DETERMINANTS OF SORGHUM BIOMASS USE FOR LIVESTOCK FEED ACROSS SORGHUM GROWING AGROECOLOGICAL ZONES IN ETHIOPIA †

[DETERMINANTES DEL USO DE BIOMASA DE SORGO PARA LA ALIMENTACIÓN DEL GANADO EN ZONAS AGROECOLÓGICAS DE CULTIVO DE SORGO EN ETIOPÍA]

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SUMMARY

Background. In mixed crop livestock farming systems in Ethiopia, sorghum stover and other crop residues are a strategic livestock feed resource. Farmer's decisions and intensity of use of sorghum stover for feed than other uses are closely associated with biophysical and socioeconomic characteristics. **Objective.** This study explores determinants of sorghum biomass uses for livestock feed in three major sorghum growing agroecological zones of Ethiopia. **Methodology.** Tobit and double hurdle models were run and likelihood ratio test was performed to select most suitable estimation technique. **Result.** Allocation of sorghum stover for feed showed a significant association with sorghum growing agro-ecological zones, highest in the lowland (86.73%) and the lowest in highland sorghum growing agroecological area (61.75%). Econometric model result revealed that among other factors; availability of feed from grazing and other crop residues had a negative effect on decision to use and intensity of use of sorghum stover for feed. Household's livestock ownership and family size had positive effects. **Implication.** Decision variables influenced household's decision and intensity on use of sorghum stover for feed at three major sorghum growing zone differently. **Conclusion.** Knowledge generated through this study may help any research and development efforts to enhance productivity of sorghum biomass for livestock feed and livestock improvement strategies.

Keywords: Agroecology; Crop residue; Econometric models; Feed resources; Sorghum stover.

RESUMEN

Antecedentes. En los sistemas agrícolas mixtos de ganado de cultivos mixtos en Etiopía, el rastrojo de sorgo y otros residuos de cultivos son un recurso estratégico para la alimentación del ganado. Las decisiones de los agricultores y la intensidad del uso del rastrojo de sorgo como pienso antes que otros usos están estrechamente relacionados con las características biofísicas y socioeconómicas. **Objetivo.** Este estudio explora los determinantes de los usos de la biomasa de sorgo para la alimentación del ganado en tres zonas agroecológicas principales de cultivo de sorgo en Etiopía. **Metodología.** Se ejecutaron modelos Tobit y de doble valla y se realizó una prueba de razón de verosimilitud para seleccionar la técnica de estimación más adecuada. **Resultados.** La asignación de rastrojo de sorgo para la alimentación mostró una asociación significativa con las zonas agroecológicas de cultivo de sorgo, la más alta en las tierras bajas (86.73%) y la más baja en el área agroecologica de cultivo de sorgo de las tierras altas (61.75%). El resultado del modelo econométrico reveló que, entre otros factores; la disponibilidad de alimento proveniente del pastoreo y otros residuos de cultivos tuvo un efecto negativo en la decisión de uso y la intensidad del uso del rastrojo de sorgo como alimento. La propiedad de ganado de los hogares y el tamaño de la familia tuvieron efectos positivos. **Implicación.** Las variables de decisión influyeron de manera diferente en la decisión y la

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intensidad de los hogares sobre el uso del rastrojo de sorgo como alimento en tres zonas principales de cultivo de sorgo. **Conclusión.** El conocimiento generado a través de este estudio puede ayudar a cualquier esfuerzo de investigación y desarrollo para mejorar la productividad de la biomasa de sorgo para la alimentación del ganado y las estrategias de mejora del ganado.
Palabras clave: Agroecología; Residuos de cultivos; Modelos econométricos; Recursos de alimentación; Rastrojo de sorgo.

INTRODUCTION

In Ethiopia, sorghum is regarded as a major cereal food crop, ranked second in total production, third in productivity per hectare, and in area cultivated (FAOSTAT, 2017). Nationally, sorghum production covers an area of 1.85 million hectare and engages approximately 4.96 million smallholder farmers in its production (CSA, 2018). The crop grows in the arid and semi-arid areas in dry lowland, humid lowland, intermediate and highland on the country's western, south western, north eastern, northern and eastern peripheries (Adugna and Bekele, 2013; Mindaye *et al.,* 2015). In these areas, mixed crop-livestock farming is the predominant agricultural system where subsistence farmers cultivate sorghum and raise livestock as their main sources of livelihood (Gebretsadik *et al.*, 2014; Derese *et al.,* 2018). Sorghum is cultivated for food and stover from sorghum is almost year-round animal feed (Mcguire, 2008; Gebretsadik *et al.*, 2014). For example, in the east and northeast Ethiopia, sorghum biomass provides feed for livestock starting in June as thinning of high population density until harvest in November (Dereje and Tesfaye 2008; Gebretsadik *et al.*, 2014). Livestock sector in this system has considerable economic and social importance (Makkar *et al.,* 2018). At household's level, livestock contributes up to 37% of the household incomes in such farming system (Gbremariam *et al.,* 2010). Moreover, livestock serve as draft power to plough cropping fields and the manure used to fertilize the farm (Powell and Hiernaux, 2004). The nutritive values of sorghum stover is generally low, CP contents is below 70 g/kg DM and NDF, ADF, cellulose and lignin contents ranged between 731 to 771, 474 to 512, 323 to 346 and 78.5 to 87.4 g/kg DM, respectively (Singh *et al*., 2007). A study by Torrecillas *et al.* (2011) also recorded mean NDF, ADF and ADL contents of 726, 462 and 81 g/kg DM for stover of different sorghum hybrids at physiological maturity. Although sorghum stover and crop residues in general are of poor quality because of the low nutrient density and high fibre content (Gelayenew *et al.,* 2016), their widespread availability and increasing importance and demand for livestock feed, marks them as a strategic feed resource in mixed crop-livestock farming system (Makkar *et al.,* 2018). A study by Tsigie *et al.* (2011) reported crop residues accounts up to 70% livestock feed in mixed crop-livestock farming systems. Moreover, in the context of global climate change, sorghum is likely to become more important due to its adaptability to high temperature, drought and salt tolerant. Furthermore, sorghum productivity is higher in drier areas with rainfall less than 650 mm, where other cereal stovers are not available for maintenance rations for cattle under such climatic conditions (Sanchez *et al*., 2002). However, several findings Ethiopia shows that scarcity of feed – both lack of adequate quantity and quality – remain most important constraints that farmers in mixed crop-livestock system faces, particularly in long dry season (Mengistu *et al.,* 2010). Moreover, the use of crop residue for other purposes (fuel, construction material, income and mulching) (Valbuena *et al.,* 2015) aggravated the situation.

