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AGRONOMIC PERFORMANCE, NUTRITIONAL VALUE, AND SIMULATION OF THE IMPACTS OF CLIMATE CHANGE ON GROWTH AND YIELD OF FOUR *BRACHIARIA* (TRIN.) GRISEB. (SYN. *UROCHLOA* P. BEAUV.) SPECIES UNDER TWO LOCATIONS IN CENTRAL AND WESTERN ETHIOPIA

PhD Dissertation

By

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Addis Ababa University, College of Veterinary Medicine and Agriculture

Department of Animal Production Studies

PhD program in Animal Production

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Bishoftu, Ethiopia

AGRONOMIC PERFORMANCE, NUTRITIONAL VALUE, AND SIMULATION OF THE IMPACTS OF CLIMATE CHANGE ON GROWTH AND YIELD OF FOUR *BRACHIARIA* (TRIN.) GRISEB. (SYN. *UROCHLOA* P. BEAUV.) SPECIES UNDER TWO LOCATIONS IN CENTRAL AND WESTERN ETHIOPIA

A dissertation submitted to the College of Veterinary Medicine and Agriculture, Addis Ababa University, in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Animal Production

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Statement of the author

I first declare that this dissertation is my bonafide work, and that all sources of materials used for this dissertation have been duly acknowledged. This dissertation has been submitted to the requirements for a Ph.D. Degree at Addis Ababa University, College of Veterinary Medicine and Agriculture, and is deposited at the University's Library to be made available to borrowers under the rules of the Library. I solemnly declare that this dissertation has not been submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate.

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Biographical sketch

I, the author of this dissertation, was born in November 1986 in Bila Town, Gudeyya Bila District, East Wallaga Zone, Oromia, Ethiopia. I completed my primary and secondary education at Bila Primary and Bako Secondary Schools. Then, I joined Asella Agricultural Technical Vocational and Education Training College and graduated with a Diploma in Animal Science in 2006. Following my graduation, I began working as a livestock expert at the Gudeyya Bila District Agricultural Office, where I served for one year and 10 months. In June 2008, I was affiliated with Wallaga University as a technical assistant and served for one and a half years. In November 2009, I worked as a technical assistant at the Ethiopian Institute of Agricultural Research Center, Debre Zeit Agricultural Research Center. Thereafter, I joined Yardstick International College and graduated with a Bachelor of Science (B.Sc.) degree in Agribusiness Development and Management in 2013. In 2014/15, I pursued a Master of Science (M.Sc.) degree in Animal Production at Addis Ababa University, College of Veterinary Medicine, and graduated in July 2016. In November 2016, I rejoined Wallaga University as a lecturer in the Department of Animal Science. As an instructor, I served for five years by teaching and guiding students in the field of Animal Science, served as Head of the Department of Animal Science (two years), and participated in several extracurricular activities. After accumulating several years of valuable experience, I joined Addis Ababa University, College of Veterinary Medicine and Agriculture, in September 2019/20, AY to pursue a Ph.D. in Animal Production. Throughout my academic journey, I have published 14 articles in reputable journals, three of which are from my dissertation work.

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List of Acronyms and Abbreviations

°C	degree Celsius
ADF	acid detergent fiber
ADG	average daily gains
ADL	acid detergent lignin
ANOVA	Analysis of variance
AOAC	Association of Official Agricultural Chemists
BARC	Bako Agricultural Research Center
BD	bulk density
CIMMYT	International Maize and Wheat Improvement Center
CORDEX	Coordinated Regional Climate Downscaling Experiment
CO_2	Carbon dioxide
CP	crude protein
CPY	crude protein yield
CROPGRO-PFM	CROPGRO-Perennial Forage Model
CSA	Central Statistical Agency
DAP	Diammonium phosphate
DM	Dry matter
DM/day	Dry matter per day
DMI	Dry matter intake
DOMI	digestible organic matter intake
DP	dressing percentage
DSSAT	Decision Support System for Agrotechnology Transfer
DUL	drained upper limit;
DZARC	Debre Zeit Agricultural Research Center
EBW	empty body weight
ECO	ecotype
EME	estimated metabolizable energy
FAO	Food and Agriculture Organization
FBW	Final body weight
FCE	Feed conversion efficiency

GDP	gross domestic product
g/day	gram per day
g	gram
h	hour
HA	harvest area
HARC	Holetta Agricultural Research Center
HCW	hot carcass weight
IBW	initial body weight
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Reference and Information Centre
IVDMD	*In vitro* dry matter digestibility
Kg	Kilogram
LDM	Longissimus dorsi muscle
LL	lower limit of plant extractable soil moisture;
LME	Linear mixed-effect model
LSD	least significant difference
m^2	square meter
MJ/kg	megajoules per kilogram
mm	millimeters
MRR	marginal rate of return
N/ha	nitrogen per hectare
NDF	Neutral detergent fiber
N	Nitrogen
NR	Net return
NRC	National Research Council
ns	non-significant
NSC	noug seed cake
OC	organic carbon
OM	Organic matter
SOC	Soluble organic carbon
PH	Plant height

RCP	Representative Concentration Pathway
REMA	rib-eye muscle area
RF	Rainfall
RMSE	Root mean square error
SBW	slaughter body weight
SEM	Standard Error Mean
SOM	soil organic matter
SPE	species genetics file
SSAT	saturated soil water content
SSDW	subsample dry weight
SSFW	subsample fresh weight
ppm	parts per million
$t\ ha^{-1}$	tonnes per hectare
TBWG	Total body weight gain
TEO	Total edible offal
TEOC	Total edible offal components
TFW	total fresh weight of the harvested area
TN	total nitrogen.
TNEO	Total non-edible offal.
TNEOC	total non-edible offal components
TR	total returns
TVC	total variable costs
ΔNR	change in net return
ΔTR	change in total return
ΔTVC	change in total variable cost

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Agronomic Performance, Nutritional Value, and Simulation of the Impacts of Climate Change on Growth and Yield of four *Brachiaria* (Trin.) Griseb. (Syn. *Urochloa* P. Beauv.) Species Under Two Locations in Central and Western Ethiopia

Abstract

Ethiopia has the largest livestock population in Africa, yet productivity is limited by chronic feed shortages, largely due to shrinking pasturelands, poor-quality crop residues, and the increasing impacts of climate change. Improved forages like Brachiaria grass offer a promising solution. However, adaptation must prioritize not only biomass yield but also nutritional quality and climate resilience. This study aimed to evaluate the agronomic performance, feeding value, and simulate the growth and yield of Brachiaria species under future climate scenarios in central and western subhumid agroecology of Ethiopia. Four Brachiaria (syn. Urochloa) species—B. mutica, B. brizantha, B. decumbens, and B. humidicola— was compared with Rhodes and Desho grasses (2020–2022). Results showed significant effects of species, year, and interactions. B. mutica revealed the highest DM yield, followed by B. brizantha and Desho grass. CP yield showed a similar pattern. The highest CP content was in B. humidicola, followed by B. mutica and B. brizantha, while Desho grass had the lowest. No significant differences were observed in NDF and lignin. Rhodes grass had the highest ADF, while B. humidicola had the highest ash content. IVDMD was highest in B. humidicola and B. brizantha, and lowest in Rhodes grass. B. mutica and B. brizantha emerged as the most promising forages for subhumid areas. In the feeding value trial, Arsi-Bale rams were fed B. mutica hay supplemented with 100, 200, 300, or 400 g/day of concentrate (noug seed cake and wheat bran). Higher supplementation significantly improved DM intake, digestibility, and growth rates. Rams fed 300 g and 400 g showed the highest gains, with no significant difference between them. Carcass traits, including carcass weight, dressing percentage, and rib-eye area improved with increased supplementation. Economic analysis showed that 200–300 g/day supplementation offered the best cost–performance balance. Thus, supplementing B. mutica hay with 300 g/day of concentrate optimizes growth and return, while 200–300 g/day is recommended for cost-effective feeding. Further research is needed to validate these findings under small-holder farmer conditions. The CROPGRO-PFM

simulation model predicts that B. brizantha showed increases in shoot (9%), herbage (11%), and stem (25%) biomass, but a 7% reduction in leaf biomass and CP content. B. humidicola followed a similar trend. In contrast, B. mutica showed projected biomass reductions of up to 34% by the end of the century and a 14–20% drop in CP content. Overall, B. brizantha and B. humidicola appear more resilient to climate change, while B. mutica is more vulnerable. Further research is recommended to refine adaptive strategies, improve crop management, and support sustainable livestock production in Ethiopia.

Keyword: *Brachiaria*, CROPGRO-PFM, Climate change impact, Digestibility, Dry matter yield, Nutritional value, Supplementation

CHAPTER 1. General Introduction

1.1. General Background and Justification of the Study

Ethiopia possesses the largest livestock population in Africa, with an estimated population of 66.26 million cattle, 38.01 million sheep, 45.72 million goats, 2.14 million horses, 10.02 million donkeys, 0.36 million mules, and 41.35 million chickens (CSA, 2022). The sector contributes substantially to both households and the national economy, accounting for approximately 49 percent of agricultural gross domestic product (GDP) and up to 21 percent of the national GDP (Shapiro *et al*., 2017). Livestock supports the livelihoods of more than 80 percent of rural communities by providing income, milk, meat, manure, and draught power while also generating foreign exchange earnings (Behnke, 2010; ICPALD, 2013; Asresie & Zemedu, 2015). Moreover, the sector is evolving, driven by a rapidly growing demand for livestock products.

Despite its economic significance, this sector has underperformed relative to expectations (Bachewe *et al*., 2018). Supply has not kept pace with demand, primarily because of low productivity, with feed shortages being the foremost bottleneck (FAO, 2018). In Ethiopia, the major feed resources include natural pasture (57.77%) and crop residues (29.75%), whereas improved forage contributes less than 1% (CSA, 2022). However, the availability of natural pastures has declined over time due to poor management and the expansion of crop farming (Hassan *et al*., 2020). Crop residues, although increasing over time, are characterized by high fiber content (>55%) and low crude protein content (<7%) (Fekadu *et al*., 2010). Overall, feed shortages, particularly of grasses and fodder, continue to limit livestock productivity (Assefa *et al*., 2016). Furthermore, climate change has intensified feed challenges, highlighting the urgent need for high-quality drought-resilient forage technologies that can be integrated into existing feeding systems (Wheeler & Reynolds, 2013).

Improved forage species have a significant potential to enhance feed availability and productivity in ruminant farming, especially when nutrient-rich, high-biomass varieties are utilized. Efforts to introduce improved forage crops in Ethiopia began in the mid-1960s with the intention of increasing high-quality roughage availability in mixed farming

systems (Assefa *et al*., 2016; Feyissa *et al*., 2022). However, adoption rates remain low, with less than 1 percent of farmers participating (CSA, 2022; Tesfaye & Tessema, 2023). Adoption of improved pastures is notably higher in market-oriented systems such as crossbred dairy production and livestock fattening, where economic returns are greater (Kebebe, 2015; Tesfaye & Tessema, 2023).

Forage research programs have been going on over the past decades for selecting suitable forage grass species that have identified several species that are adapted to Ethiopia's diverse agro-ecological zones (Feyissa *et al*., 2022; Zeleke *et al*., 2022). Evaluations of various species have led to the release of promising forage varieties assessed for ease of establishment, biomass yield, and resistance to pests and diseases. Among these, *Brachiaria* grass stands out as a promising option for alleviating ruminant feed shortage.

Brachiaria originates from tropical Africa, particularly East Africa, including Ethiopia (CIAT, 1992; Renvoize *et al*., 1996; Tegegn *et al*., 2019). Outside Africa, it has been commercially adopted and has significantly enhanced livestock industries in Latin America, the Caribbean, Asia, and Australia (Jank *et al*., 2014; Schiek *et al*., 2018). *Brachiaria* offers high herbage biomass, superior nutritional value, drought tolerance, adaptability to low-fertility soils, carbon sequestration, and enhanced nitrogen use efficiency through the inhibition of biological nitrification (IBN) (Arango *et al*., 2014; Moreta *et al*., 2014; Rao *et al*., 2014). Moreover, several initiatives are promoting *Brachiaria* as a climate-smart forage species to support East Africa's growing livestock industry (González *et al*., 2016; Muinga *et al*., 2016; Schiek *et al*., 2018).

Selecting forage species with high adaptability, nutritional quality, and climate resilience is essential in Ethiopia. However, past programs have primarily focused on environmental adaptation and biomass yield, with limited attention paid to nutritional quality, animal performance, and the impacts of climate change. Thus, establishing a comprehensive database of forage quality, feeding value, and productivity under future climate scenarios across Ethiopia's agro-ecological zones is vital to support the adoption and effective utilization of improved forage.

Brachiaria grass, recognized for its adaptability and nutritional value, offers a promising solution for enhancing livestock feeding systems in Ethiopia (Feyissa *et al*., 2022; Zeleke *et al*., 2022; Dereje *et al*., 2024). Its integration into feeding programs can significantly improve growth performance and carcass characteristics, particularly when supplemented with protein-rich diets (Adnew *et al*., 2021). Studies have shown that strategic supplementation of forage significantly improves feed conversion efficiency, growth rates, and carcass quality (McDonald *et al*., 2010; Huang *et al*., 2023; Osman *et al*., 2023).

A major challenge in forage development lies in assessing the long-term climate change impacts on forage production, despite the availability of a range of forage options and their nutritional profiles (Santos *et al*., 2022). This concern arises because forage growth and grass characteristics are highly sensitive to climatic variables such as rainfall, temperature, and solar radiation (Taiz & Zeiger, 2002; Zarei *et al*., 2021). The effect of climate change on forage crop production can be assessed by agro-climatic zoning methods, which link plant productivity with weather conditions using either mechanistic or empirical agro-meteorological models. In response, various crop models have been developed to simulate the long-term influence of environmental changes and management practices on plant growth (Andrade *et al*., 2015). Among these, the CROPGRO-Perennial Forage model has been effectively utilized to evaluate the growth and biomass yield of *Brachiaria* grass and other tropical perennial forage species (Lara *et al*., 2012; Pedreira *et al*., 2011; Pequeno *et al*., 2014; Brunetti *et al*., 2021).

CROPGRO-PFM, incorporated into the Decision Support System for Agrotechnology Transfer (DSSAT) software, simulates the growth and yield of forage crops based on climate, soil, and management inputs (Hoogenboom *et al*., 2019, 2024). It is useful for projecting the long-term sustainability and resilience of forage species amid anticipated climate challenges (Santos *et al*., 2022). Originally, the CROPGRO model was developed for annual crops and has been adapted for perennial forage, allowing simulations of defoliation and regrowth cycles (Rymph *et al*., 2004; Pequeno *et al*., 2017). Recent refinements have enhanced the accuracy of the model for estimating forage growth and yield for various species, including *Brachiaria* (Pequeno *et al*., 2017). Studies also indicate that minimal parameterization is required when extending this model to new species within

the same genus, as internal code features and the modular template system allow for efficient customization (Pequeno *et al*., 2017). Implementing this model in Ethiopia could provide critical insights into sustainable forage management under changing climatic conditions.

In general, there is a real need to investigate the agronomic performance and nutritive and feeding value of *Brachiaria*, and simulating/projecting the impacts of climate change on the growth and yield of *Brachiaria* grass in Ethiopia.

1.2. General Objective

The general objective of this study was to evaluate biomass yield, nutritional quality, and feeding value and to simulate the impacts of climate change on the growth and yield of *Brachiaria* species grown in central and western sub-humid environments.

1.3. Specific objectives

1. To evaluate agronomic performance, dry matter (DM) yield, and nutrient quality of *Brachiaria* species grown at Bishoftu and Bako and identify promising species for further promotion.
2. To evaluate the production performance (feed intake, digestibility, and body weight change) of Arsi-Bale sheep fed *Brachiaria mutica* hay basal diet supplemented with graded concentrate mixtures.
3. To simulate the growth and yield of *Brachiaria* species using the CROPGRO-Perennial Forage Model under present and future climate change scenarios in central and western Oromia, Ethiopia.

CHAPTER 2: Herbage Yield and Nutritive Value of Selected Grasses in Sub-humid Agro-ecological Environments in Ethiopia

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Abstract

The availability of improved forage, such as *Brachiaria* grass, is less than 1% in Ethiopia. This could be crucial for livestock farming to meet the growing demand for livestock and livestock products. Different grass cultivars performed differently. Therefore, this study compared the performance of *Brachiaria* cultivars with that of other grass cultivars in two sub-humid agro-ecological areas of Ethiopia, represented by Bishoftu and Bako areas. Four Brachiaria (*B. brizantha* (DZF-13379), *B. humidicola* (DZF-9222), *B. decumbens* (DZF-10871), and *B. mutica* (var. DZF-483), and two grass cultivars, Rhodes grass (*Chloris gayana* var. Massaba) and Desho grass (*Pennisetum glaucifolium* var. kindu kosha), were evaluated at Bako and Bishoftu for three years during the rainy season. The experiment was carried out using a randomized complete block design (RCBD), with 3 replications. Cultivars and years had significant ($P < 0.001$) effects on herbage dry matter (DM) yield, crude protein (CP) yield, and plant height, whereas location affected ($P < 0.01$) only DM yield. Cultivar × year interaction had significant ($P < 0.05$) effects on DM yield, CP yield, and plant height, while cultivar × location had significant effects on all parameters except CP yield. Additionally, cultivars significantly ($P < 0.001$) impacted the *in vitro* dry matter digestibility (IVDMD) as well as the nutritional content (CP, ash, acid detergent lignin (ADL), neutral detergent fiber (NDF), and ADF). Thus, all cultivars had potential as alternative ruminant feeds, whereas *B. mutica*, followed by *B. brizantha*, was superior, yielding cultivars in the subhumid agro-ecological areas of Ethiopia.

Keywords: Brachiaria cultivars, crude protein yield, dry matter yield, nutritive value, plant height

2.1. Introduction

There is substantial evidence that the livestock sector significantly contributes to Ethiopia's national economy and livelihood system. According to Shapiro *et al*. (2017), the sector accounts for approximately 49 percent of agricultural GDP and up to 21 percent of national GDP. This sector serves multiple functions, including food and nutritional security, as a source of milk and meat, income, manure, and draught power for smallholder farmers. However, it contributed far less than expected, mainly because of feed shortages (Fantu *et al*., 2018; FAO, 2018). The availability of feed in Ethiopia's crop and livestock systems depends mainly on natural pastures and crop residues, while improved forage, such as *Brachiaria* grass, is only 0.57 % (CSA, 2021). However, these feed resources are threatened by overexploitation and lack of high-quality feed (FAO, 2018; Mengistu *et al*., 2017). Furthermore, pressures arising from climate change and variability exacerbate these long-standing feed problems (Habte *et al*., 2022). These drawbacks highlight the importance of introducing improved forage for inclusion in the existing feeding systems (Feyissa *et al*., 2022).

Brachiaria (*syn. Urochloa*) are among the potential grasses that are important for sustainable forage production and are resilient to the detrimental effects of climate change (Njarui *et al*., 2021; Wheeler & Reynolds, 2013). The genus contains the most productive tropical forage grass species that originate in Africa and are widely grown in tropical Latin America and South Asia (Cheruiyot *et al*., 2020). Consequently, there has been a surge of interest in *Brachiaria* grass in East Africa (González *et al*., 2016; Muinga *et al*., 2016; Schiek *et al*., 2018). This is due to its adaptability to a wide range of soils, climates, and growing conditions in both the tropics and subtropics (Cheruiyot *et al*., 2018). Moreover, *Brachiaria* grasses have shown promising results in improving livestock productivity as they have better nutritional quality and biomass production (Maina *et al*., 2020). Furthermore, *Brachiaria* grasses have several environmental benefits, such as the ability to sequester carbon, increase nitrogen use efficiency through biological nitrification inhibition (BNI), effective as cover crops to control soil erosion, and control crop pests through push–pull pest management (Arango *et al*., 2014; Moreta *et al*., 2014; Rao *et al*., 2014).

Desho grass (*Pennisetum glaucifolium*) is an indigenous forage grass species in Ethiopia (Kebede *et al*., 2023). In addition to its use as animal feed, Desho grass conserves soil water and serves as a means of income generation for smallholder farmers. Desho thrives well in different soil types, has the potential to produce large amounts of biomass per unit area, is suitable for different forage production strategies, is acceptable for different livestock species, and increases livestock productivity (Atumo, 2022). Morphologically, it is closer to the *genus Brachiaria*, which shares the acidic and wetter areas of Ethiopia (Yirgu *et al*., 2017). Rhodes grass (*Chloris gayana*) is a tropical grass widely used in grazing and cut and carry systems in warm areas. *Chloris gayana* is best suited to areas with 600–1200 mm of rainfall. It is moderately drought tolerant, grows best at high temperatures, and is relatively frost tolerant (Sollenberger *et al*., 2020).

To capitalize on these potential forages and close the feed deficit gap, the comparative evaluation of *Brachiaria* with other important grass species should be the main research approach to demonstrate the suitability of forage for greater adoption in Ethiopia (Feyissa *et al*., 2022). Forage production and grass characteristics are highly sensitive to climatic factors, such as rainfall, temperature, and incoming solar radiation (Hart *et al*., 2022; Izaurralde *et al*., 2011), and their productivity can differ significantly and be influenced by a variety of factors, such as cultivar, location, soil type, and management options (Budiman *et al*., 2012; Changshun *et al*., 2014). Information regarding these factors is critical for optimizing feed production and utilization to increase animal productivity. According to (Gebremariam & Belay, 2021), it is important to document information on the nutritional value of feeds for their inclusion in livestock feeding programs.

This study aimed to compare the growth, herbage accumulation, and nutritive value of four *Brachiaria* cultivars, *Brachiaria mutica* (DZF-483), *Brachiaria decumbens* (DZF-10871), *Brachiaria brizantha* (DZF-13379), and *Brachiaria humidicola* (DZF-9222), and two grass cultivars, Desho grass (*Pennisetum glaucifolium* var. kindu kosha) and Rhodes grass (*Chloris gayana* var. Massaba) in two sub-humid agro-ecological in Ethiopia. The information generated is believed to be valuable to identify promising grass cultivars for further utilization under the sub-humid agro-ecological conditions of Ethiopia.

2.2. Materials and Methods

2.2.1. Study sites

The experiment was carried out at Debre Zeit Agricultural Research Center (Bishoftu), (08^0 44'N, $38^0$38'E; elevation: 1900 m asl), and the Bako Agricultural Research Center, ($09^0$06'N, $37^0$09'E; elevation: 1650 masl), in the sub-humid agro-climatic zone of central and western Ethiopia, respectively, during the main rainy season from 2020 to 2022. The soil type at the Debre Zeit center is predominantly *Eutric vertisol, Vertic andosols*, and *Haplic andosols* (Tafesse & Esayas, 2003). The experimental plots were laid out on *Eutric vertisol* with a clay texture and a neutral to slightly alkaline. The dominant soil type in the Bako center is *Alfisols*, which are clay in texture and acidic (Negassa *et al*., 2007).

2.2.2. Plant materials, experimental design and treatments

Vegetative root split planting materials were collected from the Debre Zeit Agricultural Research Center (DZARC) and transplanted in mid-June 2020 under rain fed conditions without supplementary irrigation. Six grass cultivars were used: four *Brachiaria* cultivars: (*B. brizantha* (DZF-13379), *B. humidicola* (DZF-9222), *B. decumbens* (DZF-10871), and *B. mutica* (var. DZF-483)) and two other grass cultivars, Desho grass (*Pennisetum glaucifolium* var. kindu kosha) and Rhodes grass (*Chloris gayana* var. Massaba). *Brachiaria* cultivars were selected based on their superior performance in previous trials in DZARC (unpublished data), while a recently released grass variety, Desho grass (Feyissa *et al*., 2022), and a popular grass species, Rhodes grass, were used as controls.

Experiments were conducted in each location using a randomized complete block design (RCBD) with three replications. A well-prepared 12 m^2 plot (3m long and 4m wide) was used to plant the materials. The planting spaces between rows and within plants were 50 cm and 25 cm, respectively. The transplanted materials were of the same age and 2-3 plants were placed in each hole at a depth of 10 cm. Nitrogen and phosphorus fertilizers were applied at a rate of 18N and 46P kg/ha (DAP), and 46N kg/ha as urea at transplanting and soon after harvesting in a band along the planting furrow. Hand weeding management practices were performed when appropriate.

2.2.3. Data collection and measurement

Dry matter (DM) yield and plant height were measured during the rainy season. The first harvest was carried out three months after the establishment period; in the following year, after clipping at the early onset of the rainy season, it was harvested at an interval of 60 days until the end of the rainy season, leaving a stubble height of 10 cm above the ground by hand using a sickle. The fresh herbage yield was weighed in the field immediately after the entire plot was mowed for each harvest. Plant height (cm), which is the distance from the soil surface to the uppermost point of the stem as the mean of five randomly selected plants (one per crown) from the middle row of each plot, was measured immediately before each mowing. A sample of 300 g of freshly harvested biomass from every replication of the treatments was cut into small pieces and dried at 65 ° C for 72 h in an oven to determine the dry matter yield. DM yield (t/ha) = (10×TFW×SDW)/ (HA×SFW), where 10 is a constant for the conversion of yield (kg/m2) to tons/ha, TFW is the total fresh weight of the harvested area (kg), SDW is the sample dry weight (g), HA is the harvest area (m^2), and SFW is the subsample fresh weight (g). Simultaneously, a composite sample of 400 g for each treatment was collected and dried in the shade for laboratory analysis.

Chemical analyzes of the feed samples were performed at the Debre Zeit and Holetta Agricultural Research Centers Feed and Animal Nutrition Laboratory. The grass samples were dried at 105 ° C overnight and ground to pass through a 1 mm sieve. The total DM was then determined. The nitrogen (N) content was determined using *the Kjeldahl* method, and CP was calculated as N × 6.25. The total ash content was determined by igniting the samples in a muffle furnace overnight at 550 ° C. Neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) were determined according to (van Soest & Robertson, 1985). The dry matter yield (DMY) was multiplied by the CP content of the feed samples to determine the crude protein yield (CPY). *In vitro* dry matter digestibility (IVDMD) was determined using the modified Tilley and Terry method (Tilley & Terry, 1963).

2.2.4. Statistical analysis

All data were analyzed using a linear mixed model approach through the *Lmer* function in R, v. 4.1.2 (R Foundation for Statistical Computing, http://www.r-project.org). For mean comparisons, cultivars, location, year, and their interactions were treated as fixed factors. In all cases, the block, the interaction of location, and the year were treated as random factors. Mean comparisons of the effect were performed using the '*lsmeans*' package in R (Lenth, 2016). Nutritive value parameters were analyzed using one-way ANOVA for the significant difference among the grass cultivars. Tukey's honestly significant difference post hoc test was used to separate significant differences between cultivars. The statistical model used for the analysis of DM yield and other related agronomic traits was as follows. $Yijkx = \mu + Cj + Lk + Yx + (Cj*Lk) + (Cj*Yx) + (Cj*Lk*Yx) + \varepsilon ijkx$, where $Yijkx$ is the response variable, μ is the overall mean, Cj is the effect of *the* j^{-th} grass cultivar, Lk is the effect of *the* k^{-th} location, Yx is the effect of x^{-th} year, $Cj*Lk$ is the interaction between cultivars and locations, $Cj*Yx$ is the interaction between cultivar and year, $Cj*Lk*Yx$ is the interaction among cultivar, location, and year, and $eijxk$ is the random error.

2.3. Results

2.3.1. The climate condition of experimental sites

Long-term weather information (1990–2022) and test years (2020–2022) at the Debre Zeit and Bako Agricultural Research Center are summarized in Table 2.1. The rainy season covers April to December, and maximum rain is received in the *Kiremt season* (June to September) in both locations. Compared with the long-term climatic data, the test years were characterized by higher rainfall at both sites. As expected from its normal climatic characteristics, the western sub-humid location received more rainfall and temperatures than the central (Bishoftu) location.

Table 2.1. Rainfall and mean daily temperature variations over the experimental period and the long term (1990-2022 years).

