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Identifying determinants, pressures and trade-offs of crop residue use in mixed smallholder farms in Sub-Saharan Africa and South Asia

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ABSTRACT

Crop residues (CR) have become a limited resource in mixed crop-livestock farms. As a result of the increasing demand and low availability of alternative resources, CR became an essential resource for household activities, especially for livestock keeping; a major livelihood element of smallholder farmers in the developing world. Farmers' decisions on CR use are determined by farmers' preferences, total crop production, availability of alternative resources and demand for CR. Interaction of these determinants can result in pressures and trade-offs of CR use. Determinants, pressures and trade-offs are shaped by the specific socio-economic and agro-ecological context of these mixed farms. The objective of this paper is to provide a comparative analysis of the determinants of CR use and to examine some options to cope with pressures and trade-offs in 12 study sites across Sub-Saharan Africa and South Asia. Drawing on socio-economic data at household and village level, we describe how cereal intensification and livestock feed demand influence use, pressures and trade-offs of CR use across study sites, specifically cereal residue. Our results show that in low cereal production and livestock feed demand sites, despite a low demand for CR and availability of alternative biomass, pressures and trade-offs of CR use are common particularly in the dry season. In sites with moderate cereal production, and low–moderate and moderate livestock feed demand, alternative biomass resources are scarce and most residues are fed to livestock or used to cover household needs. Subsequently, pressures and potential trade-offs are stronger. In sites with low cereal production and high livestock feed demand, pressures and trade-offs depend on the availability of better feed resources. Finally, sites with high cereal production and high livestock feed demand have been able to fulfil most of the demand for CR, limiting pressures and trade-offs. These patterns show that agricultural intensification, better management of communal resources and off-farm activities are plausible development pathways to overcome pressures and trade-offs of CR use. Although technologies can largely improve these trends, research and development should revisit past initiatives so as to develop innovative approaches to tackle the well-known problem of low agricultural production in many smallholder mixed systems, creating more sustainable futures.

1. Introduction

Crop residues (CR) have become a limited resource in mixed crop-livestock farms, which form the dominant farming system in the developing world (Herrero et al., 2009, 2010). Persistent low agricultural production, combined with increasing human populations and a decrease or degradation of communal resources have often led to increasing dependence on CR use in these mixed systems. This dependence is critical as CR becomes an essential resource for many household activities including: livestock keeping, obtaining additional cash, cooking, construction and/or soil conservation (Owen and Jayasuriya, 1989; McIntire et al., 1992;

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Williams et al., 1997). Particularly in these mixed systems, livestock keeping is a central livelihood element and CR a fundamental feed source (McIntire et al., 1992; Tarawali et al., 2011).

The use of CR depends on four major interacting factors: farmers' preferences; crop production levels; access to alternative biomass resources; and biomass demand (de Leeuw, 1997; Erenstein et al., 2011). Farmers' decisions on CR use reflect their own needs and preferences (e.g. using or selling residues). Total crop production largely determines the amount of CR available for the household in a growing season. The mix of crops grown also has implications for the quality of the CR; in comparison to legume residues, cereal residues have a much higher carbon to nitrogen ratio. Access to and affordability of alternative biomass resources determine the opportunity costs for a household to sell, use or replace CR. For example, access to communal lands reduces a household's need to collect and use CR as livestock feed or fuel (McIntire et al., 1992; Valbuena et al., 2012). Finally, biomass demand depends on household needs including livestock feed, cash, fuel, construction materials and soil fertility.

Farmers' decisions are also shaped by overall pressures on CR, which occur when crop production fails to meet the household demand for CR. On the production side, crop productivity remains lower than its potential in some parts of South Asia and especially in Sub-Saharan Africa (Koning and Smaling, 2005; Kuyvenhoven, 2008), indicated by considerable yield gaps (Nin-Pratt et al., 2011). Furthermore, communal areas such as grasslands and woodlands are often degraded and/or shrinking and thereby reducing the availability of alternative biomass resources. On the demand side, human populations and their income levels continue to increase, generating ever-greater demand for livestock products and thus feed, as well as biomass resources for fuel, soil improvement through mulching and for construction materials. The nature and interaction of all these influences on CR use are context specific and shaped by the dynamics and interplays of drivers at different levels. Major drivers include agro-ecological constraints and opportunities; human population dynamics; urbanisation/migration; institutional developments; and agricultural policies influencing access to information and markets (Anderson, 1992; Tiffen, 2003; Kuyvenhoven, 2008; Satterthwaite et al., 2010). At the same time, individual households react differently to similar drivers depending on their specific resource endowments and livelihood strategies (Tittonell et al., 2010; Giller et al., 2011b; Homann-Kee Tui et al., 2013).

Where CR availability is limited and two or more competing uses exist the decisions on CR use have to consider spatial and temporal trade-offs. These are particularly important on mixed farms, especially where crop production does not meet CR demand and alternative resources are not accessible or affordable (Latham, 1997; Tittonell et al., 2007; Rufino et al., 2011). A prominent example of such a trade-off is that between using CR as mulch or as livestock feed. Proponents of Conservation Agriculture (CA) packages promote the use of CR as mulch to enhance medium-term crop production through improving soil fertility, despite the direct and short-term benefits of feeding CR to livestock or selling them (Wall, 2007; Giller et al., 2011a).

The objective of this paper is to provide a comparative analysis of the determinants and pressures on CR use and to examine some potential trade-offs. Particular emphasis is given to the four major factors affecting CR use: farmers' preferences, crop production, alternative resources and biomass demand. This study is based on a trans-regional household-level survey in four regions across Sub-Saharan Africa (SSA) and South Asia (SA) with contrasting conditions. We build on previous work done at village level illustrating the potential of CR use as soil amendment (i.e. mulch) in the same regions (Valbuena et al., 2012). We discuss alternative options for balancing the income and environmental benefits of CR use and ways for increasing biomass production, while reducing pressure and potential trade-offs.

2. Methods

2.1. Data collection

For the purposes of this study 12 sites across 9 countries in 4 (sub-)tropical regions were selected to illustrate the diversity of mixed farming systems in SSA and SA (Fig. 1). The regions include: Eastern Africa (Ethiopia, Kenya), Southern Africa (Malawi, Mozambique, and Zimbabwe), Western Africa (Niger and Nigeria) and South Asia (Bangladesh and India). This site selection was based on regional expert knowledge within the regions where participating research centres are based. Through informed expert discussion and secondary data, mixed crop-livestock systems were selected with contrasting agro-ecological conditions, levels of agricultural intensity and market development (Table 1). In Ethiopia, India and Niger, two contrasting sites were selected in each