In general, farmers choice of crop residues for livestock feed often depends on different interrelated biophysical and socioeconomic factors (Erenstein *et al.*, 2011). The demand for crop residues is high in areas of feed sources from communal and private grazing lands are low (Tittonell *et al.,* 2007). Potential demand tends to be lower in agroecologies of high crop production (Blummel *et al.,* 2013). Concomitantly, farmer's level of resource endowment such as livestock and land holdings determine crop residues for livestock feed and other competing uses (Erenstein *et al.,* 2011; Valbuena *et al.*, 2015). Research findings in Ethiopia on crop residue utilization for feed and other purposes and factors associated with intensity of uses are minimal, and mainly focused on maize stover (Jaleta *et al.*, 2015; Valbuena *et al.,* 2015; Alkhtib *et al.,* 2016; Duncan *et al.,* 2016) . Others have also explored determinants of improved feed technologies adoption success and intensity (Gebremedhin *et al.,* 2003; Abebe *et al.,* 2018). Therefore, understanding and identifying important biophysical and socioeconomic factors that determines intensity of sorghum biomass production and its stover use for livestock feed under different agroecological settings, is crucial to tackling well-known problems of low livestock production and productivity, thereby creating sustainability in the system. The present study characterized household's socioeconomic characters, available feed resources and use of sorghum biomass for feed and other purposes in different sorghum growing agro-ecological zones of Ethiopia. Moreover, using econometric models, this study explores key socioeconomic and biophysical factors associated with intensity of sorghum biomass use for livestock feed. Apart from quantifying and describing the situations, outputs from this study has implication for research-for-development efforts to improve availability and quality of sorghum residues and other feed options that can enhance livestock production and productivity in this system.

MATERIALS AND METHODS

Description of the study area

Three sorghum growing agroecological zones with mixed crop-livestock farming systems in Ethiopia were selected from Oromia and Amhara National Regional States of Ethiopia. East Hararghe Zone from the Oromia, North Gonder and North Wollo Zones from the Amhara National Regional States were selected to represent the highland, lowland and the intermediate (mid-altitude) sorghum growing agroecologies, respectively. The sites differ in agro-ecological potential for sorghum production; farm resources (land and livestock characteristics) and availability of feeds (Figure 1 and Table 1).

Household survey, data and descriptive statistics

Following purposive selection of three contrasting sorghum growing agroecological zones, a stratified multi-stage sampling procedure was implemented to select sample households. The first stage involves selection of two districts from the intermediate site and three districts from both highland and lowland sites. In each district, one to two Kebeles (the smallest administrative unit below district) were selected using simple random sampling at second stage. Selection of districts and Kebeles were made on the basis of livestock density and sorghum production potential for mixed crop-livestock farming system. Household sample sizes within each Kebele was determined using a proportionate to census list of households in each Kebele as described in Cochran (1963). Accordingly, 116, 107 and 95 households were selected from the highland, lowland and intermediate altitude sorghum growing agroecological zones, respectively, making a total of 318 households used in this study.

Table 1. Description of sorghum growing agroecological study sites in Ethiopia.

	Sorghum growing agroecological zone		
	East Hararghe(Highland)	North Wollo(Intermediate)	North Gonder(Lowland)
Agroecological characteristics[1]			
Agroecology	Highland	Intermediate	Lowland
Climate	Cool and sub-humid	Warm semiarid	Cool and humid
Altitude	>1900	1600-1900	<1600
Average annual Temp (ºC)	11.5-17.5	17.5-20.0	20.0-27.5
Average annual rainfall (mm)	1200-2200	800-1200	200-800
Livestock ownership (TLU) [2]			
Cattle	1.24	1.63	2.75
Small ruminants	0.64	0.77	0.92
Equine	0.83	0.81	0.85
Total	1.88	2.41	3.68
Feed Resources (% of total sum) [2]			
Grazing	25.05	29.48	39.83
Crop Residue	56.69	46.68	40.91
Improved forage	1.06	0.44	0.16
Hay	2.62	13.06	15.32
Grain Byproduct	4.36	0.86	0.93
Others	10.21	9.48	2.85
Crop residue productivity yield (t /ha)[2]			
Sorghum	5.35	4.37	5.73
Maize	8.07	1.90	2.82
Barley	1.67	1.97	2.50
Wheat	2.74	2.54	2.94
Teff	NA	1.80	2.84
Pulse	1.94	1.35	1.36
Total crop residue	19.77	13.93	18.19

