in the study
b EU member states considered were France, Germany, Poland, UK, Spain, Denmark, Italy, Romania and Hungary
c Wheat, barley, oat, rye, and triticale
d The authors considered 39 residues from 26 different crops cultivated in India.

1.4 THE IMPACT OF RESIDUE USE ON FOOD SECURITY

The availability of crop residues strongly depends on many factors, including their current functions, competing uses and logistical challenges. They provide many regulating services and thereby maintain healthy soils which are crucial for crop production. At the same time, they provide several provisioning services on farm such as animal feed or construction materials. In some instances, they even function as a commodity providing a source of income for the farmer. The issue of residue use is therefore closely related to local livelihoods. Especially the impact on the food security of smallholders and family farmers[3] is likely to be considerable. A closer look at the definition of food security helps to illustrate this point. According to FAO, food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (WFS, 1996). It has four dimensions, namely: availability, access, utilization and stability as further elaborated below (EC/FAO, 2008) and summarized in table 3:

1. The first pillar, the physical availability of food, addresses the supply side of food security and is determined by the level of food production, stock levels and net trade. In concrete terms, this pillar helps explain how residues can – or cannot – contribute to an increase in the availability of food.

2. The second pillar, the economic and physical access to food, describes how food security is linked to incomes, expenditures, markets and prices. In the context of residue use, this pillar explains how the extra income generated through the sale of surplus residues can contribute to food security, or how expenditures for energy, fertilizer or animal feed can be reduced or replaced by on-farm residue use.

3. The third pillar of food security, food utilization, is commonly understood as the way the body makes the most of various nutrients in the food. Sufficient energy and nutrient intake by individuals is the result of good care and feeding practices, food preparation, and diversity of the diet and intra-household distribution of food. Residues are often used as alternative to fuelwood and other sources of energy for food preparation. The provision of safe and nutritious food requires energy as one crucial input to cook the food and boil drinking water. A number of key staple food crops are only palatable and fully digestible after cooking. Furthermore, if the cooking time is reduced because of lack of fuel, protein intake is often lowered. In many areas, families can eat only one cooked meal a day instead of two simply because they lack fuel. Hence, without access to energy, food security is significantly reduced. Furthermore, on-farm energy from residues is often used for food processing, storage and cooling.

4. The fourth pillar of food security, the stability of the other three dimensions over time, stresses that food security is only given when food access, availability and utilization are provided on a steady basis. Adverse weather conditions, economic factors such as rising

3 As defined by FAO (FAO, 2014), family farming includes all family-based agricultural activities, and is linked to several areas of rural development. Family farming is a means of organizing agricultural, forestry, fisheries, pastoral and aquaculture production which is managed and operated by a family and predominantly reliant on family labour, including both women's and men's. Both in developing and developed countries, family farming is the predominant form of agriculture in the food production sector. Although dependent on the country definition, the term family farming is often used interchangeably with smallholder farming.

food prices or deteriorating natural resources may interrupt this steadiness and therefore have a negative impact on a person's food security status. The latter is of particular relevance to residues and food security, if the removal of crop and wood residues affects the productivity of the agro- ecosystem and the surrounding landscape where residues are commonly sourced from free-standing bushes and trees, as well from forests.

TABLE 3.

How the use of crop residues for energy can impact the food security of family farmers. The areas to be addressed are structured according to the four dimensions of food security, namely: availability, access, utilization and stability.

FOOD SECURITY PILLAR		POTENTIAL EFFECT
1. Availability	↓	1.1. Soil productivity declines when primary residues are unsustainably reduced, and subsequently yields decrease.
	↓	1.2. The availability of animal feed declines, and subsequently food availability (milk & meat) is reduced.
2. Access	↑	2.1. Family farmers might generate extra income through the sale of residues or through the sale of energy.
	↑	2.2. Family farmers reduce their expenditures for energy through on-farm energy production – be it for cooking, processing, storing or cooling. However, they might increase their expenditures for fertilizers.
	↑	2.3. When family farmers or the rural landless are employed by communal or commercial energy operators to collect, transport or store residues, they can generate extra income.
	↓	2.4 Increasing costs of crop and wood residues may lead to income losses for traditional buyers of these materials and affect poor farmers who cannot afford alternatives, such as synthetic fertilizer or animal feed.
3. Utilization	↑	3.1. When family farmers are using residues as a source for cooking energy, they increase their energy security and thereby their nutritional status and food safety.
	↑	3.2. When family farmers are using residues for processing, storing and cooling food for their own consumption, they increase their energy security, and thereby their nutritional status and food safety.
4. Stability	↓	4.1. When family farmers unsustainably harvest residues from their farming system, they impact the long-term soil fertility and thereby food stability (see also 1. above).
	↑	4.2. When farm residues are burnt in the field instead of being used for other purposes, they cause major air pollution and impacts on ecosystems and human health. The use of residues for energy can significantly decrease these impacts.

1.5 ADDRESSING POTENTIAL IMPACTS OF CROP AND WOOD RESIDUE USE ON FOOD SECURITY

To inform decision-making in the area of sustainable residue management for food security requires information and decision support tools as well as a mechanism for their implementation and the subsequent exploitation of data. The study presented here has generated some of the data needed to build such a decision support tool.

Where do we currently stand? Several studies assess the availability of residues at global and/or national levels. One striking feature of these studies is the diversity of their results, due to differences in the assumptions made, and parameters and methods used. On the other hand, to the best of our knowledge, currently **there is hardly any concrete guidance material** for sustainable residue management in the growing bioenergy[4] sector. This is all the more the case for decisions to be made at farm level. Only few existing manuals explain how sustainable residue management for specific crop residues should look like in a particular context, - this is in particular the case for corn residues in the United States (e.g. Gallagher & Baumes, 2012). But for most residue types in a particular agro-ecological zone there is no available information or guidance, particularly in developing countries.

To this end, FAO in collaboration with Wageningen University has set out to explore the first potential effects of crop residue management on the availability pillar of food security (point 1.1, Table 3). Therefore this study does not provide a comprehensive analysis on the role of crop residue management on food security but rather a review and several data elaborations on the impact of crop residue management on soil quality, soil structure and yields.

Soil organic carbon (SOC) mediates essential ecological processes related with soil fertility and crop production; hence it was considered a reliable proxy for soil quality. Concerning soil structure, bulk density and soil aggregate were considered as trustworthy indicators to study the response of soil structure to residue management.

1.6 SOIL ORGANIC CARBON AND CROP YIELDS

Residues contain considerable amounts of carbon, which, when returned to the soil, have important functions: SOC provides a wide range of benefits for crop production and ecosystem stability including improved water and nutrient retention, higher soil biodiversity, enhanced yield response to fertilizers and protection from sediment losses (Lemus, 2013; Tilman et al. 2013; Anderson-Teixera et al., 2009; Chikowo & Mapfumo, 2004).

Carbon is present everywhere on earth – in the soils (4 500 Pg), the oceans (38 400 Pg), in fossil fuels (4500 Pg), in the world's biota (620Pg) and in the atmosphere (750 Pg) (Lal, 2004). However, soils have lost between 50 to 75% of the original SOC pool due to ongoing erosion, mineralization and leaching in agricultural ecosystems (Lal, 2006b). The unsustainable removal of residues is one of the reasons for this to happen. Removal of crop residues as a source of bioenergy can therefore have severe adverse impacts on SOC levels, and ultimately the quality of the soil.

Likewise, there is a strong link between soil quality and crop yield (Reilly and Fuglie, 1998). The increase in crop yields through SOC enhancement can be explained through an increased availability of water capacity, through an improved supply of nutrients and through an enhanced soil structure and other physical properties (Lal, 2006a).

4 Bioenergy is energy generated from biofuels, which are fuels derived from biomass (FAO, 2004). Biofuels can be further subdivided by type (solid, liquid, and gas) and by origin (forest, agriculture, and municipal waste). Biofuels from forests and agriculture come from a wide range of sources, including forests, farms, specially grown energy crops, and residues and waste after harvesting or processing of wood, food crops and fish.

This triple effect is particularly evident in soils of the tropic and subtropics where the SOC pool has been depleted through extractive practices by resource-poor farmers or unsustainable business practices. Lal reported about a long-term African experiment in Nigerian maize fields where a severe decline in soil quality due to residue removal was observed (Lal, 2006b). Furthermore, negative impacts on soil properties, e.g. a strong increase in bulk density and a decrease in infiltration rate, were shown. A comparison of sites with and without residue application after 13 years revealed that crop yields almost doubled where residues were retained (2.7 t ha^{-1} $year^{-1}$) compared to where they were removed (1.5 t ha^{-1}) (Lal, 2006b; Juo et al., 1995; 1996). In India, seed grain yield of mustard increased by 360 kg ha^{-1} $year^{-1}$ when the SOC pool increased by 1 t in the 0 to 15 cm soil layer (Shankar et al., 2002). In Argentina, Diaz-Zorita et al. (1999) found that wheat yields were reduced by 40 kg ha^{-1} $year^{-1}$ when SOM levels taken from soil samples from the upper 20 cm soil layer, decreased by 1 t ha^{-1} $year^{-1}$.

Experiments from temperate zones also show a clear effect of SOC decrease on crop yield. For instance, wheat yield decreased by 39 kg ha^{-1} $year^{-1}$ in one and 19 kg ha^{-1} $year^{-1}$ in another Canadian location when SOC decreased by 1t in the 0 to 7.5 cm soil layer (Larney et al., 2000). Another experiment from the United States showed that wheat yield declined by 26.5 kg ha^{-1} $year^{-1}$ when 1 t of SOC ha^{-1} was lost in the 0 to 50 cm soil layer (Bauer and Black, 1994).

However, while these and many other experiments show that SOC can have substantial effects on crop yields where SOC pools are depleted, this is not always the case. Other studies have shown that there is no or very little decrease in crop yield when the SOC pool is reduced. Yet others even demonstrated that crop yield decreased despite an increase in SOC (Lal, 2006a).

Collecting and analysing this kind of data is an essential first step in order to provide guidance on sustainable residue management. Given the large complexity and interplay of different parameters that determine the sequestration of organic carbon in soils and its impact on crop yields, it is necessary to single out under which circumstances residue retention plays a vital role in maintaining SOC and promoting yields and, under which circumstances SOC can be removed without harming soil quality and reducing crop yields.

To get a better understanding of this complexity, we conducted a meta-analysis to address the following hypothesis: crop residues application (i) is associated with higher SOC concentrations (ii) impacts soil properties like bulk density and soil aggregation and (iii) if the increased SOC related with residues application positively affects yields.

CHAPTER 2

METHODOLOGY

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). More particularly, all studies containing the key words "soil organic carbon crop residues" from the past ten years (January 2014-2003) were examined. Studies excluded were those that (i) did not show comparisons between treatments with residues applied and residues removed, (ii) publications reporting soil samples at a soil depth lower than 15 cm, (iii) papers presenting results from model elaborations and (iv) literature reviews. Furthermore, within each study treatments in which C-input other than crop residues (i.e. compost, manure) were applied were not included. All other publications were taken into account.

2.1.1 Soil Organic Carbon (SOC)

The literature reports soil organic carbon using different units, soil depths and methods of determination. 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, 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:

$$\text{SOC (g kg}^{-1}\text{)} = \frac{\text{SOC (t ha}^{-1}\text{)}}{\text{TSW (t ha}^{-1}\text{)}} * 1000 \tag{1}$$

Studies reporting soil organic carbon 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 (Bernal et al., 1998).

$$\text{SOC (g kg}^{-1}\text{)} = \frac{\text{OM (\%)}}{1.72} * 10 \tag{2}$$

2.1.2 Amount of residues applied and C-input

Not all of the publications that were consulted reported on the amount and the C concentration of the residues that were applied annually. When this information was not provided, the amount of residues was calculated using harvest index (HI) and crop yield (Y) data as follows:

$$\text{Crop residue applied (t ha}^{-1}\text{ year}^{-1}) = \frac{(1\text{-HI}) * \text{Y(t ha}^{-1}\text{year}^{-1})}{\text{HI}} \tag{3}$$

Whereas total C-input was calculated as:

$$\text{C input (t ha}^{-1}\text{ year}^{-1}) = \text{Crop residue applied (t ha}^{-1}\text{ year}^{-1}) * \text{C concentration (\%)} \tag{4}$$

Table 3 shows the HI and C-concentration values used for such calculations.

TABLE 3.

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
soybean	0.300	35.00
rice	0.475	42.50
barley	0.450	42.50

2.1.3 Apparent Humification Index

The *Apparent Humification Index* (AHI) relates the increase in soil organic carbon in a certain soil layer over a specified period of time to the total input of carbon applied to the soil during the same period. This indicator provides a rough estimate of the amount of C input added through residues application that stabilized into humus within the study period. It is termed 'apparent' because a substantial fraction of the C input to soil occurs through decaying plant roots, not included in the calculation. AHI (%) was calculated with the following equation:

$$\text{AHI} = \frac{\text{Final SOC (t ha}^{-1}) - \text{Initial SOC (t ha}^{-1})}{\sum_{\text{years}}^{n} \text{C - Input (t ha}^{-1})} \tag{5}$$

It should be noted that SOC in this case is expressed in mass units as t ha^{-1} within a given soil layer. As not all studies reported the same soil depth, AHI was calculated for both the 0-20 and the 0-30 cm soil layers. The first category included also he studies that reported soil carbon at depths of 0-15 cm.

2.1.4 Water Productivity

Water Productivity (WP) was calculated by dividing yields data to average annual rainfall and expressed in kg mm^{-1} ha^{-1} $year^{-1}$. Its delta (Δ) was calculated as follows:

$$\Delta WP = \frac{WP_{R+} (kg\ mm^{-1}\ ha^{-1}\ year^{-1}) - WP_{R-} (kg\ mm^{-1}\ ha^{-1}\ year^{-1})}{WP_{R-} (kg\ mm^{-1}\ ha^{-1}\ year^{-1})} \quad (6)$$

Where R+ indicated treatments in which residues were retained while R- indicated treatments in which residues were removed.

2.1.5 Pedoclimatic data

The majority of the publications reported both average annual temperature and average rainfall. When these data were not provided the on-line world climate general database (http://www.worldclimate.com/) was consulted as suggested by Virto et al. in 2012.

In the descriptive analysis of the database, 'tropical' and 'temperate' climates were defined according to the average annual rainfall: average temperature ratio. If this ratio was lower than 35, climates were defined as tropical; if it was greater than 35, climates fell in the temperate category.

The Köppen-Geiger climate classification updated by Kottek et al. in 2006presented in its latest version 1961 by Rudolf Geiger. A huge number of climate studies and subsequent publications adopted this or a former release of the Köppen-Geiger map. While the climate\nclassification concept has been widely applied to a broad range of topics in climate and climate change research as well as in physical geography, hydrology, agriculture, biology and educational aspects, a well-documented update of the world climate classification map is still missing. Based\non recent data sets from the Climatic Research Unit (CRU was used in the classificatory analysis. This categorization was adopted in order to distinguish further between dry and humid climate and improve the discriminatory power of the classification trees. Figure 1 shows the world map according to the updated climate classification. Köppen & Geiger categorized the world area in five climatic zones: equatorial, dry, warm temperate, snow and polar. The second letters in the classification (Figure 1) indicate precipitation while the third indicates temperature. In this study just the first categorization was used. A detailed explanation of the criteria adopted to define each climate category can be found in Appendix I.

Concerning soil texture, some papers reported texture class according to the USDA triangle while others provided sand, silt and clay concentration. In order to obtain both classifications the USDA texture triangle was used. When the category of the USDA was reported, the mean clay silt and sand contents were ascribed to the soil under consideration. Conversely, when sand, silt and clay concentration were reported, the texture triangle was used to name the soil. Due to the uneven distribution of data points in the various textural classes, soils were further regrouped in five broader classes as illustrated by Table 4.

TABLE 4.

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

2.2 STATISTICAL ANALYSIS

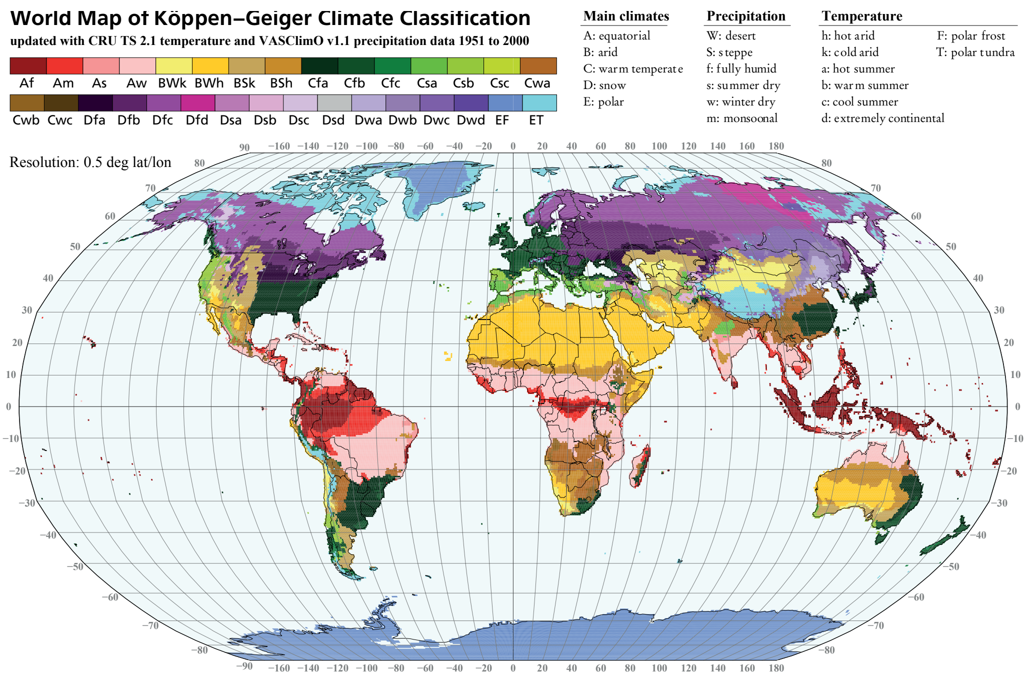
All statistical analyses were performed using R 3.0.2 for Windows (32-bit). Principal Component Analysis (PCA) was carried out using the "prcomp" R function. When studying SOC the following variables were included in the analysis: N-fertilizers, average annual rainfall, average annual temperature, silt + clay concentration, C-input and SOC. These variables were selected since (i) they were assumed to be relevant to test the hypothesis, (ii) they formed a set of variables in which two variables described each production factor, 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. Yield records were not included in the SOC analysis since data from different crops could have biased the analysis. Conversely, when maize yield was investigated yield data were added to the variables set.

The PCA was performed to analyse the structure of the variance in the dataset, and to reveal which variables were mostly associated with SOC and yield variability. PCA provides an indication of the degree of association between variables but not on their interdependence. Moreover, the contribution of each variable to the variance observed in the dependent variable may vary in different conditions. To unravel this, classification and regression tree analysis (CART) were performed on more homogeneous subsets of the dataset, using the "rpart" function of R for two subsets: 'tropical' (equatorial + dry areas) and 'temperate' (warm temperate + snow areas).

All trees were 'pruned' at the point where the x-error was minimized. When running these analyses for SOC we included the following variables: climate, C-input, residues application management (removed, incorporated or left as mulch), annual N-fertilizers application and texture. Whereas, when regression trees were performed for yield, SOC was included as additional independent variable. Yields data were not included in the CART for SOC for the same reason mentioned for PCAs.

FIGURE 1.

World Map of Koppen-Geigger Climate Classification updated by Koppek et al (2006).



Source: Koppek et al., 2006.

CHAPTER 3

RESULTS

3.1 DATABASE

A total of 1 072 publications were found when searching for the selected keywords "soil organic carbon crop residues" within the reference period (January 2003 - 2014). Of the 1 072 publications, only 157 were considered to be significant from the relevance of the title and abstract. Subsequently, publications were carefully screened in order to take into account only studies comparing treatments in which residues were retained on farm versus removed from the fields. Studies that explored the effect of inversion tillage versus no-till practices on SOC rather than focusing on the influence of crop residues management were discarded (67 papers). Finally a total of 90 publications were included in the database. The final database embraced a wide range of climatic conditions, farming systems, crops and edaphic characteristics. Observations were obtained from 32 countries covering a large series of average annual temperatures, average annual precipitations, farming systems, and soil texture classes. Table 5 presents the ranges of observations for some of the variables just mentioned.

It should be noted that not all the papers reported data both on crop yield and SOC so that the actual number of observations used for elaborations varied according to the analysis performed.

TABLE 5.

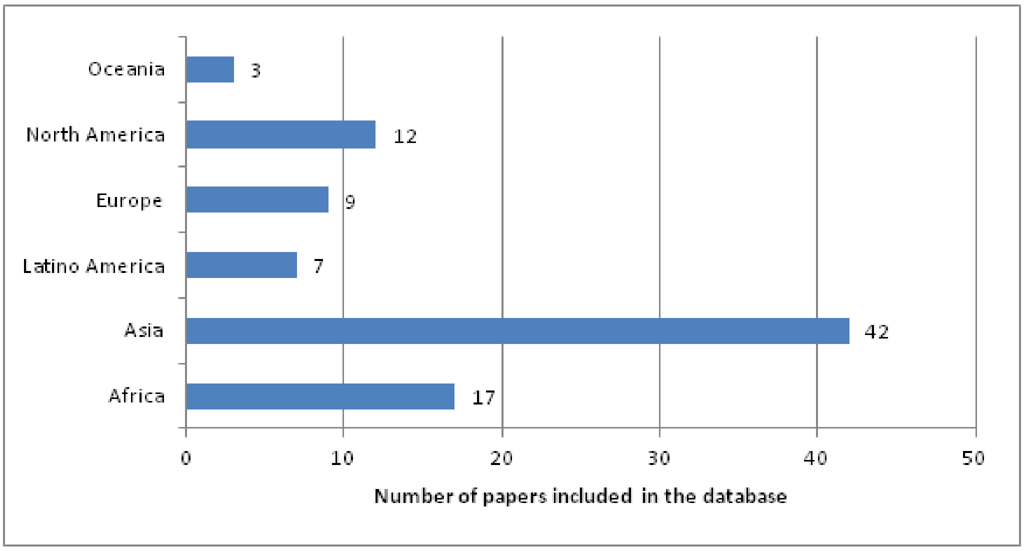
Range (Max-Min) of the observations of some of the considered variables in this study

COUNTRIES (N)	32
T (°C)	0.3 - 35
Rainfall range (mm $year^{-1}$)	54 - 2000
Silt + Clay (%)	6.6- 99.4
Crops (n)	7
Farming systems	Sub-Saharan African smallholders farm - North American maize monoculture

Figure 2 shows the location of the studies included in the database.

FIGURE 2.

Location of the studies included in the database.

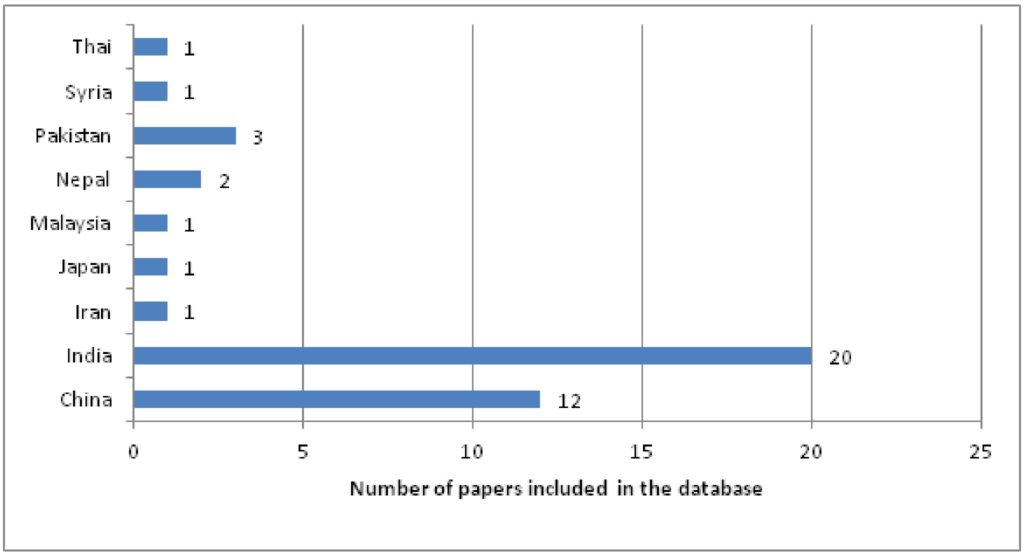


Numbers on the top of the bars denote number of papers included.

It can be argued that Asia is overrepresented compared with other continents such us Oceania or Central and South America. However, 11 and 19 studies showed results from China and India, respectively (Figure 3), two very large countries characterized by a large variety of climate and farming systems.

FIGURE 3.

Location of the Asian studies included in the database.