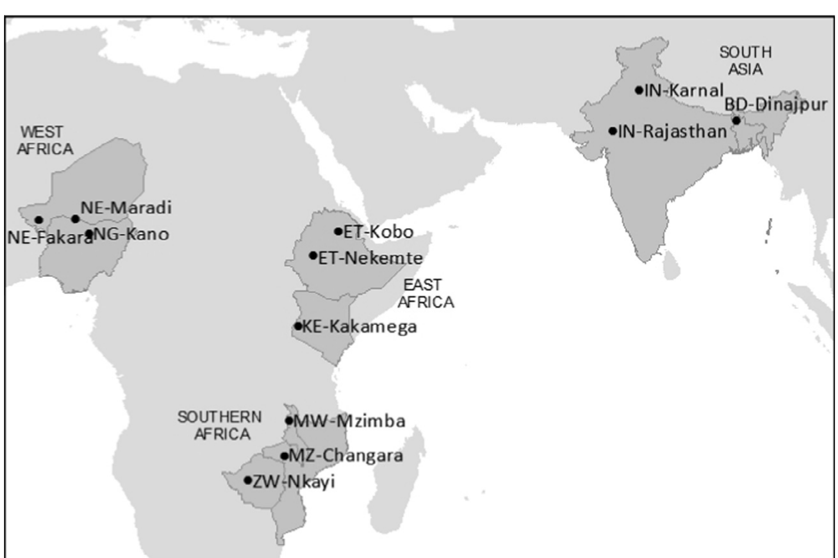

Fig. 1. Location of the study sites.

country, while in each of the other countries only one site was selected. In each site, 8 villages were randomly selected by distance and road access to one or two main local markets. The distances were defined as near and far to both main regional markets and roads, according to the local distribution of infrastructure and settlements. For instance, in Bangladesh distances to markets and roads ranged only between 5 and 10 km, while in Zimbabwe the range was between 10 and 50 km (e.g. ZW-Nkayi). In each of the 96 selected villages, quantitative village-level surveys were conducted between 2010 and 2011 with groups of 10–30 farmers with different age, gender, land and livestock ownership. The questionnaire included data on village population, land use and management, cropping, CR use, herd composition and input/output prices (Valbuena et al., 2012).

A census list of all the households was collected for each village to obtain an overview of household wealth distribution, using farm size and livestock ownership as a proxy. Table 1 shows the variability of assets among households, as well as the relevance of non-farm activities across sites. For the subsequent household survey four wealth categories were created for each village, according to cultivated land and livestock ownership, expressed in tropical livestock units (tlu). Within these classes households were then ranked by livestock density (tlu/cultivated land). Subsequently five households were randomly selected from each wealth category, equally distributed along the density distribution, resulting in a sample of 20 households per village and 160 households per site. This selection procedure ensures that the diversity of critical variables amongst households is captured within villages even at a comparatively small sample size, enabling the comparison of households and villages from different sites and countries. Our focus was on CR use; therefore, only households currently cultivating land were included in the household survey.

For this survey, a total of 1920 household-level interviews were conducted in 96 villages in 2011. All interviews used the same structured questionnaire, with the same codes and units. The scope of the survey included: (i) general household structure and decision-making; (ii) assets, income and expenditure, access to information and services, levels of food security; (iii) land and crop management; (iv) CR use, trends, and preferences; (v) livestock herd structure and management; and (vi) limitations to agricultural production.

2.2. Data analysis

The paper presents descriptive and comparative analyses of CR use in diverse mixed farming systems. Two major analyses were conducted. Firstly, we grouped the 12 sites in 5 clusters with similar levels of agricultural intensity, represented as cereal intensity and livestock density at village level. Our previous work (Valbuena et al., 2012), had identified cereal intensity (i.e. CR supply) and livestock density (i.e. CR feed demand) as major determinants of CR use at the selected sites. Cereal intensity was calculated as the total amount of cereal produced in the village for the observed year, divided by the total land of the village, including both cropland and uncultivated land (e.g. communal land and fallows). To deal with the large variation in cereal productivity, the logarithm of this annual productivity was used. To calculate livestock density, the total number of livestock in the village was converted to tropical livestock units (TLU; equal to 250 kg of body weight) and divided by the total village area, including both cropland and uncultivated land (e.g. communal land and fallows). Households with relatively high non-farm income (e.g. remittances and own business) were also calculated to analyse the importance of agriculture in the total household income and its relation with CR determinants and use.

Secondly, we aggregated the household information of each site, to describe the determinants of and pressures on CR use for each site. Although this aggregation simplifies the diversity of farming systems within sites, it allows comparison of the CR uses between sites. This analysis was structured along the four determinants of CR use: CR supply, access to alternative biomass resources, demand for biomass, and farmers' preferences for CR use (Erenstein et al., 2011). The analysis of CR supply was based on crop production, focusing on cereals. Although sites differ in terms

Table 1
Main biophysical and socio-economic characteristic of the research sites. *Source:* Valbuena et al. (2012) and census lists.

Region	Southern Africa			West Africa			East Africa			South Asia		
Country	Mozambique	Zimbabwe	Malawi	Niger		Nigeria	Ethiopia		Kenya	India	Bangladesh	India
Location	Changara	Nkayi	Mzimba	Fakara	Maradi	Kano	Kobo	Nekemte	Kakamega	Rajasthan	Dinajpur	Karnal
Site code	MZ-Changara	ZW-Nkayi	MW-Mzimba	NE-Fakara	NE-Maradi	NG-Kano	ET-Kobo	ET-Nekemte	KE-Kakamega	IN-Rajasthan	BD-Dinajpur	IN-Karnal
Agro-ecology[a]	Semi-arid	Semi-arid	Semi-arid	Semi-arid	Semi-arid	Semi-arid	Semi-arid	Highlands	Highlands	Semi-arid	Humid (irrigated)	Semi-arid (irrigated)
Rainfall (mm/yr)	731	637	831	473	446	764	819	1915	1880	680	1939	630
Density (people/ha)	1.6	1.8	3.2	2.0	2.7	3.3	2.8	2.3	9.7	4.2	7.1	5.6
Main crops	Maize, millet, sorghum, cowpea, g.nut	Maize	Maize	Millet, cowpea	Millet, sorghum cowpea	Sorghum cowpeag.nut	Sorghum, teff	Maize, teff	Maize, beans	Maize	Rice	Rice–wheat
Livestock	Cattle, goats	Cattle	Cattle, goats	Cattle, sheep, goats	Cattle, sheep, goats	Cattle sheep goats	Cattle	Cattle	Cattle-dairy	Cattle, buffalo, goat	Cattle, goat	Buffalo cattle
Agri. intensification[b]	+	+	++	+	+	++	+	+	++	+	++	+++
Market development[c]	+	++	+	+	++	+++	+	+	++	++	++	+++
Site variability[c]												
Distance market (km)	25.7 ± 17	33.4 ± 18	8.2 ± 4	10.9 ± 6	16.4 ± 9	8.7 ± 5	8.8 ± 5	11.6 ± 6	9.2 ± 6	10.7 ± 7	5.7 ± 3	9.2 ± 5
Village size [No. hh[d]]	129 ± 58	104 ± 31	217 ± 14	108 ± 64	294 ± 182	256 ± 74	126 ± 75	47 ± 13	193 ± 128	118 ± 31	343 ± 310	390 ± 242
Cultivated land (ha/hh)	1.3 ± 1.0	2.3 ± 1.4	1.2 ± 1.0	9.5 ± 5.6	2.7 ± 2.5	4.3 ± 3.2	0.9 ± 0.5	1.5 ± 1.0	0.4 ± 0.5	0.2 ± 0.6	0.6 ± 1.5	1.1 ± 2.5
Herd size (TLU/hh)	3.5 ± 9.2	6.6 ± 13.3	1.3 ± 3.3	1.5 ± 3.4	1.4 ± 2.6	3.0 ± 3.5	2.3 ± 3.2	4.8 ± 4.4	1.7 ± 2.5	3.1 ± 2.6	1.8 ± 2.0	2.8 ± 3.2
Non-farm income (%hh)[e]	80	73	71	23	53	92	11	18	75	99	62	29

