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Tradeoffs around crop residue biomass in smallholder crop-livestock systems – What's next?

Pablo Tittonell [a,*], Bruno Gérard [b], Olaf Erenstein [b]

[a] Wageningen University and Research Centre, P.O. Box 430, 6700 AK Wageningen, Netherlands
[b] International Maize and Wheat Improvement Centre (CIMMYT), Apdo. Postal 6-641, CP 06600 Mexico, D.F., Mexico

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ABSTRACT

Much has been written on the tradeoffs that smallholder farmers face when having to allocate their biomass resources among competing objectives such as feed, fuel, mulch, compost or the market. This paper summarises yet a new body of evidence from 10 studies on tradeoffs in the allocation of cereal crop residue biomass between soil management and livestock feeding in developing regions, published in the special issue of Agricultural Systems 'Biomass use tradeoffs in cereal cropping systems: Lessons and implications from the developing world'. The studies cover a diversity of socio-ecological contexts, farming system types and scales of analysis. We reflect on their main findings and methodological progress, and on the new and not-so-new implications of these findings for research and action in the development agenda. We propose stylised graphical models to portray tradeoffs and plausible trajectories towards synergies, in the hope that such generalisations would prevent further efforts to 'reinvent the wheel' in the realm of tradeoffs analysis. We advocate an ex-post impact assessment of recent investments in systems research to help focus such research further and clearly define its future role in prioritizing and targeting development interventions.

1. Introduction

The analysis of tradeoffs between competing uses for crop residue biomass has occupied a large volume of the specialized literature over the last two decades (e.g., Powell et al., 1995; Powell and Williams, 1995; Sain and Barreto, 1996; Renard, 1997; Dugué et al., 1998; Erenstein, 2002; Powell et al., 2004; Baudron et al., 2014). Much insight has been gained into their drivers, their magnitude and their consequences. Yet, such knowledge has seldom been translated into generalizable concepts or used to inform practical recommendations for management or policies. A possible explanation for this is the location-, system-, farm type- and scale-specificity, and intrinsic complexity of crop residue tradeoffs (Erenstein et al., 2015). The literature indicates that crop residue biomass is a valuable resource for smallholder farmers, often in short supply, that can be alternatively used to feed livestock, as domestic fuel, as building material or as soil amendment, either through composting, direct incorporation or mulching. The relative importance of these various uses differs across farming system types, as determined by their agro-ecological potential, population density/farm sizes, and markets (Valbuena et al., 2012).

Different authors tend to analyse these tradeoffs from the perspective of their own discipline, e.g., by assessing their potential as feed for livestock intensification (Lenne et al., 2003; Blummel et al., 2009; Herrero et al., 2010; Thornton, 2010; Tarawali et al., 2011), their availability as mulching material for conservation agriculture (Scopel et al., 2004), or their contribution to nutrient cycling in agroecosystems at different scales (Powell et al., 1996; Buerkert and Hiernaux, 1998; Ikpe and Powell, 2002; Zingore et al., 2011). Recent developments in the bioenergy sector (Wilhelm et al., 2007; Service, 2014) prompted the use of crop residue biomass as feedstock for this industry to be included in tradeoffs analysis, notably in regional to global assessments (e.g., Lal, 2008; Dixon et al., 2010). The methods used to assess – and increasingly to quantify – tradeoffs have evolved significantly over the last decades: from participatory assessments of tradeoffs (Defoer et al., 1998; Dougill et al., 2002), to direct measurements of biomass flows in the field, surveying and collection of large datasets across contrasting environments and/or the use of sophisticated modelling techniques at different spatio-temporal scales (e.g. Thornton and Herrero, 2001; Thornton et al., 2003; Stoorvogel et al., 2004; Claessens et al., 2009; Mekasha et al., 2014). Recent examples of an array of methods to analyse tradeoffs across diverse farming systems were compiled in this special issue of Agricultural Systems (cf. Table 1 in Erenstein et al., 2015).

* Corresponding author.
E-mail address: pablo.tittonell@wur.nl (P. Tittonell).

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The analysis of these studies and of the previous literature on tradeoffs around crop residue biomass allocation, particularly to soil amendment vs. livestock feeding, points to a need to (i) distil generalizable patterns to categorise and describe tradeoffs in contrasting socio-ecological contexts, (ii) use these insights to inform the development of management strategies, desirable system trajectories and policies. In other words, and in view of all the knowledge, quantitative and qualitative evidence available, what should be the next step? Is it possible to summarise the various patterns observed into a generic conceptual framework to inform recommendations? Are there knowledge gaps that require further research? We are aware of the challenge posed by these questions, and of the somewhat partial geographical coverage from which we will draw our conclusions. Yet, we feel that further investments in tradeoffs analysis without a framework to translate them into policies and actions to overcome such tradeoffs would be rather futile. The objective of this paper is to summarise the main findings of the studies on tradeoffs in the allocation of crop residue biomass particularly between soil management and livestock feeding published in this special issue to contribute some answers to the questions aforementioned.

2. Theoretical framework

Tradeoffs between any two competing objectives can be depicted as in Fig. 1. In this example, they are generically termed as 'utility of use as feed' (F) vs. 'utility of use as soil amendment' (S), referring to the utility derived from crop residue biomass allocated to either use, without specifying units. In this simplified model there is no other possible use for crop residues, so that the crop residue biomass is partitioned between objectives F and S. This is obviously not the case in most farming systems, as residues are subject to multiple uses. But for illustrative purposes we focus our analysis on these two competing objectives that were also the key tradeoffs analysed in most of the studies in this special issue (cf. Table 1 in Erenstein et al., 2015). The tradeoffs between these two competing objectives, which draw on mutually exclusive crop residue uses at a single point in time, may be best described by one of the three curves proposed in Fig. 1, termed *Regime A*, *B* and *C* (cf. Tittonell, 2013). *Regime A* corresponds to a situation of strong competition between objectives F and S. *Regime B* corresponds to a situation of substitutability in which the rate of replacement or conversion from S to F or vice versa is inversely proportional. *Regime C* describes a situation in which complementarities are possible within a wide range of fulfilment of both F and S. Synergies between both objectives may also be possible when different time horizons are considered; for example, if soil amendments would allow for subsequent increases in feed productivity, then the effect of soil amendment on feed utility might be potentially positive in the longer term.