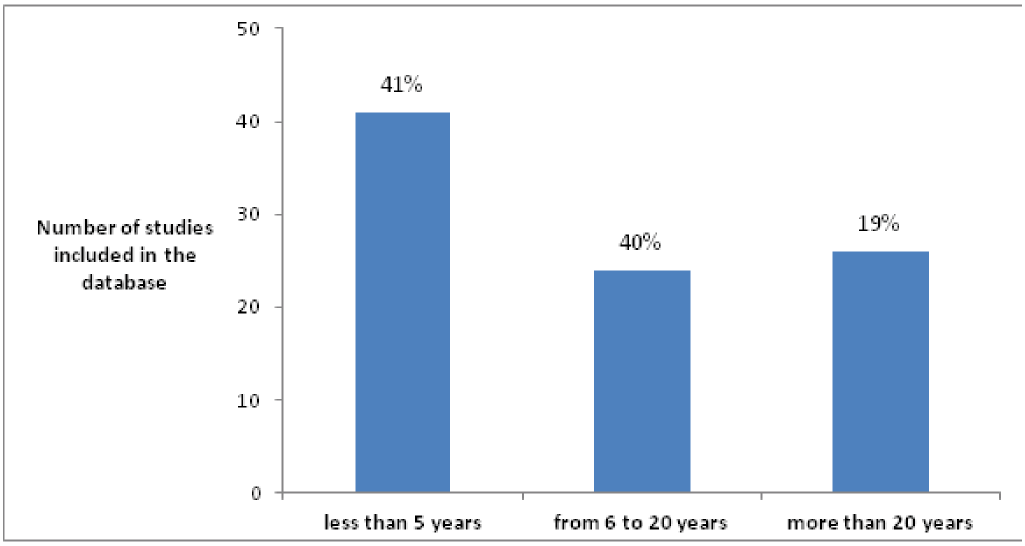


Numbers on the top of the bars denote number of papers included.

Regarding the duration of the experiments, short and medium-term trials were the most represented in the database. In fact 80 percent of observations referred to studies repeated for less than 5 years or from 6 to 20 years whereas long-term studies (more than 20 years of trials) accounted only for 19 percent of the total observations (Figure 4).

FIGURE 4.

Duration of the studies included in the database.



Numbers above the bars denote relative percentage for observation of each group.

3.2 AGGREGATED EFFECT OF CROP RESIDUE REMOVAL ON SOC

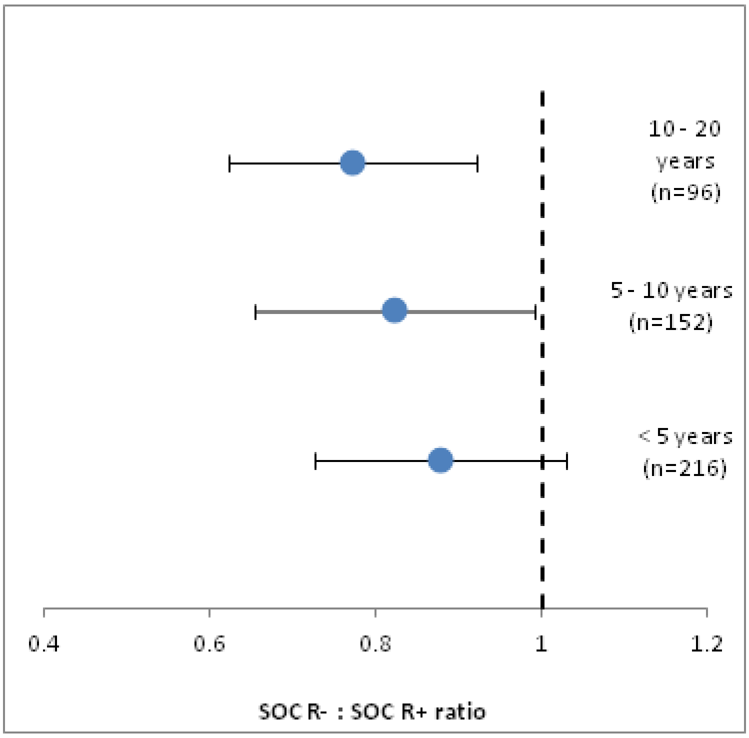
The analysis of all the possible comparable pairs of observation (n=464) showed that treatments which included residues (R+) had significantly higher SOC concentration compared with treatments in which residues were removed (R-). This appeared to be valid for both tropical and temperate environments. Residues removal by average resulted in about 13% (±16%) less SOC both in temperate and tropical regions. However, such numbers have to be carefully considered since the dataset encompasses wide variability. The following sections will try to elucidate where this variation lies by exploring the complex interaction between crop residues and the considered factors on SOC storage.

3.2.1 SOC and duration of the trials

Figure 5 illustrates the influence of residues management on SOC according to the duration of the trials. Overall, removing residues affected SOC negatively. However, the magnitude of this drop increased with the duration of the trials. Considering data reported by studies in which residues were removed for less than 5 years, residues removal resulted in a reduction of SOC by 12% (±15%). In longer studies SOC declined at bigger rates. In fact, in trials repeated for 5 to 10 years SOC dropped by 18% (±17%) and by 23% (±15%) in study from 10 to 20 years long.

FIGURE 5.

Ratio between final SOC concentration in treatments with residues removed (R-) and treatments with residues applied (R+), as affected by the duration of the trials.



Indicators represent average values whereas error bars denote standard deviation, (n=464).

3.2.2 Texture and residues application effects on SOC

Figure 6 shows the SOC concentration as related to soil silt and clay content. The boundary line indicates the SOC envelope. The graph illustrates that soils characterized by finer texture could potentially store more SOC than coarser soils.

This trend is confirmed by Figure 7 that additionally displays the role of crop residues application in increasing SOC in all texture classes. Moreover, Figure 8 suggests that the Apparent Humification Index (AHI) can likely be higher in finer soils. A higher AHI means that a greater proportion of the C-input provided by crop residues application (plus crop root biomass C) is stabilized into humus.

It should be noted that in Figure 6 and 8, the high amount of points below the boundary lines demonstrates the high variability existing among soils with similar soil texture. This confirmed that, though texture played a role in storing SOC, other variables were involved in determining the effect of crop residues on SOC and its actual concentration.

FIGURE 6.

SOC as influenced by the concentration of silt and clay regardless of residues application (n=464).

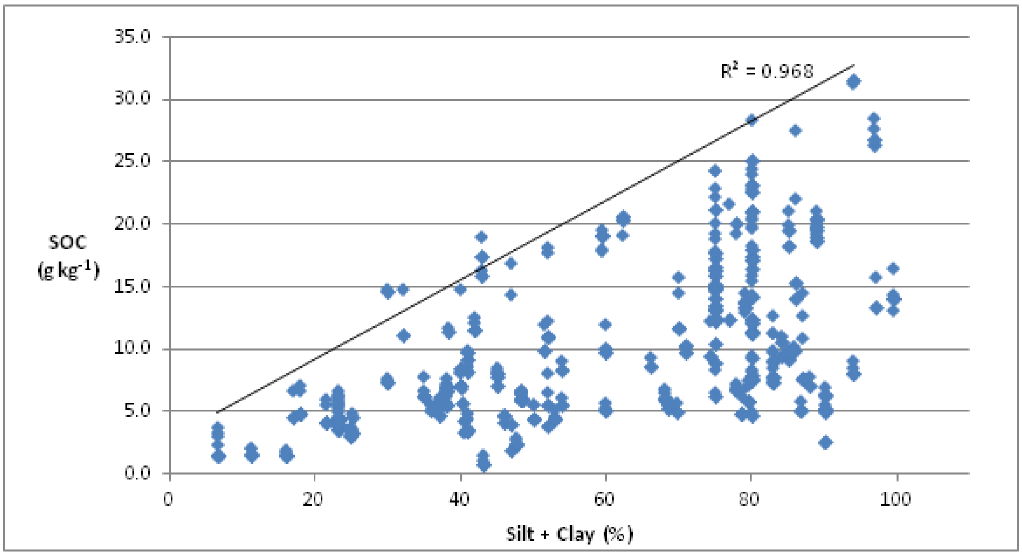
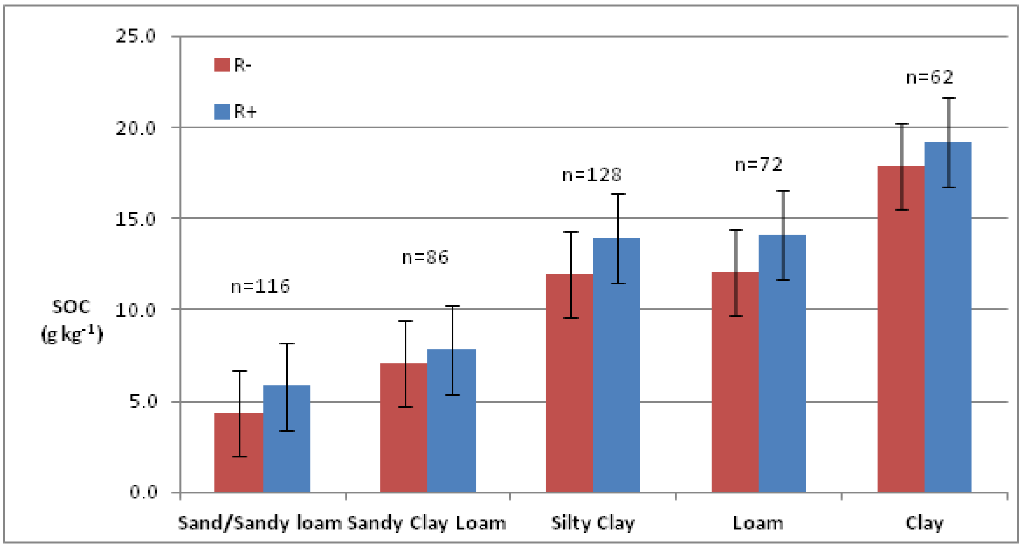


FIGURE 7.

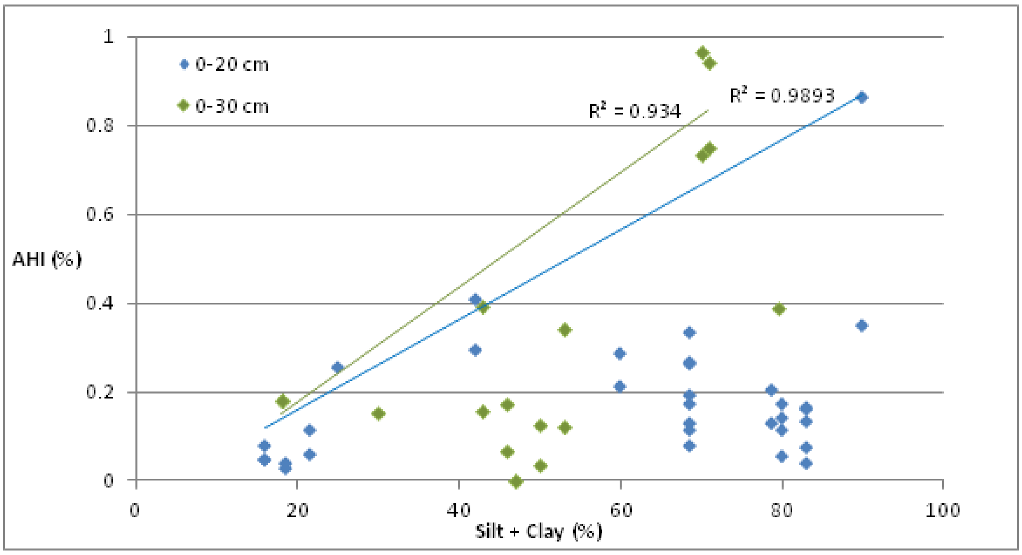
Average SOC according to different soil texture classes. R+ stands for treatments in which residues are applied while R- for treatments not including residues application.



Data labels indicate number of observations. Error bars denote standard errors (n=464).

FIGURE 8.

Apparent Humification Index related to soil texture of the considered soils (n=52).

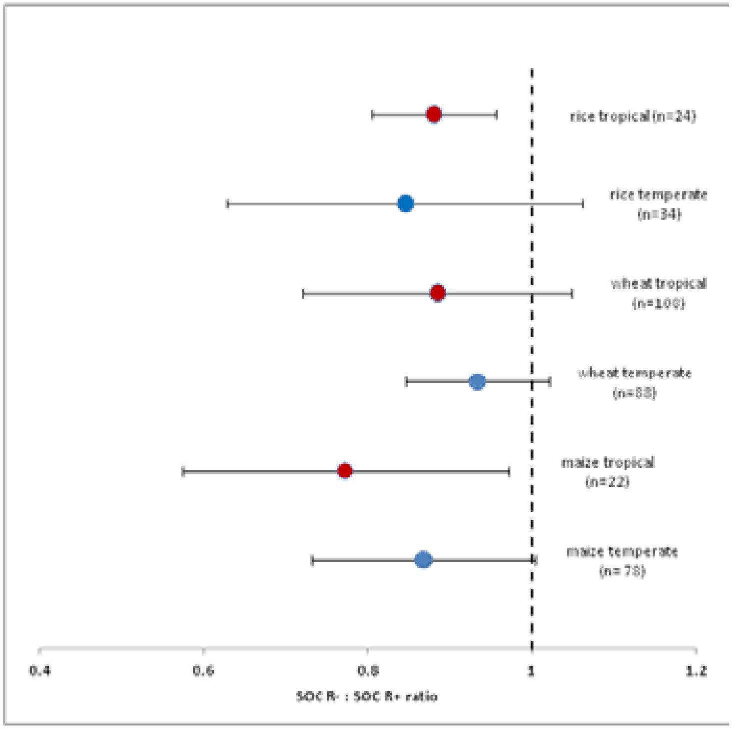


3.2.3 Residues effects on SOC according to different crops cultivation

The influence of residues application in different crop fields is illustrated in Figure 9. Residues removal in maize plots decreased SOC by about 13% (±14%) and 23% (±20%) in temperate and tropical region, respectively. In wheat fields SOC losses were more moderate, with plots in temperate and tropical region showing 7% (±9%) and 12% (±16%) less SOC when residues were removed, respectively. By contrast, the trend in rice farms was reversed. Rice fields in tropical environments appeared to be less sensible to residues removal with a SOC drop by 12% (±8%) compared with the 15% (±22%) lower SOC registered in temperate locations. However in the latter case variation was very significant.

FIGURE 9.

Ratio between final SOC concentration in treatments with residues removed (R-) and treatments with residues applied (R+), as affected by different crops.



Indicators represent average values whereas error bars denote standard deviation (n=354).

3.2.4 PCA for SOC

PCA is a functional statistical elaboration to comprehend how variables responsible for a given process are related to each other and which of them is/are the most influencing. More specifically, PCA groups the variables in a reduced number of components and extracts those able to explain the majority of the variation. In the previous chapters it was demonstrated that SOC may vary according to soil type, climatic areas and management. Therefore a PCA was run in order to understand which of the selected variables was greatly influencing SOC.

Results showed that SOC was very weakly correlated with temperature, rainfall and silt + clay concentration. However, the need to extract more 4 PCs to explain high proportion of variance did not provide solid information to draw strong conclusions and justify the need for classificatory statistical methods as CARTs.

A detailed explanation of the PCA outcomes and their interpretation can be found in the Appendix II.

3.2.5 CART for SOC in tropical environment

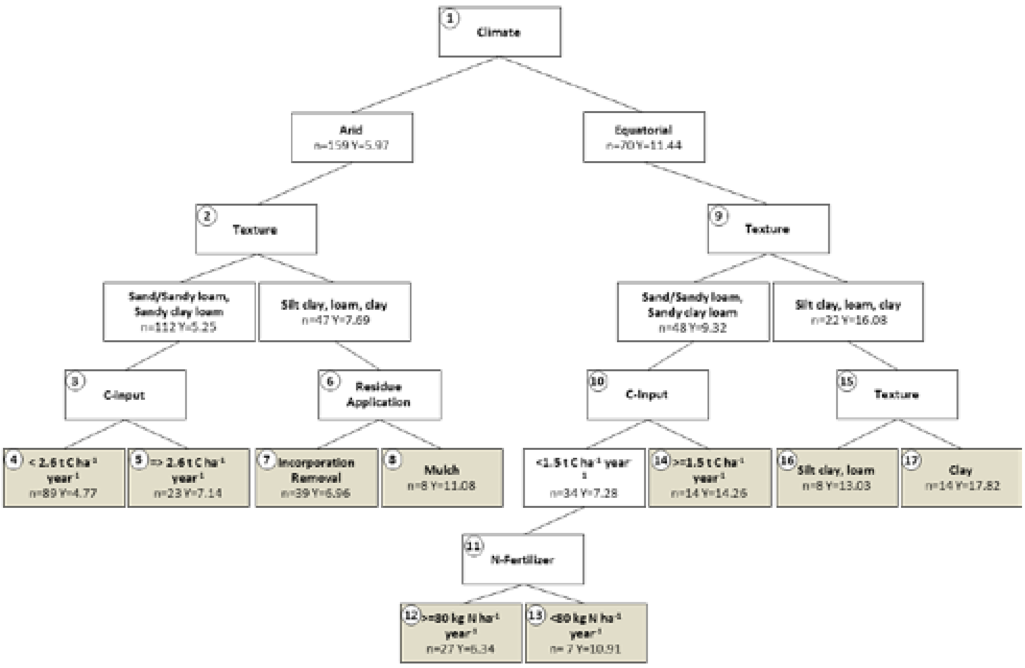
Figure 10 shows the regression trees concerning SOC concentration in tropical environments. Overall, the effect of residues application (both method and actual C-input rate) on SOC was subordinated to the effects of soil texture, climate. The first criterion to split the entire set of SOC observations was climate, with arid tropical climates exhibiting much less SOC than equatorials ones, about 6 and 11.5 g kg^{-1}, respectively. In both climates, data were further categorized according to soil texture (Figure 10, nodes 2 and 9), differentiating finer (silt clay, loam and clay soils) from coarser (sand/sandy loam, sandy clay loam) ones. In the latter soils category C-input became the next classificatory variable (Figure 10 nodes 3 and 10). However, the actual C-input rate differed between climatic zones, with more than 2.5 and 1.5 t of C ha^{-1} $year^{-1}$ being the cutoff point in arid and equatorial tropical climates, respectively (Figure 10 nodes 3 and 10).

In equatorial climatic areas a further data separation based on N-fertilizers took place. At N-application lower than 80 kg of N ha^{-1} $year^{-1}$ SOC concentration was higher compared with larger N-fertilizations (Figure 10 nodes 11, 12 and 13), but only 7 data represented this category.

Data regarding silt clay, loam and clay soils located in equatorial climates were further split according to soil texture, with clay soils exhibiting a higher SOC concentration than silt clay and loam soils (Figure 10, nodes 16 and 17). Whereas, in arid locations the surface application of crop residue had a positive effect on SOC concentration compared with residues incorporation or removal (Figure 10, nodes 7 and 8).

FIGURE 10.

Regression trees SOC for tropical environment (n=229). Y represents average SOC values expressed in g kg^{-1}, dark coloured box indicates the terminal nodes of the tree.



3.2.6 CART for SOC in temperate environment

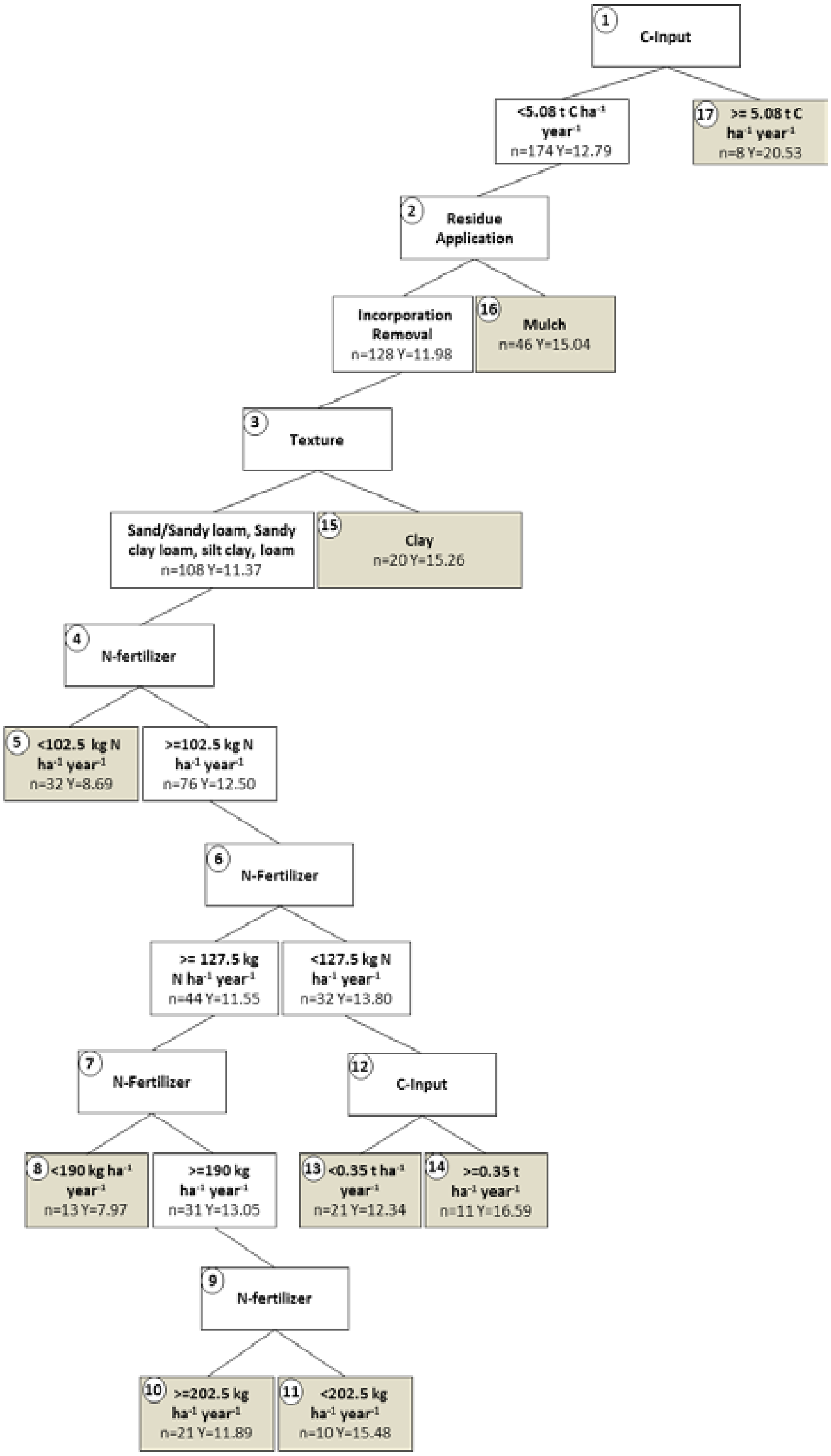
Figure 11 illustrates the classification and regression tree on SOC obtained from the temperate dataset. The first splitting criterion was C-input. In temperate areas the application of more than 5 t of C ha^{-1} $year^{-1}$ via crop residue resulted in almost doubled SOC concentration compared with lower application rate (Figure 11, nodes 1 and 17). However this category consisted in few observations (n=8) and showed high variability (SOC ranged between 10 and 29 g kg^{-1}). At lower C-input rate, the way in which crop residue were applied determined the next split (Figure 11, node 2). Leaving crop residue on the soil surface resulted in an average SOC concentration of about 15.04 g kg^{-1} (Figure 11, node 16), whereas in the case of residues removal or incorporation average SOC concentration was about 11.98 g kg^{-1} (Figure 11, node 3).

The dataset was, further splitted according to soil texture and data on clay soils were separated from the other soil types (sand/sandy loam, sandy clay loam, silty clay and loam) (Figure 11, nodes 3, 4 and 15). The former category exhibited an average higher SOC concentration compared with the latter (Figure 11, nodes 3 and 4). The subset on coarser soils was divided depending on N-fertilizer application (Figure 11, node 4). Although N-fertilization appeared to be the main an important determinant of SOC for these soil types (Figure 11, nodes 4,5,6,7,8,9,10 and 11) data were not completely clear. In fact, not clear trends on the effect of N on SOC concentrations could be identified. In some nodes higher N-application rates were associated with higher SOC concentrations (Figure 11, nodes 5, 6, 8, 9) while in others N-fertilization seemed to have a negative effects on SOC (Figure 11, nodes 10, 11, 7 and 12).

Finally, the input of 0.35 t of C ha^{-1} $year^{-1}$ via crop residue incorporation increased SOC concentration in soils other than clay when N-fertilizer were applied at rate between 102.5 and 127.5 kg of N ha^{-1} $year^{-1}$ (Figure 11, nodes 13 and 14).

FIGURE 11.

Regression trees SOC for temperate environment (n=182). Y represents average SOC values expressed in g kg-1, dark coloured box indicates the terminal nodes of the tree.



3.3 RESIDUES INFLUENCE ON SOIL PROPERTIES

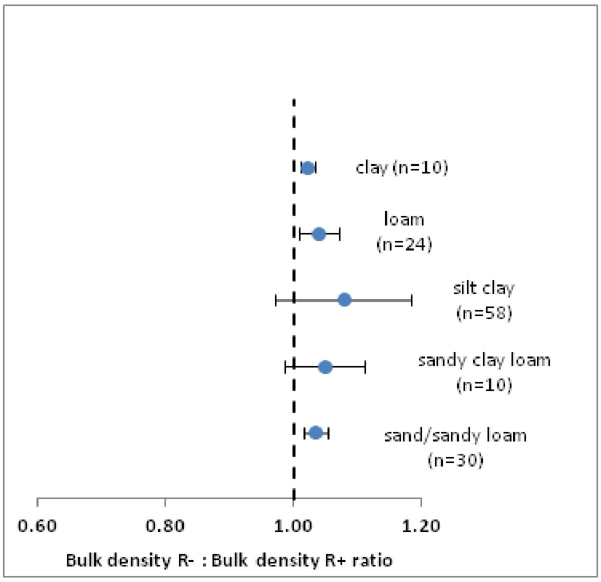
3.3.1 Bulk density

17 studies reported data on soil bulk density which resulted in a total of 136 observations. The forest plot in Figure 12 shows the effect of crop residues on bulk density. Regardless of soil texture class, crop residues removal resulted in higher bulk density compared with treatments in which residues were retained. Figure 12 reports that bulk density increased by 3 (±1.8%), 5 (±6.2%), 8 (±10.6%), 4 (±3.1%) and 2% (±10.6) in sand/sandy loam, sandy clay loam, silt clay, loam, and clay soils, respectively. However, sandy clay loam and clay texture class included only ten observations. Furthermore, it should be considered that due to the limited amount of data, the different tillage management was not taken into account.

