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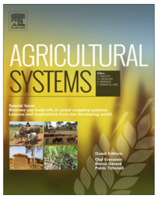

Economic trade-offs of biomass use in crop-livestock systems: Exploring more sustainable options in semi-arid Zimbabwe

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ABSTRACT

In complex mixed crop-livestock systems with limited resources and biomass scarcity, crop residues play an important but increasingly contested role. This paper focuses on farming systems in the semi-arid areas of Zimbabwe, where biomass production is limited and farmers integrate crop and livestock activities. Conservation Agriculture (CA) is promoted to intensify crop production, emphasizing the retention of surface mulch with crop residues (CR). This paper quantifies the associated potential economic trade-offs and profitability of using residues for soil amendment or as livestock feed, and explores alternative biomass production options. We draw on household surveys, stakeholder feedback, crop, livestock and economic modeling tools. We use the Trade-Off Analysis Model for Multi Dimensional Impact Assessment (TOA-MD) to compare different CR use scenarios at community level and for different farm types: particularly the current base system (cattle grazing of maize residues) and sustainable intensification alternatives based on a CA option (mulching using maize residues ± inorganic fertilizer) and a maize–mucuna (*Mucuna pruriens*) rotation. Our results indicate that a maize–mucuna rotation can reduce trade-offs between CR uses for feed and mulch, providing locally available organic soil enhancement, supplementary feed and a potential source of income. Conservation Agriculture without fertilizer application and at non-subsidized fertilizer prices is not financially viable; whereas with subsidized fertilizer it can benefit half the farm population. The poverty effects of all considered alternative biomass options are however limited; they do not raise income sufficiently to lift farmers out of poverty. Further research is needed to establish the competitiveness of alternative biomass enhancing technologies and the socio-economic processes that can facilitate sustainable intensification of mixed crop-livestock systems, particularly in semi-arid environments.

1. Introduction

Smallholder farmers in the semi-arid tropics combine farm and off-farm activities to achieve food security, and preserve or improve their livelihoods. Diversified systems, using the complementarities of crop production and livestock husbandry, appear to be robust opportunities for farmers to reduce vulnerability to climatic shocks and improve adaptive capacity to continuous changes in the social–ecological context (Ellis and Freeman, 2004; Lemaire et al., 2013). In particular, where external inputs are relatively inaccessible, animal manure provides essential nutrients for crop growth, while crop residues (CR) provide essential animal feed (McIntire et al., 1992). Using animal draught power farmers can prepare land in time, which improves water and nutrient use efficiency and increases crop yields (Tittonell et al., 2007). In addition to crop input functions, livestock serve as the most important on-farm capital and insurance in times of drought (Moll, 2005), equating livestock to an asset that can be converted to cash. The cash from livestock can be used to buy food and cover shortfalls in crop production. Livestock also make an important contribution to quality of life as the cash from livestock sales can

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be used for educational purposes and also to pay for medical expenses (van Rooyen and Homann-Kee, 2009).

Resources for conducting the different farm activities, including crop production, soil conservation and livestock husbandry are often limited. Limited access to biomass, nutrients, water, and labor creates short and long-term trade-offs in resource allocation (Erenstein, 2002; Giller et al., 2009; Thierfelder et al., 2012). Within a community, farm households are diverse in terms of resource endowments; their level of resource access determines how they will be affected by the trade-offs and what options they have to reduce the trade-offs (Dorward et al., 2009). The trade-offs on biomass use are increasingly contested, particularly on CR allocation for feed and soil amendment in sub-Saharan Africa (e.g. Giller et al., 2009). Crop residues play an important yet often underestimated economic role as the link between crop and livestock activities (McIntire et al., 1992; FAO, 2001a). Crop residues are mostly used as animal feed (Valbuena et al., 2012). Semi-arid Zimbabwe illustrates a case where rangeland feed resources are increasingly being converted into cropland, and CR therefore increasingly serves the important function of supplementing livestock feed, especially during the dry season from May until October (Rufino et al., 2011). Even though the nutritive value of cereal residues is relatively low, feeding CR to livestock during dry periods and droughts sustains survival when little alternative feed is available (Holness, 1999; Masikati, 2011). It also sustains body condition of draught animals, for early preparation of fields after the first rains.

The consequence of feeding most of the CR to livestock is that there are few alternatives to return biomass to the fields, limiting the replenishment of organic material and protection of the soils (e.g. against wind or water erosion). Although animal manure provides important nutrients for crop growth, recommended volumes of 8–10 t/ha are rarely achieved (Mapfumo and Giller, 2001). Investing land and labor in biomass producing cover crops has largely failed because smallholder farmers prefer using their land for food production or would prefer feeding the biomass to livestock (Mazvimavi and Twomlow, 2009). Therefore, the design of more sustainable farming systems needs to account for the limited access to resources, potential trade-offs on resource allocation and the diversity of smallholder households. This design should go beyond describing potential trade-offs of biomass allocation (Baudron et al., 2014), and should offer feasible and more sustainable pathways to overcome the biomass production gap (Keating et al., 2010; Power, 2010).

One option to improve the sustainable intensification of these farming systems is the use of CR as mulch, thereby recycling biomass and improving fertility and water management of inherently infertile and often depleted soils. In Zimbabwe mulching has been promoted since 2004 as one of the Conservation Agriculture (CA) components, providing crop-based food security (FAO, 2001b; Hobbs et al., 2008; Kassam et al., 2010). Even though CA has a high potential for improving crop productivity it faces several challenges particularly in semi-arid areas (Erenstein, 2002, 2003). Naudin et al. (2011) infer a critical amount of about 2–3 t residue mulch/ha to maintain soil fertility. Retaining these volumes of CR is difficult in areas with low residue production, where farmers prefer feeding the CR to livestock and where open grazing is a traditional practice (Giller et al., 2009; Valbuena et al., 2012). Furthermore, substantial fertilizer application is required to prevent N immobilization when mulching CR with high C:N ratios (Rusinamhodzi et al., 2011; Nyamangara et al., 2013b). The soil health effects of mulching also depend on the length of consistent mulching and build up over time (Thierfelder et al., 2012). Apart from limited biomass in areas like semi-arid Zimbabwe, the access to fertilizer and the lack of immediate yield benefits are major constraints for the uptake of CA practices.

An alternative option is to diversify the cropping system by producing fodder legumes, low cost/input technologies that can address soil fertility amendment and provide quality livestock feed at the same time (Maasdorp and Titterton 1997; FAO, 2011). Mucuna (*mucuna pruriens*) has been identified as one possibly attractive option for smallholder mixed farming systems. It was originally introduced and promoted as a cover crop in commercial farming systems to improve crop productivity (Buckles et al., 1998). It was later recognized for maintaining soil fertility, also under low soil fertility conditions and for its drought tolerance (Cook et al., 2005). Experiments in Zimbabwe confirmed high mucuna biomass production (2–6 t/ha) and feed quality (12.5% Crude Protein) under smallholder conditions in sub-humid and semi-arid areas, on poor quality soils and without P-fertilizer application (Maasdorp et al., 2004; Masikati, 2011). In on-farm experiments farmers choose mucuna over other legume crops for its high seed and biomass yield, low susceptibility to pests and diseases, and also for its insecticidal effects and ability to suppress weeds such as *imperata cylindrica* and *striga* species (dito). Despite its advantages, mucuna has not been widely adopted by smallholder farmers in southern Africa (Homann-Kee Tui et al., 2013). With government and development agents focussing on staple food production, attention on feed and fodder technologies has been limited and is only recently regaining interest.

The objective of this paper is twofold: (i) to make explicit the economic value and trade-offs of biomass allocation options for different types of smallholder crop-livestock farming systems in semi-arid Zimbabwe; and (ii) to analyse how alternative options could reduce such trade-offs, reducing the biomass trap for these smallholder households. This study combines household questionnaires, crop and livestock modeling tools, secondary data from on-farm experiments and an economic model to calculate the net returns and economic trade-offs of biomass use.