Variables	Bako		Bishoftu	
	Test year	Long term	Test year	Long term
Rainfall (mm)	1494.95	1281.4	853.8	473.2
Rainfall (*Kiremt seasons*) (mm)	1077.2	894.2	681.9	345.1
Temp. minimum (^{0}c)	14.35	13.8	9.2	11.2
Temp. minimum (*Kiremt seasons*) (^{0}c)	14.8	14.7	10.9	13.0
Temp. maximum (^{0}c)	28.65	28.5	26.55	27.1
Temp. maximum (*Kiremt seasons*) (^{0}c)	26.2	25.2	24.75	25.7

NB. *The Kiremt seasons include months from June to September* (Ehsan *et al*., 2021)

2.3.2. Effects of cultivars, location, year, and their interactions on yield and yield components

Table 2.2 displays a combined analysis of variance for plant height, dry matter (DM) yield, and crude protein (CP) yield of the four cultivars of Brachiaria, Rhodes grass, and Desho grass that were studied throughout a three-year period (2020–2022) in both the central and western environments. Variations among cultivars and years were significant ($P < 0.001$) for all tested parameters, while location was significant ($P < 0.01$) for DM yield. Cultivar × year interactions were significant ($P < 0.001$) for all tested parameters, while cultivar × location interactions were significant ($P < 0.05$) only for the DM yield and plant height.

Table 2.2. Plant height (PH), dry matter yield (DM) and crude protein (CP) yield (combined analysis over three years (2020–2022) and two locations: central and western sub-humid environments (Bishoftu and Bako, respectively).

Source of variation	D.F	Plant Height (cm)	DM yield (t ha^{-1})	CP yield (t ha^{-1})
		F-values		
Cultivar (C)	5	114.71***	17.58***	34.43***
Location (L)	1	1.19	13.51**	3.01
Year (Y)	2	19.99***	174.54***	196.27***
C*L	5	10.41***	2.72*	0.93
L*Y	2	10.41***	2.39	3.89*
C*Y	10	9.05***	14.3***	16.87***

D.F. = degrees of freedom; PH = plant height; DM = dry matter; CP = crude protein. t ha^{-1} = tonnes per hectare. *, ** and ***: significance at P < 0.05, 0.01, and 0.001. respectively.

2.3.3. Growth and yield performance

Combined analyses showed that *B. mutica* was a significant ($P < 0.05$) top-ranking cultivar in terms of dry matter yield (Table 2.3). *B. brizantha* and Desho grass ranked the second and third highest DM yields, respectively, but they did not differ ($P > 0.05$) from all cultivars except *B. humidicola*. Low DM yield was observed for *B. humidicola* but did not differ ($P > 0.05$) from *B. decumbens* and Rhodes. In Bishoftu, *B. mutica* showed numerically the highest DM yield but statistically it did not differ ($P > 0.05$) from all other cultivars except *B. humidicola*. Similarly, although a low DM yield was observed for *B. humidicola,* it did not differ ($P > 0.05$) from Rhodes and *B. decumbens. B. mutica,* followed by *B. brizantha,* had the highest DM yield in Bako. However, *B. brizantha* did not differ ($P > 0.05$) from Desho and *B. decumbens*. Low DM yield was observed for environments but did not differ ($P > 0.05$) from *B. humidicola* and *decumbens* Rhodes and Desho.

Compared to the experimental year, a relatively low dry matter yield was obtained during the year of establishment (2020) for all cultivars. Desho grass, followed by *B. mutica* and

Rhodes grass, showed significantly ($P < 0.05$) the highest DM yield in 2020. *Brachiaria* (*humidicola* and *brizantha*) showed the lowest DM yield during the establishment year, although they didn't differ ($P > 0.05$) from *B. decumbens*. In 2021, all cultivars showed their own maximum DM yield, except *B. brizantha,* which had shown the highest in 2022. *B. mutica* showed the highest DM yield in 2021 but did not differ ($P > 0.05$) *from Brachiaria* (*decumbens* and *brizantha*) or Desho. *B. humidicola,* which exhibited the lowest DM yield, did not differ ($P > 0.05$) from Rhodes, Desho and *B. brizantha*. In 2022, *B. brizantha,* followed by *B. mutica,* showed significantly ($P < 0.05$) the highest DM yield. Low DM yield was observed for Rhodes, while it did not differ ($P > 0.05$) *from Brachiaria* (*humidicola* and *decumbens*) and Desho grass.

Table 2.3. DM yield (t ha^{-1}) (*LS means*) of grass cultivars tested for three years in two locations.

Cultivar	Location		Year			Combined analysis
	Bishoftu	Bako	2020	2021	2022	
B. mutica (var. DZF-483)	13.57^{a}	12.84^{a}	6.82^{ab}	17.2^{a}	15.59^{ab}	13.2^{a}
B. brizantha (DZF-13379)	11.46^{a}	11.23^{ab}	2.59^{c}	14.64^{abc}	16.8^{a}	11.34^{ab}
Desho grass (var. kindu kosha)	12.94^{a}	9.67^{bc}	8.78^{a}	14.66^{abc}	10.48^{c}	11.30^{ab}
B. decumbens (DZF-10871)	11.2^{ab}	9.57^{bc}	4.04^{bc}	15.01^{ab}	12.11^{bc}	10.39^{bc}
Rhodes grass (var. Massaba)	11.11^{ab}	8.31^{c}	7.87^{a}	12.24^{bc}	9.03^{c}	9.71^{bc}
B. humidicola (DZF-9222)	8.57^{b}	8.19^{c}	2.2^{c}	11.38^{c}	11.56^{c}	8.38^{c}
Mean	11.5	9.97	5.38	14.21	12.6	10.72
SEM	0.68	0.68	0.83	0.83	0.83	0.48
P-level	<0.01	<0.01	<0.001	<0.001	<0.001	<0.001

$^{a-d}$ means with different letters are significantly different.

Like for DM yield, *B. mutica* attained the highest plant height but did not differ ($P > 0.05$) from *B. brizantha* and Rhodes grass (Table 2.4). In contrast, *B. humidicola* achieved a lower plant height. *B. mutica* showed significantly ($P < 0.05$) the highest plant height in both locations. *B. brizantha* had the second highest plant height but did not differ ($P > 0.05$) from Rhodes grass in Bishoftu, while vice versa in Bako. Throughout the years, the highest

plant height was observed for *B. mutica,* although it did not differ significantly ($P > 0.05$) from that of *B. brizantha* in 2022. Low plant height was observed in *B. humidicola* throughout the experimental period.

Table 2.4. Plant height (cm) (*LS means*) of grass cultivars (combined analysis over three years and two locations).

Cultivars	Location		Year			Combined analysis
	Bishoftu	Bako	2020	2021	2022	
B. mutica (var. DZF-483)	116.2^{a}	127.7^{a}	136^{a}	123^{a}	106.8^{a}	121.9^{a}
B. brizantha (DZF-13379)	96.5^{b}	104.3^{b}	94.8^{c}	103.2^{b}	103.2^{a}	100.4^{ab}
Rhodes grass (var. Massaba)	98.2^{b}	99.8^{bc}	111^{b}	97.2^{b}	88.8^{b}	99.0^{ab}
B. decumbens (DZF-10871)	91.1^{bc}	93.7^{c}	89.8^{cd}	89.8^{cd}	86.3^{b}	92.4^{c}
Desho grass (var. kindu kosha)	85.8^{cd}	79.4^{d}	82.7^{cd}	79.8^{c}	85.3^{b}	82.4^{d}
B. humidicola (DZF-9222)	79.2^{d}	70.4^{e}	77.5^{d}	79.8^{c}	67.2^{c}	74.8^{e}
Mean	94.5	95.9	98.63	95.47	89.6	94.63
SEM	0.87	0.87	3.34	3.34	3.34	6.02
P-level	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

$^{a-d}$ means with different letters are significantly different.

2.3.4. Crude protein yield

The crude protein yields of perennial grass cultivars over three years in the two locations are shown in Table 2.5. The results of the combined analysis showed that the crude protein yield was significantly ($P < 0.001$) influenced by the cultivars. *B. mutica* had the highest crude protein yield but did not differ ($P > 0.05$) from *B. brizantha*. Similarly, the highest crude protein yield was observed for *B. mutica,* followed by *B. brizantha,* at both locations. In the establishment year (2020), *B. mutica* had the highest crude protein yield but did not differ from Desho and Rhodes grass. Low CP yield was observed for *B. humidicola* but did not differ ($P > 0.05$) from *B. brizantha, B. decumbens* and Desho. Similarly, in 2021, *B. mutica,* followed by *B. brizantha,* and *B. humidicola,* showed the highest ($P < 0.05$) crude protein yield. In 2022, *B. brizantha,* followed by *B. mutica,* had the highest crude protein

yield, while *B. humidicola* ranked as the third crude protein yield, but the other cultivars did not differ significantly ($P > 0.05$).

Table 2.5. Crude protein yield (t ha^{-1}) (*LS means*) of the cultivars tested for three years at two locations.

Cultivar	Location		Year			Combined analysis
	Bishoftu	Bako	2020	2021	2022	
B. mutica (var. DZF-483)	1.67^{a}	1.62^{a}	0.92^{a}	2.02^{a}	2^{ab}	1.64^{a}
B. brizantha (DZF-13379)	1.43^{ab}	1.41^{ab}	0.33^{c}	1.75^{ab}	2.18^{a}	1.42^{ab}
B. humidicola (DZF-9222)	1.19^{bc}	1.19^{bc}	0.25^{c}	1.63^{abc}	1.68^{b}	1.19^{bc}
B. decumbens (DZF-10871)	1.1^{bc}	1^{c}	0.43^{bc}	1.5^{bc}	1.22^{c}	1.05^{c}
Desho grass (var. kindu kosha)	1.09^{bc}	0.84^{c}	0.63^{abc}	1.27^{c}	1^{c}	0.97^{c}
Rhodes grass (var. Massaba)	1.06^{c}	0.98^{c}	0.78^{ab}	1.3^{c}	0.97^{c}	1.02^{c}
Mean	1.26	1.18	0.57	1.59	1.5	1.21
SE	0.09	0.09	0.11	0.11	0.11	0.06
P-level	<0.08	<0.08	<0.001	<0.001	<0.001	<0.001

$^{a-d}$ means with different letters are significantly different.

2.3.5. Nutritional content

The combined analysis of the nutritive composition of the forage grass cultivars grown for three years in two locations is presented in Table 2.6. The crude protein content (CP%) was significantly ($P < 0.01$) influenced by cultivar. A higher CP content was observed in *Brachiaria* (*humidicola, mutica, and brizantha*). A low CP content was observed for Desho grass. The NDF content did not differ ($P > 0.05$) in any of the grass cultivars tested. The ADF content was significantly ($P < 0.01$) influenced by cultivar. The highest ADF value was observed for Rhodes grass, but it did not differ significantly ($P < 0.05$) from all cultivars tested except *B. mutica*.

The ash content was significantly ($P < 0.01$) influenced by cultivar (Table 2.6). The highest ash content was observed in *B. humidicola,* followed by *Brachiaria (brizantha* and *decumbens).* Low Ash content was observed for Desho grass and Rhodes grass but did not

differ significantly (P > 0.05) except for *B. mutica.* The lignin concentrations of the tested cultivars did not differ significantly (P > 0.05). *In vitro* dry matter digestibility was significantly (*P* < 0.001) influenced by the cultivar (Table 2.6). *B. humidicola* was superior to all investigated grass cultivars in terms of *in vitro* dry matter digestible content but did not differ (*P* < 0.05) from *B. brizantha*. *B. mutica* showed the third *in vitro* dry matter digestibility content but did not differ (*P* > 0.05) from Desho and *B. decumbens*. Rhodes grass had a low *in vitro* dry matter digestibility content.

Table 2.6. Nutrient composition (%) of grass cultivars tested in central and western sub-humid areas.

Cultivar	DM	CP	NDF	ADF	Ash	ADL	IVDMD
B. humidicola (DZF-9222)	93.52	13.3^{a}	72.1	41.5^{ab}	11.32^{a}	8.44	59.2^{a}
B. mutica (var. DZF-483)	93.51	12.7^{a}	75.3	39.8^{b}	8.82^{b}	8.81	53.9^{b}
B. brizantha (DZF-13379)	93.37	12.5^{a}	72.2	44.9^{ab}	8.27^{b}	10.55	56.2^{ab}
Rhodes grass (var. Massaba)	93.85	10.5^{b}	77	47.2^{a}	8.62^{b}	9.24	50^{c}
B. decumbens (DZF-10871)	93.58	10.5^{b}	73.7	42.9^{ab}	9.79^{ab}	9.62	50.4^{c}
Desho grass (var. kindu kosha)	93.54	8.6^{c}	72.3	44.2^{ab}	8.69^{b}	8.3	55.5^{b}
Mean	93.56	11.35	73.73	43.42	9.25	9.16	54.19
SEM	0.16	0.51	1.9	1.3	0.49	1.63	0.92
P-level	0.41	< 0.001	0.15	< 0.001	< 0.001	0.58	< 0.001

$^{a-d}$ Means with different letters are significantly different; CP = crude protein; NDF = neutral detergent fiber; ADF = acid detergent fiber; ADL = acid detergent lignin; IVDMD = *In vitro* dry matter digestibility.

2.4. Discussion

The test locations represent the diversity of rainfall, temperature patterns, and soil types that characterize the sub-humid environments of central and western Ethiopia. The amount of rainfall that covers more than 70% during the main rainy season (*kiremt*) and the higher temperatures that occurred in the test years relative to the long-term data are consistent

with the predicted effects of climate change in the region (IPCC, 2022) and add interest to our results from the perspective of future climate scenarios on forage grasses.

Because growing circumstances varied between test sites and years, it was hypothesized that cultivar × location and cultivar × year interactions would show up in forage yield attributes. Indeed, the patterns of microclimate (rainfall and temperature) and soil differed slightly between the experimental sites and years, which affected the yield of the grass cultivars. This implies a change in the ranking order of cultivars over location and year. The significant interaction of the yield traits in the present study was in agreement with the report by Wassie *et al*. (2018), which showed a significant effect of the interactions (cultivar × altitude and cultivar × harvest date) on *Brachiaria brizantha* in northwest Ethiopia.

Our findings supported earlier reports of *Brachiaria mutica* (var. DZF-483)'s high forage yield in sub-humid conditions (Assefa *et al*., 2016; Bantihun *et al*., 2022). In addition to DM yield, *B. mutica* had the highest CP yield, ranking as the highest yield among the cultivars tested. Furthermore, the dry matter yield of forage *Brachiaria mutica* (DZF-483) obtained in our results (13.2 t ha^{-1}) was almost similar to the result (13.3 t ha^{-1}) reported during this same variety registration (Assefa *et al*., 2016) and also higher than the result of 11.8 t ha^{-1} that was reported in the northwest highlands of Ethiopia by Bantihun *et al*. (2022).

Brachiaria brizantha (DZF-13379) ranked second and showed an increasing trend from year to year in forage dry matter yield in our study, which indicated the potential and importance of this cultivar. The Debre Zeit Agricultural Research Center Forage program team chose this cultivar as a candidate variety for registration, and our results validate and complement their earlier work (unpublished data). The average yield of 5.4 t ha-1 reported for *Brachiaria brizantha* ecotypes cultivated at low and mid altitudes in northwest Ethiopia was less than the dry matter yield of *B. brizantha*, which was 11.34 t ha-1 in the present study (Wassie *et al*., 2018).

In contrast, the dry matter yield of Desho grass (*P. glaucifolium* cv. Kindu kosha) varied with location (altitude) from high in Bishoftu to moderately low in Bako, from 12.94 to 9.67 t ha^{-1}, respectively. The current results for the dry matter yield of Desho grass were

also lower than those reported in other studies conducted at higher altitudes in Ethiopia (Asmare *et al*., 2017; Jabessa *et al*., 2021; Faji *et al*., 2022). This is in agreement with Mengistu *et al*. (2019), who indicated that highland environments were more ideal for the growth and development of Desho grass species.

The dry matter yield obtained for *Brachiaria decumbens* (10.39 t ha^{-1}) in our study was lower than that reported for *U. decumbens* (11.40 t ha^{-1}) under supplementary irrigation conditions in Holetta, Ethiopia, by Faji *et al*. (2022), which might be due to irrigation supplementation. Rhodes grass (*Chloris gayana* cv. Massaba) forage dry matter yield in our study, 9.71 t ha^{-1}, was much lower than that reported by Faji *et al*. (2022), which was 14.93 t ha^{-1} that was grown under irrigation supplementation in Holetta, Ethiopia. On the other hand, although the dry matter yield of *Brachiaria humidicola* was the lowest, this cultivar has higher CP and IVDMD. It ranked third in CP yield, indicating better nutritional importance. Other researchers also confirmed that, in addition to its good forage, this cultivar is known for its restoration ability when established on degraded land (Damene *et al*., 2020).

In this study, all cultivars had CP concentrations >7%, which met the minimum crude protein requirements (7%) for the synthesis of microbial proteins in the rumen that can support at least the maintenance requirements of ruminants (Van Soest, 1994). The CP concentration for *Brachiaria mutica* in our study was slightly higher than that (11.6%), reported by Bantihun *et al*. (2022). The significantly ($P > 0.05$) except *B. decumbens*, Desho and Rhodes cultivars were also higher in CP than the that reported by Faji *et al*. (2022) in Holetta under irrigation supplementation. On the contrary, the CP concentration of Rhodes grass is much lower than the result reported by Jayasinghe *et al*. (2022). Furthermore, as Faji *et al*. (2022) cited Lonsdale (1984), the feeds were classified based on their CP concentration as low, medium, and high protein sources with percentages of <12%, 12–20%, and >20% CP, respectively. According to this classification, *Brachiaria humidicola* and B. *mutica* can be classified as a medium- protein feed source, whereas the other tested cultivars classified as low-protein feed sources.

Fiber content (defined by NDF and ADF), an estimate of the amount of plant cell wall rather than cell content, is inversely related to digestibility and forage intake. Therefore, a

high content of NDF indicates the indigestible portion of the feed, which is an indicator of the low quality of the feed. Our results for the NDF content for all grass cultivars fell above 65%. According to Van Soest (1994), NDF content of tropical grasses within the limit (65% and above) is classified as low-quality roughage feed. However, our results of NDF content are contrary to what was reported by Faji *et al*. (2022) who indicated that perennial grass species varied in NDF content. Similarly, the ADF content is an indicator of low forage intake. Forage grasses with a higher ADF content have a lower intake (Van Soest, 1994). In the present study, *B. mutica* (var. DZF-483) with its ADF content of 39.8% can be considered to have a higher intake than other evaluated perennial grass cultivars. The varied ADF content of the cultivars observed in our study could be due to the genotypic and phenotypic characteristics of the grass cultivars.

The ash content of any feed is an indicator of the inorganic content (minerals) and an indirect estimator of the organic matter content. Most forages had ash contents ranging from 5 to 12%, which is in agreement with the results of Wassie *et al*. (2018). According to Van Soest (1994), a lignin content greater than 6% negatively affects the digestibility of grass forage. The evaluated grass cultivars in the present study had higher values. In the current study, *in vitro* dry matter digestibility declined slightly with an increase in NDF, ADF, and ADL. This may be due to the fact that higher levels of NDF, ADF, and ADL induce lignin to be deposited in the cell walls and increase the percentage of stems, which are less digestible than the leaf fraction that has a high fiber and lignin content (Van Soest, 1994). Our results were consistent with Faji *et al*. (2022), who reported that IVDMD levels of perennial grasses were inversely proportional to NDF, ADF, and ADL, which are more slowly degraded in the rumen, affecting microbial synthesis and animal performance. Similarly, the variation in the nutritional composition in our results is consistent with the results of Faji *et al*. (2022), who reported that the nutritional composition of forage crops can vary with genotypic characteristics and environmental conditions.

2.5. Conclusion

Our results are likely to be of great interest for the sub-humid environments of Ethiopia, considering that they were generated from two characteristics with climatic contrasting locations and characterized by a consistent value of the grass cultivar for production traits

between sites. The grass cultivars evaluated in this study show promise for producing forage with high nutritive value and can serve as viable alternatives for smallholder farmers. These cultivars exhibited optimal organic matter digestibility and significantly high crude protein (CP) concentrations, making them suitable forage supplements in smallholder systems. Based on their superior biomass production and acceptable nutritive value, *Brachiaria mutica* (var. DZF-483), followed by *Brachiaria brizantha* (DZF-13379), are recommended for study areas and other areas with similar agroecological conditions. Thus, our findings offer important insights into the selection of suitable grass cultivars for adaptation and utilization. Additionally, future studies should assess the performance of livestock fed these grass cultivars as a basal diet so as to define the concentrate supplementation recommendations for livestock producers.

CHAPTER 3: Agronomic Performance and Nutritive Value of Four *Urochloa* Species, Desho and Rhodes Grass Grown in Sub-humid Central Ethiopia

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Abstract

Improved forage grasses with high quality and biomass are a crucial additional feed source for cereal-livestock farming systems in Ethiopia. This study compared the performance of 4 *Urochloa* (Syn. *Brachiaria*) species (*U. brizantha* (DZF-13379), *U. humidicola* (DZF-9222), *U. decumbens* 'Basilisk' (DZF-10871) and *U. mutica* (DZF-483)) with other 2 commonly used grasses, Rhodes grass (*Chloris gayana* var. Massaba) and Desho grass (*Pennisetum glaucifolium* var. Kindu kosha), over 3 years during the main rainy season in Bishoftu in a sub-humid area of central Ethiopia. The experiment was conducted using a randomized completel block design. There was significant variation among species for agronomic parameters. The species × year interaction was significant for dry matter yield, plant height, and plot cover but not significant for leaf-to-stem ratio. Nutritional value (ash, acid detergent fiber (ADF), crude protein (CP) and *in vitro* dry matter digestibility (IVDMD)) was significantly different among species with no differences for neutral detergent fiber (NDF) and acid detergent lignin (ADL). All species showed potential as alternative ruminant feeds, especially *U. mutica* and *U. brizantha* having the highest yield in the sub-humid environment.

Keywords: Dry matter yield, grass species, leaf to stem ratio, plant height, quality.

3.1. Introduction

Feed shortages in quantity and quality are a recurrent challenge to livestock production and productivity in tropical Africa. In Ethiopia's highland crop-livestock mixed farming system, the availability of year-round feed is limited (FAO 2018; Feyissa *et al*. 2022; Mekonnen *et al*. 2022). The combination of feed scarcity and low feed quality makes it difficult to meet the maintenance requirements for livestock throughout the year (Feyissa *et al*. 2022). Currently, pressures from climate change exacerbate these long-standing feed problems (Habte *et al*. 2022). Introducing improved forages in such systems has been proposed to offer alternative good-quality feeds to improve livestock productivity and close feed gaps (Feyissa *et al*. 2022).

Urochloa (Syn. *Brachiaria*) includes many tropical grass species that originated on the African continent and are extensively grown in tropical Latin America and South Asia (Cheruiyot *et al*. 2020). Although there are over 100 species in this genus, many are underutilized and only a few, such as *Urochloa brizantha* (syn. *Brachiaria brizantha*) (A. Rich.) Stapf (palisade grass); *U. decumbens* (syn. *Brachiaria decumbens*) Stapf (signal grass) and *U. humidicola* (syn. *Brachiaria humidicola*) (Rendle) Schweick (Koronivia grass) are commercially exploited as forage crops (Miles *et al*. 2004). Recently, improved *Urochloa* grass has been introduced and cultivated by thousands of farmers in eastern Africa to provide alternative high-quality feed resources for livestock producers (Cheruiyot *et al*. 2020; Maina *et al*. 2020).

In addition to providing better quality feed, *Urochloa* grasses show adaptability to a wide range of agroecology and soil types (Cheruiyot *et al*. 2018). Their deep root systems allow them to extract nutrients and moisture, which helps them tolerate low soil fertility and dry spells in tropical regions (Ndayisaba *et al*. 2020). They also contribute to carbon sequestration, enhanced nitrogen use efficiency via biological nitrification inhibition (BNI), effective soil erosion control and management of crop pests through push-pull pest management techniques (Arango *et al*. 2014; Moreta *et al*. 2014; Rao *et al*. 2014). *Urochloa* grasses have shown promising results in improving livestock productivity through better quality and higher biomass (Maina *et al*. 2020).

Currently, there is interest in evaluating the adaptability and performance of *Urochloa* grass species under climatic conditions for the highland smallholder livestock producers of Ethiopia. Comparative yield evaluation of *Urochloa* with other important grass species was identified as the main research approach to demonstrate the suitability of forages for wider adoption in Ethiopia (Feyissa *et al*. 2022). In the present study, the agronomic performance of 4 *Urochloa* species (*U. mutica* (DZF-483), *U. decumbens* 'Basilisk' (DZF-10871), *U. brizantha* (DZF-13379), and *U. humidicola* (DZF-9222)), and 2 other grass species (Desho grass (*Pennisetum glaucifoliium* var. Kindu kosha) and Rhodes grass (*Chloris gayana* 'Massaba') were evaluated to compare the growth, herbage accumulation, and nutritive value in the highlands of central Ethiopia.

3.2. Materials and Methods

The experiment was conducted during the main rainy season from 2020 to 2022 at the Debre Zeit Agricultural Research Center (Bishoftu) (08^0 44' N, $38^0$38' E; elevation 1900 masl) in the sub-humid agroclimatic zone of central Ethiopia. The center is 47 km East of Addis Ababa, on the road to Adama. The soil type of experimental plots is reported to be *Eutric Vertisols* (Tafesse and Esayas, 2003).

Four *Urochloa* species (*U. brizantha* (DZF-13379), *U. humidicola* (DZF-9222), *U. decumbens* 'Basilisk' (DZF-10871) and *U. mutica* (DZF-483)) were compared to Desho grass (*Pennisetum glaucifolium* Var. Kindu kosha) and Rhodes grass (*Chloris gayana* Var. Masaba). *Urochloa* species were selected based on their superior performance from earlier trials, while a recently released local variety of Desho grass and Rhodes grass, both popular forage grass species, were used for comparison.

The experiment was conducted using a Randomized Complete Block Design (RCBD) with 3 replicates. Vegetative root splits of 12 months of age were transplanted using 2-3 splits per hole at a depth of 10 cm in mid-June 2020 under rain-fed conditions without supplementary irrigation in well-prepared 12 m^2 plots with 50 cm between row and 25 cm within row spacing. Nitrogen and phosphorus fertilizers were applied at the rate of 18 kg N/ha and 46 kg P/ha (as diammonium phosphate (DAP), and 46kg N/ha as urea at

transplanting and immediately after each harvest in a band along the planting furrow. Weed management and regular monitoring of disease and insects were performed as appropriate.

3.2.1. Data collection

Dry matter (DM) yield, plant height, plot cover and leaf-to-stem ratio were measured during the rainy season (June–Sept). The first harvest was carried out 3 months after establishment in the first year (2020) and at intervals of 60 days (2 cuts/rainy season) in 2021 and 2022. Plant height from the soil surface to the uppermost point of the stem was measured on 5 randomly selected plants/plot and expressed as a mean. Visual observation for plot cover was rated on a 1-10 scale (where 1=poor and 10=excellent). The leaf-to-stem ratio was determined by cutting plants from 2 randomly selected consecutive rows and separating by hand into leaf (lamina) and stem (leaf sheath + stem). Samples of each plant part were weighed, homogenized and subsampled and dried in a forced draft drying oven at 65 °C for 72 h. Fresh herbage yield was sampled by cutting the entire plot at a stubble height of 20 cm by hand using a sickle and weighing immediately. A subsample of 300 g of freshly harvested biomass was cut into small pieces and dried at 65 °C for 72 h in an oven to calculate dry matter yield as: DM yield (t/ha) = (10×TFW×SSDW)/ (HA×SSFW), where: TFW is the total fresh weight of the harvested area (kg); SSDW is the subsample dry weight (g); HA is the harvest area (m^2); SSFW is the subsample fresh weight (g).

A sample of 400 g from each treatment was collected at harvest and dried under the shade for laboratory analysis. Nutritional analyses of feed samples were performed at the Bishoftu Agricultural Research Center Food and Nutrition Laboratory and at Holetta Agricultural Research Center Animal Feed and Nutrition Laboratory. Grass samples were dried at 105 °C overnight and ground to pass through a 1 mm sieve. The total ash content was determined in a furnace at 550 ºC for 6 h. Neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid detergent lignin (ADL) contents were determined according to Van Soest and Robertson (1985). Nitrogen (N) was determined using the Kjeldahl method and *in vitro* dry matter digestibility (IVDMD) was determined using the modified Tilley and Terry method (Tilley and Terry 1963).

