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Editorial

Biomass use trade-offs in cereal cropping systems in the developing world: Overview

1. Introduction

Agricultural systems variously produce food, feed, fiber, fuel, and environmental goods. The relative emphasis varies over space and time – associated *inter alia* to inter-related developments in demand, technology and policy. Cereal cropping systems in the developing world traditionally emphasize food production with residual agricultural biomass (or crop residues) as an important by-product. Crop residues often have multiple uses such as livestock feed, household fuel source, soil amendment, construction and/or marketed for cash income. A number of trade-offs exist between these biomass uses, often reinforced by emerging drivers such as demographic pressure, increasing demand for livestock products and the development of fodder markets. In addition, there are recent developments, such as the increasing advocacy of conservation agriculture practices. Conservation agriculture calls for the retention of substantial crop residues as mulch in the field, thereby often competing with prevailing uses such as animal feed and/or conflicting with established crop management practices. There is also increasing advocacy for second generation biofuels (ethanol production from hemi-cellulosic material) – albeit that for now these are unlikely to have substantial short term implications for most smallholders across large swathes of the developing world as biofuel use is primarily limited to traditional biofuel uses and mainly informal and small scale.

Despite these already prominent and changing biomass use trade-offs our understanding is often only partial, primarily based on anecdotal evidence and with limited systematic assessments. A number of factors contribute to this relative lack of information and knowledge—including:

- biomass produced in annual cropping systems is primarily a under-reported by-product;
- the incomplete understanding of biomass use strategies by farmers;
- the relative lack of developed biomass markets and a number of associated market failures (Erenstein, 1999). Only sparingly are developed crop residue markets reported – including in the intensive systems of northern India (Erenstein and Thorpe, 2010; Erenstein, 2011) and around urban centers in southern India (Blummel and Rao, 2006);
- various temporal and technical difficulties in assessing biomass production and valuing the alternative biomass uses and trade-offs; and
- the highly variable biomass production in rainfed systems, the variable biomass use and the inherent context specificity of biomass use trade-offs.

Indeed, biomass use trade-offs show variations between annual crops, supply and demand side factors, and their interrelated associations with the agro-ecological and institutional environment. This special issue aims to take stock of biomass use trade-offs in annual cropping systems in the developing world and to stimulate further research and development.

The special issue contributes to a limited, diverse but growing literature. The literature to date can be broadly grouped into three major themes:

- *Agricultural system analysis:* Crop residue use has been variously analyzed within the context of agricultural system analysis – particularly as it relates to nutrient and carbon cycling; crop-livestock interactions; and system sustainability and dynamics. This has long been an area of interest – although analysis at higher aggregation levels (above the plot or farm) is often only conceptual with limited quantitative empirical analysis thus far, with a few exceptions (McIntire *et al.*, 1992; Erenstein and Thorpe, 2010; Erenstein *et al.*, 2011; Hellin *et al.*, 2013; and landscape level work particularly in Niger by Hiernaux and associates [Buerkert and Hiernaux, 1998; Turner and Hiernaux, 2002; Schlecht and Hiernaux, 2004; La Rovere *et al.*, 2005; Hiernaux *et al.*, 2009]). Land use change in response to increasing demographic pressure can also imply evolving tradeoffs and privatization of crop residues (e.g. Mekasha *et al.*, 2014);
- *Technological change within systems analysis:* Retention of crop residues as mulch is a critical component of conservation agriculture – which is increasingly being advocated globally. Crop residues are already variously used within agricultural systems (see preceding bullet) – such that retention of crop residues for conservation agriculture has implications for current uses and potentially leads to trade-offs. This has spurred an increasing number of studies (Erenstein, 2002, 2003, 2011; Naudin *et al.*, 2012; Valbuena *et al.*, 2012; Jaleta *et al.*, 2013; Baudron *et al.*, 2014), including implications of other technological changes and reviews (Schiere *et al.*, 2000; Dixon *et al.*, 2010; Klapwijk *et al.*, 2014);
- *Agricultural biomass as a resource:* There is an increasing research interest in agricultural biomass as a potentially underutilized resource – linked to (1) one or more of the interrelated concerns about agricultural sustainability, feeding livestock and climate change (Erenstein *et al.*, 2013; Herrero *et al.*, 2013) and (2) biomass use as second generation biofuel (Kim and Dale, 2004; Lal, 2005, 2008; Bringezu *et al.*, 2009; Sarkar *et al.*, 2012).

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The special issue primarily contributes to the first two themes drawing from several recent and on-going studies. The third theme of biomass as an (underutilized) resource potentially would exacerbate the biomass use trade-offs – but empirical evidence within the context of the developing world is still scant.

