Assessing the potential of dual-purpose maize in southern Africa: A multi-level approach

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ABSTRACT

This paper explores the potential and challenges of increasing production of food and feed on existing maize fields in mixed crop-livestock systems in the semi-arid areas of southern Africa. It integrates results from different sources of data and analysis: 1. Spatial stratification using secondary data for GIS layers: Maize mega-environments combined with recommendation domains for dual-purpose maize were constructed for Malawi, Mozambique and Zimbabwe, stratifying the countries by demand factors (livestock densities and human population densities) and feed availability. Relative biomass contributions to feed resources from rangelands were compared to those from croplands to explore the usefulness of global datasets for feed supply estimations. 2. Verification through farming systems analysis: the potential demand for maize residues as feed (maize cropping patterns, maize yields and uses, feed deficits) was compared at contrasting sites, based on household survey data collected on 480 households in 2010. 3. Maize cultivar analysis: Genotypic variability of maize cultivars was compared to evaluate the potential contribution (stover quantity and quality) of dual-purpose maize to reduce feed deficits. The study results illustrate high spatial variability in the demand for and supply of maize residues. Northern Malawi is characterized by high livestock density, high human population density and high feed availability. Farmers achieve maize yields of more than 2 t/ha resulting in surplus of residues. Although livestock is important, southwest Zimbabwe has low livestock densities, low human populations and low feed availability; farming systems are more integrated and farmers make greater use of maize residues to address feed shortages. Central Mozambique also has low cattle densities, low human populations and low feed availability. More rangelands are available but maize yields are very low and livestock face severe feed shortages. The investigation of 14 advanced CIMMYT maize landraces cultivars and 15 advanced hybrids revealed significant variations in grain and stover yield and fodder quality traits. Where livestock densities are high and alternative feed resources are insufficient, maize cultivars with superior residue yield and fodder quality can have substantial impact on livestock productivity. Cultivars at the higher end of the quality range can provide sufficient energy for providing livestock maintenance requirements and support about 200 g of live weight gain daily. Maize cultivars can be targeted according to primary constraints of demand domains for either stover quantity or stover fodder quality and the paper proposes an approach for this based on voluntary feed intake estimates for maize stover.

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1. Introduction

Food security for rural households in southern Africa is generally determined in terms of maize production, the region's major staple crop (Grant et al., 2012; Langyintuo et al., 2008; Calcaterra, 2002). Therefore, maize has been identified as one of the key agricultural commodities to enhance food production and food security at continental and sub-regional levels (AU, 2006). Nevertheless, maize yields remain low in many parts of southern Africa (except for

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South Africa), stagnating at around 1 t/ha for the last decade (Smale et al., 2011; Kassie et al., 2012). Past growth in total maize production has been achieved through land expansion instead of crop intensification. However, expansion of agricultural land is increasingly restricted given the reduction of available land and the large resource constraints facing farmers in the region (e.g. labor, capital).

At the same time, increasing importance of livestock as a source of revenue suggests that investments in this sector offer a clear opportunity to improve rural livelihoods and the overall agricultural growth of the region (Chilonda and Minde, 2007; Nin Pratt and Diao, 2008). A promising method of enhancing crop and livestock productivity is increasing the availability and quality of cereal residues as livestock feed (Amede et al., 2009; Alkemade et al., 2012). Feed availability is a major bottleneck for improving livestock production and productivity in the region (associated with animal health, Holness, 1999). This bottleneck can become more severe with the increasing expansion of cropland on communal rangelands, an essential source of livestock feed in the region (De Leeuw, 1997).

Improved dual-purpose maize varieties for food and feed provides a promising technological option to intensify both crop and livestock production by simultaneously increasing the availability and quality of grain production and livestock feed (Berhanu et al., 2012; Blümmel et al., 2012). The potential of these dual-purpose technologies in southern Africa would depend on: the environment, i.e. agro-ecological and socio-economic context of agricultural production (Notenbaert et al., 2012), farm management, i.e. crop-livestock farming systems (Ojiem et al., 2006); and genetics, i.e. quality and quantity of food and feed production of different maize cultivars (Sharma et al., 2010). The objective of this study is to assess the potential of dual-purpose maize on food and feed production and to better target promising cultivars by accounting for the environment, management and genetics on crop-livestock farms in southern Africa. This assessment is a multi-level analysis combining assessments of dual-purpose maize at landscape and farming system levels in mixed crop-livestock systems in Malawi, Mozambique and Zimbabwe, as well as including the genetic variability of prominent maize cultivars.

2. Material and methods

2.1. Countries and study sites

Countries were selected based on secondary data and expert consultation to represent contrasting mixed crop-livestock systems in southern Africa, including sites in Malawi, Zimbabwe and Mozambique (Chilonda et al., 2008).

Farming systems studies were implemented in each of the three countries at selected sites that represent contrasting maize-based systems with different challenges and opportunities for improved dual-purpose maize. The studies were part of the System-wide Livestock Programme (SLP) project on crop residue use, determinants and trade-offs, southern Africa case study (Homann-Kee Tui et al., 2012). Mzimba in northern Malawi has higher rainfall (av. 700–750 mm per year) and relatively high levels of human populations (57 persons per km^2) than the other two sites. Agricultural production is more intensified and oriented towards crop production. Nkayi in southwest Zimbabwe and Changara in Central Mozambique have lower rainfall (av. 600–650 mm persons year) and lower human population densities (23 and 19 persons per km^2, respectively); agricultural production is more extensive and livestock is more prominent in agricultural production than in the other site.

2.2. Analytical approach

The assessment of the environment, management and genetics of dual-purpose maize integrates three levels of analysis and research outputs that will generate a better understanding of the potential and viability of this technology on improving agricultural production in southern Africa (Fig. 1). These three levels of analysis are:

a. A nested landscape analysis to spatially identify the potential of dual-purpose maize, based on feed biomass production and demand in the three countries (i.e. environment).
b. A farming system analysis to understand and verify the feasibility of the previous spatial analysis based on resource allocation and management in three selected study sites (i.e. management).
c. A maize cultivar analysis to evaluate the potential contribution of different improved dual-purpose maize cultivars in enhancing feed supply (i.e. genetic).

2.2.1. Landscape analysis

This nested landscape analysis combines GIS databases to better understand the production and demand for feed in mixed crop-livestock systems at a country level. Firstly, data on the distribution of mixed crop-livestock systems is used to identify major areas where dual-purpose varieties could have a niche. Secondly, data on the agro-ecological potential of specific maize cultivars (Maize Mega Environments) is used to better target dual-purpose varieties. Thirdly, Recommendation Domains are used to further stratify the niche of this technology by supply and demand factors. Finally, spatial analyses of rangeland and cropland production are included to quantify the contribution of feed resources. These spatial databases were raster layers with different spatial resolutions (pixel size). To be able to combine them, they were converted to vector data, overlaid and integrated by using Raster to Polygon tool and other Geoprocessing tools in ArcGIS 10. The databases, which are all publicly available, include:

Mixed crop-livestock systems: Distribution of mixed crop-livestock systems were defined using the ILRI/FAO global livestock production systems classification (Robinson et al., 2011), based on criteria developed by Thornton et al. (2002) (<450 persons per km^2 to differentiate from landless intense systems; >60 days LGP and >20 persons per km^2 to differentiate from livestock-only systems).

Maize Mega Environments: The potential of maize varieties is based on the CIMMYT's Maize Mega Environments (MME; Bellon et al., 2005), developed for matching maize cultivars with climatic key variables such as day length, rainfall precipitation and temperature. These climatic variables were used as layers to stratify by agro-ecological potential (Hartkamp et al., 2000).