3.2.2. Statistical analysis

The Linear mixed-effect model (LME) approach was used to analyze the forage yield and nutritive value data using the 'lme4' package (Bates *et al*. 2015) in R (statistical analysis software). Pasture species, year and interaction of pasture and year were considered as fixed effects and the effects of plots within replicated blocks were considered as random effects of the model. Harvesting years were included as repeated measures because they were measured from the same plot. Mean comparisons of the effects were performed using the '*lsmeans'* package (Lenth 2016) in R for the cultivar across years. Nutritive value was separately analyzed using one-way ANOVA to determine significant differences among the pasture species. The statistical model used was: $Y_{ijkx} = \mu + C_j + Y_x + (C_j * Y_x) + \varepsilon_{ijkx}$, where: Y_{ijkx} is the response variable; μ is the overall mean; C_j is the effect of jth grass cultivar; Y_x is the effect of jth year; $C_j * Y_x$ is the interaction between cultivar and year; e_{ijxk} is the random error.

Tukey's honestly significant difference post hoc test was used to separate significant differences between pasture species.

3.3. Results

Average annual rainfall for the experimental years (2020-2022) was 814.8 mm with a long-term mean (1990-2020) of 473.2 mm (Table 3.1). Compared with the long-term climatic data, the trial period had higher rainfall, especially during the *Kiremt* season (June to September), the main rainy season in Ethiopia.

Table 3.1. Mean rainfall and temperature variation over the trial years and long-term (1990-2020).

Months of the year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall, trial years (mm)	5.9	4.8	28.3	39.2	71.4	117.5	217.9	213.9	96.0	19.4	0.0	0.4
Rainfall, long-term mean (mm)	7.5	10.7	34.6	29.6	29.4	65.3	129.9	107.4	42.5	8.2	3.5	4.6
Mean daily min temperature trial years (^{0}C)	7.2	8.5	10.3	11.7	11.1	11.5	11.5	11.1	10.4	7.0	5.2	5.1
Mean daily max temperature trial years (^{0}C)	26.6	27.7	29.2	29.4	28.1	26.4	21.3	22.3	23.2	24.3	24.3	24.6
Mean daily min temperature long-term (^{0}C)	9.3	10.4	11.8	13.2	12.9	12.6	13.5	13.5	12.5	9.3	7.8	7.5
Mean daily max temperature long-term (^{0}C)	26.7	28.0	28.9	28.9	29.2	27.9	25.0	24.4	25.4	29.2	26.2	25.8

3.3.1. Effects of species, year, and their interaction on agronomic traits.

A combined analysis of variance for DM yield, plant height, plot cover and leaf to stem ratio of the 4 *Urochloa* species, Rhodes grass and Desho grass showed that there was significant variation among species (P<0.01) for DM yield, plant height, plot cover and leaf to stem ratio (Table 3.2). Significant (P<0.05) species × year interactions were observed for all the parameters except for leaf-to-stem ratio.

Table 3.2. Species, year and their interaction effects on agronomic traits in Bishoftu.

Parameters	Species	Year	Species × Year
DM yield (t/ha)	**	***	**
Plant height (cm)	***	**	***
Plot cover	***	**	***
Leaf to Stem ratio	**	ns	ns

ns=non-significant; *=P< 0.05; **=P< 0.01; ***=P< 0.001.

The combined analysis indicated significant differences in forage dry matter yield among species (Table 3.3). *U. mutica* followed by Desho grass had the highest DM yield, but they did not differ significantly from other species, except for *U. humidicola*. Variation among species in experimental periods was also significant except for 2021. Low dry matter yields were observed during the establishment year compared to 2021 and 2022.

Table 3.3. Dry matter yield (t/ha) of grass species tested for 3 years at Bishoftu.

Species	2020	2021	2022	Combined analysis
U. brizantha (DZF-13379)	2.61^{b}	14.53	17.23^{a}	11.46^{ab}
U. humidicola (DZF-9222)	2.13^{b}	11.6	11.98^{ab}	8.57^{b}
U. decumbens (DZF-10871)	4.38^{ab}	15.75	13.44^{ab}	11.19^{ab}
U. mutica (DZF-483)	6.72^{ab}	17.02	16.96^{a}	13.57^{a}
Rhodes grass (Massaba)	8.52^{a}	14.97	9.84^{b}	11.11^{ab}
Desho grass (Kindu kosha)	8.66^{a}	17.2	12.97^{ab}	12.94^{a}
Mean	5.03	15.18	13.74	11.47
SEM	1.38	1.38	1.38	0.83

Means with different letters are significantly different. SEM=standard error of the mean.

The combined analysis indicated that *U. mutica* was the tallest (P<0.05) followed by Rhodes grass and *U. brizantha* (Table 3.4). Species varied significantly in plant height across all the experimental periods. Low plant height was observed in *U. humidicola* throughout the experimental period.

Table 3.4. Plant height (cm) of grass species tested for 3 years at Bishoftu.

Species	2020	2021	2022	Combined analysis
U. brizantha (DZF-13379)	96^{bc}	99^{b}	94.5^{a}	96.5^{b}
U. humidicola (DZF-9222)	75^{d}	83.5^{c}	79.2^{b}	79.8^{d}
U. decumbens (DZF-10871)	92^{bcd}	100.7^{b}	80.5^{b}	91.1^{bc}
U. mutica (DZF-483)	132.7^{a}	116.5^{a}	99.3^{a}	116.2^{a}
Rhodes grass (Massaba)	107^{b}	99^{b}	88.5^{ab}	98.2^{b}
Desho grass (Kindu kosha)	84.7^{cd}	81.8^{c}	90.8^{ab}	85.8^{cd}
Mean	97.9	96.75	88.8	94.6
SEM	4.68	4.68	4.68	2.28

Means with different letters are significantly different. SEM=standard error of the mean.

The combined analysis indicated that *U. mutica*, Desho, *U. brizantha,* and *U. decumbens* had higher plot cover than *U. humidicola* and Rhodes grass (Table 3.5). There was also significant variation in plot cover among the cultivars across the experimental period.

Table 3.5. Plot cover and 3 year mean leaf to stem ratio of grass species tested for 3 years at Bishoftu.

	Plot cover				mean leaf-to-stem ratio[1]
Species	2020	2021	2022	Combined analysis	
U. brizantha (DZF-13379)	6^{b}	8^{ab}	9^{a}	7.67^{a}	0.92^{a}
U. humidicola (DZF-9222)	6^{b}	7^{a}	7.3^{bc}	6.78^{b}	0.91^{a}
U. decumbens (DZF-10871)	6^{b}	8.7^{a}	8^{abc}	7.56^{a}	0.96^{a}
U. mutica (DZF-483)	7.7^{a}	8.3^{a}	8.3^{ab}	8.11^{a}	0.87^{a}
Desho grass (var. Kindu kosha)	7^{ab}	8.7^{a}	7.7^{bc}	7.78^{a}	0.87^{a}
Rhodes grass (var. Massaba)	7^{ab}	8.3^{a}	7^{c}	7.44^{b}	0.72^{b}
Mean	6.6	8.2	7.9	7.6	0.83
SEM	0.32	0.32	0.32	0.27	0.07

[1]Leaf stem ratio presented as 3 year mean (no species x year interaction); [a-d]Means with different letters are significantly different; SEM=standard error of the mean.

3.3.2. Nutritional value

Ash, ADF, CP and IVDMD were significantly different ($P<0.05$) among species, while NDF and ADL were not significantly different (Table 3.6).

Table 3.6. Nutritional value (%) of perennial forage grass species evaluated in Bishoftu.

Species	DM	Ash	NDF	ADF	ADL	CP	IVDMD
U. brizantha (DZF-13379)	93.18	7.96^{b}	73.4	43.9^{ab}	10.58	12.73^{a}	54.2^{b}
U. decumbens (DZF-10871)	93.37	9.66^{ab}	73.1	43.4^{ab}	10.01	10.23^{ab}	51.4^{bc}
U. humidicola (DZF-9222)	93.43	11.98^{a}	70.6	41.1^{ab}	9.18	12.93^{a}	57.8^{a}
U. mutica (DZF-483)	93.54	9.04^{ab}	76	38^{b}	8.6	12.43^{a}	52.6^{b}
Desho grass (var. Kindu kosha)	93.6	8.91^{ab}	73.7	43.9^{ab}	9.79	8.27^{b}	54.6^{ab}
Rhodes grass (var. Massaba)	93.93	8.69^{b}	77.1	48.3^{a}	9.79	9.43^{ab}	48.6^{c}
Mean	93.69	9.37	73.98	43.1	9.66	11	53.2
SEM	0.2	1.14	2.53	1.88	2.06	0.78	1.27

$^{a-d}$Means with different letters are significantly different. NDF=neutral detergent fiber; ADF=acid detergent fiber; ADL=acid detergent lignin; CP=crude protein; IVDMD=*In vitro* dry matter digestibility; SEM=standard error of the mean.

3.4. Discussion

The occurrence of species × year interactions for agronomic traits was expected because of climatic variation between the test years. There was a change in the ranking order of grass species over the years owing to the non-uniformity of growing conditions (rainfall, temperature) during the experimental periods. These results agree with those of Wassie *et al*. (2018), who reported significant species × accession × year interactions. All species were able to persist through the dry season from year to year.

Given the feed supply challenges faced by smallholders in mixed crop-livestock systems, cultivating *Urochloa* grasses can alleviate feed shortages (Midega *et al*. 2018). This study showed that *Urochloa* species are capable of producing similar herbage yield to the native Desho grass and higher yield than Rhodes grass, a fairly well adopted forage grass in Ethiopia. *Urochloa* species can be easily integrated into cropping systems, providing additional benefits such as soil conservation and land rehabilitation (Cheruiyot *et al*. 2018; Horrocks *et al*. 2019; Damene *et al*. 2020). *Urochloa* grasses are adaptable to rain-fed

conditions, enabling farmers to produce surplus feed during the growing season that can be stored for use during periods of scarcity (Cezário *et al*. 2015).

The results confirmed the high forage yield of *U. mutica* (DZF-483) in subhumid environments, as reported previously by Assefa *et al*. (2016) and Bantihun *et al*. (2022). Dry matter yield of *U. mutica* (DZF-483) obtained during 2022 (16.96 t/ha) was higher than the 13.3 t/ha reported during variety registration (Assefa *et al*. 2016) and also higher than 11.8 t/ha reported in the northwest highlands of Ethiopia by Bantihun *et al*. (2022). *U. decumbens* 'Basilisk' dry matter yields (11.26 t/ha) were comparable with the results of Faji *et al*. (2022), who reported 11.40 t/ha in Holetta, Ethiopia. *U. brizantha* (DZF-13379) displayed increasing forage dry matter yield each year, indicating the potential and importance of this cultivar as a candidate variety for registration (unpublished data). Dry matter yield of *U. brizantha* of 11.2 t/ha was higher than yields of 5.09 t/ha reported for other *U. brizantha* ecotypes grown in northwestern Ethiopia (Wassie *et al*. 2018). *U. humidicola* had the lowest yield but has additional advantages such as restoration ability when established on degraded lands (Damene *et al*. 2020).

Dry matter yield of Desho grass was lower than those reported in other studies at higher altitudes in Ethiopia (Asmare *et al*. 2017; Faji *et al*. 2022; Jabessa *et al*. 2021). This is supported by Mengistu *et al*. (2024), who indicated that the origin of Desho grass was highland and mid-elevation areas and that highland environments were better for the growth and development of Desho grass. Rhodes grass (*Chloris gayana* var. Massaba) dry matter yields were much lower than those reported by Faji *et al*. 2022 under supplementary irrigation in Holetta. This difference could be due to weather, soil type and irrigation.

All species had CP concentrations greater than 7%, meeting the minimum crude protein requirements for the synthesis of microbial proteins in the rumen needed to support the maintenance requirements of ruminants (Van Soest 1994). *U. humidicola, U. brizantha* and *U. mutica* were classified as medium protein feed sources and the remaining species were categorized as low-protein feed sources using the classification of Lonsdale (1989). CP concentrations of *U. mutica, U. decumbens,* Desho, and Rhodes grass were higher than those reported by Bantihun *et al*. (2022) and Faji *et al*. (2022).

Ash ranged from 8–12%, which is in agreement with the report of Wassie *et al*. (2018). NDF was higher than the values (65%) for tropical grasses reported by (Van Soest 1994), classifying them as a low-quality roughage. The variable ADF reported may be due to the different grass genotypes and species. Faji *et al*. (2022) reported that nutritive value can vary with genotype, harvesting stage and environment. *U. humidicola* is more digestible than the other perennial grass species evaluated, although IVDMD showed a decline with an increase in NDF, ADF and ADL. This could be attributed to lignin deposition in the cell wall and an increased proportion of stem in the forage with ageing. Results for nutritive value of *U. decumbens,* Desho grass and Rhodes grass in the current study were higher than those reported by Faji *et al*. (2022). Differences between these results and those of other studies are probably due to the differences in the edaphic, climatic, and biotic conditions of the study environment as well as the maturity stage at harvest, management and supplementary irrigation.

3.5. Conclusion

The *Urochloa* grasses compared well with other grasses evaluated in this study with the potential to produce forage with good nutritive value and serve as alternative options for smallholders in rain-fed sub-humid environments in Central Ethiopia. These grasses demonstrated optimal organic matter digestibility and remarkably high crude protein (CP) concentration, making them excellent forage supplements in systems where crop residues are the primary feed resource. *U. mutica*, followed by *U. brizantha*, may be particularly recommended due to their higher biomass production and adequate forage nutritive value. Further studies should be conducted on the performance of animals fed these grasses as a basal diet to make recommendations to livestock producers in the area.

CHAPTER 4: Feed Intake, Digestibility, Growth, Carcass Characteristics, and Economic Benefits of Yearling Arsi-Bale Rams Fed *B. Mutica* Hay Supplemented With a Graded Level of Concentrate Feed.

Abstract

This study evaluated the effects of supplementing *B. mutica* hay with graded levels of a concentrate mixture (noug seed cake and wheat bran) on intake, digestibility, growth performance, carcass characteristics, and economic return in yearling Arsi-Bale rams. Twenty-eight rams, averaging one year of age and an initial weight of 16.79 ±1.74 kg, were randomly assigned to one of four dietary treatments. The rams were fed a basal diet of *B. mutica* hay supplemented with 100 g, 200 g, 300 g, and 400 g of concentrate per day, designed as treatments T1, T2, T3, and T4, respectively. The experiment was laid out in a randomized complete block design (RCBD) with seven blocks. The results showed significant improvements ($p < 0.05$) in dry matter intake, nutrient digestibility, and feed conversion efficiency (FCE) with increasing concentrate levels. Rams fed T3 and T4 exhibited the highest body weight gain and carcass yields, though differences between them were not statistically significant ($p > 0.05$), suggesting 300 g as economically optimal level. Additionally, Meat chemical compositions such as crude protein and fat contents has increased with higher concentrate levels. The partial budget analysis revealed higher economic returns with moderate supplementation levels (200–300 g). In conclusion, supplementing *B. mutica* hay with 300 g of concentrate optimizes growth, carcass yield, and economic efficiency in Arsi-Bale sheep, providing a viable strategy for smallholder sheep production. Nonetheless, on-farm validation is necessary to tailor this strategy for different breeds and production environments, improving the sustainability of sheep feeding systems.

Keywords: Arsi-Bale sheep, *B. mutica*, Carcass, Digestibility, Dry matter intake, Profitability, Growth, Nutrient intake.

4.1. Introduction

In Ethiopia, smallholder farmers' livelihoods heavily depend on agriculture, with the livestock sector playing an integral role. Livestock is essential for poverty alleviation, national income growth, and foreign exchange earnings while also enhancing food security and contributing to climate change mitigation and adaptation (AGP-LMD, 2013; Shapiro *et al*., 2017). Among livestock, sheep (*Ovis aries*) are extensively raised in mixed farming systems across diverse agro-ecological zones (Gebremichael, 2008; Gizaw *et al*., 2010), with a population of approximately 38 million heads (CSA, 2022). Despite their adaptability and significant population, the contribution of sheep to the national economy remains underwhelming (Behnke, 2010; AGP-LMD, 2013; Jemberu *et al*., 2022).

A major constraint to the productivity of Ethiopian livestock, including sheep, is inadequate nutrition (FAO, 2018; McNamara & McKune, 2018; Management Entity, 2021; Assefa *et al*., 2024). The primary feed sources for sheep in Ethiopia are natural pasture and crop residues (Tolera *et al*., 2012; Assefa *et al*., 2016; Mengistu *et al*., 2017). However, these feeds often fail to meet the optimal nutritional requirements necessary for maintenance, growth, and milk production (Van Soest, 1994; NRC, 2007; McDonald *et al*., 2010; Desta, 2024). Nutrient deficiencies, particularly in protein or nitrogen, impair rumen microbial activity, reduce feed intake, and result in poor body conditions. As a result, sheep are marketed with average hot carcass yields of only 10 kg, reportedly the lowest in the world (Legese & Fadiga, 2014). This limited productivity translates to low per capita meat consumption and minimal income, impacting both household and national levels and falling below the average for Sub-Saharan African countries (Eshetie *et al*., 2018).

Enhancing livestock production and productivity is critical to meet the growing demand for livestock products in Ethiopia. Given the persistent feed shortages, introducing improved forage varieties like *B. mutica* offers a promising solution for sustainable and efficient feeding strategies (Feyissa *et al*., 2022). This recently released forage variety has been recognized for its high biomass yield and good nutritional profile (Zeleke *et al*., 2022; Dereje, *et al*., 2024). However, realizing its full potential requires a comprehensive

evaluation beyond biomass production and adaptability, including assessments of nutrient composition, intake, and digestibility.

Basal diets like grass or roughage feed such as *Brachiaria* require supplementation with protein concentrate feeds to meet the nutritional needs of growing animals (Da Silva *et al*., 2020; Osman *et al*., 2023). Proper supplementation enhances nitrogen availability to rumen microbes, thereby improving feed intake, digestion efficiency, and animal productivity (Rufino *et al*., 2020; Mwangi *et al*., 2024). Although previous research has demonstrated the positive effects of concentrate supplementation with other forage bases, limited studies have investigated the integration of concentrate feeds with *B. mutica* hay, particularly for small ruminants.

Among the key factors affecting sheep productivity and efficiency, forage quality and availability play a crucial role. Feed intake, particularly dry matter (DM) intake, is a critical determinant of growth performance, directly affecting weight gain, carcass yield, and meat quality. Animal characteristics such as breed, age, and physiological stage further influence feed intake and growth. According to NRC (2007), the recommended DM intake for 30 kg sheep is 780 g/day, equivalent to 2.6% of body weight. Feeding trials in various parts of Ethiopia have also shown that the DM intake of some indigenous sheep ranged between 480 and 843 g/day (Asmare *et al*., 2016; Diba *et al*., 2018; Yadete, 2019). Furthermore, strategic feeding practice can significantly enhance feed intake; for example, indigenous sheep supplemented with protein- and energy-rich diets show marked improvement in feed intake and growth rates (Ayele & Urge, 2019; Gadissa *et al*., 2021).

Carcass yield and meat quality depend heavily on feeding regime, along with breed, age, and sex. Although indigenous sheep typically produce lower carcass weights, concentrate-based diets significantly enhanced slaughter weight, dressing percentage, and overall carcass quality (Tibebu *et al*., 2019; Worku *et al*., 2020; Atsbha *et al*., 2021). Improved feeding practices also enhance key meat characteristics such as fat composition, water-holding capacity, and tenderness, which are factors that drive consumer preference and marketability (Da Silva *et al*., 2020; Ponnampalam *et al*., 2024). Feeding systems incorporating high-quality forage, such as *Brachiaria* grass, have been shown to improve

these metrics. Additionally, supplementing such forage with protein rich diets produces higher-quality meat (Wang *et al*., 2021).

Existing studies have shown that Farta sheep fed a diet of *Brachiaria spp.* supplemented with a concentrate mixture containing equal proportions of noug seed cake and wheat bran (300 g/day) achieved a daily weight gain of 82.7 g in Ethiopia (Adnew *et al*., 2021). Seid *et al*. (2021) reported that Arsi-Bale Sheep breed fed Desho grass hay supplemented with up to 400 g/day of concentrate feed attained a daily weight gain of 97.2 g. Similarly, Kebede *et al*. (2020) found that roughage feed (partial substitution hay with sugar cane tops silage and hay) supplemented with a concentrate mix (350 g/day) resulted in daily weight gains ranging from 81 to 91 g. Nevertheless, a significant knowledge gap exists regarding the performance of Arsi-Bale sheep fed a basal diet of *B. mutica* grass supplemented with varying levels of concentrate mixtures.

This study hypothesizes that feeding a basal diet of *B. mutica* hay supplemented with graded levels of concentrate mixtures will result in varying responses in feed intake, digestibility, growth performance, and carcass traits in Arsi-Bale rams. Identifying the optimal supplementation level is expected to maximize nutritional value, animal productivity, and economic profitability for growing Arsi-Bale rams. Therefore, the objective is to determine the optimal concentrate supplementation level for *B. mutica* hay basal diets by assessing feed intake, digestibility, growth performance, carcass characteristics, and the profitability for yearling Arsi-Bale rams.

4.2. Materials and Methods

4.2.1. Animal care and ethical issues

Animal care and ethical issues, with regard to this study, were carefully evaluated, and the experiment was carried out according to animal care protocols approved by the Animal Research Ethical Review Committee of the Addis Ababa University, College of Veterinary Medicine and Agriculture with approval number VM/ERC/06/01/15/2023. Directive 2010/63/EU of the European Union guidelines (2010) concerning the treatment and use of animals for research and development purposes were also employed.

4.2.2. Experimental site

The experiment was conducted at Debre Zeit Agricultural Research Centre (DZARC) 47 km southeast of the capital, Addis Ababa. The center is located between 08º 44'N latitude and 38º58'E longitude at an altitude of 1900 m a.s.l in sub-humid areas of Ethiopia. The area receives a mean annual rainfall of 473 mm, having a bimodal pattern and the average maximum and minimum air temperatures are 27.1 and 11.2 °C, respectively. The soil type at the Center is predominantly *Eutric vertisols, Vertic Andosols,* and *Haplic Andosols* (Tafesse & Esayas, 2003), whereas the feeding grass was established on *Eutric vertisols*.

4.2.3. Feeds and feeding management

Recently released *Brachiaria* grass, *B. mutica* (DZF-483 variety), was established on 0.5 ha of land at DZARC in June 2022. It was fertilized at a rate of 100 kg ha^{-1} urea (H_2NCONH_2) (46% N) and 100 kg ha^{-1} DAP (diammonium phosphate $(NH_4)_2HPO_4$), which is composed of 18% N, 46% P_2O_5), to maximize biomass production, weed control was carried out manually. The following year, it was harvested 2 months after the onset of the main rain season (June - July) and again at the end of September (2 months after the first harvest) (August – September). The harvested grass was chopped manually into pieces 1-10cm, dried under shade, and stored in a dry cool place until the commencement of the feeding trial. This chopped grass could facilitate the intake of animals. Supplemental feeds, including noug (*Guizotia abyssinica*) seed cake, wheat bran, and salt, were purchased and stored in a cool and dry place until the beginning of the feeding trial.

Table 4.1. Chemical composition of feed ingredients.

Feed ingredients	DM%	Nutrients (%DM)				
		OM	CP	NDF	ADF	ADL
B. mutica hay	93.18	91.3	12.3	75.3	48.4	9.0
Wheat bran	89	83	15.5	55	46	4.5
Noug seed cake	93	78	36	40.5	35.8	16.5

Abbreviations: ADF = acid detergent fiber; ADL = acid detergent lignin; CP = crude protein; DM = Dry matter; NDF = neutral detergent fiber; OM = organic matter.

4.2.4. Experimental animals and their management

Twenty-eight yearling intact Arsi-Bale ram lambs with 16.79 ±1.74 kg (mean ± SD) initial body weight were purchased from local markets around Bishoftu. Soon after arrival at the experiment station, they were quarantined for twenty-one days in a separate house. During this time, all animals were ear-tagged and vaccinated against ovine pasteurellosis and sheep pox and treated with a broad-spectrum anti-parasitic agent (Ivermectin). The lambs were offered treatment diets for fourteen days for acclimatization. The acclimatization period was followed by 10 days of digestibility trial. After five days of free access to feed, the actual 90 days of the feeding period followed. During these periods, the lambs were housed in individual pens equipped with feeding and watering troughs. The pens and troughs were cleaned every day before offering feed. Tap water was provided for all animals *ad libitum*.

4.2.5. Research design and treatments

The feeding trial was arranged in a randomized complete block design (RCBD) with four treatments and seven replications. Initial body weights, taken after overnight fasting on two consecutive days at the end of the acclimatization period, were used as a blocking factor. Lambs were then grouped into 7 blocks. Subsequently, all animals within the block were randomly assigned to each dietary treatment. The basal diet consisted of *B. mutica* (var. DZF-483) hay, supplemented with a concentrate mixture (CM) of 100, 200, 300, and 400 g DM/day was used as T1, T2, T3, and T4, respectively which were considered as treatments. The concentrate mixture was composed of 49.5% noug seed cake, 49.5% wheat bran, and 1% common salt. The proportion of feed ingredients in the concentrate mixture was based on the recommended range for growing indigenous lambs (Kebede, 2015; Gadissa *et al*., 2021; Ebrahim & Alemayehu, 2024). The concentrate supplements also fit the recommendations of the National Research Council (NRC, 2007) for protein (12%) and energy requirements (10 MJ/kg) of growing ram at least to guarantee 50 g/d average daily weight gain as cited by Roba *et al*. (2022).

4.2.6. Digestibility trial

The digestibility trial was carried out prior to the growth performance trial. Each sheep was equipped with fecal collection plastic bags and allowed a 3-day acclimatization period, followed by a 7-day feces collection period. Fecal samples were collected in the morning, placed in plastic sheet bags, weighed, and stored at −20°C. At the end of the collection period, the fecal samples from each animal were pooled, and 10% of the pooled samples were dried at 60ºC for 72 hours; ground to 1mm and then analyzed. Throughout the trial, daily feed offers, and refusals were recorded for each animal, and dry matter intake was calculated by subtracting refusals from feed offers.

The apparent dry matter (DM) and nutrient digestibility were calculated using the method described by McDonald *et al*. (2010), as follows.

$$\text{Apparent DM digestibility (\%)} = \frac{\text{DMI} - \text{Fecal DM}}{\text{DMI}} * 100$$

$$\text{Apparent nutrient digestibility (\%)} = \frac{\text{Nutrient Intake} - \text{Fecal nutrient output}}{\text{Nutrient Intake}} * 100$$

4.2.7. Feed intake and body weight change

Throughout the experimental period, daily feed offers and refusals were weighed and recorded for each animal to determine daily feed intake. The basal diet was provided *ad libitum,* with a 20% refusal rate adjusted every week based on individual animal intake from the previous days. Supplements were offered twice daily in equal portions at 8:00 AM and 2:00 PM to each experimental lamb. Any unconsumed feed was discarded and weighed the following morning before fresh feed was added. Sample offers and refusals, pooled per treatment over the experimental period, were thoroughly mixed and sub-sampled to determine chemical composition analysis.

The live body weight of each animal was recorded at the start of the feeding trial and every 15 days thereafter, following an overnight fast to eliminate the effect of gut fill. Total body weight gain (TBWG) was calculated as the difference between final and initial body weight (IBW). Average daily gain (ADG) was determined by dividing TBWG by the number of

feeding days. Feed conversion efficiency (FCE) was calculated as the ratio of ADG to daily feed intake, providing an indication of feed utilization and how efficiently the lambs converted feed into body mass.

4.2.8. Carcass evaluation

At the conclusion of the experimental period, twelve lambs (three from each dietary treatment) were randomly selected for slaughter. Prior to slaughter, the lambs were fasted for 14 hours, with free access to water. The animals were weighed just before slaughter to obtain their slaughter body weight (SBW). They were euthanized by severing their jugular veins and carotid artery with a knife. During slaughter, the skin, forefeet, hind feet, head, and all the viscera and fat depots (scrotal, kidney, pelvic, and gut fat) were removed to determine the hot carcass weight (HCW).