Although crop residues have since long been used in agricultural systems – they are variously used and even more variously valued. The latter is particularly challenging in the context of trade-off analysis. In one extreme scenario the crop residues could have no perceived use value – and can actually imply a cost where farmers perceive their presence as detrimental and go at length to remove or destroy them during or prior to land preparation (e.g. rice straw in the NW Indo-Gangetic Plains of India – Erenstein, 2011). In the other extreme scenario the crop residues provide tangible value and are exhaustively collected (e.g. wheat straw in the NW Indo-Gangetic Plains of India – Erenstein, 2011). There is an associated evolutionary gradient of crop residue rights from open access through communal rights to private residue rights – with established property rights giving rise to the emergence of residue markets (Erenstein, 1999), including *in situ* stubble grazing contracts in Mexico (ibid) and *ex situ* hauling, trading and monetization in India (wheat in the NW - Erenstein, 2011; sorghum in the S - Blummel and Rao, 2006). Privatization of crop residues in previously open grazing systems has also been reported in Niger (La Rovere *et al.*, 2005). Important factors influencing pressure on crop residues are the land use ratio between rangeland/fallow and crop land (Mekasha *et al.*, 2014) and system productivity (Valbuena *et al.*, 2012). Understanding these context specific factors is critical in terms of understanding the system, spatial, temporal, and scale implications across agricultural systems and how these dimension the biomass values.

In terms of agricultural system, crop residue use and valuation will vary between a crop farmer, a crop-livestock and livestock farmer – although the special issue will primarily focus on mixed crop-livestock farms given their prevalence across the developing world. But even mixed crop-livestock farms within a specific setting are far from uniform – with different relevant farm types based on resource endowments and system components (crop, livestock, other) influencing crop residue use and its valuation. One particular valuation challenge is that system components such as crop and livestock each combine different functions – be it for self-consumption, for market or other purposes – and different temporal dimensions and interactions. Any specific setting has a *spatial* context – and crop residue use can be expected to differ between year-round biomass producing environments (e.g. humid tropics) and highly seasonal biomass producing environments (e.g. semi-arid); or an area in proximity to urban markets and a remote location. Any specific setting also has a *temporal* context – as crop residue use and value can be expected to differ as crop-livestock systems intensify. In addition to the overall system trajectory, systems are also subject to other changes – be it in terms of an innovation or a shock/stress within the agricultural system – which can alter the biomass valuation in any given context. Finally the *scale* of analysis influences crop residue use valuation and trade-offs – be it at the level of plot/animal, the sub-system (crop/livestock), the farm, the village, the region, the country or higher scales. For example, transhumance and land use changes at the landscape level impact the use of crop residues and their tradeoffs at farm and field levels (e.g. Turner *et al.*, 2015).

2. Scope of special issue

The special issue primarily deals with biomass use trade-offs in cereal farming systems and the lessons and implications from the developing world. It primarily revolves around the analysis of competing interests retaining crop residues to maintain soil health, typically as mulch as advocated in conservation agriculture, vis-à-vis other crop residue uses, particularly as livestock feed. The analytical challenge of these trade-offs is that they: 1) involve less tangible longer term soil health/sustainability benefits with more immediate short term opportunity costs; and 2) that the actual trade-offs are typically context specific due to numerous associated factors and their inter-linkages.

Table 1
Overview of the papers in the special issue "Biomass use trade-offs" (Theme; management and systems; ecology and geography).

#	Paper	Theme	Management options/contrasts	System options/contrasts	Ecology	Geography
1	Turmel et al. (2015)	CRM effects (soil)	3 CRM practices (surface retention, incorporation, removal)			Global
2	Jaleta et al. (2015)	CRM determinants	3 CR uses (feed, fuel, soil)	3 Maize production potentials (low, medium, high)	(Sub)Humid to semi-arid	Eastern Africa (Ethiopia)
3	Castellanos-Navarrete et al. (2015)	Nutrient cycling at farm scale	1 CR use (CR - > feed - > manure - > soil)	10 Case study farms	Humid (tropical mid-altitude)	Eastern Africa (Kenya)
4	Naudin et al. (2015)	Mixed farm optimization	3 CRM options (conventional, CA × 2 soil cover) × herd size	3 Farm types (prototypes) × 2 dairy/forage markets	Humid (tropical mid-altitude)	Eastern Africa (Madagascar)
5	Homann-Kee Tui et al. (2015)	CRM options (alternatives)	4 CRM options (CA × 3 fertilizer, mucuna)	3 Farm types (livestock holding)	Semi-arid	Southern Africa (Zimbabwe)
6	Beuchelt et al. (2015)	CRM trade-offs	2 CR uses (feed, soil) linked to CA intro	Spatial fodder balance (deficit, surplus)	Semi-arid	Mesoamerica (Mexico)
7	Magnan (2015)	CRM social trade-offs	3 CR uses (communal grazing, private grazing, soil)	2 Farm types (poor, rich)	Semi-arid	Northern Africa (Morocco)
8	Andrieu et al. (2015)	CRM multi-level trade-offs	3 CR uses (communal grazing, ex situ feed, compost)	3 Farm types (livestock, rich, poor) × 3 levels (plot, farm, village)	Sub-humid	Western Africa (Burkina)
9	Baudron et al. (2015)	CRM multi-level trade-offs	2 CR uses (feed, soil) × 3 fertilizer levels	4 Farm types (2 draught power × 2 cotton)	Semi-arid	Southern Africa (Zimbabwe)
10	Valbuena et al. (2015)	CRM determinants + trade-offs	5 CR uses (feed, soil, fuel/construction, traded, burned)	5 Clusters (cereal intensity × livestock density)	(Sub)Humid to semi-arid	Sub-Saharan Africa and South Asia
11	Tittonell et al. (2015)	Synthesis				

