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High-cut harvesting of maize stover and genotype choice can provide improved feed for ruminants and stubble for conservation agriculture

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Core Ideas

- Harvesting maize stover at high stubble height provides an upper fraction with improved feed quality.
- Maize genotypes with higher yields of both grain and stover fractions were identified.
- High stubble height and genotype choice enhance optimal allocation of stover fractions for feed and mulch.
- Partitioning of maize stover into fractions is valuable to optimize demands for feed and mulch.

Abstract

In smallholder crop-livestock systems where maize (*Zea mays* L.) is a staple cereal, the stover is usually an important, but low quality ruminant feed. Maize stover has various competing uses and optimal allocation of stover, particularly for forage and mulch, is essential for improving whole-farm productivity and sustainability. Knowledge that feed quality increases with height in maize stover provides opportunities. An experiment investigated the effects of a high cutting height of stover at grain harvest (cut at two internodes below the lowest ear) on the yields and feed quality of the upper and lower stover (stubble) fractions. Measurements were made on six maize genotypes at two sites during two cropping seasons in Ethiopia. The upper stover fraction (USF) on average comprised 674 g $kg^{-1}$of the entire stover and was also substantially higher ($P < 0.001$) than lower stover fraction (LSF) in *in-vitro* dry matter digestibility (IVDMD) (527 vs. 450 g kg^{-1} DM) and total N concentrations (8.8 vs. 6.2 g kg^{-1} DM), and lower in fiber. Stems (including leaf sheath and tassel), husks (including shank) and leaf blade comprised

484, 310, and 206 g $kg^{-1}$of the USF, respectively. Yields and feed quality of stover varied among genotypes and environments. Use of an USF can provide a feedstuff of increased nutritional quality for ruminants but the efficacy of the LSF for mulch requires investigation. In conclusion a simple management change to harvest maize stover at higher stubble height combined with use of appropriate genotypes can provide higher quality feed while leaving stubble for conservation agriculture.

Abbreviations: ADF, acid detergent fiber corrected for the ash concentration of the residue; CA, conservation agriculture; CR, crop residues; DDM, digestible dry matter; DM, dry matter; IVDMD, *in-vitro* dry matter digestibility; LSR, leaf-to-stem ratio; LHSR, leaf and husk-to-stem ratio; LSF, lower stover fraction; ME, metabolisable energy; N, total nitrogen; NDF, neutral detergent fiber assayed with α–amylase and corrected for the ash concentration of the residue; NIRS, near infrared reflectance spectroscopy; USF, upper stover fraction; WS, whole stover.

1. INTRODUCTION

In smallholder mixed crop-livestock systems, livestock provide inputs for crop production such as manure for soil fertility and traction, while crops provide crop residues (straws and stovers) as ruminant feed (Larbi *et al*., 2002). Shortages of livestock feed in quantity and quality and low soil nutrient status constrain an increase in crop and livestock outputs (whole-farm productivity) in smallholder mixed crop-livestock systems (Anon, 1992). Crop residue management or use is an integral component affecting the sustainability of crop-livestock systems in the tropics (Duncan *et al*., 2016; Larbi *et al*., 2002).

Although maize (*Zea mays* L.) in crop-livestock smallholder systems in developing countries is grown primarily for food the stover is an important resource with many uses. Along with crop residues (CR), more generally a large proportion of the stover is usually needed as a feed for ruminant and equine livestock (Erenstein *et al.*, 2013; Thornton *et al*., 2010). However, stover and CR are also needed for other purposes including mulch for conservation agriculture (CA), construction, fuel, and to provide bioenergy feedstock (Clay *et al,* 2019).

In the context of developing countries, two major issues constrain better use of maize stover as a feed for ruminants. First, maize stover harvested at grain maturity is, like most cereal CR, generally of poor nutritional value with low concentrations of nitrogen (N) and other essential nutrients, low content of metabolizable energy (ME), and high concentrations of fiber (Ertiro *et al.*, 2013; Kabaija & Little, 1988). Maize stover fed alone is usually associated with low voluntary intake and poor animal performance (Tolera & Sundstøl, 2000). Second, among the competing uses for maize stover, and CR more generally, the largest and increasing demand is for mulch in CA (Baudron *et al.*, 2014; Duncan *et al.*, 2016; Jaleta *et al.*, 2015; Rusinamhodzi *et al.*, 2015). Mulching, such as by retention of CR, is an important soil management technique for sustainability and CA. It provides benefits by reducing soil erosion, retaining water, enhancing nutrient cycling, sustaining soil organic carbon, buffering temperature fluctuations, supporting microbial communities, increasing soil fertility, improving soil structure and increasing agricultural productivity (Chen *et al.,* 2018; Clay *et al.,* 2019; Erenstein, 2003).

The high demand of CR for feed for ruminants often leads to shortages of CR for mulch (FAO, 2018; Tittonell *et al.*, 2015). Thus a major challenge for many smallholder farmers is to produce and retain enough CR to obtain the changes and benefits from CA (Baudron *et al.,* 2014). Crop residues are often used (or sold) for livestock feed, construction, and fuel. The multiple uses and competing applications of CR create many management challenges and trade-offs (Clay *et al.,* 2019;

Erenstein *et al.,* 2015). All approaches to maintenance of soil organic matter and soil fertility need to recognize the importance and need for integration of livestock in mixed-farming systems (Giller *et al.*, 2015) for whole-farm productivity outcomes. For instance, Mupangwa *et al*. (2019) suggested that smallholders may utilize fractions of CR more efficiently for livestock feeding during months of feed shortage than for CA due to the limited gain in maize productivity obtained when maize residue is used as mulch in South African farming systems. Clearly there is extensive current development of CA (Stevenson *et al.,* 2014; Erenstein *et al*., 2015; Clay *et al.,* 2019) that should improve understanding of the biological consequences of various uses of CR and better inform the necessary trade-off decisions. Thus, the better use and optimal allocation of stover, especially as feed or mulch, are the major and increasing challenges for long-term whole-farm productivity in smallholder crop-livestock systems.