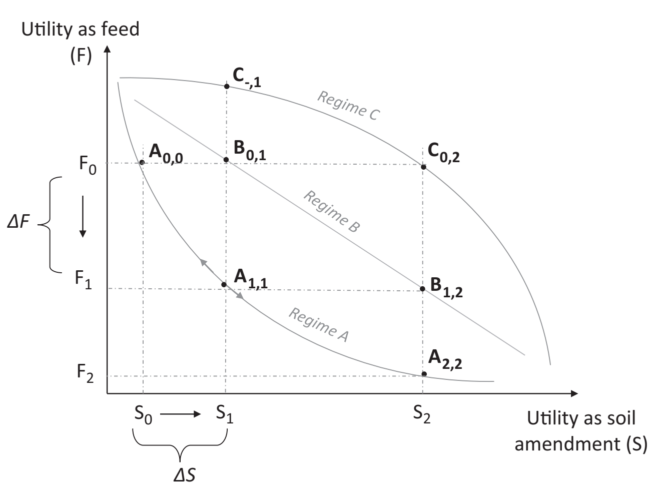

Fig. 1. Conceptual tradeoff curves between crop residue uses as soil amendment vs. livestock feeding. The three regimes describe situations of strong competition (A), substitutability through exact inverse proportionality (B) and possible complementarities (C). See text for further explanation.

Let us first assume a competition scenario where the farmer uses most crop residues for F and little for S – i.e. a utility of residue biomass F_0 and S_0 in Fig. 1 represents a current allocation pattern, and that the rate of conversion is described by *Regime A.* Increasing the allocation of crop residues to soil amendment (i.e. to increase the utility of soil amendment by an amount ΔS to a level S_1) will entail a strong reduction in the utility as feed (ΔF) down to a level F_1. The system experienced a shift from point $A_{0,0}$ to $A_{1,1}$. The utility S_1 could indicate, for example, a minimum target level of crop residue amendment necessary to maintain soil fertility in the medium term. The utility F_1 would then indicate the new level of livestock utility, that underwent a substantial reduction due to e.g. having reduced herd size and/or substantially lower herd productivity due to insufficient feeding. Within *Regime A*, conservationists may advocate S_1 to be insufficient for soil fertility maintenance in the long term and the corresponding need to further shift from point $A_{1,1}$ to $A_{2,2}$ to achieve a soil amendment target S_2 that is deemed preferable to target S_1 but further reducing utility of feed to F_2. The level F_2 could indicate, for example, a curtailed livestock utility because livestock productivity is now so low it barely provides any livestock functions.

Regime A depicts a high degree of competition between the utility derived from feed and soil amendment and correspondingly severe tradeoffs. *Regime B* provides for substitutability and *Regime C* for complementarities – which imply increasingly favourable tradeoff scenarios. In Fig. 1 the current (S_0) and minimum target (S_1) levels of allocation of crop residues to soil amendment would correspond with higher levels of feed utility when the tradeoffs are described by *Regimes B* or *C*. The initial feed utility target level F_0 can be achieved only with negligible utility for soil amendment under regime A (point $A_{0,0}$) but substantially higher utility levels within *Regime B* (point $B_{0,1}$, meeting the minimum soil fertility needs) and within *Regime C* (point $C_{0,2}$, meeting longer term soil fertility needs). A noteworthy assumption in this simplified model is that the quality of crop residue biomass does not change across system regimes. In reality, however, inclusion of legume intercrops together with cereals may lead to greater biomass production and feed quality improvements (e.g., Naudin et al., 2011), thereby resulting in greater livestock productivity and potentially allowing regime shifts. If, instead, legumes are included in rotation with cereals this might eventually result in lower total annual biomass productivity (e.g. Thierfelder et al., 2012a,b), increased feed use and faster decomposition of legume residues or weathering losses (Erenstein, 2002: 120–2), aggravating biomass tradeoffs.

The utility maximizing position for any regime – and the associated tradeoffs by moving along any regime – are based on preferences, perceived benefits and risks, or sheer costs and constraints imposed by endogenous (e.g. resources) or exogenous factors (e.g. relative prices). New technologies, new agroecosystem designs, policies and/or development interventions may provoke (i) changes that result in system shifts within a certain regime, (ii) changes that allow system jumps from one regime to the next or (iii) changes that create new regimes. Based on this set of heuristics, it is possible to recognise cases in which the three regimes may represent, either:

1. Different socio-ecological contexts, being observed or proposed as scenarios;

2. Different farm types within a certain territory (e.g. more or less resource endowed, market- vs. subsistence-oriented, etc.);
3. Different scales of analysis of the same system; or
4. Different system configurations alongside a trajectory of change or an intensification pathway.

We will illustrate this through the analysis of the various cases presented in this special issue, and use the framework when analysing the implications of their results for delineating possible future system trajectories.

The strength of crop-livestock interactions and therefore the severity of tradeoffs for crop residue use as feed vs. soil amendment varies across socio-ecological contexts, determined by their agro-ecological potential, market opportunities, population densities (land availability) and type of farming system prevailing (Powell and Williams, 1995; La Rovere et al., 2005; Manyong et al., 2006). Fig. 2 presents a scheme developed by the former System-wide Livestock Program (SLP) led by the International Livestock Research Institute (ILRI) that shows the relative importance of different sources of livestock feed across farming system types, defined here rather loosely as 'farming intensity'. In less favoured areas, where crop production is not possible or relatively marginal, grazing is the main source of feed for livestock, complemented with increasing amounts of opportunistic biomass sources (e.g. tree branches, household waste, etc.). As conditions for crop production improve, and land available for grazing declines due to higher human population densities, crop residue biomass becomes increasingly important as source of feed, from dry season grazing to almost year-round cut and carrying. In yet more conducive environments, with greater market connectivity and agro-ecological potential, cultivated fodder crops and improved pastures become increasingly important feed sources, often complemented with/supplemented by concentrates (not shown in Fig. 2).