The database used for soil bulk density analysis is reported in Appendix III

FIGURE 12

Ratio between bulk density in treatments with residues removed (R-) and treatments with residues applied (R+), according to different soil texture classes.



Indicators represent average values whereas error bars denote standard deviation (n=136).

3.3.2 Soil Aggregation

19 studies explored the influence of crop residues on soil aggregation. However, these data were presented in different units: eight studies expressed aggregation in aggregate size distribution, six in mean weight diameter and five in percentage of water stable aggregates. Data from the first group of publications were extracted and a small database was created. However, no remarkable trends were found, mainly because of the limited amount of data available and the diverse tillage management of the considered studies.

The database used for analysis is reported in Appendix IV.

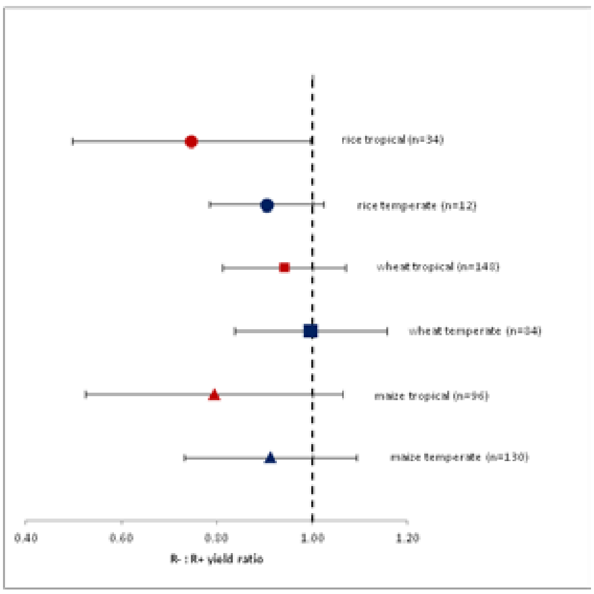
3.4 RESIDUES INFLUENCE ON YIELD

3.4.1 Residues management effect on yield for different crops

On average crop residues removal were associated with a decrease in yield by 8% (±18%). Rice, wheat and maize were the most represented crops in the database. The influence of crop residues management on yield varied among these three crops and such variation is illustrated in Figure 13. Excluding wheat yields recorded in temperate region, yields resulted to be affected by crop residues management, with greater effects in tropical areas. On average, residues removal in temperate regions provoked a drop by 9 and 10% in maize and rice yields, respectively, and had no effects on wheat. In tropical climatic zones, yields decreased by 21, 6 and 25% in maize, wheat and rice fields, respectively, where residues were not retained on farm. Furthermore, it should be noted that the variability of the yield response to residues removal was higher for maize and rice in tropical climatic areas.

FIGURE 13.

Ratio between Yield in treatments with residues removed (R-) and treatments with residues applied (R+), for rice maize and wheat. Indicators represent average values whereas error bars denote standard deviation (n=504).



3.4.2 PCA for Maize yields

As for SOC, a PCA using maize yield data was performed to identify the main variables which defined yields. Maize yields were correlated with N-fertilization and they appeared to be independent by SOC concentration. However, given that many PCs were needed to explain a high proportion of variance, PCA did not allow to draw strong conclusions. A detailed explanation of the results and their interpretation from the PCA on maize yield data is reported in Appendix Va.

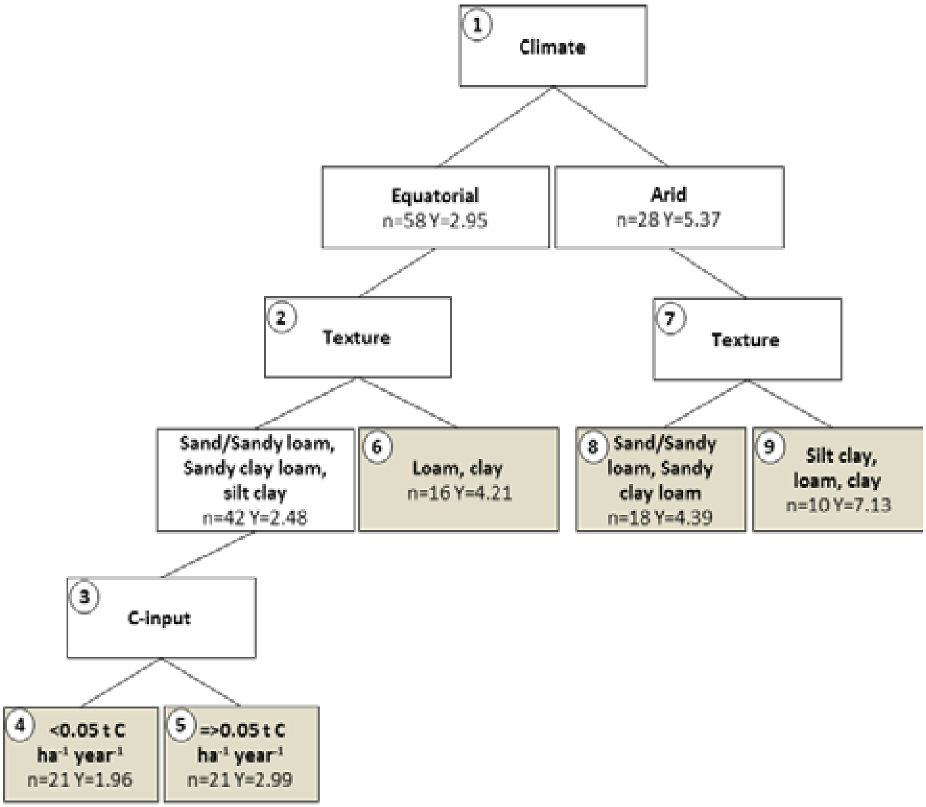
3.4.3 CART for Maize Yields

Figure 14 illustrates regression tree analysis for maize yields in tropical environments. Overall, the influence of crop residues appeared to be subordinated to climate and soil texture. The first node separated data according to subclimatic classes. In arid tropical regions (right split), soil texture appeared to be of primary importance in defining yields (Figure 14, node 7). In particular, maize yields were sensibly higher than in coarser soils (sand/sandy loam and sandy clay loam) compared with finer textured soils (silt clay, loam, clay) (Figure 14, nodes 7, 8 and 9) with grain production of about 7.13 and 4.39 t ha^{-1} $year^{-1}$, respectively. In the former texture class (n=10), maize yields varied between 5.5 and 7.3 t ha^{-1} $year^{-1}$ whereas in the latter class (n=18), yields ranged between 3 and 6 t ha^{-1} $year^{-1}$ (Figure 14, node 9).

Considering equatorial climates, texture was a crucial criterion in determining yields, with finer soils (loam and clay having the highest yields (Figure 14, node 2). In coarser soils (sand/sandy loam, sandy clay loam and silt clay) about 50 kg of C ha^{-1} $year^{-1}$ resulted averagely in an additional tonne of maize grain (Figure 14, nodes 4 and 5). Concerning yield fluctuations, they ranged between 0.5 and 5.5 t ha^{-1} $year^{-1}$ when residues were applied (Figure 14, node 5), while grain production varied from 0.5 to 3.5 t ha^{-1} $year^{-1}$ when residues were removed (Figure 14, node 4).

FIGURE 14.

Regression trees for maize yields in tropical environment (n=86). Y represents average maize yields values expressed in t ha^{-1} year^{-1}, dark coloured box indicates the terminal nodes of the tree.

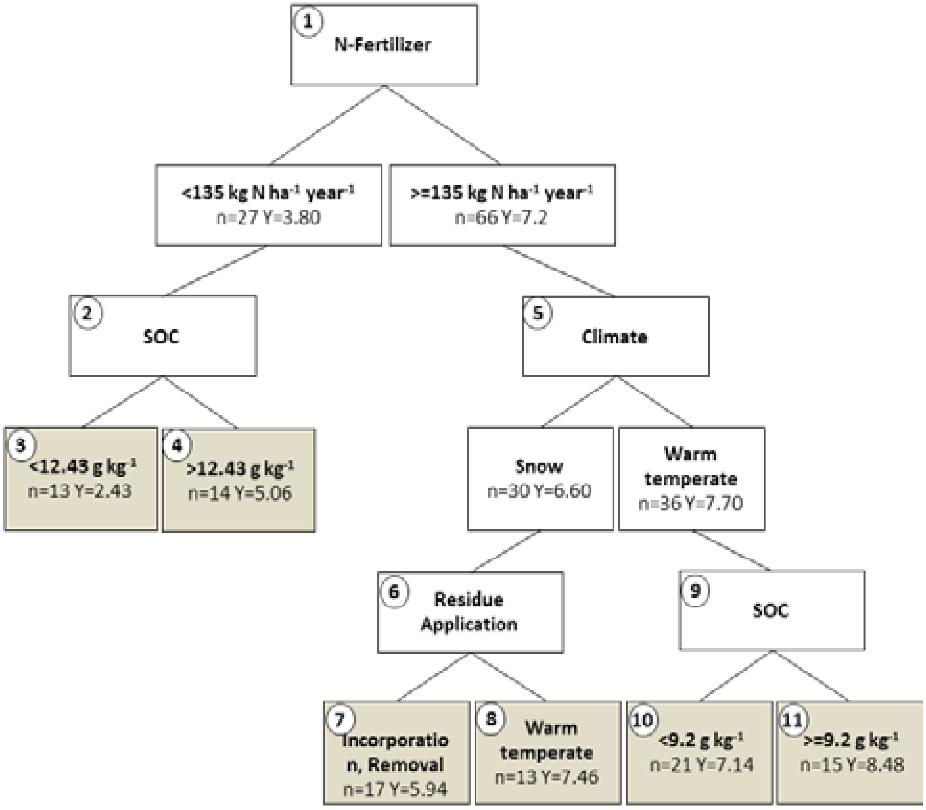


In temperate environments, N-fertilization represented the first splitting factor (Figure 15, node 1). When large N-rates (more than 135 kg of N ha^{-1} year^{-1}) were applied, data were divided according to climatic area: warm temperate and snow (Figure 15, node 5). In the former climatic regions, a SOC concentration higher than 9.2 g kg^{-1} increased maize yield on average by more than a tonne compared with lower SOC concentration (Figure 15, node 7 and 8). Maize yields varied between 6.5 to 11 t ha^{-1} year^{-1} and between 5.5 and 8.5 t ha^{-1} year^{-1} in soils with higher (n=15) and lower (n=21) concentration, respectively (Figure 15, node 10 and 11).

In snow climatic locations, yields were affected by crop residues management (Figure 15, node 6, 7 and 8). Mulch was associated with higher productivity, with mean maize yields equal to about 7.5 t ha^{-1} year^{-1} (Figure 15, node 8), compared with the 6 t ha^{-1} year^{-1} recorded in treatments with residues removed or incorporated (Figure 15, node 7). However, both categories showed wide variation: from 3 to 9.5 t ha^{-1} year^{-1} for mulch applications and from 3 and 8.5 t ha^{-1} year^{-1} in the case of residues removal or incorporation.

FIGURE 15.

Regression trees for maize yields in temperate environment (n=93). Y represents average maize yields values expressed in t ha^{-1} year^{-1}, dark coloured box indicates the terminal nodes of the tree.



In farming systems where N was applied at a lower rate than 135 kg of N ha^{-1} year^{-1}(left split), soils with a SOC concentration less than about 12.5 g kg^{-1} showed the lowest yield records: an average yield of about 2.6 ha^{-1} year^{-1} and a range between 0.8 and 4.5 t ha^{-1} year^{-1} (Figure 15, node 3). On the contrary, a higher SOC level almost doubled maize production (Figure 15, node 4)

3.4.4 PCA for wheat yields

PCA using wheat yield data was performed to identify the main variables which defined yields. Maize yields were correlated with N-fertilization and they appeared to be independent by SOC concentration. However, given that many PCs were needed to explain a high proportion of variance, PCA did not allow to draw strong conclusions. A detailed explanation of the results and their interpretation from the PCA on maize yield data is reported in Appendix Vb.

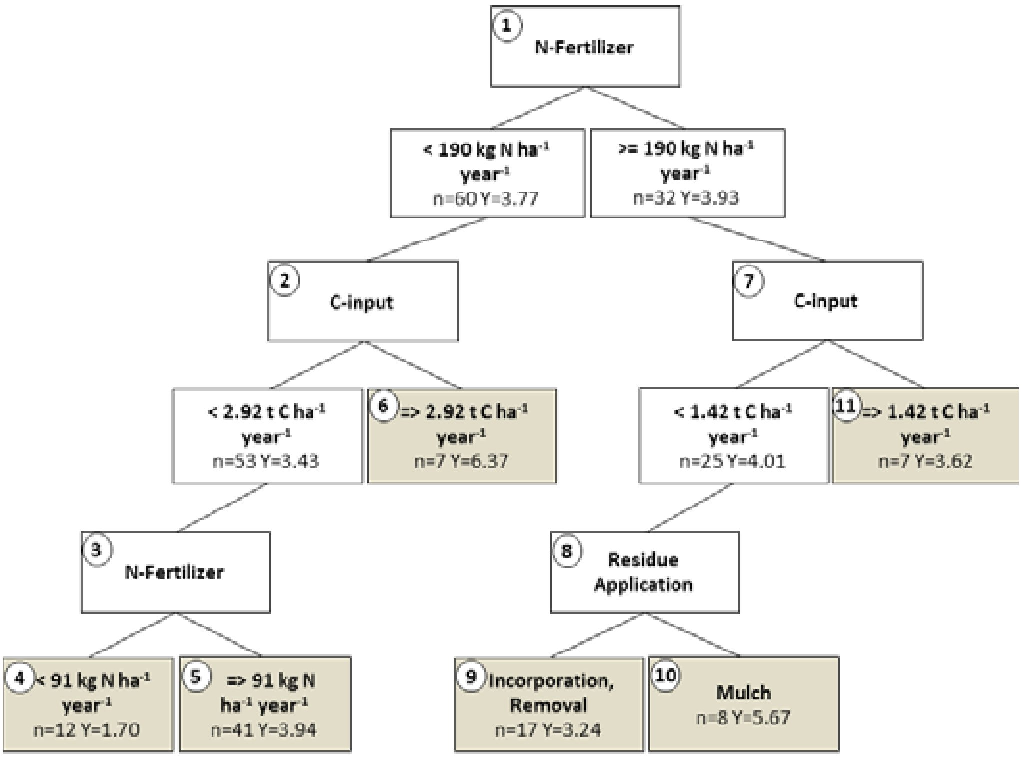
3.4.5 Regression trees for Wheat Yields

Wheat yields in tropical climates were primarily affected by N-fertilizations and secondly by C-Input (Figure 16, node 1,2 and 7). With N-application higher than 190 kg of N ha^{-1} year^{-1}, data were further divided depending on the amount of C added through residues, with 1.42 t of C ha^{-1} year^{-1} being the cutoff point (Figure 16, node 7). When a lower C amount was added, a differentiation was made between residues incorporation or removal and mulch (Figure 16, nodes 8, 9 and 10). In the case of residues removal or incorporation (n=17), mean yield was about 3.2 t ha^{-1} year^{-1}, and the dataset was characterized by a marked variation with yield oscillating between 1 and 11.5 t ha^{-1} year^{-1}(Figure 16, node 9). In mulched soils (n=8), yields were much higher with mean values of about 5.7 t ha^{-1} year^{-1} and a range between 2 and 6 t ha^{-1} year^{-1}(Figure 16, node 10).

In production systems, where less than 190 kg of N ha^{-1} year^{-1} were applied (left split), the amount of C-input determined the next node but the cutoff point was greater than in high N-fertilized systems (Figure 16, node 2). In fact, when more than 2.9 t of C ha^{-1} year^{-1} were retained on farm, yields improved, though this category was based on just seven observations (Figure 16, node 6). With lower addition of C, N-rate was again crucial in determining yields (Figure 16, node 3). Specifically, average yield associated with N-fertilizations greater or equal to 91 kg of N ha^{-1} were about 4 t ha^{-1} year^{-1}, whereas at lower N-rate yield dropped dramatically with average values equal to 1.7 t ha^{-1} year^{-1} (Figure 16, nodes 4 and 5). Nevertheless, the former category was determined by 41 observations and yield variation was much higher (between about 1 and 6 t ha^{-1} year^{-1}) compared with the latter one (between about 1.2 and 3 t ha^{-1} year^{-1}) which included 12 observations.

FIGURE 16.

Regression trees for wheat yields in tropical environment (n=92). Y represents average wheat yields values expressed in t ha^{-1} year^{-1}, dark coloured box indicates the terminal nodes of the tree.

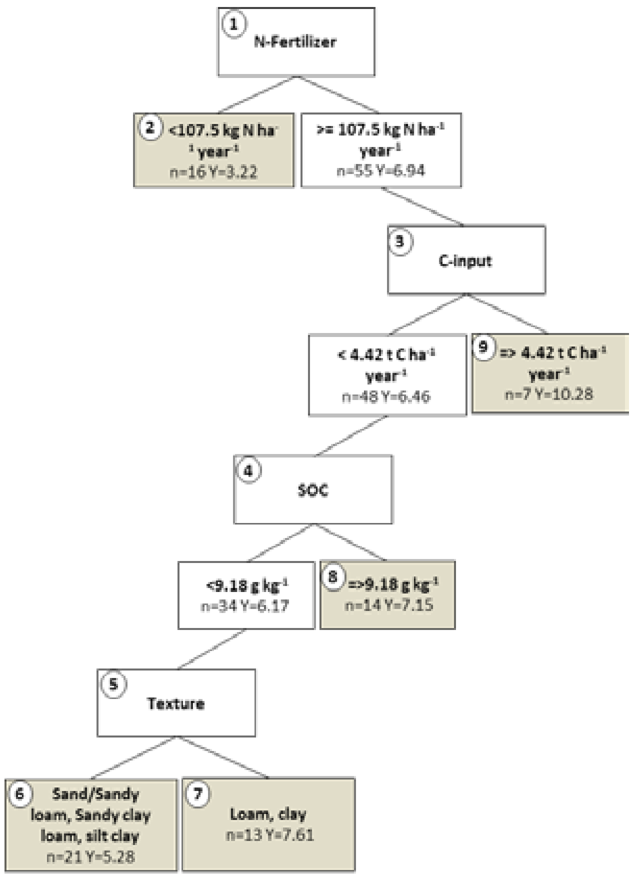


Also in temperate climatic areas, the effect of crop residues management on wheat yields was subordinated to N-application. N-fertilization (Figure 17, node 1) determined the first split with 107 kg of N ha^{-1} year^{-1} being the cutoff point. At higher N-rate (right split), data were categorized according to C-Inputs (Figure 17, node 3). When a substantial amount of C was retained on farm (C-inputs more than 4.42 t of C ha^{-1} year^{-1}), yields were the highest registered with an average value of about 10.3 t ha^{-1} year^{-1} (Figure 17, node 9) and a range between 7 and 14 t ha^{-1} year^{-1}. However, only seven observations determined this category. At lower C-applications SOC played a role (Figure 17, nodes 4 and 8). In soils with SOC concentration lower than about 9.2 g kg^{-1}, soil texture determined the last split, identifying loam and clay soils more yielding than coarser soils (Figure 17, nodes 5, 6 and 7).

When N-applications were lower than 107 kg of N ha^{-1} year^{-1} (left split) wheat yields were the lowest recorded in the database, with an average value of about 3.2 t ha^{-1} year^{-1} and a range between 1 and 4 t ha^{-1} year^{-1}(Figure 17 node 2).

FIGURE 17

Regression trees for wheat yields in temperate environment (n=71). Y represents average wheat yields values expressed in t ha-1 year-1, dark coloured box indicates the terminal nodes of the tree.

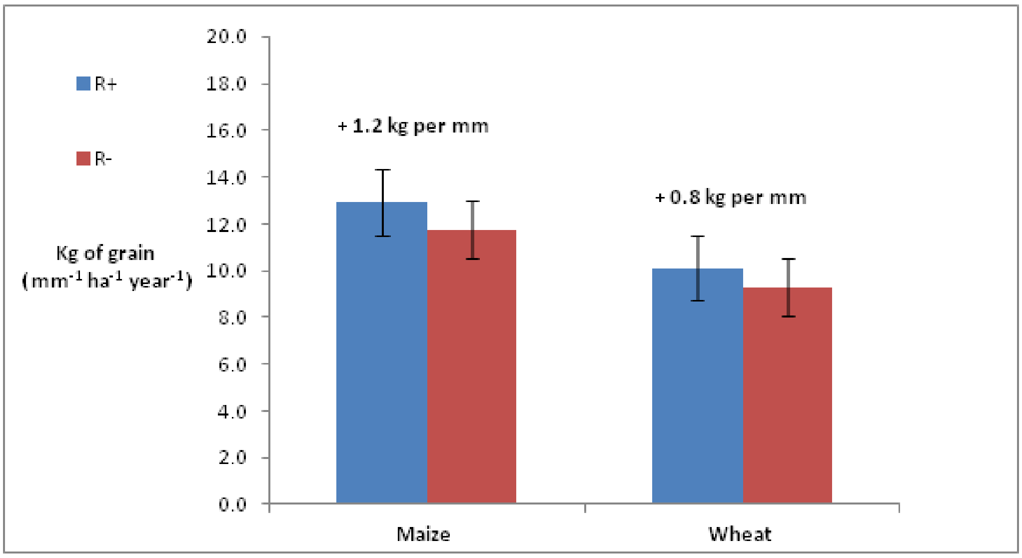


3.4.6 Crop residues effects on Water Productivity (WP)

Figure 18 shows the average WP for maize and wheat. In this case, rice was excluded from the analysis since paddy rice data might bias results. Overall, maize had generally higher water productivity than wheat and crop residues management influenced WP in both crops. Figure 18 illustrates that residues application (R+) increased WP compared with residues removal (R-). In fact, an additional millimetre of rainfall increased yield by 1.2 and 0.8 kg ha^{-1} year^{-1} in maize and wheat fields, respectively.

FIGURE 18.

Average WP for tropical and temperate climates according to residues retained (R+) and residues removed treatments (R-). Error bars denote standard error (n=438).

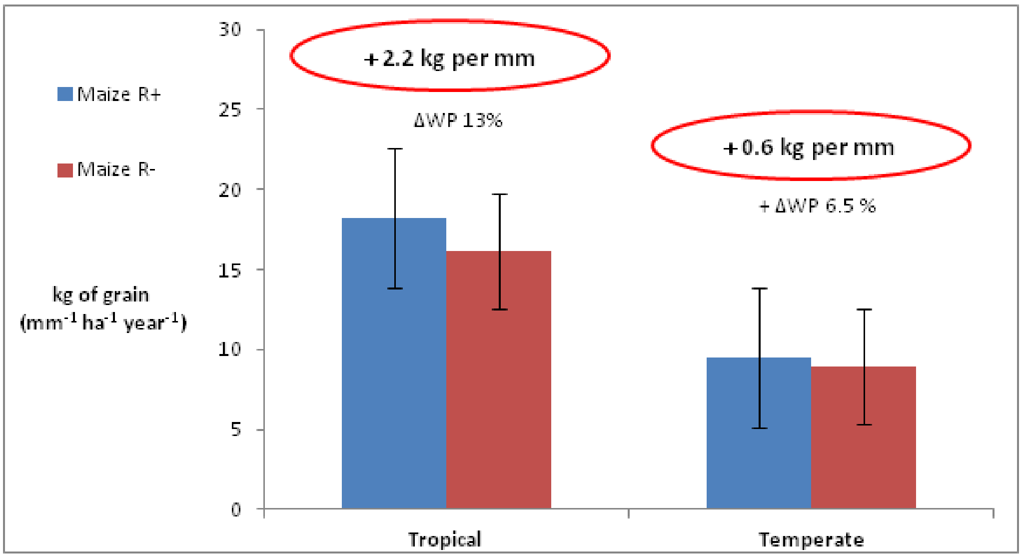


The following analysis focused on maize, as this crop is cultivated in wider climatic conditions and farming systems compared to wheat. In fact maize is the main food and cash crop in many arid and equatorial regions as well as an important cereal in temperate climate, where it is intensively cultivated. This is also evident in the database, where observations on maize yield in tropical environments were fairly balanced between arid and equatorial climate. By contrast, just two observations reported data on wheat yields from arid areas.

The effect of residues application on maize WP appeared to be more significant in tropical than in temperate climates (Figure 19). Specifically, residues application increased maize yield on average by 0.6 and 2.2 kg of grain per additional mm ha^{-1} year^{-1} in temperate and tropical areas, respectively. The same trend was observed when considering relative values, with ΔWP being double in tropical compared with temperate areas.

FIGURE 19.

Average maize WP for tropical and temperate climates according to residues retained (R+) and residues removed treatments (R-). Error bars denote standard error (n=232).