Although farmers in some regions use *in situ* grazing of maize stover, in most regions of developing countries the traditional practice at grain harvest is to cut and carry the bulk of the maize stover to the homestead and to store it for use as ruminant feed (*ex situ*) during the dry season (Ertiro *et al.*, 2013; Hellin *et al*., 2013). Stover is usually harvested to ground level. However in some regions of east Africa farmers use a high stubble height at harvest (e.g. the stover is cut at two internodes below the lowest ear) and the upper stover fraction (USF) is used *ex situ* as feed while the lower stubble used for mulch, *in situ* grazing, or other purposes (Dejene, 2018; Duncan *et al*., 2016). Cutting stover at a high stubble height should be a simple management change to provide an USF of higher nutritive value and palatability as a feed, while also leaving the lower stover fraction (LSF) for mulch. The USF should contain the majority of the leaf and husk that have higher concentrations of nutrients and lower concentrations of fiber, and be a more palatable feedstuff than the whole stover (WS). This follows from the general observation that the upper parts of most grasses are higher in nutritive value and more palatable for ruminants than the entire plant (Van Soest, 1994), and is supported by reported measurements of N, dry matter (DM) digestibility and fiber in the morphological fractions of maize stover (Liang *et al*., 2015). Furthermore grazing ruminants selectively ingest the leaf and husk of maize stover resulting in higher intakes of nutrients (Fernandez-Rivera & Klopfenstein, 1989; Klopfenstein *et al.*, 2013; Petzel *et al.*, 2018). This principle of using a higher stubble height to provide forage of higher nutritive value has been established for maize silage production in the context of developed countries (Bernard *et al.*, 2004; Kennington *et al.*, 2005; Neylon & Kung, 2003; Oliveira *et al.*, 2013) but, to our knowledge, has not been used in the context of smallholder agriculture in developing countries and particularly with maize stover harvested at grain maturity.

Another approach to increase the nutritive value and the amount of maize stover available is through use of improved genotypes. Dual purpose maize genotypes that provide higher yields of WS as well as grain, and also stover of higher feed quality, are available for some environments (Blümmel *et al.*, 2013). However, there is a lack of information on the effects of using various cutting heights on the attributes of stover fractions, or the possible interactions between stover feed quality versus stubble height and genotypes. Combining the benefits of a higher stubble height with genotype choice should provide greater benefits than either approach alone, but requires an understanding of the benefits and limitations of genotypes and genotype x environment interactions on stover feed quality and yields. These technologies are likely to provide options for improved management flexibility for the use and allocation of maize stover. Farm productivity and efficiency is likely to be improved by optimal allocation of maize stover fractions to the purposes for which they are most useful and valuable. Cognizance of the issues, trade-offs and management decisions required will be particularly important where the availability of CR is less than the demand, as typically occurs in eastern and southern Africa (Duncan *et al.*, 2016; FAO, 2018; Jaleta *et al.*, 2015; Rusinamhodzi *et al.*, 2015) and many other regions of developing countries (Erenstein *et al*., 2015; Hellin *et al.,* 2013; Valbuena *et al*., 2012).

The relationships between yields of maize grain, and stover yields and nutritional attributes of WS have been investigated (Blümmel *et al.*, 2013), but no investigations have evaluated the variation among stover fractions that may allow better use of maize biomass. The present study examined the hypotheses that: (i) an USF of maize stover would provide a feedstuff of increased nutritive value for ruminants as well as providing a LSF for CA or other needs, and (ii) a higher nutritive value of the USF is consistent across maize genotypes and growing environments, and in particular with higher-yielding genotypes.

2. MATERIALS AND METHODS

2.1. Study site description

Field studies were conducted in the 2013 and 2014 cropping seasons at two sites in Ethiopia at Bako (9°12’N, 37°08’E, 1650-m altitude, nitisols) and Melkassa (8°24’N, 39°21’E, 1550-m altitude, andosol) (Eyasu, 2016; MARC, 2014). Additional information of site soil (0-30 cm) pH, organic carbon and total N have been reported by Seyoum *et al.* (2018). These sites represented mid-altitude sub-humid and semi-arid areas, respectively, and together they represent the major maize growing area in Ethiopia (Nigussie *et al.*, 2001) and are also representative of many regions of eastern and southern Africa. Cumulative rainfall, and maximum and minimum temperatures at the two sites during the 2013 and 2014 cropping seasons are presented in Supplemental Figures S1 and S2. Planting dates were 5 June 2013 (B2013) and 6 June 2014 (B2014) at Bako, and the 4 July 2013 (M2013) and 9 July 2014 (M2014), at Melkassa. Rainfall, maximum temperature (MaxT), and minimum temperature (MinT), varied considerably between sites and seasons (Figures S1 and S2). At both sites rainfall was higher in the 2013 than in the 2014 cropping season. The total-cropping season rainfalls at Bako for 2013 and 2014 were 1190 and 790 mm, respectively. Rainfall was well distributed throughout the growing season in both years, although substantial rain (>550 mm) fell in June and July in 2013 (Figure S1). The total cropping season rainfalls at Melkassa were 682 and 478 mm during the 2013 and 2014 seasons respectively, but the majority of this rain was in July 2013 during the vegetative stage of crop growth (Figure S2). The average maximum temperature during May to December was marginally higher (27.5^{O}C) at Melkassa than Bako (26.3 ^{O}C) (Figures S1 and S2).

2.2. Experimental design and crop husbandry

Three early (MH-130, SC-403, and THI3321) (~138 day) and three medium (BH-540, BH-543, and BH-546) (~148 day) maturing maize genotypes were evaluated at each site in a randomized complete block design with three replications. Early and medium maturing genotypes account more than 85% of the area cultivated for maize in Ethiopia. These genotypes are well adapted to eastern and southern Africa maize growing environments, morphologically diverse (droopy vs. upright leaf), had different time of release (old and new) and were developed by different organizations (i.e. both public and private research organizations such as Ethiopian Institute of Agricultural Research (EIAR), International Maize and Wheat Research Center (CIMMYT), Pioneer-Hi Bred, and Seed Co). All genotypes were planted in six rows of 5.1-m length plot with 75-cm inter-row spacing. Seeds were hand-planted at the onset of rainfall at two seeds per hill and later thinned to one seedling per hill within 10 days after emergence to achieve a plant density of 5 plants m^{-2}. All phosphorus (20 kg P ha^{-1}) and one third of nitrogen (15.3 kg N ha^{-1}) were applied at planting as a basal dose and the remaining N (30.7 kg N ha^{-1}) was side-dressed about 35 days after emergence. Both sites had been cropped with maize in the previous season.