Within the range of farming systems in which crop residues are an important source of feed, their availability may be more or less limiting following the local agro-ecological potential. In high potential areas, and where farm sizes are larger than a location-specific threshold, there may be surpluses of crop residue biomass, which are often sold on the market. Tradeoffs are typically experienced in areas of lower potential that host relatively dense human populations, or rather where human and livestock populations exceed the carrying capacity of the agroecosystem, such as many parts of the Sahel in Africa. But also within a single rural community, the least endowed households may experience crop residue shortages, even when they do not possess livestock, while the more endowed ones may experience surpluses. Finally, it is important to point out that the theoretical relationships shown in Figs. 1 and 2 do not explicitly take into account the market price of crop residues or the economic benefits that may be obtained by allocating them to soil fertility maintenance (through increased crop yields), to livestock feeding (through increased livestock milk yield or body weight gains or corporal condition) or to other activities. Neither do they differentiate – at least explicitly – between the associated short and long-term impacts: Whereas the benefit of feeding crop residues to livestock may translate into more or less direct economic benefits, such as greater milk yields, weight gains, higher stocking or even survival rates, the benefit of allocating crop residues to soil may become evident only after a certain period of time (build-up delay). Except when residues are applied as mulch to increase water capture and conservation, which may have an immediate effect on crop growth, longer periods of time are necessary for soil quality improvements – e.g. for nutrients contained in residue biomass becoming available to crops or for soil organic matter content and soil structure to be improved. In other words, and from an ecological perspective, we are analysing tradeoffs between relatively fast (animal responses to feed) and slow (soil quality improvement) variables.

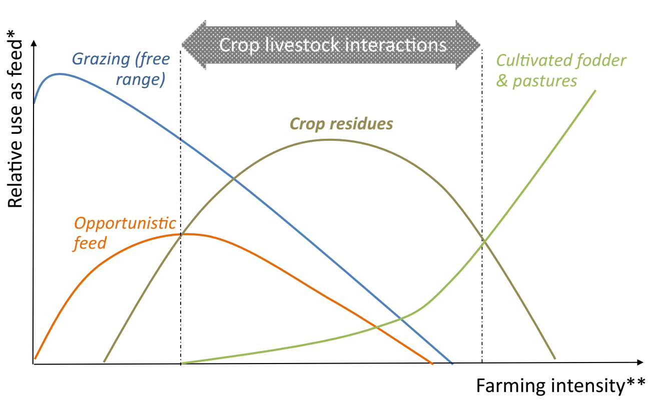

Fig. 2. Hypothesised relationships between farming intensity or agro-ecological potential and the importance of crop residue biomass as a source of feed. Relative importance of various biomass sources as feed (*only roughages are considered, not concentrates) is shown along a gradient of farm intensity (**defined by the number of cropping seasons per year, population density, market connectivity), developed by the former System-wide Livestock Program-SLP by B. Gérard (Adapted from Paul et al., 2013).

3. Key findings from the special issue

3.1. Feeding the soil or feeding the cow?

Crop residues left as mulch have a positive role in maintaining or restoring soil health as reviewed by Turmel et al. (2015), through (i) a chemical contribution to nutrient balances, soil organic carbon, soil pH, CEC; (ii) an enhancing role on soil biological activities, both positive (e.g. promoting earthworm activity) and negative (e.g. promoting soil borne diseases); and (iii) a physical/mechanical role improving soil structure and aggregate stability, protecting the top-soil against wind and water erosion, reducing run-off and so improving rain water retention at field scale. Most of the contributions to this issue have emphasized the role of crop residues in the context of conservation agriculture, attempting to address challenging questions regarding adoption/adoptability of mulching practices and related tradeoffs in mixed crop-livestock farming systems where demand on crop by-products as animal feed is often high (cf. Fig. 2).

There is a need to develop decision support on crop residue allocation going beyond 'blanket' and rigid recommendations regarding the amount of mulch required to enhance or maintain crop productivity and avoid reversible and irreversible land degradation. The short and long term agronomic and economic returns to mulching are site specific and depend on a number of factors and their interactions: (i) amount, quality, and type of residues; (ii) soils and land characteristics (texture, water holding capacity, and slope); (iii) crop management, particularly tillage management practices (i.e. primary, reduced or no tillage, permanent raised bed, strip tillage, etc.), weed and pest management; (iv) climate and rainfall regimes. At a given site there can be large inter-seasonal or inter-annual variation in mulching benefits due to specific seasonal rainfall patterns and rain events, but also variation across soil types on the landscape. For example, in humid and temperate regions or in low lying heavy soils mulching can lead to increasing nutrient leaching or promoting soil born fungal diseases. Unless better ex-ante site specific assessments of the short and long term value of crop residues used as mulch are developed, tradeoff analyses between 'feeding the soil vs. feeding the cow' will remain blurry relying on few scattered empirical evidences from field experimentation. There is a need to develop a more coherent approach, harmonized protocols, prospective analyses and modelling, and open data sharing in order to develop robust decision support systems (Corbeels et al., 2014).

Stating the obvious, farmers are the key decision makers when it comes to allocate crop residues to both maintain their land productivity and feed their livestock. Their rationale in doing so is driven by their know-how, experience, perceived risks and expected returns on resource and labour investments, the relative importance of their farming enterprise in their livelihood strategy (i.e. vis-à-vis off-farm income), and external factors such as input/output markets for both crop and livestock products and the policy environment, including private and communal institutions around resource use (e.g. regulation of rice straw burning in the Indian Punjab – Kumar et al., 2015; open grazing of fields after harvest in many SSA systems – this issue). Farmers' perceived returns on investment and associated risks, as well as financial liquidity around planting or harvesting times, tend to drive their decisions more strongly than any objective assessment of returns and their likelihood (e.g., Tittonell et al., 2007). To make ends meet, poor smallholder families often curtail their investment horizons, resulting in a bias towards short term returns which might jeopardize long term land productivity. So in the case of crop residue allocation, one can expect that crop-livestock farmers favour feeding their livestock, that have critical multi-functions, to the detriment of long term maintenance of their productivity base (Barrett et al., 2002). This bias towards feeding crop residues to livestock is highlighted by several contributions in this special issue. In Ethiopia, Jaleta et al. (2015) report that crop residue use as soil amendment or mulch remains a major challenge with 56% of maize stover used as feed, 31% as fuel and only a negligible fraction left on the fields. In Western Kenya (Castellanos-Navarrete et al., 2015), on average 72% of maize residues were used to feed cattle, 22% kept in the field, and only 5% added to a compost pile together with manure. In addition most of the hay from legumes intercropped with maize was harvested and fed to cattle. The study also highlighted the poor nutrient cycling efficiency that results from inadequate manure management. Given the economic importance of dairy production for those Kenyan farmers, Napier grass is now grown or purchased by most of them, increasingly replacing green maize stover and maize residue biomass as feeds. In the central highlands of Mexico, Beuchelt et al. (2015) report exhaustive maize crop residue use as feed; 70–95% for ex-situ cattle feeding and 1–30% stubble grazing, leaving very little as mulch.