CHAPTER 4

DISCUSSION

The influence of crop residues on soil organic carbon (SOC) has been identified as a key factor to mitigate climate change and sustain soil fertility (Lal, 2013), and one that must be carefully considered when defining sustainable removal rates for biofuel production (Johnson et al., 2014; Kludze et al., 2013). An extensive review of the scientific literature published during the last decade was conducted to compile quantitative evidence on the effects of crop residue management (incorporation in soil, removal, mulching) on SOC, on two selected soil physical properties and on crop yields. A large meta-database was thus obtained and analysed using descriptive and multivariate statistics and data mining techniques to investigate in which contexts and under which conditions, crop residue removal may negatively affect soil carbon, physical properties and crop yields. The ultimate goal is to provide a knowledge base to develop sustainable crop residues management strategies for food and energy production.

The scientific literature on the topic published during the last ten years is broad. Yet only 90 publications focused exclusively on the effect of different residue management practices on SOC and crop yields. The majority of the papers, rather, investigated the impact of conservation agriculture [5]and no tillage, in which crop residues retention on the soil surface is but one practice within a broader technological package (Kassam et al., 2010 and 2009; FAO, 2008). A greater effort has been invested to study these effects during the last decade in Asia (particularly in India and China), Africa and North America as compared to Latin America, Europe and Oceania. Nevertheless, is possible that relevant data were collected before 2003, especially in trials exploring crop residue effects on cropping system performance associated with conservation agriculture. Derpsch et al. (2010) supported this hypothesis. In US the first experiment was carried out in the 1940's and in the 1970's in Argentina and Brazil. The trials and the success of adoption of conservation agriculture has been moderate in EU, while it has been larger in Oceania, especially in Australia, in the last few years (Derpsch et al., 2010). In China, residue management and no tillage practices have been studied more frequently in the last decades and total area under conservation agriculture has considerably increased in the last few years. The same trend was observed in Africa (Derpsch et al., 2010) where it has been intensively promoted, not without criticisms (e.g., Giller et al., 2009).

5 FAO indicates Conservation Agriculture as an approach to managing 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 main principles: (i) minimum soil disturbances, (ii) permanent organic soil cover and (iii) diversified crop rotations. (http://www.fao.org/ag/ca/).

4.1 EFFECT OF CROP RESIDUE MANAGEMENT ON SOC

Soils are regarded as a valuable sink for atmospheric C, and the addition of C via crop residues as an effective and inexpensive mean to increase SOC (Lal, 2004). Overall, our compilation of cases from around the world shows that residue removal decreased SOC by 13 percent on average (Figure 5), but such response was characterized by a marked variation, as recently reported also by Liu et al. (2014). This agrees with previous studies suggesting that the net increase of SOC via crop residue retention, which is governed by different factors, is largely site dependent (Badía et al., 2013; Leal et al., 2013; Nayak et al., 2012; Blanco-Canqui & Lal, 2007). Such factors include: soil type (parent material, texture, depth, topographic position, drainage, original vegetation, etc.), soil initial status (degraded vs. non-degraded, soils newly opened for cultivation vs. soils with a long history of cultivation, etc.), climate (especially the ratio between rainfall and temperatures throughout the year), land use and management (cropping systems, rotations with grasslands or other perennial crops, fertilizer use, irrigation, etc.), and the time horizon being considered (i.e. we analysed studies ranging from 1 to 55 years in length).

Different studies that investigated the effect of residue retention on SOC through different time horizons reported a general increase in SOC, although the actual rate of increase varied considerably according to the initial SOC content and the soil C saturation limit of each particular soil (Liu et al., 2014; West & Six, 2007; Akala & Lal, 2000). Liu et al. (2014) found that the response ratio of SOC to straw applications was negatively related with the initial SOC as: (i) soils with low initial SOC have faster accumulation in the first's years and that (ii) these soils have longer SOC response to residues application, as more time is needed for the soil to get C saturated (Liu et al., 2014; West & Six, 2007). Considering Figure 5 in the present study, one can argue that SOC decreased constantly throughout the years when residues were removed compared with treatments in which they were retained. However, it has been shown that SOC decreases at high rates immediately after a profound change in land use or management, at gradually slower rates in the long run, and stabilizes when a new equilibrium is reached (David et al., 2009; Lugato et al., 2006; Arrouays & Pelissier, 1994). West & Six (2007) applied this concept also to SOC accumulation and saturation, suggesting that different soil management practices can actually contribute to defining new equilibria, increasing attainable SOC saturation (West & Six, 2007; Ingram & Fernandes, 2001).

Soil texture is an important determinant of the capacity of soils to store carbon, with higher silt and clay fractions corresponding with higher SOC contents (e.g., Feller & Beare, 1997), as also seen in this study (Figure 6 and 7). The silt and clay concentration plays an important role in the SOC turn over 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 (Bationo et al., 2007; John et al., 2005; Six et al., 2002; Ingram & Fernandes, 2001; Hassink, 1997). Furthermore, finer soil particles are associated with higher water retention in soils that, particularly in arid climates, enhances biomass production and ultimately increases the availability of soil C inputs from roots and aboveground residues (Kong & Six, 2010). Yet a marked variation was observed in SOC contents within texture classes (cf. Figure 6). This variation can be explained by different farm management, climatic conditions and type of clay mineral (Six et al., 2002; Hassink, 1997).

The same reasons may contribute to explain the variability found in Figure 8, which showed that the apparent humification index (AHI), a measure of changes in SOC relative to the total input of C to soil with crop residues, tended to be higher in finer textured soils. Greater values of AHI could be related to the higher capacity of silt and clay particles to protect SOC from mineralization. However, Liu et al. in 2014 reported that the variation in SOC caused by crop residues application had a negative relationship with clay content. According to the authors, the degradation rate of freshly added OM was significantly lower at high clay concentrations, resulting in a lower amount of humified SOC (Liu et al., 2014).

Climatic factors, which govern SOC decomposition, were the next in explaining the variability observed in crop residue effects on SOC. Because of this, the classification and regression tree (CART) analyses were run separately for two subsets of data, corresponding to studies from tropical (equatorial and arid climate) and temperate (warm temperate and snow climate) regions. SOC levels were on average lower in tropical than in temperate regions due to the faster turnover of the organic matter in tropical compared with temperate soils. Higher soil temperature stimulates the activity of the microbial biomass which lead to higher decomposition rate of the organic material, compared with temperate environments (Garten, 2011; Franzluebbers et al., 2001; Ingram & Fernandes, 2001). The effect of crop residue management on SOC appeared to be subordinated to climate and texture in tropical environment with much stronger influence on SOC dynamics in coarser soils (Figure 10). Conversely, in temperate regions crop residue management appeared to have a greater influence on SOC followed by soil texture and N-fertilization (Figure 11).

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 (Bationo et al., 2007). In such contexts, crop residues not only represent a source of organic carbon to soil, but their retention is also an effective means to reduce SOC losses induced by wind or water erosion, and mitigate soil temperature to reduce organic matter decomposition (Blanco-Canqui, 2013). According to CART analysis, threshold levels of 2.5 and 1.5 t of C ha^{-1} $year^{-1}$ applied in crop residues were needed to minimally maintain SOC in arid and equatorial tropics, respectively (Figure 10). Although this is reasonable given the climatic and edaphic conditions that limit SOC stabilization in this climatic area, the application of such amounts of C inputs seems unrealistic in smallholder tropical farming systems from these regions. In fact more than 3 and 5 t ha^{-1} $year^{-1}$ of maize stover would be needed to satisfy such C requirements. This is barely available in these areas, where biomass productivity is often low and competing use of residues exists (Valbuena et al., 2012).

In finer soils in arid climates the way in which crop residue were applied affected SOC concentration. Although this category consisted in few observations, mulching corresponded with greater SOC concentrations as compared with residues incorporation or removal (Figure 10). This may be related with the capacity of the mulch layer to decrease soil temperature, hence, moderating soil organic matter decomposition (Bationo et al., 2007; Subke et al., 2006).

In temperate areas the application of large amounts of crop residue (more than 5 t of C ha^{-1} $year^{-1}$, which translates in about 10 t of crop residue ha^{-1} $year^{-1}$) was associated with higher SOC (Figure 11), though, this category was based on few observations. A study carried out in three sites in Ohio confirmed these foundlings, reporting that the amount of residues left on the soil surface was significantly related with SOC (Blanco-Canqui & Lal, 2007). Additionally, mulching appeared to be effective in increasing SOC at a C-input application rate lower than 5 t of C ha^{-1} $year^{-1}$. This can be particularly valid in erosion prone sites, where mulching forms a physical barrier against SOC losses (Osborne et al., 2014; Blanco-Canqui & Lal, 2007).

In the CART of both tropical and temperate subsets the analysis discriminated mulched soils from soils in which residues were either incorporated or removed, with the former group presenting higher SOC contents (Figure 10 and 11). Previous studies reported higher SOC when residues were left on the soil surface compared with unmulched soils, both in temperate and tropical climates (Dai et al., 2013; Ram et al., 2013; Wuest & Gollany, 2013; Loke et al., 2012; Blanco-Canqui & Lal, 2007). 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. (2014) reported a slightly higher effect on SOC when residues were incorporated than when kept as mulch, whereas Virto et al., (2012) indicated C-input to be the main factor explaining 30 percent 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 (Figure 10); whereas, in temperate regions the effect of N-fertilizer use was subordinated to the effect of crop residue management (both application method and actual rate) and texture. The role of N in increasing SOC is related with the increase in above- (and secondarily below-) ground biomass and therefore it depends on the actual N-rate applied and on the initial N availability in the soil (Brown et al., 2014; Gong et al., 2012; Tang et al., 2012; Dalal et al., 2011; Allmaras et al., 2004). When the N is available in the soil, any additional units of N has little effect on biomass production and ultimately on SOC. Conversely in N-limited systems, N-application increases biomass production significantly, which translates into larger amounts of crop residues produced that may input greater amounts of C to the soil (Brown et al., 2014). The unclear results displayed in Figure 10 and 11 can, therefore, be caused not only by the uneven sample size of the two categories, but also by different initial soil N-pools.

4.2 EFFECT OF CROP RESIDUE MANAGEMENT ON SOIL PHYSICAL PROPERTIES

Soil bulk density, calculated as the ratio between soil mass and total soil volume including voids, represents a proxy for soil porosity (water holding capacity, soil aeration) and compaction. Although only 17 papers reviewed provided these data, this study showed that crop residue application decreased soil bulk density – increased porosity – compared with residue removal (Figure 12). Several studies reported similar findings (Reijnders, 2013; Naresh, 2013; Thangarajan et al., 2013; Blanco-Canqui & Lal, 2007; Mohanty et al., 2007). Residue retention generally decreases bulk density especially when applied as mulch as it: (i) protects soils from the compaction force of raindrops which may seal the superficial soil layer, (ii) enhances earthworm activity and density, and (iii) provides OM which is considerably lighter (lower density) than the mineral soil fraction (Blanco-Canqui & Lal, 2009). Blanco-Canqui et al. (2009) reported that bulk density changes as a response to residues application were smaller in clay soils. In addition, the same authors argued that at higher residues application rates the resilience of soils to soil compaction forces increased. In this study, it was expected to find a trend in which coarser soils would exhibit greater changes in bulk density than fine textured soils. Data on clay soils had the lowest variation in bulk density following residues application. However, no clear trend in soil bulk density variation following residue application was observed according to soil texture (Figure 12). The limited amount of data for some of the soil texture classes may be responsible for this.

Aggregation of soil particles is widely recognized as a reliable indicator to assess soil structure. In this study, a subset of data was created with the papers that reported specifically on the effect of crop residue application on aggregate size distribution (n = 43 cases), but the data analysis did not reveal any clear trend. The literature shows soil structure to vary strongly across climatic conditions, SOC contents, soil texture, clay mineralogy, soil management and biotic influences by plants and microorganisms (Gentile et al., 2013; Pulido Moncada et al., 2013; Bronick & Lal, 2005). Soil structure is a crucial factor in maintaining plant growth and soil functioning which mediates essential soil and plant processes such us soil water movement and retention, root growth, nutrient uptake, gas exchange (Martens, 2000). Crop residue application was reported to affect soil structure through its effect on (i) the regular supply of organic matter (Reijnders, 2013), (ii) the provision of binding agents, such us humic compounds, polysaccharides, organic mucilage (Martens, 2000), (iii) the supply of degradable material and energy for the metabolic activity of soil biota which contributes further to the formation of organo-mineral particles and endorses their aggregation (Lal, 2009). Furthermore, when considering aggregation the role of tillage is crucial as it induces a decrease in C-rich macro aggregates in favour of C-depleted micro aggregates (Six et al., 2002).

4.3 EFFECT OF CROP RESIDUE MANAGEMENT ON CROP PRODUCTIVITY

Overall, crop productivity[6] was on average 8 percent lower when crop residues were removed than when they were retained (Figure 13). This result is consistent with the study of Liu et al. (2014) who found crop yields to increase by 12.3 percent when straw residues were retained. According to these authors, such increase was determined by the capacity of crop residues to enhance soil nutrient pool, increase soil water availability, and improve physical and biological soil fertility (Liu et al., 2014). Yet the effect of crop residue management on crop yield varied widely across crop types. This variability suggests, again, that the impact of crop residue management on crop yield depends on factors such us soil type, agricultural management, topography and climate (Huang et al. 2013)

Yields recorded in temperate regions were, in general, less sensible to crop residue removal than in tropical areas. A possible explanation can be found in the large use of external inputs which characterized temperate farming systems (Vitousek et al., 2009). By contrast, in tropical systems low external input agriculture dominates crop production (Vitousek et al., 2009). In this context crop residue management can have a crucial role in determining yields, as this represents a valid and cost effective mean to reduce soil erosion, increase water storage and improve the availability of nutrients (Branca et al., 2013; Rezig et al., 2013; Scopel et al., 2004). Particularly in dry areas, where water availability strongly limits crop productivity, the effects of residues retention, especially when applied as mulch, is more pronounced and can contribute to stabilize yields over time (Okeyo et al., 2014; Scopel et al., 2004; Tolk et al.,1999).

4.3.1. Effect on maize yields

Maize is the main food and cash crop in many tropical farming systems characterized by erratic rainfall patterns. In these systems, plant water availability is amongst the most important factors determining crop productivity, hence, the variation in seasonal rainfall represents a major factor responsible for yield fluctuations that can explain the wide variability displayed in Figure 13 (Rusinamhodzi et al., 2011). Following the effects of climate and soil type, the amount of organic C-inputs played an essential role in determining maize yields in tropical environments (Figure 14). Specifically, results showed that the application of about 50 kg ha^{-1} $year^{-1}$ of C (roughly about 100 kg of crop residues ha^{-1} $year^{-1}$) via crop residues can sensibly increase maize productivity in coarse soils (Figure 14). Abdourhamane Toure et al. (2011) 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 (Buerkert & Hiernaux, 1998). 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

6 Strictly speaking, although the intention was to examine effects on crop productivity, most studies reviewed presented only one or a few years of yield data; for this reason, the analysis often refers to yields and only to productivity when yields are the average value of a number of years.

infiltration and reduced runoff), thereby enhancing maize yields (Scopel et al., 2004). This is in agreement with the results presented in Figure 18 and 19. They demonstrated that water productivity was generally higher in the case of residue retention compared with residue removal. Moreover, the increase in water productivity brought about by crop residue retention doubled in the tropics compared with temperate climates.

Unexpectedly, C-input or residue retention did not appear to be among the main maize yield determinants in arid climates. 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, where the availability of crop residue biomass may be insufficient to bring the desired effects on water storage (Figure 14).

Mulching was associated with greater maize yields in snow climates at high N-fertilization rates (Figure 15). No strong evidence supporting this trend was found in the literature. Although mulch is effective in reducing erosion, it has been reported to also increase risks when coolest soil temperatures occur in spring and to maintain the topsoil excessively wet. The combination of these two factors can hamper seed germination and emergence, thereby affecting yields (Blanco-Canqui & Lal, 2009 and 2007; Dam et al., 2005). This appeared to be valid especially in glaciated soils, so that the favourable effects of crop residue retention are more pronounced in excessively drained and erosion-prone soils rather than in deep, clay and glaciated soils (Humberto Blanco-Canqui & Lal, 2007).

SOC appeared to be an additional important factor in defining maize yields in temperate region (Figure 15). In maize production the cutoff point was about 12.5 and 9 g kg^{-1} at N-rate lower than 135 kg of N ha^{-1} $year^{-1}$ and in warm temperate climate at higher N-rate, respectively. Both these cutoff points were considerably low, according to EU which identify poor SOC soils at lower concentration than 20 g kg^{-1} (EU, 2012; Van-Camp et al., 2004). The increased yields related to higher SOC concentration is associated with the capacity of SOC to provide a wide range of benefits for crop production and ecosystem stability including improved water and nutrients retention, appropriate soil structure, higher soil biodiversity, enhanced yield response to fertilizers and protection from sediment losses (Lemus, 2013; Anderson-Teixeira et al., 2009; Tilman et al., 2009).

One should take into account that many of the data on maize production from mulched soils located in temperate climates come from conservation agriculture fields. Especially in the US more than 13.5 million ha of maize (40 percent of the total maize production) are farmed under conservation tillage (>30 percent residues retained) and 8 million ha of maize (24 percent of the total maize production) under reduced tillage (15-30 percent of residues retained)(CTIC, 2008). This can explain both the wide variation found in this dataset and the higher yields recorded for mulched soils. In CA cropping systems crop residue application is coupled with massive external inputs (fertilizers, pesticides, herbicides) and minimum soil disturbance. Therefore, it is possible that the increase in maize yield attributed to mulched soil in Figure 16 is actually given by the higher intensity of these cropping systems rather than solely by residues application.

4.3.2. Effect on wheat yields

On average, wheat in temperate areas did not yield appreciably more when crop residues were retained as observed in tropical environments (Figure 13). This is consistent with the results of other studies reporting from Ireland (Brennan et al., 2014) and Pakistan (Bakht et al., 2009). 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 to 550 mm year^{-1} and where average temperature was 22.7°C (Mj. Iqbal & Quamar, 2011), yields increased by 30 percent times as a response to crop residue retention.

Organic C-inputs via crop residue application were important yield determinants immediately after N-fertilization in tropical wheat production (Figure 16). The combination of N-input (lower than 190 kg of N ha^{-1} year^{-1}) and crop residue retention led to double wheat yields in the tropics (Figure 16). Although this category was based on a few observations, coupling N-fertilization with organic amendments has been shown to be extremely effective in increasing yields, especially in tropical soils (Gentile et al., 2013; Chikowo & Mapfumo, 2004; Breman et al., 2001). Crop residue retention ameliorates physical and biological soil fertility, while fertilizers guarantee an optimal nutrient pool minimizing the risk of N-immobilization (Gentile et al., 2013). At really high N application rates (more than 190 kg of N ha^{-1} year^{-1}) the size of C-inputs and then the method of crop residues application were crucial for wheat production. However, extremely high N-rate and C-input did not result in greater yields (Figure 16), whereas with smaller amounts of crop residues available, mulching led to the highest wheat yield, 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 (Figure 16).

Wheat yield was also affected by SOC concentration in temperate regions. SOC concentrations lower than 9 g kg^{-1} appeared to be a limiting factor for wheat productions when N-fertilization was higher than 107 kg of N ha^{-1} year^{-1} and at C-input application lower than 4.5 t of C ha^{-1} year^{-1}(Figure 17). Therefore, at low N-applications N was clearly the factor that limited wheat yields. Once the N-pool was enriched by N-application the role of SOC on soil biological, chemical and physical fertility became crucial to maintain wheat yields.

4.3.3. Effect on rice yields

Rice yields tended to be affected by crop residue management in both climatic areas, with yields that were on average 16 percent (±20 percent) lower when crop residues were removed (Figure 13). Results obtained by Huang et al. (2013) confirmed these findings. The authors investigated the effect of crop residue management on rice yields in China, reporting that residue retention increased grain production by 5.2 percent on average. Crop residue management appeared to be more effective in warmer regions; as yields increased by 3.3 and 6.7 percent in areas with an average annual temperature between 10-15 and 15-20°C, respectively (Huang et al., 2013). It should be noticed, however, that the dataset on rice consisted of a much smaller number of observations than those on maize and wheat (Figure 13).

CHAPTER 5

CONCLUSIONS

The analysis of more than 1 000 scientific papers published in the last decade on the effects of crop residue management on soil organic carbon, soil structure and crop yields has led to the following major conclusions:

1. The removal of crop residues after harvest decreased SOC contents; the rate at which SOC decreased was determined by complex interactions of topography, management and climate, so it appeared to be site-specific. Crop residue addition to soil stabilized SOC in temperate and tropical areas. In tropical climates the actual C-input rate was crucial in sustain SOC in coarse soils, regardless of the way crop residue were applied. In temperate climates large crop residue application was associated with higher SOC concentration, while at a more moderate C-input rate mulching had a positive impact on SOC before texture and N-fertilization.
2. The retention of crop residues after harvest decreased soil bulk density, thereby increasing soil porosity and reducing or avoiding soil compaction. The analysis of the data available did not allow quantifying the impact of crop residue management on soil aggregation, in spite of what is shown in the relatively small number of published studies reviewed.
3. Crop yields were affected by crop residue removal at varying degrees, depending on crop species and on the climatic region considered. In tropical environments, crop residue retention was associated with higher maize and wheat yields. Such higher yields were not necessarily the result of increases in soil carbon; they appeared to be directly influenced by crop residue retention, due to their capacity to improve soil water dynamics in erratic rainfall locations and enhance the soil nutrient pool. In temperate environments, low yields were associated with low SOC concentrations.
4. The different magnitude in which crop residue retention affected SOC and crop yields suggested that their management has to be contextualized. In the tropics, particularly in coarse soils located in arid areas, crop residue removal is not recommended, as this will decrease soil fertility and negatively impact yields. In temperate areas, mulch application should be preferred and crop residue removal should be avoided in soils that are depleted or show inherently low levels of carbon and nutrients. Partial crop residue removal can be considered in this climatic area when soils are well endowed in carbon and nutrients. The appropriate rate of residue removal must be studied carefully to avoid soil depletion and loss of soil physical quality in the mid- to long-term.

5. The classification and regression tree analysis was a valuable statistical means of unravelling the interacting effects of the various factors mediating the impact of crop residue management on soil carbon, soil structure and crop yields. Homogeneous groups of cases were built out of a very heterogeneous data population. Yet little can be said about the actual mechanisms involved at this level of analysis. In-depth studies combining field trials, measurements and simulation models are needed to provide more accurate estimates; specifically, trials that disaggregate the effect of crop residues from the effect of the other components of technological packages such as conservation agriculture.
6. Finally, this study presented preliminary results on the importance to contextualize crop residue management and related policies. Effective agricultural and biofuel management cannot neglect the essential role of crop residues on agro-ecosystems and food security. To achieve this, future policies must consider ecological and management constraints, in order to advance sustainable agricultural and the biofuel sector. In this context, the regression trees presented in this study can be integrated with findings from other research investigating the other components which define the effects of crop residue management on food security. Such integration can represent a solid basis to build an effective decision support tool for sustainable crop residue management.

CHAPTER 6

AREAS FOR FURTHER WORK

6.1 IMPROVING REGRESSION TREES ON THE EFFECT OF CROP RESIDUE APPLICATION ON SOIL QUALITY AND YIELDS

This study analysed a large database from a wide diversity of farming systems located in diverse climatic, soil and topographic conditions. One of the aims was to cover to the extent possible the diversity of soils and cropping systems worldwide. Although the analysis was extensive and robust from a quantitative perspective, it was quite 'shallow' when it came to explaining the processes behind the soil mechanisms that underpin the main findings. This was also evident from the principal component analysis both of SOC and yields (Appendix II and VI). From this level of analysis, with the high variation (determined by climatic, management and topographic factors) that characterized the dataset, it was not possible to draw strong conclusions on the relationship between crop residue management, soil fertility management and crop production. For example, the keywords used to retrieve literature and data from published studied led to a limited set of publications reporting on the effect of crop residue management on bulk density and even a lower number for soil aggregation. Perhaps more evidence could be retrieved using other, more specific key words for these soil properties and other processes influenced by crop residue management: the impact of crop residues on erosion, nutrient balances, soil temperature, to name just a few. The same could be done for different crops. The availability of several databases for each of the diverse processes triggered by crop residue application would lead to an improved understanding of this practice on agricultural land and production. Consequently this would provide a better contextualization of the roles of crop residue in different agro-ecosystems.

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 when calculating the total amount of C added to soil via crop residues. Both C concentration and HI vary according to management and ecological characteristics (Wilts et al., 2004; Hay, 1995). Furthermore, the quantification of carbon inputs to soil considered only the aerial plant biomass – straw or stover – while carbon inputs from below ground biomass – roots – was not considered. The few publications that measured SOC originated from root biomass using 13C techniques, reported that C inputs from below ground biomass can be substantial. For instance, in a maize corn field in the USA, roots contributed between 22 and 40 percent of the total SOC (Collins et al., 1999). Kong & Six, (2010) using 13C marking estimated that 52 percent of the maize root C remained in the soil after one year, while only 4 percent of the C was incorporated in the soil with crop residue biomass, suggesting much faster rates of decomposition of the latter. A recent study reported that, although roots produce less biomass, they can contribute equally to shoot on SOC enrichment, due to the higher content in recalcitrant compounds (Comeau et al., 2013). As root biomass is also affected by N-fertilization, the effect of this practice on SOC accumulation stabilization observed in this study could be overrated.