NA: not applicable; [1]Mindaye *et al.* (2015); [2]CSA (2018)

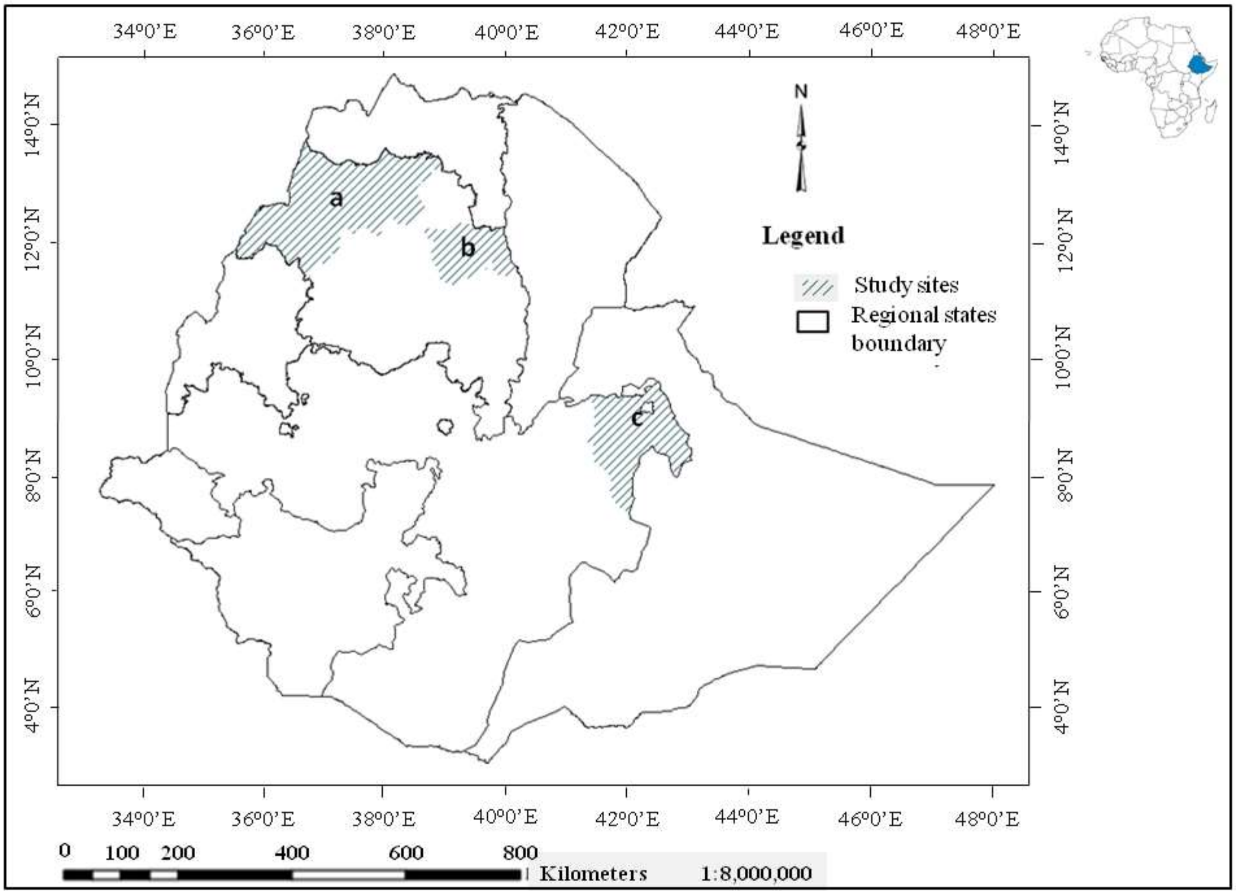

Figure 1. Map of Ethiopia showing study sites (a, b and c represents North Gonder, North Wollo and East Hararghe Zones, respectively).

Prior to administration of the questionnaire, check lists were first prepared to gather preliminary information. Based on information, semi-structured questionnaires were prepared in an array of areas covering, household characteristics, socioeconomic aspects, feed resources availability, and other related variables hypothesized to influence sorghum biomass use for livestock feed. The questionnaires were administered to 5-10 randomly selected farmers per study site. Based on feedback, fully structured questionnaires were prepared and administered to household head during 2018/2019 cropping season. Crop residue (CR) yield was estimated from respective grain yield, conversion factors of 2.0, 1.5, 2.0, 1.2 and 2.5 for wheat, teff, maize, pulse and sorghum respectively, as described in FAO (1987). Livestock holdings per household for the different species and classes obtained from household survey were converted into Tropical Livestock Units using conversion factors of 1.0, 0.7, 0.6, 0.5 and 0.2 for oxen, cows, bull/steer, heifers and calves respectively, respectively (Otte and Chilonda, 2002). Whereas, conversion factors of 0.1 for sheep and goats, 0.5 for donkeys and 0.8 for horses were used.