Note: CR: crop residue; CRM: crop residue management; CA: conservation agriculture.

In addition to this introduction and a synthesis paper, the special issue includes one review and nine case studies across a wide range of the developing world – with an emphasis on mixed cereal–livestock smallholder systems particularly from Africa (Table 1). In addition to the aforementioned focus within an agricultural systems perspective, the special issue intended to capture a wide range of studies to illustrate the alternative ways in which such challenging analysis is being conducted in contrasting settings drawing from recent and/or on-going empirical research. Table 1 includes a number of indicators to help the reader position the focus of the papers – be it in terms of the targeted theme, management and system options/contrasts, ecology and geography. The review paper (Turmel *et al.*, 2015) looks into the crop residue management (CRM) effects particularly on the soil. The subsequent papers look into the determinants of CRM (Jaleta et al, 2015) and implications of CRM for nutrient cycling at farm scale (Castellanos-Navarrete *et al.*, 2015). The subsequent papers examine the implications of conservation agriculture for CRM – be it in terms of land use options (Naudin *et al.*, 2015), technological options (Homann-Kee Tui *et al.*, 2015) and prevailing feed use (Beuchelt et al, 2015). The latter paper and particularly the subsequent three papers investigate trade-offs across levels and individual farms – be it in terms of social trade-offs between farm households (Magnan, 2015) to the inter-linkages between the plot – farm – community in a specific village (Andrieu et al, 2015) or region (Baudron et al., 2015). The final paper (Valbuena *et al.*, 2015) provides a comparative analysis of both the CRM determinants and trade-offs across contrasting sites. Each of the papers is briefly introduced further hereafter.

Turmel *et al.*, 2015 review the inter-linkages between crop residue management practices and soil health. Recycling crop residues in crop fields is often a key premise in sustainable crop production systems to ensure future crop production from any given plot, based on the need to recycle nutrients and organic matter and their contribution to soil quality. The review paper looks into the black box behind this premise with a focus on cereal-based systems in developing countries. They review how crop residue management practices – particularly surface retention, incorporation or removal – influence soil chemical properties (organic carbon, pH, cation exchange capacity and nutrient availability), soil physical properties (structure, surface runoff and soil loss, moisture content, temperature) and soil biological properties (microbial activity, earthworms). Most studies show primarily positive effects of retaining crop residues on these soil attributes, with occasional negative effects on crop performance often associated with nitrogen immobilization, waterlogging and decreased soil temperature. They then briefly touch upon how alternative crop residue uses in mixed crop-livestock systems co-determine crop residue management and suggest some potential interventions that could reduce these residue trade-offs in favor of promoting long-term soil health.

Jaleta et al, 2015 assess the three main crop residue uses (particularly as a feed, fuel or soil amendment) in mixed maize-based smallholder systems in Ethiopia using data from a large nationwide household survey. Their data show a preferential use of cereal straw as feed, followed by maize stover which is again preferred over sorghum stover. Overall maize stover is primarily used as feed (56% of biomass) and fuel (31%), but the feed share is negatively associated with maize production potential. Using multivariate models the paper shows the determinants of households' maize stover use to include access to information, farm and livestock herd size, cropping patterns, agro-ecology and crop residue production levels.

Castellanos-Navarrete *et al.*, 2015 assess nutrient cycling efficiencies at the farm scale for 10 case study farms in Western Kenya, one of the world's most densely populated areas. Most (73%) of maize stover in these mixed crop-livestock smallholder farms is used for cattle feeding – but overall poor nutrient cycling efficiencies of manure (e.g. only 27% of excreted nitrogen reached the soil) result in a critical lack of nutrients and organic residues in crop fields. Although their analysis calls for the need to consider farmers' resource endowment and livestock production strategies, this is thwarted by the overall context of land scarcity and few rewarding off-farm employment opportunities.