Recommendation Domains: Recommendation Domains (RDs) for better targeting of dual-purpose maize cultivars were developed following the approach of Notenbaert et al. (2012) based on three strategic demand and supply criteria: (i) livestock density (here cattle and small ruminants); (ii) human population density; and (iii) feed availability from crop residues of maize, small grains, legumes, sugar cane, roots and tubers. For each of the variables (livestock density, human population density, feed availability), two classes were defined, high (H) and low (L). To separate the two classes, cut off points were defined that represent the averages across mixed farming systems in southern Africa and combining the following data layers: (i) Livestock density of 9 Tropical Livestock Units (TLU)/km^2 — pixel size of 10 km × 10 km resolution, FAO layers (Wint and Robinson, 2007); (ii) Human population density of 36 PPL/km^2 — pixel size of 1 km × 1 km resolution, using the Global Rural Urban Mapping Project (GRUMP) layers (CIESIN, 2004); (iii) Feed availability of crop residues of 20 t/km^2 — pixel

Sources of data and analysis

Outputs

Nested landscape analysis: Environment

- Mixed crop-livestock systems
- Maize Mega Environments
- Recommendation Domains
- Range- and cropland biomass

Maps and summary statistics on the demand and supply of feed

Farming systems analysis: Management

- Assessment of local resource allocation and management

Potential demand for dual-purpose cultivars verified in local context

Maize cultivar analysis: Genetics

- Assessment of genetic variability in feed traits

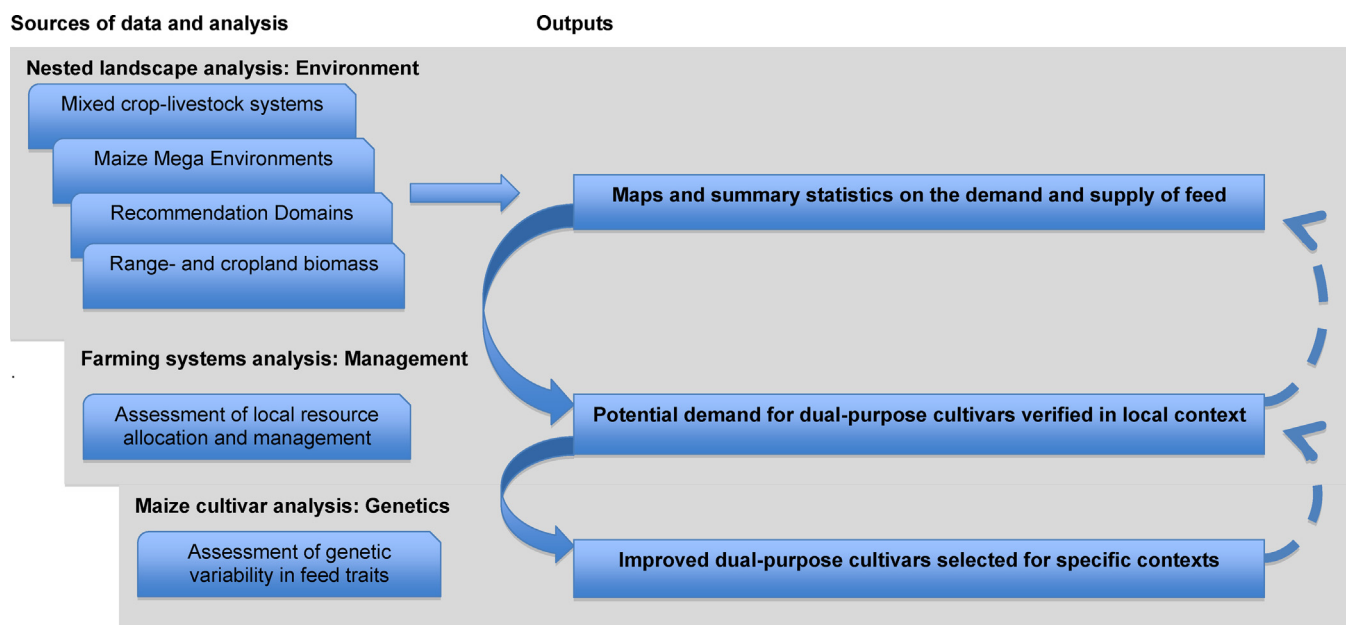**Improved dual-purpose cultivars selected for specific contexts**

Fig. 1. Schematic diagram of the multi-level research approach used in this study.

size of 10 km × 10 km resolution, using the Spatial Production Allocation Model (SPAM) layer (SPAM, 2000, v3.0.r6). Total production of all major crops was calculated and weighed by the cropped area.

Range- and cropland biomass: In addition to feed availability from croplands we also assessed the biomass production from rangelands. We assessed the cumulative Net Primary Productivity (NPP) for the years 2000–2011 and then calculated the average annual NPP. The distribution of the NPP was mapped using improved global datasets — pixel size of 1 km × 1 km resolution, MODIS, developed by Zhao et al. (2005, 2006) and Zhao and Running (2010). Rangelands and cropped areas were differentiated using the dataset developed by Ramankutty et al. (2008) on global pastures and croplands — pixel size of 10 km × 10 km resolution. The contribution from rangelands relative to croplands was compared based on the area proportion of pastures and croplands, and feed supply from crop residues estimated from the SPAM datasets.

Biomass available from rangelands was estimated using a conservative figure of 30% of the assessed NPP production (De Leeuw and Tothill, 1990).

Finally, the biomass from rangelands and croplands was related to an upper estimated voluntary feed intake 3% body weight per TLU, resulting in a maximum total biomass requirement of approximately 2.75 t per TLU and year. Accounting for the intra-annual variability and the spatial distribution of feed quality of croplands and rangelands was beyond the scope of this study. The biomass values present best-possible estimations to inform the spatial stratification and characterization of RDs.

2.2.2. Farming system analysis

Based on the landscape analysis, three contrasting sites were selected to better understand how dual-purpose maize could fit different crop-livestock systems. Given the large diversity of agro-ecologies across the three countries, we opted to combine the landscape analysis with in-depth farming system analysis at sites with different levels of agricultural intensification.

The farming systems analysis in the three selected sites was based on focus group discussions and household level survey conducted with a total of 480 households between 2009 and 2010 (for details see Homann-Kee Tui et al., 2012). For the purpose of this paper we present descriptive statistics that elucidate agricultural/livestock production with emphasis on uses of maize residues.

2.3. Assessment of a range of maize cultivars from Southern Africa for dual-purpose traits and their potential impact on livestock productivity

2.3.1. Residue fodder quality analysis

Two groups of maize cultivars chosen from CIMMYT maize breeding trials in Zimbabwe previously investigated for residue fodder quantity and quality traits at ILRI, India (Vivek, unpublished) were revisited: (1) advanced hybrids and (2) open-pollinated mostly landraces. Residue samples were analyzed for metabolizable energy (ME) content as described by Ramana Reddy (Ramana Reddy et al., 2013), to estimate the potential of different maize to contribute to the energy requirement of livestock. The statistical differences for the given grain and stover traits between landrace and advanced hybrid maize cultivars were assessed.

2.3.2. Energy requirements for livestock maintenance and predictions of maize residue intake

Net energy requirements for maintenance of TLU (250 kg live weight) were calculated as $0.53 (250/1.08)^{0.67} + 0.0043 \times 250 = 21.4$ MJ/day according to McDonald et al. (2011). Efficiency of use of metabolizable energy (ME) for maintenance (k_m) was also calculated according to McDonald et al. (2011) as: $k_m = 0.35q + 0.503$ with q the metabolizability calculated as: ME/18.4. Similarly efficiency of ME utilization for live weight gain was calculated as: $k_l = 0.78q + 0.006$ (McDonald et al., 2011) and the energy content of 1 kg of live-weight gains was taken as 11.4 MJ (McDonald et al., 2011). Voluntary residue intake (VFI) of a TLU was predicted based on residue ME content based on the equation of Ravi et al. (2013) as: VFI (kg/kg LW) = $-3.6 + 3.52$ ME (MJ/kg).

3. Results

3.1. Landscape analysis

3.1.1. Crop-livestock systems and maize potential

The importance and spatial distribution of mixed crop-livestock systems and areas under maize differs across the three countries (Fig. 2). Mixed crop-livestock systems cover almost 45% of the total area in Malawi (31,000 km²), 44% in Zimbabwe (177,000 km²)
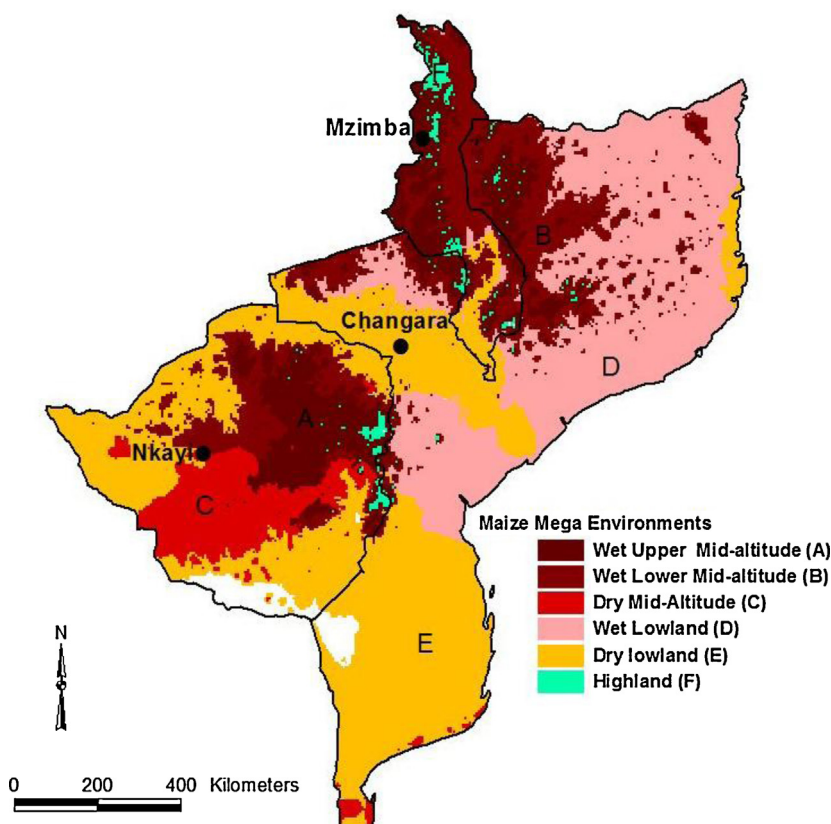
Fig. 2. Maize mega environments across Malawi, Zimbabwe and Mozambique and at the selected field project sites in each country sites.
Data source: Hartkamp et al. (2000).

and 21% in Mozambique (153,000 km^2). The maize area within the mixed systems, including range- and cropland, is about 28% (8600 km^2) in Malawi, 8% (14,636 km^2) in Zimbabwe and 2% (2707 km^2) in Mozambique.