2. Material and methods

2.1. Study area: Nkayi District

This study was implemented in Nkayi District in semi-arid Zimbabwe (Fig. 1), characterized by low and variable rainfall (Natural region III and IV; Vincent and Thomas, 1957). Soils are mostly deep Kalahari sands (Arenosols), with pockets of clay and clay loams, inherently infertile, with N, P and S deficits. These soils have suffered degradation due to extended periods of crop production under limited fertility management. Human population growth and expansion of households has led to an increase of croplands by 13% against a reduction of rangelands and forests by 14% in the past 20 years (ICRISAT, 2010). Similar livestock densities on smaller rangeland areas aggravate degradation processes and increase feed shortages (Powell et al., 2004). Land use is relatively extensive (Rockstrom et al., 2003), but with a strong integration of crops and livestock (Homann-Kee Tui et al., 2013).

In Nkayi District crop productivity is currently very low, around 650 kg/ha of maize (Mazvimavi et al., 2010; Masikati, 2011). During the 1990s, however, when maize production was promoted along with improved seed and fertilizer, yields were commonly around 1500 kg/ha (Government of Zimbabwe, 2002). Currently, crop input use is low and largely limited to maize production. Only one fifth of the farming households apply inorganic fertilizer with an average fertilizer rate of 54 kg/ha, whereas only a third apply manure at an average rate of 1.5 t/ha (Homann-Kee Tui et al., 2013). Animal traction is used to prepare 96% of the cropland. Conservation Agriculture, although widely promoted, is practiced by less than 10% of the households. Planting basins are the most common CA option, but these are associated with higher labor

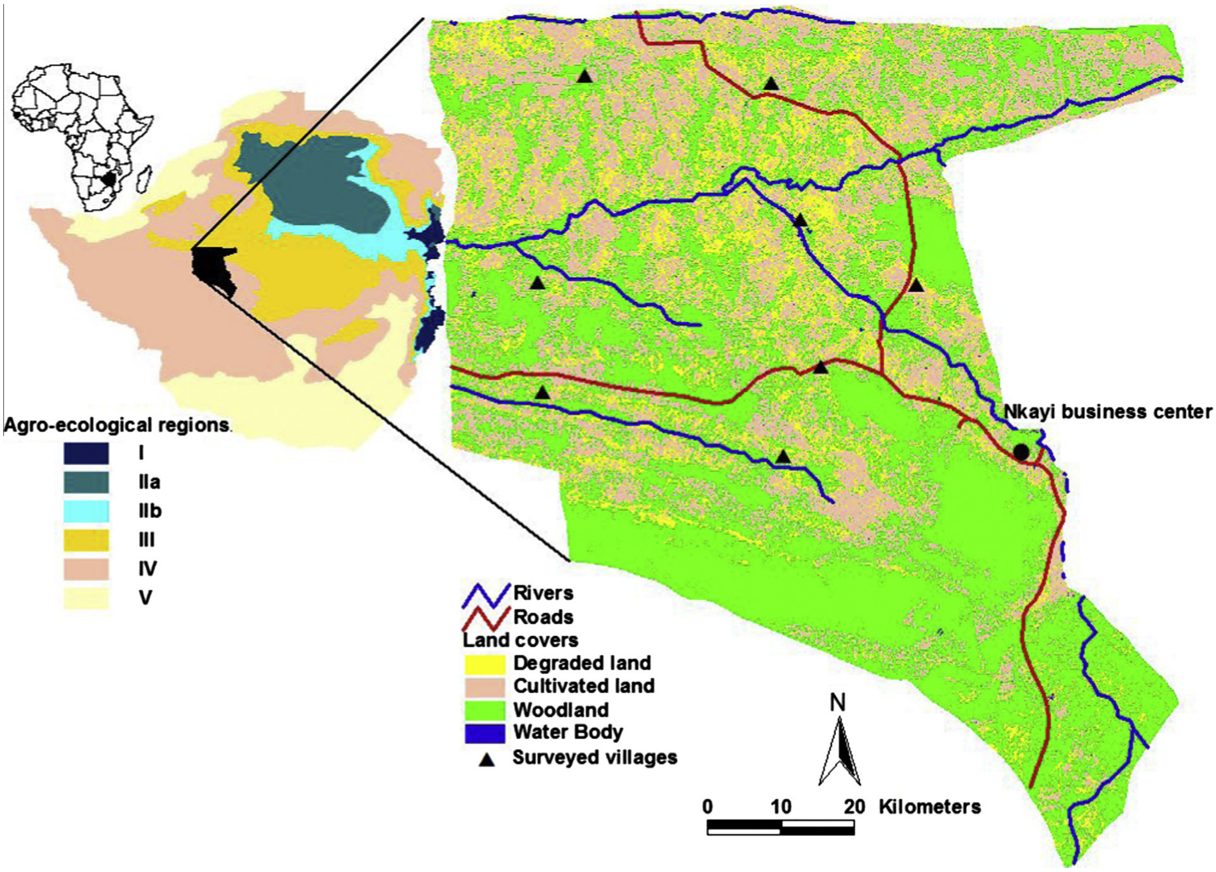

Fig. 1. Study site Nkayi District in West Zimbabwe and agro-ecological regions in Zimbabwe (ICRISAT GIS office, 2013).

requirements. Livestock production is recommended as the most appropriate form of land use that can be intensified by growing drought-resistant fodder crops (Holness, 1999). About 60% of the households keep cattle, mostly for draught power, manure, milk and sale (Homann-Kee Tui et al., 2013). Cattle mortality rates are high (~15%), implying that valuable resources are being wasted and important income options from selling cattle not realized. Average milk yields remain low (1.5 l per cow and day). Feed deficits are common but less than 3% of farmers grow forages. Farmers estimated using about 20% of the available maize residues for kraal feeding, with most CR (about 60%) being grazed *in situ*.

2.2. Data collection

The quantification of net returns of different farm activities and the ex-ante analysis of economic trade-offs of biomass use were based on various combined datasets. Eight villages were selected based on their distance to the market, nearby and far from main roads and the market place. Village level focus group discussions were conducted in 2010 to better understand local land use systems, and collect price information for agricultural inputs and outputs. Between 20 and 30 farmers from different backgrounds attended each group discussion. Household questionnaires were conducted in 2011 with 20 households of each of the selected village ($n = 160$). This selection was based on stratified random sampling accounting for levels of land and livestock ownership. Data collected include socio-economic household characteristics, crop and livestock inputs and outputs and estimated expenditures for crop and livestock activities, for the one-year observation period preceding the surveys (Table 1). In 2012, feedback workshops engaged farmers and other local stakeholders in verifying research results and identifying promising options for more sustainable intensification of smallholder agriculture in each of the selected villages. Finally, secondary data were used to verify household and village level data on input and output prices, crop and livestock production and to quantify the effect of alternative options in crop and livestock production and costs (see Appendix 1).

2.3. Net returns for different types of households

Households were stratified in three categories based on cattle herd size, as this influences farmers' wealth status and the ability to invest in alternative technologies. Prices for crop and livestock production (P) are derived from the median of estimated village prices by farmers. The quantities (Q) and costs (C) of cereal grains and CR are assessed for each individual farmer for the one-year observation period (Appendix 1).

The values of crop outputs were obtained from the grain outputs collected during the household survey and the harvest index (HI, in Zimbabwe: 0.4 for maize, 0.35 for sorghum, and 0.3 for millet and legumes – adapted from Hay and Gilbert, 2001). Cost components for crop production included farmers' estimates of cash expenses for maize production during the observed year, including land preparation and (in)organic inputs. The costs for animal draught power used for field preparations are based on field sizes, proportion of the fields prepared using animal tillage and village prices for draught power (cd subscript, see equations in Section 2.4.1). The costs of manure applied were calculated from estimated quantities of manure applications and village prices for manure (cma subscript). Opportunity costs of draught power and manure were factored in even if households did not pay cash for these services.