Descriptive statistics were used to summarize households demographic and farm resources characteristics. One way analysis of variance was employed and Tukeys' HSD mean comparison procedure was employed to test mean differences. The analysis was in Statistical Package for Social Sciences (SPSS) version 20. Double hurdle and Tobit models were used to assesses determinants of decision to use sorghum biomass for livestock feed and intensity of uses.

Specification of empirical models

Double hurdle model: The double hurdle model consists of two separate hurdles. The first hurdle is the decision on the use of sorghum biomass for livestock feed. The second hurdle is the share of sorghum biomass (i.e. in %) allocated for livestock feed, which is conditional on the first decision. This model has two separate latent variables, y_{1i}^*, which represent use of sorghum biomass for livestock feed and the intensity of use, y_{2i}^* (Cragg 1971). Below are participation and intensity of participation equations used.

i) Participation in use of sorghum biomass for livestock feed:

$y_{1i}^* = x_{1i}'\beta_1 + u_{1i}$
$y_{1i} = 1\ if\ y_{1i}^* > 0$
$0\ when\ y_{1i}^* \leq 0$

ii) Intensity of sorghum biomass use for livestock feed:

$y_{2i}^* = x_{2i}^{'}\beta_2 + u_{2i}$
$y_{2i} = y_{2i}^*\ when\ y_{1i}^* > 0$
$y_{2i} = 0\ when\ y_{1i}^* \leq 0$

y_{1i} and y_{2i} are observed success in use of sorghum biomass for livestock feed and intensity of use, respectively. x_{1i}' and x_{2i}' are vector of explanatory variables of the 1st and 2nd decisions, respectively. The two hurdles were linear in parameters (*ß*), with disturbance terms ™ and u randomly distributed with a bivariate normal distribution.

Tobit Model: The stochastic model underlying Tobit may be expressed as:

$y_i^* = x_i\beta + u_i$
$y_i = y_i^*\ if\ y_i^* > 0$
$y_i = 0\ if\ y_i^* \leq 0$
i = 1,2, ...N (1)

N is the number of observations, y_i is the dependent variable, X_i is a vector of independent variables, β is a vector of estimated parameters and $u_i \sim N(0, \sigma^2)$ is an independently distributed error term. The coefficients indicate the direction of adoption intensity and disaggregated into the probability of adoption and the expected adoption intensity. Stata Version 12 was used for data analysis.

To choose between Tobit and double hurdle models, likelihood ratio statistic was computed as (Greene, 2011):

$$\Gamma = -2[\ln L_T - (\ln L_P + \ln L_{TR})] \sim {\chi_k}^2$$

Where, L_T, L_P and L_{TR} are log-likelihoods of the Tobit, probit and truncated regression models, respectively. The null hypothesis is that the Tobit model is appropriate model. Rejection of the null hypothesis ($\Gamma > {\chi_k}^2$) imply double-hurdle model appropriate than the Tobit model.

The Γ test results suggest the rejection of Tobit model. That is, the test statistic Γ = 74.64, 64.20 and 62.04 for highland, intermediate and lowland agroecological zone respectively, exceeds the critical value χ2 (11) = 24.72 distribution. Additionally, Akaike's Information Criterion (AIC) is included as alternative model selection criterion (model with the lowest AIC is preferred). Both confirm superiority of the double-hurdle specification over Tobit model. This suggests that the decision to adoption and intensity of adoption are separate.

Rationale for inclusion of the explanatory variables

Household characteristics: Younger farmers/household heads are more risk takers and willing to improve their farming practices by adopting new technologies to diversify their livelihoods than their older counterparts (Omollo *et al.*, 2018). Older household heads are expected to adopt less because of their shorter planning horizons (Gebremedhin *et al.*, 2003). In this study, being younger favour negatively allocation of sorghum biomass for feed. Furthermore, female-headed households has limited farm resources such as land and livestock than male-headed households (Adesina *et al.*, 2000). Moreover, collection and transportation of crop residues from farm to homestead is labor demanding. This study hypothesized that male-headed households allocate more sorghum biomass for feed. better educated Household heads are expected to show higher levels of adoption (Gebremedhin *et al.*, 2003). This study hypothesizes that being educated has positive influence on the allocation of sorghum biomass for feed. Households' family size is associated with availability of labor forces for collection, transportation and storing of sorghum biomass efficiently to use for livestock feed (Gebremedhin *et al.*, 2003).

Farm resource characteristics: Households with large owned cultivated land might increase their capacity to produce more grain from multiple crops or single crop; hence, more biomass from sorghum and other crops (Wortmann *et al.*, 2009). Therefore, competition between use of sorghum for feed and others uses could be less when the biomass production is high (Jaleta *et al.*, 2013). Therefore, we hypothesize increased household farmland size could favor sorghum biomass use for feed. Moreover, Households with larger number of livestock holdings has increased demand for livestock feed (Jaleta *et al.*, 2013; Valbuena *et al.*, 2015). Hence, we anticipate that larger number of livestock holding favor sorghum biomass use for feed.

Availability of alternative feed sources from grazing: Availability of feeds from grazing lands is expected to have negative effects on use of crop residue for livestock feed because of better nutritional quality of feed from grazing (Erenstein *et al.*, 2011; Blummel *et al.*, 2013; Valbuena *et al.*, 2015). We hypothesize that availability of feed from grazing negatively influence use of sorghum biomass for livestock feed.