[a] Includes primarily rain-fed agriculture, unless otherwise indicated.
[b] Relative indicator based on expert knowledge: low (+), medium (++), high (+++).
[c] Values are means and values in brackets are standard deviations.
[d] hh refer to household.
[e] Percentage of households with more than 50% of non-farm income, including selling of agricultural labour, off-farm income and remittances.

of crop intensity and diversity, cereals are the dominant staple crops in all the selected mixed crop-livestock systems. Variables related to crop production included cultivated land, irrigated land, input use, frequency of land cultivation, cereal grain and residue yields. Frequency of land cultivation was converted into the percentage of the total area cultivated during the year. If village land was cultivated twice a year, the respective value of frequency of land cultivation would double. Cereal productivity was calculated by aggregating the cereal production of all farmers and dividing it by their cropped cereal area. Cereal residue yields were estimated by the reported grain yields times the harvest index reported in the literature for the major crops in each region (Bationo and Mokwunye, 1991; Tittonell et al., 2005; Haftamu et al., 2009; Maobe et al., 2010).

Access to alternative resources was calculated as the proportion of the village area under fallow and communal land (e.g. rangelands), as well as the proportion of the cropland under fodder crops. Demand for biomass was calculated by human and livestock population densities (total livestock population per village land), feeding strategies (investments in feed representing a demand for higher quantity and/or quality of feed) and feed shortages (feed shortages indicating that the relative demand for feed cannot be met).

Farmers' preferences were examined based on whether they agreed or disagreed with the following two statements: CR are vital resource feed; and better to use CR as feed than mulch. Additionally, major limiting resources for crop and livestock production (e.g. access to water, information, inputs, improved varieties/breeds) were ranked by farmers. Based on this ranking, limiting resources were weighted and averaged for the sampled population of each site. CR uses and their trends in the past five years were also assessed. The analysis focused on cereal residues, the predominant CR type at all the selected sites (Valbuena et al., 2012). Five major cereal CR uses were differentiated: livestock feed (stall feeding and grazing), soil amendment (mulch and compost), household uses (for fuel and construction), traded (sold and collected by others) and burnt. CR uses were assessed in percentages for each crop type. The aggregated volumes of cereal residue used for the different purposes were calculated by multiplying the total cereal residue production with the percentages of the different uses of all the surveyed households for each site.

3. Results

3.1. Clusters of agricultural intensity

Five clusters of cereal intensity and livestock feed demand at village level can be distinguished (Fig. 2). The low–low cluster has relatively low levels of cereal intensity and livestock feed demand; it is found at the sites of Southern Africa. The moderate-low cluster shows higher cereal intensity and is located at the sites of West Africa. The moderate-moderate cluster is characterized by higher levels of cereal intensity and livestock feed demand; the two sites falling into this cluster are located in Ethiopia. The low–high sites show higher levels of livestock feed demand as compared to low levels of cereal intensity; the two sites are located in Kenya and India. Finally, the high-high cluster shows high levels of both cereal intensity and livestock feed demand; these sites are located in South Asia.

3.2. Cereal CR use determinants

3.2.1. Cereal CR supply

Cereal grain and residue production vary across sites and regions depending on agro-ecological conditions, farm sizes, access to inputs and the levels of irrigation and mechanization (Table 2).

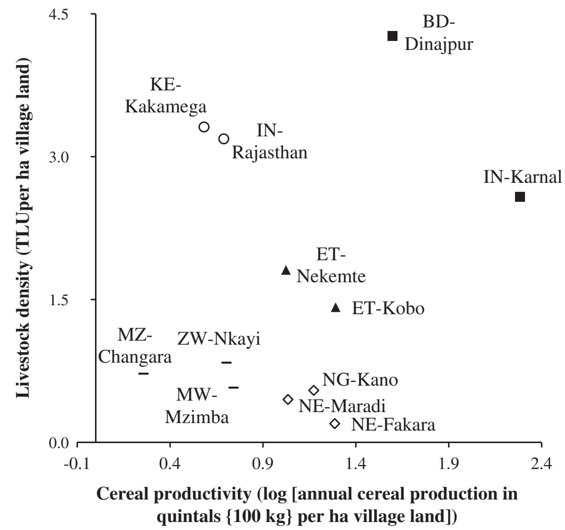

Fig. 2. Proxies for crop intensification and livestock feed demand at village level in study sites. Dashes represent low–low; trapezoids moderate–low; triangles moderate–moderate; circles low–high; and squares high–high sites. *Source: household and village surveys*

In low–low sites, crop production is either dominated by maize (MW-Mzimba and ZW-Nkayi), or mixed (in MZ-Changara the cropping pattern includes maize, sorghum, millet, cowpea and groundnut). Average farm sizes tend to be moderate, ranging between 1 and 2 ha. Given the lack of irrigation, limited access to inputs, soils of inherently low fertility and a mono-seasonal growing period, crop yields are low and are mainly determined by rainfall. Nevertheless, the conditions for crop production differ among these sites, e.g. MW-Mzimba has higher agro-ecological potential (i.e. rainfall, see Table 1) and better access to inputs compared to ZW-Nkayi and particularly MZ-Changara. This is reflected in higher crop yields and residue production in Mzimba. In fact, farmers in MZ-Changara and ZW-Nkayi reported access to inputs, especially inorganic fertilizer, and water as critical constraints to crop production

In the moderate-low cluster the intercropping of cereals (millet and sorghum) and legumes (cowpea and groundnuts) dominates the cropping system. Due to relatively low population density and reported low soil fertility (Abdoulaye and Sanders, 2005), farm sizes are the largest in NE-Fakara, on average 12 ha. Due to the lack of irrigation, relatively low availability of inputs, low soil fertility and only one cropping season, crop production here also depends on rainfall. Input use and cereal yields tend to be higher in NE-Maradi and NG-Kano, where markets are better developed. Still, farmers in NE-Maradi and NG-Kano perceived access to land as a major limitation for crop production, reflecting low productivity and lack of access to non-cultivated land. In contrast, farmers in NE-Fakara reported access to inputs as the major limitation to crop production. Because of the agro-ecological conditions and low input use, cereal residue yields are also low in this cluster, particularly in NE-Fakara. This low productivity is partly offset by larger farm sizes compared to the low–low cluster.