Surveys summarized by Valbuena et al. (2015) over 12 sites across sub-Saharan Africa and South Asia showed large inter-site diversity in terms of pressure on crop residues, cropping intensity, feeding strategies (thereby validating empirically Fig. 2). At sites with sparse population and livestock densities, dominated by extensive agricultural systems that occupy less than 50% of the land available for cultivation (Nkayi in Zimbabwe; Changara in Mozambique; Mzimba in Malawi) open grazing provides a large share of cattle feed but cereal residues are also widely used (circa 90%, 80%, and 55% of crop residues used as feed for Nkayi, Changara, Mzimba respectively – somewhat challenging Fig. 2). At sites with intermediate population densities and moderate to high livestock densities (Niger, Nigeria and Ethiopia) with frequencies of land cultivation ranging from 88% to 96%, crop residues are an important source of feed and barely used as soil amendment – aggravating susceptibility to land degradation and soil erosion. Fertilizer use in those sites is still limited with soil nutrient mining and the largest cereal yield gaps. The sites with more intensive farming systems (Kakamega in Kenya, Rajasthan and Karnal in India, Dinajpur in Bangladesh) have a higher 'carrying capacity' for livestock population (2.6–4.3 TLU ha^{-1}) and higher rural population densities (particularly Dinajpur and Karnal). The more intensely exploited sites have better endowed environments (Kakamega) or are irrigated (Dinajpur and Karnal), and well connected to input/output/feed markets with much higher use of mineral fertilizer compared to the other study sites. High cereal productivity in Karnal, Dinajpur, and limited use of crop residues as feed in Kakamega allow more retention of crop residues as soil amendment.

In addition to meat, milk and egg products, livestock has important functions regarding farm power, nutrient cycling and soil improvement through the use of manure, providing draft power for land preparation and transport. In smallholder systems livestock plays a critical role as a capital saving mechanism and risk mitigation strategy in case of crop failure (Kazianga and Udry, 2006). It is common for smallholder farmers to sell livestock in years of low crop production to purchase food and to restock in good years (Homann-Kee Tui et al., 2015), although the efficiency of the scheme depends on risk idiosyncrasies. In transhumant and semi-transhumant systems, livestock mobility permits exploitation of biomass resources outside the farm and village boundaries in case of drought (Turner et al., 2014) and to maintain the herd in difficult years. In addition, livestock endowment has often a strong cultural dimension as a sign of social status. Livestock productivity in many smallholder systems is low (Andrieu et al.; Baudron et al.; Jaleta et al.; Homann-Kee Tui; Valbuena et al.;) yet the demand for livestock products is increasing. Technical livestock innovations (e.g. livestock health, breeding, feeding, mechanization) could improve the productivity of those systems – but an entire shift in the configuration of livestock system may be needed to intensify production (cf. Tittonell et al., 2009). And this needs to be paired with more enabling policy and market environments, adapted rural financial mechanisms and good governance at local, regional and national levels. Valbuena et al. (2015) through their analysis of a range of very diverse crop-livestock systems, provide a pseudo 'chronosequence' of how those systems could evolve.

3.2. Alleviating biomass tradeoffs

Increasing biomass productivity by any means will contribute to alleviate biomass tradeoffs, as there will be simply more of the limiting resource available. Agricultural productivity and hence crop biomass in smallholder systems are often limited by insufficient nutrient availability. This has led several authors to advocate for synthetic and mineral fertilisers together with improved crop cultivars as an entry point to raise agricultural productivity in sub-Saharan Africa (Sanchez et al., 1997; Vanlauwe and Giller, 2006; La Rovere et al., 2008; Vanlauwe et al., 2014). Yet, a growing number of studies from the region shows that (i) crops respond poorly to synthetic and mineral fertilizer on degraded soils or on soils with inherently poor water holding capacity (e.g. Wopereis et al., 2006; Tittonell et al., 2008; Rusinamhodzi et al., 2012), and that (ii) repeated fertiliser applications and crop residue incorporation in soil without organic matter additions are ineffective at building soil fertility (soil C, total N, pH, CEC) in the long term in tropical climates (Zingore et al., 2006; Kintché et al., 2010; 2015; Ripoche et al., 2015). Adequate soil organic management is thus a prerequisite to get good responses to fertilizer investments (e.g., Bationo et al., 2006; Yémélou et al., 2014), especially on degraded soils. Yet organic matter resources may be difficult to come by in enough quantities in several African agroecosystems (Tittonell and Giller, 2013). This evidence, together with the empirical observation that fertilisers are often unavailable to smallholder farmers in rural Africa, led Sommer et al. (2014) to argue that conservation agriculture can be an effective way to improve soil responsiveness to the small amounts of fertilisers that farmers are able to afford.

Through the use of the economic TradeOff Analysis model for Multi-Dimensional Impact assessment (TOA-MD, Antle, 2011) and scenario analysis, Homann-Kee Tui et al. (2015) suggest that conservation agriculture in maize based systems of semi-arid Zimbabwe appears viable only with fertilizers. But they also show relatively low potential adoption rates, irrespective of whether fertilizer is subsidized or not (27–55% potential adoption depending on farmer type and fertilizer subsidies). They simulated alternative conservation agriculture and fodder crop options for different farm types (based on livestock endowment) – although those options are not mutually exclusive and could also have been combined in the scenario analysis. They suggest a limited potential of technical innovations alone to improve the livelihoods of smallholder farmers and lift them out of poverty.