The agro-ecological potential for maize varieties also differs across countries. Malawi has high agro-ecological potential. Although the total area under maize is less, Malawi has the largest maize production of the three countries with currently about 3.3 million tons per annum. The Wet Upper Mid-Altitude maize environment (MME A) covers almost half of the area (48%). Wet Lower Mid-Altitude (MME B) covers 23%, Dry Lowland (MME E), covers 18% and Highland (MME F) covers 11%. Mzimba, the farming systems study area is located in MME A.

Zimbabwe has lower agro-ecological potential. Despite a larger area under maize, the country produces only about 1.1 million tons of maize per annum. Dry lowlands (MME E) cover 30% of the area, Wet Upper Mid-Altitude (MME A) covers 26%, Dry Mid-Altitude (MME C) covers 21% and Wet Lower Mid-Altitude (ME B) covers 20%. Most of the maize in Zimbabwe is produced in MMEs C (35%), A (26%) and E (28%). It is important to note that the drylands (MME E and C), which are of relatively low agro-ecological potential for maize production, cover about half of the land in mixed crop systems and produce large quantities of maize. The study area in Nkayi is located in MME C.

In Mozambique land use is comparatively extensive and maize production is only about 0.4 million tons per annum. The country has large agro-ecological areas of high potential with Wet Lowlands (MME D) covering 48% of the area. Dry Lowlands (MME E, 28%) are also common, and smaller areas are with Wet Lower Mid-Altitude (MME B, 14%) and Wet Upper Mid-Altitude (MME A, 8%). Maize coverage is on average only 16%, but in few pockets with maize coverage goes up to 61%. Most maize is produced in MME D

(40%) and MME A (24%). The study area in Changara is located in MME E.

3.1.2. Recommendation domains for improved dual-purpose maize cultivars

The landscape analysis illustrates that biomass production and demand are also differently distributed across the three countries. Large areas in Malawi show high livestock and human population densities and high cropping densities (Table A.1). High livestock densities are found in 44% of the area, high human population density in 76% of the area and high cropping density in 58% of the area. The most common RDs are LHH (27%), followed by HHH (19%), HHL (15%) and LHL (15%). Highest demand for dual-purpose maize can be expected in MME A and MME B, which sustains more than 75% of the country's ruminants and human population. MME A and B also produce more than 70% of the maize, coverage of cropland with maize is around 50%. In both MEs, RD LHH produces most maize and residue biomass, but livestock population densities are comparatively low, resulting in large potential volumes of maize residue surplus (Tables A.1 and A.2). The study case in Mzimba has high livestock and human population density, and high cropping density (HHH).

In Zimbabwe, human and cropping densities are lower than in Malawi with only 28% of the land having high human population densities and with only 13% having high cropping density. In contrast, livestock density in Zimbabwe is high in about 72% of the country. Most common are RDs HLL covering 43% of the area followed by LLL (21%) and HHL (19%). These RDs fall to a large extent into the dryland areas (MME E and C, with RDs HLL, LLL and HHL each >20%). Traditionally rangelands sustained livestock production in these areas; with cropland expansion there is now an important gap to supplement livestock nutrition. Nkayi represents
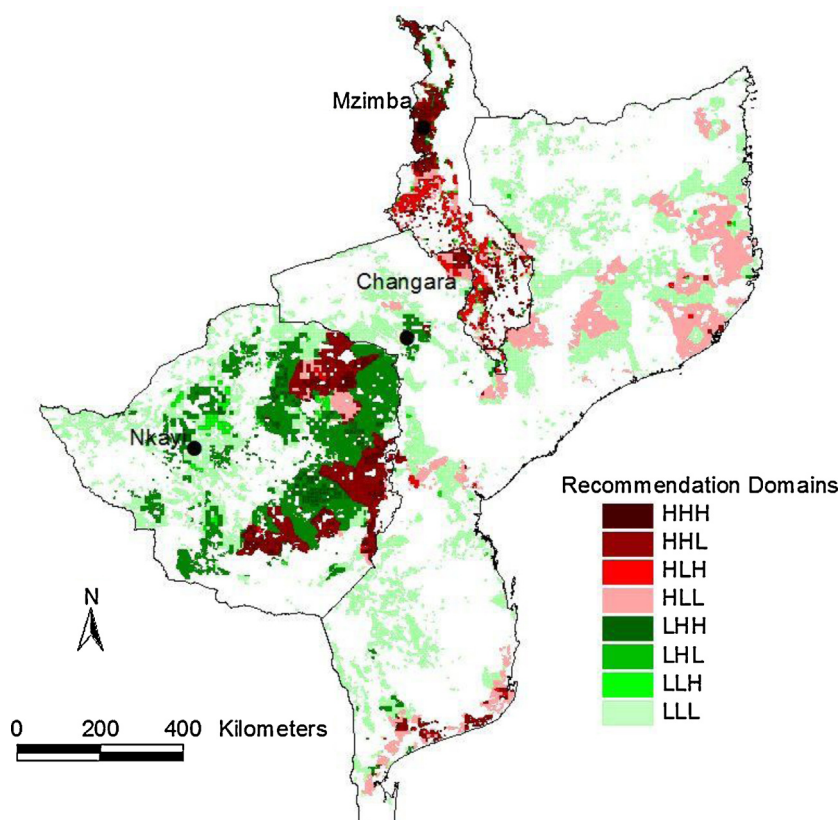
Fig. 3. Recommendation domains for maize based on livestock numbers, human population and cropping intensities in areas with mixed crop-livestock systems in Malawi, Zimbabwe and Mozambique and at the selected field project sites in each country. (1) Abbreviations: HHH (High livestock density, High human population density, High cropping density), HHL (High livestock density, High human population density, Low cropping density), HLH (High livestock density, Low human population density, High cropping density), HLL (High livestock density, Low human population density, Low cropping density), LHH (Low livestock density, High human population density, High cropping density), LHL (Low livestock density, High human population density, Low cropping density), LLH (Low livestock density, Low human population density, High cropping density), LLL (Low livestock density, Low human population density, Low cropping density). (2) Note: White areas are those with land use others than mixed crop livestock systems.

Data sources: http://www.fao.org/ag/againfo/resources/en/glw/home.html (mixed systems, livestock populations), http://beta.sedac.ciesin.columbia.edu/gpw (human populations); http://mapspam.info/2012/01/spam2000v3-0-6 (crop production).

a dryland area (MME C), even though with low livestock and low human population densities and low cropping density (LLL).

In Mozambique, only 5% of the land has high livestock density whereas high human population and 2% of the land by high cropping density characterize 41% of the land. The wet and dry lowlands (ME D and E) seem to have a comparatively greater potential for dual-purpose maize, since more than 70% of the country's livestock are found here. They cover 73% of the area with mixed crop-livestock systems and about two-thirds of the country's maize is grown there. The largest RDs are LLL (56%) and LHL (37%), and cover large parts of MME D and E. Like in Zimbabwe, there could be a demand for maize residues if other feeds are not available. Changara represents such an important livestock area in MME E and in RD LLL.

3.1.3. Rangeland and cropland biomass

The analysis of biomass production on range- and croplands illustrates lowest total NPP in southern Zimbabwe and Mozambique and an increase in northern direction (Fig. 3). As expected, NPP is higher in Malawi compared to Zimbabwe and Mozambique. Due to larger area share, however, the rangelands produce more biomass in Mozambique and Zimbabwe (17.8 and 7.5 Mio t, respectively) as compared to Malawi (1.0 Mio t). Part of this biomass can be used for livestock feeding (Table 1).

At the study sites, the NPP assessment confirms higher total biomass (crop and rangelands) in Mzimba, Malawi (7.4 t/ha),

as compared to Changara, Mozambique, and Nkayi, Zimbabwe (6.2 t/ha and 5.3 t/ha, respectively, Fig. 4). In terms of biomass available to feed livestock, Mzimba has more crop residues as compared to Nkayi and Changara (0.6 t/ha, 0.3 t/ha, 0.2 t/ha, respectively). The biomass from rangelands is however higher in Changara and Nkayi as compared to Mzimba (0.8 t/ha, 0.6 t/ha, 0.3 t/ha, respectively), owing to the higher percentages of rangelands as indicated by Ramankutty et al. (2008). However, in Changara and Nkayi the inter-annual variability is also higher as compared to Mzimba, illustrating higher risk in production and feed availability (Fig. 5).

