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Crop residue management and soil health: A systems analysis

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ABSTRACT

Due to the scarcity of alternative organic amendments, the retention of crop residue in fields can be considered key in promoting physical, chemical, and biological attributes of soil health in agricultural systems of developing countries. However, due to multiple other uses, small landholders in these countries are faced with trade-offs in managing crop residues. This article reviews crop residue management practices, mainly surface retention, incorporation or removal, describing their advantages and limitations in cereal-based agroecosystems in developing countries. The benefits of residue retention are regionally variable and depend on both agroclimatic and socioeconomic factors. Most studies from developing countries in Asia, Latin America, and Africa show positive effects of retaining crop residues on soil quality, soil organic matter and carbon storage, soil moisture retention, enhanced nutrient cycling, and decreased soil loss, among other environmental and soil health benefits. Variation was observed in the effect of surface retention vs. incorporation on various soil properties indicating the importance of taking into account abiotic factors such as climate, soil texture, study duration, sampling methods, and agronomic practices when assessing the impact of these practices. Negative effects of residue retention on crop performance attributed to nitrogen immobilization, waterlogging and decreased soil temperature have also been reported in some environments. Residue trade-offs in mixed crop-livestock systems in developing countries can limit the amount of residue retained. However, interventions such as intensification, partial retention, improved return of nutrients from manures, and the provision of substitutes to the current functions of livestock (e.g. mechanization, insurance) could reduce these residue trade-offs in favour of promoting long-term soil health.

1. Introduction

The world's human population has increased four times in the last century alone. This population boom, in part a result of improved agricultural and industrial techniques, places continued pressure on food production in order to feed the growing numbers. Intensified food production over the years has taken a toll on the health of agricultural soils (FAO, 2011) as well as their quality (Verhulst et al., 2010a). Increased soil degradation in turn is linked to decreases in crop yields, which have been clearly observed in parts of Africa, Asia, and Latin America (Kaiser, 2004). Soil health is defined as "the capacity of soil to function as a living system" (FAO, 2011), while soil quality is its "fitness for use" (Larson and Pierce, 1994). In an agricultural context, high soil quality means a highly productive soil with low levels of degradation (Fuentes et al., 2009). Soil quality for sustainable crop production is related to soil health. As a living system the soil consists of organisms whose activities include nutrient cycling, symbiotic relationships with plant roots, pest, weed and disease control, and soil aggregate formation and aeration which influence susceptibility to erosion and water infiltration. A healthy soil is rich in organic matter which allows a high diversity of soil organisms to flourish and act as a reservoir of soil nutrients and moisture. The addition of regular inputs of organic amendment is necessary to increase or maintain soil organic matter content and thus contributes to soil health (FAO, 2011).

The most ready and accessible form of biomass is crop residue, the biomass that remains after a crop is harvested. The residue derived from crops is considered "the greatest source of soil organic matter" (Tisdale et al., 1985) for agricultural soils. Among the major cereal crops that produce large amounts of crop residue are maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L.), and rice (*Oryza sativa* L.) (Blanco-Canqui and Lal,

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2009). The global area harvested for these crops in 2010 was about 217 million ha for wheat, 162 million ha for maize, 154 million ha for rice, and 41 million ha for sorghum (FAO, 2012). Maize and wheat alone make up the main source of 40% of foods consumed worldwide, with people in developing countries obtaining 25% of their calories from them (Aquino-Mercado et al., 2008). Incorporating residue or retaining crop residue on the soil surface is known to have multiple benefits on soil quality (Wilhelm et al., 2007; Blanco-Canqui and Lal, 2009). However, small landholders in developing countries are faced with a trade-off in managing crop residue. Residues may be removed completely for use as biofuel or livestock feeding or grazed in situ by livestock. Farmers may also burn off crop residue to "clear" the field for tillage and planting. A change in traditional crop residue management is conditioned by the long-term environmental and economic benefits of retaining crop residues. This article reviews the literature on the influence of crop residue management and trade-offs on soil quality and health in order to examine its advantages and limitations in cereal-based agroecosystems. The review focuses on studies examining physical, chemical and biological properties of agricultural soils in developing countries where animal pressure on crop residue often poses a trade-off on maintaining soil quality, and high levels of soil degradation threaten the sustainability of agricultural systems.

2. Management practices relating to crop residue

The residue from cereal crops is managed and used in several ways. Those farmers that raise livestock remove the residue to feed their animals or else allow their own or neighbors' livestock to graze on their fields. Some sell it to be used as animal fodder or as biofuel to supplement their income, while still others burn it because there is no market for the crop residue or remove it because it is sometimes easier to use machinery without crop residues on the field (Erenstein, 2002). In the case that crop residues are retained, they may either be left on the soil surface or incorporated into the soil. These different residue retention practices are associated with different tillage practices and thus it can be difficult to separate the effects on soil quality. Conventional tillage (CT) practices often involve initial tillage by moldboard plowing, followed by secondary tillage by disking, harrowing or field cultivating. This form of tillage buries all superficial crop residues in the soil (Tisdale et al., 1985). Farmers in developing countries with poor access to herbicides rely on tillage for weed control thus incorporating residues in the process. Some farmers in regions where open range grazing is practiced, such as the Central Mexican Plateau, opt to incorporate their residues to protect them from grazing by their neighbor's animals (Personal communication, Mexico, 2012). 'Winter ploughing' i.e. ploughing crop residues into the soil after harvest, when the soil is still moist, is also a common practice in certain areas of Southern Africa (see e.g. Rufino et al., 2011).

Retaining crop residue on the soil surface is considered by many to maintain physical, chemical, and biological properties in agricultural soils (Wilhelm et al., 1986; Wilhelm et al., 2007). Agricultural systems using zero or reduced tillage such as conservation agriculture recommend a permanent or semi-permanent organic soil cover (Fuentes et al., 2009). Some general types of conservation tillage that retain crop residue, leaves and roots on or near the surface include chiseling, stubble mulching, and no-till (NT) (Tisdale et al., 1985). When using NT systems, it is particularly essential to leave residue on the surface rather than remove it as the combination of NT with residue removal or burning may have an even greater negative effect on soil quality in the long-term than CT practices due to excessive soil compaction and reduced water infiltration (Baudron et al., 2012; Govaerts et al., 2006a).