RESULTS

Demographic and farm resource characteristics

Household demographic profiles are presented in Table 2. Out of the total respondents, 15.09% were female headed households, and a majority of these were from highland sorghum growing agro-ecology. The overall mean family size per household was 6.03 and the highest was observed at highland sorghum growing site followed by lowland site. Irrespective of sorghum growing sites, 52.52% of the respondents were illiterates and a small proportion attended formal education (i.e. reading and writing). Likewise, most of the family members in the literate categories attended primary than secondary education in all study sites.

There was significant difference (P< 0.001) mean land holding per household in three study sites. The overall mean holding per household was 1.24 and significantly highest holdings per household was observed in lowland sorghum growing site followed by intermediate site. Farmers in the three sorghum growing sites allocate larger proportion cropland for sorghum than other crops; 67, 69 and 57 % of cropland is allocated for sorghum production at the highland, lowland and intermediate sorghum growing agroecological sites. The overall mean land allocated for sorghum per household was 0.62 ha and significantly (P< 0.001) highest in lowland sorghum growing site followed by intermediate site (Table 3). There was a significant difference (P< 0.001) in total livestock holding per household across sorghum growing sites. The overall mean total livestock holding per household was 3.63 TLU and significantly highest mean livestock holding per household was found in lowland sorghum growing sites followed by the highland site. Similar trend was observed in mean cattle holding per household. Other livestock species (i.e. small ruminants and equines) holding per household also showed significant variation (P<0.001); significantly lower mean number of small ruminants and equines holding per household were observed in intermediate sorghum growing site (Table 3).

Significantly (P< 0.001) highest mean sorghum residue was produced at highland and lowland sorghum growing sites. Similarly, higher maize stover (6.49 t/ha) was produced at highland sorghum growing site. At highland and intermediate sorghum growing agroecologies, sorghum residue was preceded by maize residue (Table 3).

Feed resource characteristics

Available feed resources and their percent contributions are shown in Table 4. Available feed resources across the three agroecological zones were categorized into six groups: open grazing (communal open grazing lands, aftermath and roadside grazing), pasture (harvested from privately owned or communal enclosed areas), crop residues, improved forage, hay and others (concentrates and other grain by-products).

The percentage contribution of feed resources to the total feeds varied across the different sorghum growing agroecological zones (Table 4). Overall, the contribution of crop residue’s was highest (51.56%) followed by grazing (23.28%), with the smallest grain by-products and concentrates (4.14%). Across sorghum growing sites, the contributions of crop

Table 2. Demographic characteristics of households.

Variables	East Hararghe (Highland)	North Wollo (Intermediate)	North Gonder (Lowland)	Overall mean
Age of HH head	39.47 (1.08)	45.40 (1.30)	43.59 (1.22)	42.63 (0.69)
Family size	7.03 (0.25)	4.84 (0.17)	6.00 (0.19)	6.03 (0.13)
Gender (%)				
Male	67.24	93.68	96.26	84.91
Female	32.76	6.32	3.74	15.09
Education level (%)				
Illiterates	53.45	38.95	63.55	52.52
Reading and writing	0.00	7.36	1.87	2.83
Primary	39.65	43.16	28.04	36.79
Secondary	6.90	10.52	6.54	7.86

Values in parentheses indicate standard error.

Table 3. Farm resource characteristics and crop residue yields of sorghum growing households.

Variables	East Hararghe (Highland)	North Wollo (Intermediate)	North Gonder (Lowland)	Overall mean
Land Holding (ha)	0.55 (0.04)^{c}	0.99 (0.10)^{b}	2.20 (0.17)^{a}	1.24 (0.08)***
Land allocation(ha)				
Sorghum	0.28 (0.02)^{c}	0.4 (0.03)^{b}	1.16 (0.13)^{a}	0.62 (0.05)**
Maize	0.18 (0.02)^{b}	0.22 (0.02)^{ba}	0.25 (0.03)^{a}	0.20 (0.02)*
Teff	NA	0.48 (0.06)	0.62 (0.07)	0.55 (0.05)^{NS}
Wheat	0.18 (0.05)	0.35 (0.09)	0.36 (0.05)	0.32 (0.04)^{NS}
Beans	0.12 (0.02)^{b}	NA	0.40 (0.06)^{a}	0.26 (0.04)**
Livestock holding ownership (TLU)				
Cattle	1.41 (0.14)^{b}	2.15 (0.10)^{b}	5.07 (0.59)^{a}	2.86 (0.23)***
Shoats (Sheep and Goats)	0.35 (0.04)^{a}	0.11 (0.02)^{b}	0.33 (0.05)^{a}	0.27 (0.02)***
Equines (donkeys and Horses)	0.25 (0.03)^{a}	0.08 (0.02)^{b}	0.21 (0.03)^{a}	0.18 (0.02)***
Total livestock	2.00 (0.16)^{b}	2.33 (0.11)^{b}	5.60 (0.62)^{a}	3.31 (0.24)***
Crop residue (t/ha)				
Sorghum	4.70 (0.28)^{a}	2.99 (0.28)^{b}	4.60 (0.56)^{a}	***
Maize	6.49 (0.66)^{a}	3.04 (0.36) ^{b}	4.49 (0.89) ^{b}	*
Teff	NA	1.21 (0.15)	1.50 (0.12)	NS
Wheat	2.57 (0.72)	1.79 (0.51)	4.00 (0.55)	NS
Beans	2.15 (0.33)	NA	1.98 (0.31)	NS

Values in parentheses indicate standard error; ^{a,b,c} Means in a row with different superscripts differ significantly (P<0.05).