Table 1
Base system characteristics of 160 mixed farms used for the analysis, by farm types, in Nkayi District.

Items	Units	0 Cattle	1–8 Cattle	>8 Cattle	Total	
		Mean	Mean	Mean	Mean	Std. Dev.
Proportion in community	%	42.5	38.1	19.4		
Household members	People	5.9	6.9	7.4	6.6	2.5
Proportion of female headed households	%	27.9	31.1	22.6	28.1	
Net returns maize	US$/farm	60	163	63	99	122
Net returns other crops	US$/farm	32	58	51	45	53
Net returns cattle	US$/farm	0	485	1363	449	596
Net returns other livestock	US$/farm	9	19	15	14	29
Off-farm income	US$/farm	223	292	295	263	219
Farms with maize	%	98.5	100.0	100.0	100.0	0.1
Maize area	Ha	1.1	1.4	1.8	1.3	0.8
Maize grain yield	kg/ha	497	826	675	657	531
Farms with small grains	%	23.5	32.8	41.9	30.6	46.2
Small grain area	Ha	0.7	0.7	1.0	0.8	0.8
Small grain yield	kg/ha	393	726	327	512	622
Farms with legumes	%	33.8	49.2	48.4	42.5	49.6
Legume area	ha	0.4	0.4	0.5	0.4	0.3
Legume yields	kg/ha	452	722	388	557	541
Cattle*	TLU	0	5.4	13.9	4.7	4.7
Other livestock*	TLU	0.3	0.5	1.6	0.6	0.9

* Herd size: Cattle = 1.14 TLU, donkeys = 0.5 TLU, goats and sheep = 0.11 TLU.

The value of livestock outputs was derived from the economic value of draught power, milk, manure and animals sold. First, the value of draught power (ld subscript) was calculated based on the number of draught animals in the herd, village price for draught power, a ploughing period of 38 days/year, and weighed by 0.96 to account for the villages' actual area cultivated with draught power. Second, the value of milk (lmi subscript) was calculated from the number of lactating animals in the herd, a lactation period of 157 days for cattle and 93 days for goats (Ngongoni et al., 2006), the average milk yield per animal and the village price for milk. Third, the value of manure (lma subscript) was calculated from the number of animals, daily manure production (dry weight) estimated as 2.7% kg bodyweight (Haileslassie et al., 2009), adjusted by utilization factor of 0.7 (i.e. the estimated proportion of manure used for fertilizing the fields), and village price for manure. Fourth, the value of the number of animals sold, given away and consumed (lh subscript) was calculated based on village prices. Other important herd flows (births and mortalities) were factored in the annualized herd asset (herd assets = herd size at the end of the year + herd size at the beginning of the year/2). Cost components for livestock production included farmers estimated cash expenses for external inputs (le subscript). Feed costs to maintain livestock condition during the dry period were factored in as opportunity costs, even if farmers would not buy feed (lf subscript). A 90 days dry season feeding period was assumed; during the rainy season livestock feed entirely on rangelands (Masikati, 2011). Farmers estimated that during this period livestock obtain about 40% of their daily feed requirements (=0.4 × 2.5% bodyweight) from CR.

2.4. Economic trade-offs: The TOA-MD model

To calculate the economic trade-offs associated with biomass use, the Trade-Off Analysis model for Multi Dimensional Impact assessment (TOA-MD) was used. TOA-MD is a parsimonious model that simulates potential technology adoption rates and welfare impact across entire, heterogeneous farm populations and for different types of households (Antle, 2011). In the TOA-MD each farmer operates a specific production system and earns net returns per defined time period. When the production system changes because of the adoption of an alternative technology or policy, the returns for each farmer also change. Following this, technology adoption is modeled as the proportion of farmers who would obtain a positive net return after correcting for the opportunity costs associated with the technology (Antle and Valdivia, 2011).

This study expands available TOA-MD methods, by assessing the full values of the multiple crop and livestock outputs and cross linkages within an integrated mixed crop-livestock farming system. We estimated the monetized output values and valued the outputs used, consumed or sold at opportunity costs. We assumed that the alternative systems (CA and maize–mucuna rotation) would affect the maize and cattle activities, with cattle as main consumers of maize residues. The total cultivated land would not change, and the other crop and livestock activities would not be affected.

2.4.1. Alternative options for biomass allocation

The current system (conventional tillage, no mulching, predominantly grazing of CR) was compared with two alternative systems to quantify economic trade-offs of different CR uses: (1) CA on a third of the maize land with different fertilizer applications; (2) crop-diversification by converting a third of the maize land into a maize–mucuna rotation (Fig. 2). The third of the area that could be allocated to CA or mucuna was determined during feedback workshops with farmers.

2.4.1.1. Conservation Agriculture option. The comparison included different fertilizer use rates and subsidies, to better differentiate the impact of CA and fertilizer use on farm net returns:

- S2a: CA with no fertilizer;
- S2b: CA with the recommended fertilizer rates (132 kg/ha NPKS) at full cost; and
- S2c: CA with the recommended fertilizer rates at subsidized rates.

The expected effects of the CA treatments on maize grain and residue yields were determined using the 2009–11 Protracted Relief Program panel survey data (PRP, Nyamangara et al., 2013a). Average maize yields without CA treatments as assessed

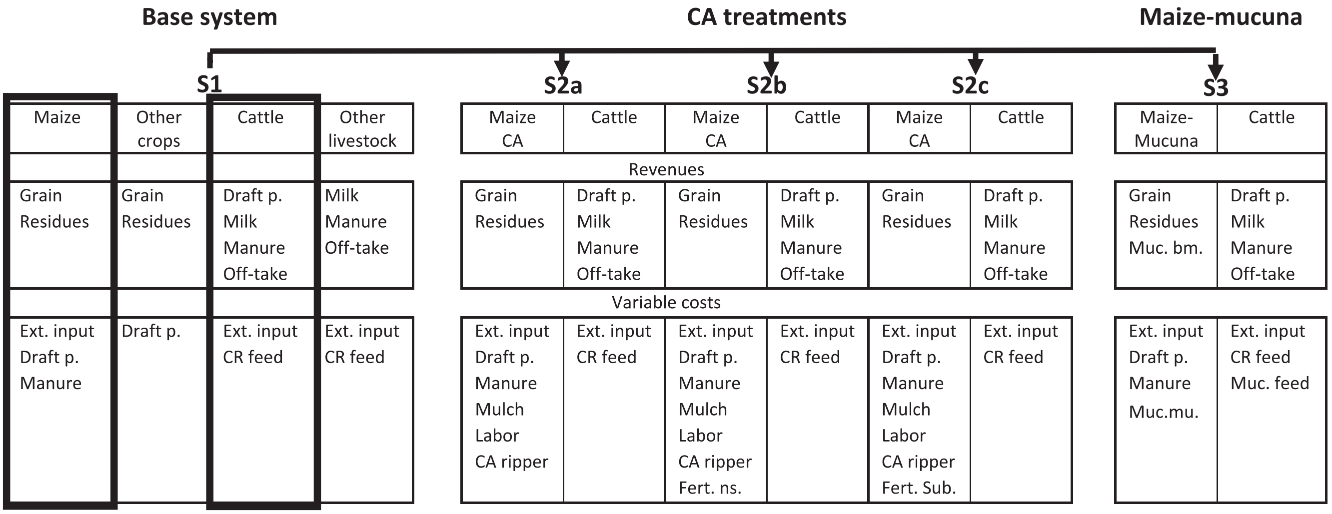

Fig. 2. Overview on net return components under farmer practice, CA treatments and maize–mucuna rotation. Note: Other crops and other livestock in base system assumed unaffected. CA treatments: 2a: without fertilizer; 2b: with non-subsidized fertilizer; 2c: with subsidized fertilizer.

by the PRP survey (767 kg/ha) were slightly above those obtained from the household survey (710 kg/ha). According to PRP data, mulching without fertilizer application resulted in lower maize grain yields (518 kg/ha, 67.5%, relative yield), while mulching with fertilizer application increased maize grain yields (1760 kg/ha, 229.5%, relative yield).