Feeding crop residues to livestock is a very common practice in developing countries, where the bulk of milk and meat is produced by mixed crop-livestock smallholdings (Herrero et al., 2010; Valbuena et al., 2012). In most systems, simultaneously fulfilling livestock demand for crop residues and retaining in the fields (incorporated or as surface mulch) quantities that are adequate to maintain soil fertility cannot be achieved i.e. trade-offs exist. The strength of these crop residue trade-offs depends on several factors including (1) the benefits vs. the (opportunity) costs of residue retention, (2) the intensity of the production systems considered, and (3) the existence or not of alternatives to the functions livestock is playing, in addition to the production of animal products (see Section 4 below).

3. Influence of crop residue on soil quality

Crop residue returns organic matter to the soil where it is retained through a combination of physical, chemical, and biological activities that interact and affect soil quality, including nutrient cycling (Fig. 1). The influence of residue management on some important chemical properties (soil organic carbon, soil pH and cation exchange capacity), on physical properties (soil structure, runoff, erosion, soil compaction, soil temperature, and moisture content), and on biological properties (soil biodiversity and soil microbial biomass) are discussed below. Crop yield results that may be presented in this paper are done so in the context of the contribution to crop residue after harvest, since greater crop yields will leave greater crop residue after harvest. Moreover, if better yields allow for sufficient levels of crop residue cover, then a greater quantity of residue will be available for animal feed or other purposes (Lal, 1995; Govaerts et al., 2005).

3.1. Influence on soil chemical properties

3.1.1. Soil organic carbon

Soil organic carbon (SOC) is considered an important indicator of soil quality and agricultural sustainability because it improves soil aggregate stability and soil water retention, and provides a reservoir of soil nutrients (Liu et al., 2006). SOC is naturally removed from the soil through soil heterotrophic and autotrophic respiration, where carbon (C) is released as CO_2. However, human activities such as land-use changes, in particular conversion to agricultural fields and pasture, removal of crop residues and direct feeding to livestock, release even greater amounts of C into the atmosphere as CO_2 (Prentice et al., 2001). Agricultural practices disturb the SOC pool, which represents a large potential source of greenhouse gasses; soil C loss can thus lead to lower soil quality and pressure on sustainable crop production and food security (Lal, 2004, 2007).

SOC levels can be maintained by either increasing organic matter inputs, slowing down decomposition rates or both (Paustian et al., 1997a). Nutrient availability and carbon storage depend on soil organic matter (SOM) content, which can be divided into the labile pool and the humus pool. The labile pool is easily decomposed by microorganisms, while the humus pool is more resistant to decomposition and therefore allows for carbon storage in the soil. This pool remains stable through both physical and chemical stabilization (Oades, 1993). Crop residue contributes directly to SOM and its decomposition is the initial stage in the humus formation process leading to C storage.

Crop residue retention is key to increasing and/or maintaining SOC levels; however, its effect may be controlled by soil type, climate and management factors (Govaerts et al., 2009b). For example in Zimbabwe, Chivenge et al. (2007) measured higher SOC in sandy soils under the mulch ripping treatment with residue

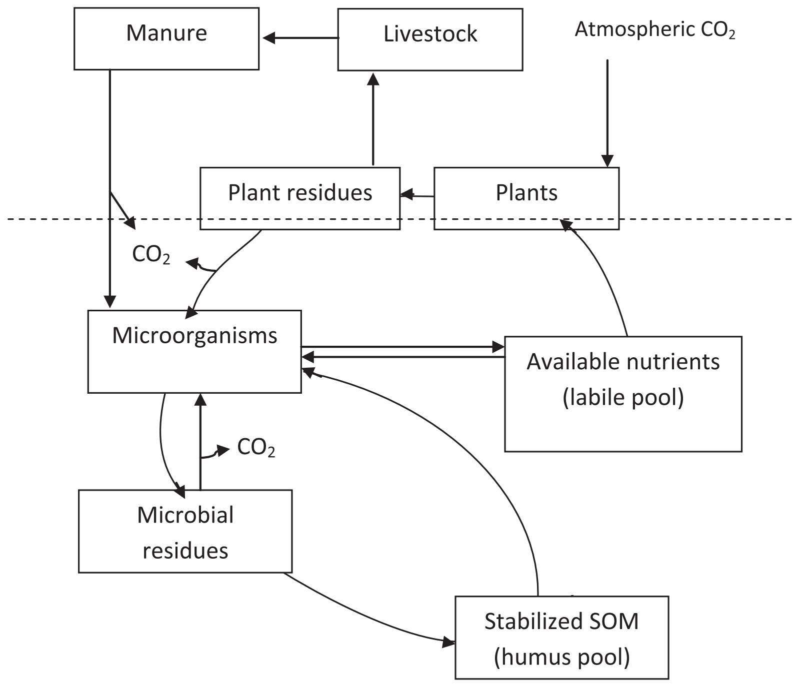

Fig. 1. Simplified model of plant residue inputs transformed by soil microorganisms. Plants capture carbon from the atmosphere through photosynthesis and produce plant residue biomass. In mixed crop-livestock systems, livestock consume part of the crop residues. Manures that contain some available nutrients are returned to the soil and further decomposed by microorganisms. Residues that are retained in the soil are decomposed by microorganism. Decomposition and respiration produce CO_2 and microbial residue which releases nutrients (C, N, S, and P). These are then taken up by plants, thus restarting the cycle. Organic residue is also physically and chemically stabilized in the soil as humus [adapted from McGill and Cole (1981)].

retention compared to clean ripping with residue removed, and attributed this to the residue retention. The soil type (sandy soil with greater coarse fractions) appeared to play a role since no significant differences in SOC were observed in red clay soils with the same experiment.