In the moderate-moderate cluster, cropping is dominated by cereal production: sorghum and teff in ET-Kobo; and sorghum, maize and teff in ET-Nekemte. Farms tend to be of moderate size, ranging between 1.5 and 2 ha. Irrigation is also lacking and input use relatively low. Crop production is limited to one major cropping season, and sometimes accompanied by an additional crop in the short rainy season. Rainfall and soil fertility are higher than in the previous two clusters, but soil fertility is reported to be declining and erosion is common during the long rainy season (Hurni, 1988; Pender et al., 2001). Input use tends to be more

Table 2
Land use, cultivated areas and major inputs/outputs: major proxies of CR production. *Source:* household surveys

Cluster[a]		Low–low			Moderate–low			Moderate–moderate		Low–high		High–high	
Sites		MZ-Changara	ZW-Nkayi	MW-Mzimba	NE-Fakara	NE-Maradi	NG-Kano	ET-Kobo	ET-Nekemte	KE-Kakamega	IN-Rajasthan	BD-Dinajpur	IN-Karnal
Cropland													
Surveyed households	(ha)	236	301	212	1908	595	782	201	225	71	44	80	460
Frequency land cult	(% per year)	31	51	47	88	98	96	97	87	153	96	166	173
Irrigated	(% cropland)	2	0	4	0	0	0	3	8	4	57	75	100
Inputs for cropland[b]													
Manure	(qtl/ha)	0.1	3.8	0.6	0.2	0.5	9.1	0.4	0.4	3.1	31.5	47.9	129
Fertilizer	(kg/ha)	0	7	101	0	5	12	16	54	288	131	378	532
Estimated cereal production													
Grain yield[c]	(ton/ha)	0.4 ± 0.3	0.7 ± 0.7	1.6 ± 1.2	0.3 ± 0.4	0.5 ± 0.4	0.5 ± 0.4	1.5 ± 0.9	1.0 ± 0.8	1.5 ± 1.2	1.3 ± 0.8	5.3 ± 1.0	4.3 ± 0.8
Residue yield[d]	(ton/ha.yr)	1.0 ± 0.7	1.3 ± 1.4	3.0 ± 2.1	0.7 ± 1.0	1.1 ± 1.0	1.1 ± 1.0	1.5 ± 0.9	1.0 ± 0.8	2.3 ± 1.9	3.0 ± 2.1	8.7 ± 3.2	7.0 ± 2.5
Residue production	(ton/farm.yr)	1.4 ± 1.7	1.9 ± 1.3	2.2 ± 1.7	5.2 ± 5.5	2.6 ± 2.5	3.6 ± 4.6	3.3 ± 2.2	2.7 ± 2.4	0.9 ± 1.3	1.0 ± 1.3	4.9 ± 8.7	21.3 ± 23
Major limiting resources on crop production													
First		Water	Inputs	Inputs	Soil	Land	Land	Water	Inputs	Inputs	Water	Soil	Labour
Second		Inputs	Water	Soil	Inputs	Soil	Soil	Land	Soil	Soil	Land	Inputs	Inputs

[a] Clusters: crop intensity-livestock density.
[b] Includes intercropping cereal-legumes and legumes.
[c] Seasonal productivity.
[d] Productivity derived from grain yield using harvest index.

common in ET-Nekemte compared to ET-Kobo. Still, farmers reported soil fertility and input access as major limiting resources in ET-Nekemte, while water and land were seen as major limiting resources in the drier site of ET-Kobo. Despite the better agro-ecological conditions, cereal residue yields and production per farm remain comparable to the other two clusters. Production of cereal grain and residues is higher in ET-Kobo, where long-maturing sorghum varieties (around 8 month growing cycle) are commonly grown.

In the low–high cluster, the major staple cereal is also maize. Farm sizes are small; crop production is limited to one major cropping season in IN-Rajasthan, whereas there is an additional short season in KE-Kakamega. Abundant rainfall in KE-Kakamega allows not only the intercropping of maize and beans, but also the production of other annual and perennial crops including sugarcane, cassava and banana. In IN-Rajasthan, the use of ponds fed by rainfall (depending on the rainfall of the monsoon) allows irrigation in almost half of the cultivated area during winter. Input use is higher than in the previous sites resulting in higher crop production intensity. Despite the availability of irrigation and the use of inputs farmers reported access to water and land as major limiting resources in IN-Rajasthan; for KE-Kakamega, farmers highlighted access to inputs and soil fertility as key production constraints. Although farmers achieve moderate cereal residue yields, they produce the lowest amount of cereal residue per farm of all clusters, which is a reflection of the small farm sizes.

Finally, in high-high sites, cropping is dominated by a rotation of cereals (mostly rice, wheat and maize). Farm sizes are small in BD-Dinajpur and relatively large in IN-Karnal, where around half of the village households are landless. Agro-ecological conditions are better in Bangladesh. However, greater mechanisation and better access to irrigation and inputs allow for higher production intensity in IN-Karnal. In both sites conditions allow at least two cropping seasons a year. Still, input access is seen as limiting crop production; other constraints cited were soil fertility in BD-Dinajpur and labour in IN-Karnal. Cereal grain and residue yields are the highest of all the study sites; partly as a result of larger farm sizes. Residue production reaches on average more than 20 tons per farm in IN-Karnal and about 5t in BD-Dinajpur.

3.2.2. Demand for biomass and alternative resources

Demand for biomass is largely determined by human needs (e.g. fuel, construction) and livestock feed demand (Table 3). Access to alternative resources can reduce the amount of CR use to fulfil this demand, and this is mainly seen in the low–low sites. Where human and livestock densities are relatively low, biomass demand is relatively low. In MW-Mzimba and MZ-Changara, for instance, only half of the households own livestock compared to ZW-Nkayi, where around 75% of the households own livestock and most farmers rely on animal tillage for field preparations. Milk production is also low in terms of the number of households producing milk and the overall quantity produced; only half of households produce milk in ZW-Nkayi. Rangelands, which cover ~50% of the village area and also provide a source of alternative resources for fuel and construction, provide an important source of alternative feed and supply more than two thirds of the feed for large ruminants (Fig. 3). Farmers consider water access as a major limiting factor for livestock intensification in MZ-Changara and ZW-Nkayi while in MW-Mzimba and ZW-Nkayi inputs were also highlighted. Still, CR are a key feed resource to overcome the regular dry season feed shortages. These shortages are especially pronounced in MZ-Changara and ZW-Nkayi, where farmers have accordingly started intensifying the use of CR for feed through collection, storage and stall-feeding. In contrast, in MW-Mzimba overall biomass production is relatively high when compared to livestock demand.