2.3. Field data collection and stover sampling

Immediately before grain harvest at physiological maturity the morphological characteristics of plant height (ground level to the tip of the plant), ear height (ground level to the upper-most ear insertion), and above-ear height (height from the upper-most ear insertion to the tip of the plant) were measured in four randomly selected plants for each plot. All plants in the middle two rows of each plot, from an area of 7.65 m^2 were hand-harvested to ground level for measurements of stover fraction yields. After being weighed, four randomly selected maize plants from each of the three replicated plots were sub-sampled; fresh weights of aboveground biomass were recorded and separated into two fractions. These comprised: (1) the upper part of the stover fraction (USF) that included all stover above the 2nd node below the first attached ear from the base of the plant (husks with shank, upper-stems (including the upper-leaf sheath and tassel) and upper-leaf blade); (2) the lower part of the stover fraction (LSF) that included the remaining stover above ground level (lower-stems, including lower-leaf sheath, and lower-leaf blade). Neither grain nor cobs were included in the USF or LSF. The yields and composition and *in-vitro* DM digestibility (IVDMD) of WS were calculated from the stover fractions. These harvest procedures were designed to mimic harvest scenarios of farmers using either a conventional low stubble height or a high stubble height as observed in some regions of east Africa (Dejene, 2018). Sub-samples of the USF and LSF were mechanically chopped to less than 10 cm in length. Fresh weights were measured and the samples (500 g) were then oven dried at 60°C for 48 h (until weight loss ceased) and weighed.

In 2014, additional measurements were made of the stem thickness and of the morphological components within the upper and lower stover fractions. The upper and lower stem diameters were measured from four randomly selected plants from the middle two rows before harvest. Measurements were made using vernier callipers at the midpoint of the second internode counted from top-to-bottom and bottom-to-top of the plant, respectively. The USF and LSF samples within each plot were further manually separated into morphological components. The USF was separated into: (1) upper-leaf blade; (2) upper-stems including upper-leaf sheath and tassel, and (3) husks including the shank. The lower stover was separated into: (1) lower-leaf blades and (2) lower-stems, including the lower-leaf sheath. The leaf-to-stem ratio (LSR) in both upper and lower stover, and the leaf and husk-to-stem ratio (LHSR) in the USF, were calculated. Sub-samples (500 g) of the stover morphological fractions were mechanically chopped to less than a 10 cm length and dried as described above. The yields and quality attributes were calculated on a dry basis.

2.4. Stover chemical composition and in vitro dry matter digestibility analyses

2.4.1. Stover sample processing and laboratory analyses

Stover sub-samples were ground through a 1-mm screen using a laboratory hammer mill (Christy and Norris Limited, Chelmsford, UK) and stored at ambient temperature. Samples were air-freighted to Australia and, to meet quarantine requirements, were gamma irradiated (25k Gray) before transport to laboratories. Total N, neutral detergent fiber (NDF) assayed with α–amylase and corrected for ash concentration and acid detergent fiber (ADF) corrected for ash concentration, and *in-vitro* DM digestibility (IVDMD) were estimated using near infrared reflectance spectroscopy (NIRS; Dejene, 2018).

The NIRS calibrations used to measure the feed chemical composition and IVDMD described below were based on established northern Australian (NA) forage calibrations (unpublished results, D B Coates and R M Dixon) that had been developed primarily with tropical C_4 grass and legume samples (n = 409 - 1688, depending on the attribute). These data sets were expanded and validated with additional reference samples to represent crop residues (CR) in east African farming systems. Of the CR samples from Ethiopia (n = 2851), a subset of 470 samples (maize stover fractions and whole stover (n = 203) from the two sites in the present experiment, and from 2 other sites (Hawassa and Adamitullu), and also samples of the CR of common bean, chickpea, faba bean and soybean (n = 267); 15–42% of each of these species or subclasses were selected) (Dejene, 2018). These additional reference samples were selected on the basis of high standardized global H values (Mahalanobis distance)^2/f, where f is the number of factors in the model (Shenk & Westerhaus, 1991) with stratification so that each of the morphological fractions of maize and grain legume species, genotypes, year, sites and grain legume crop growth stages at harvest was represented. These reference samples were analysed for chemical composition and IVDMD by the laboratory procedures described below and were then included with the calibration data from NA. The combined data (NA + CR) were used to calculate and validate improved calibration equations for concentrations of total N, NDF and ADF, and IVDMD. These improved calibrations were used to predict the attributes in the maize stover samples in the present experiment (for further details see Dejene, 2018).

The validation statistics of the NIRS calibration for predicting maize stover samples showed that concentrations of N (n = 201), NDF (n = 203) and ADF (n = 203) and IVDMD (n = 203) were well predicted by NIRS with the coefficient of determination in validation (R^2_v) 0.97, 0.96, 0.95 and 0.90, respectively. The relative predictive determinant (RPDv = the ratio of the standard deviation of validation data set to bias corrected standard error of performance (SEP(C)) in the validation set) (Patil *et al.,* 2010) were 5.67, 5.04, 4.67 and 2.93, respectively. Also the standard errors of performance (SEP) were 0.9, 15.7, 13.1 and 28.4 g kg^{-1} DM for the total N, NDF and ADF concentrations and IVDMD, respectively.

Total N was determined using a LECO combustion system (TruMac® CN analyser 2013 version1.3x;LECO Corporation, St. Joseph, MI, USA) that complied with AOAC (2005) analysis #990.03. Both the NDF and ADF were analysed using an ANKOM^{200} Fiber Analyser (Model200, ANKOM Technology, Macedon, NY, USA) with F57 filter bags (ANKOM 57 micron pore size-ANKOM Technology, NY) (Anonymous, 1995a; Vogel *et al.,* 1999) followed by incineration of the fiber residue to correct for ash (Mertens, 2002; 2011). *In-vitro* DM digestibility was determined with the filter bag method in a DAISYII incubator (ANKOM Technology, Macedon, Fairport, NY, USA)

(Anonymous, 1995b; Holden, 1999). Rumen fluid was obtained from two rumen fistulated steers fed a high quality forage diet, and was prepared as described by Holden (1999). Bags were incubated in rumen fluid and buffer for 48 h at 39.5 ± 0.5^{0}C (Anonymous, 1995b), and then with acid-pepsin solution for another 24 h (Holden, 1999) before bags were dried and weighed. A laboratory standard sample (*Astrebla* spp C_4 grass) and empty blank bags were included in each batch. Laboratory errors in the current study were controlled at an acceptable level, with a coefficient of variation between duplicate analyses of less than 5%. Digestible dry matter (DDM) yields of the USF and LSF and whole stover were calculated from the yields and IVDMD of the respective stover fractions.