Climatic factors that influence decomposition rates can also affect the potential amount of SOC accumulation with residue surface retention vs. incorporation. Salinas-Garcia et al. (2001) examined organic C sequestration under rain-fed maize production in two different regions in Mexico, Apatzingán and Casas Blancas, during a 6-year experiment. In both regions, the authors found that SOC content was greater, 46% in Casas Blancas and 39% in Apatzingán, under all four conservation tillage treatments with residues retained (NT with 100%, with 66% and with 33% amount of residue, and minimum tillage) compared to the conventional tillage treatment (disking and disk plowing) and NT with 0% residue. This was likely because crop residue on the surface under no-tillage comes less in contact with soil microorganisms (Salinas-Garcia et al., 2001), and therefore decomposition is more gradual compared to conventional tillage where residue comes in close contact with microorganisms when mixed in the soil (Reicosky et al., 1997). Similarly, in Varanasi, India, another region with high temperatures and decomposition rates, SOC and total N were highest under minimum tillage with residue retained on the surface compared to incorporation (Kushwaha et al., 2001).

Management factors such as incorporating by tillage or leaving crop residue on the soil surface additionally influence the effect of crop residue retention on SOC in the soil profile. Conventional tillage is usually considered responsible for C losses by increasing decomposition rates (Reicosky, 2003). Tillage disturbs soil structural stability (Kay, 1990) and redistributes organic matter, influencing microbial activity at the soil surface that releases carbon (Carter, 1986). In this way, cultivation has led to a 30–50% reduction in pre-cultivation SOC levels in agricultural soils (Schlesinger, 1985). However, a meta-analysis of soil C case studies by Govaerts et al. (2009b) found inconclusive results. In 7 of the 78 cases examined, the soil C stock was lower in zero tillage compared to conventional tillage; in 40 cases it was higher, and in 31 cases there was no significant difference. In choosing adequate management practices, understanding decomposition and SOM stabilization is key in predicting the fate of carbon, as well as nutrients, added to the soil through crop residue and other soil amendments (Christensen, 1987).

Although several studies have observed higher SOC content under no-tillage with residue retention (Burle and Mielniczuk, 1997; Paustian et al., 1997a; Bayer et al., 2000; Govaerts et al., 2009b), this practice concentrates C on the soil surface (Baker et al., 2007). In contrast, tillage affects the distribution of SOC in the soil profile by incorporating residues in the soil, thus increasing SOC in deeper layers (Yang and Wander, 1999; Gál et al., 2007; Jantalia et al., 2007). When the whole soil profile is studied the same total amount of SOC may be stored with both surface retention and incorporation (Poirier et al., 2009). In the silt loam soils of the Northern China Plain, Dong et al. (2009) found that SOC content for the conventional tillage without surface residue, rotary tillage with incorporated chopped residue, no-tillage with surface chopped residue, and no-tillage with standing residue treatments was highest in the 0–5 cm layer, but decreased with depth up to 30 cm. Under the conventional tillage with residue treatment, SOC content was highest in the 5–10 cm layer below the surface. Moldboard ploughing is usually shown to decrease C stocks, but in this study there was a significant increase in the conventional tillage with residue treatment, emphasizing once more the variable effect on SOC caused by crop residue management practices.

In order to obtain more accurate assessment of the influence of residue management practices on SOC, it is thus recommended to sample the entire plow depth (VandenBygaart and Angers, 2006) so that shallow sampling does not present a bias towards no-till practices including residue retention (Baker et al., 2007). In addition, many factors (e.g. time period, soil, climate, experiment) should be taken into account when comparing results from residue surface retention and incorporation (Ahuja et al., 2006). Although the benefits of conservation agriculture systems such as no-till with surface residue are well documented, whether it contributes more to carbon sequestration than tillage and residue incorporation remains unclear and results may depend more on soil sampling methods than on direct effects on SOC stocks (Baker et al., 2007). Moreover, the majority of the data is from research in temperate climates and information on this subject is particularly lacking in tropical and subtropical regions (Govaerts et al., 2009b).

3.1.2. Soil pH

Retention of crop residues can affect soil pH since the direction of change in soil pH is related to the chemical composition of the residue and soil properties (Tang and Yu, 1999; Xu and Coventry, 2003; Butterly et al., 2011). Residues high in ash alkalinity and nitrogen such as some legume residues will have a greater effect on pH compared to residue with lower content such as wheat (Xu and Coventry, 2003). Moreover, soil properties that affect rate of residue decomposition such as texture, moisture content, temperature, available N, SOC and initial pH control the effect of residue on soil pH (Jarvis et al., 1996). Changes in pH from crop residue addition are correlated with the concentration of organic anions in the residue and the nitrogen content of the residue (Tang and Yu, 1999; Butterly et al., 2011). The decomposition of organic anions contributes to the change in soil pH by two mechanisms: (1) decarboxylation of organic anions that consume H^+ anions; if the initial soil pH is less than the pKa of the weak acid group of the organic carbon then the H^+ will associate with the organic anions and vice versa (Bonn and Fish, 1991), and (2) ligand exchange with hydroxyl groups of aluminum and iron oxides. Mineralization of nitrogen contributes to changes in soil pH by initially consuming H^+ during the ammonification process and subsequently releasing H^+ during nitrification. Due to disequilibrium in the nitrogen cycle the overall effect is acidifying. Thus the final soil pH is determined by the balance of these reactions (Xu and Coventry, 2003).

The effect of residue retention on pH is generally restricted to the topsoil layer; however it remains unclear whether incorporation vs. surface retention has an influence. In central Mexico, Govaerts et al. (2007c) observed that after five years pH was higher (7.0) in the 0–5 cm surface layer when maize and wheat residues were retained on the surface compared to removed (6.6) or incorporated with conventional tillage (6.7), but there was no significant effect in the subsoil layer (5–20 cm). Similarly in a 5-year study in the semi-arid soils of central Spain, López-Fando and Pardo (2009) found that soil pH in the 0–5 cm layer was lower under NT with residue retained and zone tillage with paraplow (where a large amount of residue still remains on the surface) compared to CT and minimum tillage with chisel plow. However, in West Africa, Lal (1997) observed that the average soil pH decreased in both treatments where maize residues were retained on the surface and incorporated. The initial pH was 6.7 in the 0–10 cm layer which decreased in the first 3 years, but stabilized in the remaining 4 years of the study to 5.6 when residues were retained on the surface and 5.4 when incorporated.