Naudin *et al.*, 2015 explore trade-offs between conservation agriculture practices and herd size in the context of crop-dairy smallholder farms in Madagascar. They use linear programming to optimize total net farm income for 3 farm prototypes – each with characteristic land endowments and land use options – under varying scenarios, including varying herd size, 2 mulch cover thresholds and 2 different milk/forage market settings. Their various optimization solution spaces generally include mulch retention in at least a substantial share of fields with conservation agriculture being profitable at the farm level even under increasing livestock pressures. Their results do show various trade-offs – including the potential of only partial residue retention while using part of the biomass to feed cattle and reliance on complementary forage markets – but overall conservation agriculture and livestock are shown as compatible and complementary.

Homann-Kee Tui *et al.*, 2015 focus on mixed crop-livestock smallholder systems in semi-arid areas where crop residue use as feed is particularly important during the dry season and being challenged by conservation agriculture practices. They look into the potential economic trade-offs associated with different crop residue use scenarios, particularly retention of crops residues in combination with different fertilizer use scenarios and a maize–mucuna rotation for different farm types based on livestock herd. Their results indicate that a maize–mucuna rotation can potentially reduce trade-offs between crop residue uses for feed and mulch – although further research is needed to establish the competitiveness of such alternative biomass enhancing technologies and the socio-economic processes to facilitate their uptake.

Beuchelt et al, 2015 explore the implications of conservation agriculture practices on crop residue use in Mexico's mixed maize-livestock smallholder systems. The paper cascades the analysis starting with a high spatial analysis of the fodder balance at the national level and then zooming in to the community level to the household level in Mexico's central highlands. Crop residues contribute up to 40% of fodder availability in Mexico, but whereas Mexico has a national fodder surplus, areas such as the central highlands have a deficit. Crop residues are an important income source and risk buffer, and retention of crop residues as mulch leads to social and income trade-offs – particularly in fodder deficit areas. Using regression analysis the paper estimates that retention of some 45% of crop residues maximizes gross margins for farm households in the study area.

Magnan, 2015 analyses crop residue management implications in relation to property rights and a conservation agriculture practice (no till with residue retention) across two contrasting household types in mixed cereal-livestock smallholder systems in Morocco. Communal stubble grazing is a common practice in extensive mixed systems which inherently restricts crop residue management options. Individual farmers may start to enforce property rights over crop residues to ensure either restricted grazing or retention as mulch, particularly when the shadow price of crop residues increases. The paper shows how the decisions of one farmer to enforce property rights has a cascading effect by diminishing the amount of residue available for communal grazing, and consequently makes the adoption of conservation agriculture practices by other farmers more costly, and in the end may prevent other farmers from adopting.

Andrieu et al, 2015 looks at crop residue management implications across scales in a case study village with an agro-pastoral system in Burkina Faso. Using process models they analyze three different crop residue uses (communal grazing, ex situ feed, composting) for three farm types (predominantly livestock, resource rich and resource poor) across three levels (plot, farm, and village). In the current setting farmers left most (80%) of cereal crop residues in their fields at harvest time – which was subsequently primarily consumed during communal stubble grazing. Increased private crop residue use by collecting them for ex situ feed use and particularly for composting can increase soil fertility and crop production at the plot and farm scale – but typically reduced fodder self-sufficiency at the village scale and negatively impacted the N balance of the savannah-derived rangelands.

Baudron et al., 2015 assess multi-level trade-offs (plot, farm and landscape) of different sorghum residue uses (feed, mulch) with varying nitrogen fertilization in mixed crop-livestock smallholder farms in semi-arid northern Zimbabwe. Crop yield response to mulching is subject to the interaction between mulch and N fertilization levels associated with N immobilization. Animal traction is an important input to crop production with total cotton production increasing with cattle density, but at the cost of increasingly lower levels of residue retention. Their analysis thus illustrates that the optimum level of residue retention inherently depends on the scale of analysis.

Valbuena *et al.*, 2015 provide a comparative assessment of crop residue use and trade-offs in mixed crop-livestock smallholder farms in 12 study sites across Sub-Saharan Africa and South Asia. They highlight how crop residue use is determined by the interaction of farmers' preferences, levels of production, demand for biomass and access to alternative resources and how these are related to the level of crop and livestock intensification. In contrast to the prevailing focus on one study site in most other papers in this issue, their meso-level analysis across study sites provides insight into the major drivers that affect crop residue production and use such as agro-ecological conditions, human and livestock population dynamics, infrastructure and markets. Indeed, they illustrate how agricultural intensification can assist in increasing biomass availability thus reducing trade-offs.

The special issue concludes with a brief synthesis paper "Trade-offs around crop residue biomass in smallholder crop-livestock systems – What's next?" by the Guest Editors (Tittonell *et al.*, 2015). Pulling together the reported findings in different locales using different approaches they present an overarching conceptual framework and summarize the key findings, before distilling the major implications for methods, system trajectories and policy.

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