2.5. Statistical analyses

Analysis of variance was performed for yields, morphological traits and nutritional attributes of the stover using a general linear model in SAS software (SAS, 2009). Homogeneity of variance was tested as described by Shapiro & Wilk (1965) prior to combined analyses over environments. Genotypes x environment interactions were examined using pooled analysis of variance that partitioned the total variance into the components of genotype, environment, genotype x environment interaction and pooled error. Environment (site-year combination) and replication were treated as random model in the analysis while the genotype was treated as fixed model. Differences among means were compared using the least significant difference (LSD) test ($P < 0.05$) in PROC MIXED with the PDIFF option of the LSMEANS statement. The association between the grain yield and yields of stover DM and DDM was examined using regression and graphs were developed using Sigma plot 10.0 (Systat Software, SanJose, CA) and R software (R CoreTeam, 2017).

3. RESULTS

3.1. Yields of maize grain and stover fractions, stover proportions, and morphological traits

Both the genotype and environment were significant ($P < 0.05$) sources of variation (> 83%) for yields of grain, stover fractions and whole stover, and stover morphological traits, but there were no significant ($P > 0.05$) G x E interactions for most yield and stover morphological parameters measured (Table 1). On average across the sites and years the yields of grain, USF and LSF were 5.80, 5.94 and 2.94 t ha^{-1}, respectively (Table 2). The yields of grain and USF varied ($P < 0.05$) among genotypes from 5.18 to 6.60 t ha^{-1} and from 5.40 to 6.56 t ha^{-1}, respectively. In general the grain and USF yields were higher in the higher rainfall environment of Bako (6.43 and 6.59 t ha^{-1} for B2013 and 7.44 and 6.04 t ha^{-1} for B2014, respectively) than in the lower rainfall environment of Melkassa, but the proportion of USF in whole stover was not affected by environment (Tables 1 and 2). Genotypes TH13321 and BH-546 had consistently higher yields of both grain (6.60 and 6.60 t ha^{-1}, respectively) and USF (6.56 and 6.38 t ha^{-1}, respectively) than the other genotypes. Moreover, the LSF yield was also high for genotype BH-546 (Table 2).

The proportion of USF was greater in the early-maturing than the medium-maturing genotypes. (Table 2).The USF accounted for, on average,674 g kg^{-1} of the whole stover, being highest (753 g kg^{-1}, $P < 0.05$) for the shortest genotype (MH-130) and lowest ($P < 0.05$) (602 and 626 g kg^{-1}) for the tallest genotypes (BH-543 and BH-546), respectively (Table 2).

TABLE 1 Analysis of variance and percent variation accounted by genotype (G), environment (E) and G x E for the attributes of plant height (PH), ear height (EH), above-ear height (AEH) (cm), upper stover fraction (USF) as a proportion of whole stover (WS), and yields (t ha^{-1}) of grain, stover fractions, WS and digestible dry matter (DDM) in USF, lower stover fraction (LSF) and WS for six maize genotypes, three each from early and medium maturity groups, grown at Bako and Melkassa in Ethiopia in the 2013 and 2014 cropping seasons.

Source of variation		Height			Proportion	Yield				DDM yield		
	df	PH	EH	AEH	USF	Grain	USF	LSF	WS	USF	LSF	WS
Genotype (G)	5	41.0***	74.0***	31.1***	89.7***	12.5***	30.7***	80.0***	51.3***	37.4***	86.5***	51.3***
Environment (E)	3	55.6***	21.3***	65.8***	$3.9^{ns\dagger}$	82.4***	57.3***	14.4**	40.6***	45.4**	5.2^{ns}	40.6***
G x E	15	2.1^{ns}	2.9^{ns}	1.9^{ns}	3.8^{ns}	3.6**	6.7^{ns}	3.3^{ns}	4.7^{ns}	9.8^{ns}	5.2^{ns}	4.7^{ns}
Residual	46	1.3	1.7	1.2	2.6	1.4	5.3	2.2	3.4	7.4	3.1	3.4
CV, %		5.5	8.7	6.1	4.9	13.3	10.6	16.1	10.3	10.9	18.2	10.3

**Significant at the 0.05 probability level. **Significant at the 0.01 probability level. ***Significant at the 0.001 probability level. †ns, nonsignificant.*

TABLE 2 Least squares means for plant height (PH), ear height (EH), above-ear height (AEH), upper stover fraction (USF) as a proportion of whole stover (WS), and yields of grain, USF, lower stover fraction (LSF), WS and digestible dry matter (DDM) of USF, LSF, and WS for six maize genotypes, three each from early and medium maturity groups, grown at Bako and Melkassa in Ethiopia in the 2013 and 2014 cropping seasons .

Source of variation	Height			Proportion	Yield				DDM yield		
	PH	EH	AEH	USF	Grain	USF	LSF	WS	USF	LSF	WS
Genotype	cm			g kg^{-1}			t ha^{-1}				
MH-130[a]	201	96	105	753	5.19	5.83	1.91	7.7	3.07	0.88	3.9
SC-403[a]	234	109	125	696	5.82	5.40	2.35	7.8	2.77	0.98	3.7
TH13321[a]	239	108	132	710	6.60	6.56	2.73	9.3	3.38	1.28	4.7
BH-540[b]	250	133	117	655	5.18	5.72	3.01	8.7	3.02	1.30	4.3
BH-543[b]	255	147	108	602	5.42	5.76	3.81	9.6	3.19	1.77	5.0
BH-546[b]	260	136	124	626	6.60	6.38	3.82	10.2	3.33	1.75	5.1
LSD	10.8	8.6	5.9	27.3	0.63	0.52	0.39	0.8	0.28	0.20	0.4
SE	3.8	3.0	2.1	9.6	0.22	0.18	0.14	0.3	0.10	0.07	0.1
Environment (site-year)	cm			g kg^{-1}			t ha^{-1}				
B2013[c]	251	123	128	669	6.43	6.59	3.33	9.9	3.41	1.41	4.8
B2014[d]	263	132	130	687	7.44	6.04	2.80	8.8	3.10	1.23	4.3
M2013[e]	226	119	107	665	4.50	5.54	2.89	8.4	2.94	1.33	4.3
M2014[f]	220	111	108	674	4.84	5.60	2.74	8.3	3.05	1.33	4.4
LSD	8.9	7.1	4.8	ns[†]	0.52	0.42	0.32	0.6	0.23	ns	0.3
SE	3.1	2.5	1.7	8.0	0.18	0.15	0.11	0.2	0.08	0.06	0.1
Mean	**240**	**121**	**118**	**674**	**5.80**	**5.94**	**2.94**	**8.9**	**3.13**	**1.33**	**4.5**

[a]Early-maturing genotypes. [b]Medium-maturing genotypes. [c]Bako site in 2013 cropping season. [d]Bako site in 2014 cropping season. [e]Melkassa site in 2013 cropping season. [f]Melkassa site in 2014 cropping season.