Data on total edible offal components (TEOC) were carefully recorded, including the weight of the heart, liver with gall bladder, tail, kidneys, empty gut, and fat (kidney and heart). Total non-edible offal components (TNEOC) were also recorded, consisting of the weight of the head, lung with trachea, skin and leg, spleen, testis, penis, bladder, and gut contents. The difference between SBW and gut content was used to determine the empty body weight (EBW) of slaughtered animals.

Dressing percentage (DP) was calculated by dividing the HCW by SBW and/or dividing HCW by EBW. Both the left and right rib-eye muscle area (REMA) were measured by cutting between the 12^{th} and 13^{th} ribs perpendicular to the backbone. The REMA was first traced on transparency paper, and the traced areas were then transferred to square paper. The area of the squares (0.25 cm^2 each) that fell within the traced region was counted. For partial square paper, the sum of the two sides was used as the REMA.

4.2.9. Chemical analysis of feeds and meat samples

The chemical analyses of all feed, refusals, and fecal samples was conducted at Holetta Agricultural Research Center (HARC) Animal Nutrition Laboratory. The samples were Oven dried at 105°C overnight, crushed using a laboratory mill to pass through a 1mm sieve, and stored for subsequent analysis of dry matter (DM) and ash content (AOAC,

1990). For crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and acid detergent lignin (ADL), the samples were dried at 65 °C in an air-drafted oven for 48 hours (van Soest & Robertson, 1985). The nitrogen (N) content was determined using the micro-Kjeldahl method, and CP was calculated as N × 6.25. The metabolizable energy (EME) intake of experimental animals was estimated from its digestible organic matter intake (DOMI) by using: EME (MJ/kg DM) = DOMI × 0.016 (McDonald *et al*., 2010).

Meat chemical composition was analyzed at the Food and Nutrition Laboratory of the Ethiopian Institute of Agricultural Research. Meat samples were collected from the *longissimus lumborum* (Longissimus dorsi muscle) between the 10th and 13th ribs. The samples were chopped, thoroughly mixed, and frozen at −20 °C until partially dried. They were then dried at 55 °C for 72 hours, packed in polyethylene bags, and stored at 4 °C for proximate chemical analysis.

For dry matter (DM) determination, 2 g of the dried meat sample was weighed into a pre-weighed crucible and dried in an oven at 105 °C until a constant weight was achieved. Ash content was determined by incinerating the dried samples in a muffle furnace at 600 °C for 12 hours, followed by cooling in a desiccator and weighing. The ash content was expressed as a percentage of the dried sample weight. Nitrogen (N) content was analyzed using the Kjeldahl method (AOAC, 1990), and crude protein was calculated by multiplying the nitrogen content by 6.25.

4.2.10. Partial budget analysis

The partial budget analysis was conducted to evaluate the profitability of feeding *B. mutica* hay with varying levels of a concentrate mixture containing noug seed cake, wheat bran, and salt to Arsi-Bale sheep, following standard guidelines (Upton, 1973). This analysis measures profit or losses, net benefits, or differences between gains and losses resulting from the proposed change. The analysis considered main input costs, including sheep prices, feed costs, and labor expenses. The purchase price of sheep was used, and the cost of both basal and concentrate feed treatments was estimated as the total feed cost. The cost of *B. mutica* hay was estimated based on the market price of a bale of natural pasture hay.

The selling price of each animal was estimated by three experienced individuals involved in sheep trading in the area.

Total return (TR) was calculated as the difference between the selling and purchase prices of each animal. Total variable costs (TVC) included the costs of all inputs that change with the feed treatment, such as hay, concentrate, medication and labor costs. Net return (NR) was calculated as the difference between total returns (TR) and total variable costs (TVC): NR = TR − TVC.

The change in net return (ΔNR) was determined by subtracting the change in total variable cost (ΔTVC) from the change in total return (ΔTR), which serve as a reference criterion for adopting new technologies: ΔNR = ΔTR −ΔTVC. The diet with the lower concentrate feed cost was used in comparison to the change in TVC. The marginal rate of return (MRR) was calculated to measures the increase in net income (ΔNR) for each additional unit of expenditure (ΔTVC) and expressed as a percentage: MRR = ΔNR / ΔTVC.

4.2.11. Statistical analysis

All data collected were subjected to analysis of variance using the General Linear Model procedure of the R program (version 4.4.1). Mean separation was done using the least significant difference (LSD) at 5% probability. The statistical models used are described as: $Y_{ijk} = \mu + Ti + Bj + \varepsilon ijk$, where Y_{ijk} is the observation of the ith treatment; μ is the overall mean, Ti is the ith treatment (i = 4), Bj is the jth block effect and εijk is random error.

4.3. Results

4.3.1. Chemical compositions of experimental feed

The chemical compositions of the diets used in the current study are presented in Table 4.1. The major ingredients considered in the analysis of the chemical composition of the feeds are *B. mutica* hay, wheat bran and noug seed cake. Even if salt is included in the treatment diets, its chemical elements are fixed and known. A similar amount of dry matter (DM) is obtained in the feed components of the *B. mutica* hay and noug seed cake with slightly lower values for wheat bran. Higher crude protein (CP) content (36%) was recorded for noug seed cake (NSC) followed by wheat bran whereas *B. mutica* grass hay

showed the lowest as it is common for most grass species. On the contrary, the lowest NDF and ADF was observed for NSC while the highest is for *B. mutica* grass hay.

4.3.2. Feed and nutrient intake

Table 4.2 presents the nutrient intake of Arsi Bale sheep fed *B. mutica* with varying levels of a concentrate mixture as a supplement. Dietary treatments differ significantly (P<0.01) for the intake of dry matter, organic matter and crude protein. The highest DMI and nutrient intake was observed for the sheep that consumed a basal diet with the highest concentrate level (T4) but did not differ significantly (P>0.01) from T3 except for CPI. Lowest intake was observed for the sheep fed on a basal diet with the lowest concentrate supplement level (T1) but did not differ significantly (P>0.01) from T2 for DMI, OMI, NDFI, and ADFI. CPI had shown a significant (P<0.001) increase with the increasing level of concentrate feed (T1<T2<T3<T4). ME (MJ/kg) was highest for T3 but did not differ (p > 0.05) from T4.

Table 4.2. Nutrient intake (g/h/day) of Arsi Bale sheep fed *B. mutica* hay supplemented with graded level of concentrate mixtures.

Measurement	T1	T2	T3	T4	Mean	SEM	p-value
DMI	738.7^{b}	781.2^{b}	844.3^{a}	893.9^{a}	814.5	14.5	<0.001
OMI	665.4^{b}	694.6^{b}	745.9^{a}	782.5^{a}	722.1	11.8	<0.001
CPI	96.3^{d}	116.5^{c}	135.3^{b}	156.5^{a}	126.1	4.4	<0.001
NDFI	477.3	484.7	503.4	515.5	495.2	7.04	ns
ADFI	315.3	325.2	332.7	343.5	329.2	4.8	ns
ME (MJ/kg)	10.1^{b}	10.2^{b}	10.9^{a}	10.4^{ab}	10.4	0.13	0.01

[a-d] Means with different superscripts within factor across rows are significantly different at P < 0.05; DMI = Dry matter intake; OMI = Organic matter intake; CPI = Crude protein intake; NDFI = Neutral detergent fiber intake; ADFI = Acid detergent fiber intake; SEM = Standard Error Mean.

4.3.3. Digestibility

Table 4.3 indicates the apparent digestibility coefficients of dry matter and nutrients in Arsi-Bale sheep fed *B. mutica* grass hay as a basal diet and supplemented with a graded

level of concentrate mixture. The average digestibility of dry matter (DM), OM, and CP reveal significant differences ($p < 0.05$) across the treatment groups. The composition of ME (MJ/kg) has also differed ($p < 0.05$) among groups fed different dietary treatments. DM digestibility increased from T1 to T4, with T4 achieving the highest digestibility even though it did not differ ($p > 0.05$) from T3. The digestibility of OM and CP was highest for T3 but did not differ ($p > 0.05$) from T4. In contrast, the digestibility of neutral detergent fiber (NDF) and acid detergent fiber (ADF) did not show significant differences ($p > 0.05$) among the treatments.

Table 4.3. Average DM and nutrient digestibility percentage of Arsi-Bale (n = 28) lambs fed *B. mutica* supplemented with graded level of concentrate mixture.

Measurements	T1	T2	T3	T4	Mean	SE	P-value
DM	57.7^{b}	57.7^{b}	58.1^{ab}	62.2^{a}	58.9	0.9	0.02
OM	63.1^{b}	63.9^{b}	68.2^{a}	64.9^{ab}	65	0.83	0.01
CP	76.5^{b}	77.7^{ab}	81.9^{a}	80.6^{ab}	79.2	0.85	0.02
NDF	49.5	49.1	53.03	49.8	50.3	1.25	ns
ADF	49.5	50	53.6	46.5	49.9	1.2	ns

$^{a-d}$ Means with different superscripts within factor across rows are significantly different at $P < 0.05$; DM = Dry matter; OM = Organic matter; CP = Crude protein; NDF = Neutral detergent fiber; ADF = Acid detergent fiber; ME = Metabolizable energy; SEM = Standard Error Mean.

4.3.4. Performances of rams

Dietary treatments had shown significant ($p < 0.001$) differences in all growth parameters studied (final body weight (FBW), total body weight gain (TWG), average daily gain (ADG), dry matter intake (DMI), and feed conversion efficiency (FCE)) whereas initial body weight (IBW) had no significant differences ($p > 0.05$) among the treatments, indicating that the initial weights of the sheep were almost similar across all groups (Table 4.4). The FBW, TBWG, ADG, DMI, and FCE were significantly increased with increased levels of concentrate supplementation from T1 to T4. Consequently, the highest value is observed for sheep fed on *B. mutica* hay supplemented with T4 but did not differ ($p > 0.05$) with those groups fed T3. Low FBW, TBWG, ADG, and FCE were observed for sheep fed

B. mutica hay with the lowest concentrate supplementation (T1). Low DMI was also observed for the T1 but did not differ ($p > 0.05$) with those groups fed T2.

Table 4.4. Growth performance and feed efficiency of Arsi-Bale sheep fed *B. mutica* supplemented with graded level of concentrate mixture.

Parameters	T1	T2	T3	T4	Mean	SEM	p-value
IBW (kg)	16.68	16.93	16.96	16.89	16.87	0.33	ns
FBW (kg)	22.43^{c}	24.11^{b}	25.89^{a}	26.32^{a}	24.69	0.44	<0.001
TBWG (kg)	5.75^{c}	7.18^{b}	8.93^{a}	9.43^{a}	7.82	0.3	<0.001
ADG (g/d)	66.1^{c}	82.51^{b}	102.63^{a}	108.37^{a}	89.9	3.48	<0.001
FCE	0.09^{c}	0.11^{b}	0.12^{a}	0.12^{a}	0.11	0.003	<0.001

[a-c] Means with different superscripts within factor across rows are significantly different at $P < 0.05$; ADG = Average daily gain; DMI = Dry matter intake; FBW = Final body weight; FCE = Feed conversion efficiency (g ADG/g DMI/d); IBW = Initial body weight; TBWG = Total body weight gain; SEM = Standard Error Mean.

Figure 4.1 illustrates the live weight changes of Arsi-Bale lambs fed *B. mutica* hay supplemented with varying levels of concentrate mixtures. During the initial 15 days of the feeding trial, live weight changes were comparable across all treatment groups, with no noticeable dietary effect. However, differences in response to dietary treatments became evident after this period. As shown in the figure, the body weight of lambs across all treatments showed a slight increase during the first and second 15-day intervals. Thereafter, steady and progressive (linear) weight gain was observed, continuing through to the end of the feeding period.

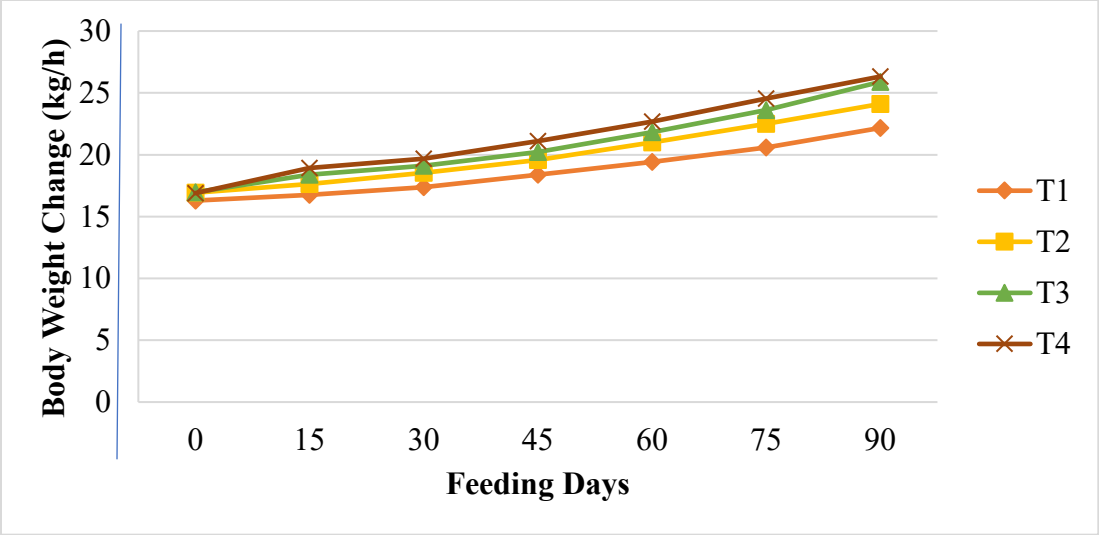


Figure 4.1. Biweekly live weight change of Arsi-Bale sheep subjected to different diets.

4.3.5. Carcass components

Carcass parameters of Arsi-Bale sheep fed on *B. mutica* hay with a graded level of concentrate mixture is presented in Table 4.5. These parameters, including slaughter body weight (SBW), empty body weight (EBW), hot carcass weight (HCW), rib eye muscle area (REMA), and dressing percentage (DP) differ ($p < 0.05$) significantly among treatments. Sheep-fed diets with the highest levels of concentrate supplements exhibited the highest values. Specifically, sheep fed *B. mutica* hay with 400 g concentrate supplement showed significantly higher SBW, EBW, HCW, REMA, and DP values though did not differ ($p > 0.05$) significantly with lambs fed with 300 g concentrate supplement.

Table 4.5. Carcass parameters of lambs fed *B. mutica* hay with graded level of conc. mix.

Carcass Parameters	T1	T2	T3	T4	Mean	SEM	P-value
SBW (kg)	21.3^{c}	22.8^{bc}	24.2^{ab}	24.9^{a}	23.3	0.63	<0.002
EBW (kg)	15.9^{c}	17.7^{b}	18.4^{ab}	19.3^{a}	17.8	0.49	<0.001
HCW (kg)	9.6^{c}	10.5^{bc}	11.6^{ab}	12.7^{a}	11.1	0.39	<0.002
REMA (cm^2)	15.5^{b}	16.8^{ab}	17.8^{ab}	18.7^{a}	17.2	0.48	<0.02
Dressing Percentage							
SBW basis	45.4^{b}	46^{b}	47.9^{ab}	50.9^{a}	47.6	0.89	<0.01
EBW basis	59^{b}	60.8^{ab}	62.9^{ab}	65.6^{a}	62.2	0.82	<0.02

$^{a-c}$ Means with different superscripts within factor across rows are significantly different at $P < 0.05$; HCW = Hot carcass weight; REMA = Rib eye muscle area; SBW = slaughter body weight; EBW = empty body weight; SEM = Standard Error Mean.

4.3.6. Edible non-carcass components

The heart, kidney, kidney fat, heart fat, and tongue weights were not affected (p> 0.05) by the level of concentrate mixture (Table 4.6). However, the liver with gall bladder, tail, empty gut, and total edible offal (TEO) weights were significantly affected by the level of concentrate mixture. Consequently, significantly higher liver and gall bladder, tail, empty gut, and TEO in sheep that consumed T4 but did not differ (p> 0.05) significantly with T3. Low tail, empty gut, and TEO were observed for T1 but did not differ (p> 0.05) significantly with T2.

Table 4.6. Edible offal components of sheep fed *B. mutica* hay with graded level of concentrate mix.

Parameters	T1	T2	T3	T4	Mean	SEM	P-value
Liver	0.2^{b}	0.25^{a}	0.28^{a}	0.29^{a}	0.26	0.01	<0.001
Heart	0.07	0.09	0.08	0.08	0.08	0.004	ns
Kidney	0.05	0.06	0.07	0.07	0.06	0.003	ns
Empty gut	1.3^{b}	1.4^{b}	1.68^{a}	1.66^{a}	1.51	0.06	<0.01
Tongue	0.06	0.07	0.06	0.07	0.06	0.004	ns
Kidney fat	0.01	0.02	0.03	0.03	0.03	0.004	ns
Heart fat	0.01	0.00	0.02	0.02	0.01	0.003	ns
TEO	1.71^{b}	1.9^{b}	2.22^{a}	2.22^{a}	2.02	0.11	<0.001

[a-b] Means with different superscripts within factor across rows are significantly different at P < 0.05; TEO = Total edible offal; SEM = Standard Error Mean.

4.3.7. Non-edible offal components

The head, spleen, lung with trachea, penis with urethra, bladder, and gut content did not differ (P < 0.05) significantly for lambs fed on *B. mutica* with graded level of concentrate (Table 4.7). However, testicles, skin and leg, and total non-edible offal (TNEO) were significantly higher for T4 but did not differ (P>0.05) with T3 and T2.

Table 4.7. Nonedible offal components of sheep fed *B. mutica* with graded level of concentrate mix.

Parameters	T1	T2	T3	T4	Mean	SEM	P-value
Head	1.11	1.28	1.16	1.29	1.21	0.03	ns
Testicle	0.17^{b}	0.22^{ab}	0.26^{ab}	0.28^{a}	0.23	0.02	<0.05
Spleen	0.03	0.03	0.03	0.03	0.03	0.001	ns
Lung with trachea	0.20	0.23	0.23	0.24	0.22	0.01	ns
Penis with urethra	0.04	0.04	0.05	0.05	0.05	0.003	ns
Bladder	0.01	0.02	0.02	0.02	0.02	0.002	ns
Skin and leg	1.86^{b}	2.27^{a}	2.23^{a}	2.52^{a}	2.22	0.08	<0.01
Gut content	5.39	5.17	5.77	5.60	5.48	0.24	ns
Tail	0.24	0.24	0.31	0.58	0.34	0.05	<0.05
TNEO	9.04^{b}	9.49^{ab}	10.1^{ab}	10.6^{a}	9.8	0.3	<0.05

[a-b] Means with different superscripts within factor across rows are significantly different at $P < 0.05$; TNEO = Total non-edible offal; SEM = Standard Error Mean.

4.3.8. Meat chemical compositions

Table 4.8 highlights the significance ($P < 0.05$) of meat quality characteristics such as moisture, fat, ash, and CP of *longissimus lumborum* (LL) of Arsi Bale sheep fed different dietary treatments (T1 to T4). The moisture content of the meat varied significantly across treatments, with T1 showing the highest moisture level but did not differ ($P > 0.05$) with T2 and T3. Fat and Crude protein content varies significantly among treatments ($P < 0.01$), with T4 and T3 recording the highest values. Ash content, indicative of the mineral composition of the meat, also shows significant differences across treatments ($P < 0.001$). T4 and T3 exhibited higher ash content compared to T2 and T1.

Table 4.8. Meat composition of Arsi-Bale lambs fed different dietary treatments.

Parameters	T1	T2	T3	T4	Mean	SEM	P-value
Moisture	76.4^{a}	75.2^{ab}	73.1^{ab}	71.3^{b}	74	0.68	0.03
Fat	3.8^{c}	5.7^{b}	7.8^{a}	7.9^{a}	6.3	0.53	<0.001
Ash	0.96^{b}	0.99^{b}	1.65^{a}	1.73^{a}	1.34	0.11	<0.001
CP	20.5^{c}	20.8^{bc}	23.2^{ab}	23.5^{a}	22	0.47	0.005

[a-c] Means with different superscripts within factor across rows are significantly different at $P < 0.05$; CP = Crude protein; SEM = Standard Error Mean.

4.3.9. Partial budget analysis

The profitability of rams fed with *B. mutica* hay at varying levels of concentrate mix supplement is summarized in Table 4.9. Although the purchase price of lambs was similar across all treatments, with no significant difference ($p > 0.05$), other economic variables showed notable differences depending on the concentrate supplement level. The total feed cost increased significantly ($p < 0.001$) with higher concentrate inclusion. Treatment T4 had the highest feed cost, while T1 had the lowest. Consistent with the feed cost, TVC rose significantly ($p < 0.001$) from T1 to T4, with T4 incurring the highest total variable cost and T1 the lowest. The final selling price of lambs and total returns from lambs exhibited significant differences among the treatments, with T4 achieving the highest, significantly different from T1 and T2 but not from T3. Although net return (NR) varied numerically across treatments, no significant difference ($p > 0.05$) was found among them. The mean net return across treatments was ETB 609, with T3 achieving the highest NR and T1 the lowest. The MRR values decreased with increasing concentrate supplement levels, which was the highest observed in T2, followed by T3, with T4 showing a significant drop.

Table 4.9. The economic return of rams fed *B. mutica* hay with graded level of conc. mix.

Variables	T1	T2	T3	T4	mean	SEM	P-value
Purchased price of lambs (ETB)	3090	2971	3205	3057	3081	49.16	ns
Total Feed Cost (ETB)	815^{d}	1061^{c}	1321^{b}	1580^{a}	1194	55.17	<0.001
Total variable cost (ETB)	1081^{d}	1326^{c}	1586^{b}	1846^{a}	1460	55.17	<0.001
Sold price of lambs (ETB)	4671^{b}	4957^{b}	5486^{a}	5514^{a}	5157	99.13	<0.001
TR (ETB)	1581^{c}	1957^{b}	2281^{ab}	2457^{a}	2069	81.03	<0.001
NR	500	631	695	611	609	50.38	ns
ΔTR	-	376	700	876	-	-	-
ΔTVC	-	245	405	765	-	-	-
ΔNR	-	131	195	111	-	-	-
MRR = ΔNR/ΔTVC	-	0.53	0.48	0.15	-	-	-

[a-d] Means with different superscripts within factor across rows are significantly different at $P < 0.05$; ETB = Ethiopian Birr; ΔNR = Change in net return; ΔTVC = Change in total variable cost; MRR = Marginal rate of return; NR = Net return; TR = Total return; SEM = Standard Error Mean.

4.4. Discussion

4.4.1. Chemical compositions of diet

The variations in feed chemical composition observed in this study are attributed to inherent differences in the nutritional content of the feedstuffs used. The CP content of *B. mutica* hay used in this study (12.3%) was somewhat identical to the CP content of 12.7% reported in an earlier agronomic study (Dereje *et al*., 2024). This disparity in CP concentration could be due to soil type and weather. This CP level exceeds the minimum threshold required to support optimal rumen function (>7% CP) (Van Soest, 1994; McDonald *et al*., 2010), but it falls short of the 16% CP required for growing sheep (Gadissa *et al*., 2021) and lower than optimum dietary crude protein content reported by Kebede (2015). This suggests that additional, high-quality protein sources are needed to enhance animal productivity beyond maintenance levels. Furthermore, the high NDF content in *B. mutica* hay (75%) classifies it as a low-quality feed, since roughage with NDF concentration greater than 65% is categorized as low-quality feed (Van Soest, 1994). According to McDonald *et al*. (2010), although the NDF fraction of feed is only partially digestible by most animal species, it can be more effectively utilized by ruminants through microbial fermentation in the rumen.

4.4.2. Nutrient intake and digestibility

The findings on dry matter intake (DMI), nutrient intake, and digestibility coefficients indicate that sheep-fed diets with higher concentrate levels, exhibited greater intake and digestibility. These results suggest that as levels of concentrate supplementation increased from 100g to 400g in diets, DM intake and nutrient intake (OMI and CPI) in sheep significantly improved and growth rates enhanced. This effect is attributed to the rapid degradability of concentrates in the rumen, contributing to improved diet intake and digestibility (Chen *et al*., 2021; Tedeschi *et al*., 2019; Tsega *et al*., 2021). This result aligns with previous studies (Bosa *et al*., 2012; De Carvalho *et al*., 2017; Roba *et al*., 2022), indicating a direct relationship between dietary CP content and DMI and its digestibility. Similarly, Mekuriaw & Asmare (2018) observed improved DM and nutrient intake when *Ficus thonningii* leaf was replaced with a concentrate mix (noug seed cake and wheat

bran(50:50)) supplement in Washera lambs. The mean DM intake (814 g/day) recorded here was higher than the 796.8 g/day reported by Kebede *et al*. (2020) for the same sheep breed fed sugarcane tops silage/hay (as a partial substitute for natural pasture hay) with 350 g/day concentrate supplementation (49.6% noug seed cake and 34.8% wheat bran and 14.6% ground maize).

The significant increase in CP intake and digestibility underscores the importance of protein in sheep diets for enhanced growth performance. Higher protein levels correlate with better growth rates and overall performance. Additionally, the metabolizable energy (ME) values observed highlight the importance of energy availability for growth and maintenance. These findings highlight the importance of balanced diets that meet sheep's nutritional requirements, particularly during critical growth phases (Gadissa *et al*., 2021; Vega-Britez *et al*., 2024). Thus, optimizing dietary formulations not only enhances nutrient intake and digestibility but also supports better nutritional management, improving lamb growth performance (Kebede, 2015). On the other hand, neutral detergent fiber (NDF) and acid detergent fiber (ADF) intake, along with their digestibility, remain stable across treatments, suggesting that dietary modifications did not significantly affect fiber levels.

4.4.3. Performances of rams

The study demonstrates increasing the concentrate supplementation levels from 100g to 400g in diets of sheep enhance growth performance and feed conversion efficiency (FCE). The findings underscore the value of supplementing *B. mutica*-based diets with graded levels of concentrate to improve sheep growth and efficiency. Consequently, higher weight gain and FCE were observed in sheep fed *B. mutica* with 300 g and 400 g of concentrate supplement. These results align with the findings of Kebede (2015), who reported higher body weight gain and FCE in the same sheep breeds fed diets with higher crude protein levels compared to lower-protein diets. This outcome may be attributed to increased intake of crude protein and metabolizable energy, which support rumen microbial populations and enhance nutrient utilization (Van Soest, 1994; Wang *et al*., 2021). Similarly, Gadissa *et al*. (2021), Roba *et al*. (2022), and Begna *et al*. (2023) observed higher body weight gain and

FCE in various Ethiopian sheep breeds fed diets with higher levels of crude protein and metabolizable energy compared to those on lower levels of these nutrients.

The average daily gain (ADG) of 91.1 g/day recorded in the present study exceeded the average values of 87.2 g/day reported by Kebede *et al*. (2020). Similarly, it was higher than the result of Tsega *et al*. (2021) reported 55.4 g/day for the same breed fed on a tef straw-containing sugarcane bagasse diet with 400 g/day concentrate supplementation, respectively. This result also surpasses the ADG reported for Hararghe highland sheep fed a basal hay diet supplemented with varying *Ficus sur* fruits (FSF) (Diba *et al*., 2018b). However, a higher ADG of 126 g/day was noted for Brazilian Suffolk lambs fed on Marandu (*B. brizantha*) grass with different concentrate supplementation levels (Vega-Britez *et al*., 2024), although the FCE of 10.4 reported in the current study was superior. This discrepancy could be attributed to breed differences.

Overall, a concentrate (wheat bran and noug seed cake (49.5:49.5)) supplementation level of 300 g can be considered the optimum inclusion rate for *B. mutica*-based diets, as no significant difference in growth performance was observed between the 300 g and 400 g concentrate supplement levels.