6.2 FURTHER STEPS FOR A COMPREHENSIVE DECISION SUPPORT TOOL

1. This study represents a first step towards the development of a decision tree for sustainable crop residue management. Only the effects of crop residue management on soil quality and crop production were presented. On that basis we have developed a first approximation of decision trees for the different aspects that have been assessed through regression trees. This is presented in Appendix VII. However, they should be considered only as a preliminary step towards a more comprehensive and valid decision approach, and therefore should not be used for decision-making. This is because many other aspects have to be considered to design a comprehensive decision support tool for crop residue management such as:
2. A typology of different residue types, aimed to identify those whose use is not that performant in terms of soil management or animal feed, and therefore could be prioritized for bioenergy production. Such differentiation would include crop/wood residues, between primary (harvesting)/secondary (processing) residues; this will ultimately determine which types can be used or should be prioritized for different purposes. The typology will show which residues are readily available and free for use (e.g. those that are currently burnt) and which are already being used.
3. A prioritization of the different competing uses of crop and wood residues between the agricultural, livestock, bioenergy and other sectors and how they are related to the four pillars of food security. This will require intensive data collection, both through further literature reviews and site-specific field testing. This work should be focused further on local decision-making processes, including trade-off maps and agent-based systems.
4. An analysis of the logistics involved, as this is often a major constraint in the feasibility of residue use when it implies transportation within diverse supply chains. Although this aspect does not relate directly to food security concerns of residue projects, it does determine their viability in the first place.

The possibility of using residues for bioenergy purposes and reintroducing the obtained by-products from such processes (i.e. biochar) in agricultural soils or as animal feed (as suggested by well-known concepts such as circular agriculture or cascading use of biomass). Where ecological and management constraints discourage residue removal, this can be particularly important. In such context, it would be useful to understand if and at what degree, the incorporation of valuable by-products (i.e. for SOC and nutrients) from bioenergy production processes might offset the negative impact on soil fertility and crop production of residue removal.

Such an in-depth analysis of the main uses and their possible synergies and trade-offs are needed to provide robust information crucial to develop an effective decision support tool.

Box 1. Potential Applications: BEFS-RA tool

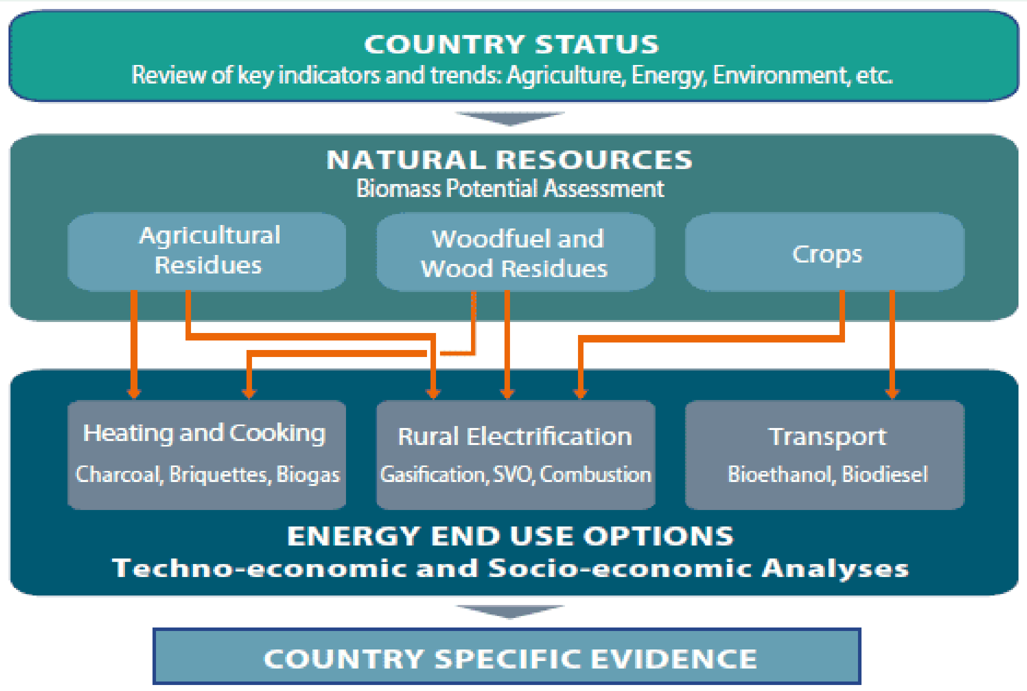
The energy team in the NRC division of FAO has developed a useful tool, called BEFS-RA, to obtain initial indications of the bioenergy potential and related risks, trade-offs and opportunities. BEFS-RA aims to (i) support both policy-makers and technicians in describing energy, agriculture and food security context at county, regional and country scale and (ii) estimate the amount of raw materials sustainably available for bioenergy production, assessing investment required, economic profitability and financial viability.

The BEFS RA includes all the bioenergy options (liquid, gaseous and soil biofuel) and different energy end uses (cooking, heating, transport, rural electrification). In terms of feedstock BEFS RA covers agricultural residues for more than 25 crops and fuelwood and forest residues.

The tool consists of three modules as shown by Figure 21: Country status, natural resources and energy use options.

FIGURE 25

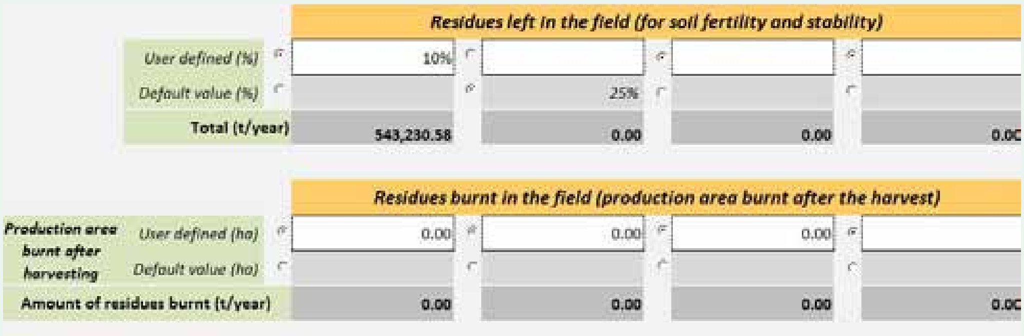
Graphic visualization of the modules of the BEFS RA tool. Source: FAO, 2014



In the natural resource module the user can define the amount of residues which are left in the soil for soil fertility and stability (Figure 22). In case that the user does not specify this value the tool provides 25% as default value. This estimate is a constant value for all the climatic zones, countries and regions.

FIGURE 26

Screen print of the Agricultural residues module of the BEFS RA tool.



Although the tool is flexible as it allows the user to freely choose the amount of residues to be retained, the default value can be updated according to the findings of this review. This would be extremely helpful, especially when the user is not familiar with the concept of soil fertility and farm management. Specifically, crop residues retention could be set to 100 percent for coarse soil located in arid climate and for soils with low SOC concentration situated in temperate areas. The exact location of the areas that satisfy such conditions can be identified by using the climatic map (Figure 1), the OC pool map (Figure 23) and the soil texture map (Figure 24). All these data can be then summarized in a World crop residues management map. Figure 25 help to visualize this process. For intermediate situations, further literature research is needed in order to give reasonable percentage of crop residues removal. Here data on N-fertilization and biomass production can be integrated, as recommended by CART analysis. Finally, this world crop residue map could identify areas in which crop residues should be avoided or carefully assessed, areas in which crop residue removal has lower impact on soil fertility and productivity, advising sustainable removal rates of crop residues to inexpert users.

FIGURE 27

World SOC pool map. Source: FAO, 2014.

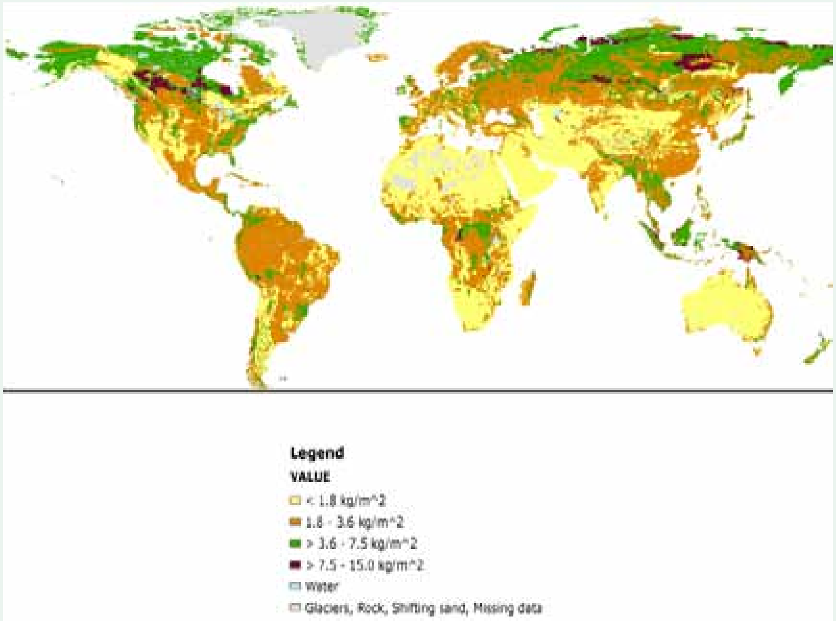


FIGURE 28

World soil texture map. Source: NASA, 2014.

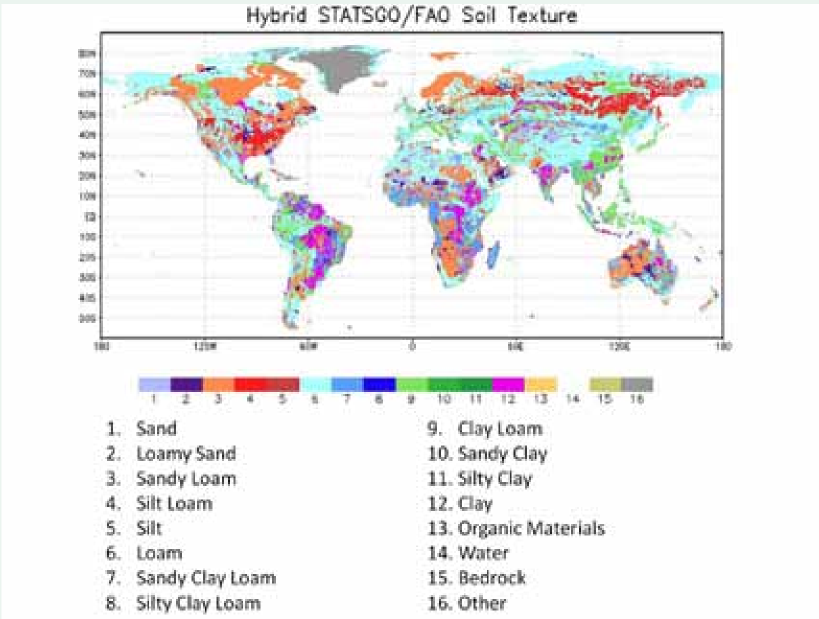
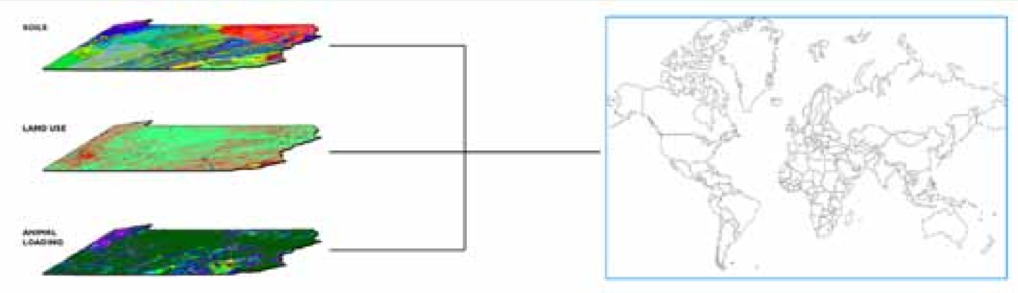


FIGURE 29

Visualization of the integration of climate, SOC and soil texture map in a world crop residue management map. This map would present in darker colour regions in which residues removal is not recommended and in gradual lighter colours regions where residues removal can be considered.



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APPENDIX I

TABLE A

Climate description and criteria according to Köppen-Geiger classification. Tann= annual mean near-surface (2m) temperature; Tmax= monthly mean temperatures of the warmest months; Tmin= monthly mean temperatures of the coldest months; Pann= accumulated annual precipitation; Pmin= precipitation of the driest month; Psmin= lowest monthly precipitation values for summer; Psmax= highest monthly precipitation values for summer; Pwmin= lowest monthly precipitation values for winter; Pwmax= highest monthly precipitation values for winter; Pth=dryness threshold introduced for arid climates (depends on Tann). Precipitation is expressed in mm whereas Temperature is in °C. Source: Koppek et al., 2006.

Type	Description	Criterion
A	**Equatorial climates**	**Tmin ≥ 18 °C**
Af	Equatorial rainforest, fully humid	Pmin ≥ 60 mm
Am	Equatorial monsoon	Pann ≥ 25(100–Pmin)
As	Equatorial savannah with dry summer	Pmin < 60 mm in summer
Aw	Equatorial savannah with dry winter	Pmin < 60 mm in winter
B	**Arid climates**	**Pann < 10 Pth**
BS	Steppe climate	Pann > 5 Pth
BW	Desert climate	Pann ≤ 5 Pth
C	**Warm temperate climates**	**–3 °C < Tmin < 18 °C**
Cs	Warm temperate climate with dry summer	Psmin < Pwmin, Pwmax > 3 Psmin and Psmin <40 mm
Cw	Warm temperate climate with dry winter	Pwmin < Psmin and Psmax > 10 Pwmin
Cf	Warm temperate climate, fully humid	neither Cs nor Cw
D	**Snow climates**	**Tmin ≤ –3 °C**
Ds	Snow climate with dry summer	Psmin < Pwmin, Pwmax > 3 Psmin and Psmin <40 mm
Dw	Snow climate with dry winter	Pwmin < Psmin and Psmax > 10 Pwmin
Df	Snow climate, fully humid neither	Ds nor Dw
E	**Polar climates**	**Tmax < 10 °C**
ET	Tundra climate	0 °C ≤ Tmax < 10 °C
EF	Frost climate	Tmax < 0 °C

APPENDIX II - PCA FOR SOC

Table b shows the correlation matrix of the considered variables and Figure a offers a graphic rappresentation of the matrix. SOC appeared to be weakly correlated with temperature (-0.38), followed by soil texture (0.29) and by rainfall regime (0.22).

TABLE B.

Correlation matrix of the considered variables

	SILT + CLAY	N-FERTILIZERS	C-INPUT	SOC	TEMPERATURE	PRECIPITATION
Silt + Clay	1.0000					
N-Fertilizers	0.3354	1.0000				
C-Input	0.0913	0.2881	1.0000			
SOC	**0.2944**	-0.0367	0.0518	1.0000		
Temperature	0.4295	-0.3478	-0.1575	**-0.3792**	1.0000	
Precipitation	0.0553	-0.3568	-0.0988	**0.2193**	0.3610	1.0000

FIGURE A.

Graphical visualization of the correlation matrix. Darker colours indicate stronger correlations.

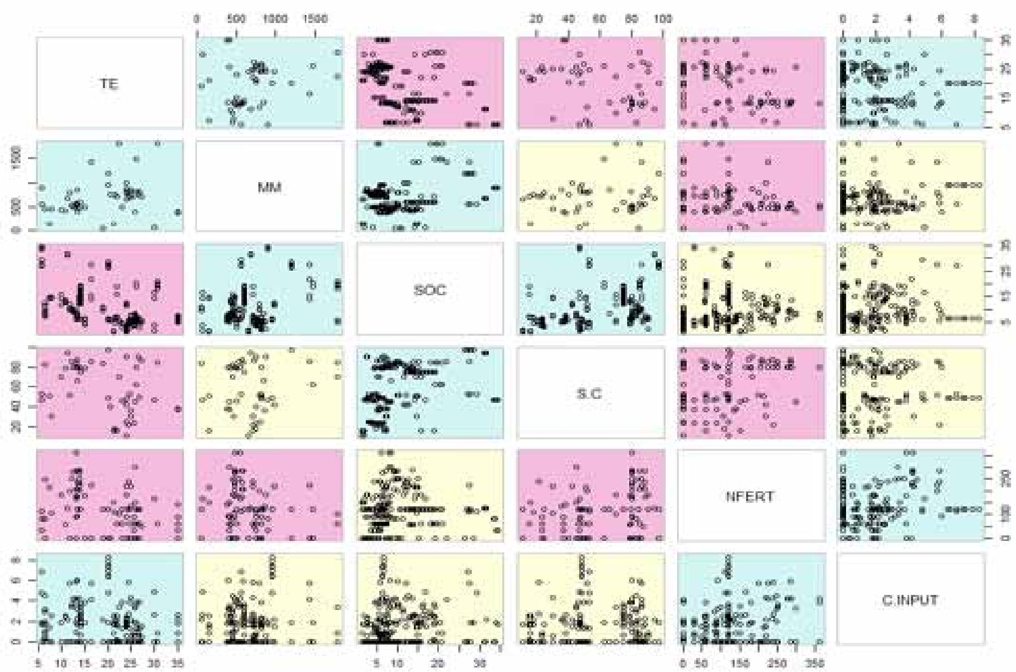


Figure b illustrates the scree plot obtained when processing PCA for SOC. The drop following the first two components indicated that those components were meaningful. Neverthless, the extraction of principal components (PC) 1 and 2 made it possible to explain barely 60% of variation (Table c).

Table d reports the loadings of each variable for PC1 and PC2. The first PC is determined almost equally by soil texture, N-fertilization and annual temperature (Table 6). When more than one variable defines one component, this suggests that these parameters vary together. Therefore, PC1 increases with decreasing scores of Silt + Clay and N-fertilization and increasing scores of annual temperature. Concerning PC2, this component is defined by rainfall and SOC.

FIGURE B.

Scree plot of the PCA carried out for SOC. Horizontal axis refers to principal components.

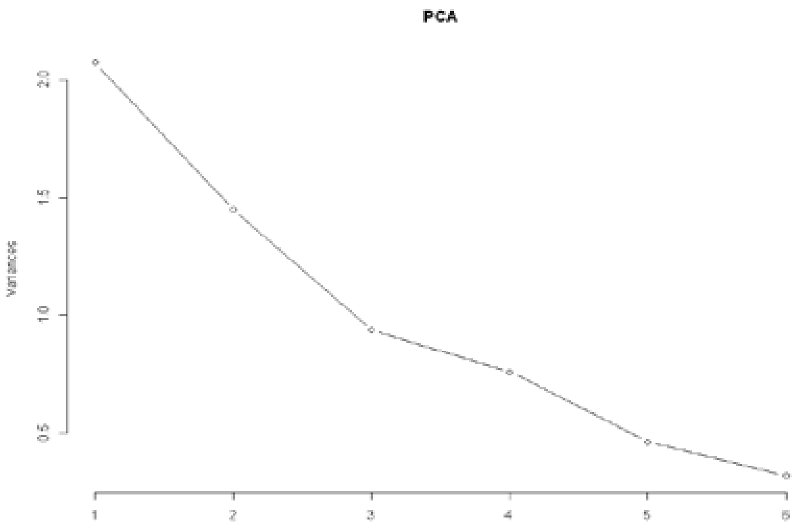


TABLE C.

Standard deviation, proportion of variance and cumulative proportion of the six PCs.

	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 D.

Loadings of each of the extracted components.

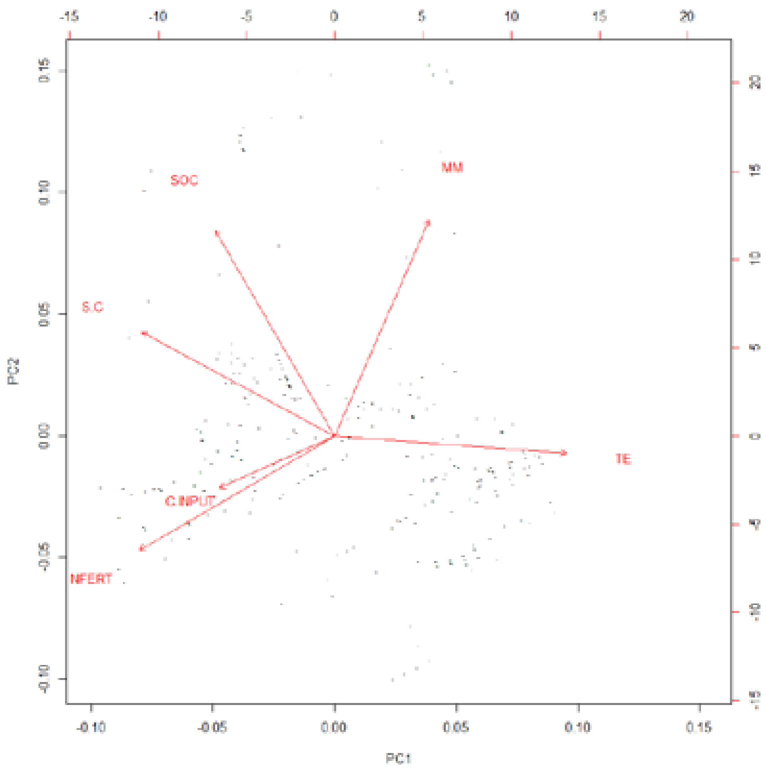
	PC1	PC2
Silt + Clay	-0.4747409	0.30587022
N-Fertilization	-0.4793547	-0.33510784
C-Input	-0.2834071	-0.15274499
SOC	-0.2935698	0.60381886
Temperature	0.5694520	-0.05121624
Rainfall	0.2325119	0.63529111

A biplot using these two components is presented in Figure c. This graph is useful to visually analyse the relationship between the considered variables. Here, every red arrow is associated with a variable. The closer the angle described by two variables to 90° and 270° the weaker the correlation. Conversely, an angle of 0 or 180° indicates a correlation equal to 1 or -1, respectively. Figure c shows that the arrows indicating rainfall and soil texture were the closer to the one standing for SOC; whereas the angle described by the SOC arrow and those ones representing the amount of C added via residues application (C-Input) and N-fertilization was about 90° indicating very small or no relations. Concerning temperature, this indicator described an angle of about 130° in the opposite direction, demonstrating the negative influence of temperature on SOC.

Finally, PC1 seemed inversely related to management practices (C-input and N-fertilizers), but weakly correlated with SOC, whereas PC2 represented the site productivity potential with rainfall almost parallel to the Y-axis. However, given the low correlation among variables and the small variance described by PC1 and PC2, little can be deducted from this analysis.

FIGURE C.

Biplot of PCA on SOC data. MM stands for precipitation, S.C for silt + clay concentration, TE for temperature, C.INPUT for C-Input and NFERT for N-fertilizations.