3.1.3. Cation exchange capacity

Cation exchange capacity (CEC) is the capacity of the soil to hold cations for exchange with the soil solution and is an indicator of soil fertility. Soil residue retention increases SOM content and thus increases the soil's pH dependent CEC. As with SOM, the effect of residue on CEC may be limited to the topsoil layer (Duiker and Beegle, 2006) and it remains unclear if there is a difference between surface retention vs. incorporation. Govaerts et al. (2007c) observed that after five years, CEC increased in the topsoil when residues where retained compared to soils without residue, but there was no difference in the 5–20 cm layer. In West Africa, Lal (1997a) observed that while residue retention increased CEC both when residues were retained on the surface and incorporated, the increase in CEC was greatest when residues were retained on the surface.

3.1.4. Nutrient availability

Addition of crop residues can influence the availability of nitrogen to the crop. Addition of legume residues with a low C/N composition can result in N mineralization, whereas cereal residues with a high C/N composition can temporarily immobilize N during the decomposition process (Govaerts et al., 2006b; Aulakh et al., 1991). Denitrification losses of mineral nitrogen fertilizer can also be greater when residues are left on the surface due to higher soil moisture content and if fertilizers are not properly incorporated (Aulakh et al., 1984).

Residue retention has been found to increase the concentration of P in the top soil. This can be attributed to redistribution of P mined from the lower soil layers (Zibilske et al., 2002). Also, in strongly weathered soils the addition of residues can indirectly increase the availability of phosphorus. Humic molecules and low molecular weight aliphatic acids released during the decomposition of crop residues can block Al-oxide adsorption sites and reduce overall adsorption of P (Haynes and Mokolobate, 2001). This effect is dependent on the quality of the residue; legumes are generally more effective due to increased decomposition rates (Nziguheba et al., 1998).

3.2. Influence on soil physical properties

3.2.1. Soil structure

Soil structure is an important component in determining the sustainability of a crop production system and its resistance to soil degradation by erosion. In agricultural soils, soil structure and the physical stabilization of SOM can be altered by factors such as rainfall (Bertol et al., 2007; Panachuki et al., 2011), tillage, machinery-use and residue management (Kay, 1990; Hakansson and Reeder, 1994; Karlen et al., 1994; Blanco-Canqui et al., 2006). Retaining crop residue can improve soil structure through various mechanisms: (1) increasing soil aggregation through adding organic matter to the top soil, (2) protecting soil aggregates from raindrop impact, and (3) protecting soil from compaction caused by raindrop impact (Havlin et al., 1990; Carter, 1992; Paustian et al., 1997a; Six et al., 2006; Jacobs et al., 2009; Verhulst et al., 2010a).

The ability of soil aggregates to remain intact when experiencing stress is a useful measure to determine soil structural stability. Soil aggregates and their stability influence soil porosity, movement of water, gas, and nutrients through the soil system, and root development (Verhulst et al., 2010a). Soil aggregates can also protect SOM by forming organo-mineral complexes so tight that microorganisms cannot access the organic matter within them thus protecting it from decomposition (Edwards and Bremner, 1967). Since SOM is key in the formation of soil aggregates (Verhulst et al., 2010a), its loss is of great concern, particularly when it is common in agricultural soils in certain types of landscapes. Results from the Indian Himalayas show that leaving crop residues on the surface may be important in improving topsoil aggregate stability in areas with hilly terrains, heavy rainfall and highly eroded soils. Bhattacharyya et al. (2012) conducted a 6-year field experiment with a lentil (*Lens esculentus* L.)-finger millet (*Eleusine coracona* L.) rotation on sandy loam soil comparing different tillage systems with residues incorporated or left on the soil surface. They found that year-round no-tillage (NT–NT) and one-seasonal no-tillage followed by conventional tillage (NT–CT) treatments, where crop residues were left on the surface, had significantly higher water-stable macroaggregates in the surface soil layer (0–5 cm) compared to year-round conventional tillage (CT–CT) and one-seasonal conventional tillage followed by no-tillage (CT–NT), where residues were incorporated. The improved soil aggregation in the NT–NT and NT–CT treatments contributed to higher SOC concentrations in the soil surface. This was explained by the higher crop residue biomass on the surface which led to slower biomass incorporation and decomposition in the absence of tillage, and subsequently more stable aggregation and SOC accumulation in the surface soil layer (Lal et al., 1994; Paustian et al., 1997b). Continuous NT and seasonal NT–CT practices that keep residue on the surface thus indicate valid management practices for retaining SOC and aggregate stability in soils highly susceptible to erosion (Bhattacharyya et al., 2012). Similarly, Caesar-TonThat et al. (2010) observed greater aggregate stability in treatments with plant residue retention on the soil surface, likely due to additional organic N from the residues which can stimulate microbial activity and production of adhesive agents. They concluded that a surface residue retention with no-till system is better than incorporation since incorporating residues into the soil increases soil temperature and can lead to higher residue mineralization (Campbell and Souster, 1982), reducing soil aggregation (Caesar-TonThat et al., 2010).

Although addition of residue is an important factor stimulating aggregate formation, tillage may be a more dominant factor. A study conducted in a clay-loam soil of the major rice-producing region of central China, where no-tillage practices have become increasingly popular, showed significantly higher proportions of 0.5–2 mm water-stable aggregates and of particulate organic C in surface soils under continuous NT with or without residue of a rice (*Oryza sative* L.)-rape (*Brassica napus*) rotation than in single or continuous CT without residue. In this case, the lack of soil disturbance allowed organic matter to accumulate in the topsoil and promote macroaggregate formation even in the NT without residue retention (Li et al., 2012). Despite evidence that residue retention can improve aggregate stability of the topsoil, contrasting results have been observed in subsoils under tillage practices with or without residue retention. In the 5–15 cm layer, Bhattacharyya et al. (2012) observed no differences in macroaggregate proportions under different tillage systems incorporating or leaving surface crop residue, while Li et al. (2012) recorded decreased macroaggregate proportions in the 5–30 cm layer under no-tillage with or without residue compared to conventional tillage treatments without crop residue. Some other studies have either observed an increase in the proportion of macroaggregate fractions in the whole plow layer (Chen et al., 2009) or no significant differences in the subsoil layer under reduced tillage (Jacobs et al., 2009). Nevertheless, though there may be differences in the distribution of macroaggregate proportions throughout the soil profile, it is clear that the surface layer remains the vital horizon that receives external inputs (seed, fertilizer, pesticides) for crop production. As the layer that is also most affected by rainfall and is the interface between soils and the atmosphere, the role of surface organic matter is essential in protecting top soil aggregates, preventing erosion, allowing water infiltration, and retaining nutrients (Verhulst et al., 2010a).