In the moderate-low sites, biomass demand tends to be intermediate. Human population densities are higher than in the low–low cluster although NE-Fakara is an exception with the lowest densities of all sites. Livestock densities are low reflecting the large farm sizes and a greater prominence of small ruminants in the herd structure. Herds are often a mix of small and large ruminants in the Niger sites and are dominated by small ruminants in NG-Kano. Milk production is common only in NE-Maradi, but yields are low. Feed intake of large ruminants depends more on CR than in the low–low cluster (Fig. 3). In the sites of Niger however, alternative sources of feed are also important, particularly through transhumance. Concentrates (i.e. cereal bran) are also commonly used. Farmers consider feed availability as the major limiting resource in livestock production in all sites. Given the high land degradation

Table 3
Livestock structure and feeding: major proxies of CR demand. *Source:* village data

Cluster [a]		Low–low			Moderate–low			Moderate–moderate		Low–high		High–high	
Sites		MZ-Changara	ZW-Nkayi	MW-Mzimba	NE-Fakara	NE-Maradi	NG-Kano	ET-Kobo	ET-Nekemte	KE-Kakamega	IN-Rajasthan	BD-Dinajpur	IN-Karnal
Livestock													
Herd size surveyed hh[b]	(total tlu)	549	552	250	348	246	432	464	641	369	263	335	887
Share of small ruminant	(% total tlu)	21	9	18	17	45	75	6	18	6	16	9	0
hh with ruminants	(% hh)	53	74	45	80	95	94	83	83	78	78	95	94
Density[c]	(tlu/ha)	0.7	0.8	0.6	0.2	0.5	0.5	1.4	1.8	3.2	3.3	4.3	2.6
milk production	(% hh)	24	53	19	10	64	8	69	59	71	61	41	94
	(l/day all hh)	57	101	40	23	97	37	113	147	370	97	103	1102
Shortages CR as feed[d]	(% hh)	77	43	68	70	99	66	61	79	72	48	2	2
Major limiting resources on livestock production													
First		Water	Inputs	Inputs	Feed	Feed	Feed	Water	Feed	Feed	Land	Inputs	Inputs
Second		Feed	Water	Information	Water	Land	Land	Land	Land	Inputs	Water	Feed	Information
Additional resources													
Fodder grass	(% area)	0	0	0	0	0	0	0	0	1.4	0	0	17
Uncultivated land	(% area)[e]	69	49	53	13	2	4	25	22	13	45	0	0

[a] Lusters: crop intensity-livestock density.
[b] hh stands for household.
[c] Source Valbuena et al. (2012).
[d] Shortage period longer than six months.
[e] Village area, mainly communal grassland/rangeland and fallows.

reported in NE-Fakara (Bielders et al., 2002) and the lack of uncultivated areas in the other two sites, alternative biomass resources are typically short in supply.

Biomass demand in moderate-moderate sites is higher than in previous clusters partly related to the higher human and higher livestock population densities in these sites. Average herd sizes tend to be larger in ET-Nekemte than in ET-Kobo; both sites rely on cattle for field tillage. Milk production is slightly higher than in previous clusters, reaching an average of 1–1.6 L a day. More than half of the feed for large ruminants comes from CR in ET-Kobo while in ET-Nekemte it is only one third (Fig. 3). Land access for grazing was cited as a key constraint in both Ethiopian sites; high quality feed is seen a major limiting resource for livestock production in ET-Nekemte. Uncultivated areas provide most of the alternative feed resources, and also offer alternative fuel resources.

Biomass demand in the low–high cluster is high as a result of the high human and livestock densities found in these sites. The majority of households own livestock. Milk production is common and yields are relatively high. In KE-Kakamega milk production is on average 3 L a day; almost 21% of the cattle are dairy crossbreeds and therefore require better quality feed. The feed composition of large ruminants in IN-Rajasthan is dominated by CR with biomass from communal forests providing alternative feed sources (Fig. 3), while in KE-Kakamega cut-and-carry fodder grasses (e.g. Napier grass) are most important. Still, farmers reported access to quality feed and inputs as major limiting factors in KE-Kakamega; and again access to land and water in IN-Rajasthan. Due to the high population density, uncultivated areas tend to be small in KE-Kakamega, resulting in few alternative resources for feed and fuel.

Finally, the high-high cluster also has a high demand for biomass, with some of the highest densities of human population and livestock of all the study sites. Most households manage livestock: buffalos in IN-Karnal, and cattle in BD-Dinajpur. Milk production is common in both sites and yields are particularly high in IN-Karnal. Despite the high demand for feed, CR supply less than half of the feed intake of large ruminants. Different sources, such as fodder crops, concentrates and fallow land provide most of the feed. The major limiting resource in this cluster is access to livestock inputs, as well as access to feed in BD-Dinajpur and information for further intensification in IN-Karnal.

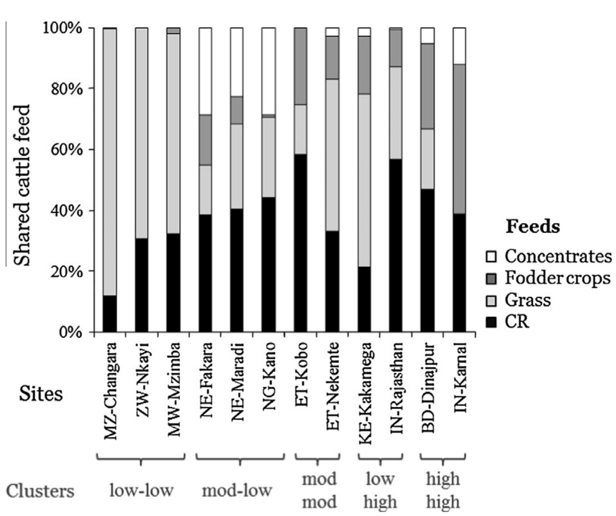

Fig. 3. Feed composition for large ruminants at a site level. *Source:* household survey

3.2.3. Preferences and residue use

Farmers' preferences are reflected in their decisions on the current use of available CR. Both preferences and uses vary within and across the clusters (Table 4), also influencing the pressures on and trade-offs of CR uses. In low–low sites, given the low demand for biomass and the ready availability of alternative resources, CR is generally considered to be a common resource enabling more labour-extensive uses of cereal residue (Fig. 4). The major cereal residue use is free grazing by livestock (~50–90% of cereal residue) and only few farmers leave cereal residue in the field specifically for soil amendment. Residue left on the soil might however also be grazed during the dry season or eaten by termites. Approximately half of farmers considered CR as a vital feed, particularly during the dry season when other alternative resources are depleted. In ZW-Nkayi, farmers are now collecting and feeding residues to improve feed supply and also to increase the amounts of organic fertilizers. On the other hand, farmers in MW-Mzimba, where more biomass is available, have traditionally burnt considerable volumes of cereal residue. Due to a growing awareness of the positive effects of using CR for soil amendment by extension and NGOs, increased amounts are being retained in the field.

In moderate-low sites, most farmers consider CR as a vital feed resource. This preference corresponds to an intermediate biomass demand, low levels of crop production and low availability of alternative biomass resources. In fact, most cereal residue are used either as livestock feed or for household activities (Fig. 4). This is particularly evident in NG-Kano, where farmers prefer to use cereal residue as livestock feed rather than for soil amendment; a large proportion of the cereal residues is also used for household activities. In recent years, the practice of collecting CR has become more common as a consequence of the growing biomass demand. Besides trading small portions of cereal residues, in NE-Fakara and NG-Kano, farmers often sell legume residues (~25% on average) generating alternative income. This gives a good example of the important role that CR can play in farmers' livelihoods, integrating crop and livestock components, and providing basic household needs.

In the moderate-moderate cluster, despite slightly higher cereal production, the high demand for biomass for household uses and livestock feed results in high pressures on CR. In fact, most farmers consider CR as an essential feed and more than 60% of the cereal residues are used as livestock feed (Fig. 4). Also, about 20% of the cereal residue is used for household purposes. Despite this strong demand, ET-Nekemte farmers still use some cereal residues for soil amendment or burnt it.