4.4.4. Carcass characteristics

The results of this study indicate that carcass parameters significantly improved with increasing levels of concentrate supplementation. The observed higher SBW, EBW, HCW, REMA, and DP at higher concentrate levels suggest that nutritional supplementation plays a critical role in enhancing growth performance and carcass yield in sheep. These findings align with previous research, which shows that increased concentrate levels can improve nutrient intake and energy availability, resulting in better growth rates and enhanced carcass characteristics (Tadesse *et al*., 2016; Atsbha *et al*., 2021; Begna *et al*., 2023).

According to Gadissa *et al*. (2021), a well-formulated ration containing 16% crude protein can improve feed intake, live weight gain, hot carcass weight, and overall performance of sheep. Notably, the sheep fed 400g of concentrate exhibited the best performance, whereas

it did not differ significantly from those fed 300g in carcass parameters, suggesting a potential threshold effect of concentrate supplement for the *B. mutica* basal diet.

The average carcass weight (11.1 kg) observed in the present study falls within the range (6.9-12.1 kg) reported for the same breed of sheep fed two varieties of maize silage or stover forms, supplemented with wheat bran and noug seed cake (Negewo *et al*., 2019). Additionally, this result is slightly higher than the national average carcass weight of Ethiopian sheep (10 kg) (Legese & Fadiga, 2014) and higher than the average result (9.2 kg) reported for the same breed fed various levels of sugarcane bagasse (Tsega *et al*., 2021). However, the recorded HCW in this study was lower than that of Begait lamb (17.20–19.50 kg) fed on grass hay supplemented with different concentrate mixtures, as reported by Atsbha *et al*. (2021).

Many scientific studies have reported a positive correlation between carcass weight and rib eye area (Atsbha *et al*., 2021; Melese *et al*., 2017; G. Mengistu & Assefa, 2022), which is consistent with the findings of this study. Additionally, in this study, both hot carcass weight and rib eye area showed a positive association with dressing percentage, which significantly improved with increased concentrate supplementation. The dressing percentage, calculated on both SBW and EBW bases, reflects the proportion of the meat carcass and serves as an important metric for assessing the efficiency of converting live weight into marketable meat (Boler, 2014). This is a critical factor for producers aiming to maximize profitability (Abdollahy *et al*., 2012).

4.4.5. Meat chemical compositions

In the current study, LL's moisture, fat, protein, and ash contents were influenced by diets. A reduction in moisture content with increased concentrate supplementation (T4 to T1) might indicate a higher dry matter deposition in muscle and fat tissue, as concentrate promote better nutrient absorption and growth. This trend is in line with the general understanding that as fat deposition increases, moisture content typically decreases due to the inverse relationship between fat and water in meat composition (An *et al*., 2022).

Meat with higher fat content, as observed in T3 and T4, tends to be juicier and more flavorful, making it desirable in markets that prioritize profit (Schumacher *et al*., 2022). Conversely, leaner meat, like that seen in T1, may appeal more to health-conscious consumers (Pannier *et al*., 2014). The optimum fat content for meat is reported to range from 2% to 10% (Ponnampalam *et al*., 2016), and the fat levels observed in this study (3.8%–7.8%) fall within this range. Comparing the fat content of this study to the higher values reported by Ayele *et al*. (2018) and Worku *et al*. (2020) suggests an understanding of how different breeds or management conditions can influence fat levels. However, the results are comparable to those reported for Hararghe highland sheep by Diba *et al*. (2015) and Begna *et al*. (2023). Overall, the marked difference between treatments highlights how concentrate feed influences fat deposition in muscle, a critical quality determinant in lamb meat which agrees with Ponnampalam *et al*. (2024).

The increase in CP content with higher concentrate supplementation is expected, as concentrates such as noug cake provide more readily available protein sources. The higher protein content in T4 and T3 suggests that these diets may better promote muscle development and growth, potentially resulting in higher-quality meat (Ponnampalam *et al*., 2016). However, the observed variation across treatments indicates that optimal levels of concentrate are essential for maximizing protein deposition. Overall, lower moisture content and higher fat and CP contents recorded for meat obtained from sheep fed *B. mutica* diets with various levels of concentrate mix can be attributed to increased dietary energy and protein intake. Dietary energy and protein intake tend to reduce moisture and enhance fat and CP levels in meat (Claffey *et al*., 2018). Additionally, the moisture and protein values observed in this study ranging from 70.80–80.30% for moisture and 18.5–23.4% for protein align with the range indicative of superior quality meat (Bezerra *et al*., 2016; Abdallah *et al*., 2020; Atsbha *et al*., 2021).

4.4.6. Partial budget analysis

The results of the partial budget analysis indicate that supplementing *B. mutica* hay with graded levels of concentrate positively influenced the economic returns from lamb feeding lambs. Higher levels of concentrate supplement resulted in increased feed and variable

costs, but also enhanced the selling price and total return of the lambs, as seen in T3 and T4. This trend reflects the positive impact of concentrate supplement feeding on lamb growth that improved market value, aligning with studies showing that dietary supplementation often enhances animal performance and economic return.

However, the lack of significant differences in net return among treatments and the decreasing trend in MRR with increased concentrate use implies that while higher concentrate levels can improve sale prices, the profitability gains diminish relative to the costs incurred. This suggests that a moderate level of concentrate supplement (as seen in T2 and T3) may offer a more balanced return, optimizing both cost efficiency and market returns without excessively inflating the variable costs. The MRR in this study 0.53, 0.48, and 0.15 for T2, T3, and T4, respectively indicates that to attain the required body weight by supplement feeding, each additional unit of 1 ETB increment per sheep to purchase supplement feed resulted in a profit of 0.53 ETB for T2, 0.48 ETB for T3, and 0.11 ETB for T4, respectively. The result achieved in the present study was lower than 1.7–3.1 (Tekliye *et al*., 2018). This may be the variations in purchasing and selling price of sheep, variations in sheep breeds used, and differences in basal diet and supplements used in different experiments.

4.5. Conclusion

In conclusion, this study highlights the critical role of dietary management in improving sheep production. Supplementing *B. mutica* hay with a concentrate mixture, comprising noug seed cake and wheat bran, significantly improved the performance of Arsi-Bale sheep. Higher levels of concentrate supplementation (300-400 g/day) enhanced dry matter intake, nutrient digestibility, and feed conversion efficiency, resulting in superior growth performance and carcass yields. The increased crude protein content in the supplement facilitated improved performance, although the economic analysis indicated that higher concentrate supplementation elevated feed costs. Notably, moderate supplementation levels (200-300 g/day) yield economic returns, indicating the cost-effectiveness of balanced concentrate use. Despite these promising results, the on-site experimental conditions may limit the generalizability of the findings to typical on-farm settings.

Additionally, the study did not assess the potential impact of *B. mutica*-based diets on methane emissions, a critical factor in climate change, and the variability of feed prices over time may influence the economic outcomes. Future research should investigate the effectiveness of concentrate supplementation under smallholder farmers conditions and across different sheep breeds to support broader applicability and sustainable production strategies.

CHAPTER 5: Simulating the Growth and Yields of *Brachiaria Brizantha* Using the CROPGRO-Perennial Forage Model Under Present and Future Climate Conditions in Subhumid Environments of Ethiopia.

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Abstract

Brachiaria is a crucial forage crop in tropical and subtropical regions, but there is limited research on its response to climate change in Ethiopia. This study aimed to (1) calibrate and evaluate the performance of the CROPGRO-Perennial Forage model and (2) assess the impact of climate change on future *Brachiaria brizantha* yield in the subhumid environments of Ethiopia. Field data collected from Debre Zeit (Bishoftu) and Bako Agricultural Research Centers were used to calibrate and evaluate the model for accurately simulating rainfed growth and biomass yield. Weather data such as daily rainfall, temperature, and solar radiation were obtained from Bishoftu and Bako weather stations. Historical and projected climate scenarios for the near future, mid-century, and the end of the 21st century were obtained from CORDEX-Africa dataset under two Representative Concentration Pathways (RCP4.5 and RCP8.5). The model calibration process focused on adjusting key parameters related to senescence and dormancy, vegetative partitioning, and N stress to improve the model's performance. Simulation results for future climate scenarios indicated an expected increase in biomass accumulation, with positive responses in the shoot, herbage biomass, and stem. However, leaf biomass and crude protein percentage of herbage are expected to decline. Overall, the production of *B. brizantha* is anticipated to increase in subhumid Ethiopian environments. Using simulations of CROPGRO-PFM can account for uncertainties about the impact of future climate change on Brachiaria grass. Further studies on Brachiaria forage responses under different management practices are advisable, to provide comprehensive information to policymakers and planners.

Keywords: *Brachiaria brizantha*, Climate change, CROPGRO-PFM, Simulation, Ethiopia

5.1. Introduction

Ethiopia's livestock industry relies heavily on natural pastures and crop residues for feed, which are threatened by overexploitation and low-quality feed sources (Mengistu *et al*., 2017; FAO, 2018). The contribution of improved forage species is negligible, representing 0.38% (CSA, 2022), exacerbating the difficulties faced by livestock production. Moreover, the pressures of climate change further complicate these issues (Habte *et al*., 2022). In response to these, there is a growing interest in introducing improved forage species, such as *Brachiaria* grass, to address the challenges faced by livestock production (González *et al*., 2016; Schiek *et al*., 2018; Feyissa *et al*., 2022).

Originally from Eastern and Central Africa, *Brachiaria* grass is extensively cultivated across tropical regions as a key component of forage-livestock production systems (Namazzi *et al*., 2020; Tegegn *et al*., 2019; Jank *et al*., 2014). Ethiopia, in particular, is recognized as a center of diversity for species such as *Brachiaria brizantha* (A. Rich.) Stapf (Tegegn *et al*., 2019). This grass species exhibits several advantageous traits, including drought tolerance, adaptation to low-fertility soils, carbon sequestration, biological nitrification inhibition (BNI), and ability to mitigate greenhouse gas emissions (Arango *et al*., 2014; Moreta *et al*., 2014; Rao *et al*., 2014). Despite these potential, *Brachiaria* remains underutilized in East Africa, including Ethiopia (Cheruiyot *et al*., 2020; Njarui *et al*., 2021). However, recent initiatives aim to promote its cultivation in support of the growing livestock sector in the region (Maass *et al*., 2015; Maina *et al*., 2020). Furthermore, its emergence as a climate-smart forage species highlights its potential success under future climate conditions (Djikeng *et al*., 2014; Njarui *et al*., 2021).

Given the profound climate change impact on forage production, assessing *Brachiaria* yield under changing climates is critical for future livestock feed security. Climate change significantly affects forage production, necessitating comprehensive evaluation using agro-climatic zoning methods (Andrade *et al*., 2015; Santos *et al*., 2022). In this context, mechanistic crop simulation models provide valuable insights into the complex interactions among plant genetics, environment, and management practices (Pedreira *et al*., 2011; Timlin *et al*., 2024). Among such models, CROPGRO-PFM, integrated into DSSAT 4.8.2

software, offers a systems based approach to agronomic research for simulating forage crop growth and yield, making it particularly useful for analyzing the potential impacts of climate change on *Brachiaria* grass (Jones *et al*., 2003; Hoogenboom *et al*., 2020; Hoogenboom *et al*., 2024). The model has been widely developed and applied to simulate the growth of various forage species, including *Paspalum notatum* (Bahiagrass) (Rymph, 2004), *Brachiaria brizantha* cv. Marandu (Pequeno *et al*., 2014), *Urochloa brizantha* (Palisade grass) (Pedreira *et al*., 2011), *Cynodon dactylon* (Bermuda grass) (Pequeno *et al*., 2017), *Brachiaria brizantha* (Piatã palisade grass) (Bosi *et al*., 2020), *Megathyrsus maximus* (Guinea grass) (Brunetti *et al*., 2021). The model was also used for assessing the long-term production of *Urocloa brizantha* under different environments in Brazil (Santos *et al*., 2022).

Comprehensive assessments of the impacts of climate change on *Brachiaria* production in the central and western midlands of Ethiopia's sub-humid agroecologies remain limited. While several studies have been conducted at the broader East African scale (Djikeng *et al*., 2014; Njarui *et al*., 2021) and others have explored the adaptability of *Brachiaria* grass in northwestern Ethiopia (Wassie *et al*., 2018), but they have not extensively addressed the future implications of climate change on this forage species in detail. To address this gap, the present study utilizes climate projections from the CORDEX-Africa dataset to evaluate the potential yield responses of *Brachiaria brizantha* under different Representative Concentration Pathways (RCPs). The analysis specifically draws on data from station trials conducted in the sub-humid regions of central and western Ethiopia.

Thus, our study aimed to (1) calibrate and evaluate the CROPGRO-PFM for simulation of rainfed growth and yield of *Brachiaria brizantha*, and (2) assess the impacts of climate change on *Brachiaria brizantha* yield using climate simulation outputs from CORDEX Africa under high and moderate Representative Concentration Pathways (RCPs) scenarios in the central and western subhumid environments of Ethiopia. Our null hypothesis states that the standard model developed for Marandu palisade grass could accurately simulate the growth and forage production of *B. brizantha* in Ethiopian environments by parameterizing specific genotypic characteristics.

5.2. Materials and Methods

5.2.1. Field data

The data were collected from two field experiments Debre Zeit Agricultural Research Center (DZARC), Bishoftu, (08^0 44'N, $38^0$58'E; elevation:1900 masl), and Bako Agricultural Research Center (BARC) ($09^0$06'N, $37^0$09'E; elevation:1650 masl), in the sub-humid agro-climatic zones of central and western Ethiopia, respectively. Weather data for the experimental period (Figure 5.1) were obtained from a weather station at each location.

The physical and chemical characteristics of the soils were extracted from the International Soil Reference and Information Center (ISRIC, 2013). The complete soil profile used for the simulation in DSSAT format is presented in Table 5.2. The basic soil parameters required as model inputs included silt and clay content (%), soil organic carbon concentration (%), pH in water, lower limit of plant extractable soil water (cm^3 cm^{-3}), drained upper limit (cm^3 cm^{-3}), saturated upper limit (cm^3 cm^{-3}), and bulk density (g cm^{-3}). The soils used in the study were fertile Eutric vertosols and Alfisols at Bishoftu and Bako sites, respectively, which did not require amendments.

Brachiaria grass cultivar [*Brachiaria brizantha* (Hochst. Ex A. Rich.) Stapf.], syn. *Urochloa brizantha* (A. Rich.) accession DZF-13379) was established in 3 × 4 m plots, with three replicates in June 2020 which detailed agronomic performance described in the earlier study (Dereje *et al*., 2024). Harvesting occurred periodically during the three main rainy seasons, only once in 2020, and twice in 2021 and 2022 (from June to the end of September). The plots were fertilized during planting and immediately after each harvest at a rate of 100 kg ha^{-1} urea (H_2NCONH_2) (46% N) and 100 kg ha^{-1} DAP (diammonium phosphate) $(NH_4)_2HPO_4$) 18% N, 46% P_2O_5), to provide a total annual application of 128 kg and 192 kg of N for the establishment year and consecutive experimental periods.

Harvesting was conducted from June to September 2020, during the establishment year, with a single harvest performed at 90 days. In both 2021 and 2022, harvesting occurred twice per year, at 60-day intervals, from June to early October (Table 5.1). At the beginning

of June, coinciding with the onset of rain, the grass was cut to aboveground height of 20 cm. After 60 days, the first harvest of each year was completed. Each subsequent harvest was also performed at 20 cm above ground height to promote consistent regrowth.

Consequently, forage mass was quantified one day earlier to each harvest which was once for 2020 and twice every 2021 and 2022. The forage was clipped 20-cm aboveground (stubble height) and was sampled randomly in each plot from three 0.25m by 1m quadrats per harvest. These samples were hand-sorted into leaves (lamina), and stems (leaf sheath + stem), then weighed in the field. Leaf and stem masses were dried separately in a forced-draft oven at 65 ºC for 72 hours before being weighed. After forage mass samples were collected, the entire plot was mechanically harvested at a 20-cm stubble height and fertilized. Herbage dry matter (DM) yield was calculated based on the dry weights of the samples and then estimated per hectare.

Simultaneously, a composite of herbage subsample was collected and dried in the shade for CP determination at the Debre Zeit Agricultural Research Center Feed and Animal Nutrition Laboratory. Then the samples were dried at 105 °C overnight and ground to pass through a 1 mm sieve. The nitrogen (N) content was determined using *the Kjeldahl* method, and crude protein (CP) was calculated as $N \times 6.25$ (AOAC, 1990).

Furthermore, soon after the final harvest of each year, the aboveground mass below 20 cm (stubble height) was harvested using the same quadrat size (0.25m ×1m) to characterize MOW, which is the residual living stubble. These samples were sorted into live leaves (lamina) and live stems (leaf sheath + stem) and weighed in the field. Then it was dried in a forced-draft drying oven at 65°C for 72 hours and weighed. These components were combined with the measured leaf and stem above 20 cm to characterize the total leaf and total stem mass. Additionally, the forage mass collected both above and below stubble height was combined to characterize the shoot biomass.

Table 5.1. Herbage biomass (Mean ± STD) and date of harvesting of *B. brizantha* collected for Bako and Bishoftu sites.

Location	Sampling date	Herbage biomass, Kg DM ha^{-1}
Bako	09/05/2020	2576±4231
	07/30/2021	8674±1867
	09/30/2021	6084±723
	07/29/2022	9514±2707
	09/28/2022	6854±47
Bishoftu	09/11/2020	2608±4199
	08/09/2021	8684±1877
	10/08/2021	5844±963
	08/09/2022	10781±3974
	10/08/2022	6449±358

5.2.2. Crop model inputs and setup

Data used for the simulation including location, soil characteristics, weather data, and crop establishment details were compiled into an experimental management file, referred to as "File X". Transplanting was chosen planting method, with a planting rate of 2000 kg per hectare. The herbage biomass harvested was described in "File T". An important component of the forage model is the "MOW input file", which defines harvest-related parameters such as harvest dates, the mass of non-harvested live biomass remaining after harvest (referred to as stubble mass or MOW), percentage of leaves in the stubble (RSPLF), and re-staged number of leaf (MVS), hypothetical leaves number left on the main tiller axis after harvest. For this study, the measured stubble mass below 20 cm was used as the MOW value. RSPLF was standardized at 30%, and the MVS parameter was set at 3 in the MOW file across all treatments as suggested by Pedreira *et al*. (2011) and Pequeno *et al*. (2014). Additionally, for future climate yield projections, we adjusted the RSPLF to 30% and MOW value to 2000 Kg DM per hectare based on the recommendation of Pequeno *et al*. (2014). All other parameters, including the management file and harvest pattern, were kept consistent with the current study.

In this study, the CENTURY module is employed for simulating soil organic carbon (SOC) and soil nitrogen (N), following Gijsman *et al*. (2002). This module effectively captures

the decay of plant residues on the soil surface and sloughed roots within the soil, processes typical of perennial forage species. Hence, it is endorsed for use in CROPGRO-PFM simulations (Brunetti *et al*., 2021). The assumed values for stable organic carbon fractions and residual inputs from previous crops were adopted from Pequeno *et al*. (2014), given that both studies were conducted in tropical environments with pasture as the preceding crop. The model represents soil organic matter (SOM) fractions three distinct pools: active (microbial) SOM present in surface mulch and soil layers (SOM1), intermediate SOM (SOM2), and passive or stable SOM (SOM3) (Gijsman *et al*., 2002). We also used the Penman-Monteith FAO 56 model to estimate potential evapotranspiration (ET). This choice was based on findings by Pequeno *et al*. (2017), which indicate that the Priestley-Taylor method tends to overestimate ET in relatively arid regions.

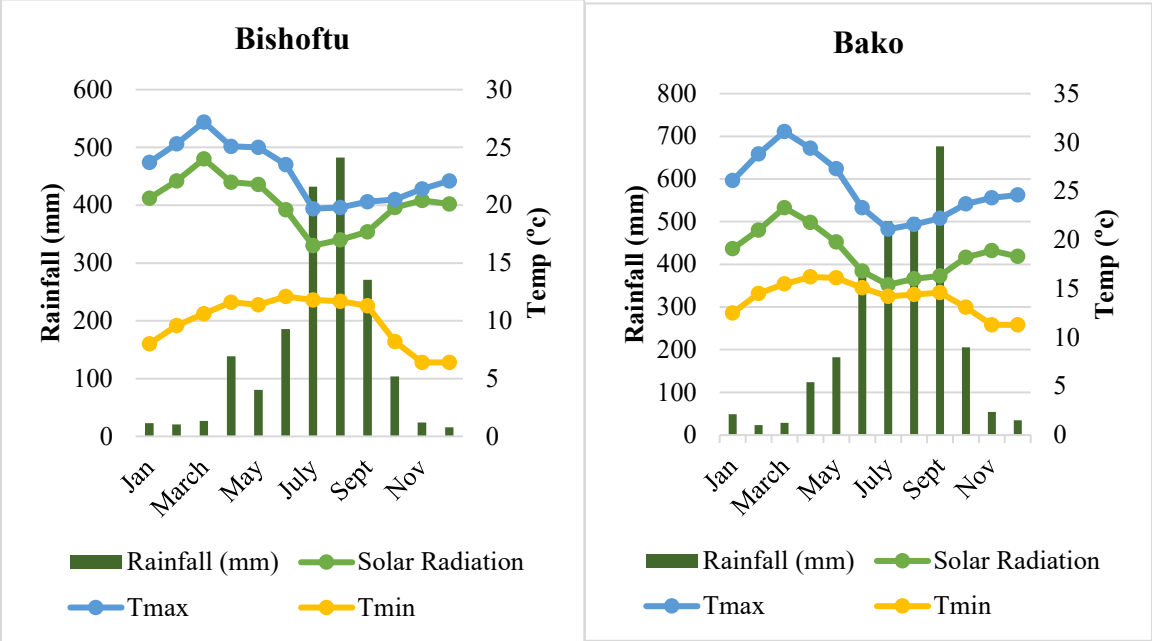


Figure 5.1. Monthly weather data during the experimental period (2020-2022) in Bishoftu and Bako, Ethiopia

Table 5.2. Soil profile created with the DSSAT Sbuild program for the Bishoftu and Bako experimental site

Location	Depth	Clay (%)	Silt (%)	LL (mm/mm)	DU (mm/mm)	SSAT (mm/mm)	BD (g/cm3)	OC (%)	TN (%)	Root Growth Factor
Bishoftu	5	38.8	26.3	0.192	0.358	0.440	1.27	2.11	0.12	1
	15	40.7	25.6	0.203	0.369	0.446	1.29	1.79	0.09	0.85
	30	43.1	24.5	0.217	0.384	0.455	1.32	1.36	0.07	0.70
	60	45.5	23.4	0.231	0.398	0.464	1.37	0.87	0.06	0.50
	100	45.6	22.8	0.231	0.397	0.463	1.43	0.50	0.05	0.38
	200	44	22.4	0.222	0.388	0.456	1.49	0.29	0.05	0.05
Bako	5	40.4	26	0.221	0.368	0.446	1.25	2.78	0.12	1
	15	42.2	25.2	0.231	0.379	0.452	1.26	2.35	0.09	0.82
	30	44.8	24.1	0.247	0.394	0.462	1.3	1.8	0.07	0.65
	60	47.1	23	0.259	0.407	0.47	1.35	1.15	0.06	0.38
	100	47.1	22.5	0.260	0.407	0.469	1.41	0.67	0.05	0.19
	200	45.7	22.1	0.251	0.398	0.462	1.46	0.37	0.05	0.05

Source: (ISRIC, 2013), LL = lower limit of plant extractable soil moisture; DUL = drained upper limit; SSAT = saturated soil water content; BD = bulk density; OC = organic carbon; TN = total nitrogen.

5.2.3 Model calibration

The CROPGRO-PFM, parameterized for *B. brizantha* cv. Marandu palisade grass by Pequeno *et al*. (2014) and included in the DSSAT version 4.8.2 (Hoogenboom *et al*., 2020), was employed to simulate the growth and yield for the current study. The Marandu palisade parameters was chosen as it belongs to the same genus as the *B. brizantha* accession 13379 genotype used in the current study (Andrade *et al*., 2015; Pequeno *et al*., 2017; Brunetti *et al*., 2021). However, to enhance the accuracy and reliability of the model, the CROPGRO-PFM model was calibrated and evaluated through a structured four-phase process, and the parameters of the genotype files were changed manually by the trial-and-error method.

Phase 1: Default simulation. In this phase, we evaluated the CROPGRO-PFM model's ability to simulate field observations without any calibration. We used input data specific to the Bishoftu experimental site, including weather, soil surface, profile characteristics, fertilizer application, and initial conditions. However, genetic coefficients (species, ecotype, and cultivar) were according to parameters defined by Pequeno *et al*. (2014) for Marandu palisade grass.

Phase 2: Calibration of genetic coefficients in the ecotype file affecting senescence and dormancy. In this phase, we test the hypothesis that CROPGRO-PFM calibrated for Marandu palisadegrass can accurately simulate *B. brizantha* in Ethiopia, with modification only of those specific characteristics related to the ecotype parameter, and with no changes of the genetic coefficients that define the species traits. Thus, genetic coefficient specific to the ecotype file, the relative strength of allocation of assimilates to shoot versus storage tissues based on photoperiod sensitivity (RDRMT) was adjusted. In addition, genetic coefficients specific to the species file, the daylength effect on partitioning (FNPTD), and stem abscission as a function of the abscised leaf mass (gram stem per gram leaf abscised) (PORPT), were also adjusted.

Phase 3: Calibration of genetic coefficients affecting vegetative partitioning. Parameters affecting leaf and stem biomass proportions, the dry matter partitioning to leaf as a function of V-stage, fraction (YLFEST), dry matter partitioning to stem as a function of V-stage,

fraction (YSTEST), and dry matter partitioning to storage as a function of V-stage, fraction (YSREST) were adjusted.

Phase 4: Calibration of Nitrogen stress parameters. In this phase, model simulations were improved by adjusting nitrogen (N) stress parameters. Modifying this parameter shifted the allocation of resources to shoot growth, resulting in improved model performance. This comprehensive calibration and evaluation process ensures that the CROPGRO-PFM model is finely tuned to simulate the growth and forage production of *B. brizantha* accurately under the rainfed condition of the Ethiopian subhumid.

5.2.4. Statistical analysis for model evaluation and parameterization

To evaluate model performance after optimization or calibration, we used the Bako dataset, which was not involved in the calibration process and was solely used for model evaluation. Then simulated output for shoot biomass (aboveground biomass above and below 20 cm), herbage, leaf and stem biomass, and crude protein (CP) percentage of herbage were compared with the observed field values. For model evaluation, we also employed statistical metrics such as root-mean-square error (RMSE) and Willmott agreement index (*d-statistic*) (Willmott *et al*. 2011; Yang *et al*. 2014). The equation for RMSE is as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Yi - \hat{Y}i)^2}$$

Where N is the total number of data points for comparison, Yi is a given observed value and $\hat{Y}i$ is the corresponding value predicted by the model.

The Willmott agreement index is given by: $d = 1 - \left[\frac{\sum_{i=1}^{N}(Yi-\hat{Y}i)^2}{\sum_{i=1}^{N}(|\hat{Y}i-\bar{Y}i|+|Yi-\bar{Y}i|)^2}\right]$, $0 \leq d \leq 1$

where N represents the number of observed data, Yi is a given observed value, $\hat{Y}i$ is the corresponding predicted value from the model, and $\bar{Y}i$ is the mean of the observed data.
A better model prediction is indicated by an observed-to-simulated ratio close to 1, with smaller RMSE and *d*-statistics values approaching 1.

5.2.5. Climatic data and scenarios

Daily weather data for the period 2020–2022, including rainfall, maximum temperature (Tmax), minimum temperature (Tmin), and solar radiation, were collected from DZARC and BARC weather stations (Figure 5.1). Less than 5% of the rainfall and temperature records were missing. For short data gaps (less than four consecutive days), simple interpolation methods were applied using data from nearby weather stations to ensure continuity.