Surface residue retention plays an important role in protecting soil aggregates from raindrop impact. According to Panachuki et al. (2011), residue cover is the most important factor in dissipating the impact of rainfall and thus preventing soil aggregates from breaking down. In the Yaqui Valley in the state of Sonora, Mexico, surface residue is used for animal feed or tilled into the soil, and irrigation water is becoming increasingly scarce. Comparing conventional tillage and zero-tillage under full and reduced irrigation both with residue retention, Verhulst et al. (2011a) noted increased aggregate stability in the 0–5 cm layer in permanent raised beds compared to conventionally tilled beds due to surface residue protection from raindrop impact. Further, leaving residues on the surface protects the soil from surface compaction. Soil compaction reduces porosity, water content, water infiltration, and air movement. Soil bulk density increases under compaction, which can affect nutrient availability and hence crop growth, as well as lead to nutrient input losses through surface runoff (Jung et al., 2010). The effects of crop residue on soil compaction depend on residue management practice, machinery use, and duration of the study, as well as soil texture (Puget and Lal, 2005). Without residue, soil compaction can increase significantly after continuous NT over a number of years. In addition, compaction causes seal-over and crusting that leads to runoff and erosion, reducing soil quality. In northwestern Mexico, penetration resistance was highest in soils with zero-tillage and burnt crop residue (Verhulst et al., 2010b). With residue on the surface, higher infiltration rates under NT were recorded compared to NT without residue retention (Govaerts et al., 2009a), indicating that the negative effects of soil compaction can be avoided by retaining surface residue.

Soil compaction can be a particular issue in clayey soils under mechanized no-till, in the absence of residue. Alfisols in various regions of Africa, on which food crops such as maize and sorghum are grown, have clay and gravel subsoils, low organic matter content, and a tendency to crust on the surface, properties that make them prone to compaction. In the humid and subhumid regions of Africa, no-till combined with residue retention has been found to be a valid method of controlling soil compaction (Kayombo and Lal, 1993). In Ibadan, Nigeria, for example, Franzen et al. (1994) recorded lower bulk density and penetration resistance in a tropical Alfisol under no-till with mulch compared to without mulch. Thus, in no-tillage systems, soil residue retention plays a particularly important role in preventing soil compaction.

3.2.2. Surface runoff and soil loss

Residue retention on the soil surface can also provide physical soil protection against water and soil loss. In addition, crop residues cause a lower sediment load in surface runoff during rainfall (Bertol et al., 2007). In a crop management experiment with simulated rainfall applications in southwestern Brazil, Panachuki et al. (2011) recorded high runoff and soil loss under NT without residue, significantly less under NT with 2 t ha^{-1} of surface soybean residue, and no runoff or soil loss under NT with 4 t ha^{-1} of surface soybean residue. Water infiltration rates were likewise higher in NT with surface residue (Tisdall and Oades, 1982). The high water and soil losses from NT without surface residue were likely due to hardening of the soil surface caused by rain impact in the absence of ground cover, which increases surface runoff and decreases water infiltration (Verhulst et al., 2010b). The protective influence of residue retention on the surface was further emphasized by the high runoff and soil loss levels in the disk-harrow treatments with 2 and 4 t ha^{-1} of soybean residue, which were incorporated rather than left on the soil surface (Panachuki et al., 2011).

In northern Ethiopia, agricultural practices including residue removal for fodder or grazing by livestock after harvest have resulted in soil erosion and low land productivity. Araya et al. (2011) found that after 3 years of a wheat (*Triticum* sp.)-teff (*Eragostis tef*) rotation, soil loss and runoff were significantly lower in permanent raised beds with 30% standing stubble compared to furrows without surface residue and CT without surface residue. This was explained by increased aggregate stability and the mulching effect of the standing stubble, consistent with the results of Gebreegziabher et al. (2009) and Oicha et al. (2010). The findings from these studies suggest the importance of minimum or no-tillage combined with residue cover in protecting soil aggregates and reducing soil loss and surface runoff (Govaerts et al., 2007c; Panachuki et al., 2011).

3.2.3. Soil moisture content

Moisture retention is considered one of the main benefits of surface residue cover, in terms of yield increase, in rainfed climates where crop production is limited by soil moisture. Residue retention has been demonstrated to slow down runoff and reduce evaporation, contributing to greater soil water content and resilience in drought-prone areas (Verhulst et al., 2011b). Since residues also prevent surface compaction and sealing, infiltration rates for zero-tillage under full irrigation can be significantly higher than under conventional tillage (Verhulst et al., 2011a). In Himachal Pradesh, India, local farmers are faced with uneven rainfall and suboptimal soil temperatures. In a 3-year study conducted on the silty-clay loam soils of the region, Acharya et al. (1998) observed significantly higher moisture content in the 0–15 and 15–30 cm soil layers under conservation tillage with mulch of wild sage and eupatorium compared to conventional farming practices (tillage after harvest) in the area. The mulch in these treatments contributed to higher wheat grain yield compared to the conventional tillage treatments where crop residue was incorporated in the soil.

In another part of the Himalayas, in the north eastern region of India, water is scarce as rainwater runs off slopes. On the ground level, rice is produced and the crop residue is removed for animal feed or burned after harvest; traditional ploughing practices add to soil degradation. A rice system study within the region comparing NT with surface residue, minimum tillage with residue incorporation, and CT with residue removed, revealed that both NT and minimum tillage treatments with residue maintained higher soil moisture (Ghosh et al., 2010). In the valley upland area under a rice-pea rotation with NT, Ghosh et al. (2010) reported better pea crop performance with 75% and 50% rice residue on the soil surface. This was ascribed to increased water retention by the residue cover since NT without surface residue exhibited water loss. Verhulst et al. (2011b) found similar results in the semiarid, subtropical highlands of central Mexico. After 15 years, NT with residue had higher soil moisture content than CT with or without residue or NT with residue removed. The average maize yields during this time were higher in NT with residue compared to CT and NT without residue, reflecting more crop resilience during dry periods.