APPENDIX III- DATABASE ON BULK DENSITY

Authors	Date	depth soil sample (cm)	Application	Climate	Texture	Silt + Clay (%)	Bulk density R- (Mg m-3)	Bulk density R+ (Mg m-3)
Lenka & Lal	2013	10	M	TEMPERATE	silt loam	80	1.5	1.4
Lenka & Lal	2013	10	M	TEMPERATE	silt loam	80	1.5	1.2
Lenka & Lal	2013	10	M	TEMPERATE	silt loam	80	1.5	1.4
Lenka & Lal	2013	10	M	TEMPERATE	silt loam	80	1.5	1.2
Kahlon et al.	2013	15	I	TEMPERATE	silt loam	80	1.6	1.5
Kahlon et al.	2013	15	I	TEMPERATE	silt loam	80	1.6	1.5
Kahlon et al.	2013	15	M	TEMPERATE	silt loam	80	1.5	1.4
Kahlon et al.	2013	15	M	TEMPERATE	silt loam	80	1.5	1.3
Dai et al.	2013	20	M	TEMPERATE	silt loam	85	1.4	1.5
Das et al.	2013	30	M	TROPICAL	sandy loam	30	1.6	1.6
Das et al.	2013	30	M	TROPICAL	sandy loam	30	1.6	1.6
Das et al.	2013	30	M	TROPICAL	sandy loam	30	1.6	1.6
Ram et al.	2012	15	M	TROPICAL	sand	16	1.5	1.4
Ram et al.	2012	15	M	TROPICAL	sand	16	1.5	1.4
Ram et al.	2012	15	M	TROPICAL	sand	16	1.5	1.4
van Donk et al	2012	20	I	TEMPERATE	silt	90	1.6	1.6
Nayak et al.	2012	30	I	TROPICAL	sandy loam	46	1.5	1.4
Nayak et al.	2012	30	I	TROPICAL	sandy loam	46	1.5	1.4
Nayak et al.	2012	30	I	TROPICAL	sandy loam	46	1.5	1.4
Nayak et al.	2012	30	I	TROPICAL	sandy clay loam	50	1.6	1.5
Nayak et al.	2012	30	I	TROPICAL	sandy clay loam	50	1.6	1.4
Nayak et al.	2012	30	I	TROPICAL	sandy clay loam	50	1.6	1.4
Nayak et al.	2012	30	I	TROPICAL	clay	79	1.5	1.4
Nayak et al.	2012	30	I	TROPICAL	clay	79	1.5	1.4
Nayak et al.	2012	30	I	TROPICAL	clay	79	1.5	1.5
Nayak et al.	2012	30	I	TROPICAL	loam	53	1.5	1.5
Nayak et al.	2012	30	I	TROPICAL	loam	53	1.5	1.5
Nayak et al.	2012	30	I	TROPICAL	loam	53	1.5	1.5
Soon et al.	2012	60	I	TEMPERATE	silt loam	80	1.1	0.9
Soon et al.	2012	60	M	TEMPERATE	silt loam	80	1.1	1.0
Srinivasarao et al.	2011	40	I	TROPICAL	clay	87	1.5	1.5
Srinivasarao et al.	2011	40	I	TROPICAL	clay	87	1.5	1.5
Walia et al.	2010	30	UNK	TROPICAL	loamy sand	25	1.5	1.5
Walia et al.	2010	30	UNK	TROPICAL	loamy sand	26	1.5	1.5

Database used for the analysis of the effect of crop residue management on bulk density

Authors	Date	depth soil sample (cm)	Application	Climate	Texture	Silt + Clay (%)	Bulk density R- (Mg m-3)	Bulk density R+ (Mg m-3)
Kang et al.	2009	15	I	TEMPERATE	loam	60	1.5	1.5
Kang et al.	2009	15	I	TEMPERATE	loam	60	1.5	1.4
Kang et al.	2009	15	I	TROPICAL	loamy sand	60	1.7	1.6
Du et al.	2009	20	I	TROPICAL	silt loam	70	1.0	0.9
Du et al.	2009	20	I	TROPICAL	silt loam	70	0.9	0.9
Gami et al.	2009	30	UNK	TEMPERATE	clay loam	70	1.3	1.3
Blanco-Canqui and Lal	2007	2	M	TEMPERATE	silt loam	78	1.3	1.2
Blanco-Canqui and Lal	2007	2	M	TEMPERATE	silt loam	78	1.3	1.3
Blanco-Canqui and Lal	2007	2	M	TEMPERATE	silt loam	78	1.3	1.3
Blanco-Canqui and Lal	2007	2	M	TEMPERATE	silt loam	78	1.3	1.4
Blanco-Canqui and Lal	2007	2	M	TEMPERATE	silt loam	78	1.2	1.1
Blanco-Canqui and Lal	2007	2	M	TEMPERATE	silt loam	78	1.2	0.8
Blanco-Canqui and Lal	2007	2	M	TEMPERATE	silt loam	78	1.2	1.1
Blanco-Canqui and Lal	2007	2	M	TEMPERATE	silt loam	78	1.2	1.2
Blanco-Canqui and Lal	2007	2	M	TEMPERATE	silt loam	78	1.2	1.1
Blanco-Canqui and Lal	2007	2	M	TEMPERATE	silt loam	78	1.2	1.2
Blanco-Canqui and Lal	2007	2	M	TEMPERATE	silt loam	79	1.2	1.2
Blanco-Canqui and Lal	2007	2	M	TEMPERATE	silt loam	79	1.2	1.2
Virto et al.	2007	30	M	TEMPERATE	clay loam	71	1.7	1.7
Virto et al.	2007	30	I	TEMPERATE	clay loam	71	1.7	1.6
Dolan et al.	2006	45	UNK	TEMPERATE	silt loam	80	1.3	1.3
Dolan et al.	2006	45	UNK	TEMPERATE	silt loam	80	1.3	1.3
Dolan et al.	2006	45	UNK	TEMPERATE	silt loam	80	1.3	1.3
Zeleke et al.	2004	15	I	TEMPERATE	loam	52	1.2	1.1
Zeleke et al.	2004	15	I	TEMPERATE	loam	52	1.2	1.1
Zeleke et al.	2004	15	I	TEMPERATE	loam	54	1.2	1.1
Zeleke et al.	2004	15	I	TEMPERATE	loam	54	1.4	1.4
Surekha et al.	2003	15	I	TEMPERATE	sandy clay loam	42	1.3	1.3
Surekha et al.	2003	15	I	TEMPERATE	sandy clay loam	42	1.3	1.3

Database used for the analysis of the effect of crop residue management on bulk density

APPENDIX IV – DATABASE ON SOIL AGGREGATION

Authors	Date	Silt + Clay (%)	depth soil sample (cm)	Application	Soil texture class	Macro Aggregates	Micro Aggregates	MACRO/ MICRO
Wang et al.	2014	74.2	0-10	R	clay	55	45	1.23
Wang et al.	2014	74.2	0-10	M	clay	59	42	1.41
Wang et al.	2014	74.2	10-20	R	clay	47	53	0.88
Wang et al.	2014	74.2	10-20	M	clay	57	43	1.33
Wang et al.	2014	74.2	20-30	R	clay	69	31	2.19
Wang et al.	2014	74.2	20-30	M	clay	58	42	1.38
Paul et al.	2013	85	0-15	R	clay	66	34	1.94
Paul et al.	2013	85	0-15	M	clay	68	32	2.13
Paul et al.	2013	85	0-15	R	clay	58	42	1.38
Paul et al.	2013	85	0-15	I	clay	57	43	1.33
Paul et al.	2013	85	15-30	R	clay	80	20	4.00
Paul et al.	2013	85	15-30	M	clay	78	22	3.55
Paul et al.	2013	85	15-30	R	clay	78	23	3.44
Paul et al.	2013	85	15-30	I	clay	72	28	2.57
He et al.	2012	51	0-10	M	loam	84	17	5.06
He et al.	2012	51	0-10	R	loam	82	18	4.52
He et al.	2012	51	10-20	M	loam	85	15	5.67
He et al.	2012	51	10-20	R	loam	82	18	4.65
He et al.	2012	51	20-30	M	loam	84	17	5.06
He et al.	2012	51	20-30	R	loam	82	18	4.59
Soon et al.	2012	80	0-60	R	silt loam	71	29	2.45
Soon et al.	2012	80	0-60	I	silt loam	53	47	1.13
Soon et al.	2012	80	0-60	M	silt loam	49	51	0.96
Fuentes et al.	2012	62	0-10	I	clay loam	80	20	4.00
Fuentes et al.	2012	62	0-10	M	clay loam	80	21	3.88
Fuentes et al.	2012	62	0-10	R	clay loam	68	32	2.13
Fuentes et al.	2012	62	0-10	R	clay loam	76	24	3.17
Fuentes et al.	2012	62	0-10	I	clay loam	78	22	3.60
Fuentes et al.	2012	62	0-10	M	clay loam	80	20	4.00
Fuentes et al.	2012	62	0-10	R	clay loam	76	25	3.08
Fuentes et al.	2012	62	0-10	R	clay loam	79	21	3.76
Fuentes et al.	2012	62	0-10	I	clay loam	76	24	3.17
Fuentes et al.	2012	62	0-10	M	clay loam	77	24	3.26
Fuentes et al.	2012	62	0-10	R	clay loam	72	29	2.51
Fuentes et al.	2012	62	0-10	R	clay loam	77	23	3.35
Benbi & Senapati	2010	40.2	0-15	R	sandy loam	34	66	0.52
Benbi & Senapati	2010	40.2	0-15	I	sandy loam	44	56	0.80
Lichter et al.	2008	62	0-15	M	clay loam	63	37	1.70
Lichter et al.	2008	62	0-15	I	clay loam	47	53	0.90
Lichter et al.	2008	62	0-15	R	clay loam	51	49	1.06
Blanco-Canqui et al.	2007	80	0-50	R	silt loam	39	61	0.64
Blanco-Canqui et al.	2007	80	0-50	M	silt loam	78	22	3.55
Blanco-Canqui et al.	2007	80	0-50	M	silt loam	88	12	7.33

Database used for the analysis of the effect of crop residue management on soil aggregation

APPENDIX V - PCA FOR CROP YIELDS

A. Maize Yields

Table e and Figure d shows the correlation matrix of the considered variables. Maize yields appeared to be correlated with N-fertilizers application.

TABLE E.

Correlation matrix of the considered variables

	S.C	NFERT	C.INPUT	SOC	YIELD	TE	MM
S.C	1.0000						
NFERT	0.3273	1.0000					
C.INPUT	0.1036	0.4962	1.0000				
SOC	0.2762	-0.3082	-0.0411	1.0000			
YIELD	0.3637	0.7005	0.3493	-0.1510	1.0000		
TE	-0.3341	-0.4548	-0.2692	0.4823	-0.2155	1.0000	
MM	0.0814	-0.4422	-0.2809	0.6439	-0.1930	0.8842	1.0000

FIGURE D.

Graphical visualization of the correlation matrix for maize yield data. Darker colours indicate stronger correlations.

Figure e shows the scree plot for the PCA on maize yield data. The drop following the first two PCs suggested to extract those components. In this case, the extraction of PC1 and PC2 made possible to explain 68% of variation (Table f).

Table g describes the variables and the loadings for PC1 and PC2. The first component was negatively related with N-fertilizers and positively with climatic conditions (Temperature and rainfall). PC2 is mainly governed by negative values of SOC and Silt + Clay.

FIGURE E.

Scree plot of the PCA carried out for maize yield. Horizontal axis refers to principal components.

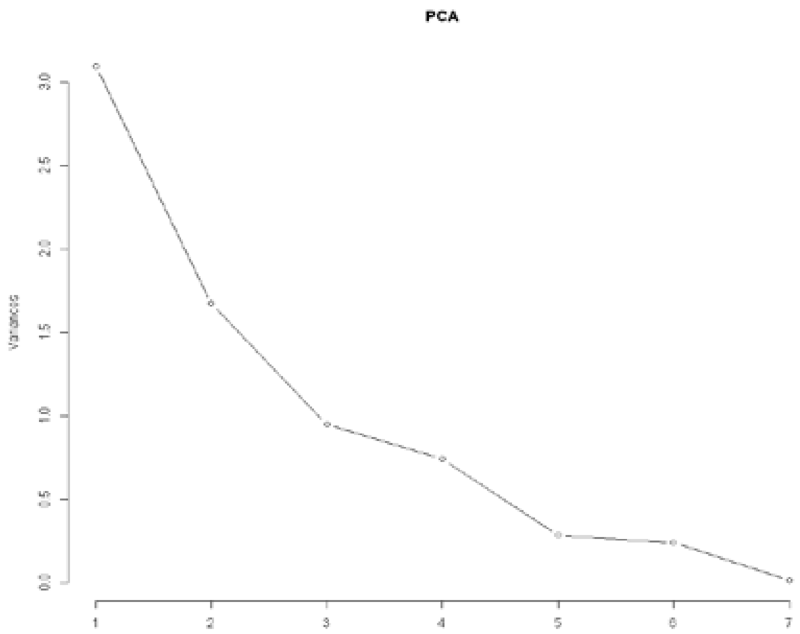


TABLE F.

Standard deviation, proportion of variance and cumulative proportion of the PCs.

	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 G.

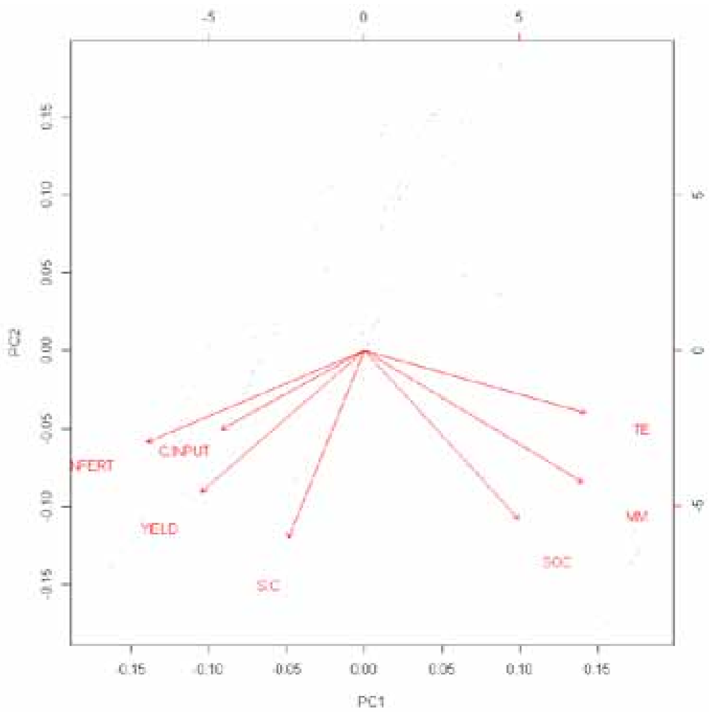
Loadings of each of the extracted components.

	PC1	PC2
S.C	-0.1614548	-0.5418
NFERT	-0.4621568	-0.264
C.INPUT	-0.3045704	-0.2298
SOC	0.3287946	-0.4881
YIELD	-0.3480551	-0.41
TE	0.4721631	-0.1797
MM	0.4641057	-0.3811

The biplot presented in Figure f illustrates that the arrows indicating C-Input, N-fertilizers and silt + clay are the closer to the yield indicator, while the SOC, precipitation and Temperate seemed not influential.

FIGURE F

Biplot of PCA on maize yields data. MM stands for precipitation, S.C for silt + clay concentration, TE for temperature, C.INPUT for c-input, NFERT for n-fertilizations and YIELD for maize yield.



Finally correlation matrix and PCA showed that maize yields were mainly associated with N-rate whereas SOC and yield appeared to be independent. However, the variance explained by two components was not at such to provide solid information to draw strong conclusions.

B. Wheat Yields

Table h and Figure g shows the correlation matrix of the considered variables. As maize also wheat yields appeared to be correlated with N-fertilizers application.

TABLE H.

Correlation matrix of the considered variables

	TE	MM	SILT.CLAY	NFERT	SOC	C.INPUT	YIELD
TE	1.0000						
MM	-0.2796	1.0000					
SILT.CLAY	-0.7792	0.0633	1.0000				
NFERT	-0.2747	-0.2102	0.4498	1.0000			
SOC	-0.4980	0.1378	0.3272	-0.0004	1.0000		
C.INPUT	-0.1543	-0.2301	0.2230	0.3380	0.0906	1.0000	
YIELD	-0.4367	-0.0358	0.4662	0.5143	0.1376	0.3368	1.0000

FIGURE G.

Graphical visualization of the correlation matrix for wheat yield data. Darker colours indicate stronger correlations.

Figure h shows the scree plot for the PCA on maize yield data. The drop following the first two PCs suggested to extract those components. In this case, the extraction of PC1 and PC2 made possible to explain 68% of variation (Table i).

FIGURE H.

Scree plot of the PCA carried out for wheat yield. Horizontal axis refers to principal components.

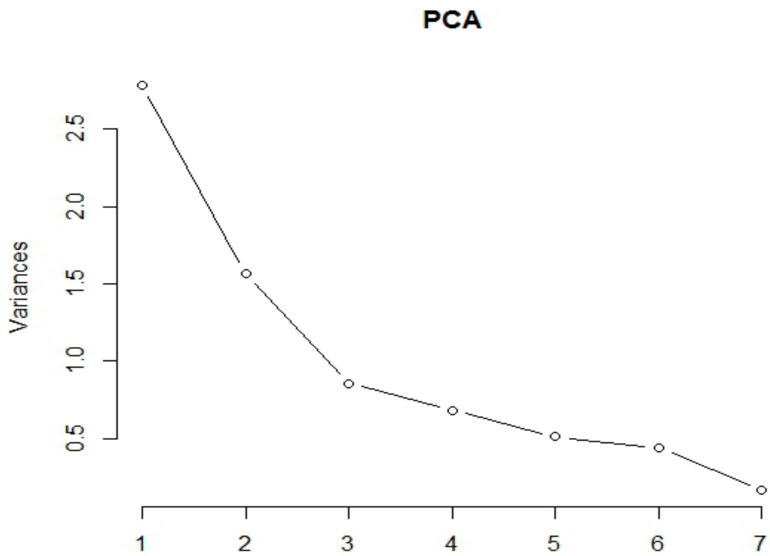


Table l describes the variables and the loadings for PC1 and PC2. The first component was negatively related with temperature and soil texture, and positively with yields (Temperature and rainfall). PC2 is mainly governed by negative values of precipitation and positive values of C-input.

TABLE I.

Standard deviation, proportion of variance and cumulative proportion of the PCs.

	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 L.

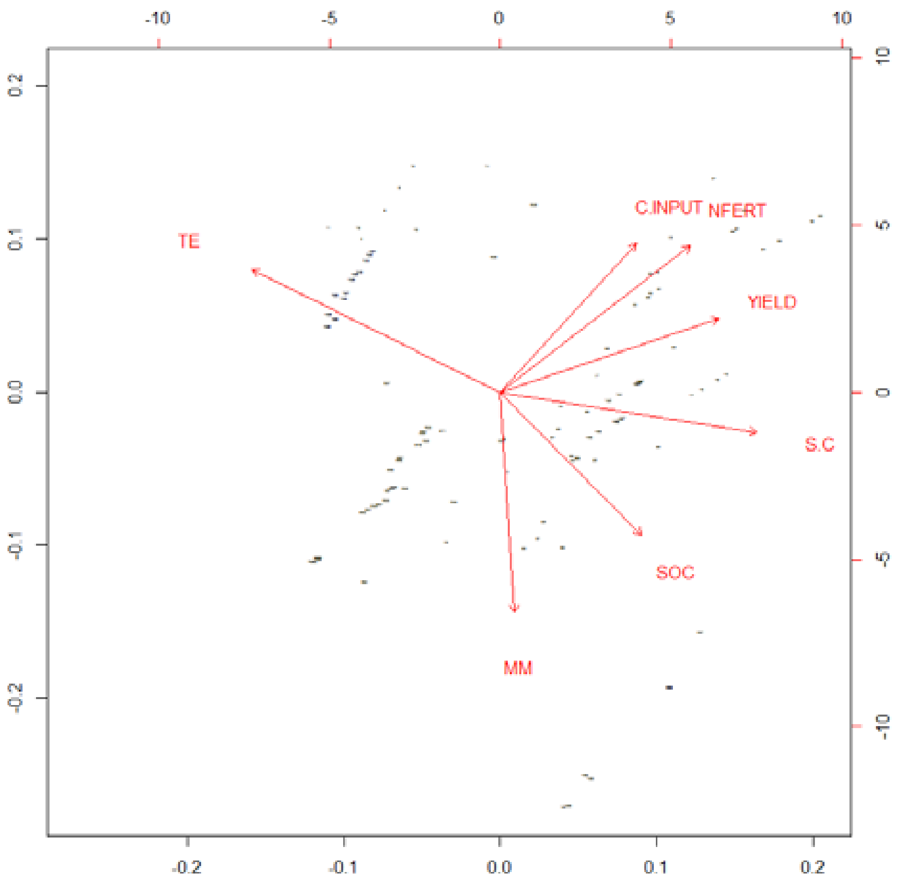
Loadings of each of the extracted components.

	PC1	PC2
MM	0.0291660	-0.599823
TE	-0.4963635	0.333342
S.C	-0.5133541	-0.109947
NFERT	0.3797623	0.399392
SOC	-0.2822617	-0.390718
C.INPUT	0.2720567	0.405881
YIELD	0.4374175	0.200227

The biplot presented in Figure i illustrates that the arrows indicating C-Input, N-fertilizers and Silt + Clay are the closer to the wheat yield indicator, while the SOC, precipitation and Temperate seemed not influential.

FIGURE I

Biplot of PCA on wheat yields data. MM stands for precipitation, S.C for silt + clay concentration, TE for temperature, C.INPUT for c-input, NFERT for n-fertilizations and YIELD for maize yield.



APPENDIX VI – DATABASE ON SOC AND YIELDS

Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm year^{-1})	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} year^{-1})	TILL	C-INPUT (t C ha^{-1} year^{-1})	RES. APPL	Crop	YIELD R+(t ha^{-1} year^{-1})	YIELD R-(t ha^{-1} year^{-1})
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	2.8	2.7
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	4.0	3.8
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	4.1	3.9
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	6.2	5.9
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	7.3	6.9
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	7.5	7.0
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	8.5	7.0
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	9.5	7.5
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	9.3	7.4
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	9.6	8.5
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	9.4	6.8
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	9.5	7.0
Wang et al.	2014	12	29	45	30	9	421	China	clay loam		12.2	9.5	150			M	maize	9.5	7.5
Gentile et al.	2013	1.5	29	33	15	26	1480	Ghana	silt clay loam	22.6	19.0	20.3	0		1.9	I	maize		
Gentile et al.	2013	1.5	29	33	15	26	1480	Ghana	silt clay loam	22.6	20.3	20.6	120		1.9	I	maize		
Gentile et al.	2013	1.5	75	22	15	20	1200	Kenya	clay	29.4	28.4	26.4	0		1.9	I	maize		
Gentile et al.	2013	1.5	75	22	15	20	1200	Kenya	clay	29.4	27.6	26.8	120		1.9	I	maize		
Gentile et al.	2013	1.5	5	6	15	24	660	Zimbabwe	sand	2.5	2.0	1.5	0		1.7	I	maize		
Gentile et al.	2013	1.5	5	6	15	24	660	Zimbabwe	sand	2.5	2.1	1.6	120		1.7	I	maize		
Gentile et al.	2013	1.5	20	5	15	24	800	Zimbabwe	sandy loam	5.2	3.4	3.0	0		1.7	I	maize		

Database used for the analysis of the effect of crop residue management on SOC and yield

Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm year^{-1})	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} year^{-1})	TILL	C-INPUT (t C ha^{-1} year^{-1})	RES. APPL	Crop	YIELD R+(t ha^{-1} year^{-1})	YIELD R-(t ha^{-1} year^{-1})
Gentile et al.	2013	1.5	20	5	15	24	800	Zimbabwe	sandy loam	5.2	3.7	3.2	120		1.7	I	maize		
Paul et al.	2013	5	64	21	30	31	1800	Kenya	clay	13.5	21.0	19.5	60	CT	0.9	I	maize	6.0	6.4
Paul et al.	2013	5	64	21	30	31	1800	Kenya	clay	13.5	21.0	19.5	60	CT	0.9	I	maize	4.2	3.9
Paul et al.	2013	5	64	21	30	31	1800	Kenya	clay	13.5	21.0	19.5	60	CT	0.9	I	maize	2.9	3.3
Paul et al.	2013	5	64	21	30	31	1800	Kenya	clay	13.5	21.0	19.5	60	CT	0.9	I	maize	4.8	4.5
Paul et al.	2013	5	64	21	30	31	1800	Kenya	clay	13.5	20.0	18.2	60	MT	0.9	M	maize	6.2	4.8
Paul et al.	2013	5	64	21	30	31	1800	Kenya	clay	13.5	20.0	18.2	60	MT	0.9	M	maize	3.5	3.7
Paul et al.	2013	5	64	21	30	31	1800	Kenya	clay	13.5	20.0	18.2	60	MT	0.9	M	maize	3.1	2.6
Paul et al.	2013	5	64	21	30	31	1800	Kenya	clay	13.5	20.0	18.2	60	MT	0.9	M	maize	4.5	3.5
Kahlon et al.	2013	22	15	65	15	11	1016	US	silty loam	16.2	19.8	17.1	0	CT	3.4	I	no crop		
Kahlon et al.	2013	22	15	65	15	11	1016	US	silty loam	16.2	20.9	17.1	0	CT	6.8	I	no crop		
Kahlon et al.	2013	22	15	65	15	11	1016	US	silty loam	16.2	22.9	21.0	0	NT	3.4	M	no crop		
Kahlon et al.	2013	22	15	65	15	11	1016	US	silty loam	16.2	28.4	21.0	0	NT	6.8	M	no crop		
Gupta Choudhury et al	2013	5	23	18	30	24	750	India	sandy clay loam		8.6	8.2	150	CT		I	wheat-rice		
Gupta Choudhury et al.	2013	5	23	18	30	24	750	India	sandy clay loam		9.7	9.2	150	MT		I	wheat-rice		
Gupta Choudhury et al.	2013	5	23	18	30	24	750	India	sandy clay loam		9.9	9.7	150	NT		M	wheat-rice		
Moreno-Cornejo et al.	2013	2	24	36	30	17	300	Spain	loam	19.3	18.0	19.1	170	CT		I	broccoli	10.7	11.1

Database used for the analysis of the effect of crop residue management on SOC and yield

Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm year^{-1})	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} year^{-1})	TILL	C-INPUT (t C ha^{-1} year^{-1})	RES. APPL	Crop	YIELD R+(t ha^{-1} year^{-1})	YIELD R-(t ha^{-1} year^{-1})
Moreno-Cornejo et al.	2013	2	24	36	30	17	300	Spain	loam	19.3	17.9	19.1	170	CT		I	broccoli	10.9	10.8
Moreno-Cornejo et al.	2013	2	24	36	30	17	300	Spain	loam	19.3	19.5	19.1	170	CT		I	broccoli	11.8	11.8
Sun et al.	2013	31	26		15	18	1727	China		16.2	24.1	19.7	70	CT	6.8	I	rice	7.8	5.3
Sun et al.	2013	31	26		15	18	1727	China		16.2	28.4	19.7	70	CT	13.5	I	rice	8.2	5.3
Sun et al.	2013	31	26		15	18	1727	China		16.2	25.2	19.7	70	CT	9.8	I	rice	8.1	8.2
Ram et al.	2013	3	6	10	15	21	146	India	sand	1.5	1.6	1.5		CT	0.9	M	wheat	5.9	5.0
Ram et al.	2013	3	6	10	15	21	146	India	sand	1.5	1.7	1.5		CT	1.7	M	wheat	6.0	5.0
Ram et al.	2013	3	6	10	15	21	146	India	sand	1.5	1.9	1.5		CT	2.6	M	wheat	6.0	5.0
Buysse et al.	2013	53	12	85	25	10	800	Belgium	clay		15.7	13.3			1.0	I	sugar beet-legume-cereal		
Rezig et al.	2013	5	15	32	20	30	68	Sudan	sandy loam	4.9	14.3	1.9	0	CT	2.6	I	wheat-guar	1.6	1.0
Rezig et al.	2013	5	15	32	20	30	68	Sudan	sandy loam	4.9	16.8	4.0	165	CT	4.9	I	wheat-guar	3.8	2.6
Dai et al.	2013	4	25	60	20	13	581	China	silt loam		9.9	9.2	285		5.9	M	maize	10.2	9.9
Dai et al.	2013	4	25	60	20	13	581	China	silt loam		9.9	9.2	285		5.9	M	maize	7.7	8.5
Dai et al.	2013	4	25	60	20	13	581	China	silt loam		9.9	9.2	285		5.9	M	maize	9.4	10.5
Dai et al.	2013	4	25	60	20	13	581	China	silt loam		9.9	9.2	285		5.9	M	maize	10.1	10.7
Dai et al.	2013	4	25	60	20	13	581	China	silt loam		9.9	9.2	285		5.9	M	wheat	13.3	13.2
Dai et al.	2013	4	25	60	20	13	581	China	silt loam		9.9	9.2	285		5.9	M	wheat	11.1	11.5
Dai et al.	2013	4	25	60	20	13	581	China	silt loam		9.9	9.2	285		5.9	M	wheat	10.1	10.8
Dai et al.	2013	4	25	60	20	13	581	China	silt loam		9.9	9.2	285		5.9	M	wheat	14.0	12.6