Table 4. Feed resource and percent contribution in three sorghum growing agroecological zones.

Feed resource types	East Hararghe (n=116)	North Wollo (n=95)	North Gonder (n=107)	Overall mean (n=318)
Improved forage	11.78 (1.17)^{a}	5.48 (1.15)^{b}	3.20 (1.11)^{b}	6.82 (0.70)***
Crop residue	58.71 (2.78)^{a}	48.95 (3.20)^{b}	45.76 (3.72)^{b}	51.56 (1.87)**
Grazing	15.35 (1.73)^{c}	25.44 (2.34)^{ab}	29.06 (3.01)^{a}	23.28 (1.41)**
Pasture	4.28 (0.77)^{b}	7.18 (1.20)^{b}	14.68 (2.12)^{a}	8.37 (0.84)***
Hay	5.55 (0.91)^{b}	8.94 (1.54)^{a}	3.41 (0.59)^{c}	5.51 (0.66)***
Others	4.40 (0.82)	4.07 (0.74)	3.95 (0.77)	4.15 (0.45)^{NS}

Values in parentheses indicate standard error; ^{a,b,c} Means in a row with different superscripts differ significantly (P< 0.05).

residues and improved fodder were higher in the highland agroecology. In the contrary, the contributions of grazing and pasture were higher in the lowland agroecology. The contribution of hay was highest in the intermediate and lowest in the lowland agro-ecology.

Sorghum residue allocation for different purposes

Allocation of total sorghum stover for different uses is presented in Table 5. Sorghum stover allocated for feed showed a significant association with sorghum growing agro-ecological zones, highest at the lowland sorghum growing site (North Gonder; 86.73%) and lowest at highland site (East Hararghe; 61.75%). In contrast, sorghum stover as allocated for fuel was high in both the highland and lowland agroecologies. Use of sorghum stover for soil mulching and selling was very limited.

Table 5. Mean percent allocation patterns of sorghum stover for different purposes at the three sorghum growing agro-ecological zones of Ethiopia.

Alternative uses	East Hararghe (Highland)	North Gonder (Lowland)	North Wollo (Intermediate)	Over all mean
Animal feed	67.75 (2.60)[c]	86.73 (1.60)[a]	81.3861.82[ab]	78.62 (1.30)***
Soil mulching	6.88 (1.34)[a]	4.28 (1.22)[a]	1.3360.70[b]	4.16 (0.68)*
Fuel	19.98 (1.49)[a]	7.37 (1.10)[b]	16.0161.70[a]	14.46 (0.88)***
Sell	4.88 (1.63)	1.52 (0.44)	1.0160.48	2.47 (0.63)[NS]

Values in parentheses indicate standard error; [a,b,c] Means in a row with different superscripts differ significantly ($P< 0.05$).

Econometrics model analysis

The econometric results of factors affecting for farmer's decision and level of utilization of sorghum biomass uses for livestock feed in three major sorghum growing agroecological zones are presented in Tables 6 and supplementary Table 1.

The double hurdle model result is presented in Table 6. The table presents factors associated with decisions to use sorghum stover for livestock feed (participation) and factors associated with intensity of allocation of sorghum stover for feed (intensity of use). Factors affecting farmer's decisions to use sorghum biomass for livestock feed varies with agroecological zones. Household size and education level at highland and livestock and availability of crop residue other than sorghum at intermediate growing zone showed significant effects on the decision to participate in sorghum biomass use for feed. One unit increase in family labor resulted in 31.6% increase in probability of the decision to use sorghum biomass for livestock feed at highland sorghum growing zone. Moreover, one unit increase in livestock ownership expressed in TLU resulted 76.7% increase in probability of decision to use sorghum biomass for livestock feed in the intermediate zone. Similarly, a one percent increase in crop residues from other crops decreased the probability of household decision to use sorghum biomass for feed by 4.6% at this zone.

Household family size, livestock holding, availability of feeds from grazing and crop residues other than sorghum had significant effect on quantity of sorghum biomass used for feed across sorghum growing agroecological zones. One unit increase in household size increased the quantity of sorghum biomass used for feed by 19 and 14% in the intermediate (North Wollo) and lowland (North Gonder) sorghum growing zones, respectively. Similarly, increase in livestock ownership by one TLU increased sorghum biomass used for livestock feed by 20.4 and 98.3% at highland and intermediate sorghum growing agroecological zones, respectively. Moreover, a one percent increase in quantity of other crop residues decreased quantity of sorghum biomass by 78.4%, 76.1% and 72.4% in highland, intermediate and lowland sorghum growing agroecological zones, respectively. A one percent increase in availability of feed from grazing decreased sorghum biomass used for livestock feed by 25.3% and 0.7% at highland and lowland sorghum growing agroecological zones, respectively. A one-year increase in household age resulted in increase quantity of sorghum biomass used for livestock feed by 27.4% in the intermediate sorghum growing zone.