. LSD, least significance difference at $P < 0.05$; SE, standard error; [†]ns, nonsignificant.

The contributions of the morphological components, the LSR, the LHSR and stem diameters, varied ($P < 0.05$) among genotypes and also by environments ($P < 0.001$) for some attributes (Supplemental Tables S1 and S2). Within the USF the upper-stem constituted the highest proportion (mean 484 g kg^{-1}), followed by the husk (310 g kg^{-1}) and then upper-leaf (206 g kg^{-1}). Stems formed most (mean 809 g kg^{-1}) of LSF (Table S1). The LHSR in the USF varied ($P < 0.05$) among genotypes, ranging from 0.91 to 1.22 and varied between environments ($P < 0.05$). The stem diameter in both upper and lower stover varied ($P < 0.05$) among genotypes, ranging from 0.78 to 0.93 cm and from 1.92 to 2.33 cm, respectively. However no such differences were observed between environments (Table S2).

The DDM yield of USF averaged 3.13 t ha^{-1} and ranged from 2.77 to 3.38 t ha^{-1}, and was highest for the genotypes with highest yields of grain and USF (TH13321 and BH-546 yielding 3.38 ± SD 0.48 t $ha^{-1}$and 3.33 ± SD 0.24 t ha^{-1}, respectively) (Table 2). The DDM yields of the various morphological components of stover also varied among genotypes ($P < 0.01$) except for the DDM yield of upper-leaves (Supplemental Table S4). Genotypes TH13321 and BH-546 had higher DDM yields than the other genotypes for all the morphological fractions measured.

3.2. Chemical composition and *in-vitro* DM digestibility of upper and lower stover fractions and their morphological components

Both genotype and environment affected ($P < 0.01$ or $P < 0.001$) the stover quality attributes (> 82% of the variation) with environment always having the greater effect, but there were no significant ($P > 0.05$) G x E interactions for most stover quality attributes measured (Table 3). The IVDMD (mean 527 g kg^{-1} DM) and N concentration (mean 8.5 g kg^{-1} DM) of USF were higher ($P < 0.001$ or $P < 0.05$) than in LSF (by 77 and 2.3 g kg^{-1} DM units, respectively) or in whole stover (by 25 and 0.8 g kg^{-1} DM units, respectively; Table 4). The IVDMD and N concentration of the USF varied among genotypes ($P< 0.01$), ranging from 513 to 554 g kg^{-1} DM and 7.8 to 9.7g kg^{-1} DM, respectively. At Melkassa lower IVDMD and total N concentrations, and higher NDF and ADF concentrations ($P < 0.05$) were observed in both the upper and lower stover during the 2013 than the 2014 cropping season. However no such differences between years were observed at Bako.

TABLE 3 Analysis of variance and percent variation accounted by genotype (G), environment (E), and G x E for the attributes *in-vitro* dry matter digestibility (IVDMD), total N (N), neutral detergent fiber (NDF) and acid detergent fiber (ADF) concentrations (g kg^{-1} DM) of upper and lower stover fractions and whole stover for six maize genotypes, three early and three medium maturity, grown at Bako and Melkassa in Ethiopia in the 2013 and 2014 growing seasons.

Source of variation	df	Upper stover				Lower stover				Whole stover			
		IVDMD	N	NDF	ADF	IVDMD	N	NDF	ADF	DMD	N	NDF	ADF
Genotype (G)	5	36.9***	37.2**	10.7*	29.2***	23.6***	28.3**	30.3***	35.6***	20.1***	26.2*	15.2**	29.2***
Environment (E)	3	56.8***	45.9**	82.0***	65.3***	64.7***	55.5***	51.9***	46.0***	71.4***	56.0**	74.9***	61.5***
G x E	15	2.6^{ns†}	7.0^{ns}	4.1^{ns}	2.8^{ns}	8.5**	8.7^{ns}	12.9**	14.2***	5.1^{ns}	7.7^{ns}	6.4^{ns}	6.0^{ns}
Residual	46	3.7	9.9	3.3	2.7	3.3	7.5	4.9	4.1	3.4	10.1	3.5	3.2
CV, %		3.0	15.4	2.7	2.9	5.6	22.7	3.7	4.6	3.4	16.9	2.8	3.4

**Significant at the 0.05 probability level. **Significant at the 0.01 probability level. ***Significant at the 0.001 probability level. †ns, nonsignificant.*

TABLE 4 Least squares means for *in-vitro* dry matter digestibility (IVDMD), and concentrations of total N (N), neutral detergent fiber (NDF), and acid detergent fiber (ADF) of upper and lower stover fractions and whole stover for six maize genotypes, three each from early and medium maturity groups, grown at Bako and Melkassa in Ethiopia in the 2013 and 2014 growing seasons.