Database used for the analysis of the effect of crop residue management on SOC and yield

Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm year^{-1})	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} year^{-1})	TILL	C-INPUT (t C ha^{-1} year^{-1})	RES. APPL	Crop	YIELD R+(t ha^{-1} year^{-1})	YIELD R-(t ha^{-1} year^{-1})
Brennan et al.	2013	3	22	34	30	10	840	Ireland	loam				0	CT	1.4	I	wheat	3.1	2.8
Brennan et al.	2013	3	22	34	30	10	840	Ireland	loam				140	CT	3.0	I	wheat	6.9	7.0
Brennan et al.	2013	3	22	34	30	10	840	Ireland	loam				180	CT	4.3	I	wheat	7.8	7.8
Brennan et al.	2013	3	22	34	30	10	840	Ireland	loam				220	CT	4.1	I	wheat	8.2	8.4
Brennan et al.	2013	3	22	34	30	10	840	Ireland	loam				260	CT	4.7	I	wheat	8.6	8.7
Brennan et al.	2013	3	22	34	30	10	840	Ireland	loam				0	NT	1.5	M	wheat	3.2	3.6
Brennan et al.	2013	3	22	34	30	10	840	Ireland	loam				140	NT	3.1	M	wheat	6.8	6.8
Brennan et al.	2013	3	22	34	30	10	840	Ireland	loam				180	NT	4.4	M	wheat	7.0	7.4
Brennan et al.	2013	3	22	34	30	10	840	Ireland	loam				220	NT	4.4	M	wheat	7.8	7.7
Brennan et al.	2013	3	22	34	30	10	840	Ireland	loam				260	NT	5.1	M	wheat	8.0	7.7
Thierfelder et al.	2013	5	12	6	30	22	748	Zambia	loamy sand	5.8	6.6	4.8	109	NT	2.2	M	wheat	5.0	3.6
Thierfelder et al.	2013	5	12	6	30	22	748	Zambia	loamy sand	5.8	6.6	4.8	109	NT	2.2	M	maize	5.1	4.9
Thierfelder et al.	2013	5	12	6	30	22	748	Zambia	loamy sand	5.8	6.6	4.8	109	NT	2.2	M	maize	4.7	4.1
Thierfelder et al.	2013	5	12	6	30	22	748	Zambia	loamy sand	5.8	6.6	4.8	109	NT	2.2	M	maize	3.9	3.3
Thierfelder et al.	2013	5	12	6	30	22	748	Zambia	loamy sand	5.8	6.6	4.8	109	NT	2.2	M	maize	3.9	3.0
Thierfelder et al.	2013	5	12	6	30	22	748	Zambia	loamy sand	5.8	6.6	4.8	109	NT	2.2	M	maize	4.5	3.0
Thierfelder et al.	2013	5	12	6	30	22	748	Zambia	loamy sand	5.8	7.1	4.8	109	NT	1.7	M	maize-cotton	5.1	3.6
Thierfelder et al.	2013	5	12	6	30	22	748	Zambia	loamy sand	5.8	7.1	4.8	109	NT	1.7	M	maize-cotton	6.2	4.9

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Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm year^{-1})	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} year^{-1})	TILL	C-INPUT (t C ha^{-1} year^{-1})	RES. APPL	Crop	YIELD R+(t ha^{-1} year^{-1})	YIELD R-(t ha^{-1} year^{-1})
Thierfelder et al.	2013	5	12	6	30	22	748	Zambia	loamy sand	5.8	7.1	4.8	109	NT	1.7	M	maize-cotton	6.0	4.1
Thierfelder et al.	2013	5	12	6	30	22	748	Zambia	loamy sand	5.8	7.1	4.8	109	NT	1.7	M	maize-cotton	4.5	3.3
Thierfelder et al.	2013	5	12	6	30	22	748	Zambia	loamy sand	5.8	7.1	4.8	109	NT	1.7	M	maize-cotton	4.6	3.0
Thierfelder et al.	2013	5	12	6	30	22	748	Zambia	loamy sand	5.8	7.1	4.8	109	NT	1.7	M	maize-cotton	4.0	3.0
Zhao et al.	2013	24	15	65	30	13	478	China	silt loam		7.7	7.5	360		3.8		maize	6.4	5.8
Zhao et al.	2013	24	15	65	30	13	478	China	silt loam		8.4	7.9	360		3.8		wheat	4.6	4.2
Zhao et al.	2013	8	15	65	30	14	474	China	silt loam		12.1	12.3	475	CT	4.3	I	wheat	6.0	5.9
Zhao et al.	2013	8	15	65	30	14	474	China	silt loam		12.1	12.3	475	NT	4.3	M	wheat	8.3	7.8
Wuest & Gollany	2013	5	10	69	25	11	420	US	silt loam	12.0	13.8	13.4	58	NT	2.5	M	wheat	4.3	1.0
Wuest & Gollany	2013	5	10	69	25	11	420	US	silt loam	12.0	13.6	13.4	58	NT	2.5	M	wheat	4.2	1.0
Wuest & Gollany	2013	5	10	69	25	11	420	US	silt loam	12.0	13.6	13.4	58	NT	2.5	M	wheat	3.9	1.0
Wuest & Gollany	2013	5	10	69	25	11	420	US	silt loam	12.0	13.0	13.4	58	NT	2.5	M	wheat	4.0	1.0
Das et al.	2013	4	10	20	30	25	706	India	sandy loam	7.0	7.5	7.4	220	NT	0.6	M	cotton-wheat-gram		
Das et al.	2013	4	10	20	30	25	706	India	sandy loam	7.0	7.7	7.4	220	NT	4.3	M	cotton-wheat-gram		
Laird & Chang	2013	32	15	65	30	7	820	US	silt loam	26.2	24.0	23.2		CT		I	maize-soybean		

Database used for the analysis of the effect of crop residue management on SOC and yield

Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm $year^{-1}$)	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} $year^{-1}$)	TILL	C-INPUT (t C ha^{-1} $year^{-1}$)	RES. APPL	Crop	YIELD R+(t ha^{-1} $year^{-1}$)	YIELD R-(t ha^{-1} $year^{-1}$)
Laird & Chang	2013	32	15	65	30	7	820	US	silt loam	26.2	24.4	22.5		MT			maize-soybean		
Laird & Chang	2013	32	15	65	30	7	820	US	silt loam	26.2	23.1	25.2		NT		M	maize-soybean		
Sun et al.	2013	6	26	68	20	13	650	China	silt loam	7.3	8.5	8.0				M	wheat-maize		
Sun et al.	2013	6	26	68	20	13	650	China	silt loam	7.3	9.0	8.0				I	wheat-maize		
Alijani et al.	2012	2	15	65	30	13	396	Iran	silty loam	6.7	7.8	7.6	92	MT	3.2	I	wheat	7.0	6.3
Alijani et al.	2012	2	15	65	30	13	396	Iran	silty loam	6.7	8.2	7.6	92	MT	6.0	I	wheat	7.3	6.3
Mohammad et al.	2012	4	32	37	15	24	475	Pakistan	clay loam	5.2	5.6	5.3		CT	1.7	I	wheat	2.1	1.6
Mohammad et al.	2012	4	32	37	15	24	475	Pakistan	clay loam	5.2	5.6	5.3		CT	2.8	I	wheat	2.7	2.7
Mohammad et al.	2012	4	32	37	15	24	475	Pakistan	clay loam	5.2	5.6	5.3		CT	0.8	I	wheat	1.6	1.4
Mohammad et al.	2012	4	32	37	15	24	475	Pakistan	clay loam	5.2	5.6	5.3		CT	1.2	I	wheat	1.5	1.4
Mohammad et al.	2012	4	32	37	15	24	475	Pakistan	clay loam	5.2	5.9	5.5		NT	2.0	M	wheat	2.0	1.7
Mohammad et al.	2012	4	32	37	15	24	475	Pakistan	clay loam	5.2	5.9	5.5		NT	3.3	M	wheat	3.0	2.6
Mohammad et al.	2012	4	32	37	15	24	475	Pakistan	clay loam	5.2	5.9	5.5		NT	1.1	M	wheat	1.6	1.0
Mohammad et al.	2012	4	32	37	15	24	475	Pakistan	clay loam	5.2	5.9	5.5		NT	1.4	M	wheat	1.7	1.1
Ghimire et al.	2012	4	23	20	30	21	2000	Nepal	sandy clay loam	14.5	16.3	15.9		CT	5.1	I	wheat rice		

Database used for the analysis of the effect of crop residue management on SOC and yield

Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm year^{-1})	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} year^{-1})	TILL	C-INPUT (t C ha^{-1} year^{-1})	RES. APPL	Crop	YIELD R+(t ha^{-1} year^{-1})	YIELD R-(t ha^{-1} year^{-1})
Ghimire et al.	2012	4	23	20	30	21	2000	Nepal	sandy clay loam	14.5	18.9	17.4		NT	5.1	M	wheat rice		
Krupnik et al.	2012	2	40	44	20	19	54	Senegal	silt clay/silt clay loam	9.6	11.0	9.4	0		2.1	I	rice	3.6	3.1
Krupnik et al.	2012	2	40	44	20	19	54	Senegal	silt clay/silt clay loam	9.6	11.0	10.6	122	CT	2.1	I	rice	6.9	6.2
Nayak et al.	2012	26	18	28	30	23	500	India	sandy loam	3.1	4.6	4.2		CT	1.3	I	rice	4.6	2.1
Nayak et al.	2012	26	18	28	30	23	500	India	sandy loam	3.1	4.7	4.7		CT	3.8	I	rice	5.9	5.6
Nayak et al.	2012	25	28	22	30	27	818	India	sandy clay loam	4.6	5.6	4.4	60	CT	3.8	I	rice	3.9	1.4
Nayak et al.	2012	25	28	22	30	27	818	India	sandy clay loam	4.6	5.5	4.4	60	CT	1.3	I	rice	4.2	3.9
Nayak et al.	2012	25	18	35	30	25	818	India	loam	2.9	5.1	4.4	60	CT	3.8	I	rice	3.4	1.8
Nayak et al.	2012	25	18	35	30	25	818	India	loam	2.9	4.6	4.4	60	CT	1.3	I	rice	4.0	4.1
Nayak et al.	2012	23	50	30	30	26	818	India	clay	9.2	7.5	5.8		CT	3.8	I	rice	3.6	1.3
Nayak et al.	2012	23	50	30	30	26	818	India	clay	9.2	7.1	5.8		CT	1.3	I	rice	3.7	3.5
Djigal et al.	2012	16	62	19	30	17	1450	Madagascar	clay				30	CT	1.4	I	maize	3.7	3.5
Djigal et al.	2012	16	62	19	30	17	1450	Madagascar	clay				60	CT	2.4	I	soya	1.5	1.5
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	CT	3.3	I	soyabean	1.9	1.9
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	CT	3.3	I	soyabean	1.5	1.4
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	CT	3.3	I	soyabean	1.8	1.9
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	CT	3.3	I	soyabean	1.9	2.0
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				25	CT	3.3	I	soyabean	2.4	2.5
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				25	CT	3.3	I	soyabean	2.4	2.5

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Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm year^{-1})	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} year^{-1})	TILL	C-INPUT (t C ha^{-1} year^{-1})	RES. APPL	Crop	YIELD R+(t ha^{-1} year^{-1})	YIELD R-(t ha^{-1} year^{-1})
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				25	CT	3.3	I	soyabean	2.4	2.4
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				25	CT	3.3	I	soyabean	2.4	2.4
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	NT	1.6	M	soyabean	2.0	2.0
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	NT	1.6	M	soyabean	1.6	1.5
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	NT	1.6	M	soyabean	1.9	1.9
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	NT	1.6	M	soyabean	1.9	1.9
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				25	NT	1.6	M	soyabean	2.7	2.5
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				25	NT	1.6	M	soyabean	2.5	2.4
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				25	NT	1.6	M	soyabean	2.5	2.5
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				25	NT	1.6	M	soyabean	2.4	2.3
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	CT	3.3	I	wheat	1.4	1.2
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	CT	3.3	I	wheat	1.3	1.2
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	CT	3.3	I	wheat	1.0	1.3
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	CT	3.3	I	wheat	1.1	1.4
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				150	CT	3.3	I	wheat	3.9	3.8
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				150	CT	3.3	I	wheat	4.1	4.0
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				150	CT	3.3	I	wheat	3.9	3.9
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				150	CT	3.3	I	wheat	4.4	4.4
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	NT	1.6	M	wheat	1.2	1.3
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	NT	1.6	M	wheat	1.2	1.4
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	NT	1.6	M	wheat	0.9	1.1
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				0	NT	1.6	M	wheat	1.1	1.2

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Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm year^{-1})	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} year^{-1})	TILL	C-INPUT (t C ha^{-1} year^{-1})	RES. APPL	Crop	YIELD R+(t ha^{-1} year^{-1})	YIELD R-(t ha^{-1} year^{-1})
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				150	NT	1.6	M	wheat	4.2	4.6
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				150	NT	1.6	M	wheat	3.9	4.2
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				150	NT	1.6	M	wheat	3.4	3.4
Aulakh et al.	2012	4	18	28	30	23	500	India	sandy loam				150	NT	1.6	M	wheat	4.3	4.3
He et al.	2012	5	17	34	30	7	146	China	loam	14.6	14.8	14.5	215	NT	1.4	M	maize-wheat	5.4	5.6
He et al.	2012	5	17	34	30	7	146	China	loam	14.6	14.8	14.5	215	NT	1.4	M	maize-wheat	6.1	6.0
He et al.	2012	5	17	34	30	7	146	China	loam	14.6	14.8	14.5	215	NT	1.4	M	maize-wheat	6.4	6.2
He et al.	2012	5	17	34	30	7	146	China	loam	14.6	14.8	14.5	215	NT	1.4	M	maize-wheat	11.8	11.4
He et al.	2012	5	17	34	30	7	146	China	loam	14.6	14.8	14.5	215	NT	1.4	M	maize-wheat	6.1	5.8
He et al.	2012	5	17	34	30	7	146	China	loam	14.7	14.9	14.5	216	MT	1.4	M	maize-wheat	5.6	5.6
He et al.	2012	5	17	34	30	7	146	China	loam	14.7	14.9	14.5	216	MT	1.4	M	maize-wheat	6.3	6.0
He et al.	2012	5	17	34	30	7	146	China	loam	14.7	14.9	14.5	216	MT	1.4	M	maize-wheat	6.3	6.2
He et al.	2012	5	17	34	30	7	146	China	loam	14.7	14.9	14.5	216	MT	1.4	M	maize-wheat	12.0	11.4
He et al.	2012	5	17	34	30	7	146	China	loam	14.7	14.9	14.5	216	MT	1.4	M	maize-wheat	6.2	5.8
Hou et al.	2012	7	22	66	20	13	567	China	silt loam	6.0	7.7	7.1	285	NT	1.7	M	maize	10.0	11.0
Hou et al	2012	7	22	66	20	13	567	China	silt loam	6.0	7.7	7.1	285	NT	2.3	M	wheat	4.0	4.0
Hou et al	2012	7	22	66	20	13	567	China	silt loam	6.0	7.7	7.1	285	NT	2.3	M	wheat	5.9	5.9

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Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm $year^{-1}$)	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} $year^{-1}$)	TILL	C-INPUT (t C ha^{-1} $year^{-1}$)	RES. APPL	Crop	YIELD R+(t ha^{-1} $year^{-1}$)	YIELD R-(t ha^{-1} $year^{-1}$)
Hou et al	2012	7	22	66	20	13	567	China	silt loam	6.0	7.7	7.1	285	NT	2.3	M	wheat	4.7	4.6
Hou et al	2012	7	22	66	20	13	567	China	silt loam	6.0	7.7	7.1	285	NT	2.3	M	wheat	6.0	5.8
Hou et al	2012	7	22	66	20	13	567	China	silt loam	6.0	7.7	7.1	285	NT	2.3	M	wheat	6.1	6.2
Hou et al	2012	7	22	66	20	13	567	China	silt loam	6.0	7.7	7.1	285	NT	2.3	M	wheat	6.2	6.3
Hou et al	2012	7	22	66	20	13	567	China	silt loam	6.0	7.7	7.1	285	NT	1.7	M	maize	7.1	7.0
Hou et al	2012	7	22	66	20	13	567	China	silt loam	6.0	7.7	7.1	285	NT	1.7	M	maize	7.5	7.5
Hou et al	2012	7	22	66	20	13	567	China	silt loam	6.0	7.7	7.1	285	NT	1.7	M	maize	6.0	6.3
Hou et al	2012	7	22	66	20	13	567	China	silt loam	6.0	7.7	7.1	285	NT	1.7	M	maize	5.5	5.6
Hou et al	2012	7	22	66	20	13	567	China	silt loam	6.0	7.7	7.1	285	NT	1.7	M	maize	7.5	7.6
Van Donk et al.	2012	3	5	85	20	9	508	US	silt				90	NT	2.6	M	soyabean	4.5	3.9
Van Donk et al	2012	3	5	85	20	9	508	US	silt				90	NT	1.2	M	soyabean	3.8	3.3
Loke et al.	2012	31	18		30	24	743	South Africa									wheat	2.3	2.1
Loke et al.	2012	31	18		30	24	743	South Africa									wheat	2.2	2.0
Loke et al.	2012	31	18		30	24	743	South Africa									wheat	1.9	1.9
Loke et al.	2012	31	18		30	24	743	South Africa									wheat	2.5	2.3
Srinivasarao et al.	2012	22	75	12	40	27	723	India	clay	3.5	5.0	5.1	50	CT	0.5	I	sorghum	1.1	1.0
Srinivasarao et al.	2012	22	75	12	40	27	723	India	clay	3.5	5.8	5.1	50	CT	1.5	I	sorghum	0.9	1.0
Iqbal et al.	2011	2	22	16	20	35	379	Pakistan	sandy clay loam	2.1	6.6	6.9	140	NT	0.9	M	wheat	3.2	3.5

Database used for the analysis of the effect of crop residue management on SOC and yield

Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm year^{-1})	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} year^{-1})	TILL	C-INPUT (t C ha^{-1} year^{-1})	RES. APPL	Crop	YIELD R+(t ha^{-1} year^{-1})	YIELD R-(t ha^{-1} year^{-1})
Iqbal et al.	2011	2	22	16	20	35	379	Pakistan	sandy clay loam	2.1	6.7	6.9	140	NT	1.8	M	wheat	3.5	3.5
Iqbal et al.	2011	2	22	16	20	35	379	Pakistan	sandy clay loam	2.1	7.6	6.9	140	NT	2.6	M	wheat	2.9	3.5
Iqbal et al.	2011	2	22	16	20	35	379	Pakistan	sandy clay loam	2.1	6.2	5.6	140	MT	0.9	M	wheat	3.2	3.5
Iqbal et al.	2011	2	22	16	20	35	379	Pakistan	sandy clay loam	2.1	6.9	5.6	140	MT	1.8	M	wheat	3.5	3.5
Iqbal et al.	2011	2	22	16	20	35	379	Pakistan	sandy clay loam	2.1	7.2	5.6	140	MT	2.6	M	wheat	2.9	3.5
Iqbal et al.	2011	2	22	16	20	35	379	Pakistan	sandy clay loam	2.1	5.7	6.6	140	CT	0.9	M	wheat	3.2	2.9
Iqbal et al.	2011	2	22	16	20	35	379	Pakistan	sandy clay loam	2.1	6.6	6.6	140	CT	1.8	M	wheat	3.5	2.9
Iqbal et al.	2011	2	22	16	20	35	379	Pakistan	sandy clay loam	2.1	7.1	6.6	140	CT	2.6	M	wheat	2.9	2.9
Dalal et al.	2011	40	65	24	30	18	685	Australia	clay	19.0	18.9	18.7	0			M	wheat		
Dalal et al.	2011	40	65	24	30	18	685	Australia	clay	19.0	19.3	18.9	30			M	wheat		
Dalal et al.	2011	40	65	24	30	18	685	Australia	clay	19.0	19.6	18.7	90			M	wheat		
Lou et al.	2011	12	15	68	20	7	450	China	silt loam	9.8	7.5	7.3	0	CT	0.3	I	maize	0.7	0.6
Lou et al.	2011	12	15	68	20	7	450	China	silt loam	9.8	7.8	7.3	0	CT	0.4	I	maize	0.9	0.6
Lou et al.	2011	12	15	68	20	7	450	China	silt loam	9.8	8.5	7.3	0	CT	0.8	I	maize	0.9	0.6
Lou et al.	2011	12	15	68	20	7	450	China	silt loam	9.8	9.0	7.7	83	CT	1.0	I	maize	2.6	2.0
Lou et al.	2011	12	15	68	20	7	450	China	silt loam	9.8	9.8	7.7	83	CT	1.7	I	maize	3.6	2.0
Lou et al.	2011	12	15	68	20	7	450	China	silt loam	9.8	11.3	7.7	83	CT	2.9	I	maize	3.7	2.0
Lou et al.	2011	12	15	68	20	7	450	China	silt loam	9.8	9.9	9.1	248	CT	2.0	I	maize	4.4	4.0

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Lou et al.	2011	12	15	68	20	7	450	China	silt loam	9.8	11.3	9.1	248	CT	3.2	I	maize	5.4	4.0
Lou et al.	2011	12	15	68	20	7	450	China	silt loam	9.8	12.6	9.1	248	CT	4.5	I	maize	5.4	4.0
Malhi et al.	2011	28	20	40	15	2	475	Canada	loam	13.8	12.0	10.0	0	NT		M	cereal-canola		
Malhi et al.	2011	28	20	40	15	2	475	Canada	loam	13.8	10.0	9.7	0	NT		I	cereal-canola		
Sommer et al.	2011	5	65	10	15	17	349	Syria	clay	6.1	6.5	6.3	40	CT		R	cereal-legume		
Sommer et al.	2011	5	65	10	15	17	349	Syria	clay	6.1	8.3	8.8	40	MT		I	cereal-legume		
McHunu et al.	2011		17	15	15	13	684	South Africa	sandy loam	10.5	14.8	11.1		NT		M	maize		
Sarkar & Kar	2011	3	18	23	30	27	1200	India	sandy loam	3.4	3.3	4.3	100	MT			rice	4.5	4.2
Sarkar & Kar	2011	3	18	23	30	27	1200	India	sandy loam	3.4	3.3	4.3	100	MT			wheat	1.5	1.4
Canellas et al.	2010	55	40	37	40	25	1080	Brazil	clay loam/ clay		21.7	12.5				I	sugarcane		
Sombrero & de Benito	2010	10	35	35	30	10	448	Spain	clay loam	10.5	14.5	11.7	182	MT	1.8	M	cereal		
Sombrero & de Benito	2010	10	35	35	30	10	448	Spain	clay loam	10.5	15.8	11.7	182	NT	1.9	M	cereal		
Samahadthaiy et al.	2010	10	2	5	15	28	1200	Thailand	sand	2.1	2.3	1.5					rice-groundnut		
Samahadthaiy et al.	2010	10	2	5	15	28	1200	Thailand	sand	2.1	3.3	1.5					rice-groundnut		
Samahadthaiy et al.	2010	10	2	5	15	28	1200	Thailand	sand	2.1	3.0	1.5					rice-groundnut		
Samahadthaiy et al.	2010	10	2	5	15	28	1200	Thailand	sand	2.1	3.7	1.5					rice-groundnut		

