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Crop residue management and soil health: A systems analysis

Marie-Soleil Turmel [a], Alicia Speratti [b], Frédéric Baudron [c], Nele Verhulst [a], Bram Govaerts [a,*]

[a] International Maize and Wheat Improvement Centre (CIMMYT), Apdo. Postal 6-641, 06600 Mexico, D.F., Mexico
[b] Institute for Resources, Environment and Sustainability, University of British Columbia, Vancouver, British Columbia, Canada
[c] International Maize and Wheat Improvement Centre (CIMMYT), Shola Campus, ILRI, P.O. Box 5689, Addis Ababa, Ethiopia

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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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* Corresponding author. Address: International Maize and Wheat Improvement Centre, Apdo. Postal 6-641, 06600 Mexico, D.F., Mexico. Tel.: +52 55 5804 2004; fax: +52 55 5804 7558.

E-mail address: b.govaerts@cgiar.org (B. Govaerts).

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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

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