Source of variation	Upper stover				Lower stover				Whole stover			
Genotype	IVDMD	N	NDF	ADF	IVDMD	N	NDF	ADF	IVDMD	N	NDF	ADF
						g kg^{-1} DM						
MH-130[a]	526	8.0	764	436	460	5.7	775	525	510	7.5	767	458
SC-403[a]	513	7.8	773	461	418	4.9	811	560	485	6.9	785	491
TH13321[a]	517	7.9	752	443	466	5.9	752	504	502	7.3	752	460
BH-540[b]	528	8.9	773	446	433	7.0	788	557	496	8.3	778	484
BH-543[b]	554	9.7	761	426	465	6.8	799	542	519	8.5	776	472
BH-546[b]	523	8.7	783	452	458	6.7	797	541	499	7.9	788	485
LSD	13.1	1.1	17.3	10.7	20.9	1.1	23.9	20.1	13.8	1.1	18.1	1.31
SE	4.6	0.4	6.1	3.8	7.3	0.4	8.4	7.1	4.9	0.4	6.4	4.6
Environment (site-year)					g kg^{-1} DM							
B2013[c]	517	7.8	773	447	421	4.9	792	546	485	0.69	780	480
B2014[d]	513	8.6	768	452	437	6.6	789	545	489	0.80	775	481
M2013[e]	532	8.3	795	455	459	6.2	811	552	508	0.76	800	488
M2014[f]	545	9.4	735	422	482	7.0	757	509	525	0.86	742	451
LSD	10.7	0.9	14.1	8.8	17.0	0.9	19.5	16.5	11.3	0.09	14.8	10.7
SE	3.8	0.3	5.0	3.1	6.0	0.3	7.0	6.0	4.0	0.03	5.2	3.8
Mean	**527**	**8.5**	**768**	**444**	**450**	**6.2**	**787**	**538**	**502**	**7.7**	**774**	**475**

[a] *Early-maturing genotypes.* [b] *Medium-maturing genotypes.* [c] *Bako site in 2013 cropping season.* [d] *Bako site in 2014 cropping season.* [e] *Melkassa site in 2013 cropping season.* [f] *Melkassa site in 2014 cropping season. LSD, least significance difference at P <0.05; SE, standard error.*

There were generally large differences due to genotype and environment ($P < 0.05$) in both the IVDMD and N concentrations of the various morphological components within the upper and lower stover measured at both sites in 2014 cropping season (Supplemental Table S3). The IVDMD of stem and husk components in the USF were higher ($P < 0.0001$) in the lower rainfall environment at Melkassa (514 and 592 g kg^{-1} DM, respectively) than in the higher rainfall environment at Bako (462 and 538 g kg^{-1} DM, respectively) (Table S3).

Analysis of the pooled data from mean values for each of the genotypes in each environment showed that grain yield was correlated with both the DM yield (r = 0.61; $P < 0.001$) and DDM yield of the USF (r = 0.50; $P < 0.001$) (Supplemental Figures

S3a and S3b). However, grain yield was correlated to a lesser extent with the DM yield of LSF (r = 0.26; $P < 0.05$) and was not related to the DDM yield of LSF (r = 0.15; $P = 0.21$). Furthermore, the correlations between grain yield with yields of DM and DDM of the USF were closer for early-maturing genotypes (r = 0.73 and 0.62, respectively; $P < 0.001$) than for medium-maturing genotypes (r = 0.55; $P < 0.001$ and r = 0.37; $P < 0.05$, respectively).

4. DISCUSSION

4.1. Yields of grain and stover, chemical composition and *in-vitro* DM digestibility of upper and lower stover and their morphological components

There was substantial variation among genotypes in yields of grain and stover, stover chemical composition, IVDMD, and the DDM yields of the upper and lower stover. This is in agreement with the report of Liang *et al.* (2015) that there was variation in yields of biomass and nutrients and stover quality attributes among five maize cultivars in a study in China that might result from genetic differences in morphological characteristics of various cultivars or maturity at harvest.

In accord with the hypothesis that the USF of maize stover would be higher in nutritive value, the, concentrations of N and IVDMD were higher, and those of ADF were lower, in the USF than the LSF (Table 4). This was likely due to N translocation from older to younger plant tissues (Kalmbacher, 1983) and the expected gradient of physiological cell wall age and lignification from the base to the top of the stem of the maize plant. It has been shown that in general the N concentration and IVDMD of the stem tissue decreases, and the ADF concentration increases, from the top to the bottom of the stem of grass plants; thus there is a trend for increasing N concentration and IVDMD with increasing height in the plant (Jung *et al.*, 1998; Lam *et al.*, 2013).

The genotype differences in nutritional quality of the USF and LSF (Tables 3 and 4) appeared to be associated primarily with the differences in the proportions of morphological fractions, and especially in the stem proportion (Tables S1 and S2). Stem comprised the largest fraction of both the USF and LSF (484 and 809 g kg^{-1} DM, respectively) (Table S1) and stem had the lowest IVDMD (488 and 426 g kg^{-1}DM in USF and LSF, respectively) (Table S3). This is in agreement with the report of Tolera and Sundstøl (1999) that the stem comprises the highest proportion (450 to 530 g kg^{-1}) of maize stover, and is the most important fraction influencing its nutritive value. Similarly, Hansey *et al.* (2010) reported that at physiological maturity of maize the stems comprised the largest fraction of the plant (460 g kg^{-1}) and had the lowest neutral detergent fiber digestibility (380 g kg^{-1}). Furthermore the differences in N concentration and IVDMD of each morphological fraction of the stover in the current study were in agreement with the previous reports (Li *et al.*, 2014; Lynch *et al.*, 2014; Tang *et al.*, 2008; Tolera & Sundstøl, 1999). It is well established that in grass plants such as maize the leaf is higher in N concentration and DM (or organic matter) digestibility than the stems (Petzel *et al.*, 2019; Tolera & Sundstøl, 1999).

The two genotypes with the highest grain yields in the current study (TH13321 and BH-546) also had high yields of DM and DDM in the USF. In addition, genotype BH-546 had higher yields of DM and DDM in the LSF than other genotypes (Table 2). These results demonstrated that superior genotypes that have higher yields of both grain and stover fractions, and also higher stover nutritional quality, can be identified. Furthermore, a strong association observed in the present study between upper stover DDM yield and grain yield ($r = 0.50$; $P < 0.001$) indicates that there is opportunity to select genotypes for higher yields of both grain and DDM in the USF (Figure S3b). The higher yielding genotypes (TH13321 and BH-546) in the present study also had a LHSR (1.07 and 1.11, respectively) in the USF comparable with the other genotypes (MH-130, SC-403, BH-540 and BH-543) (Table S2). These traits are easily measured in the field and if the LHSR provides consistent prediction of the yield of DDM in USF, it may be useful for rapid screening to identify genotypes with higher yields and nutritive value of USF. Combining the most appropriate genotype with higher stubble heights should offer opportunities to supply more maize stover of higher quality as a feed for livestock and a greater quantity of mulch for soil amendment, potentially reducing conflict between the allocations of the stover to competing uses. It has been shown that multi-objective crop improvement programs can improve both human food and livestock feed and at least in some circumstances may be easily out-scaled (McDermott *et al.*, 2010).