Historical baseline climate data (1980-2009) were used to assess climate change impacts for the near future (2010-2039), mid-century (2040-2069) and end of the 21st century (2070-2099). Future climate projections were based on an ensemble average of 20 global circulation models (GCM) and 10 regional climate models for the Coordinated Regional Downscaling Experiment (CORDEX), provided by the World Climate Research Program (Giorgi *et al*., 2009). The CORDEX-Africa dataset, available at (http://cordex.org/domains/region-5-africa/), offers regionally downscaled daily climate data for Africa at a spatial resolution of 0.44° × 0.44°. Climate projections were made using two Representative Concentration Pathways (RCPs) from CMIP5: RCP4.5 and RCP8.5. These RCPs represent greenhouse gas concentration trajectories and associated radiative forcing levels used for climate modeling (Nazarenko *et al*., 2015). RCP4.5 reflects a stabilization scenario reaching 4.5W/m² by 2100, while RCP8.5 represents a high-emission scenario with radiative forcing rising to 8.5 W/m² by the end of the century (IPCC, 2014).

5.3. Results

The default model (Pequeno *et al*., 2014) simulated with the inputs observed from Bishoftu field experiments is presented in Table 5.3. During the first year of the study, rainfall was sufficient for crop water requirements, with water stress occurring only in 2021 and 2022. Nitrogen (N) stress was also observed but with lower intensity (Figure 5.2). Overall, the experiment conducted in Bishoftu experienced less water and nitrogen stress compared to Bako, allowing for model calibration under optimal conditions. In contrast, the Bako experiment was used for model evaluation under similar harvest and management schedules.

Table 5.3. Means and statistics for simulations of *B. brizantha* from 2020-2022, simulated using initial *B. brizantha* cv. Marandu by Pequeno *et al*. (2014) before calibration

Parameter	Obs.	Sim.	RMSE	Ratio (obs/sim)	Willmott's *d*	r-Square
Bishoftu						
Shoots, Kg DM ha^{-1}	9124	7743	1701	0.83	0.94	0.93
Herbage, Kg DM ha^{-1}	6873	5581	1635	0.79	0.90	0.87
Leaf, Kg DM ha^{-1}	4293	4399	546	1.05	0.97	0.91
Stem, Kg DM ha^{-1}	4831	3344	1561	0.62	0.85	0.94
Crude prot, %	12.73	12.76	2.50	1.00	0.41	0.34
Bako						
Shoots, Kg DM ha^{-1}	9046	7431	1936	0.78	0.92	0.90
Herbage, Kg DM ha^{-1}	6740	5208	1868	0.73	0.87	0.82
Leaf, Kg DM ha^{-1}	4193	4116	711	0.99	0.95	0.81
Stem, Kg DM ha^{-1}	4851	3315	1584	0.61	0.83	0.95
Crude prot, %	12.27	9.47	4.09	0.78	0.26	0.09

Kg DM ha^{-1} = Kilogram dry matter per hectare

5.3.1. Model calibration and improvement

To enhance the model, we implemented a series of systematic manual improvements, with a focus on the *d*-statistic and RMSE metrics. We then reviewed the modified parameters by comparing the simulated outcomes using the new parameter values against those from the original values, documenting both the initial and final parameter states.

5.3.1.1. Parameters affecting senescence and dormancy

The CROPGRO-PFM model was modified to enhance its accuracy in simulating *B. brizantha* forage growth and biomass accumulation. The adjustments mainly focus on the effects of daylength on dormancy and senescence. The model's parameters related to the effect of daylength on partitioning (FNPTD) and the relative dormancy sensitivity to daylength effect (RDRMT; Table 5.4) were adjusted to more accurately represent seasonal changes in daylength. This resulted in reduced the longest daylength for maximum shoot partitioning. Overall, the model now assigns less biomass to storage tissues and more to shoot growth under shorter day lengths and is more sensitive to changes in daylength within a narrower range of longer daylengths. Additionally, the model was updated to reduce the proportion of stem abscission based on leaf abscission (PORPT; Table 5.4).

Table 5.4. Initial and final values of species parameters affecting dormancy, senescence, and N stress modified in the species genetics file (SPE) and ecotype (ECO).

Parameter	Description	Initial value	Final value
FNPTD (2–3)	Effect daylength on partitioning (h)	12.0 16.0	11.5 14.5
RDRMT	Relative partitioning or dormancy sensitivity in response to day length effect on biomass partitioning (ECO)	0.475	0.45
PORPT	Stem abscission expressed as the ratio of stem mass to abscised leaf mass (gram stem per gram leaf abscised) (SPE)	0.27	0.19
NSTFAC	Photosynthates reallocation from shoot to root due to N stress (0–1) (SPE)	0.7	0.6

5.3.1.2. Parameters affecting biomass partitioning

Limited calibration of some species files related to vegetative partitioning parameters was conducted (Table 5.5), to ensure accurate simulation of leaf and stem biomass (Tables 5.6). It is important to note that we did not parameterize the rate of node appearance to predict the observed dates of growth stages or leaf number. The simulated V-stage was referenced only to define the dry matter partitioning function. The parameterization (YLFEST, YSTEST, YSREST) resulted in a progressive shift from leaf to stem between V-stages 3 and 10, with a slight adjustment in storage partitioning (Table 5.5).

Table 5.5. Initial and final values of species parameters affecting biomass partitioning were modified in the species file (SPE) of Marandu Palisade to simulate *B. brizantha*.

Parameter	Description	Initial value	Final value
XLFEST (not changed)	Leaf number/vegetative growth stage at which biomass partitioning is determined	0.0, 2.0, 3.0, 5.0, 7.0, 10.0, 30.0, 40.0	0.0, 2.0, 3.0, 5.0, 7.0, 10.0, 30.0, 40.0
YLFEST	Fraction of dry matter partitioned to leaves as a function of V-stage	0.80, 0.80, 0.72, 0.63, 0.52, 0.51, 0.50, 0.50	0.80, 0.80, 0.58, 0.50, 0.49, 0.49, 0.48, 0.48
YSTEST	Fraction of dry matter partitioned to stems as a function of V-stage	0.10, 0.10, 0.14, 0.17, 0.32, 0.36, 0.35, 0.35	0.10, 0.10, 0.30, 0.31, 0.38, 0.38, 0.37, 0.37
YSREST	Fraction of dry matter partitioned to storage as a function of V-stage	0.01, 0.01, 0.03, 0.04, 0.04, 0.04, 0.04, 0.04	0.01, 0.01, 0.02, 0.03, 0.04, 0.04, 0.04, 0.04

5.3.1.3. Parameters on shifting partitioning from shoot to root for N stress effect

The simulation showed that nitrogen stress affected both locations in 2022 (Figure 5.2). Thus, the parameter controlling the effect of nitrogen stress on biomass distribution between shoots and roots, NSTFAC, was adjusted (Table 5.4). Following this adjustment, nitrogen stress was almost negligible for Bako and completely absent for Bishoftu (Figure 5.3).

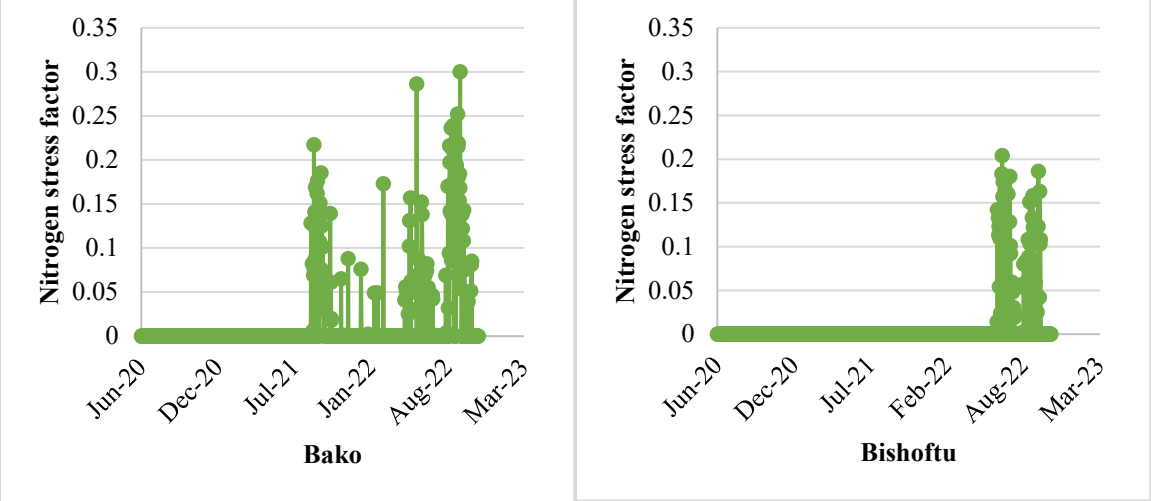


Figure 5.2. Simulated nitrogen stress factor using the initial model version by Pequeno *et al*. (2014) as a function of date for *B. brizantha* in Bako and Bishoftu before calibration.

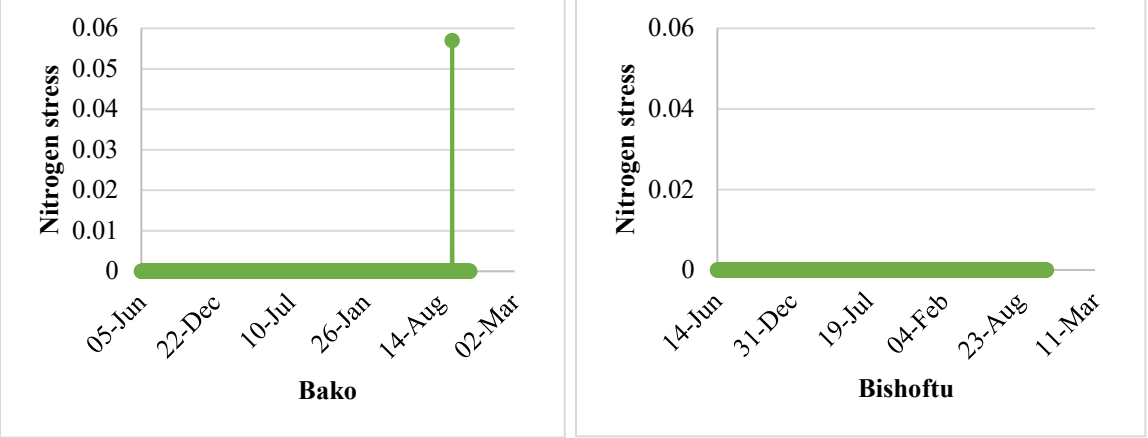


Figure 5.3. Simulated nitrogen stress factor for *B. brizantha* after calibration.

5.3.2. Statistical evaluation of model performance

The model's performance after calibration is presented in Table 5.6. After calibration, the model showed improved performance, with simulated values closely matching observed values. The RMSE for shoot biomass, herbage biomass, and stem biomass was significantly decreased. Additionally, the *d*-statistics and r-square values for the shoot, herbage, leaf, and stem biomass improved notably. However, the statistics for the crude protein percentage of the herbage did not improve at either location.

Table 5.6. Simulations (Means and statistics) for the rainfed *B. brizantha* grass from 2020 to 2022, using the *B. brizantha* cv. Marandu by Pequeno *et al*. (2014) after calibration

Variable Name	Obs.	Sim.	RMSE	Ratio (obs/sim)	Willmott's *d*	r-Square
Bishoftu						
Shoots, Kg DM ha^{-1}	9124	8706	969	0.92	0.98	0.96
Herbage, Kg DM ha^{-1}	6873	6531	946	0.90	0.97	0.93
Leaf, Kg DM ha^{-1}	4293	4271	518	1.02	0.98	0.91
Stem, Kg DM ha^{-1}	4831	4435	677	0.83	0.98	0.97
Crude prot, %	12.73	11.96	2.44	0.94	0.44	0.36
Bako						
Shoots, Kg DM ha^{-1}	9046	8887	1488	0.92	0.96	0.93
Herbage, Kg DM ha^{-1}	6740	6649	1444	0.91	0.94	0.89
Leaf, Kg DM ha^{-1}	4193	4069	741	0.98	0.94	0.81
Stem, Kg DM ha^{-1}	4851	4817	1009	0.88	0.95	0.97
Crude prot, %	12.27	8.91	4.70	0.74	0.23	0.11

5.3.3. Climate change scenarios

The results from the CORDEX Africa output under the two CMIP5 Representative Concentration Pathways (RCP4.5 and RCP8.5), focusing on mean changes in projected climate over three future periods (near future, mid, and end century) for Bako, Ethiopia (Table 5.7), and Bishoftu, central Ethiopia (Table 5.8), revealed an increase in temperature and rainfall, compared with the baseline (1980–2010). The projected mean minimum temperatures at Bako for the baseline, near future, mid, and end century were 11.6, 12.7, 14.4, and 15.9◦C, respectively, whereas the mean seasonal maximum temperatures for the corresponding periods were 26.4, 24.8, 26.0, and 27.1◦C. Similarly, at Bishoftu, 11.1, 12.5, 14.2, and 15.8◦C mean minimum, and 25.5, 26.1, 27.4, and 28.6◦C mean maximum

temperatures were projected for the baseline, near future, mid, and end century, respectively. Mean rainfall ranging from 1173 to 2473, 1264 to 3334, and 1531 to 4347 mm at Bako is projected, for the near future, mid and end century, respectively whereas at Bishoftu 847.1 to 1719.1, 987.7 to 2418.1 and 1063.3 to 3079.2 for the corresponding period were observed.

Table 5.7. Mean changes in projected climate over three future periods under RCP4.5 and RCP8.5, relative to the corresponding values for baseline data in Bako, Ethiopia.

Period	RF (%)	Tmin (ºC)	Tmax (ºC)	Average CO_2 conc. (ppm)	RF (%)	Tmin (ºC)	Tmax (ºC)	Average CO_2 conc. (ppm)
	RCP 4.5				RCP 8.5			
2010-2039	3.47	1.48	1.35	423	4.13	1.7	1.25	432
2040-2069	6.24	2.68	2.2	499	9	3.83	2.73	571
2070-2099	7.78	3.23	2.73	532	16.49	6.31	4.55	801

RF=Rainfall; Baseline [CO_2], assumed 360 ppm, RCP=Representative Concentration Pathways.

Table 5.8. Mean changes in projected climate over three future periods under RCP4.5 and RCP8.5, relative to the corresponding values for baseline data in Bishoftu, Ethiopia.

Period	RF (%)	Tmin (ºC)	Tmax (ºC)	Average CO_2 conc. (ppm)	RF (%)	Tmin (ºC)	Tmax (ºC)	Average CO_2 conc. (ppm)
	RCP 4.5				RCP 8.5			
2010-2039	2.80	1.66	1.39	423	3.04	2.06	1.32	432
2040-2069	4.52	2.89	2.32	499	6.48	4.21	2.92	571
2070-2099	5.97	3.58	2.82	532	11.76	6.75	4.85	801

RF=Rainfall; Baseline [CO_2], assumed 360 ppm, RCP=Representative Concentration Pathways.

5.3.4. Future yield simulations

Table 5.9 shows the simulated yield of shoots, herbage biomass, leaf, stem (Kg DM ha^{-1}), and crude protein percentage of herbage *B. brizantha* under near future, mid-century, and end of the 21st century for RCP 4.5 and RCP 8.5 scenarios compared to the baseline period of 1980-2010 for the Bako and Bishoftu. The result indicates the leaf biomass is expected to decline in response to future climate conditions (Figure 5.4b) except for Bishoftu's near future under RCP8.5. It is predicted to decline by 6% and increase by 1% for the near future, decline by 5% and 6% for mid-century, and by 8% and 16% by the end of the 21st century under RCP4.5 and RCP8.5, respectively. However, stem biomass is predicted to

increase for all future periods, except for Bako the near future under RCP4.5. The stem biomass is predicted to increase by 10% and 12% for the near future, by 26% and 31% for mid-century, and by 35% and 37% for the end of the 21st century under RCP4.5 and RCP8.5, respectively.

Shoot biomass, for both locations, is predicted to increase for all future periods, except for Bako near future under RCP4.5 (Figure 5.4a). It is predicted to increase by 2% and 6% for the near future, by 10% and 12% for the mid-century, and by 13% and 10% for the end of 21st century, under RCP4.5 and RCP8.5, respectively. Similarly, the herbage biomass is expected to show a pattern similar to that of the shoot biomass and overall, it is expected to increase by 11%. Herbage biomass is predicted to increase by 3% and 8% for the near future, by 13% and 15% for mid-century, and by 17% and 12% for the end of 21st century. The crude protein percentage of herbage is expected to decrease for both locations under both RCPs for all future periods, except for Bako under the near future RCP4.5. Crude protein is expected to increase by 3% and decrease by 9% for the near future, decrease by 12% and 15% for the mid-century, and decrease by 15% and 19% for the end of 21st century under RCP4.5 and RCP8.5, respectively.

Table 5.9. Median yield changes over three future periods, as simulated by the CROGRO-PFM model based on CORDEX Africa under RCP4.5 and RCP8.5.

Parameters	1980-2010	2010-2039		2040-2069		2070-2099	
	baseline	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Bako							
Leaf, Kg DM ha^{-1}	4018	3697	3976	3920	3926	3859	3464
Stem, Kg DM ha^{-1}	4259	4118	4320	4946	5136	5303	5322
Shoot, Kg DM ha^{-1}	8278	7815	8296	8867	9061	9162	8786
Herbage, Kg DM ha^{-1}	6533	6057	6538	7095	7298	7396	7020
Crude prot, %	10.34	11.91	9.97	9.95	9.81	9.87	9.32
Bishoftu							
Leaf, Kg DM ha^{-1}	3917	3779	4037	3658	3529	3484	3182
Stem, Kg DM ha^{-1}	3626	4492	4439	4923	5118	5250	5386
Shoot, Kg DM ha^{-1}	7543	8271	8476	8581	8646	8734	8568
Herbage, Kg DM ha^{-1}	5793	6518	6720	6820	6878	6965	6803
Crude prot, %	12.35	11.19	10.52	9.8	9.33	9.26	8.8

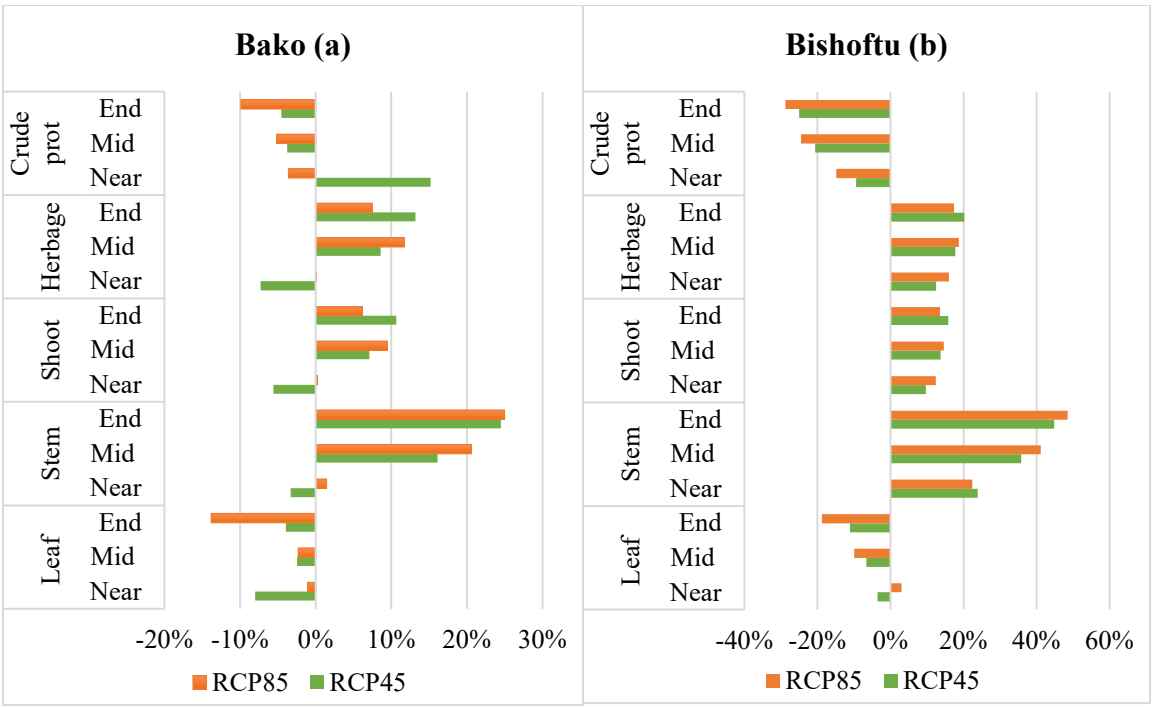


Figure 5.4. Yield gained/lost (compared to the historical value) simulated using CROGRO-PFM for RCP4.5, RCP8.5 for the near future, mid, and end of 21st century for Bako (left) and Bishoftu (right).

5.4. Discussion

5.4.1. Model calibration and modification

The most important result of this study is that the calibrated *Brachiaria brizantha* model demonstrated high accuracy in simulating the growth of *B. brizantha* under rainfed subhumid conditions in Ethiopian agroecology. This is consistent with previous studies (Pequeno *et al*., 2017; Brunetti *et al*., 2021; Smith *et al*., 2023; Bender *et al*., 2024), which have shown that improving parameters related to dormancy and vegetative partitioning enhances simulation outcomes, particularly for tropical grasses. Additionally, the overestimation of water and nitrogen stress, as noted by Korir *et al*. (2021), often leads to underestimation of biomass. In this study, adjustments to nitrogen stress parameters addressed this issue, improving the accuracy of the biomass simulations.

The model parameters adjusted to represent the effect of daylength in seasonal changes, FNPTD and RDRMT, led to more realistic regrowth patterns and distribution of

aboveground biomass. In Brazilian conditions, the daylength parameter (FNPTD) was adjusted to increase allocation to storage and reduce shoot growth during winters (April–September) (Pequeno *et al*., 2014). This means that the model increases assimilate allocation to storage organs, indicating dormancy, and decreases allocation to shoot. This reflects the natural response of plants to prepare for adverse conditions by storing energy rather than investing in shoot biomass (Brunetti *et al*., 2021). On the other hand, in Ethiopia, where April–September falls in the growing (rainy) season, the model was conversely adjusted to decrease allocation to storage tissues and prioritize shoot growth. This adjustment reflects the lower threshold for inducing shoot growth rather than storage during this period. The reduced proportion of stem abscission based on leaf abscission (PORPT) helps retain more biomass in the stem, leading to increased overall stem mass accumulation (Table 5.6). The model also takes into consideration the senescing of leaf sheaths after the leaf laminae, with the dead sheath material contributing to stem mass (Brunetti *et al*., 2021). The modified PORPT also helped more accurately represent how plants respond to different daylengths, thus improving its ability to simulate forage growth by capturing the subtleties of forage biomass accumulation and senescence.

Modifying vegetative partitioning parameters led to increased stem mass and, consequently, shoot biomass results significantly better fit for these variables. During early regrowth of tropical forage species, biomass production is mostly composed of leaves (Brunetti *et al*., 2021). However, in the later growth stage, a considerable amount of biomass is allocated to the stem, including during prolonged vegetative growth (Poorter *et al*., 2012; Mganga *et al*., 2021). Thus, leaf and stem mass can be enhanced by adjusting partitioning, particularly by increasing stem mass for longer regrowth (Pequeno *et al*., 2014).

Nitrogen stress significantly affects the distribution of biomass between shoots and roots; and because of this, it is considered a crucial factor for accurately simulating the growth of warm-season grasses (Brunetti *et al*., 2021). This highlights the importance of properly setting model parameters under nitrogen stress conditions. To address this, the parameter controlling the effect of nitrogen stress on biomass distribution between shoots and roots, NSTFAC was adjusted. Originally coded at 0.7 in the model, it has now been changed to

0.6. This adjustment allows for a more realistic simulation of plant responses to nitrogen stress, with the model now allocating more biomass to shoots than to roots.

5.4.2. Model performance

The results of the CROPGRO-PFM simulation indicated that the *B. brizantha* cv. Marandu, as studied by Pequeno *et al*. (2014) and parameterized for *B. brizantha* accession DZF-13379 under rainfed conditions in Ethiopia, could effectively be used for future yield assessments of *B. brizantha* under future climate scenarios. The model demonstrated improved performance, with simulated values closely matching observed data, lower RMSE values, d-statistics closer to 1, and r-square values above 81% for all parameters tested, except for crude protein percentage. However, further calibration and/or code modification of the model may be necessary to enhance the accuracy of crude protein percentage.

5.4.3. Climate change scenarios and yield simulations

This analysis underscores the importance of using high-resolution regional climate data from CORDEX Africa and an ensemble approach to capture large-scale trends and local variability (multiple GCMs and RCMs) for generating robust historical and future climate projections, which is critical for climate impact assessments and decision-making. This aligns with Kassahun *et al*. (2023), who highlight the value of such an approach in generating reliable climate scenarios for sub-Saharan Africa. The projected increase in temperature and CO_2 concentrations reflects broader trends reported for sub-Saharan Africa (Maino & Emrullahu, 2022). Additionally, the study shows a trend of increased rainfall across all future periods, which aligns with the IPCC (2007) projections. However, the rainfall patterns specific to Ethiopia remain inconsistent, as noted in previous studies (Conway & Schipper, 2011; Hadgu *et al*., 2014).

Given these projected climatic changes, their impact on forage yield was assessed. The study found no significant changes in yield across different future climate scenarios (near future, mid-century, and end-century). However, shoot, herbage and stem biomass are projected to increase likely due to slightly higher rainfall, elevated CO_2 effects (enhancing

C4 crop productivity), and increased temperatures. Under these conditions, the crop model advances the vegetative stage more rapidly, accelerating crop maturity (Moore *et al*., 2021). This results in a greater allocation of biomass to the stem and a reduction in leaf growth. In addition, with fixed harvest dates, the harvested forage will be more mature, containing a higher stem proportion and lower CP content , which could be mitigated by harvesting more often under climate scenarios (using a degree-day approach) (Coblentz *et al*., 2018).

Under both RCP 4.5 and RCP 8.5 scenarios, the study projects a 25% increase in stem biomass, a 9% increase in shoot biomass, and an 11% increase in herbage biomass. Conversely, leaf biomass is expected to decrease by 7%. This indicates that while stem and shoot growth might benefit from future climate conditions (higher temperatures and CO_2 concentrations), leaf growth may be negatively affected. Overall, these projections suggest that plant growth in the subhumid regions of Ethiopia might be less adversely impacted by future climate conditions than previously expected, with elevated greenhouse gases and warmer temperatures having mixed effects on different plant components (stem vs. leaf) (Brychkova *et al*. 2022; Habermann *et al*. 2019).

Several studies support these findings, reporting increased biomass production in grasslands due to elevated CO_2 (eCO_2) and rising temperatures (Ergon *et al*., 2018; Brychkova *et al*., 2022; Puche *et al*., 2023). Moreover, elevated CO_2 concentrations have been shown to enhance the photosynthetic rate in C4 plants (Habermann *et al*., 2022). Our findings are also consistent with the report by Brychkova *et al*. (2022), which suggests that the current and future climates are suitable for the production of forages such as Rhodes grass and Napier grass. However, the quality of herbage, as indicated by its crude protein percentage, is expected to decline by 11%. This suggests that while biomass production may increase, the nutritional quality of grass used for animal feed could suffer under higher greenhouse gas concentrations and warmer temperatures. This finding aligns with the report by Habermann *et al*. (2022), which found that elevated CO_2 reduces the crude protein content of tropical grasses.

5.5. Conclusion

The study highlights the critical role of *Brachiaria brizantha* as a climate-smart forage species for enhancing livestock feed security in Ethiopia's subhumid regions. Utilizing the CROPGRO-Perennial Forage Model, the research calibrated and evaluated the model to accurately simulate the growth and yield of *B. brizantha* under varying climate conditions. The findings reveal that while initial model predictions were satisfactory, adjustments in parameters related to senescence and dormancy, vegetative partitioning, and nitrogen stress significantly improved the model's predictive accuracy. Despite this, there are still areas where model performance, especially for predicting crude protein content, did not achieve the same level of accuracy as other parameters, indicating the need for further refinement. Overall, the study underscores the potential of *B. brizantha* in mitigating the challenges posed by climate change and emphasizes the need for its broader adoption to support livestock production in Ethiopia. However, further research on different *Brachiaria* cultivars under different management practices such as harvesting dates considering degree of days and model improvements is necessary to fully understand the broader impacts of climate change on forage production across diverse Ethiopian agroecologies.