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Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm $year^{-1}$)	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} $year^{-1}$)	TILL	C-INPUT (t C ha^{-1} $year^{-1}$)	RES. APPL	Crop	YIELD R+(t ha^{-1} $year^{-1}$)	YIELD R-(t ha^{-1} $year^{-1}$)
Halpern et al.	2010	16	10	9	20	6	979	US	loamy sand	25.3	25.0	24.1	180	CT	29.5	R	maize		
Halpern et al.	2010	16	10	9	20	6	979	US	loamy sand	26.3	34.2	27.6	180	MT	27.1	I	maize		
Halpern et al.	2010	16	10	9	20	6	979	US	loamy sand	28.5	33.6	27.3	180	NT	27.6	M	maize		
Du et al.	2010	7	20	66	30	12	536	China	silt loam		10.1	9.9	250	CT	3.7	I	wheat		
Du et al.	2010	7	20	66	30	12	536	China	silt loam		10.2	9.9	250	MT	3.7	M	wheat		
Du et al.	2010	7	20	66	30	12	536	China	silt loam		9.9	9.9	250	NT	3.4	M	wheat		
Sharma et al.	2010	3	26	23	20	20	950	India	sandy clay loam	5.9	6.3	6.0	120	CT	4.8	I	rice-wheat	6.5	3.1
Sharma et al.	2010	3	26	23	20	20	950	India	sandy clay loam	5.9	6.6	6.0	120	CT	7.4	I	rice-potato-mungbean	5.9	5.3
Sharma et al.	2010	3	26	23	20	20	950	India	sandy clay loam	5.9	6.5	6.0	120	CT	6.9	I	rice-rapessed-mungbean	5.1	5.9
Sharma et al.	2010	3	26	23	20	20	950	India	sandy clay loam	5.9	6.5	5.9	120	CT	7.3	I	rice-potato-mungbean	5.1	5.9
Sharma et al.	2010	3	26	23	20	20	950	India	sandy clay loam	5.9	6.6	6.0	120	CT	8.3	I	rice-rapessed-mungbean	5.8	5.1
Sharma et al.	2010	3	26	23	20	20	950	India	sandy clay loam	5.9	6.5	5.9	120	CT	6.5	I	rice-wheat	4.7	5.8
Sharma et al.	2010	3	26	23	20	20	950	India	sandy clay loam	5.9	6.6	6.0	120	CT	7.9	I	rice-rapessed-mungbean	4.6	5.1
Sharma et al.	2010	3	26	23	20	20	950	India	sandy clay loam	5.9	6.4	6.1	120	CT	6.4	I	rice-wheat	5.2	4.6

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Sharma et al.	2010	3	26	23	20	20	950	India	sandy clay loam	5.9	6.5	5.9	120	CT	7.3	I	rice-potato-mungbean	0.0	0.0
Anyanzwa et al.	2010	2	8	7	15	22	707	Kenya	sandy	8.3	15.8	6.9	60	MT	1.6	M	maize	3.3	2.6
Anyanzwa et al.	2010	2	8	7	15	22	707	Kenya	sandy	8.3	15.8	6.9	60	MT	2.2	M	maize	4.5	3.4
Anyanzwa et al.	2010	2	8	7	15	22	707	Kenya	sandy	8.3	18.8	7.2	60	MT	1.7	M	maize	3.6	2.0
Anyanzwa et al.	2010	2	8	7	15	22	707	Kenya	sandy	8.3	18.8	7.2	60	MT	2.6	M	maize	5.4	5.0
Anyanzwa et al.	2010	2	8	7	15	22	707	Kenya	sandy	8.3	18.8	7.2	60	MT	1.7	M	soyabean	0.3	0.3
Anyanzwa et al.	2010	2	8	7	15	22	707	Kenya	sandy	8.3	18.8	7.2	60	MT	2.6	M	soyabean	0.4	0.4
Walia et al.	2010	23	10	15	30	24	713	India	loamy sand	3.1	3.5	3.3	50				rice wheat		
Walia et al.	2010	23	10	15	30	24	713	India	loamy sand	3.1	3.6	3.3	50				rice wheat		
Du et al.	2009	25	9	70	20	15	500	China	silt loam	6.7	6.2	4.9	180	CT	1.9	I	wheat-maize		
Du et al.	2009	25	9	70	20	15	500	China	silt loam	6.7	6.7	4.9	180	CT	3.8	I	wheat-maize		
Koga & Tsuji	2009	4	22	25	30	6	902	Japan	sandy clay loam	34.5	34.5	33.6		MT	1.9	M	wheat	3.4	3.2
Koga & Tsuji	2009	4	22	25	30	6	902	Japan	sandy clay loam	34.6	34.0	33.4		CT	1.7	I	wheat	3.4	3.2
Koga & Tsuji	2009	4	22	25	30	6	902	Japan	sandy clay loam	34.6	34.0	33.4		CT	1.9	I	wheat	3.3	2.9
Koga & Tsuji	2009	4	22	25	30	6	902	Japan	sandy clay loam	34.5	34.5	33.6		MT	1.7	M	wheat	3.4	3.3

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Benbi & Senapati	2010	7	17	24	15	21	750	India	sandy loam	4.8	6.8	5.7			18.0	I	wheat-rice		
Gami et al.	2009	23	35	35	30	22	1800	Nepal	clay loam		5.7	5.0	100	CT	3.4		rice-wheat		
Patiño-Zúñiga et al	2009	8	38	37	15	14	600	Mexico	clay loam		13.2	10.4	120	NT		M	maize		
Fuentes et al.	2009	14	38	37	20	14	600	Mexico	clay loam		17.7	12.2	120	NT	2.4	M	maize	5.0	3.2
Fuentes et al.	2009	14	38	37	20	14	600	Mexico	clay loam		16.4	13.1	120	NT	2.6	M	maize	5.5	4.5
Fuentes et al.	2009	14	38	37	20	14	600	Mexico	clay loam		15.0	12.4	120	CT	0.7	I	maize	1.5	3.2
Fuentes et al.	2009	14	38	37	20	14	600	Mexico	clay loam		14.6	13.2	120	CT	1.8	I	maize	3.8	4.2
Fuentes et al.	2009	14	38	37	20	14	600	Mexico	clay loam		16.0	14.9	120	NT	3.4	M	maize	7.0	6.2
Fuentes et al.	2009	14	38	37	20	14	600	Mexico	clay loam		16.3	12.5	120	NT	3.7	M	maize	7.7	6.0
Fuentes et al.	2009	14	38	37	20	14	600	Mexico	clay loam		14.0	13.6	120	CT	2.5	I	maize	5.3	5.2
Fuentes et al.	2009	14	38	37	20	14	600	Mexico	clay loam		15.1	12.6	120	CT	1.9	I	maize	4.0	5.2
Lafond et al.	2009	50	60	20	15.2	8	434	Canada	clay		41.9	41.4	80	CT	1.4	I	wheat	2.3	2.2
Yadvinder-Singh et al.	2009	3	28	13	15	24	713	India	sandy clay loam	3.6	4.4	3.5		CT	3.7	B/I	wheat	6.3	6.6
Yadvinder-Singh et al.	2009	3	28	13	15	24	713	India	sandy clay loam	3.6	4.8	3.6		NT	3.7	B/M	wheat	6.3	6.4
Yadvinder-Singh et al.	2009	3	18	50	15	24	713	India	sandy clay loam	5.6	6.5	6.0		CT	3.7	B/I	wheat	7.1	7.0
Yadvinder-Singh et al.	2009	3	18	50	15	24	713	India	sandy clay loam	5.6	6.8	6.1		NT	3.7	B/M	wheat	6.9	7.0
Adiku et al.	2009	4	30	10	20	28	1200	Ghana	sandy clay loam	18.1	14.7	8.5	0			M	maize		
Bakht et al.	2009	3	35	55	30	23	364	Pakistan	silt clay loam	5.2	5.1	5.0		CT		I	wheat	2.3	1.9

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Bakht et al.	2009	3	35	55	30	23	364	Pakistan	silt clay loam	5.2	5.2	5.1		CT		I	wheat	2.9	2.1
Bakht et al.	2009	3	35	55	30	23	364	Pakistan	silt clay loam	5.2	5.6	5.2		CT		I	wheat	2.6	2.0
Kang et al.	2009	3	10	15	15	24	427	India	loamy sand	3.9	4.8	4.5		CT		I	wheat	6.3	5.9
Kang et al.	2009	3	20	40	15	24	850	India	loam	4.4	5.3	5.1	60	CT	2.9	I	wheat	6.5	6.5
Kang et al.	2009	3	20	40	15	24	850	India	loam	4.4	5.7	5.1	60	CT	2.4	I	wheat	6.8	6.5
Sandoval-Estrada et al.	2008	3	15	65	15	11	1102	Chile	silt loam								wheat	6.7	6.8
Singh et al.	2008	3	35	55	15	24	881	India	silt clay loam	2.4	2.6	2.5	181	CT	0.5	I	sorghum	1.2	1.2
Singh et al.	2008	3	35	55	15	24	881	India	silt clay loam	2.4	2.6	2.5	181	CT	0.5	I	sorghum	1.1	1.0
Yaduvanshi & Sharma	2008	3	23	25	15	24	814	India	sandy clay loam	2.1	2.7	2.3	90		1.8	M	wheat	2.9	2.9
Yaduvanshi et al.	2008	3	23	25	15	24	814	India	sandy clay loam	2.1	2.7	2.3	90		1.9	M	wheat	2.9	2.5
Yaduvanshi et al.	2008	3	23	25	15	24	814	India	sandy clay loam	2.1	2.7	2.3	90		1.6	M	wheat	2.5	2.2
Yaduvanshi et al.	2008	3	23	25	15	24	814	India	sandy clay loam	2.1	2.9	2.4	120		2.2	M	wheat	3.5	3.7
Yaduvanshi et al.	2008	3	23	25	15	24	814	India	sandy clay loam	2.1	2.9	2.4	120		2.4	M	wheat	3.7	3.6
Yaduvanshi et al.	2008	3	23	25	15	24	814	India	sandy clay loam	2.1	2.9	2.4	120		2.3	M	wheat	3.6	3.3
Monaco et al.	2008	11	9	43	30	12	792	Italy	sandy loam	11.6	12.0	9.9	200	CT	5.7	I	maize		
Manojlovic et al.	2008	33			30	11	608	Serbia	loam		1.6	1.4	130	CT		I	maize		

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Yan et al.	2007	25	20	40	15	16	1250	China	loam	14.0	18.8	17.6	150		1.0		wheat		
Singh et al.	2007	16	13	9	15	24	713	India	loamy sand	3.6	5.6	4.2	240	CT	2.7	I	wheat-rice		
Singh et al.	2007	16	13	9	15	24	713	India	loamy sand	3.6	5.9	4.2	240	CT	5.9	I	wheat-rice		
Potter et al.	2007	7	12	25	20	20	785	Mexico	sandy loam		5.8	5.7		NT	0.7	M	maize		
Potter et al.	2007	7	12	25	20	20	785	Mexico	sandy loam		5.8	5.7		NT	1.4	M	maize		
Potter et al.	2007	7	12	25	20	20	785	Mexico	sandy loam		6.0	5.7		NT	2.1	M	maize		
Potter et al.	2007	5	12	40	20	17	1099	Mexico	loam		12.3	11.1		NT	0.6	M	maize		
Potter et al.	2007	5	12	40	20	17	1099	Mexico	loam		17.8	11.1		NT	1.2	M	maize		
Potter et al.	2007	5	12	40	20	17	1099	Mexico	loam		18.1	11.1		NT	1.8	M	maize		
Potter et al.	2007	7	16	59	20	16	998	Mexico	silt loam		55.8	50.9		NT	0.6	M	maize		
Potter et al.	2007	7	16	59	20	16	998	Mexico	silt loam		59.4	50.9		NT	1.3	M	maize		
Potter et al.	2007	7	16	59	20	16	998	Mexico	silt loam		62.5	50.9		NT	1.9	M	maize		
Potter et al.	2007	7	59	19	20	27	650	Mexico	clay		6.6	6.8		NT	0.5	M	maize		
Potter et al.	2007	7	59	19	20	27	650	Mexico	clay		7.0	6.8		NT	1.2	M	maize		
Potter et al.	2007	7	59	19	20	27	650	Mexico	clay		7.3	6.8		NT	1.7	M	maize		
Potter et al.	2007	8	47	40	20	18	828	Mexico	silt clay/ clay		10.8	7.6		NT	0.5	M	maize		
Potter et al.	2007	8	47	40	20	18	828	Mexico	silt clay/ clay		12.7	7.6		NT	1.0	M	maize		
Potter et al.	2007	8	47	40	20	18	828	Mexico	silt clay/ clay		14.5	7.6		NT	1.8	M	maize		
Potter et al.	2007	4	77	22	20	20	800	Mexico	clay		14.3	14.0		NT	0.9	M	maize		
Potter et al.	2007	4	77	22	20	20	800	Mexico	clay		13.1	14.0		NT	1.7	M	maize		

Database used for the analysis of the effect of crop residue management on SOC and yield

Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm year^{-1})	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} year^{-1})	TILL	C-INPUT (t C ha^{-1} year^{-1})	RES. APPL	Crop	YIELD R+(t ha^{-1} year^{-1})	YIELD R-(t ha^{-1} year^{-1})
Potter et al.	2007	4	77	22	20	20	800	Mexico	clay		16.5	14.0		NT	2.4	M	maize		
Chivenge et al.	2007	9	4	13	30	22	900	Zimbabwe	loamy sand		6.7	4.5	114	NT		M	maize		
Chivenge et al.	2007	9	59	20	30	22	900	Zimbabwe	clay		14.5	13.8	114	NT		M	maize		
Wang et al.	2007	11	10	20	40	8	462	China	sandy loam	15.0	14.8	14.6	105	CT	2.6	I	maize		
Blanco-Canqui & Lal	2007	10	15	65	30	12	878	US	silt loam		15.9	12.1		NT	3.4	M	wheat		
Blanco-Canqui & Lal	2007	10	15	65	30	12	878	US	silt loam		22.6	12.1		NT	6.8	M	wheat		
Virto et al.	2007	10	35	36	30	14	525	Spain	clay loam	5.9	10.2	10.2		NT		M/B	barley	3.7	3.6
Virto et al.	2007	10	35	36	30	14	525	Spain	clay loam	5.9	9.7	10.2		CT		I/B	barley	3.7	3.6
Wang & Dalal	2006	33	65	24	20	18	685	Australia	clay	16.2	19.7	19.9	0	CT		I	wheat barley		
Wang & Dalal	2006	33	65	24	20	18	685	Australia	clay	16.2	19.9	20.4	90	CT		I	wheat barley		
Wang & Dalal	2006	33	65	24	20	18	685	Australia	clay	16.2	19.6	19.5	0	NT		M	wheat barley		
Wang & Dalal	2006	33	65	24	20	18	685	Australia	clay	16.2	21.0	20.5	90	NT		M	wheat barley		
Monneveux et al.	2006	3	41	37	30	23	840	Mexico	clay/clay loam	19.0	19.2	20.1					maize		
Dolan et al.	2006	23	15	65	45	7	799	US	silt loam	25.6	18.2	17.5	200	NT			corn soyabean		
Dolan et al.	2006	23	15	65	45	7	799	US	silt loam	25.6	20.4	16.4	200	MT			corn soyabean		
Dolan et al.	2006	23	15	65	45	7	799	US	silt loam	25.6	19.7	18.0	200	CT			corn soyabean		
Banerjee et al.	2006	2	35	55	15	27	750	India	silt clay loam	6.2	6.9	6.4	120	NT	0.9	M	wheat		

Database used for the analysis of the effect of crop residue management on SOC and yield

Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm $year^{-1}$)	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} $year^{-1}$)	TILL	C-INPUT (t C ha^{-1} $year^{-1}$)	RES. APPL	Crop	YIELD R+(t ha^{-1} $year^{-1}$)	YIELD R-(t ha^{-1} $year^{-1}$)
Banerjee et al.	2006	2	35	55	15	27	750	India	silt clay loam	6.2	6.4	6.3	120	CT	0.6	I	wheat		
Shittu & Fasina	2006	2	14	29	20	27	1367	Nigeria	sandy loam	1.8	1.1	0.7			1.4	I	maize	3.0	3.1
Shittu & Fasina	2006	2	14	29	20	27	1367	Nigeria	sandy loam	1.8	1.4	0.7			1.5	M	maize	3.2	3.0
Lugato et al.	2006	35	29	37	30	13	850	Italy	clay loam	10.5	9.4	8.6	120	CT		I	maize-sugarbeet-soyabean		
Gangwar et al.	2006	3	17	19	15	25	863	India	sandy loam	4.0	5.5	5.1	135		2.1	I	wheat	4.7	4.1
Gangwar et al.	2006	3	17	19	15	25	863	India	sandy loam	4.0	5.5	5.1	135		2.1	I	wheat	4.2	3.6
Gangwar et al.	2006	3	17	19	15	25	863	India	sandy loam	4.0	5.5	5.1	135		2.1	I	wheat	5.9	5.4
Scopel et al.	2005	5	15	25	20	25	525	Mexico	sandy loam		8.0	7.0		NT	0.4	M	maize	1.2	0.8
Scopel et al.	2005	5	15	25	20	25	525	Mexico	sandy loam		8.0	7.0		NT	0.4	M	maize	2.8	1.6
Scopel et al.	2005	5	15	25	20	25	525	Mexico	sandy loam		8.0	7.0		NT	0.4	M	maize	4.2	2.0
Scopel et al.	2005	5	15	25	20	25	525	Mexico	sandy loam		8.0	7.0		NT	0.4	M	maize	3.7	0.4
Scopel et al.	2005	5	15	25	20	25	525	Mexico	sandy loam		8.0	7.0		NT	0.4	M	maize	3.4	1.9
Scopel et al.	2005	5	15	25	20	25	525	Mexico	sandy loam		8.2	7.0		NT	1.1	M	maize	2.2	0.8
Scopel et al.	2005	5	15	25	20	25	525	Mexico	sandy loam		8.2	7.0		NT	1.1	M	maize	3.2	1.6
Scopel et al.	2005	5	15	25	20	25	525	Mexico	sandy loam		8.2	7.0		NT	1.1	M	maize	4.3	2.0
Scopel et al.	2005	5	15	25	20	25	525	Mexico	sandy loam		8.2	7.0		NT	1.1	M	maize	4.2	0.4
Scopel et al.	2005	5	15	25	20	25	525	Mexico	sandy loam		8.2	7.0		NT	1.1	M	maize	3.8	1.9
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	5.7	3.6	0	CT	0.9	M	sorghum-castor	0.6	0.7
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	5.0	3.6	0	CT	0.9	M	sorghum-castor	1.1	1.0

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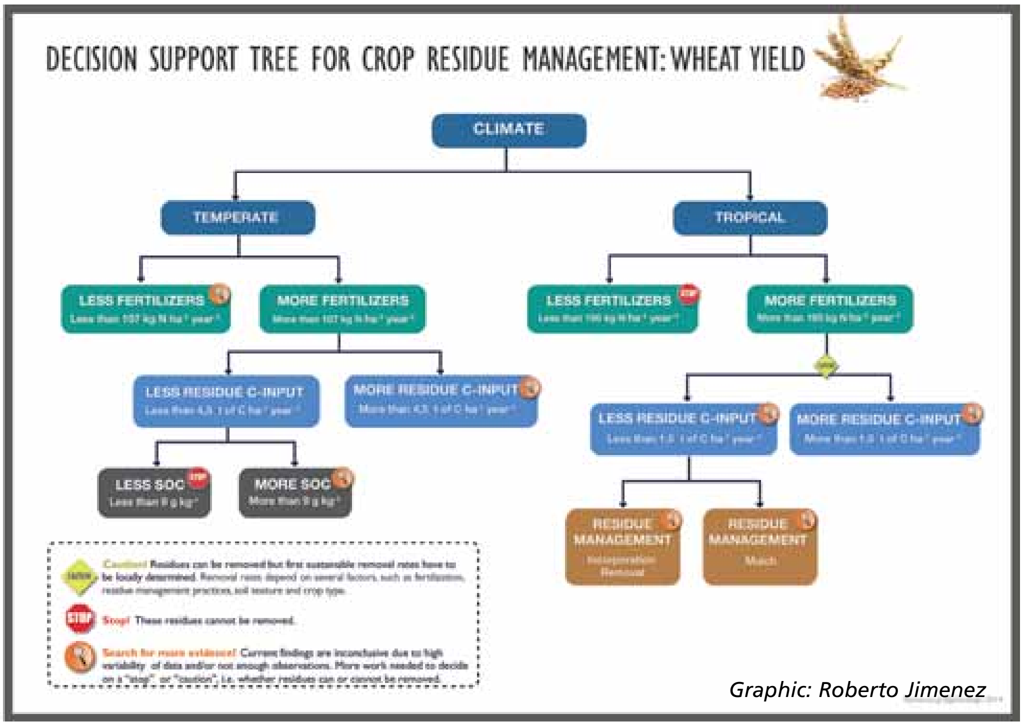
Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm $year^{-1}$)	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} $year^{-1}$)	TILL	C-INPUT (t C ha^{-1} $year^{-1}$)	RES. APPL	Crop	YIELD R+(t ha^{-1} $year^{-1}$)	YIELD R-(t ha^{-1} $year^{-1}$)
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	5.3	3.6	30	CT	0.9	M	sorghum-castor	1.4	1.3
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	5.6	3.6	30	CT	0.6	M	sorghum-castor	1.5	1.4
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	6.1	3.8	60	CT	0.9	M	sorghum-castor	0.7	0.7
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	6.6	3.8	60	CT	0.6	M	sorghum-castor	1.1	1.0
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	6.2	4.0	90	CT	0.9	M	sorghum-castor	1.5	1.3
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	6.4	4.0	90	CT	0.6	M	sorghum-castor	1.6	1.4
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	5.4	4.3	0	MT	0.8	M	sorghum-castor	0.5	0.6
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	4.0	4.3	0	MT	0.8	M	sorghum-castor	0.8	0.8
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	5.7	4.4	30	MT	0.8	M	sorghum-castor	0.9	0.9
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	4.5	4.4	30	MT	0.8	M	sorghum-castor	1.0	1.0
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam										
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	6.0	4.5	60	MT	0.8	M	sorghum-castor	0.5	0.6
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	5.5	4.5	60	MT	0.8	M	sorghum-castor	0.9	0.8
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam										
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	5.8	4.5	90	MT	0.8	M	sorghum-castor	1.0	0.9

Database used for the analysis of the effect of crop residue management on SOC and yield

Authors and date	Date	Years	Clay (%)	Silt (%)	Depth (cm)	T (oC)	Precipitation (mm year^{-1})	Location	Texture	SOC I (g kg^{-1})	SOC R+(g kg^{-1})	SOC R-(g kg^{-1})	FERT (kg N ha^{-1} year^{-1})	TILL	C-INPUT (t C ha^{-1} year^{-1})	RES. APPL	Crop	YIELD R+(t ha^{-1} year^{-1})	YIELD R-(t ha^{-1} year^{-1})
Sharma et al.	2005	7	13	10	15	26	746	India	sandy loam	3.7	6.3	4.5	90	MT	0.8	M	sorghum-castor	1.1	1.0
Williams	2004	53	15	65	60	11	422	Canada	silt loam	5.7	5.0	4.6	90	CT		I	wheat		
Zeleke et al.	2004	3	20	32	15	19	990	Ethiopia	loam	3.9	6.5	3.9	0	CT		I	maize		
Zeleke et al.	2004	3	20	32	15	19	990	Ethiopia	loam	3.9	8.1	5.5	100	CT		I	maize		
Zeleke et al.	2004	3	20	32	15	19	990	Ethiopia	loam	5.5	6.1	5.5	0	CT		I	maize		
Zeleke et al.	2004	3	40	14	15	20	1317	Ethiopia	sandy clay	5.5	9.0	8.3	100	CT		I	maize		
Ibno Namr & Mrabet	2004	18	60	20	20	20	349	Morocco	clay	13.0	14.3	14.2		NT		M	wheat		
Ibno Namr & Mrabet	2004	18	60	20	20	20	349	Morocco	clay	13.0	14.1	14.2		NT		M	wheat		
Odunze	2003	2	15	20	15	24	1074	Nigeria	sandy loam	5.7	6.7	6.3					maize		
Odunze	2003	2	15	20	15	24	1074	Nigeria	sandy loam	5.7	7.8	6.3					maize		
Surekha et al.	2003	5	27	15	15	24	988	India	sandy clay loam	10.8	12.1	11.5	220	CT	1.5	I	rice	5.0	4.7
Surekha et al.	2003	5	27	15	15	24	988	India	sandy clay loam	10.8	12.5	11.5	220	CT	2.2	I	rice	5.4	4.7
Mubarak et al.	2003	2	34	5	30			Malaysia	sandy clay loam	1.3	11.7	11.5				I	maize-groundnut		
Curtin & Fraser	2003	6	27	67	15	11	680	New Zealand	silt loam / silt clay loam		31.3	31.6	125	CT	2.2	I	wheat	5.3	5.3

Database used for the analysis of the effect of crop residue management on SOC and yield

APPENDIX VII – EXAMPLE OF A DECISION SUPPORT TREE FOR CROP RESIDUE MANAGEMENT



Graphic: Roberto Jimenez

ENVIRONMENT – CLIMATE CHANGE – BIOENERGY – MONITORING AND ASSESSMENT

FAO - ENVIRONMENT AND NATURAL RESOURCES MANAGEMENT WORKING PAPER

In the last decade, the increased interest in bioenergy production has led to the need for improved crop residue management. Crop residues have historically been used for many other purposes: to sustain healthy soils for food production, as feed and bedding for livestock, and as raw material for heating and cooking. As the link between crop residue management and food security is evident, one needs to decide whether or to which extent the removal of crop residues for bioenergy production is possible. Building science-based decision support tools can guide stakeholders in this decision process. The study presents a first attempt in designing such a decision support tool for soil residue management.

The study seeks to explore the effect of crop residue management on soil quality and yield, two crucial aspects for food security. More than 1 000 peer-reviewed journal papers of the past ten years were studied in order to assess (i) whether crop residue application is associated with higher soil organic carbon (SOC), (ii) whether it ameliorates soil structure and (iii) if the change in SOC related to residue application has a positive impact on yields.

The findings of this report demonstrate that crop residue management has to be contextualized, suggesting the need for site-specific residue management schemes. In coarse soils located in tropical climates and in SOC-depleted soils located in temperate climates, crop residue removal is not advisable.

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