The low–high sites present another pattern; crop production is low at both sites. In KE-Kakamega fodder grass production however reduces the dependence on cereal residue as livestock feed, and allows a higher and increasing use of these residues for soil amendment (Fig. 4). In contrast, farmers in IN-Rajasthan use most of the cereal residues for livestock feeding. Despite those differences, some cereal residues are traded and many farmers reported an increasing demand for cereal use both for livestock feeding and for soil amendment. Although legumes are commonly grown in KE-Kakamega, most of these legume residues are burnt to use their ashes for traditional food preparation.

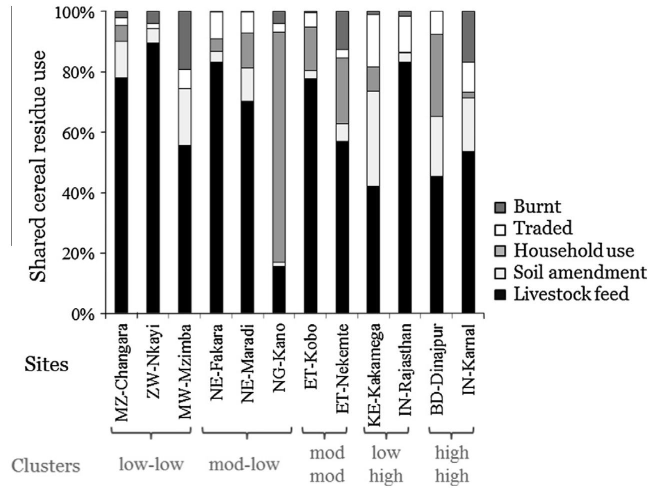

Fig. 4. Relative cereal residue use at site level. *Source:* household survey

The comparatively high crop yields at the high-high sites appear more than adequate to meet CR demand, including trading. Still, almost half of the cereal residues are used for livestock feeding (Fig. 4). In BD-Dinajpur the rest of the cereal residues are mainly used for mulching and for household purposes; in IN-Karnal for mulching and burning. Almost half of the farmers reported an increase in cereal residue use as both a livestock feed and for soil amendment.

3.3. Interactions of CR use determinants

The results from interactions between the four major factors influencing cereal residue use as livestock feed and soil amendment are summarised in Fig. 5. Cereal residues tend to be rather used as livestock feed than for soil amendment at sites with high cereal residue production per farm and moderate demand for feed, e.g. the moderate-low sites in Niger, where farmers have less access to alternative feed resources but still some access to firewood. Less feed biomass is available at sites where livestock density is substantial, but levels of crop production are relatively low, and either access to communal resources also limited (moderate-moderate sites in Ethiopia and low–high site IN-Rajasthan) or livestock cereal residues are largely fed to livestock (low–low site ZW-Nkayi). In low–low site MZ-Changara biomass from cereal residues is limited, but rather fed to livestock, even though substantial rangelands are still available The moderate-low site of NG-Kano seems an exception; with a higher human but lower livestock CR demand, significant legume production and a lack of other alterna-

Table 4
Preferences, patterns and trends of CR use across study sites. *Source:* household survey

Cluster[a]	Low–low			Moderate–low			Moderate–moderate			Low–high		High–high	
Site		MZ-Changara	ZW-Nkayi	MW-Mzimba	NE-Fakara	NE-Maradi	NG-Kano	ET-Kobo	ET-Nekemte	KE-Kakamega	IN-Rajasthan	BD-Dinajpur	IN-Karnal
Farmers' preferences[b]:% farmers agreeing with													
	CR are vital feed resources	53	77	46	80	91	96	96	90	63	83	95	93
	Better to use CR as feed than mulch	64	56	8	46	56	89	90	77	17	76	56	44
Farmers (%) reporting an increased use of cereal residue as													
	Stall feed	3	9	2	29	73	63	84	40	61	46	46	10
	Soil amendment	5	4	23	10	36	3	4	15	42	31	46	9

[a] Clusters: crop intensity-livestock density.
[b] CR generalises all crop residues.

tive resources, small amounts of cereal residues are fed to livestock and none are used for mulching.

The amount of cereal residue used as soil amendment increases as crop production increases, along with better access to alternative resources and small herds (low–low site in MW-Mzimba). The amount of cereal residue used as mulch also increases when crop production is limited compared to CR demand, but alternative and better feed resources are available and needed (low–high site in KE-Kakamega). As expected, larger amounts of cereal residues can be used for both, feeding livestock and amending soils, when crop production surpasses biomass demand (high-high sites).

The four major factors also influence decisions and trade-offs of alternative residue use or disposal (Fig. 6). Despite the large amounts of cereal residue fed to the livestock, for soil amendment and household use, large quantities of cereal residues were burnt in the field in the high-high site of IN-Karnal. Here, ~565 tons of cereal residue were burnt in the field because farmers preferred having a cleared field before then new cropping season. In NG-Kano, ~240 tons of cereal residues were either used for fuel or as construction material, given a higher human CR demand and limited access to alternative resources. A similar case was found in BD-Dinajpur, where ~170 tons were only used as fuel. In the moderate-moderate site of ET-Nekemte, ~50 tons of cereal residues were burnt for fuel, related to the intermediate human demand and reflecting farmers' preferences to clear the fields and control potential pests. In the low–low, moderate-low in Niger and low–high sites, use of cereal residues for fuel or construction material was limited. However, in MW-Mzimba, ~68 tons of cereal residues were burnt in the field, in response to the lower livestock demand compared to cereal residue production as well as for clearing purposes.

4. Discussion

The comparative analysis based on the four major factor influencing CR use shows that the combination of farmers' preferences, crop production, access to alternative resources and biomass demand is a useful conceptual framework to better understand determinants and use of CR in mixed farming systems (Erenstein et al., 2011). The results presented in this study are based on only one year's data, but no major agro-ecological and socio-economic disruptions were reported that would affect the patterns of CR use. This study aggregates household data to compare CR uses, determinants and trade-offs among contrasting sites, but does not investigate the diversity of CR uses within sites. The results of this study, based on household level data, provide a more detailed understanding of CR uses than our previous work, based on village-level data (Valbuena et al., 2012). The household analysis however brings forward lower rates of cereal residue used as livestock feed for various sites (IN-Karnal, BD-Dinajpur, KE-Kenya, NE-Fakara, NE-Maradi) and higher feed use for MW-Mzimba. Similarly, in BD-Dinajpur, ET-Nekemte and ZW-Nkayi the proportion of livestock feed coming from CR was lower, while in NG-Kano higher in this analysis compared to the village-level data. The different tools for capturing farmers' estimated biomass production and use can explain such differences, which are within a range that does not change the content of the results.