Although the majority of studies have found positive effects of residue retention on soil water some negative consequences have also been reported in certain environments. For example, in semi-arid areas with small and frequent rainfall events, residue cover can intercept rainfall and increase subsequent evaporation (Kozak et al., 2007; Cook et al., 2006). Conversely, in areas with excess rainfall, residue retention can lead to excessive soil moisture and water logging (Rusinamhodzi et al., 2011). A study by Thierfelder and Wall (2009) illustrates the contrasting effects of soil residue retention on soil moisture and crop yield. Working in two sites with sandy soils in Zambia and Zimbabwe, Thierfelder and Wall (2009) found that infiltration rates and moisture retention were high in conservation agriculture treatments with hand seeding and minimum tillage with surface residue retention as opposed to conventional moldboard ploughing with all residues removed, burnt or grazed. Higher water availability in the conservation agriculture treatments resulted in significantly greater yields in the first season in the Zimbabwe site, but in the Zambia site in the same season, crop yields were low despite high infiltration rates and moisture content. High rainfall amounts and reduced runoff in these treatments contributed to water accumulation which reduced yields. Further research in Zimbabwe confirmed that when residues were conserved, yields were higher in dry years and lower in wet years; yields were reduced due to waterlogging (Thierfelder and Wall, 2012). A way to prevent the negative impact of water accumulation in areas with heavy rain can be by using permanent raised beds that allow runoff of excessive water along furrow bottoms while retaining residue on bed tops (Sayre, 2004). Nevertheless, if rainfall is not excessive, conservation practices with surface residue retention can reduce the risk of crop failures and low crop residue production due to lack of water, especially in regions with infertile soils and unreliable rainfall such as Southern Africa (Thierfelder and Wall, 2009).

3.2.4. Soil temperature

Retaining residues on the soil surface has been noted to decrease daytime soil temperature (Verhulst et al., 2010a). In hot, tropical climates, this effect is beneficial since soil temperature may be too high for optimum plant growth whereas in cooler climates the effect can be detrimental to plant development. Acharya et al. (1998), for instance, recorded lower maximum soil temperature and higher minimum soil temperature in the 0–5 cm surface soil layer under minimum tillage with mulch treatments compared to the CT with no-mulch treatment. This created a more favorable environment for root growth. The lowering effect of surface residue on temperature is consistent with results of other studies as well (Osuji, 1990; Oliveira et al., 2001).

In cooler climates, however, reduced soil temperature from residue cover can be a disadvantage as it could slow down early crop growth and lower crop yields (Verhulst et al., 2010a). The effect of crop residue on soil temperature is controlled by the color of the residue. Sharratt and Campbell (1994) found that dark residues resulted in higher mid-day temperatures compared to lighter colored residues. Yet, this may still not be a solution in cropping systems where crops produce light colored residue. In soils under no-tillage with crop mulch in northern China, the delayed warming of soils in early spring postponed sowing and affected seed germination (Li et al., 1995; Wang et al., 2002). Thus, to address this issue, Zhang (2011) suggests using cold-resistant crops under no-till with residue treatments. Alternatively, residue can be removed from the seed zone only, in order to still maintain the beneficial effects of residue retention. In southern Ontario, Canada, Fortin (1993) observed that NT with a 30 cm band of bare soil along the corn row had higher seed zone temperature than regular NT with full residue cover, but still had the NT advantage of lower evaporation compared to CT. Despite differences in seed environment, no differences in seed emergence after 20 days or in grain yield between the treatments were reported. More studies are required to examine whether NT in-row residue removal (or strip tillage) leads to higher grain yields compared to regular NT with residue retention.

3.3. Influence on soil biological properties

Soil biodiversity consists of soil microflora (e.g. bacteria, fungi) and soil fauna, which is classified by size as microfauna (e.g. nematodes, protozoa), mesofauna (e.g. acarids, enchytraea), and macrofauna (e.g. earthworms, termites, large arthropods). These organisms can also be described through the soil food webs, with microflora and microfauna breaking down organic matter, mesofauna feeding on them, and macrofauna in turn feeding on mesofauna (Roger-Estrade et al., 2010). Soil biodiversity plays a large role in agroecosystems by affecting crop quality, occurrence of soil-borne pests and diseases, nutrient cycling, and water transfer. It can also reflect disturbance and stress, as low soil biodiversity is often due to human-caused disturbance (Brussaard et al., 2007).

3.3.1. Microbial activity

Decomposition of organic matter by soil microorganisms influences water and nutrient availability in agroecosystems, as well as soil structure. Soil microbial biomass (SMB) is defined as the living part of soil organic matter (Salinas-Garcia et al., 2002). It has been proposed as another useful and sensitive indicator of soil quality (Karlen et al., 1997) because it is a source and reservoir of biologically available nutrients and promotes soil aggregation and structural formation (Gupta and Germida, 1988; Angers et al., 1992). SMB can be affected by environmental factors such as temperature and moisture (Debosz et al., 1999), and by soil management practices such as residue inputs (Govaerts et al., 2007b).

Residue retention is an important factor in stimulating SMB and microbial activity. Lou et al. (2011), in comparing treatments with straw retained and straw removed in Northeast China, found significantly higher microbial biomass C levels when straw was retained because of improved C and N contents, increased soil moisture and porosity, and decreased soil temperature caused by the residue cover. Similarly, in studies carried out in central Mexico, higher SMB with residue retained compared to without residue were recorded (Salinas-Garcia et al., 2001; Salinas-Garcia et al., 2002; Govaerts et al., 2007a).