In the CA alternative, additional costs and benefits for maize and livestock production were included. The crop function included additional costs for fertilizer application, distinguishing subsidized and non-subsidized fertilizer (cfe subscript). Maize residues were allocated for mulching the CA land (2 t/ha, Naudin et al., 2011) (cmu subscript). Farmers with draught animals were assumed to invest in the CA ripper mechanization, recently introduced to allow coverage of larger areas at relatively low cost (25 US$ acquisition). The costs for purchasing the ripper were discounted over 5 years (cr subscript). We also assumed that the draught power set free by CA ripper mechanization was used for other fields. Farmers without cattle were assumed to use CA based planting basins which require 84.7 labor days per ha – an increase by 9 days per ha compared to the current system for farmers without draught animals (cl subscript) compared to mechanized tillage that requires only 38.6 labor days/ha (Nyamangara et al., 2013a). Retaining CR in the field as mulch is likely to require some protective measure. Costs of protection were however not included, since crop fields are usually fenced with local fencing material, and can be maintained using labor during the off-season.

Livestock production under the alternative systems was calculated with the LIVSIM (LIVestock SIMulator, Rufino et al., 2009) model, calibrated for Zimbabwean conditions (Rufino et al., 2011). LIVSIM simulates cattle production with a monthly time step based on breed-specific genetic potential and feed intake, following the concepts of Konandreas and Anderson (1982), and taking into account specific rules for herd management. Energy and protein requirements are calculated based on AFRC (1993), whereas actual feed intake is simulated according to Conrad (1966). As a result of mulching under CA there is lower CR availability during the dry season, increasing feed shortages, with repercussions on milk production, mortality and calving rates.

2.4.1.2. Mucuna option. Trade-offs associated with the three-year maize–mucuna rotation were calculated by substituting a third of the maize area with mucuna (Fig. 2). Field experiments in research-managed conditions showed that at 3.3 t/ha mucuna biomass production and with 30% of the biomass retained on the fields, maize yields increased by 67% in the following cropping season (Masikati, 2011). As a result of the limitations of smallholder households, we assumed that they will only achieve half of the researcher managed yield increase (i.e. a 34% increase in the subsequent maize yield). We assumed the other 70% of the mucuna biomass are used as livestock feed.

Introduction of mucuna generated a new yield component (cmucc subscript) as well as costs for using the biomass as mulch (cmucm subscript) or livestock feed (cmucf subscript). Since prices were not available, equivalent values were derived. The equivalent value of mucuna as mulch was derived from its N content (2%, Masikati, 2011) in comparison to inorganic fertilizer (8%). We assumed that realistically only 75% N is potentially available, and use this as basis for estimating the fertilizer effect. The equivalent feed value was derived from its CP content (13–15%) in comparison to commercial stock-feeds (17%). We used 75% of the feed value as a basis for estimating the feed effect, acknowledging that commercial stock-feed is generally preferable. Extra labor costs for production, harvesting and storage were not included, since mucuna requires similar investments as conventional maize. As for CA the costs for protective measures to retain mucuna biomass on the soil were also not included. Effects of the introduction of mucuna on livestock production were simulated with the LIVSIM model. Simulated effects on livestock are entirely due to changes in feed availability and, in particular in this case, also feed quality (energy and protein content).

The expected net returns from crop ($\sum_C$) and livestock ($\sum_L$) activities, base for the choice of alternative biomass allocations, were defined as follows, see also Fig. 2:

$$\begin{aligned}
(S1)R = {} & \textstyle\sum_C((P_{cg}Q_{cg}) + P_{cr}(Q_{cr}(1 - HI)/HI_{cr}) - C_{ce} - (P_{cd}Q_{cd}) \\
& - (P_{cma}Q_{cma})) + \textstyle\sum_L((P_{ld}Q_{ld}) + (P_{lmi}Q_{lmi}) + (P_{lma}Q_{lma}) \\
& + (P_{lh}Q_{lh}) - C_{le} - (P_{lf}Q_{lf})) \\
(2a)R = {} & \textstyle\sum_C((P_{cg\Delta}Q_{cg}) + P_{cr}(\Delta Q_{cr}(1 - HI)/HI_{cr}) - C_{ce} - (P_{cd}Q_{cd}) \\
& - (P_{cma}Q_{cma}) - (P_{cmu}Q_{cmu}) - (P_{cl}Q_{cl}) - P_{cr} + \textstyle\sum_L(P_{ld\Delta}Q_{ld}) \\
& + (P_{lmi\Delta}Q_{lmi}) + (P_{lma\Delta}Q_{lma}) + (P_{lh\Delta}Q_{lh}) - C_{le} - (P_{lf\Delta}Q_{lf})) \\
(2b,c)R = {} & \textstyle\sum_C((P_{cg\Delta}Q_{cg}) + P_{cr}(\Delta Q_{cr}(1 - HI)/HI_{cr}) - C_{ce} - (P_{cd}Q_{cd}) \\
& - (P_{cma}Q_{cma}) - (P_{cmu}Q_{cmu}) - (P_{cl}Q_{cl}) - P_{cr} - (P_{cfe}Q_{cfe}) \\
& + \textstyle\sum_L(P_{ld\Delta}Q_{ld}) + (P_{lmi\Delta}Q_{lmi}) + (P_{lma\Delta}Q_{lma}) \\
& + (P_{lh\Delta}Q_{lh}) - C_{le} - (P_{lf\Delta}Q_{lf}))
\end{aligned}$$

$$\begin{aligned}(S3)R = {} & \textstyle\sum_{C}((P_{cg\Delta}Q_{cg}) + P_{cr}(\Delta Q_{cr}(1 - HI)/HI_{cr}) + (P_{cmucc}Q_{cmucc}) \\ & - C_{ce} - (P_{cd}Q_{cd}) - (P_{cma}Q_{cma}) - (P_{cmucm}Q_{cmucm}) \\ & + \textstyle\sum_{L}(P_{ld\Delta}Q_{ld}) + (P_{lmi\Delta}Q_{lmi}) + (P_{lma\Delta}Q_{lma}) \\ & + (P_{lh\Delta}Q_{lh}) - C_{le} - (P_{lf\Delta}Q_{lf}))\end{aligned}$$

3. Results

3.1. Net returns: crops, livestock and farms

In what follows, we first compare the net returns per crop production area unit and per tropical livestock unit (TLU). We then aggregate and compare these net returns at farm level for the different household types.

3.1.1. Crop production

The current net returns of crop activities differ by types of households (Table 2). The net returns from conventional maize production are highest for households with small cattle herds (1–8 cattle). These farmers achieve higher yields and revenues at relatively low production cost. The households with no cattle achieve medium net returns per ha maize; they have low revenues, and production costs are also low. Farmers with large herds have the lowest net returns, because of high production costs for external inputs and manure application. Similar results were found for the net returns from other crops, which were higher than for maize for farms with small and large herds. Other crops also have lower variations in revenues implying less risk.

The comparison of conventional maize production with the CA applications illustrates reduced net returns under CA without inorganic fertilizer application, due to reduced yields and revenues and increased costs for using the CR as mulch (Table 3). Net returns from CA with non-subsidized fertilizer application are similar to conventional production practices; whereas with subsidized fertilizer, farmers' net returns are 30% higher. Through positive effects on maize yields, fertilizer application can improve immediate food security, but high costs of (unsubsidized) external inputs reduce profitability.