DISCUSSION

Farm resource characteristics

Mixed crop-livestock farming is main mode of agricultural system in studied sorghum growing agroecological sites. Cattle, small ruminants and equine are the dominant livestock classes reared by farm households in the study agro-ecological sites zones. The overall mean livestock holding reported in this study is higher than the values reported by CSA (2018). Crop residue contribution to livestock feed decreased in a gradient from the highland to the lowland sorghum growing agro-ecological zones. Contribution of feeds from open grazing decreased along agro-ecological gradient. However, a substitution effect of other crop residue was not observed. In the highland sorghum growing agroecological zone, residue yield from maize is higher than that of sorghum, but sorghum residue use for livestock feed is still high at this site. This implies that feeds from fallow, communal grazing lands and cultivated forages are more important.

Sorghum biomass/residue uses: Feed and other uses

The study revealed that largest proportion of sorghum stover produced on farm is used to animal feed in all sorghum growing sites. This complements the notion that crop residues are often the main feed source for cattle in mixed crop-livestock farming systems (Jaleta *et al.*, 2015). However, the percent allocated

Table 6. Double hurdle model results for determinants of decisions to allocate and intensity of allocation of sorghum biomass to feed across the three major sorghum growing agro-ecological zones in Ethiopia.

Explanatory variables	Highland (East Hararghe)		Intermediate (North Wollo)		Lowland (North Gonder)	
	Hurdle 1 (Participation)	Hurdle 2 (Intensity of use)	Hurdle 1 (Participation)	Hurdle 2 (Intensity of use)	Hurdle 1 (Participation)	Hurdle 2 (Intensity of use)
Age	-0.051 (0.038)	-0.201 (0.112)	-0.026 (0.026)	0.274*(0.133)	-0.050 (0.033)	-0.054 (0.112)
HHsize	0.316*(0.159)	0.637 (0.527)	0.047 (0.305)	0.191*(0.092)	0.161 (0.211)	0.138*(0.067)
Land	4.290 (2.445)	-0.908 (0.684)	-0.045 (0.708)	-4.669 (2.630)	-0.233 (0.223)	0.073 (0.511)
Livestock	0.932 (0.669)	0.204*(0.118)	0.767*(0.450)	0.983*(0.245)	0.012 (0.077)	0.137 (0.171)
Feed-Grazing	-0.021 (0.016)	-0.253***(0.068)	.00547 (0.108)	-.0435 (0.052)	0.004 (0.014)	-0.007*(0.033)
CR-NotSS	-0.020 (0.020)	-0.784***(0.065)	-0.046*(0.022)	-0.761 (0.000)***	-0.023 (0.015)	-0.724***(0.072)
FP-Dist	-0.019 (0.012)	0.002 (0.029)	-.024 (0.018)	.0317 (0.044)	-0.009 (0.010)	-0.015 (0.027)
Gender						
Male	0.873 (0.795)	-2.070 (2.935)	0.183 (1.188)	3.078 (6.131)	3.532 (381.427)	4.409 (6.439)
Education						
Read-Write	NA	NA	2.904	0.113*(0.06)	3.791(0.020)	-2.938 (7.705)
Primary	-0.233*(0.10)	0.695 (3.078)	0.371 (0.930)	0.604 (3.209)	0.745 (1.378)	-2.514 (2.548)
Secondary	0.643(181.78)	-0.603 (5.273)	4.242	8.723*(4.943)	2.984(557.169)	-7.570*(4.543)
ll		-428.53		-346.8087		-376.412
Sigma		11.929 (0.833)		11.952 (0.916)		9.830 (0.699)
AIC		927.50		759.6175		826.823

*, **, *** significant at the 0.05, 0.01, and 0.001 probability level, respectively.; ll: Log-likelihood; AIC: Akaike's Information Criterion; Values in parentheses indicate standard error, HHsize = Family size, Feed-Grazing = Feed from grazing land, CR-NotSS = Crop residue other than sorghum, FP-Dist = homestead distance from field plot

of sorghum stover for feed varied among sorghum growing agroecologies, highest in the lowland and lowest in highland agroecologies. This contradicts with the finding that total crop residues contribution to total livestock feed is highest in the highland sorghum growing agroecology. With relatively high demand of sorghum biomass for fuel, sell for income and soil amendment in the highland site, result high pressure on sorghum residue allocation for feed; this confirms the conclusions of previous work (Valbuena *et al.,* 2015) that when resources are scarce, crop residues represent a key resource for other uses. The high demand of sorghum biomass to livestock feed at lowland sorghum growing agroecological zone, where the relative availability of other feed resources are also better, might be linked with the high livestock population. Moreover, the high demand of sorghum biomass for fuel in the intermediate sorghum growing agroecology might be related with low livestock density and availability of other feed sources. This may also be related with shortage of fuel wood result from population pressure caused deforestation (Gesese and Ignatious, 2012). Minimal amount of sorghum biomass allocated for soil mulching at all study sites consistent with the results of Valbuena *et al.* (2012, 2015). There was an interaction between percent allocation of sorghum residue for feed and the combined availability of other crop residues. Households at highland and intermediate sorghum growing agroecological zones produced more residues from maize than sorghum and used less percent of sorghum residue/biomass as feed. Conversely, households at lowland sorghum growing agroecological zone produced more residues from sorghum than maize crop, and used more percent of sorghum residue/biomass as feed. This might be a due to a strong association between livestock herds (particularly cattle) and their feed requirements. A higher livestock population in the lowland sorghum growing agroecological zone than the other, increases demands for more feed from crop residues. On the other hand, diversifying cereals produced at household level might increase availability of feed choice that can substitute sorghum biomass, hence reduce the pressure on other use.