CHAPTER 6: Simulating the Growth and Yields of *Brachiaria Mutica* Using the CROPGRO-Perennial Forage Model Under Present and Future Climate Conditions in Subhumid Environments of Ethiopia.

Abstract

Brachiaria is an essential forage crop in tropical and subtropical regions; however, its response to climate change in Ethiopia remains underexplored. This study aimed to (1) calibrate and evaluate the CROPGRO-Perennial Forage model (CROPGRO-PFM) and (2) assess the potential impact of climate change on the future yield of *B. mutica* (DZF-478) in Ethiopia's sub-humid environments. For model calibration and evaluation, field data from Debre Zeit (Bishoftu) and Bako Agricultural Research Centers were used. Daily weather data, including rainfall, minimum and maximum temperature, and solar radiation, were obtained from the centers' meteorological stations. Historical and future climate scenarios were derived from CORDEX Africa outputs for the near future (2010-2039), mid-century (2040-2069), and end of the 21st century (2070-2099) under RCP4.5 and RCP8.5 emission pathways. Calibration refined key model parameters governing senescence, dormancy, vegetative partitioning, and nitrogen stress responses, thereby improving model performance. Simulation results revealed a predicted decline in biomass accumulation, including shoots, herbage, leaf and stem biomass, along with a reduction in crude protein content. Overall, the findings underscore the utility of CROPGRO-PFM in projecting climate change impacts and supporting evidence-based decision-making by policymakers and researchers. The production potential of *B. mutica* (DZF-478) is expected to decline in Ethiopia's subhumid regions under future climate scenarios, highlighting the need for further research on adaptive management strategies.

Keywords: *Brachiaria mutica*, Climate change, CROPGRO-PFM, Simulation, Ethiopia

6.1. Introduction

There is increasing interest in introducing improved forage species, such as *Brachiaria* grass, to enhance livestock production (Schiek *et al*., 2018; Njarui *et al*., 2021; Feyissa *et al*., 2022; Perelli *et al*., 2024). *Brachiaria* grass, native to Eastern Africa, is widely cultivated in tropical regions as a vital component of forage-livestock systems (Jank *et al*., 2014; Tegegn *et al*., 2019; Namazzi *et al*., 2020). This forage species offers numerous advantages, including drought resistance, adaptability to low-fertility soils, carbon sequestration, biological nitrification inhibition (BNI), and a potential role in reducing greenhouse gas emissions (Arango *et al*., 2014; Moreta *et al*., 2014; Rao *et al*., 2014).

Despite its advantages, *Brachiaria* remains underused in East Africa, including Ethiopia (Tegegn *et al*., 2019; Cheruiyot *et al*., 2020; Njarui *et al*., 2021). Recent efforts, however, are aimed at promoting its cultivation to boost the region's livestock sector (Maass *et al*., 2015; Maina *et al*., 2020). Furthermore, its recognition as a climate-smart forage species underscores its promise for success in future climate scenarios (Djikeng *et al*., 2014; Njarui *et al*., 2021). In addition to adaptability and nutritional quality, assessing its resilience under changing climate is important to optimize sustainable use of improved forage.

Thus, given the significant effects of climate change on forage production, evaluating *Brachiaria* grass yield under varying climatic conditions is essential to ensure future livestock feed security. Mechanistic crop simulation models, such as the CROPGRO-PFM model integrated into DSSAT 4.8.2, are valuable tools for examining plant-environment-management interactions and assessing the effects of climate change on forage crops (Jones *et al*., 2003; Hoogenboom *et al*., 2020; Hoogenboom *et al*., 2024). The model has been applied to simulate the growth and yield of various forage species, including *Paspalum notatum* (Bahiagrass) (Rymph, 2004), *Brachiaria brizantha* cv. Marandu (Pequeno *et al*., 2014), *Urochloa brizantha* (Palisade grass) (Pedreira *et al*., 2011), *Cynodon dactylon* (Bermuda grass) (Pequeno *et al*., 2017), *Brachiaria brizantha* (Piatã palisade grass) (Bosi *et al*., 2020), *Megathyrsus maximus* (Guinea grass) (Brunetti *et al*., 2021). It has also been used to assess the long-term production of *Urocloa brizantha* under different environments in Brazil (Santos *et al*., 2022).

In Ethiopia, although this variety was registered and officially released in 2015 (Feyissa *et al*., 2022; Zeleke *et al*., 2022), limited studies have examined the potential impacts of climate change on its production. To address this gap, our study utilized the historical and future climate data from CORDEX Africa under Representative Concentration Pathways (RCPs, RCP4.5 and RCP8.5) scenarios and evaluated *B. mutica* yields in the sub-humid regions of central and western Ethiopia. The objectives of our study are thus to (1) calibrate and assess the CROPGRO-PFM model for simulating the rainfed growth and yield of *Brachiaria mutica*, and (2) analyze the impacts of climate change on its yield under both high and moderate RCP scenarios in the sub-humid environments of central and western Ethiopia. Our null hypothesis posits that the standard model developed for Marandu palisade grass can accurately simulate the growth and forage production of *B. mutica* (DZF-483) in Ethiopia by incorporating specific genotypic characteristics.

6.2. Materials and Methods

The information related to field experimental data and treatments, model calibration and statistical evaluation of model performance were presented in Chapter 5 of this dissertation.

6.3. Results

6.3.1. Simulation of *B. mutica* using original *B. brizantha* adaptation

The *B. mutica* was simulated using inputs data from the Bishoftu field experiments, employing the default model parameters described by Pequeno *et al*. (2014). Model improvement was assessed through step-by-step analysis of the observed-to-simulated ratio, d-statistics, and RMSE (Table 6.1). Key parameter adjustments were identified and compared to the default values, with both initial and optimized values documented. On the other hand, data from the Bako experiment was used to evaluate the model under similar harvest schedules and management practices. The significance of the key model enhancements was emphasized, and recommendations were provided to guide future model development and improve the simulation accuracy for tropical forage grasses.

Table 6.1. Simulations (Means and statistics) for the rainfed *B. mutica* grass from 2020 to 2022, using the initial *B. brizantha* by Pequeno *et al*. (2014) before calibration

Parameter	Obs.	Sim.	RMSE	Ratio (obs/sim)	Willmott's *d*	r-Square
Bishoftu						
Shoots, Kg DM ha^{-1}	10556	7048	3949	0.66	0.61	0.57
Herbage, Kg DM ha^{-1}	8140	4962	3565	0.60	0.53	0.43
Leaf, Kg DM ha^{-1}	4812	4273	1173	0.89	0.75	0.44
Stem, Kg DM ha^{-1}	5565	2775	2920	0.48	0.48	0.59
Crude prot, %	12.34	15.23	3.09	1.23	0.16	0.03
Bako						
Shoots, Kg DM ha^{-1}	9822	7620	3307	0.77	0.66	0.48
Herbage, Kg DM ha^{-1}	7705	5738	2880	0.74	0.60	0.42
Leaf, Kg DM ha^{-1}	4673	4360	1224	0.94	0.77	0.47
Stem, Kg DM ha^{-1}	5149	3260	2297	0.62	0.53	0.49
Crude prot, %	12.8	11.65	3.08	0.91	0.39	0.04

Kg DM ha^{-1} = Kilogram dry matter per hectare

6.3.2. Model calibration

6.3.2.1. Calibration of parameters affecting senescence and dormancy

The CROPGRO-PFM model was modified to enhance its accuracy in simulating the growth and biomass accumulation of *B. mutica* forage by refining the influence of daylength on dormancy, and senescence. Key parameters including those related to daylength-driven biomass partitioning (FNPTD; Table 6.2) and dormancy sensitivity to daylength (RDRMT; Table 6.2) to better reflect seasonal variations in daylength were adjusted. These adjustments reduced the range of daylengths required for maximum shoot partitioning. As a result, the model now allocates less biomass to storage tissues and more to shoot growth under shorter daylengths, while also becoming more responsive to changes in longer daylengths within a narrower range. Additionally, the model was updated to lower the proportion of stem abscission relative to leaf abscission (PORPT; Table 6.2), enhancing its representation of senescence dynamics. The maximum leaf photosynthetic rate (LFMAX; Table 6.2) was slightly increased to align with field-measured data, ensuring a closer match to observed forage productivity.

Table 6.2. Initial and final values of species parameters affecting aboveground biomass accumulation modified in the species genetics file (SPE), ecotype (ECO) and cultivar (CUL) and the steps at which the parameters were adjusted throughout parameterization.

Parameter	Description	Initial value	Final value
FNPTD (2–3)	Effect of daylength on partitioning (h)	12.0 16.0	10.5 14.5
RDRMT	Relative partitioning or dormancy sensitivity in response to day length effect on biomass partitioning (ECO)	0.475	0.475
LFMAX	Maximum leaf photosynthetic rate measured at 30 °C, 350 vpm CO_2, and under high light intensity (mg CO_2 m^{-2} s^{-1})	1.8	2.15
PORPT	Stem abscission expressed as the ratio of stem mass to abscised leaf mass (gram stem per gram leaf abscised) (SPE)	0.27	0.21
LFSEN	Natural leaf abscission rate per photothermal day (0.014 corresponds to a leaf lifespan of approximately 66.67 days) (SPE)	0.014	0.01
ICMP	Light compensation point (mol PPFD m^{-2} day^{-1}) for the onset of senescence in lower leaves due to excessive self-shading within the crop canopy.	1.17	1.39
NSTFAC	Photosynthates reallocation from shoot to root due to N stress (0–1) (SPE)	0.7	0.6

6.3.2.2. Parameters affecting biomass partitioning

Calibration of specific species files concerning vegetative partitioning parameters (see Table 6.3) to ensure accurate simulations of leaf and stem biomass was conducted (refer to Tables 6.4). Importantly, the rate of node appearance was not set to predict the observed dates of growth stage or leaf counts and storage partitioning (YSREST) was not changed. Instead, the simulated V-stage was exclusively used to define the dry matter partitioning function. The parameterization of YLFEST, and YSTEST led to a gradual shift in biomass allocation from leaves to stems between V-stages 3 and 10 (as shown in Table 6.3).

Table 6.3. Initial and final values of species parameters affecting biomass partitioning were modified in the species file (SPE) to simulate *B. mutica* cultivar and the steps at which the parameters were modified.

Parameter	Description	Initial value	Final value
XLFEST (not changed)	Leaf number or vegetative growth stage at which biomass partitioning is determined	0.0, 2.0, 3.0, 5.0, 7.0, 10.0, 30.0, 40.0	0.0, 2.0, 3.0, 5.0, 7.0, 10.0, 30.0, 40.0
YLFEST	Fraction of dry matter partitioned to leaves as a function of V-stage	0.80, 0.80, 0.72, 0.63, 0.52, 0.51, 0.50, 0.50	0.80, 0.80, 0.54, 0.50, 0.49, 0.49, 0.48, 0.48
YSTEST	Fraction of dry matter partitioned to stems as a function of V-stage	0.10, 0.10, 0.14, 0.17, 0.32, 0.36, 0.35, 0.35	0.10, 0.10, 0.32, 0.33, 0.35, 0.38, 0.37, 0.37
YSREST	Fraction of dry matter partitioned to storage as a function of V-stage	0.01, 0.01, 0.03, 0.04, 0.04, 0.04, 0.04, 0.04	0.01, 0.01, 0.03, 0.04, 0.04, 0.04, 0.04, 0.04

6.3.3. Statistical evaluation of model performance

The model's performance before and after calibration is summarized in Table 6.4, respectively. Post-calibration, the model demonstrated improved accuracy, with simulated values aligning more closely with observed data. The RMSE values for shoot biomass, and stem biomass decreased significantly, except for leaf biomass in both locations and herbage biomass at the Bishoftu site. Furthermore, the *d*-statistics and r-square values for shoot, herbage, leaf, and stem biomass showed notable improvements. However, the calibration did not enhance the statistical accuracy for the crude protein percentage of the herbage at either location.

Table 6.4. Simulations (Means and statistics) for the rainfed *B. brizantha* grass from 2020 to 2022, using the *B. brizantha* by Pequeno *et al*. (2014) after calibration.

Variable Name	Obs.	Sim.	RMSE	Ratio (obs/sim)	Willmott's *d*	r-Square
Bishoftu						
Shoots, Kg DM ha^{-1}	10556	9609	2719	0.88	0.83	0.73
Herbage, Kg DM ha^{-1}	8140	7506	2605	0.89	0.75	0.63
Leaf, Kg DM ha^{-1}	4812	5182	1346	1.04	0.83	0.78
Stem, Kg DM ha^{-1}	5565	4428	1914	0.77	0.66	0.55
Crude prot, %	12.34	13.3	2.06	1.08	0.30	0.25
Bako						
Shoots, Kg DM ha^{-1}	9822	9643	3263	0.96	0.74	0.56
Herbage, Kg DM ha^{-1}	7705	7740	2951	0.98	0.70	0.51
Leaf, Kg DM ha^{-1}	4673	5008	1474	1.04	0.80	0.72
Stem, Kg DM ha^{-1}	5149	4636	1950	0.89	0.65	0.41
Crude prot, %	12.8	10.22	4.25	0.80	0.30	0.08

Kg DM ha^{-1} = Kilogram dry matter per hectare

6.3.4. Climate change scenarios

The results from the CORDEX Africa output under the two CMIP5 Representative Concentration Pathways (RCP4.5 and RCP8.5), focusing on mean changes in projected climate over three future periods for Bako, Ethiopia (Table 6.5), and Bishoftu, central Ethiopia (Table 6.6), revealed an increase in temperature and rainfall, compared with the baseline (1980–2010). The projected mean minimum temperatures at Bako for the baseline, near future, mid, and end century were 11.6, 12.7, 14.4, and 15.9◦C, respectively, whereas the mean seasonal maximum temperatures for the corresponding periods were 26.4, 24.8, 26.0, and 27.1◦C. Similarly, at Bishoftu, 11.1, 12.5, 14.2, and 15.8◦C mean minimum, and 25.5, 26.1, 27.4, and 28.6◦C mean maximum temperatures were projected for the baseline, near future, mid, and end century, respectively. Mean rainfall ranging from 1173 to 2473, 1264 to 3334, and 1531 to 4347 mm at Bako is projected, for the near future, mid and end century, respectively whereas at Bishoftu 847.1 to 1719.1, 987.7 to 2418.1 and 1063.3 to 3079.2 for the corresponding period were observed.

Table 6.5. Mean changes in projected climate over three future periods under RCP4.5 and RCP8.5, relative to the corresponding values for baseline data in Bako, Ethiopia.

Period	RF (%)	Tmin (ºc)	Tmax (ºc)	Average CO_2 conc.(ppm)	RF (%)	Tmin (ºc)	Tmax (ºc)	Average CO_2 conc. (ppm)
	RCP 4.5				RCP 8.5			
2010-2039	3.47	1.48	1.35	423	4.13	1.7	1.25	432
2040-2069	6.24	2.68	2.2	499	9	3.83	2.73	571
2070-2099	7.78	3.23	2.73	532	16.49	6.31	4.55	801

RF = Rainfall; Baseline [CO_2], assumed 360 ppm.

Table 6.6. Mean changes in projected climate over three future periods under RCP4.5 and RCP8.5, relative to the corresponding values for baseline data in Bishoftu, Ethiopia.

Period	RF (%)	Tmin (ºc)	Tmax (ºc)	Average CO_2 conc. (ppm)	RF (%)	Tmin (ºc)	Tmax (ºc)	Average CO_2 conc. (ppm)
	RCP 4.5				RCP 8.5			
2010-2039	2.80	1.66	1.39	423	3.04	2.06	1.32	432
2040-2069	4.52	2.89	2.32	499	6.48	4.21	2.92	571
2070-2099	5.97	3.58	2.82	532	11.76	6.75	4.85	801

RF = Rainfall; Baseline [CO_2], assumed 360 ppm.

6.3.5. Future yield simulations

Table 6.7 and Figure 6.1 presents the simulated yield of shoots biomass, herbage biomass, leaf biomass, stem biomass (Kg DM ha^{-1}), and crude protein percentage of herbage *B. mutica* for the near future, mid-century, and end of the 21st century under RCP 4.5 and RCP 8.5 scenarios, compared to the baseline period of 1980-2010 for the Bako and Bishoftu. Specific changes for leaf biomass include:

- Near future: A decline of 15% under RCP 4.5 and an increase of 4% under RCP 8.5.
- Mid-century: A decline of 15% and 19% under RCP 4.5 and RCP 8.5, respectively.
- End of the century: A decline of 25% and 34% under RCP 4.5 and RCP 8.5, respectively.

Similarly, stem biomass is predicted to decline for all future periods, except for the near future under RCP8.5 at both locations. Predicted changes include:

- Near future: A decline of 7% under RCP 4.5 and an increase of 11% under RCP 8.5.
- Mid-century: A decline of 7% under RCP 4.5 and 8% under RCP 8.5.

- End of the century: A decline of 10% under RCP 4.5 and 13% under RCP 8.5.

Like leaf and stem biomass, shoot biomass is predicted to decline for both locations and all future periods, except for the near future under RCP 8.5 (Figure 6.1). Predicted changes include:

- Near future: A decline of 2% under RCP 4.5 and an increase of 7% under RCP 8.5.
- Mid-century: A decline of 11% under RCP 4.5 and 14% under RCP 8.5.
- End of the century: A decline of 18% under RCP 4.5 and 24% under RCP 8.5.

The trend for herbage biomass closely aligns with shoot biomass. Overall, it is expected to decline by 15%. Specific changes include:

- Near future: A decline of 14% under RCP 4.5 and an increase of 9% under RCP 8.5.
- Mid-century: A decline of 15% and 18% under RCP 4.5 and RCP 8.5, respectively.
- End of the century: A decline of 23% and 31% RCP 4.5 and RCP 8.5, respectively.

The crude protein percentage of herbage is expected to decline for both locations under both RCPs for all future scenarios, except for the near future, where the average change across locations is zero. Crude protein is expected to decline by 14% and 18% for the mid-century, and by 18% and 20% for the end of the 21st century under RCP4.5 and RCP8.5, respectively. In general, the simulations indicate a decline in biomass production and CP percentage of *B. mutica* under future climate scenarios, except for RCP 8.5 from the near future towards the end of the century.

Table 6.7. Median yield changes over three future periods, as simulated by the CROGRO-PFM model based on CORDEX Africa under RCP4.5 and RCP8.5.

Parameters	1980-2010	2010-2039		2040-2069		2070-2099	
	baseline	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Bako							
Leaf, Kg DM ha^{-1}	5107	4345	5312	4301	4265	3846	3471
Stem, Kg DM ha^{-1}	4681	4024	4948	4095	4162	3962	3843
Shoot, Kg DM ha^{-1}	9788	8368	10260	8396	8427	7807	7315
Herbage, Kg DM ha^{-1}	7897	6470	8368	6484	6528	5904	5414
Crude prot, %	10	11.36	11.15	9.55	9.61	9.24	8.96
Bishoftu							
Leaf, Kg DM ha^{-1}	5203	4429	5382	4430	4043	3862	3349
Stem, Kg DM ha^{-1}	4309	4309	4993	4279	4121	4151	3938
Shoot, Kg DM ha^{-1}	9512	8737	10375	8709	8165	8012	7288
Herbage, Kg DM ha^{-1}	7419	6635	8273	6593	6047	5896	5175
Crude prot, %	12.17	10.55	10.82	9.23	8.83	8.8	8.49

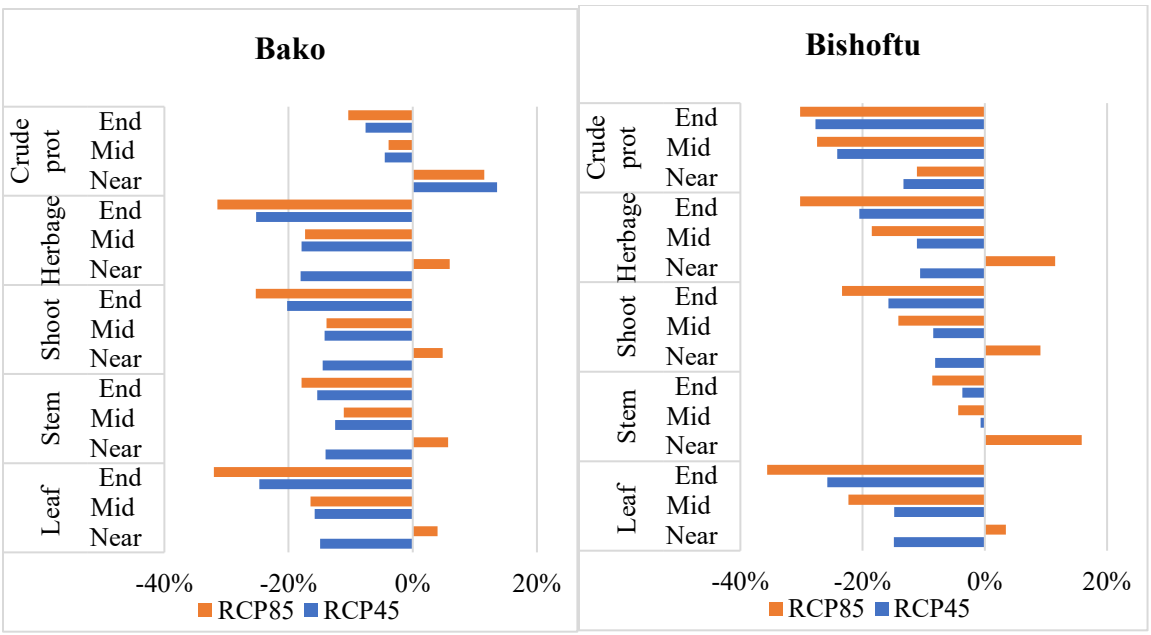


Figure 6.1. Yield gained/lost (compared to the historical value) simulated using CROGRO-PFM for RCP4.5, RCP8.5 for the near future, mid, and end of 21st century for Bako left and Bishoftu right.

6.4. Discussion

6.4.1. Model calibration and modification

The key finding of this study is that the calibrated *Brachiaria mutica* model exhibited high accuracy in simulating the growth of *B. mutica* under rainfed subhumid conditions in Ethiopian agroecology. This result is consistent with previous studies (Pequeno *et al*., 2017; Brunetti *et al*., 2021; Smith *et al*., 2023; Bender *et al*., 2024), which emphasizes that refining parameters related to dormancy and vegetative partitioning enhances simulation outcomes, particularly for tropical grasses. Additionally, as noted by Korir *et al*. (2021), the overestimation of water and nitrogen stress often leads to an underestimation of biomass. In this study, adjustments to nitrogen stress parameters addressed this issue, improving the accuracy of the biomass simulations.

The model parameters adjusted to represent the effect of daylength in seasonal changes, FNPTD and LFMAX, led to more realistic regrowth patterns and distribution of aboveground biomass. In Brazilian conditions, the daylength parameter (FNPTD) was adjusted to increase allocation to storage and reduce shoot growth during winters (April–

September) (Pequeno *et al*., 2014). This means that the model increases assimilate allocation to storage organs, indicates dormancy, and decreases allocation to the shoot. This reflects the natural response of plants to prepare for adverse conditions by storing energy rather than investing in shoot biomass (Brunetti *et al*., 2021). On the other hand, in Ethiopia, where April–September falls in the growing (rainy) season, the model was conversely adjusted to decrease allocation to storage tissues and prioritize shoot growth. This adjustment reflects the lower threshold for inducing shoot growth rather than storage during this period. The reduced proportion of stem abscission based on leaf abscission (PORPT) helps retain more biomass in the stem, leading to increased overall stem mass accumulation. The model also takes into consideration the senescing of leaf sheaths after the leaf laminae, with the dead sheath material contributing to stem mass (Brunetti *et al*., 2021). The modified PORPT also helped more accurately represent how plants respond to different daylengths, thus improving its ability to simulate forage growth by capturing the subtleties of forage biomass accumulation and senescence.

Modifying vegetative partitioning parameters led to increased stem mass and, consequently, shoot biomass results significantly better fit for these variables. Early during the regrowth of tropical forage species, biomass production is mostly composed of leaves (Brunetti *et al*., 2021). However, in the late regrowth cycle, a considerable amount of biomass is allocated to the stem, including during long vegetative regrowth (Poorter *et al*., 2012; Mganga *et al*., 2021). Thus, leaf and stem mass can be enhanced by adjusting partitioning, particularly by increasing stem mass for longer regrowth (Pequeno *et al*., 2014).

Nitrogen stress significantly affects the distribution of biomass between shoots and roots; and because of this, it is considered a crucial factor for accurately simulating the growth of warm-season grasses (Brunetti *et al*., 2021). This highlights the importance of properly setting model parameters under nitrogen stress conditions. To address this, the parameter controlling the effect of nitrogen stress on biomass distribution between shoots and roots, NSTFAC was adjusted. Originally coded at 0.7 in the model, it has now been changed to 0.6. This adjustment allows for a more realistic simulation of plant responses to nitrogen stress, with the model now allocating more biomass to shoots than to roots.

6.4.2. Model performance

The results of the CROPGRO-PFM simulation indicated that the *B. brizantha* cv. Marandu, as studied by Pequeno *et al*. (2014) and parameterized for *B. mutica* (DZF-478) under rainfed conditions in Ethiopia, could effectively be used for future yield assessments of *B. mutica* under future climate scenarios. The model demonstrated improved performance, with simulated values closely matching observed data, lower RMSE values, and d-statistics closer to 1 for all parameters tested, except for crude protein percentage. However, further calibration and/or code modification of the model may be necessary to enhance the accuracy of the crude protein percentage.

6.4.3. Climate change scenarios and yield simulations

This analysis underscores the importance of using high-resolution regional climate data from CORDEX Africa and an ensemble approach to capture large-scale trends and local variability (multiple GCMs and RCMs) for generating robust historical and future climate projections, which is critical for climate impact assessments and decision-making. This aligns with Kassahun *et al*. (2023), who highlight the value of such an approach in generating reliable climate scenarios for sub-Saharan Africa. The projected increase in temperature and CO_2 concentrations reflects broader trends reported for sub-Saharan Africa (Maino & Emrullahu, 2022). Additionally, the study shows a trend of increased rainfall across all future periods, which aligns with the IPCC (2007) projections. However, the rainfall patterns specific to Ethiopia remain inconsistent, as noted in previous studies (Conway & Schipper, 2011; Hadgu *et al*., 2014).

The study reports projected loss in forage biomass yield and CP percentage under future climate scenarios. Specifically, declines of 17%, 6%, 12%, and 15% are anticipated in leaf biomass, stem biomass, shoot biomass, and herbage biomass, respectively. Herbage quality, as indicated by its crude protein percentage, is also expected to decline by 11%. These results suggest that simulated future climate conditions, characterized by elevated greenhouse gas and warmer temperatures having mixed effects, adversely impacted the production of *Brachiaria mutica* in the subhumid regions of Ethiopia. While several studies have reported increased biomass production in tropical forages under elevated CO_2 (eCO_2)

and rising temperatures (Ergon *et al*., 2018; Brychkova *et al*., 2022; Puche *et al*., 2023), this discrepancy may arise because the conditions simulated in this study exceed the optimal range for *Brachiaria mutica*. However, the observed reduction in crude protein content aligns with Habermann *et al*. (2022), who reported that elevated CO_2 decreases the crude protein content of tropical grasses.

6.5. Conclusion

The findings reveal adjustments in parameters related to senescence and dormancy, vegetative partitioning, and nitrogen stress before the use of the CROPGRO-Perennial Forage Model. The overall simulation trend suggests the *B. mutica* adversely affected with future climate scenarios in the subhumid areas of Ethiopia. Despite this, there are still areas where model performance, especially for predicting crude protein content, did not achieve the same level of accuracy as other parameters, indicating the need for further refinement. However, further research on adaptation strategies for *B. mutica* under different management practices and fertilizer applications might be necessary to fully understand the broader impacts of climate change on forage production across diverse Ethiopian agro-ecology.