Incorporation of crop residues in the soil increases soil temperature and aeration, creating favorable conditions for microorganisms and greater contact between them and the residues, which lead to higher decomposition rates and overall SOC loss (Aulakh et al., 1991; Salinas-Garcia et al., 2001; Coppens et al., 2007; Fontaine et al., 2007;). This is consistent with the observation that fluctuations in the total organic C pool due to changes in C supply from crop residues are reflected in the microbial biomass (Franzluebbers et al., 1999). In tropical and subtropical areas with high temperatures and rainfall, no-till and surface crop residue have been observed to increase SOC content in surface soils compared to incorporation (Lal, 1997; Corazza et al., 1999; Bayer et al., 2000). This is due to less contact between surface residue and microorganisms in no-till systems, as described earlier, suggesting the importance of retaining residue on the surface rather than incorporating residues in sub-humid temperate to sub-humid tropical regions where decomposition rates are high.

Certain bacteria and fungi, such as arbuscular mycorrhizal fungi (AMF), can also improve nutrient availability to plants. AMF form symbiotic relationships with plant roots where the fungi obtain glucose from the plant and in exchange deliver phosphate through hyphae to the plant roots (Smith and Read, 2008). In addition, AMF hyphae and their production of the glycoprotein, glomalin, contribute to bonding of soil particles, which improves aggregate stability (Wright and Upadhyaya, 1998; Wright et al., 1999). Organic matter inputs can have a positive effect on AMF growth and spore populations (Caravaca et al., 2002; Emmanuel et al., 2010), whereas soil disturbance by tillage is known to negatively impact mycorrhizal hyphal development (Kabir et al., 1997; Usuki et al., 2007).

3.3.2. Earthworms

Larger soil fauna, in particular soil macrofauna such as earthworms, also play an important role in the soil environment. Earthworms are described as ecosystem engineers because their effects on the soil ecosystem can last beyond their body size and lifetime (Lavelle, 1997). They directly affect C and N cycles by consuming, storing, and cycling nutrients through their biomass (Whalen et al., 1999), releasing in particular significant amounts of N through excretion and mortality (Parmelee and Crossley Jr., 1988; Whalen et al., 2000). Indirectly, they affect C and N cycles and soil aggregate stability by mixing organic matter in the soil through their gut and in their structures (casts, burrows and middens). These activities bring microorganisms in closer contact with organic matter, thus stimulating microbial processes such as decomposition and mineralization (Lavelle, 1997; Bossuyt et al., 2006).

Earthworms have been observed to respond positively to crop residue retention and minimum soil disturbance. The cooler soil temperature, improved soil structure, and food resource provided by crop residue retained on the surface can lead to increases in earthworm number and biomass (House and Parmelee, 1985; Chan, 2001; Chan and Heenan, 2006). In contrast, the process of incorporating residue into the soil through tillage has been shown to have a negative impact on some earthworm species because tillage causes physical harm, exposes them to predators on the surface, and destroys their burrows (Edwards and Lofty, 1982; Chan, 2001; Kladivko, 2001). In a semiarid zone of Tunisia, for example, Errouissi et al. (2011) observed that no-tillage with surface residue increased soil invertebrate, including anecic earthworm, population numbers and diversity compared to conventional tillage because of improved soil properties and lack of soil disturbance.

Residue retention can have a varying effect on earthworms, however, depending on their ecological niche, as tillage may benefit endogeic (horizontal-burrowing) earthworms if residue is incorporated into the soil, providing a food source (Wuest et al., 2005). In contrast, in fields with large anecic (vertical-burrowing) earthworm numbers, burying residue in the soil instead of leaving it on the surface can reduce abundance, even with shallow tillage, since they feed on the surface (Metzke et al., 2007). In addition, Metzke et al. (2007) observed a crop × tillage interaction effect on earthworm populations. Earthworm numbers were low in all three tillage systems (two types of reduced tillage treatments and one conventional tillage treatment) under field bean, while numbers were high under the grass-clover rotation in all tillage systems. The effect of crop residue on earthworms and other soil fauna can thus vary depending on tillage frequency, plow depth, residue incorporation, and crop residue type, amount and quality (Eriksen-Hamel et al., 2009).

4. Residue trade-offs and soil health

The benefits of residue retention are site-specific and depend not only on agroclimatic factors but also on the farming system and socioeconomic factors. Since many farmers use crop residues as the main source of livestock feed, use for fodder may provide a greater short-term economic benefit than retention for maintenance of soil fertility. In some cases a portion of crop residue, depending on climatic factors, can still be retained for soil health benefits. In a 6-year study conducted in Mexico, leaving at least 60% of crop residue on the surface in Apatzingán and 30% in Casas Blancas was enough to ensure soil quality while still allowing for livestock feeding. Higher rates were required in Casas Blancas than in Apatzingán because of higher annual temperatures in Apatzingán which stimulated decomposition and C loss (Salinas-Garcia et al., 2001). Increasing maize yields may only require the retention of a fraction of the crop residues produced. For example, in a study conducted in Ghana and Nigeria, Larbis et al. (2002) found that maize grain yield increased with increasing quantities of crop residue up to a retention rate of 50%, but not beyond that rate. Similarly, Baudron et al. (2014) found that crop residue applied in excess of 3 t ha^{-1} and 1 t ha^{-1} for the Ethiopian Rift Valley and Western Kenya, respectively, did not improve crop yield significantly.