The maize–mucuna rotation promises higher per ha net returns than the CA technologies. The higher revenues stem largely from high quality mucuna biomass as maize production and revenues are lower per aggregate unit crop area than under conventional practice due to land foregone from maize production. The costs of the maize–mucuna rotation also seem high, accounting for mucuna biomass used as mulch, although these are imputed in-kind costs for internal services within the system.

Fig. 3 compares the net returns from alternative technologies on maize production for different types of farmers. For all farm types the maize–mucuna rotation seems the most profitable option as well as having less variation, i.e. less production risk associated with this technology. Farmers with small herds (1–8 cattle) have the highest net returns per unit land across the various technologies. For them mucuna can be an option of accessing high quality feed and mulch locally. Farmers without cattle might find the maize–mucuna rotation advantageous as compared to CA

Table 2
Budget analyses for conventional maize and other crops, by farm household types in Nkayi District, US$ per ha cultivated land.

Items		0 Cattle		1–8 Cattle		>8 Cattle		Sign
		Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	
Maize								
Revenue	Grain	93	81	165	125	129	76	$p < 0.05$
	Residues	28	24	50	37	39	23	$p < 0.05$
	Total	121	105	215	162	168	98	$p < 0.01$
Var. cost	Ext. inputs	15	13	29	24	50	49	$p < 0.01$
	Draft pwr.	20	11	22	11	27	15	n.s.
	Manure	4	11	7	11	44	53	$p < 0.01$
	Total	38	19	58	34	123	78	$p < 0.01$
Net return		83	102	156	163	45	92	$p < 0.05$
Other crops								
Revenue	Grain	97	35	124	51	91	50	n.s.
	Residues	42	29	53	32	36	26	n.s.
	Total	139	49	178	69	127	70	n.s.
Var. cost	Draft pwr.	22	15	28	18	33	17	n.s.
Net return		116	53	150	63	94	68	$p < 0.05$

Table 3
Budget analyses for farmer practice maize and alternative scenarios of crop residue allocation in Nkayi District, average for all farm types, US$ per ha cultivated land.

Items		Farmer practice (S1)		CA, no fertilizer (S2a)		CA fertilizer, non-subs. (S2b)/ subs. (S2c)		Maize–mucuna rotation (S3)	
		Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
Revenue	Grain	127	104	114	93	183	149	100	81
	Res./Muc.bm	38	31	34	28	55	45	173[a]	24
	Total	166	135	148	120	237	193	273	105
Var. Cost	Ext. input	27	30	27	30	27	30	27	30
	Draft pwr.	22	12	15	8	15	8	22	12
	Manure	11	24	11	24	11	24	11	24
	+CA/mulch	0	0	34	0	65/47	0	46	0
	Total	62	52	90	49	122/104	50	106	54
Net return		104	134	51	103	107/126	171/173	166	111

[a] Including about US$ 142 revenue from Mucuna biomass and US$ 31 from maize residues.

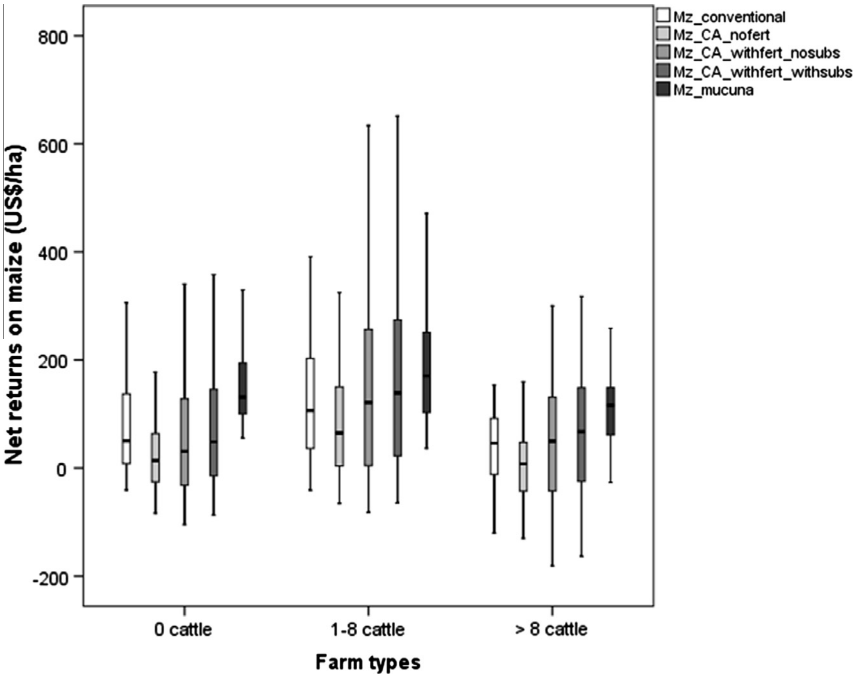

Fig. 3. Net returns of maize production under alternative scenarios of residue/biomass allocation, by farm types in Nkayi District, US$ per ha cultivated land.

practices, because of increased revenues with limited investments. Farmers with large herds (>8 cattle) have the lowest net returns per unit land; for them expanding or exchanging mucuna (e.g. draught power for mucuna) is an option to reduce the costs for external inputs.

3.1.2. Livestock activities

Net returns are higher per TLU cattle as compared to other ruminants, due to the multiple functions of cattle (Table 4). The highest revenues are from draught power, milk and manure, less from off-take (percentage of animals sold, consumed or given away in exchange for other benefits during a 1 year observation period to the initial stock). Unlike for crops, the returns per TLU are higher for farmers with large herds, notably through higher milk production and off-take rates. In comparison, farmers with small cattle herds benefit from their animals mostly through draught power. Their milk yields are lower and they cannot afford to sell and/or consume cattle as much as their neighbors with larger herds. It is important to note that few of the farmers with small herds bought cattle to invest in upgrading the cattle herd. However, farmers with small cattle herds or those without cattle derive higher benefits per unit small ruminants than farmers with large cattle herds. They generate more milk from small ruminants and they also have higher off-take rates from small ruminants. A number of farmers

Table 4
Budget analyses for conventional cattle and other ruminants in Nkayi District, by farm types, US$ per TLU.

Items		0 cattle		1–8 cattle		>8 cattle	
		Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
Cattle							
Revenue	Draft pwr.			47	32	35	16
	Milk			22	28	37	24
	Manure			20	17	23	11
	Off-take			1	54	16	27
	Total			96	38	110	39
Var. Cost	CR feed*			9		9	
	Ext. input			1	1	1	1
	Total			10	1	10	1
Net return	Total			87	32	100	39
Other ruminants							
Revenue	Milk	34	41	20	35	3	11
	Manure	13	13	16	14	15	11
	Off-take	−2	144	7	88	13	43
	Total	67	105	56	62	37	37
Var. Cost	CR feed*	9		9		9	
	Ext. input	1	1	1	1	1	1
	Total	10	1	10	1	10	1
Net return	Total	57	106	45	62	26	37

[*] Feed costs per TLU are the same across cattle and goats, due to the assumptions made on feed intake.

Table 5
Budget analyses for cattle and effects of alternative scenarios of crop residue allocation in Nkayi District, average for all farm types, US$ per TLU.

Items		Farmer practice (S1)		CA no fertilizer (S2a)		CA fertilizer (S2b, 2c)		Maize–mucuna rotation (S3)	
		Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
Revenue	Draft pwr.	43	28	43	29	44	30	45	30
	Milk	27	27	21	22	24	25	44	50
	Manure	21	15	18	13	19	13	18	13
	Off-take	6	47	6	12	9	19	36	72
	Total	97	39	88	28	96	32	144	83
Var. Cost	CR feed	9		9		9		6	
	Mucuna feed	0		0		0		11	
	Ext. inputs	1	1	1	1	1	1	1	1
	Total	10	1	10	1	10	1	18	1
Net return		88	35	78	28	87	28	128	83

invested in goats, which explains the low off-take rates, and is a strong indication that these farmers are trying to move up the livestock ladder.