Comparison of the potential biomass production from rangelands and croplands in relation to the estimated livestock feed demand is summarized in Table 1; Table A.2 provides a more detailed overview on the potential biomass availability per livestock unit in RDs and MMEs. Accordingly, Mozambique, Zimbabwe and Malawi produce around 18.9, 9.8 and 3.1 Mio tons of biomass from rangeland and croplands for potential livestock feeding, respectively (Table 1). In relation to the estimated livestock units, however, Malawi has on average more feed available (9.7 t/TLU) than Mozambique (7.3 t/TLU) and Zimbabwe (4.4 t/TLU). Across countries, biomass seems at surplus, especially in Malawi and Mozambique. As Table A.2 column B/U illustrates, biomass surplus in relation to potential livestock voluntary feed intake is found especially in RDs with low livestock density and high or low

Table 1
Area sizes (A) and total biomass (B) availability from rangelands (R) crop residues (C) and maize stover (S) and biomass availability relative to a tropical livestock unit (TLU, U) for Recommendation Domains in Malawi, Zimbabwe and Mozambique.

RDs[a]	Malawi							Zimbabwe							Mozambique						
	A	R	C	S	C:B	S:C	B/U	A	R	C	S	C:B	S:C	B/U	A	R	C	S	C:B	S:C	B/U
	'000 km²	'000 t			%		t	'000 km²	'000 t			%	'	t	000 km²	'000 t			%		t
HHH	6	151	587	162	80	28	9	7.9	351	364	198	51	54	6	0.5	22	83	12	79	14	20
HHL	4.6	114	37	13	25	35	2	34.5	1260	234	118	16	50	3	4.3	283	41	20	13	49	5
HLH	1.6	69	114	39	62	34	6	9.8	460	880	349	66	40	9	0	3	8	0	73	0	9
HLL	1.3	42	6	2	13	33	2	75.9	2924	295	211	9	72	3	3.2	261	17	6	6	35	6
LHH	8	337	1127	204	77	18	26	0.9	59	45	6	43	13	14	1.9	158	102	37	39	36	24
LHL	4.6	129	38	16	23	42	6	5.6	389	40	11	9	28	13	56.4	5902	367	129	6	35	42
LLH	2.1	117	216	70	65	32	28	5.1	298	236	84	44	36	15	0.9	77	61	11	44	18	81
LLL	2.5	68	11	5	14	45	6	36.8	1727	212	124	11	58	9	85.9	11,061	491	215	4	44	79
TOTAL	30.7	1027	2136	511	68	24	10	176.5	7468	2306	1101	24	48	4	153.1	17,767	1170	430	6	37	7

[a] Abbreviations: HHH (High livestock density, High human population density, High cropping density), HHL (High livestock density, High human population density, Low cropping density), HLH (High livestock density, Low human population density, High cropping density), HLL (High livestock density, Low human population density, Low cropping density), LHH (Low livestock density, High human population density, High cropping density), LHL (Low livestock density, High human population density, Low cropping density), LLH (Low livestock density, Low human population density, High cropping density), LLL (Low livestock density, Low human population density, Low cropping density).

Data sources: http://www.fao.org/ag/againfo/resources/en/glw/home.html (mixed systems, livestock populations); http://www.geog.mcgill.ca/~nramankutty/Datasets/Datasets.html (rangelands, cropland); http://sedac.ciesin.columbia.edu/gpw (NPP); http://mapspam.info/2012/01/spam2000v3-0-6 (crop production).

cropping density (LHH, LLH, LLL), against biomass deficits in RDs with high livestock density and low cropping density (RDs HLL and HHL).

Out of the potential biomass available for livestock, Malawi produces 2.1 Mio t biomass from croplands and about 1.0 Mio t biomass from rangelands, the greatest proportion from croplands in the cross-country comparison (Table 1). Maize residues supply between 1.3 and 5.8 t residue biomass per TLU. Potential biomass surplus is substantial at sites with high cropping density and low livestock density. Potential feed deficits were in RDs HHL (1 t/TLU) and HLL (2 t/TLU), where livestock density is high against low cropping density.
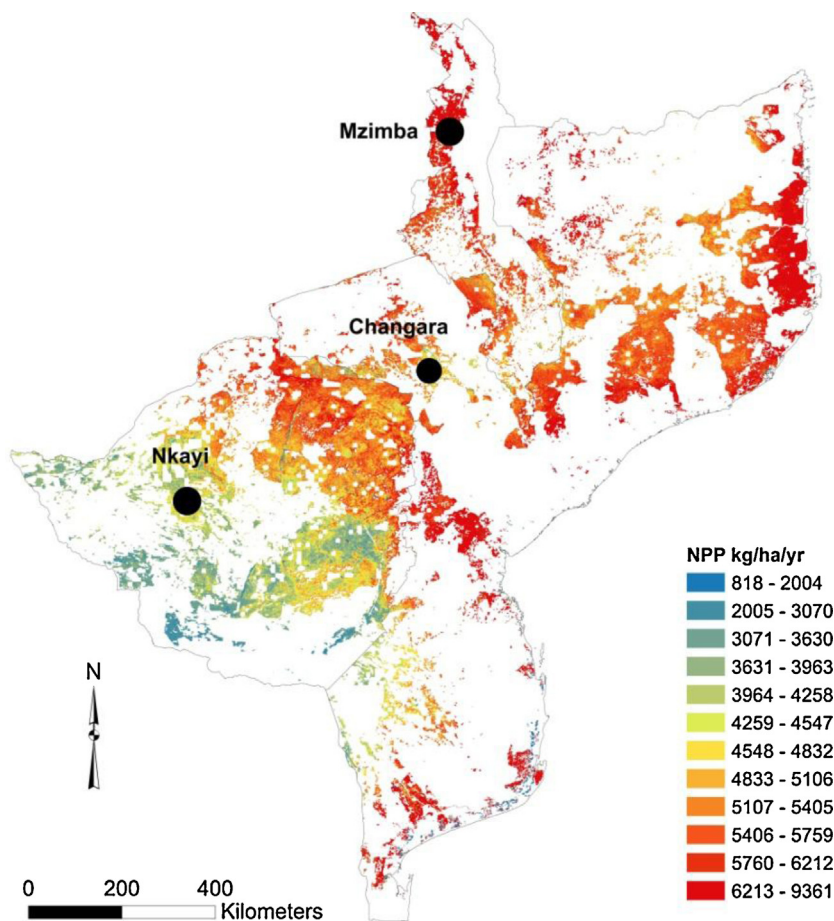
Fig. 4. Distribution of total Net Primary Productivity in areas with mixed crop-livestock systems in Malawi, Zimbabwe and Mozambique and at the selected field project sites in each country. (1) Abbreviations: NPP (Net Primary Productivity). (2) Note: White areas are those with land use others than mixed crop-livestock systems.
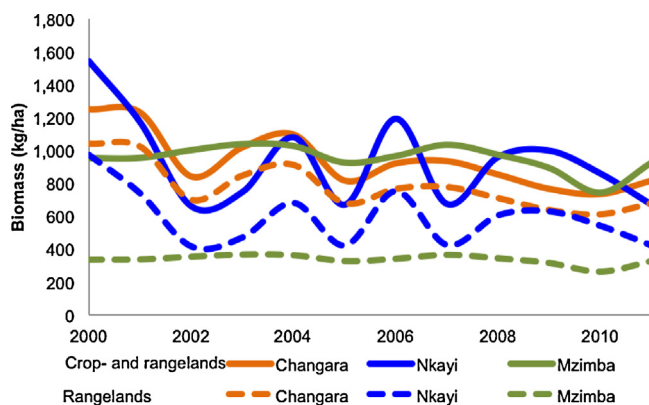*Data sources*: http://www.fao.org/ag/againfo/resources/en/glw/home.html (mixed systems); http://sedac.ciesin.columbia.edu/gpw (NPP).

Fig. 5. Annual biomass production from crop and rangelands at the selected field project sites in each country.

Data sources: http://www.fao.org/ag/againfo/resources/en/glw/home.html (*mixed systems*); http://www.geog.mcgill.ca/~nramankutty/Datasets/Datasets.html (rangelands, croplands), http://sedac.ciesin.columbia.edu/gpw (NPP).

In Zimbabwe the rangelands produce substantially more biomass to feed livestock (7.5 Mio t) and croplands produce less (2.3 Mio t). In recommendation domains with high cropping density crop residues contribute between 43 and 66% to total biomass. The contribution of maize residues to crop residues varies between 13 and 54% and maize residues supply between 0.8 and 2.4 t biomass per TLU. Maize residues dominate and contribute up to 72% to crop residue biomass, but only between 0.2 and 0.6 t biomass per TLU.