Maize performance was also influenced by environment (Table 1). The result of the present experiment supports the hypothesis that there are options for farmers to select more suitable genotypes in a given region to achieve higher yields of both stover and grain. The differences between environments for yields of grain and USF and plant height (all higher at Bako than Melkassa) are in accord with higher and well distributed rainfall during the growing seasons at the former site. The Bako site represents sub-humid areas with a high rainfall environment and the rainfall well distributed through the growing seasons, whereas the Melkassa site represents semi-arid maize growing areas with a low and erratic rainfall. The lower IVDMD and total N, and higher NDF and ADF, in both upper and lower stover at the Melkassa site in 2013 than in 2014 (Table 4), were likely due to the higher rainfall in 2013 (Figure S2). This contrasts with an absence of such between-year difference in stover quality attributes at Bako (Table 4) where there was no water stress through the cropping seasons (Seyoum *et al.*, 2018). Similarly, lower IVDMD and higher proportions of fiber in the straw of temperate barley, wheat and oat cereals grown in years with high rainfall were reported by Ørskov *et al.* (1990). This evidence indicates that quality attributes of maize stover may be partly associated with the rainfall and moisture stress during growth.

4.2. Plant morphological traits and the proportions of upper and lower stover fractions

The genotype differences observed in yields and nutritional quality of the stover fractions (Tables 2 and 4) appeared to be associated with the inherent differences in plant morphological traits (example plant heights), the proportions of morphological fractions (especially the stem proportion), and dual-purpose characteristics or maturity at harvest among the genotypes tested. The greater ear and plant heights in the medium-maturing genotypes than in the early-maturing genotypes (Table 2) were in accord with the findings of both Dijak *et al.* (1999) and Tadesse (2014) that later maturing genotypes tend to have taller plant heights. Pooled analysis of the data from both sites and years also showed that (1) strong and significant association between plant height and yields of USF ($r = 40$; $P < 0.001$), LSF ($r = 0.65$; $P < 0.0001$) and whole stover ($r = 0.63$; $P < 0.0001$), and (2) a significantly positive relationships ($P < 0.001$) between grain yield with plant height, ear height and above-ear height (Data not shown). Interestingly in the present study the higher proportions of USF in early-maturing than in medium-maturing genotypes were also associated with ear height (Table 2). If these differences occur generally and are stable they may be useful as a simple tool to inform selection of genotypes and/or cut height decisions. In addition the observation that the proportions of upper and lower stover did not vary with environment (Table 1) suggests that selection for a high proportion of USF and LSF may be based on genotype without consideration of environment.

The study demonstrated that high stubble height of maize at harvest can provide a USF substantially higher in both IVDMD and N concentration than whole stover (WS). The average increases of IVDMD and N by 25 and 0.8 g kg^{-1}DM units, respectively, relative to WS in the present study would provide substantial increases in the nutritional value of the stover as a ruminant feedstuff. Moreover, the higher leaf and husk proportion and thinner stems in the USF (Supplemental Tables S1 and S2) than in whole or lower stover is also likely to increase voluntary intake of stover and thus animal productivity.

4.3. Implications for improving productivity through crop residue management in conservation agriculture

Soil erosion and the decline of soil organic matter and fertility is one of the most important constraints to enhanced crop productivity in sub-Saharan Africa and elsewhere globally (Cong *et al*., 2016; Erenstein *et al*., 2015; Guto *et al.,* 2012; Karlen *et al.,* 2019; Sanchez & Jama, 2002). Organic resources, such as animal manures and plant residues, can enhance soil organic matter and improve long-term soil fertility. The bulky nature of animal manure and the nutrient losses at various stages from manure production to field application can limit its practicality in a wider scale under smallholder systems (Rufino *et al*., 2007). Crop residues need to be returned to the soil on a regular basis and in adequate amounts so as to maintain soil fertility. On the other hand, farmers also need to sustain and feed their livestock (Giller *et al*., 2009).

The supply of large amounts of CR required as mulch to maintain soil fertility and reduce soil erosion has been challenging due to the demands for CR to feed livestock (Baudron *et al.*, 2014; Erenstein *et al.*, 2015; Giller *et al.*, 2009; Larbi *et al.*, 2002; Rodriguez *et al.*, 2017; Tittonell *et al.*, 2015). Current recommendations are that at least 30% of the soil surface should be covered with crop residue mulch (Erenstein *et al.,* 2003). Providing this coverage of mulch will presumably be particularly difficult where crop production and biomass yields are low, or where there are high livestock populations and/or profitable markets for CR as fodders (Rusinamhodzi *et al.*, 2015; Duncan *et al.*, 2016). Balancing the use of maize residues for soil amendment and forage is an important strategy for agricultural sustainability (S.Z. Tian *et al.,* 2016). In principle it is clearly advantageous to preferentially allocate various crop residue fractions to the use for which they have the highest biological and economic value. The present study indicates the potential advantages of allocating the USF of maize stover for use as ruminant feed providing that there is little disadvantage to use of the LSF for CA.

The results of the present experiment show that the LSF remaining in the field with high stubble height would be of low quality as a feed due to the low N concentration, but feed quality would also be reduced by the low proportion of leaf and the thick, fibrous and unpalatable stems. Clearly information is needed on the suitability of the lower mature stems in maize stubble for soil coverage and mulch in each maize growing environment. However providing that the LSF is of comparable value for CA as observed in China by Liang *et al.* (2015) and S.Z. Tian *et al*. (2016), the use of a high stubble height of maize stover should provide a simple ‘win-win’ management strategy to make best use of maize stover to provide ruminant feed as well as to provide mulch. In the present experiment the highest yielding genotype (BH-546) provided upper and lower stover yields of 6.38 and 3.82 t ha^{-1}, respectively (Table 2) and could be used as ruminant feed and mulch, respectively. Two studies in Chinese farming systems in Hebei Plain and Shandong province support these conclusions. For instance Liang *et al.* (2015) reported that the upper two-thirds of the stover of several cultivars were valuable as a ruminant feed while the lower third part of the stover with higher fibre and lower N was more suitable for mulch. Also S.Z. Tian *et al*. (2016) compared four maize stover stubble heights and concluded that 34% (3.6 t ha^{-1} year^{-1}) stover retention (with a cutting height of 0.5 m) was optimal to provide a substantial amount of the USF (66%; 6.2 t ha^{-1} year^{-1}) of higher quality feed for ruminants without adverse effects on the soil C and N levels and associated economic benefits.