Withdrawal of CR from conventional grazing to mulching has limited effects on livestock performance (Table 5). Net returns per unit cattle are about 10% lower under CA without fertilizer application, and similar under CA with fertilizer application than under conventional grazing. Supplementary feeding mucuna biomass raises cattle production, notably though increased milk yields and off-take, due to higher feed quality. Other effects associated with increased herd sizes are limited. Since we are looking at a one-year period, limited effects on herd sizes are to be expected. High standard deviations in Table 5 reflect variation across the farm types, especially milk yields and off-take in the mucuna scenario. Including the feed costs for mucuna biomass reduces the total net returns per unit cattle production. Since these costs are internal services, adding mucuna as feed may provide a viable livestock intensification option.

3.1.3. Farm level comparison

Table 6 aggregates the crop and livestock activities at farm level for scenarios with conventional and alternative allocations of CR. Farmers without cattle are extremely cash and resource constrained and they also have less land for farming. A greater share of their household income stems from off-farm activities (>50%). Compared to farmers without cattle, those with small and large cattle herds make about 7 and 14 times the aggregate returns from agricultural activities. The owners of large cattle herds derive the largest share of their income from livestock, and less than 20% from off-farm activities.

The CA scenario without fertilizer application results in reduced farm net returns. Poor households without cattle lose proportionally more – about 40% of their farm net returns. The effects of CA with fertilizer application are marginal on the net returns of the different farm types. If not subsidized, the fertilizer costs tend to reduce the farm net returns. The net returns in the subsidized fertilizer scenario are similar to conventional practices.

The maize–mucuna scenario suggests the largest potential for improvement. Farmers without cattle can almost double their net returns. Those with cattle can increase net returns by about 30%, through mucuna biomass surplus, which positively affects cattle productivity.

3.2. Economic trade-offs and impacts on poverty

Here we assess the economic trade-offs of alternative CR uses for entire farms, also including off-farm income activities (Fig. 4). We compare potential welfare effects of alternative CR allocations for the community and farm types.

Fig. 4 illustrates the results from TOA-MD analysis, aggregated for the entire farming population. The proportion of farm households that is expected to improve their economic situation is located left from where the curves cross the *x*-axis (=negative opportunity costs). Those farms make benefits up to the amounts on the *y*-axis. The areas between curves and under the *x*-axis present the possible benefits. The points right from where the curve crosses the *x*-axis represent the percentage of farms that are expected not to adopt the technologies because they would lose up to the amounts on the *y*-axis. Above the *x*-axis are the costs. For the majority of farms in Nkayi District the maize–mucuna rotation is economically the most attractive option – up to 82% of the farm households would benefit and might therefore be willing to adopt the maize–mucuna rotation. The maize–mucuna rotation would provide on average net benefits of additional 269 US$/farm. Fewer farms benefit from CA with fertilizer application (46% in the subsidized and 37% in the non-subsidized scenario) and the

Table 6
Aggregated farm level net returns from crop (maize and other crops) and livestock (cattle and other ruminants) activities, under different scenarios of crop residue allocation, in Nkayi District, US$ per farm types.

Farm types	Items	Farmer practice (S1)		CA, no fertilizer (S2a)		CA fertilizer, non-subs. (S2b)		CA fertilizer, subs. (S2c)		Maize–mucuna rotation (S3)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
0 cattle	Revenue	152	108	141	101	196	139	196	139	283	149
	Var. cost	51	33	80	45	113	64	94	53	96	58
	Net return	100	92	60	86	82	125	100	123	186	101
1–8 cattle	Revenue	882	423	786	355	946	447	946	447	1292	700
	Var. cost	154	71	183	74	225	87	201	79	245	94
	Net return	723	381	598	315	716	407	740	407	1042	659
>8 cattle	Revenue	1871	627	1508	463	1779	530	1779	530	2603	1154
	Var. cost	378	152	403	162	459	184	427	170	539	188
	Net return	1491	559	1103	389	1317	442	1350	441	2062	1057

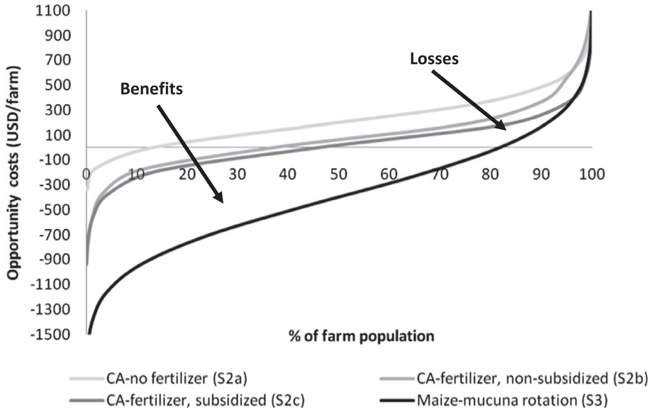

Fig. 4. Simulated economic benefits and losses from the adoption of CA and maize–mucuna rotation across the entire farm population, Nkayi District, Zimbabwe.

average net returns are less than under the current practices (a net loss of 44 US$/farm in the non-subsidized scenario, net loss of 21 US$/farm in the subsidized scenario). The comparison further illustrates that farm level effects of subsidizing fertilizer are marginal (small area between the curves CA-fertilizer, non-subsidized and CA-fertilizer, subsidized). Only about 13% of the farmers would find some advantage in adopting CA without fertilizer application; but on average this implies a net loss of 140 US$/farm.

Figs. 5a–c and Table 7 disaggregate the results by farm type, reiterating the relative unattractiveness of CA without fertilizer and the attractiveness of the maize–mucuna option. The maize–mucuna option is particularly attractive for the poor farmers without cattle (net benefits 85 US$/farm), with 91% potentially adopting against 78% for the farmers with larger cattle herds. Whether they will realize these benefits depends on whether they could generate revenue from mucuna biomass sale/exchange with other farmers. In an environment where farmers' first priority is producing food, reduced grain production might be a barrier for poor farmers to adopt this technology. The CA with fertilizer application is particularly attractive to the intermediate group. More farms with small herds would be self-sufficient in maize, 36% under the base scenario and 59% with fertilizer, albeit with higher costs and risks involved in the purchase of inorganic fertilizer. Poor farmers with no cattle would benefit from fertilizer use by improving their immediate food security situation. During the observation year only 10% of the households were food self-sufficient, whereas fertilizer application could raise this proportion to 18% of the households. Farmers with no cattle of their own can spare their CR for mulch; although by restricting other cattle from grazing their CR they might lose access to draught power exchange arrangements. The maize–mucuna rotation is associated with reduced maize grain production (only 23% of the households are self-sufficient), but does not involve external inputs. During dry years and maize failure farmers can harvest at least some mucuna biomass for supplementary feed. Considering that these farm households are also extremely cash limited and vulnerable, mucuna biomass through local seed multiplication can support these farmers to buffer dry season feed and food shortages. Trade offs are highest for farms with large cattle herds. Greater variation in net returns implies higher risks for these farmers, for either of the technologies (Fig. 5c, Table 7). As they are more livestock oriented and own more land than their neighbors, they would generate large volumes of supplementary feed under the maize–mucuna option, and sustain their food security needs through sales of livestock.