Like Zimbabwe, rangelands in Mozambique (17.8 Mio t) produce more biomass in comparison to crop residues (1.2 Mio t). Crop residues contribute between 39 and 79% to the biomass in the areas with high cropping density, and less than 15% in areas with low crop intensity. Up to 50% of the crop residue biomass stems from maize residues; relatively high proportions are found in areas with high as well as low cropping density.

3.2. Farming system analysis

The study sites fall in RDs with different levels of intensification and management and this is expected to influence the demand for maize residues as feed. Mzimba in Malawi is in an area with high agro-ecological potential (MME A) and in RD HHH, with high predicted feed demand by livestock and high levels of biomass production. We expected to find highly integrated crop-livestock production, and high demand for maize residues as incentive for adopting dual-purpose maize. Nkayi in Zimbabwe and Changara in Mozambique, both are in areas with lower agro-ecological potential, and in RD LLL, relatively extensive systems with high risks in production and livestock more important. Table 2 presents management characteristics for the different farming systems.

In Mzimba all households produce maize, but the average cultivated land per household is small (<1 ha). In contrast, only slightly more than 50% of the households have livestock and herd sizes are rather small. For maize production, farmers invest in high rates of inorganic fertilizer (>100 kg/ha) and almost half of the farmers use improved seeds. They attain relatively high maize yields, around 1.5 t/ha, and are able to sell some surplus maize. Daily milk yields at about 1 l per cow are low and cattle losses through mortalities are three times higher than consumptive off-takes. Despite high livestock densities at landscape level and the estimated biomass production from maize residues being also relatively high (1.9 t/ha; 1.2 t/TLU), farmers make relatively limited use of maize residues as livestock feed. Farmers in Mzimba have excess maize residues and also lack awareness on improved uses of maize residues. Feed quantity seems not to be a limiting factor to improve livestock production. Feed quality is the most limiting factor.

In Nkayi close to 100% of the household engage in maize production with maize fields per household almost twice the size of those in Mzimba. Average maize yields are less than 1 t/ha. Inorganic fertilizer application is low (<10 kg/ha), still many households use improved seeds. About three quarters of the households keep livestock with average herd sizes of 3.9 TLU. These farmers make greater use of the livestock functions and also support crop production. Cattle productivity is however low as reflected in high mortality rates around 15%, against a consumptive off-take of less than 2%; milk yields are also low. Dry season feed shortages are pronounced. Fewer crop residues are available than in Malawi, about 1.2 t/ha and only 0.3 t/TLU. Farmers estimated that crop residues contribute about 40% of livestock feed intake during the dry season. Apart from cattle grazing residues in situ (60%), farmers have started to collect and store maize residues. They feed about 20% of the maize residues to livestock at the kraal during the dry season. Fodder technologies are not common.

In Changara, less than half of the households produce maize. Only about a third of the households keep livestock, and herd sizes of those with livestock are comparatively large (5.5 TLU). Average maize yields are extremely low (<400 kg/ha). Livestock off-takes above 10% confirm the important role of livestock for cash income. Farmers also indicate severe feed shortages during the dry season. Cropping density is less as compared to Malawi and Zimbabwe, and more rangeland biomass is available. Livestock feed to about 75% on rangelands during the dry season. Maize residue production at about 0.6 t/ha provides less than 0.1 t of residues per TLU. These residues are largely grazed in situ.

3.3. Cultivar analysis

This section looks at genetic variations of maize cultivars in grain and residue quantity and residue fodder quality as reflected by ME content to explore the potential of improving feed resources with dual-purpose maize cultivars. Feed resources can be improved by increasing quantity and quality. However, the former is only useful when livestock consumes the additional biomass, i.e. voluntary feed intake can respond, which depends on quality aspects of the additional feed resource.

3.3.1. Variability in maize cultivars for grain and residue yield and residue fodder quality

Variations in grain and residue yields and residue fodder ME that CIMMYT Southern Africa has been targeting for higher potential areas (advanced hybrids) and for lower potential areas (landraces) are presented in Table 3. Major differences between landraces and advanced hybrids were in grain yields and corresponding harvest index (HI), which was 0.35 and 0.42 in landraces and advanced hybrids, respectively. Cultivar-dependent variations were substantial in ME yield per ha – the product of residue yield and residue ME content – where ME yields per ha varied 5.7-fold and 2.3-fold in landraces and hybrids, respectively, largely as a result in variations in residue yields. Still, residue ME content varied by about 1 MJ/kg in landraces and by 0.74 MJ/kg in hybrids. There was no significant ($P > 0.05$) relationship between residue fodder ME and grain yields.

4. Discussion

4.1. Multi-level landscape analysis to better assess the potential for dual-purpose maize

A nested and spatial explicit landscape analysis complemented by a farming system analysis allows a better assessment of the potential for dual-purpose maize in southern Africa. The landscape

Table 2
Selected indicators for maize and cattle production at the field project sites in each country.

	Units	Mzimba		Nkayi		Changara	
		Mean	SD	Mean	SD	Mean	SD
Cropland, maize grain and residue production							
Total cropland	ha/HH	1.3	1	1.9	1.3	1.5	1.1
HH with maize	% HH	100		99.4		41.3	
Maize fields	ha/HH	0.8	0.5	1.4	1.1	0.7	0.6
Maize cropping pattern							
Fertilizer	kg/ha	117.9	60.9	9.7	29.3	0	0
Org. manure	kg/ha	63.4	149.6	479.3	1170.3	0	0
Hybrid seed	% HH	42.5		41.5		13.6	
Draft power	% HH	3.8		96.2		50	
Grain yields	kg/ha	1595.6	1141.7	756.3	858.0	364.8	235.3
Proportion sold	%	10.2	14.4	6.7	13.7	2.1	7.8
Residue availability	kg/ha	1882.9	1225.3	1248.2	956.2	661.4	349.0
	kg/TLU[2]	1205.0		327.5		79.5	
Residue uses							
Grazing livestock	%	55.5	31.1	64.8	33.4	76.5	34.7
Mulching	%	19.2	27.9	6.7	17.6	8.8	6.6
Burnt	%	17.9	27	2.7	12.2	7.3	15.4
Kraal feeding	%	1.1	8.1	20.3	28.1	3.6	16.6
Herd ownership and cattle production							
HH with ruminants	% HH	53.1		74.4		34.4	
Herd sizes	TLU/HH	1.8	3.4	3.9	5.6	5.5	7.3
Dry season feeding							
Rangelands	%	60.3	22.1	61.1	24.3	75.4	11.3
CR grazed in situ	%	24.6	22.5	15.7	20.3	22.3	11
CR collected and fed		12.1	22.4	23.3	24.7	2.3	5.7
Herd dynamics							
Mortality	%	9.7	20.1	14.6	19.3	12.9	19.5
Sales	%	0	0	0.4	2.7	12.6	16.3
Consumption	%	2.9	7.3	1.1	3.8	0	0
Milk yields	l/day	1.3	0.6	1.3	0.6	1.5	0.7

(1) Total kg residues per total TLU. (2) Abbreviations: HH (household), CR (crop residues).
Data source: Homann-Kee Tui et al. (2012).

analysis confirms the results of Notenbaert et al. (2012), specifically: (i) there is a promising niche for dual-purpose maize to increase feed availability in large areas of the selected countries and (ii) there is a high spatial variability in the demand for and supply of maize residues, across and within the selected countries in southern Africa, reflecting that the potential for dual-purpose maize is heterogeneous. The spatial variability illustrated by the present study substantiates the need for better targeting maize development interventions in southern Africa (Williams, 1994; Omamo et al., 2006; Pender et al., 2006). Dual-purpose maize can

be targeted to areas with higher level of agricultural intensification and crop-livestock integration (half of the land with mixed crop-livestock systems in Malawi, parts of northeast Zimbabwe, and few areas in Mozambique) and more dry and lowland areas with extensive agriculture but large populations of livestock (half of Zimbabwe and Mozambique).

The present study modified the methodology of Notenbaert et al. (2012) by assessing the contribution of rangeland to feed resources since rangelands provide a large share of the feed resources in southern Africa. Including rangelands in the analysis could suggest

Table 3
Grain and stover traits in advanced maize hybrids and in maize landraces from Zimbabwe.

Trait	Units	Mean	Range	P > F
Landrace cultivars (n = 14)				
Grain yield[−1]	(kg/ha)	1442	192–3186	0.002
Stover yield	(kg/ha)	2660	1267–6167	0.0001
Nitrogen	(%)	0.64	0.51–0.86	0.01
Neutral detergent fiber	(%)	76.6	72.9–79.3	0.02
In vitro digestibility	(%)	48.0	44.5–50.4	0.01
Metabolizable energy	(MJ/kg)	7.00	6.40–7.43	0.02
Metabolizable energy yield	(MJ/ha)	17,102	7290–41,725	0.0001
Advanced hybrid cultivars (n = 15)				
Grain yield[a]	(kg/ha)⁻	2259	1309–3837	0.51
Stover yield	(kg/ha)	3070	2250–4667	0.0007
Nitrogen	(%)	0.53	0.41–0.65	0.27
Neutral detergent fiber	(%)	75.9	73.8–77.7	0.40
In vitro digestibility	(%)	47.8	46.3–50.5	0.03
Metabolizable energy	(MJ/kg)	6.95	6.60–7.34	0.08
Metabolizable energy yield	(MJ/ha)	20,503	14,308–32,293	0.0003

Data source: CIMMYT Southern Africa trials (Vivek, unpublished). *P > F* values indicate statistical differences/no differences for given traits between cultivars.