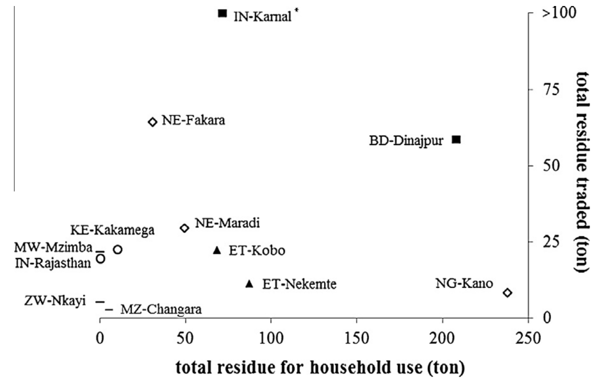

Fig. 6. Relation between the total amount of cereal residue use as construction material and household fuel (i.e. household use) and sold or collected by others (e.g. traded) for each site. Dashes represent low–low; trapezoids moderate–low; triangles moderate–moderate; circles low–high; and squares high–high sites. *For IN-Karnal the value of cereal residue traded reaches ~325 tons. *Source*: household survey

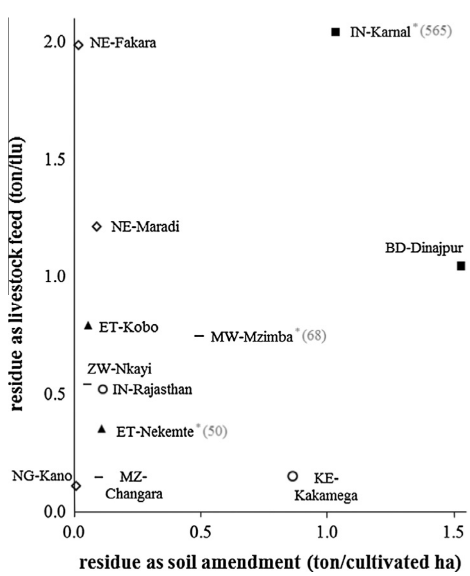

Fig. 5. Relation between the average amounts of residue used as soil amendment and livestock feed at site level. Dashes represent low–low; trapezoids moderate–low; triangles moderate–moderate; circles low–high; and squares high–high sites. *In parentheses the total amount of cereal residue burnt for sites with more than 50 ton yr^{-1}. *Source:* household survey

4.1. Determinants of CR use

The comparison of sites with contrasting levels of agro-ecologies and crop intensity confirms that CR represent a fundamental resource for crop-livestock integration and intensification, along a broad range of smallholder mixed systems (McIntire et al., 1992; Renard, 1997; Erenstein, 2002). CR is a vital dry season feed resource, providing livestock feed when other resources are scarce in sites with low cereal intensity. Beyond feed, CR also represent a key resource for fuel and construction in sites with high cereal intensity. This confirms that CR play an important role for farmers' livelihoods, in various contexts and under different levels of resource availability (Latham, 1997; de Leeuw, 1997).

The intensity and diversity of CR use is mostly related to the interaction between demand for biomass and access to alternative resources. More extensive forms of CR use are found at the low density sites in southern Africa, where alternative resources are still available. However, the gradual increase of biomass demand and the degradation of the alternative resources have led to CR becoming an increasingly private resource, particularly at the site in Zimbabwe where crops and livestock are more integrated. With increasing demand for biomass and a simultaneous decrease in the access to alternative resources, farmers have started to invest labour in collecting and regulating CR use. Collection of cereal residues for feed, construction material and fuel is a relatively recent but now common practice in the sites in West Africa and Ethiopia. As CR are being used for multiple purposes farmers have to decide about the allocation between livestock feed, construction material, fuel and even soil amendment.

In terms of soil amendment, we only saw evidence of farmers using significant amounts of CR purposely for mulching in a few cases. These results confirm the conclusions of our previous work (Valbuena et al. 2012) that using CR for soil amendment is common in only three specific cases: (i) moderate levels of cereal production, low demand for biomass and significant access to alternative feed resources (MW-Mzimba); (ii) low levels of cereal production (with residues from other crops such as sugarcane and banana), high demand for biomass but access to better quality feed resources for dairy production (KE-Kakamega); and (iii) very high levels of crop production that more than satisfy an accompanying high demand for biomass, even if alternative resources are limited (BD-Dinajpur and IN-Karnal). These results support the suggestion that the promotion of CA-mulching needs to take into account the specific agro-ecological and socio-economic conditions of mixed systems (Giller et al., 2009; Valbuena et al., 2012; Tittonell et al., 2012).

4.2. Pressures, synergies and trade-offs in CR use

Agro-ecological and socio-economic conditions limit agricultural intensification of smallholder farming systems in most of the sites in Africa and South Asia. Poorly developed infrastructure and markets aggravate the high risks, food insecurity and environmental degradation (Clute, 1982; van Keulen and Breman, 1990; Anderson, 1992). Whereas in the sites with high cereal intensity (i.e. IN-Karnal, BD-Dinajpur), policies have facilitated access to irrigation, output markets, risk-reducing subsidies and inputs, and have thereby promoted improved crop production and marketing, supplying the very high demand by human populations and livestock.

On the other hand, low levels of crop production combined with an increasing biomass demand create considerable pressures on CR use. The pressures are exacerbated by various factors: Growing human populations, whose livelihoods are often dependent on non-sustainable crop cultivation practices and natural resource extraction, while market incentives are missing as instrument for poverty alleviation, increasing their vulnerability (Dorward et al., 2003). Although livestock productivity is low in most of the study sites, livestock represent a major asset for smallholder farmers, providing draft power, manure, food, saving strategies and cash income, and thereby reducing risks and vulnerability (McIntire et al., 1992; Fafchamps et al., 1998; Schlecht et al., 2004). In particular, manure has increasingly become a private resource in Africa, as the major locally available resource to enhance soil fertility and increase crop production (Abdoulaye and Sanders, 2005). Except for the highly intensive sites at BD-Dinajpur and IN-Karnal, most farmers reported shortages of CR for livestock feed. At sites that have not intensified crop production, pressures on CR use tend to peak during the dry period when other feed resources are scarce and where access to alternative resources is limited. The needs for CR can extend into part of the growing season when livestock are excluded from the cropland while other feed sources have not yet regrown.

Pressures on CR can be reduced by using synergies between the complementary roles of CR. The sites in Ethiopia and Zimbabwe give examples where farmers use CR to feed draft power oxen at critical times of the year, thereby increasing the levels of crop production, resulting in more CR for livestock feed. Niger gives another example, where farmers without livestock pay herders to graze the CR in their fields. In exchange, the livestock manure improves the soil nutrient status, enhancing crop yields (Hiernaux and Ayantunde, 2004; Powell et al., 2004). At the site in Zimbabwe (ZW-Nkayi), farmers feed CR to their livestock in enclosures to improve feeding and manure production efficiency, thereby increasing the overall productivity of the farm. These synergies reflect a potential for more efficient use of available resources; they can improve the sustainability of farming systems under current agro-ecological and socio-economic conditions.

When synergies are not used, pressures can contribute to increase trade-offs. In particular, the removal of residue from the soil combined with the low use inorganic fertilizer and minimal return of manure increases the potential erosion and nutrient depletion of already fragile and poor soils (van Keulen and Breman, 1990; Breman et al., 2001; Haileslassie et al., 2005). To recover soil conditions, some researchers, donors and NGOs have promoted the use of CR for mulching (Conservation Agriculture), trying to increase crop production while also improving the overall sustainability of farming (Wall, 2007; FAO, 2009; Kassam et al., 2010). This practice can result in significant increases in crop production provided it is accompanied by additional input use and if agro-ecological conditions (Giller et al., 2009), the level of agricultural intensity (Valbuena et al., 2012; Baudron et al., 2012) and specific household assets (Knowler and Bradshaw, 2007) are suitable. For the promotion of mulching to succeed, proponents need to take into account the diversity of farming systems, especially the intricate linkages between crop and livestock production and consider the trade-offs, between short term livelihood benefits and long term environmental effects.