In mixed crop-livestock systems, the benefits vs the cost of residue retention depends on the value of crop residue as soil amendment vs as feed. The value of crop residue as soil amendment depends on several agroecological and socioeconomic factors (see above). The value of crop residue as feed depends on milk and meat markets. For example, Naudin et al. (2015) found that residue retention was not economically viable in Madagascar in a situation of high milk price, but that partial residue retention was the most economical residue management option in a situation of low milk price. However, the value of crop residue as feed also depends on the importance of other livestock functions, besides its production function. These include the cycling of nutrients through manure, the provision of traction for land cultivation, inflation-proof saving, insurance, and the display of status (Schiere et al., 2002; Powell et al., 2004). The importance of these livestock functions is often high in developing countries, where alternatives are lacking. Developing such alternatives could reduce crop residue demand for livestock feeding. For example, Baudron et al. (2014) estimated that the adoption of affordable mechanization to replace oxen would increase the proportion of farmers retaining at least 1 t ha^{-1} of crop residues in their fields from 3% to 25% in the Ethiopian Rift Valley, an area where traction is a main function played by cattle. It could also be hypothesized that the development of formal insurance and banking would reduce the density of livestock in many rural areas in the developing world where livestock is currently fulfilling these functions (Kurosaki, 1995). Nutrient cycling – i.e. the return to the soil through manure and urine of carbon and other nutrients taken up by livestock through grazing– is a function of particular interest when considering crop residue trade-offs. Even in situations where the bulk of crop residue is fed to livestock, crop residue trade-offs could be reduced by increasing nutrient flows from livestock to crop, through improved herd management, manure storage and manure management (Rufino et al., 2006; Tittonell et al., 2010). The use of mulch from plants of little commercial value, such as wild sage, combined with standing stubble could also be a valid alternative to farmers that require crop residue for use as animal fodder (Acharya et al., 1998). In addition, higher yields can produce more crop residue that may permit a portion to remain on the soil and the rest be fed to animals (Kayombo and Lal, 1993).

The benefit vs cost of residue retention in mixed crop-livestock systems may also depend on seasonal effects. For example, the benefit of mulching is higher during seasons receiving below average and/or poorly distributed rainfall, but lower or not significant during years receiving average or above average rainfall (Mkoga et al., 2010). Similarly, the cost of residue retention may be season-specific. For example, the value of stubble fed to livestock was found to account for about a quarter of the total value of cereal production during an average season in Morocco, but about three quarters during a drought year (Magnan et al., 2012).

Finally, the intensity of the crop residue trade-offs depends on the intensity of cropping and livestock systems. The intensity of the trade-offs is generally low in relatively intensive cropping systems, where residue production is high and tends to cover livestock demand for feed while allowing part of the residues to be retained in the field, and in extensive systems, where the existence of communal rangeland results in lower pressure on crop residues (Valbuena et al., 2012). However, strong crop residue trade-offs generally exist in systems characterized by intermediate cropping intensity. In these systems, crop residue trade-offs could be alleviated through crop intensification, as demonstrated by Baudron et al. (2015) using simulation models. In this study, increased N input in sorghum fields – N being the most limiting factor in the farming system considered – increased significantly the density of livestock that could be supported by a territory in Northern Zimbabwe. Moreover, the quantity of crop residues fed to livestock tends to be low where the intensity of livestock production is low – as livestock is fed mainly through grazing – and where it is high – as highly productive animals require feeds with a higher density of energy than cereal residues, and are fed mainly from planted fodders and supplements (Romney et al., 2004). However, the quantity of crop residue fed to livestock is high where the intensity of livestock production is intermediate. In such systems, livestock intensification may reduce the intensity of crop residue trade-offs. For example, Baudron et al. (2014) estimated that livestock intensification in Western Kenya would increase the proportion of smallholders retaining at least 1 t ha^{-1} of crop residue in their fields from 36% to 49%.

5. Conclusions

Examining crop residue effects on soil quality in developing countries in Asia, Latin America, and Africa shows a clear consistency of the importance of retaining crop residues on soil quality in agricultural systems. Physical, chemical, and biological properties related to soil health generally improve with surface residue retention although, in some environments, negative effects on crop performance have been observed. Studies comparing the benefits from combinations of minimum tillage and residue retention suggest that complete or partial retention of residue, whether incorporated or left on the surface, is more advantageous than its complete removal or its incorporation with intensive tillage practices.

Variation was observed in the effect of residue retention and surface retention vs. incorporation on various soil properties indicating the importance of taking into account abiotic factors such as regional climate, soil texture, study duration, sampling methods, and agronomic practices when evaluating different residue management practices. Various benefits of residue retention such as increased topsoil aggregation and protection from erosion, soil loss and surface compaction are increased when the residues are retained on the surface rather than incorporated. Therefore in regions with high risk of soil erosion and humid tropical areas with high decomposition rates it is particularly important to promote surface retention of residue. The effect of residue retention on soil pH is highly dependent on the quality of the residue and soil characteristics. When residues are retained on the surface the effect on increased SOC and CEC is isolated in the topsoil layer whereas when residues are incorporated the effect may be observed at greater depths. This should be considered in sampling protocols that compare different residue management practices. Soil microbial activity is increased when residues are retained, with higher decomposition rates when residues are incorporated. Earthworm populations are also stimulated by residue retention and the effect of management practices depends on the earthworms' ecological niche.

Negative effects of crop residue retention are less common; however, they have been reported in some environments. The most common negative effect is N mobilization which can reduce N availability to the crop in N limiting environments. Additionally, in cooler temperate climates, retaining residues on the surface results in lower soil temperatures which can negatively affect crop production and practices such as strip tillage should be employed. In regions with high rainfall, excess soil moisture retention can present problems with waterlogging. Conversely in semi-arid regions with light rains residues may intercept rainfall and increase evaporation.

In mixed crop-livestock systems, trade-offs exist between feeding residues to animals and retaining residues for soil quality. Ways to address these trade-offs include the use of plants with no commercial value to use as mulch in place of crop residue, or leaving as much as 30–60% or 50–75% of crop residue on the soil surface, depending on the regional soil and climate. In water limited environments, retaining residue can create a positive feedback by increasing yields due to improved soil quality and moisture retention that in turn adds more crop residue to the system that can then be used for feed. Retaining residues on the soil surface can further increase the benefits to soil health; however, many farmers in regions where open range grazing is practiced opt to incorporate their residues to protect them from grazing by their neighbor's animals.

This review highlights the need for long-term trials to understand the effects of residue management practices in different regions, particularly in the tropics, where fewer studies have been conducted. It also highlights the need for combinations of interventions at the level of the farm and the territory to design systems that maintain soil health necessary for high crop productivity, and at the same time support high livestock productivity. In the absence of alternatives, livestock functions beside production (e.g. traction, nutrient cycling, insurance, and banking) cannot be ignored. Farm-scale and landscape-scale models considering biophysical and socioeconomic factors coupled with participatory research methods can be used to identify residue management strategies that minimize trade-offs.

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