In their study site in the Sudan savannah zone of Burkina Faso, Andrieu et al. (2015) report relatively high levels of mineral fertilizer use on maize: from 44.9 kg ha^{-1} for livestock-oriented farmers who have better access to manure to 103.3 kg ha^{-1} for better endowed, market-oriented farmers. Privatization (collection) of crop residues was limited and they concluded there were no severe tradeoffs at the farm level, the biomass produced at village scale being enough to meet feed requirements even under communal grazing practices. But when different farm types are considered individually, the study reveals how livestock-mediated transfers of nutrients from less endowed farms to better endowed ones can aggravate inequity, as shown in previous studies (e.g. La Rovere et al., 2005; Zingore et al., 2011; Rufino et al., 2011).

Baudron et al. (2015) highlighted the importance to increase sorghum biomass production in the sorghum-cotton systems in Zimbabwean Mid-Zambesi valley through adequate N nutrition and use of external inputs to minimize tradeoffs between crop and livestock productions. While the analysis of nutrient networks in African crop-livestock systems revealed that biomass productivity is often uncorrelated with total nutrient (N) throughput (Rufino et al., 2009; Alvarez et al., 2014), most studies in this special issue have only marginally looked at alternative ways of bringing biomass and nutrients into the farming system. These can be seen in the study of Castellanos-Navarrete et al. (2015) that considers options such as external feed inputs, and in those of Homann-Kee Tui et al., and of Naudin et al. (2015) that assume potential inputs through biological N fixation. The inclusion of legumes in the cropping system to overcome biomass tradeoffs through either increased total biomass or better feed quality did not receive much attention in the studies compiled in this special issue, as most papers focused on ways of analysing tradeoffs and not on how to alleviate them.

3.3. Portraying system trajectories

A system trajectory can be defined as a long-term shift within a certain regime, a shift to a new regime, and/or the creation of such new regimes through systems' redesign (cf. Fig. 1 and related text). In the various studies published in this special issue (cf. Table 1 in Erenstein et al., 2015) the theoretical system regimes describing tradeoffs in Fig. 1 (i.e., *Regimes A, B and C*) corresponded to either different socio-ecological contexts (cf. Beuchelt et al., 2015; Jaleta et al., 2015; Magnan, 2015; Valbuena et al., 2015), to different farm types (cf. Castellanos-Navarrete et al., 2015; Homann-Kee Tui et al., 2015; Naudin et al., 2015) and/or to different scales of analysis (cf. Andrieu et al., 2015; Baudron et al., 2015). In this paper (Section 2) we indicated a fourth possible interpretation of these regimes as "different system configurations alongside a trajectory of change or intensification pathway". None of the studies in this special issue examined system trajectories explicitly as shifts within or across regimes. Fig. 3 illustrates how such a simple theoretical framework could be used to analyse trajectories.

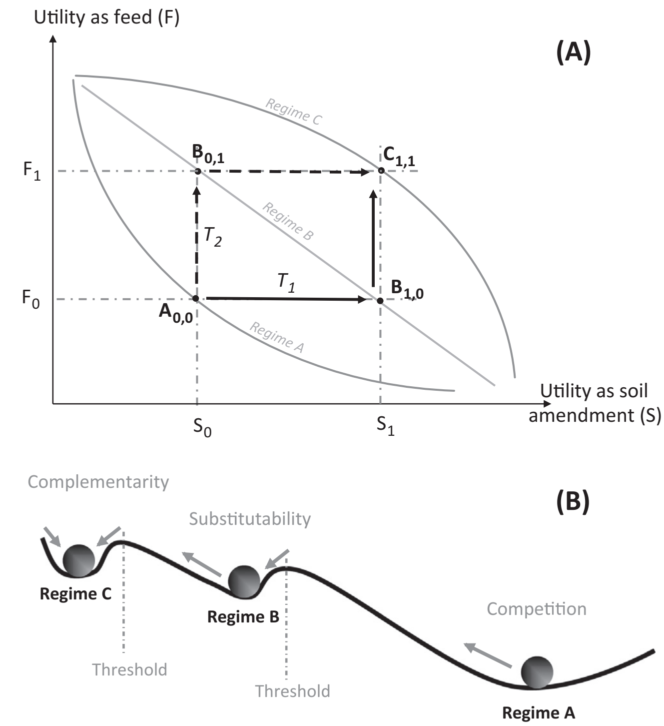

Fig. 3. Portraying possible system trajectories. (A) A system that is currently in Regime A, whose relative allocation pattern is described by point $A_{0,0}$, may reach the target point $C_{1,1}$ on regime C following two alternative trajectories, T1 or T2. (B) Moving across system regimes may imply that certain thresholds must be crossed, as represented by a stability landscape with three basins of attraction.

In Fig. 3 A, moving from a current situation represented by point $A_{0,0}$ to a desirable situation represented by $C_{1,1}$ can be done following at least two alternative trajectories. On trajectory 1 (T1), the shift is operated by first increasing crop biomass production and its allocation to soil (shift to $B_{1,0}$), so that greater soil fertility in the mid-term can lead in turn to greater biomass production and availability for livestock feeding to ultimately achieve a level F_1 in the future ($C_{1,1}$). On trajectory 2 (T2), allocation to livestock feeding is first prioritised (shift to $B_{0,1}$), in order to increase livestock productivity (milk, traction, weight gain), generating greater incomes and/or animal manure to fertilise the soil in order to achieve the target fertility level S_1 in the future. Multiple combinations and intermediate trajectories between T1 and T2 are of course possible. Yet, the assumption that income from livestock will allow investments in soil management, and vice versa, is certainly contestable. Higher incomes will not always necessarily translate into greater investments in soil fertility or in any other farming activity (cf. Tittonell, 2014a). The diversity of trajectories that smallholder households may follow is illustrated in a recent longitudinal study of Valbuena et al. (2014) in western Kenya, where it is shown that better-to-do farmers invest increasingly in a portfolio of non- and off-farm activities.