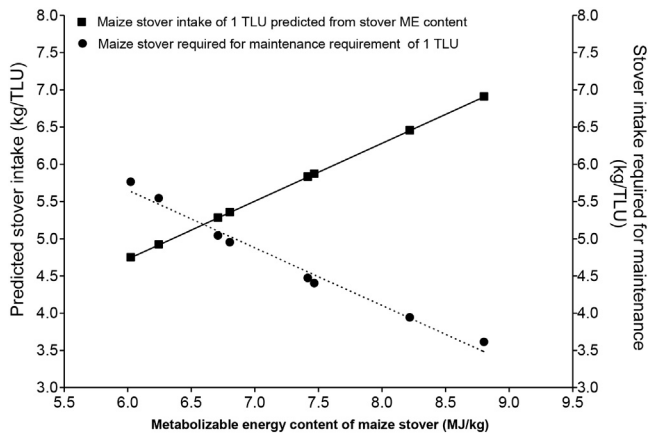[a] Only two field replications available.

Fig. 6. Relationships between maize stover metabolizable energy content and voluntary stover intake and stover requirements to provide for maintenance requirements per TLU (Tropical Livestock Unit). Stover intake was predicted from the relationships described by Ravi et al. (2013).

large surplus of biomass relative to TLU, notably in the extensively used RDs (Table 1). However, much of this biomass from rangelands might actually be of limited use since seasonal variability in its feed quality results in a decline in ME (Bredon et al., 1987) and protein digestibility (Holness, 1999), which restricts livestock voluntary feed intake (see also discussion below on maize stover intake in Section 4.2). In addition, water constraints and limited rangeland management, reported during focus group discussions at the sites, might restrict livestock from moving to areas with available feed resources (Homann-Kee Tui et al., 2012). Feed markets, that could also play a buffering role in times of feed deficits, are developed in the commercial farming sector, but are of far distance and difficult to access for most smallholder farmers. Under such conditions, dual-purpose maize residues can still make an important contribution to livestock feeding, specifically when the quality of the maize residue is superior to the fodder quality from rangelands (Section 4.2).

The landscape approach adapted in this paper can help to identify socio-ecological niches for technologies to improve feed quality and quantity, specifically dual-purpose maize varieties (Ojiem et al., 2006). Areas where investments in feed quality improvements are likely to pay off, and those that are prone to face greater feed deficits can be identified. This needs to be combined with more process oriented research and further contextualization of the trajectories for agricultural development (i.e. participatory discourse with farmers, multi-stakeholder forums) to verify the real bottlenecks and opportunities that would influence the potential for specific dual-purpose maize varieties. Specific maize cultivars (quality/quantity) can then be targeted to RDs with different biomass demand and availability, having also considered supply from rangelands. This multi-level landscape approach is exemplified in Fig. 1 and can help to scale out dual-purpose crop technologies.

4.2. Opportunities and limitations for improving feed resources in Zimbabwe, Malawi and Mozambique through choice of maize cultivars

Dual-purpose maize cultivars can mitigate feed shortages by increasing the available feed quantity. However, it is important to realize that increasing maize residue quantity will have impact only if the residue availability is below the level of voluntary feed intake of livestock for feed stuff of a given quality. Livestock respond to increasing biomass feed quality with increasing voluntary feed intake (Van Soest, 1994). These relations are exemplified in Fig. 6 using regression equations from Ravi et al. (2013) that related

maize residue ME content to residue intake per TLU (Fig. 6 solid line and square symbols). In addition, Fig. 6 shows the amount of maize residue intake required to meet the maintenance requirements of a TLU (equation from McDonald et al., 2011). At a maize residue ME content of about 6 MJ/kg VFI of a TLU would be about 4.7 kg/day (solid line, full square) whereas about 5.7 kg/day would be needed to provide for the TLU maintenance requirement (dashed line, full circles). Increasing residue quantity under this condition would only be useful if actual intake is below 4.7 kg (or more generally below the intakes indicated by the solid line). Otherwise only cultivars with higher residue quality would help the TLU to get closer to meeting its maintenance requirement or provide sufficient ME for live weight gain and/or milk production (intersect of solid and dashed line at about 6.6 MJ ME/kg). In both maize landraces and hybrids, residue ME at the higher end of the quality range (i.e. ≥7.34 MJ ME/kg, Table 3) would provide sufficient energy for the maintenance requirement and provide sufficient ME for about 200 g of live weight gain, assuming an energy content of live-weight gain of 11.4 MJ/kg. However, none of these landraces and advanced hybrids were specifically investigated for dual-purpose traits before the current one time spot-on analysis (Vivek, personal communication). Exploitable variations in maize residue traits will likely be greater after inclusion of phenotyping for maize stover quality in the investigation of larger germplasm pools. For example Zaidi et al. (2012) report ranges in maize residue ME in hybrids of 6.67–8.17 MJ/kg for South Asia and Berhanu et al. (2013) reported mean ranges of 7.8–9.2 MJ ME/kg in maize hybrids tested across multi-locations in Ethiopia. Thus dual-purpose maize cultivars with superior residue fodder quality compared to currently available cultivars might soon be available in Southern Africa.

Relating above considerations to the means and ranges in maize residue qualities in CIMMYT landraces and hybrids (Table 3) it can be calculated that, depending on maize residue ME content, 4.47 kg–5.36 kg would be required per day and 1632–1956 kg per year to provide the maintenance requirement for 1 TLU, see Table 4. This amount is far more than the total maize residue availability per TLU at Mzimba, Nkayi or Changara, which was of 1205, 328 and 80 kg/TLU, respectively (Table 2). However, maize residues will be particularly important as dry season feed for about 3 months with a requirement of approximately 400–500 kg of maize residue per TLU. These considerations suggest that improved maize residue fodder quality will be more relevant in sites such as Mzimba whereas maize residue quantity might take precedence over quality in sites such as Nkayi and Changara. However, in all sites, farmers' decisions about use of maize residues as fodder will be affected by the availability and the quality of biomass from rangelands. However, given the fact however that farmers at the sites often sold livestock to buy food when crop harvests were insufficient, boosting maize yields still seems to be a good option, best through a combination of improved crop management and technologies for enhancing crop-livestock integration, including dual-purpose crops of higher biomass and feed value. Dual-purpose maize can contribute to such positive feedbacks loops (ICRISAT, 2012).

4.3. Pressures and trade-offs in space

The spatial variability in feed supply and demand implies different pressures and trade-offs in maize residue uses across countries and sites. Livestock feed is a major use of maize residues in mixed crop-livestock systems (Valbuena et al., 2012). Therefore, when looking at other uses of residues (e.g. soil mulch, household fuel and construction), pressures and trade-offs for using maize residues are high in areas where livestock is an important livelihood activity and alternative resources are not available or affordable. This study indicates potential high pressures and trade-offs in maize residue

Table 4
Daily and yearly requirements of maize stover for the provision of the energy maintenance requirements in maize landraces and hybrid cultivars of different qualities.

	Units	Landraces			Advanced hybrids		
		ME_{Mean}	ME_{Min}	ME_{Max}	ME_{Mean}	ME_{Min}	ME_{Max}
Stover ME content	(MJ/kg)	7.0	6.40	7.43	6.95	6.60	7.34
Stover intake required for maintenance	(kg/d/TLU)	4.81	5.36	4.47	4.85	5.16	4.54
Stover intake required for maintenance	(kg/y/TLU)	1756	1956	1632	1767	1883	1657
Stover intake predicted by ME content	(kg/d/TLU)	5.26	4.73	5.64	5.22	4.91	5.56
Stover required per year at predicted intake	(kg/y/TLU)	1920	1726	2059	1 905	1792	2029

Data source: CIMMYT Southern Africa trials; own calculations.

use in Nkayi (Zimbabwe) and Changara (Mozambique) as a result of the livestock population, the low productivity of rangelands and limited investments in fodder technologies, particularly at the end of the long dry season. Even though the amount of biomass from crop residues is also low, farmers rely mainly on these residues to feed livestock during that specific period. Potential pressures and trade-offs in maize residue uses are relatively low in areas with high biomass production, despite relatively high livestock densities, e.g. Mzimba (Malawi).