Determinants of sorghum biomass use for livestock feed

In this study, effect of household size on use of sorghum stover for feed had a positive impact in all the study agroecological zones and it might be associated with labor availability to collect and store crop residues (Jaleta *et al.,* 2015). Moreover, distance of field plot from homestead had a negative effect. The effect of household size on use of sorghum stover for livestock feed is important for households whose sorghum plots are distant from homesteads. On the other hand, presence of active labor and field plots closer to the homestead encourages the household head to transport and conserve sorghum stover for use as livestock feed. Our findings are in line with Jaleta *et al.* (2015) and Alkhtib *et al.* (2016) who state that labor is important for crop residue collection and transportation to homestead. Although effect of plot size on the probability and intensity of sorghum residues use for feed was not significant, the relationship observed in this study was negative. Households with a higher landholding are likely to have more biomass production resulting in more alternative sources for feed, which may detract use of sorghum biomass for feed through a substitution effect. The positive effect of livestock ownership on adoption and intensity of sorghum biomass use to livestock feed at highland and intermediate sorghum growing agroecological zones might be associated with increased livestock feed demand from crop residues (Jaleta *et al.,* 2015; Alkhtib *et al.,* 2016) . Duncan *et al.* (2016) reported households with higher livestock density allocated more crop residues for feed than other uses. Other studies also stated that, higher livestock owned had shown positive effect on proportion of maize stover used as livestock feed (Thorne *et al.,* 2002; Gebremedhin *et al.,* 2007).

Availability of feeds other than crop by-products such as fallow land, communal grazing lands and pastures is expected to have negative effect to use crop residues for feed (Duncan *et al.,* 2016). Moreover, extensive areas with communal grazing land are more likely to meet livestock feed requirements (Rusinamhodzi *et al.,* 2016). This is evidenced by a negative relationship between availability of feed from grazing and proportion of sorghum biomass allocated to feed across all agroecological zones. In the lowland sorghum growing zone, the probability and intensity of sorghum biomass use to livestock feed decreased by only 2% as a result of a one unit increase in availability of feed from grazing. This could be linked with high availability and better access to feed from grazing by households, meaning this variable may not be an important detrimental factor. Residues from one crop could substitute role of residues from another crop (Jaleta *et al.,* 2015). This is evidenced by a strong negative association between availability of other crop residues and amount of sorghum biomass allocated for feed. This suggests an observed complementary effect could be due to alternative feed availability where farmers complement sorghum residue with other cereal residues to meet feed needs.

In general, sorghum is one of the crops which have inherited its trait to adapt and grow in harsh climate from its origin. Its uniqueness in its ability to produce under a wide array of harsh environmental conditions has recently witnessed an increasing importance of the crop as source of food and feed in the semi-arid tropics and drier parts of the world where livestock constitutes a major component of the production system. This may implies that use of sorghum stover has great potential to adopt and mitigate climate change and has a great potential for crop improvement for food and feed in such environment.

CONCLUSION

The study employed cross-section data to analyze the effect of farmers' socioeconomic and biophysical attributes on the decision and intensity of use of sorghum residue for feed in three major sorghum growing agroecologies in Ethiopia. Our findings show that crop residues are major source of feed. However, our results indicate that apart from its vital importance as livestock feed, sorghum stover has also other crucial uses, including fuel, mulching and income sources. These alternative uses may put pressure on use of sorghum residue for feed. The pressure exerted varied with sorghum growing agroecological zones. Tobit and double hurdle regression results shown that availability of feed from grazing and other crop residues are important factors that determine the decision and intensity of use of sorghum residue to feed across all sorghum growing agroecological zones. The highland sorghum growing zone produces higher crop residues from sorghum and other cereals. However, due to high demand for feed and fuel, sorghum biomass produced might not meet the demands of livestock feed requirement. This emphasizes the need to increase availability of feed by introducing crop varieties superior in food-feed traits and backyard forages. Moreover, the high pressure for competing uses, mainly for fuel, there is need to develop and promote potential substitutes to ensure adequate availability of sorghum biomass for feed.

In the lowland sorghum growing agroecological zone, the demand for alternative uses of sorghum residue is low, hence more sorghum biomass is allocated for feed. Furthermore, availability of feed from grazing is better in this zone. Allocation of more sorghum residue for feed and less for other competing uses in this zone might be higher livestock density. Enhancing quality and quantity of sorghum residue might be crucial to increase its feeding value. Moreover, improving productivity of communal and private grazing lands possibly reduce the pressure on sorghum residue uses for feed which is poor in nutritional value compared to grazing.

At the intermediate sorghum growing agroecological zone, it seems that sorghum residue is mainly used for feed and fuel. In this zone, sorghum and other crop residues production is low which may create pressure on sorghum residue use for feed. This emphasizes to increase sorghum and other crop production that can provide more residues to reduce pressure. Household's livestock ownership and labor available had positive effect on farmers' decision to use and intensity of allocation of sorghum residue for feed across sorghum growing agroecological zones, implying they are important factors to consider in any development and implementation policies for sustainable livestock development activities.

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