The TOA-MD also simulates the effects of the adaptation strategies on poverty rates in a given farm population. According to the assumptions in this assessment, currently about 90% of the population lives on less than 1 US$ per person per day (all households with no livestock and small herds, and 70% of those with large herds, Table 7). The effects of the simulated CA-options on poverty reduction are extremely limited. Maize–mucuna technologies could drop the overall poverty rate to around 78%, although primarily benefiting those few farmers with large cattle herds, and overall poverty would remain high.

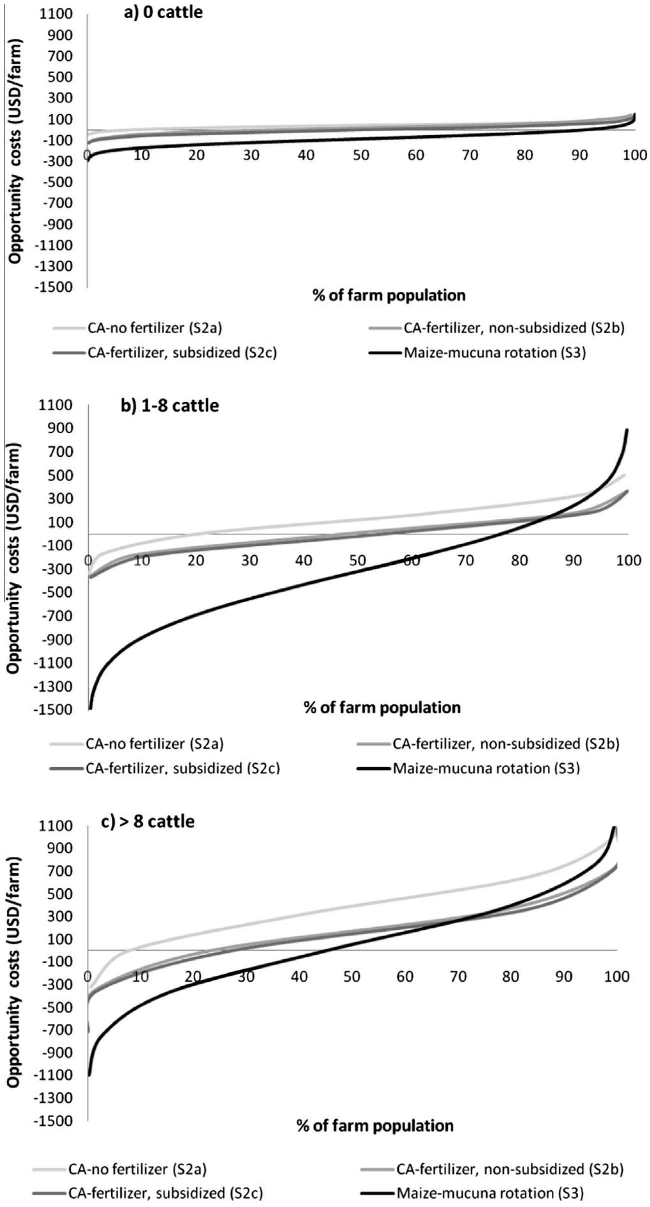

Fig. 5. (a–c) Simulated economic benefits and losses from the adoption the adoption of CA and maize–mucuna rotation, by farm types, Nkayi District, Zimbabwe.

4. Discussion

4.1. Trade-offs and profitability of CR allocation in mixed smallholder farming systems

The study results support the argument that trade-offs and profitability should be considered at farm level for better-informed discussions and decisions on how crop-livestock systems can be intensified in more sustainable ways (Pretty et al., 2011). Taking

Table 7
Economic indicators for impact of CA technologies and maize–mucuna rotation in Nkayi District, by farm types.

	0 Cattle	1–8 Cattle	>8 Cattle	Total
Potential adoption rate (% of farm population)				
CA, no fertilizer (S2a)	8	21	8	13
CA fertilizer, non subsidized (S2b)	35	48	23	37
CA fertilizer, subsidized (S2c)	50	55	27	46
Maize–Mucuna rotation (S3)	91	77	78	82
Potential net losses from technology adoption (US$ per farm)				
CA, no fertilizer (S2a)	40	126	389	140
CA fertilizer, non subsidized (S2b)	17	7	174	44
CA fertilizer, subsidized (S2c)	0	−17	142	21
Maize–Mucuna rotation (S3)	−85	−318	−571	−268
Poverty rate (% of farm population living on < 1US$ per day)				
CA, no fertilizer (S2a)	100	99	70	90
CA fertilizer, non subsidized (S2b)	100	99	67	89
CA fertilizer, subsidized (S2c)	100	98	65	88
Maize–Mucuna rotation (S3)	100	82	38	78

into account the complexity of crop and livestock activities in farming systems like those in Nkayi, this study illustrates that biomass constraints and trade-offs between CR uses for feed and mulch can be reduced.

The quantification of net returns and economic trade-off analysis has several limitations, which might lead to overestimating the expected benefits from alternative technology options (Claessens et al., 2009, 2012). We combined the ex-ante modeling with stakeholder consultation at feedback workshops to gain confidence about the implications of the modeling results (Homann-Kee Tui et al., 2013). The limitations were addressed as follows:

- Quantification of non-monetary values: To account for the intrinsic services that crop and livestock production provides and considering absence/weakness of functional markets, systems products were valued based on simplifying assumptions and farmer estimations.
- Causal relations and feedbacks of alternative biomass enhancing options in these complex systems: This was partly solved by using the TOA-MD approach, combining different data sources and farm components in order to assess the economic trade-offs of biomass allocation at opportunity costs.
- Farmers' preferences on the adoption of alternative options: Even if the biomass enhancing technologies seem to improve overall farm productivity and profitability, farmers might be reluctant to adopt them. A close interaction with stakeholders to design and verify the potential adoption of alternative options is needed.
- Exogenous factors that inhibit adoption: Barriers that influence the context in which the biomass enhancing technologies are disseminated were discussed with stakeholders at feedback workshops. Stakeholders explained key factors required to enable the widespread adoption of economically rational technologies.
- Inter- and intra-annual variation in rainfall and rainfed crop production: We used an average production year as the basis for the simulations. Seasonal variation in production and prices were not taken into account. Interpretation of results should include a consideration that high frequency of drought years implies high risk for investments, especially for external inputs.
- Accounting for labor: Quantification of labor in crop and livestock activities was beyond the scope of this study. Stakeholders confirmed that most activities are based on family labor and focus on crop production.

The results from economic modeling provide important insights on the comparative advantages of technical alternatives. Although maize is nearly universally grown and the main food staple in the study area, yields and returns are low. Farmers with small herds can obtain higher maize yields and revenues at reduced costs. There seems to be room for farmers with larger herds to achieve about 30–40% increases in maize revenues, and up to threefold higher net returns if they use their resources more efficiently. Our analysis also shows that the returns to other crops per unit area are higher than for maize, leading to the conclusion that the promotion of dual-purpose legumes merits new attention. Off-farm income provides an important complement, and income from cattle is particularly important for medium to large farms.

Considering the dominance of maize in this area, motivated by food preference and stronger support, it is important to find cost-effective options for increasing the net returns from maize. Under the current specification, maize under CA without fertilizer is not an attractive option, given lower yields and higher costs compared to farmers' current maize practices. Conservation Agriculture with subsidized fertilizer benefits almost 50% of the farm population in terms of immediate food security and economically.