Promising options to alleviate potential pressures and trade-offs depends on the factors and processes at different scales. For instance, the increasing growth of the demand for livestock products in southern Africa (i.e. beef and milk) represent a clear opportunity to intensify crop-livestock production and enhance the livelihood of poor households (Delgado et al., 1999; World Bank et al., 2013). If governments were to capitalize on local production systems and link farmers to trade to these markets, this will require more feed, increasing the trade-offs (Baltenweck et al., 2003). On the supply side, the expansion of croplands of low productivity into rangelands, associated with degradation and weak control in access to land, reduces alternative feed resources and this also increases the trade-offs. The lack of access to livestock markets and alternative saving and investment options actually influence farmers' decision to keep large numbers of animals despite feed deficit, and contribute to high pressure on trade-offs (Moll, 2005; Descheemaeker et al., 2011).

Improving the targeting and adaptation of dual-purpose maize varieties and associated improvements in crop management, post-harvesting, storage and feeding is one promising option to supply more quantity and quality feed in a cost-effective way, using the same labor, land and input investments as for maize grain production. Dual-purpose crops providing higher and more nutritious biomass are seen as a way to compensate for rangelands converted to croplands and poor quality of remaining rangelands (Sibanda et al., 2011). Dual-purpose maize can be introduced in relatively short term through the same channels that have promoted maize grain production and help farmers to achieve higher outputs per unit land, making greater use of the synergies between crops and livestock, especially where alternative feed options are limited (Thorne et al., 2002; Lenné et al., 2003; Tarawali et al., 2011).

The use of dual-purpose maize is only part of a set of promising technologies to improve the productivity and sustainability of mixed crop-livestock systems. Alternatively, diversifying cropland by introducing fodder technologies, e.g. silage production, dual-purpose legumes, fodder crops could also increase crop production and feed availability per unit land (Holness, 1999; Masikati, 2011). In addition, there is need for better rangeland management. Dual-purpose maize could help to reduce the pressure on this feed resource and/or supplement its degradation. This would however need substantial skills and institutional change for better regulating access to and management of the communal resources. To promote all these alternative technologies one needs to consider the poor access to these technologies, farmers' preferences for cereals as staple food, the high risk in production and low market participation.

5. Conclusions

This paper develops a multi-level approach for assessing the potential of dual-purpose maize technologies in southern Africa. The assessments show that there is a large potential for promoting dual-purpose maize in southern Africa. The nested landscape analysis illustrates that the potential demand for dual-purpose maize varies across and within countries and maize improvement interventions need to clearly recognize such heterogeneity. The spatial stratification by MME and demand and supply factors (RDs) can be used as simple raster for identifying areas with similar probability of dual-purpose maize adoption and extrapolation to areas with similar conditions. It is however not sufficient to assess the potential for dual-purpose maize cultivars in those areas. Further biomass assessments are required to capture the real feed supply from rangelands. Promoting dual-purpose maize as a technology that enhances productivity per unit land needs to also consider the context-specific factors and dynamics at play. From the country comparison we conclude that a higher agro-ecological potential as well as a higher demand for livestock products does not directly translate to higher demand for dual-purpose maize. A critical message is that dual-purpose maize can supply higher quality biomass at higher levels of agricultural intensification. Dual-purpose maize is equally important for the dryland areas, where there is strong presence of livestock against limited biomass quality and low maize yields. Though this integrated approach, different types of improved dual-purpose maize cultivars can be targeted to sustain intensification processes in different environments and institutional contexts.

Appendix A.

Table A.1.
Table A.2.

Table A.1

Summary statistics on area sizes, livestock (TLU, Tropical Livestock Units) and human populations, maize production (MT, Megatonnes) and percentage cropland with maize across Malawi, Zimbabwe and Mozambique, per Mega Environment and Recommendation Domain.

RDs/MEs[a]	Malawi					Zimbabwe					Mozambique				
	Area ('000 km²)	TLU ('000)	Human pop. ('000)	Maize prod. ('000 MT)	% cropland with maize	Area ('000 km²)	TLU ('000)	Human pop. ('000)	Maize prod. ('000 MT)	% cropland with maize	Area ('000 km²)	TLU('000)	Human pop. ('000)	Maize prod. ('000 MT)	% cropland with maize
A (Wet Upper Mid-altitude)															
HHH	3	53	195	1	51	2	35	115	0	38	0	3	19	0	37
HHL	3	66	220	0	45	8	104	338	0	37	1	13	73	0	65
HLH	1	21	14	0	49	5	66	126	1	48	0	0	0	0	46
HLL	1	15	19	0	47	23	333	628	1	33	0	4	5	0	53
LHH	3	21	242	12	50	0	3	20	0	24	1	4	42	0	65
LHL	2	10	129	0	56	4	25	191	0	31	6	21	300	0	49
LLH	1	4	17	0	51	1	7	22	0	42	0	0	3	0	60
LLL	0	2	8	0	50	4	26	90	0	29	5	7	91	0	42
Total	14	192	844	14	50	47	600	1530	3	35	13	52	533	1	49
B (Wet Lower Mid-altitude)															
HHH	1	10	59	0	57	2	33	84	1	60	0	1	4	0	65
HHL	0	6	27	0	60	6	106	286	0	37	0	3	20	0	56
HLH	0	2	4	0	53	1	13	31	0	36	0	0	0	0	43
HLL	0	3	4	0	51	18	258	494	0	25	0	3	3	0	41
LHH	3	16	174	10	47	0	2	12	0	32	0	3	25	0	61
LHL	2	11	121	0	60	1	3	26	0	23	10	22	497	0	37
LLH	1	3	12	0	53	2	12	47	0	20	0	0	2	0	57
LLL	1	3	12	0	47	5	31	113	0	29	10	12	154	0	34
Total	7	52	412	11	60	35	457	1092	2	30	22	43	705	1	32
C (Dry Mid-altitude)															
HHH	0	0	0	0	0	2	21	63	0	50	0	0	0	0	0
HHL	0	0	0	0	0	9	160	404	0	39	0	6	29	0	40
HLH	0	0	0	0	0	3	53	85	2	63	0	0	0	0	0
HLL	0	0	0	0	0	15	233	363	1	32	0	0	0	0	84
LHH	0	0	0	0	0	0	1	4	0	40	0	0	3	0	22
LHL	0	0	0	0	0	0	1	3	0	26	0	2	26	0	31
LLH	0	0	0	0	0	1	3	11	0	60	0	0	0	0	0
LLL	0	0	0	0	0	9	48	121	0	21	0	0	1	0	46
Total	0	0	0	0	0	38	519	1052	4	36	1	9	59	0	0
D (Wet Lowland)															
HHH	0	1	5	0	54	0	0	0	0	0	0	0	0	0	0
HHL	0	0	1	0	60	0	0	0	0	0	0	5	17	0	26
HLH	0	0	0	0	48	0	0	0	0	0	0	0	0	0	38
HLL	0	0	0	0	56	0	2	3	0	35	0	1	2	0	51
LHH	0	6	21	1	71	0	0	0	0	0	1	2	23	0	41
LHL	0	0	1	0	60	0	0	0	0	0	30	70	1502	1	24
LLH	0	1	3	0	50	0	0	0	0	0	0	0	7	0	38
LLL	0	0	0	0	71	0	0	0	0	0	42	65	1036	1	27
Total	1	8	32	1	0	0	2	3	0	0	73	143	2588	2	26
E (Dry Lowland)															
HHH	2	10	96	0	54	2	30	87	1	58	0	0	2	0	28
HHL	0	3	20	0	34	11	174	490	0	42	2	34	117	0	45
HLH	0	1	1	0	62	1	10	22	0	49	0	1	1	0	33
HLL	0	1	1	0	59	18	255	455	1	35	3	41	272	0	44
LHH	2	10	10	6	49	0	1	10	0	31	0	1	13	0	37
LHL	1	5	55	0	55	1	4	32	0	38	9	30	558	0	36
LLH	1	3	13	0	50	2	13	52	0	25	0	1	3	0	41
LLL	0	2	7	0	49	18	100	296	1	26	29	61	338	1	42
Total	5	35	202	6	62	52	586	1443	3	35	43	170	1303	1	41

Table A.1 (*Continued*)

RDs/MEs[a]	Malawi					Zimbabwe					Mozambique				
	Area ('000 km²)	TLU ('000)	Human pop. ('000)	Maize prod. ('000 MT)	% cropland with maize	Area ('000 km²)	TLU ('000)	Human pop. ('000)	Maize prod. ('000 MT)	% cropland with maize	Area ('000 km²)	TLU('000)	Human pop. ('000)	Maize prod. ('000 MT)	% cropland with maize
F (Highland)															
HHH	0	6	22	0	35	0	4	16	0	39	0	1	8	0	46
HHL	1	10	29	0	41	1	13	45	0	42	0	4	20	0	55
HLH	0	6	8	0	43	0	4	8	0	49	0	0	0	0	0
HLL	0	5	6	0	50	2	30	60	0	49	0	0	0	0	64
LHH	0	2	23	1	65	0	0	1	0	68	0	1	10	0	30
LHL	0	1	4	0	57	0	1	8	0	52	1	6	61	0	35
LLH	0	1	5	0	40	0	0	0	0	70	0	0	1	0	69
LLL	1	7	11	0	65	0	2	6	0	45	0	1	4	0	51
Total	3	38	108	1	35	4	54	144	0	35	2	13	104	0	18

Abbreviations: ME (Mega Environments), RD (Recommendation Domain), HHH (High livestock density, High human population density, High cropping density), HHL (High livestock density, High human population density, Low cropping density), HLH (High livestock density, Low human population density, High cropping density), HLL (High livestock density, Low human population density, Low cropping density), LHH (Low livestock density, High human population density, High cropping density), LHL (Low livestock density, High human population density, Low cropping density), LLH (Low livestock density, Low human population density, High cropping density), LLL (Low livestock density, Low human population density, Low cropping density).