Whether a trajectory T1 is preferable to T2 or vice versa depends on the biophysical and socioeconomic contexts in which the system operates, on the type of household in terms of resource endowment and objectives, and on the current configuration of the farm system (e.g., surface area, current land use, herd size, feeding system, investment capacity, labour availability, etc.). The various studies compiled in this special issue seem to suggest that trajectory 2 appears as a default strategy among poor farmers when they are able to own livestock; whereas conservation agriculture advocates favour variants of trajectory T1. Yet, in most of these studies the focus has been on mapping out system regimes for different contexts, farm types or scales and less on exploring options for regime shifts. The model-based assessments by Homann-Kee Tui et al., 2015; Baudron et al., 2015 and Naudin et al., 2015 do consider scenarios in which biomass productivity increases thereby alleviating tradeoffs through – presumably – a permanent regime shift. Yet none of the studies in this special issue propose out-of-the-box options to achieve synergies, such as diversification or alternate pathways (e.g., from arable cropping to agroforestry, from free grazing to confined cut and carry livestock systems, from staple cereals to marketable vegetables, and to other, non-farm, activities, etc.). Such options often imply thorough reconfigurations of current systems through their re-design (e.g. Dogliotti et al., 2014a,b; Tittonell, 2014b; Tittonell et al., 2009; Funes-Monzote et al., 2008).

Shifting across system regimes requires investment, knowledge and support, and the trajectory may exhibit non-linearity, hysteresis and thresholds (cf. Tittonell, 2014a). Fig. 3B illustrates shifts across regimes using the analogy of stability landscapes (Scheffer et al., 2001). The system is represented as a ball, and each regime is represented as a basin of attraction along an undulating landscape. When moving along the landscape, the ball tends to converge towards the bottom of each basin of attraction. A shift from regime A, characterised by strong competition between objectives S and F (cf. Fig. 1), to regime B requires energy investments to 'push the ball upwards' and to overcome a threshold, beyond which the system would find its own new equilibrium at the bottom of basin B (substitutability regime). In drawing Fig. 3B, we hypothesise that shifting from regime B to regime C requires less effort, less investment, albeit having to go through a new threshold. Examining now the various crop-livestock systems studied in this special issue in the light of these ideas suggests that they could be placed in different starting points along a stability landscape.

In the South Asian cases, for instance, access to subsidised external inputs of nutrients and water and the use of significant amounts of crop residues as soil amendment coupled with higher productivity and market orientation of livestock products seem to grant those systems long term soil productivity maintenance and increased stability. Likewise, different farm types within a single location could be placed at different positions along a stability landscape, as illustrated by most studies in this special issue. Note that development interventions should not stop at trying to get systems to shift across regimes; investments or policies can also be directed to modifying the shape of the stability landscape by e.g. lowering thresholds or enlarging desirable basins of attraction. This is hinted in the 'chronosequence' of agricultural development contexts proposed in the study of Valbuena et al. (2015). Relieving the pressure on the natural resource base requires technical and institutional innovations to be integrated and tailored to actual farm, site, and agro-ecology specific livestock functions. For example, the intensification of crop production to provide more residue biomass will, in the absence of rural saving alternatives, likely just enlarge the livestock herds. This may result in more relatively unproductive animals and not necessarily ease the pressure on crop residue biomass and the land, affecting the system's productivity and stability.

Beyond their contribution in terms of tradeoff assessment methods, the papers in this special issue contribute to the body of general knowledge around smallholder farming systems in developing countries, and in some cases on the potential role of the agricultural sector in reducing poverty. Population growth over the last 50 years has put tremendous pressure on farming systems and has aggravated sustainability concerns. For most of the systems covered by this special issue, land endowment and declining farm land per capita are a major constraint. Increasing land scarcity and the inherent limitations of agricultural intensification alone to reduce poverty in constrained smallholder systems has been eloquently raised recently (Harris and Orr, 2014; Jayne et al., 2014), although Harris and Orr failed to capitalize on the potential role of livestock production in marginal rainfed smallholder systems. Increasing land scarcity and inequitable access are major concerns and can aggravate natural resource degradation, and should receive higher priority on the policy agenda. Although challenging, particularly in the multifaceted smallholder crop-livestock sector, agricultural development remains pivotal for broad based equitable economic growth and needs to be paired with the development of non-agricultural sectors to allow for rural income growth, diversification and investments in infrastructure and market development.

4. Methods and knowledge gaps

The analysis of tradeoffs between competing crop residue biomass uses has been variously tackled – as shown by the wide body of literature including this special issue (Table 1). A key challenge has been the need to harmonize in the analyses the micro-level intricacies of agricultural systems vs. the macro-level implications – each posing their own analytical challenges not least in terms of (i) data and measurability, (ii) heterogeneity between individual farms and over space and time, as well as (iii) challenges of linking

Table 1
Methodology, data sources and location of the studies compiled in the special issue Biomass use tradeoffs (hh: households).

#	Paper	Method	Data	Location
1	Turmel et al. (2015)	Review, meta-analysis of crop-soil data	Meta-database	Global
2	Jaleta et al. (2015)	Regression analysis at farm scale	Quantitative (1430 hh)	Ethiopia
3	Castellanos-Navarrete et al. (2015)	Calculation of C and N flows at farm scale	Quali-quantitative (10 hh)	Vihiga district, Western Kenya
4	Naudin et al. (2015)	Farm-scale optimization through linear programming	Quantitative (3 prototype hh)	Lake Alaotra region, Madagascar
5	Homann-Kee Tui et al. (2015)	Tradeoff analysis model at farm scale	Quali-quantitative (160 hh)	Nkayi District, Zimbabwe
6	Beuchelt et al. (2015)	Spatially-explicit regression analysis at farm to landscape and national scale	Quali-quantitative (25 comm; 76 hh)	Central highlands of Mexico
7	Magnan (2015)	Constrained optimization multi-household model	Quantitative (2 farm types)	Middle Atlas region, Morocco
8	Andrieu et al. (2015)	Quantitative analysis of resource flows at field, farm and village scale	Quali-quantitative (30 hh)	Sudan-savannah zone of Burkina Faso
9	Baudron et al. (2015)	Coupled crop simulation, farm and agent agent-based models at field, farm and landscape level	Quantitative (176 hh)	Mid-Zambezi Valley, Zimbabwe
10	Valbuena et al. (2015)	Comparative analysis of household survey data	Quali-quantitative (12 sites)	Case study regions in Ethiopia, Kenya, Malawi, Mozambique, Zimbabwe, Niger, Nigeria, Bangladesh, India

the different analytical scales. Further analytical challenges are posed by bridging disciplinary divides: often there is a "disconnect" between crop and livestock scientists and/or social and biophysical scientists (Erenstein and Thorpe, 2010).