Crop residue management (mulching) effects on soil are complex and are influenced by many factors, and in addition the benefits of CR mulching are highly context specific (Giller *et al*., 2009; Karlen *et al.,* 2019; Mupangwa *et al.,* 2019; Oladeji *et al.,* 2006; Rufino *et al*., 2007; G. Tian *et al.,* 1993a,1993b; G. Tian *et al.,* 2007; S.Z. Tian *et al.,* 2016). For instance, the study of Larbi *et al*. (2002) suggested that 25-50% of the total CR could be removed as livestock feed without any adverse effect on grain yield and soil organic C, N, and P while retaining for mulch 50 to 75% of the total CR (3.28 to 5.60 t ha^{-1}) in the environment studied (West African humid forest and savanna zones). Similarly, Mupangwa *et al.* (2019) demonstrated that mulching at 0, 2, 4, 6 and 8 t ha^{-1} year^{-1}with maize stover resulted in little increase in grain yield over 6 years even in low rainfall locations in South Africa. These studies suggest that smallholder farmers can apply low to moderate levels of stover (e.g. 2 to 4 t ha^{-1}) and still obtain the benefits of CA (Mupangwa *et al.,* 2019).

A further consideration is that apart from their availability, the CR of maize and other cereal crops may have disadvantages of N availability especially when large amounts of low quality cereal CR are retained as mulch. The low concentrations of N and other minerals in maize stover and other cereal CR are likely to induce short-term nutrient deficiencies due to their high C:N ratio (Larbi *et al.,* 2002; Mupangwa *et al.,* 2019; Palm *et al.,* 2001; Vanlauwe & Giller, 2006) that can reduce crop yield (Giller *et al*., 2015). Combining low quality CR like maize stover with fertilizer inputs altered the temporary C and N mineralization (Gentile *et al*., 2011; Gomez-Macpherson & Villalobos, 2015; Mupangwa *et al.,* 2019), although the short-term nutrient immobilisation effect is context specific and influenced by the interactions between residue quality and agro-ecology (G. Tian *et al.,* 2007). These authors confirmed that the low quality plant residue could decompose and release N and P faster in dry than wet zones.

These studies illustrate the complexity of the processes associated with soil mulching. We hypothesize that various appropriate fractions of CR can be used for both soil mulching and livestock feeding without adversely affecting crop productivity and for improving whole-farm productivity (Baudron *et al.,* 2014). The benefits of mulching can be obtained from the taller stubble height of maize stover by retaining all of the LSF (2.73 and 3.82 t ha^{-1}) provided by the highest yielding early and medium maturing genotypes, respectively in the present study (Table 2) (Liang *et al.,* 2015; S.Z. Tian *et al*., 2016). The benefit of mulching is likely especially if combined with about 30 kg N ha^{-1} to offset the short-term N immobilization (Mupangwa *et al.,* 2019). The corresponding USF (6.56 and 6.38 t ha^{-1}, respectively) can be used as feed for ruminants to improve whole-farm productivity outcome.

A further consideration for evaluation of feed resources is that almost all studies have reported the availability of maize stover as the total above ground biomass (Baudron *et al.*, 2014; Duncan *et al.*, 2016; Ertiro *et al.*, 2013; FAO, 2018; Jaleta *et al.*, 2015; Tolera *et al.*, 1999). Consideration is needed to the amounts and attributes of various fractions of the stover relative to the practicality of separating stover fractions for different uses. The simple manipulation of height of cutting the stover, as used in the present study, provides one valuable option likely applicable globally and to many crop-livestock systems where maize and other thick-stemmed cereals sorghum and millet are major crops.

The concepts of the present study have the advantages that high stubble height: (1) is very simple and easy to implement on-farm, (2) provides an on-farm approach to obtaining forage of high feed quality for ruminants, (3) is based on well-established knowledge that the higher feed quality of the USF than the LSF is a real and consistent difference, (4) is applicable globally and to many smallholder crop-livestock systems in developing countries where maize and other thick-stemmed cereals sorghum and millet are major crops, and where there is often a scarcity of ruminant feed resources. This is the first study to demonstrate these two uses of CR from maize stover from various genotypes and environments at grain harvest maturity. It also identified superior genotypes that have higher yields of both grain and stover fractions (upper and lower stover) and also higher stover nutritional quality of the USF. This research provides new insights for multi-objective crop improvement programs for improving both human food and livestock feed, and for animal nutritionists for evaluating feed resources of various fractions of the stover relative to the practicality of separating stover fractions for different uses (feed and mulch) for improved whole-farm productivity and adoption of CA in developing countries.

5. CONCLUSION

The study established that a simple management change to cutting height of maize stover at grain harvest could provide an USF as a ruminant feed that is substantially higher in IVDMD and N concentration than whole stover. The results were in accord with the hypotheses that the high-cut procedure used (i) allowed harvests of about two-thirds of the whole stover as USF that provided about 6 t ha^{-1} of higher quality ruminant feed, while leaving about 3 t ha^{-1} of a LSF as stubble that would be less suitable for livestock feed and available for mulch, and (ii) a higher nutritive value of the USF is consistent across maize genotypes and growing environments. Obviously cutting height can be adjusted to provide the most appropriate proportions of USF and LSF for the circumstances. High-cut management of maize stover at harvest is likely best used with high-yielding genotypes and has the potential to reduce conflict between the competing uses of maize stover and improve whole-farm productivity outcome. Nevertheless, N concentrations in the USF were still generally low so that additional diet N would still be required for best use of USF as a feed for ruminants.

This study showed that recently developed varieties, TH13321 (early) and BH-546 (medium), with higher grain yield also had higher yields of stover fractions indicating that genotype selection for both higher stover fractions and grain yield can be done simultaneously. The genotype differences observed in yields and nutritional quality of the stover fractions appeared to be associated with the inherent differences in plant morphological traits (plant heights), the proportions of morphological fractions (especially the stem proportion), dual-purpose characteristics or maturity at harvest among the genotypes tested. An improved understanding of genotype differences on stover morphological traits (characteristics of plant height, ears insertion heights, and proportions of morphological fractions), yields of grain and stover fractions, and quality traits of the stover fractions should also allow more accurate estimates of the stover biomass available for livestock and mulch.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

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