Data sources: http://www.fao.org/ag/againfo/resources/en/glw/home.html (mixed systems, livestock populations), http://beta.sedac.ciesin.columbia.edu/gpw (human populations); http://mapspam.info/2012/01/spam2000v3-0-6 (crop production).

[a] RDs of the case study sites.

Table A.2

Summary Statistics on area sizes (A), total biomass (B) availability from rangelands (R) crop residues (C) and maize stover (S) and biomass availability relative to a tropical livestock unit (TLU, U) across Malawi, Zimbabwe and Mozambique, per Mega Environment and Recommendation Domain.

RDs/MEs[a]	Malawi							Zimbabwe							Mozambique						
	A ('000) km²	R ('000) t	C	S	C:B %	S:C	B/U t/TLU	A ('000) km²	R	C ('000) t	S	C:B %	S:C	B/U t/TLU	A ('000) km²	R ('000) t	C	S	C:B %	S:C	B/U t/TLU
A (Wet Upper Mid-altitude)																					
HHH	3	76	369	96	83	26	8	2	168	99	43	37	44	8	0	9	54	8	86	15	21
HHL	3	59	28	9	32	31	1	8	514	52	28	9	54	5	1	33	16	10	33	59	4
HLH	1	33	66	24	67	36	5	5	328	538	92	62	17	13	0	1	2	0	67	3	31
HLL	1	20	4	1	17	29	2	23	1176	138	81	11	59	4	0	13	2	1	13	49	4
LHH	3	107	462	13	81	3	27	0	25	17	1	40	4	13	1	52	24	16	32	65	18
LHL	2	36	16	7	31	43	5	4	275	31	6	10	20	12	6	304	30	18	9	59	16
LLH	1	33	66	21	67	32	25	1	78	96	13	55	13	24	0	10	12	3	55	21	75
LLL	0	23	4	2	15	54	12	4	251	21	14	8	68	10	5	601	33	16	5	49	86
Total	14	386	1015	172	72	17	7	47	2816	991	279	26	28	6	13	1023	174	71	15	41	23
B (Wet Lower Mid-altitude)																					
HHH	1	24	125	39	84	31	15	2	104	90	50	46	55	6	0	103	2	1	2	66	174
HHL	0	7	3	2	30	58	2	6	265	33	14	11	41	3	0	37	4	2	10	46	12
HLH	0	5	22	8	81	37	12	1	49	52	13	51	25	8	0	0	0	0	0	0	0
HLL	0	4	1	0	20	61	2	18	620	53	27	8	50	3	0	10	1	0	9	47	4
LHH	3	79	338	108	81	32	26	0	19	19	0	50	1	20	0	23	11	6	32	58	13
LHL	2	37	13	5	26	36	5	1	22	1	0	4	10	8	10	720	38	19	5	50	35
LLH	1	27	62	22	70	36	32	2	118	72	26	38	36	16	0	9	7	2	44	22	81
LLL	1	20	4	1	17	35	10	5	351	45	29	11	64	13	10	1318	54	26	4	49	113
Total	7	204	568	185	74	33	15	35	1549	366	159	19	43	4	22	2219	116	57	5	49	54

C (Dry Mid-altitude)

RD																					
HHH	0	0	0	0	0	0	0	2	71	68	43	49	64	7	0	0	0	0	0	0	0
HHL	0	0	0	0	0	0	0	9	226	63	30	22	47	2	0	12	3	1	20	50	2
HLH	0	0	0	0	0	0	0	3	67	255	221	79	87	6	0	0	0	0	0	0	0
HLL	0	0	0	0	0	0	0	15	509	0	0	0	0	2	0	0	0	0	0	100	0
LHH	0	0	0	0	0	0	0	0	6	5	4	45	77	18	0	0	0	0	0	2	2
LHL	0	0	0	0	0	0	0	0	5	1	0	17	46	11	0	10	1	0	9	14	6
LLH	0	0	0	0	0	0	0	1	32	18	17	36	91	15	0	0	0	0	0	0	0
LLL	0	0	0	0	0	0	0	9	410	45	27	10	59	9	0	5	0	0	0	58	25
Total	0	0	0	0	0	0	0	38	1325	455	341	26	75	3	1	27	4	2	13	38	4

D (Wet Lowland)

RD																					
HHH	0	2	6	3	75	58	12	0	0	0	0	0	0	0	0	0	7	0	100	2	0
HHL	0	0	0	0	0	82	3	0	0	0	0	0	0	0	0	32	3	0	9	6	7
HLH	0	0	1	1	100	75	5	0	0	0	0	0	0	0	0	0	0	0	0	50	0
HLL	0	1	0	0	0	50	6	0	3	0	0	5	82	2	0	5	0	0	0	47	3
LHH	0	15	36	12	71	33	8	0	0	0	0	0	0	0	1	75	24	11	24	45	58
LHL	0	1	0	0	0	70	6	0	0	0	0	0	0	0	30	4056	229	67	5	29	61
LLH	0	6	10	2	63	24	20	0	0	0	0	0	0	0	0	46	15	4	25	29	152
LLL	0	1	0	0	0	64	0	0	0	0	0	0	0	0	42	6817	289	122	4	42	109
Total	1	25	54	19	68	35	10	0	3	0	0	0	82	2	73	11,031	567	205	5	36	81

E (Dry Lowland)

RD																					
HHH	2	14	44	16	76	37	6	2	76	103	59	58	57	0	0	3	7	0	70	2	25
HHL	0	10	2	1	0	46	4	11	411	83	44	17	54	0	2	159	14	7	8	51	5
HLH	0	2	4	2	67	56	10	1	43	34	22	44	64	0	0	2	6	0	75	0	7
HLL	0	2	0	0	0	52	4	18	772	96	56	11	59	3	3	220	13	4	6	32	6
LHH	2	104	220	61	68	28	32	0	12	4	1	25	28	0	0	13	23	0	64	2	30
LHL	1	48	9	4	16	42	11	1	56	7	4	11	59	0	9	977	63	23	6	36	35
LLH	1	37	59	21	61	35	30	2	100	49	28	33	58	0	0	2	25	2	93	9	39
LLL	0	2	3	1	60	43	2	18	1049	97	52	8	53	0	29	2722	114	49	4	43	46
Total	5	220	340	106	61	31	16	52	2518	473	267	16	56	5	43	4098	265	85	6	32	26

F (Highland)

RD																					
HHH	0	10	43	8	81	18	9	0	9	4	2	31	58	3	0	2	14	2	88	17	12
HHL	1	9	4	1	0	29	1	1	34	4	2	11	58	3	0	68	1	0	1	31	19
HLH	0	10	21	4	68	21	5	0	3	0	0	0	63	1	0	0	0	0	0	0	0
HLL	0	6	1	1	14	36	1	2	88	7	5	7	75	3	0	2	0	0	0	77	5
LHH	0	14	71	10	84	14	42	0	0	0	0	0	7	3	0	2	20	3	91	16	24
LHL	0	2	0	0	0	53	6	0	4	0	0	0	61	7	1	24	5	3	17	53	5
LLH	0	9	19	3	68	18	21	0	0	0	0	0	0	0	0	1	1	0	50	1	20
LLL	1	3	1	0	25	60	0	0	37	3	3	8	81	24	0	27	2	1	7	55	32
Total	3	63	160	28	72	17	6	4	177	19	13	10	67	4	2	125	44	10	26	23	13

Abbreviations: ME (Mega Environments), RD (Recommendation Domain), HHH (High livestock density, High human population density, High cropping density), HHL (High livestock density, High human population density, Low cropping density), HLH (High livestock density, Low human population density, High cropping density), HLL (High livestock density, Low human population density, Low cropping density), LHH (Low livestock density, High human population density, High cropping density), LHL (Low livestock density, High human population density, Low cropping density), LLH (Low livestock density, Low human population density, High cropping density), LLL (Low livestock density, Low human population density, Low cropping density).

Data sources: http://www.fao.org/ag/againfo/resources/en/glw/home.html (mixed systems, livestock populations); http://www.geog.mcgill.ca/(nramankutty/Datasets/Datasets.html (rangelands, cropland); http://sedac.ciesin.columbia.edu/gpw (NPP); http://mapspam.info/2012/01/spam2000v3-0-6 (crop production).

[a] RDs of the case study sites.

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