A simple categorization of the methods used vs. the levels of integration considered in the studies compiled in this issue is presented in Fig. 4 (building on Table 1). The methods were ordered along a gradient of increasing determinism, with descriptive statistical models and meta-analyses at the bottom, through objective optimisation models based on technical coefficients, up to quantitative analyses based on actual measurements and mechanistic models that consider feedbacks in the system. Non-surprisingly, a quick glance at Fig. 4 reveals a major focus of most studies at farm and household level, although a few of them address more than one integration level. Each paper addresses almost a unique combination of study object, scale, type of data and method that we attempt to summarise as follows:

Study object

The farm is the most common entry point for the biomass use tradeoff analysis (Table 1 and Fig. 4) – in part associated with our underlying focus on crop-livestock farms but farm-scale decisions are the most common nexus between the crop and livestock sub-systems in smallholder agriculture. Although sharing a similar entry point at the farm level, individual studies variously analysed crop residue management determinants (2 – Jaleta et al., 2015), nutrient cycling at farm scale (3 – Castellanos-Navarrete et al., 2015), mixed farm optimization (4 – Naudin et al., 2015), or alternative management options (5 – Homann-Kee Tui et al., 2015). Other studies considered the farm scale as entry point but they included also lower and/or higher integration levels, and their interactions, as the focus of their analyses (6 – Beuchelt et al., 2015; 7 – Magnan, 2015; 8 – Andrieu et al., 2015; 9 – Baudron et al., 2015).

Scale of analysis

The scales chosen for the analysis were in all cases closely linked with the integration levels considered, as is commonly the case in the study of smallholder farming systems (Fig. 4, Table 1). Two papers specifically analyse multi-level tradeoffs – albeit one within a specific community (8 – Andrieu et al., 2015) and the other within a broader landscape (9 – Baudron et al., 2015). Magnan (7 – 2015) looks into the social consequences of the behaviour of individual farms for their neighbours, using two farms as case studies. Beuchelt et al. (6 – 2015) consider the farm scale and aggregate their results to a regional scale, without explicitly looking into cross-scale interactions. Of all the papers Valbuena et al. (10 – 2015) take on the highest scale of analysis – using a regional approach of contrasting clusters of sites (building on aggregate farm data) to analyse management determinants and tradeoffs.

Data and indicators

The different papers draw on purposively collected empirical data – except for the review by Turmel et al. (1 – 2015). Most common are sub-national data-sets, although their coverage varies from one village (8 – Andrieu et al., 2015) or a few households (3 – Castellanos-Navarrete et al., 2015), through larger subsets of farms and communities (6 – Beuchelt et al., 2015), to large nationally representative surveys (2 – Jaleta et al., 2015). Only one paper makes a supra-national comparative analysis – albeit still drawing on multiple sub-national cluster data (10 – Valbuena et al., 2015). The empirical data include a range of qualitative and quantitative indicators, with an emphasis on quantitative or hybrid sets.

Analytical method

The different papers use a diverse suite of analytical methods, including regression models (2, 5, 6); optimization models (4, 7); simulation and process models/analysis (3, 8, 9); meta-comparative (1, 10) and spatially explicit (6) analysis. These methods are sometimes used in combination. The study of Baudron et al. (9 – 2015) stands out as it combines soil, field and household data with models at field, farm and landscape level, using locally calibrated crop-soil simulation, and agent-based system models parameterised through discussions with the local communities. While field scale simulation was short term, farm and landscape scale simulations were long term to show plausible future trajectories. This resulted in the additional complexity of having to deal with different time coefficients and spatial scales in the models employed. When such complex methods are used, the obvious question that follows is whether such complexity pays off in terms of what can be learnt about the actual system. Unfortunately the authors omitted a discussion around this question.

Notwithstanding the prevailing interest for quantitative analysis, the relatively small sample sizes or number of analytical types and units in most studies of this special issue are noteworthy, and seem a direct reflection of the inherent complexity of the tradeoffs and inter-linkages involved. Also, such a diversity of scales, methods and indicators poses limitations to the generalizability of the results. Indeed, a recurring feature is the context-specificity of biomass use tradeoffs – so whereas there is a need to analyse the intricacies of the tradeoffs in their local context, that very need limits the ability to draw on empirical data that would also allow looking at the bigger picture and wider implications. Within the current set of papers, the study of Valbuena et al. (2015) is a continuation of earlier work from those authors (Valbuena et al., 2012) that adds to a yet limited set of comparative analysis along agro-ecological gradients at the meso-level (Erenstein and Thorpe, 2010; Erenstein, 2011; Erenstein et al., 2011). Such studies straddle the still prevailing divide in the literature between location-specific studies and sweeping global assessments (e.g. Herrero et al., 2013). Most papers represent also an illustration of how challenging it is to adequately and objectively value tradeoffs – linked *inter alia* to data limitations and the less tangible nature of aspects such as cultural values, or the various spatial and temporal dimensions involved.

The economic valuation of the impact of residue management on crop responses is challenging in its own right – linked to the complexities of the soil-crop residue management nexus (Turmel et al., 2015) and how these translate into crop productivity effects and longer term soil quality benefits. The economic valuation of the impact of feeding residues to livestock is also challenging in its own right – not least in terms of the many non-monetized services livestock contribute to smallholder systems (Moll, 2005) and crop residues by themselves being a relatively poor livestock feed. The economic valuation of tradeoffs reiterates the need to bridge the aforementioned disciplinary divides, pointing to a somewhat persistent knowledge gap (cf. Herrero et al., 2013). Another major remaining knowledge gap is the inter-linkages between the scales of analysis. Whereas two papers did make contributions to the analysis of multi-level tradeoffs (8, 9) – much challenging work remains to be done to more seamlessly integrate analytical levels. Particularly challenging is that tradeoffs can play out differently at different spatial and temporal scales of analysis – whereby the scale and boundaries of analysis, the analytical entry point and focus all have a potentially important role to play in determining the outcome and implications of the analysis.