4.3. Implications of intensification for sustainable CR use

Intensification can greatly relieve pressure on CR use and can minimize trade-offs. Data from sites in BD-Dinajpur and IN-Karnal show that high levels of crop production can supply sufficient biomass to meet human and livestock needs as well as for mulching. However, for improving livestock productivity, increasing cereal CR supply alone is not sufficient; rather CR have to be supplemented with higher quality feeds. The high levels of crop production in these sites are the result of multiple cropping seasons, due to irrigation, combined with an enabling policy environment, providing functional market institutions and facilitating access to irrigation and inputs. Even though agricultural production is currently low in many of the mixed systems, particularly in semi-arid areas lacking access to water, inputs and markets, a great potential for their intensification has been identified (van Keulen and Breman, 1990; Koning and Smaling, 2005; Kuyvenhoven, 2008; Herrero et al., 2009). Nevertheless, the examples of crop and livestock intensification in the high-high sites of India and Bangladesh show that policies only targeted at increasing production and improving markets can affect the sustainability of agro-ecosystems. Reports suggest that inequities in access to resources may be increased, especially where supportive regulatory frameworks are not in place (Jayaraman and Lanjouw, 1999; Bhattarai et al., 2002), and that soil fertility and the provision of water quantity and quality may be lowered (Bhandari et al., 2002; Alauddin and Quiggin, 2008; Rodell et al., 2009).

The intensification of crop and livestock production needs to follow sustainable pathways, relieving pressure on CR and reducing trade-offs. Improving the sustainability of mixed systems requires the improvement of resource use efficiency and/or the intensification of production. This can be achieved through new and/or more efficient combinations of crop-livestock activities and other inputs, and related innovations (The Montpellier Panel, 2013). A potential option is to strengthen the interaction of crop and livestock production combining resources such as draft power, organic inputs and food, and thereby improving the use efficiency of limited resources such as CR (McIntire and Gryseels, 1987;

McIntire et al., 1992). Another alternative involves the diversification of farming practices by promoting multipurpose crops or/and trees that provide food, feed and fuel offering additional biomass resources and reducing biomass demand. Although these alternatives can reduce pressures and trade-offs on CR use when properly targeted (FAO, 2011; Tittonell et al., 2012), they would also need an improvement of the socio-economic context including policies, extension services, markets, infrastructure, strengthening the linkages within the rural economy (Bhattarai et al., 2002; Hall et al., 2008; Homann-Kee Tui et al., 2013). These more sustainable alternatives of crop and livestock intensification are receiving considerable attention to address both improvements in livelihoods as well as in the sustainability of farming systems through combining more and/or better resources and technologies to increase agricultural production while minimizing negative impacts on the environment (Pretty, 1997; Matson et al., 1997; Reardon et al., 1999; Pretty et al., 2011). Another potential option is to improve the access to markets supporting the intensification of both crop and livestock production. Functional market linkages can reward farmers' investments into crops and livestock, and positive feedback loops can contribute enhancing overall system productivity (Dorward et al., 2003; Homann-Kee Tui et al., 2013). Similarly, the use of fertilizer subsidies to increase crop and CR production as in Malawi (Dorward and Chirwa, 2011), and the use of payments for environmental services may influence farmers' practices by rewarding more sustainable uses of CR (e.g. reduction in burning of CR in IN-Karnal). However, it would be necessary to address issues of feasibility, impact and scaling-up in order to develop successful approaches (Banful, 2011; Chibwana et al., 2012; Marenya et al., 2012).

Crop intensification is not the only development pathway that can deal with CR pressures and trade-offs in mixed systems. Results from the sites in Southern Africa show that alternative resources, e.g. rangelands, are fundamental to dealing with pressure on CR. Therefore, better management of these areas can help in the supply of better quality biomass resources to fulfil the demands for feed, fuel and food in these systems, as well as ensuring the provision of other ecosystem functions and services such as carbon recycling and habitat protection (Milton et al., 2003; Swinton et al., 2007). Additionally, the increasing share of non-farm activities in the household income in most of the study sites illustrates how households are trying to improve their resilience and adaptability (Reardon et al., 2000; Haggblade et al., 2010). Given the limitations in access to land and the low potential for crop production in many of these sites, livestock production might actually be a very complementary pathway to improve rural livelihoods, given an enabling policy and institutional context (Fresco and Steinfeld, 1998; Tarawali et al., 2011). Particularly, livestock intensification can enhance access to additional resources (e.g. food and capital), and improve the use efficiency of (feed) resources such as CR that are often scarce in the mixed crop-livestock systems. The relative livelihood benefits of different development pathways would depend on the agro-ecological and socio-economic conditions in particular contexts. Under the current conditions, agricultural production might not be the only pathway to allow smallholder farmers to improve their livelihoods (Dorward, 2009; Jayne et al., 2010).

Coping with CR pressures and trade-offs needs to go beyond promoting technologies (The Montpellier Panel, 2013). The successes and failures of the Green Revolution in Asia and the increasing importance of Brazil in the global food arena have shown that technologies need to be embedded within an enabling policy and institutional context including better information flow, capacity building and strengthening of markets (Birner and Resnick, 2010; Martinelli et al., 2010; Horlings and Marsden, 2011). Thus, Research and Development (R&D) should not neglect the institutional context that underlies mixed farming production and technology demand (Röling et al., 2012), nor the diversity, dynamics and complexity of these mixed systems (Giller et al., 2011b). This requires improved coordination among R&D actors, as well as enabling a real discussion and collaboration with the different stakeholders involved in agricultural production and marketing, particularly farmers (Cooke and Kothari, 2001; von Braun et al., 2005). In that sense, there might be also room for some organisations to act as "sustainable brokers" linking top-down and bottom-up initiatives to improve rural livelihoods and develop more sustainable mixed farming systems (Leach et al., 2012).

5. Conclusions

Crop residue use is determined by the interaction of farmers' preferences, levels of production, demand for biomass and access to alternative resources. In turn, these aspects are related to the level of crop and livestock intensification in smallholder mixed farming systems. Major drivers such as agro-ecological conditions, human and livestock population dynamics, infrastructure and markets affect CR production and use. While in most of the sites we studied CR production is low, creating pressure and trade-offs, sites with high cereal intensification seem to produce enough CR to meet current demand, particularly for livestock feeding. This emphasizes the need to increase agricultural production in many of these mixed farming systems, albeit in more sustainable ways. Given the increase of the share of non-farm activities in the total household income and the continuous low production in these farming systems, the R&D community needs to revisit previous achievements and failures. Based on this, R&D needs to develop innovative and integral approaches to tackle the well-known problem of low agricultural production in many smallholder mixed systems, creating more sustainable futures.

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