The maize–mucuna rotation shows potentially highest economic benefits, with positive feedbacks at the farm-level, including organic fertilizer, supplementary feed and a source of income. Masikati et al. (2015) established that mucuna can contribute to substantially higher yields of the subsequent maize crop. Complete legume biomass removal can however lead to yield penalties (Mupangwa and Thierfelder, 2013). The potential value of mucuna as high protein livestock supplementary feed has been established earlier (Maasdorp and Titterton, 1997; Pengelly et al., 2004). Murungweni et al. (2004) found the nutritional quality of mucuna biomass comparable with commercial stock feeds in dairy and cattle pen fattening diets (15% and 14% CP respectively). Feeding mucuna can also replace maize residues used for feed and avail more maize residues for soil amendment. While access to mucuna seed has been a challenge for mucuna production in semi-arid Zimbabwe, recent projects introduced mucuna seed multiplication by smallholder farmers, also on small-scale irrigation land (ICRISAT reports). More land is being converted to forage production as farmers realize that mucuna provides quality biomass for supplementing livestock when conventional crop harvests often fail. Farmers have started selling mucuna seed to other farmers and development organizations. They scored mucuna seed production higher than conventional crops for income generation and risk management (dito). Adoption of mucuna however will depend on a careful assessment of farmers' willingness to invest in feed instead of food, the local feed demand and feed transactions between farmers. Less land under maize and cultivating mucuna as a forage could then generate higher net returns per unit land than conventional maize. Further research is required also to establish whether mucuna's prospects are a product of somewhat artificial demands created by the development community or are genuinely viable in the real world of resource-poor farmers without development support.

In the current specification, maize with CA appears viable only with fertilizer. This presents a major challenge given the high costs associated with fertilizer application and other external inputs such as improved seed or herbicides. Fertilizer application has been identified as an indispensable but often missing element in CA technologies, for greater food production and more residue biomass for soil cover (Vanlauwe et al., 2013). Most CA studies focus on productivity criteria, but do not disclose the full costs involved for farmers if CA was not subsidized or supported by development and relief operations (Mazvimavi and Twomlow, 2009; Ndlovu et al., 2015). With declining soil fertility, high costs and inaccessibility of inorganic fertilizer, the challenge remains to make the external inputs available to farmers on a sustainable basis. Apart from fertilizer, high labor demands for weeding and land preparation also challenge the large-scale adoption of CA in an environment where mechanisation or herbicides are not available to farmers in the mid-term (Ndlovu et al., 2015).

Farmers manage crop-livestock interactions to reduce biomass trade-offs (Valbuena et al., 2012). In Nkayi, through collection and storage of CR farmers try to reserve some of the residues for the critical dry season period and improve the nutritional value of the residues. Historically CR are considered to be community resources. Farmers open the crop fields after grain harvest for the communities to let their animals graze on the CR. Reserving more CR implies that CR are becoming a private resource of economic value (Sibanda et al., 2011). Feeding CR to livestock increases the availability of manure, which can contribute to maintaining and increasing crop yields. Feeding CR to draught power animals enables crop intensification. Establishing these linkages within individual households and through reciprocal arrangements within communities and eventually markets would support sustainable integrated crop-livestock systems. Whereas crop sales remain insignificant in the study area, households sell livestock and reinvest into agricultural production, e.g. to acquire fertilizer or feed. Livestock markets could serve as a platform to stimulate reinvestments into agricultural production, and even encourage fodder markets, with the overall result being increased farm productivity (Duncan et al., 2013).

An analysis of the nature and potential options to reduce economic trade-offs needs to include the levels of resource endowments among smallholder households. The different types of households in Nkayi experience trade-offs and benefits differently. In the medium term, once fodder markets are established, fodder seed multiplication and/or biomass production bears the potential of a strong niche market and low cost income opportunity for resource-poor farmers. Since these farmers make higher net returns on crops other than maize, diversification into other legume crops should be promoted. Households with small herds benefit from CA, but the economic benefits from maize–mucuna rotation would be greater. Using high-quality mucuna biomass they can sustain the crop-livestock synergies, and produce more on the limited land while reducing reliance on external inputs. Households with large herds and more access to land and capital tend to focus on cattle production. Converting more land to mucuna is an option for them to substitute CR and reduce the costs for external inputs like fertilizer and animal feed.

4.2. Preconditions for sustainable intensification of CR usage

Practical approaches to enhance biomass supply and use efficiency should comprise combinations of technologies that strengthen the coupling between crops and livestock, stimulated by the right incentives (Baudron et al., 2014). Promoting combinations of technologies is thus insufficient; socio-economic processes are required through which major barriers to sustainable intensification of mixed smallholder farming systems can be removed (The Montpellier Panel, 2013). While the barriers inherent to the biomass trap may appear common to many other parts of sub-Saharan Africa, addressing them requires context-specific solutions that involve innovative public support and links to the private sector (McDermott et al., 2010). Stakeholder consultation in Nkayi District identified the following technical and institutional priorities for improvement:

- Poor access to reliable supply of inputs and services and relevant knowledge about crop and livestock production: While support given to CA-based agriculture has improved farmers' access to extension, most farmers do not have the knowledge to manage, process and use alternative crops. Even the extension system itself does often not have the adequate knowledge to act as an agent of change. More integrated crop-livestock extension services are required to assist farmers in building their crop and livestock assets. Dual-purpose legumes and fodder technologies should also be mainstreamed in extension messages.
- Poor access to crop and livestock input and output markets: Market development should stimulate diversification into alternative crop and livestock activities. Studies have shown that in reaction to improved livestock markets farmers increased offtakes and started investing in productivity enhancing technologies and bought stock feed (ICRISAT reports). Supplementing purchased feed through local production of e.g. mucuna offers opportunities for fodder markets. The more farmers will be able to afford farming inputs, the more investors will be attracted to supply inputs locally. Improved access to seed and fertilizer, with conducive government policies towards affordable prices, appear indispensable requirements now for CA applications in such semi-arid settings.
- Lack of stakeholder coordination: Collective action among stakeholders is important – to link farmers to existing and new markets, ensure relevant support services and improved capacity to adjust to changing requirements, e.g. better preparedness to reorganize the activities in case of droughts or other shocks, or better ability to respond to new market opportunities. Stakeholder-driven processes should play a much greater role for developing an attractive environment for technology adoption and incentives for market development and participation.

4.3. Beyond trade-offs: potential effects on food security and poverty

While promoting sustainable intensification options, we should acknowledge that from an entire farm perspective, the economic effects of the biomass enhancing technologies are often small. The study confirms that in Nkayi single technologies may improve immediate food security, but increasing agricultural production may only have a modest impact on the total farm income. Small farm sizes (on average < 2 ha) and low net returns from crop production (104 US$/ha for maize and 124 US$/ha for other crops) – comparable with Harris and Orr (2015) – do not allow farming families to adequately live from crop production alone. This study has shown that farmers generate substantially higher net returns by combining crop and livestock production. However, even when off-farm income was included, about 90% of the farm population was still below the poverty line. The most promising alternative technologies only reduced poverty among the top 25% of the farm households. The extremely high poverty rates can be explained by the study area and the particular condition of Zimbabwe during the study period – the second year after a major economic crisis with very low monetary transactions and limited off-farm incomes. The limited effect of CA and maize–mucuna technologies on the livelihoods of poor households and stronger effects for households with larger cattle herds seem plausible. More comprehensive approaches are needed to strengthen processes towards diversification of mixed farming systems and enhanced markets and create incentives for re-investments into the rural economies.

5. Conclusions

This study combines multiple sources of data and models in a trade-off analysis for different farm types in order to explore the economic feasibility of biomass enhancing technologies in the context of mixed farming systems in semi-arid Zimbabwe. It offers good insight into the potential and profitability of alternative biomass enhancing technologies. Technologies that strengthen crop and livestock production and the interactions while reducing dependency on external resources are available, but need to be better integrated and barriers to their adoption addressed, including profitability and risk considerations. In the medium term, in an enabling context, alternative biomass systems can strengthen the coupling of crop and livestock activities at the household and landscape level. To realize potential benefits from enhanced biomass availability and use, it is critical to improve the contextual conditions that will enable farmers to invest in and make appropriate returns on the investments. This will include processes that inform farmers and decision makers on the economic trade-offs and demonstrate the returns on fodder and CA technologies for different farm types.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agsy.2014.06.009.

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