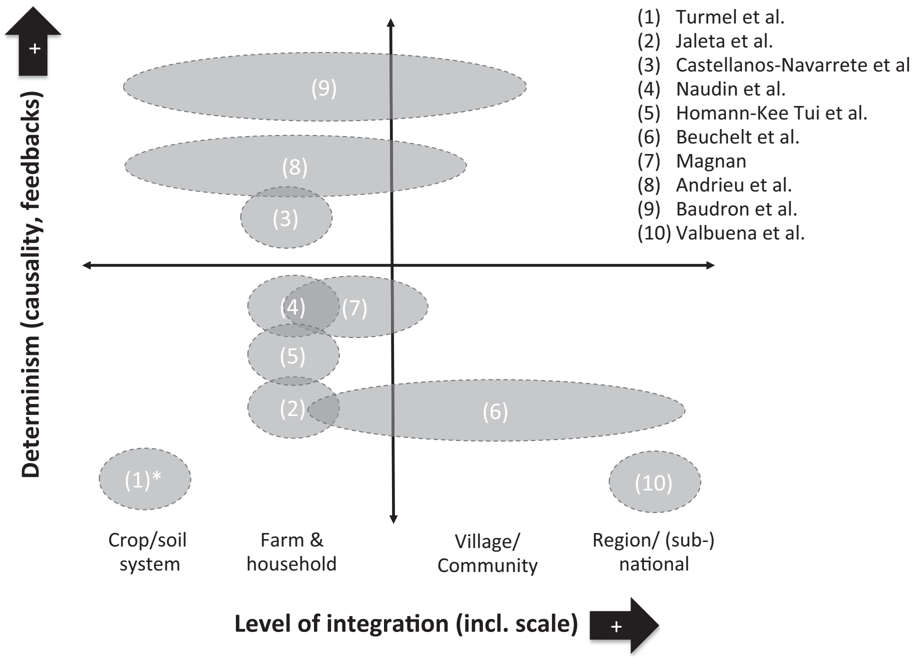

Fig. 4. Schematic representation of the nature of the various studies in the Special Issue on Biomass use tradeoffs according to the level of integration considered and of the degree of determinism used in their analyses. The study by Turmel et al. (2015) was difficult to classify using these criteria: although the authors used hard experimental data from mechanistic studies, the nature of their (meta-) analysis was rather descriptive.

5. Concluding remarks and way forward

The studies in this special issue contribute to our understanding of tradeoffs between alternative uses of crop residue biomass in smallholder agriculture, focusing on their particular use as soil amendment and as livestock feed. Given the diversity of contexts, systems and scales analysed, as well as the methods and sampling frames, it is not possible to summarise the various patterns observed into a single and generic conceptual framework to inform recommendations. What follows is simply an attempt to highlight our major findings and messages emerging from the integrated assessment of these 10 studies:

1. In spite of the progress made, further methodological challenges in the realm of tradeoffs analysis include: (i) understanding and capturing relevant system complexity and bridging disciplinary divides; (ii) the adequate and objective valuation of tradeoffs, beyond the two main objectives addressed in this special issue, and (iii) inter-linking the spatial and temporal scales of analysis and capturing cross-scale interactions.
2. In most of the less intensive systems analysed farmers prioritise livestock feeding over soil amendment, even farmers without livestock in areas with communal grazing regimes; substantial residue retention in the fields was only observed in the stockless systems studied in Malawi, and in the more productive systems of South Asia where irrigation and nutrient inputs are subsidised, and markets for crop and livestock products better developed.
3. Although the analysis of tradeoffs is often restricted to short-term horizons due to methodological (e.g. bio-economic models) or data limitations (e.g. lack of longitudinal studies), it is important to recall that different objectives and scales of analysis may require considering different time scales, fast and slow variables, and long-term system trajectories and reconfigurations (e.g., what appear as tradeoffs in the short term may turn out to be synergies in the long-term).
4. Residue retention as mulch has a number of advantages and may even be essential for soil fertility management in certain cases, but is set to remain challenging in most of the less intensive systems analysed. This does not discard conservation agriculture as such, but does call for adaptation, sequencing of practices and creative, out-of-the-box solutions to increase biomass inputs to soil through increased crop and livestock productivity.
5. Technological advocacy should not distract the research for development community from our quest to alleviate poverty. In view of the rather disappointing impact of our efforts over the last half-century (e.g. per capita food production in Africa did not change since the 1960s), it is time to consider alternative pathways of agriculture intensification – alongside non-agricultural pathways – to enhance the livelihoods and the prospects of rural people across the developing world.
6. In line with the previous point, there is a need to move from integrated *systems analysis* to comprehensive *system design*, integrating both technical and institutional innovations. In other words, we need to gradually shift our focus from addressing 'what-if?' questions through scenario or tradeoffs exploration towards solving 'how-to?' questions through goal-oriented, multidisciplinary efforts.
7. System redesign towards more sustainable outcomes requires understanding the complexity of smallholder farming systems; a condition that is necessary but certainly not sufficient. An ex-post impact assessment of the wealth of research on modelling and system analysis done over the last two decades is urgently needed to help progress such research further and clearly define its future role in prioritizing and targeting development interventions.

An obvious implication is the need for more research to better grapple with these challenges. But as repeatedly highlighted, there is a need to reconsider the type and scope of such research to avoid it just becoming another academic exercise that will be revisited in another decade or so without having made much impact on the ground. We seem to indeed be reaching similar conclusions as documented previously, and re-reading some of the literature from over the last few decades sometimes gives the impression that we are reinventing the wheel. A complicating factor in those old studies and the new ones is the need to include diversity and equity considerations in tradeoffs analysis – be they social (i.e. between diverse stakeholders within a system, e.g. crop vs. mixed vs. livestock farmers; poor vs. well-endowed farmers), spatial (e.g. upstream vs. downstream) or temporal (e.g. immediate needs vs. long term needs; intergenerational equity). For various reasons we often tend to underestimate some of these underlying dimensions, notably the temporal dimension and its far-reaching implications. Systems as well as tradeoffs evolve, with the current scenario being just a snap shot along the trajectory from the past to the future. Given the complexity of understanding the current scenarios we often fail to realize the underlying path dependencies, and that the relevant target for our research for development interventions is the future world and the future challenges our envisioned beneficiaries will be facing.

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