CHAPTER 7: Calibration and Evaluation of a CROPGRO Perennial Forage Model for *Brachiaria Humidicola* Yield Simulation Under Future Climate in Subhumid Environments of Ethiopia

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Abstract

Crop simulation models were employed to assess the impacts of climate change and aid in strategic planning and decision-making regarding forage strategies. This study focused on calibrating and assessing the CROPGRO-Perennial Forage Model's performance in simulating *Brachiaria humidicola* yield under projected future climates for high and moderate Representative Concentration Pathway (RCP) scenarios in the central and western subhumid regions of Ethiopia. The model was calibrated to accurately represent rainfed growth and biomass yield, using field data from the Debre Zeit and Bako Agricultural Research Centers. Climatic data, including rainfall, temperature, and solar radiation, were sourced from weather stations, whereas future climate scenarios for the near future, mid-century, and late-century periods were derived from the CORDEX Africa outputs under RCP4.5 and RCP8.5. The calibration process refined species parameters related to vegetative partitioning, and enhanced the *d*-statistic and reduced the root mean square error (RMSE) for herbage, leaf, stem, and total biomass accumulation. Despite projected decreases in leaf biomass, stem biomass has increased. However, there is almost no difference in herbage and total biomass accumulation under elevated greenhouse gas concentrations and warmer temperatures. Ultimately, the projected climate under both RCPs had no significant effect on *Brachiaria humidicola* grass production in Ethiopia.

Keywords: *Brachiaria humidicola,* Climate change, DSSAT, Simulation models, Ethiopia

7.1. Introduction

Perennial tropical grass species, such as *Brachiaria*, are integral to global pasture systems, provide essential forage for livestock. However, productivity is influenced by various factors, including management techniques, fertilization, soil conditions, and climatic variability. The resulting effects vary depending on the degree of temperature increase, changes in rainfall distribution, geographical location, and specific types of cultivated species (Santos *et al*., 2022). Crop growth simulation models are indispensable tools for comprehensively understanding and predicting the responses of these grasses to various factors.

Among these models, the CROPGRO Perennial Forage model, integrated into DSSAT V4.8 software, stands out for its ability to predict the critical parameters of perennial forage grasses and legumes across various seasons. Adapted from Rymph (2004) annual CROPGRO model, this version was expanded to accommodate perennial growth by introducing storage organs such as rhizomes, taproots, and crowns, along with carbohydrate and nitrogen storage pools. This modification allows the model to simulate regrowth even when the leaf area index (LAI) reaches zero owing to factors such as harvest, severe drought, or freeze-induced leaf loss. The key features embedded in the model include seasonal dormancy, freeze thresholds, and rules governing the partitioning of resources into storage organs (Brunetti *et al*., 2021). These rules cover the management of dormancy, tolerance to freezing, partitioning strategies, regrowth mechanisms, and mobilization and replenishment of carbohydrate and nitrogen reserves.

Species and cultivar-specific files encode these regulations, ensuring an accurate depiction of the growth dynamics of different grass species. Hence, by integrating parameters tailored to each species and cultivar, the model can precisely forecast crop growth and development under diverse conditions, including crucial biological processes such as photosynthesis and nitrogen uptake. This model has been widely applied to simulate the growth of various forage species and assess the effects of global climate change on tropical perennial forages, including *Brachiaria brizantha* cv. Marandu, *Urochloa brizantha*

(palisade grass), *Cynodon dactylon* (Bermuda grass), *Brachiaria brizantha* (Piatã palisade grass), and *Megathyrsus maximus* (Guinea grass) (Pedreira *et al*., 2011; Pequeno *et al*., 2014; Santos *et al*., 2019; Bosi *et al*., 2020; Brunetti *et al*., 2021).

The integration of the CROPGRO Perennial Forage model into the DSSAT V4.8 software provides researchers and practitioners with a robust platform to analyze and optimize forage production systems, contributing to improved sustainability and productivity in livestock farming (Jones *et al*., 2003; Hoogenboom *et al*., 2017). Simulation models are crucial in unraveling the complex interactions among plant genetics, environment, and management (Pedreira *et al*., 2011) and serve as valuable tools for evaluating the impacts of climate change. Through such simulations, the model offers insight into the responses of these grasses to varying environmental conditions and management strategies, thus facilitating informed decision-making in forage production (Andrade *et al*., 2015; Santos *et al*., 2022).

However, despite its extensive application, most *Brachiaria* species, such as *B. humidicola*, have not yet been incorporated into the DSSAT model, which limits its ability to assess the impact of climate change on this grass. Therefore, the objective of this study was to calibrate and evaluate the performance of CROPGRO-PFM in simulating the impact of climate change on the production of *Brachiaria humidicola* using the DSSAT model v 4.8 under the high and moderate Representative Concentration Pathways (RCP) of future climate scenarios in the central and western subhumid environments of Ethiopia.

7.2. Materials and Methods

7.2.1. Description of study area

The data used in the adaptation of the model were collected in a field trial at the Debre Zeit Agricultural Research Center (DZARC), Bishoftu (08^0 44'N, $38^0$38'E; elevation:1900 m asl), and Bako Agricultural Research Center (BARC) ($09^0$06'N, $37^0$09'E; elevation:1650 m asl), in the subhumid agroclimatic zones of central and western Ethiopia, respectively. Weather data for the experimental period were obtained from a weather station at each location (Figure 7.1 and 7.2).

The physical and chemical characteristics of the soils were extracted from the International Soil Reference and Information Center (ISRIC, 2013). The complete soil profile used for the simulation in DSSAT format is presented in Table 7.1. The basic characteristics of the soil required as input by the model were silt and clay content (%), concentration of organic carbon in the soil (%), pH of the water, lower limit of the plant extractable soil water (cm^3 cm^{-3}), drained upper limit (cm^3 cm^{-3}), saturated upper limit (cm^3 cm^{-3}), and bulk density (g cm^{-3}). The soils used were fertile Eutric vertosols and Alfisols from the Bishoftu and Bako sites, respectively, which did not require amendments.

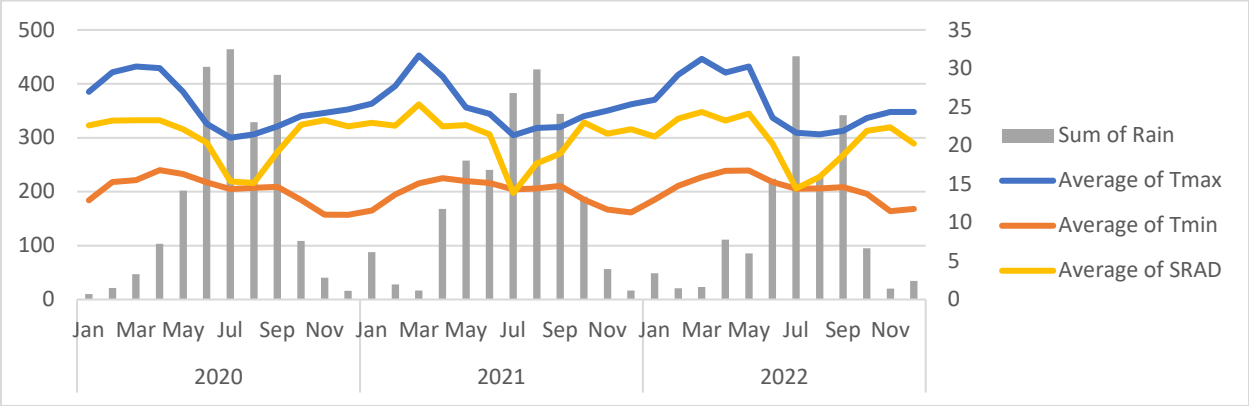


Figure 7.1. Monthly weather data for experimental period (2020-2022) in Bako, Ethiopia

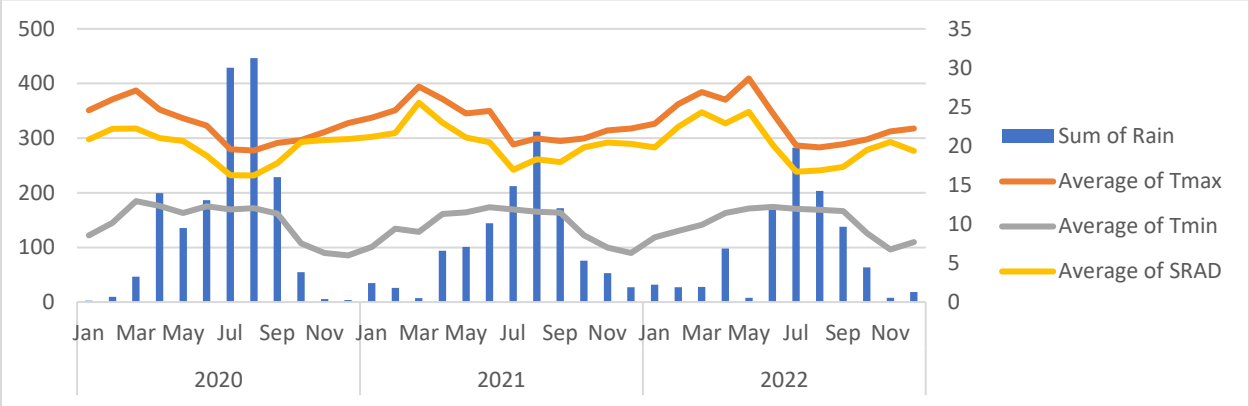


Figure 7.2. Monthly weather data for experimental period (2020-2022) in Bishoftu, Ethiopia

Table 7.1. Soil profile created with the DSSAT Sbuild program for Bishoftu and Bako, Ethiopia

Location	Depth	Clay (%)	Silt (%)	LL (mm/mm)	DU (mm/mm)	SSAT (mm/mm)	BD (g/cm3)	OC (%)	TN (%)
Bishoftu	5	40.8	29.3	0.203	0.415	0.452	1.26	2.21	0.12
	15	42.8	28.6	0.214	0.426	0.459	1.28	1.89	0.09
	30	45.2	27.5	0.229	0.439	0.469	1.31	1.43	0.07
	60	47.6	26.4	0.242	0.452	0.477	1.36	0.92	0.06
	100	47.7	25.8	0.243	0.452	0.477	1.42	0.54	0.05
	200	46.2	25.4	0.234	0.443	0.469	1.48	0.31	0.05
Bako	5	39.44	24.09	0.256	0.360	0.440	1.15	3.20	0.12
	15	41.42	23.27	0.267	0.372	0.447	1.17	2.71	0.09
	30	44.05	22.16	0.282	0.388	0.456	1.20	2.06	0.07
	60	46.29	21.09	0.295	0.401	0.464	1.25	1.32	0.06
	100	46.38	20.59	0.296	0.401	0.463	1.31	0.77	0.05
	200	44.83	20.20	0.287	0.391	0.456	1.36	0.44	0.05

Source: (ISRIC, 2013) LL = lower limit of plant extractable soil moisture; DUL = drained upper limit; SSAT = saturated soil water content; BD = bulk density; OC = organic carbon; TN = total nitrogen.

7.2.2. Plant material

The *Brachiaria* grass cultivar (*Brachiaria humidicola* (Rendle) Schweick, syn. *Urochloa humidicola* (Rendle), accession DZF-13379) was established in 3 × 4 m plots, with three replicates in June 2020. Harvesting occurred periodically during the three main rainy seasons, only once in 2020, and twice in 2021 and 2022 (from June to the end of September). The plots were fertilized immediately after each harvest at a rate of 200 kg ha^{-1} urea and DAP. Herbage mass was quantified on harvest dates at 90 days for the establishment year (2020), and 60-day frequencies for 2021 and 2022 years cut 10 cm above ground level (stubble mass) were sampled within 0.2 × 1 m quadrats for each harvest. They were hand-sorted into live leaves (lamina), live stems (leaf sheath + stem), weighed, homogenized and subsampled. Fresh subsamples were taken to the laboratory, dried separately in a forced draft oven at 65 ° C for 72 h and then weighed.

7.2.3. Climatic data and scenarios

Long-term records (1980-2009) included daily rainfall, maximum temperature (Tmax), minimum temperature (Tmin), and solar radiation were acquired from weather stations in DZARC and BARC. A minor portion, < 5% of the recorded rainfall and temperature values was absent. To address the missing gaps in the daily weather data, supplementary daily weather time series were obtained from the historical climate dataset of CORDEX Africa. Additionally, simple interpolations were employed to fill in short data gaps (less than 4 days) from neighboring reliable values.

The analysis of future climate scenarios was performed using data from CORDEX Africa, which included daily rainfall, minimum temperature, maximum temperature, and solar radiation under two CMIP5 Representative Concentration Pathways (RCP 4.5 and RCP 8.5) for the near, middle and end of the 21st century. RCPs serve as frameworks for future greenhouse gas concentrations and radiative forcing, thereby facilitating climate models to project future climate changes (Nazarenko *et al*., 2015). RCP 4.5 and RCP 8.5 were among the scenarios used by the IPCC Fifth Assessment Report (AR5) in 2014 (IPCC, 2014). RCP 4.5 represents an intermediary scenario that projects stabilization of radiative forcing at 4.5 W/m2 by 2100, while RCP 8.5 depicts a high-emission scenario that predicts a continuous increase in radiative forcing reaching 8.5 by 2100.

7.2.4. Model calibration

The CROPGRO-PFM parameterized for *Brachiaria brizantha* cv. Marandu palisade grass by Pequeno *et al*. (2014) and included in the DSSAT version 4.8 (Hoogenboom *et al*., 2020) was tailored as a initial point under the hypothesis that two genotypes of the alike genus have comparable model parameterizations of the species, cultivar, and ecotype files (Pequeno *et al*., 2017; Brunetti *et al*., 2021). The experimental data used in the simulation, including location, soil, weather, and crop establishment, were described, and entered into an experimental 'Management' file, called 'File X'. The planting method used was transplantation, in which 2000 kg per ha was used. The herbage biomass harvested was described in 'File T'.

Another characteristic specific to the forage model is the MOW input file, which is used to define the harvest dates, the amount of live biomass not harvested (MOW = stubble mass), the percentage leaf of stubble (RSPLF) and a 'restaged' leaf number (MVS) when the top growth harvest is simulated. Stubble mass was measured once during the final harvest of the experiment in 2022 and interpolated for the previous harvests. This was considered as the MOW value in the simulations and was characterized as the non-harvested mass that remained in the field. RSPLF was standardized at 30% for all treatments, as suggested by Pequeno *et al*. (2014). The MVS parameter (hypothetical number of leaves left on the primary tiller axis after harvest) in the MOW file was set to 3, according to other studies (Pedreira *et al.,* 2011; Lara *et al.,* 2012).

The CENTURY module was used to simulate soil organic carbon (SOC) and soil N (Gijsman *et al*., 2002) in our study. This module accounts for the decomposition of plant tissue that drops to the soil surface and sloughed roots within the soil, which occurs in the perennial forage species. The model considers three fractions or pools of soil organic matter (SOM) to describe organic carbon (SOC) in the soil: active (microbial) soil organic matter existing both in the surface mulch layer and in the soil (SOM1), intermediate soil organic matter (SOM2), and passive or stable soil organic matter (SOM3) (Gijsman *et al*., 2002). Three fractional pools of SOM (SOM1 = 0.01, SOM2 = 0.42, and SOM3 = 0.57) were entered into the SOM fraction file (Pedreira *et al*., 2011). The default Priestley-Taylor method, which requires only daily solar radiation and temperature, was described in detail by Ritchie (1972) and used in our study to calculate the potential ET.

7.2.5 Statistical analysis for model evaluation

The model predictions for biomass accumulation, leaf biomass, and stem biomass were compared against observed values by running simulations using actual weather, soil, and management data. Partitioning and leaf regrowth parameters were adjusted to achieve the best fit. In selecting parameter values, we considered their influence on model performance and whether they fell within the reported range in existing literature or prior knowledge. Model performance following calibration was evaluated using the observed-to-simulated ratio, root mean square error (RMSE), and the Willmott agreement index (d-statistic) as

proposed by Willmott *et al*. (2011) and Yang *et al*. (2014). The RMSE was calculated using the following equation:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Yi - \hat{Y}i)^2}$$

Where *N* is the total number of data points for comparison, *Yi* is a given observed value, and $\hat{Y}i$ is the corresponding value predicted by the model. A better model prediction produced a smaller RMSE. The Willmott agreement index is given by:

$$d = 1 - \left[\frac{\sum_{i=1}^{N}(Yi-\hat{Y}i)^2}{\sum_{i=1}^{N}(|\hat{Y}i-\bar{Y}i|+|Yi-\bar{Y}i|)^2}\right], 0 \leq \mathrm{d} \leq 1$$

where *N* is the number of observed data points, *Yi* is a given observed value, $\hat{Y}i$ is the corresponding value predicted by the model, and $\bar{Y}i$ is the mean of the observed data. A *d* index near 1 indicates a good model prediction.

A better model prediction is characterized by an observed/simulated ratio close to 1, and smaller RMSE and D-Stat values close to 1.

7.3. Results and Discussion

7.3.1. Climate change projections

The findings of the CORDEX Africa outputs, examining the effects of two representative concentration pathways of CMIP5 (RCP4.5 and RCP8.5) on projected climate changes across three future timeframes (near, mid and end of century) for Bako presented in Table 7.2 and Bishoftu Table 7.3, indicate a notable increase in temperature and rainfall compared to the baseline period (1980–2010). For Bako, the mean projected minimum temperatures for the near, mid and end of the century were 12.7 ° C, 14.4 ° C and 15.9°C, respectively. Consequently, the mean seasonal maximum temperatures for these periods were projected to be 24.8 ° C, 26.0 ° C and 27.1 ° C. Similarly, for Bishoftu, mean minimum temperatures of 12.5°C, 14.2°C, and 15.8°C, and mean maximum temperatures of 26.1 ° C, 27.4 ° C and 28.6 ° C were projected for the near future, mid-century and end of century, respectively. These findings underscore the potential impacts of climate change on the regions under study, indicating substantial increases in temperature and CO2 concentrations, aligning with sub-Saharan Africa projections (Maino & Emrullahu, 2022).

Interestingly, these temperature ranges are conducive to the growth of *Brachiaria* grasses, since a temperature range of 10-15°C is considered ideal for tropical grass growth (Moreno *et al*., 2014), a conclusion supported by other studies (Andrade *et al*., 2015; da Silva *et al*., 2012).

In terms of rainfall, projected mean rainfall ranges from 1173 to 2473 mm, 1264 to 3334 mm and 1531 to 4347 mm for Bako, and 847.1 to 1719.1 mm, 987.7 to 2418.1 mm, and 1063.3 to 3079.2 mm for Bishoftu, across the near future, mid-century, and end of century, respectively, were recorded. In general, a slight increase in rainfall is projected in future scenarios, in line with previous assessments (IPCC, 2007). However, it is worth noting that the expected rainfall patterns in Ethiopia are not consistent across all regions (Conway & Schipper, 2011; Hadgu *et al*., 2014).

Table 7.2. Mean changes in projected climate over three future time periods under RCP4.5 and RCP8.5, relative to the corresponding values for the baseline data in Bako, Ethiopia.

Time period	RF (%)	Tmin	Tmax	Average CO_2 conc. (ppm)	RF (%)	Tmin	Tmax	Average CO_2 conc. (ppm)
	RCP 4.5				RCP 8.5			
2010-2039	3.47	1.48	1.35	423	4.13	1.7	1.25	432
2040-2069	6.24	2.68	2.2	499	9	3.83	2.73	571
2070-2099	7.78	3.23	2.73	532	16.49	6.31	4.55	801

RF = Rainfall; Baseline [CO_2], assumed 360 ppm.

Table 7.3. Mean changes in projected climate over three future time periods under RCP4.5 and RCP8.5, relative to the corresponding values for the baseline data in Bishoftu, Ethiopia.

Time period	RF (%)	Tmin	Tmax	Average CO_2 conc. (ppm)	RF (%)	Tmin	Tmax	Average CO_2 conc. (ppm)
	RCP 4.5				RCP 8.5			
2010-2039	2.80	1.66	1.39	423	3.04	2.06	1.32	432
2040-2069	4.52	2.89	2.32	499	6.48	4.21	2.92	571
2070-2099	5.97	3.58	2.82	532	11.76	6.75	4.85	801

RF = Rainfall; Baseline [CO_2], assumed 360 ppm.

7.3.2. Calibration and improvement of the model

The simulation of harvested biomass (comprising leaf and stem biomass) pre-calibration yielded *d*-statistics of 0.94 and 0.89, RMSE values of 866 and 1564, and observed/simulated ratios of 0.98 and 1.19 for Bako and Bishoftu, respectively (Table 7.5). Total biomass (combining herbage and root biomass) exhibited *d*-statistics exceeding 0.98, with RMSE values of 748 and 1092, and observed/simulated ratios of 0.94 and 1.02 for Bako and Bishoftu, respectively. Leaf and stem biomass also demonstrated acceptable accuracy, simulating realistic values at both sites, although with room for enhancement.

7.3.3. Parameters affecting biomass partitioning

While our initial plan was to adopt the parameterization of *B. brizantha* species as proposed by Pequeno *et al*. (2014), we found it necessary to conduct targeted calibration of certain species files pertaining to vegetative partitioning parameters in order to achieve accurate biomass accumulation simulations (Tables 7.4). Consequently, adjustments made to partition parameters (YLFEST, YSTEST, YSREST) led to enhancements in the average *d*-statistic and RMSE (as outlined in Table 7.6). It is important to note that we did not incorporate the rate of node appearance to predict observed growth stage dates or leaf numbers, and that the simulated V stage was solely utilized for defining the dry matter partitioning function. The revised partitioning approach resulted in a reduction in the percentage of leaves during the midpoint V stage, thus significantly improving the simulation of live aboveground biomass percentages. Similarly, the parameterization led to a decrease in the percentage of stem mass during the midpoint V stage, consequently enhanced the fit for aboveground live biomass.

Table 7.4. The initial and final values of species parameters affecting biomass partitioning (during perennial/established phase) were modified in the Marandu palisade species genetics file (SPE) for the simulation of the *Brachiaria humidicola* cultivar.

Parameter	Description	Initial value	Final value
XLFEST (not changed)	Leaf number or vegetative growth stage at which biomass partitioning is determined	0.0, 2.0, 3.0, 5.0, 7.0, 10.0, 30.0, 40.0	0.0, 2.0, 3.0, 5.0, 7.0, 10.0, 30.0, 40.0
YLFEST	Fraction of dry matter partitioned to leaves as a function of V-stage	0.80, 0.80, 0.72, 0.63, 0.52, 0.51, 0.50, 0.50	0.80, 0.80, 0.70, 0.58, 0.51, 0.50, 0.50, 0.50
YSTEST	Fraction of dry matter partitioned to stems as a function of V-stage	0.10, 0.10, 0.14, 0.17, 0.32, 0.36, 0.35, 0.35	0.10, 0.10, 0.16, 0.19, 0.32, 0.36, 0.35, 0.35
YSREST	Fraction of dry matter partitioned to storage as a function of V-stage	0.01, 0.01, 0.03, 0.04, 0.04, 0.04, 0.04, 0.04	0.01, 0.01, 0.02, 0.03, 0.04, 0.04, 0.04, 0.04

7.3.4. Statistical evaluation of model performance

Following calibration, the model demonstrated significant improvement across all parameters, with simulated values closely aligning with observed values. RMSE values ranged from 590 to 1344, while r-square values ranged from 0.72 to 0.98 (Table 7.6). These results indicate that the original *B. brizantha* cv. Marandu model, as proposed by Pequeno *et al*. (2014), holds promise for accurately simulating rainfed *B. humidicola* grass production in Ethiopia. Consequently, the model can serve as a valuable tool for predicting the growth and yield of *B. humidicola* grass under varying climatic and management conditions, empowering farmers to make well-informed decisions regarding their production strategies. Moreover, utilizing the model for future climate assessments of *B. humidicola* yield under various Representative Concentration Pathways (RCPs) would offer significant benefits.

Table 7.5. Simulations (Means and statistics) for the rainfed *B. humidicola* grass dataset from 2020 to 2022 in Bako and Bishoftu, Ethiopia, simulated using the original *B. brizantha* cv. Marandu by Pequeno *et al*. (2014) before calibration

Parameter	Observed	Simulated	RMSE	Ratio (obs./sim.)	Willmott's *d*	r-Square
Bako						
Harvested Biomass (Kg ha^{-1})	4914±1452	5116±2132	866	0.98	0.94	0.92
Total Biomass (Kg ha^{-1})	5262±2997	5244±3448	748	0.94	0.99	0.97
Leaf biomass (Kg ha^{-1})	2528±1524	2686±2137	691	0.92	0.96	0.98
Stem biomass (Kg ha^{-1})	2734±1475	2557±1437	669	0.93	0.94	0.81
Bishoftu						
Harvested Biomass (Kg ha^{-1})	5065±2293	5845±2227	1564	1.19	0.89	0.67
Total Biomass (Kg ha^{-1})	5424±3709	5743±3906	1092	1.02	0.98	0.93
Leaf biomass (Kg ha^{-1})	2559±1806	2868±2296	954	1.02	0.94	0.87
Stem biomass (Kg ha^{-1})	2865±1904	2876±1744	617	1.01	0.97	0.90

Kg ha^{-1} = Kilogram per hectare

Table 7.6. Simulations (Means and statistics) for the rainfed *B. humidicola* grass dataset from 2020 to 2022 in Bako and Bishoftu, Ethiopia, simulated using the original *B. brizantha* cv. Marandu by Pequeno *et al*. (2014) after calibration

Parameter	Observed	Simulated	RMSE	Ratio (obs./sim.)	Willmott's *d*	r-Square
Bako						
Harvested Biomass (Kg ha^{-1})	4914±1452	4967±2121	845	0.95	0.94	0.92
Total Biomass (Kg ha^{-1})	5262±2997	5168±3387	742	0.93	0.99	0.96
Leaf biomass (Kg ha^{-1})	2528±1524	2597±2043	590	0.90	0.97	0.98
Stem biomass (Kg ha^{-1})	2734±1475	2572±1464	667	0.93	0.95	0.82
Bishoftu						
Harvested Biomass (Kg ha^{-1})	5065±2293	5624±2143	1344	1.14	0.91	0.72
Total Biomass (Kg ha^{-1})	5424±3709	5633±3800	944	1.01	0.98	0.94
Leaf biomass (Kg ha^{-1})	2559±1806	2766±2184	811	0.99	0.96	0.88
Stem biomass (Kg ha^{-1})	2865±1904	2867±1745	604	1.01	0.97	0.9

Kg ha^{-1} = Kilogram per hectare

7.3.5. Future yield simulations

Table 7.7 illustrates the projected changes in leaf, stem, total, and herbage biomass yields of *Brachiaria humidicola* grass in Bako and Bishoftu under different Representative Concentration Pathways (RCP) for various timeframes in the 21st century compared to a baseline period (1980-2010). Leaf biomass decreases for the future climate scenarios at both locations except for the RCP8.5 under near future climate of both locations. In contrast, stem biomass increases except for the RCP4.5 under near future climate scenario at Bako. Total biomass and Herbage biomass increases at Bako except for the RCP4.5 under near future climate whereas at Bishoftu increases except for the RCP4.5, RCP8.5 and RCP8.5 under near, mid and end of 21st climate scenarios.

Overall, leaf biomass decreases, while stem biomass increases (Figure 7.3), suggesting a shift in resource allocation under stress conditions. These findings align with previous studies indicating a decrease in leaf photosynthesis and a content of nitrogen forage under elevated CO2 concentrations (Zheng *et al*., 2018, 2019; Ecker *et al*., 2020). Total biomass had shown slightly no difference, with herbage biomass following a similar pattern.

Table 7.7. Median yield (kg/ha) changes over three future time periods, as simulated by the CROGRO-PFM model based on CORDEX Africa under RCP4.5 and RCP8.5.

	Baseline climate	2010-2039	2010-2039	2040-2069	2040-2069	2070-2099	2070-2099
Parameters	1980-2009	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Bako							
Leaf biomass	2613	2419	2691	2591	2571	2601	2296
Stem biomass	2547	2320	2602	2669	2851	2902	2872
Total biomass	5160	4739	5292	5260	5422	5502	5168
Herbage biomass	4965	4289	5209	5147	5478	5639	4977
Bishoftu							
Leaf biomass	2770	2569	2770	2457	2400	2371	2222
Stem biomass	2680	2857	2951	2994	3033	3113	3090
Total biomass	5450	5427	5720	5451	5433	5485	5312
Herbage biomass	5278	5244	5824	5294	5261	5365	5024

RCP = Representative Concentration Pathways

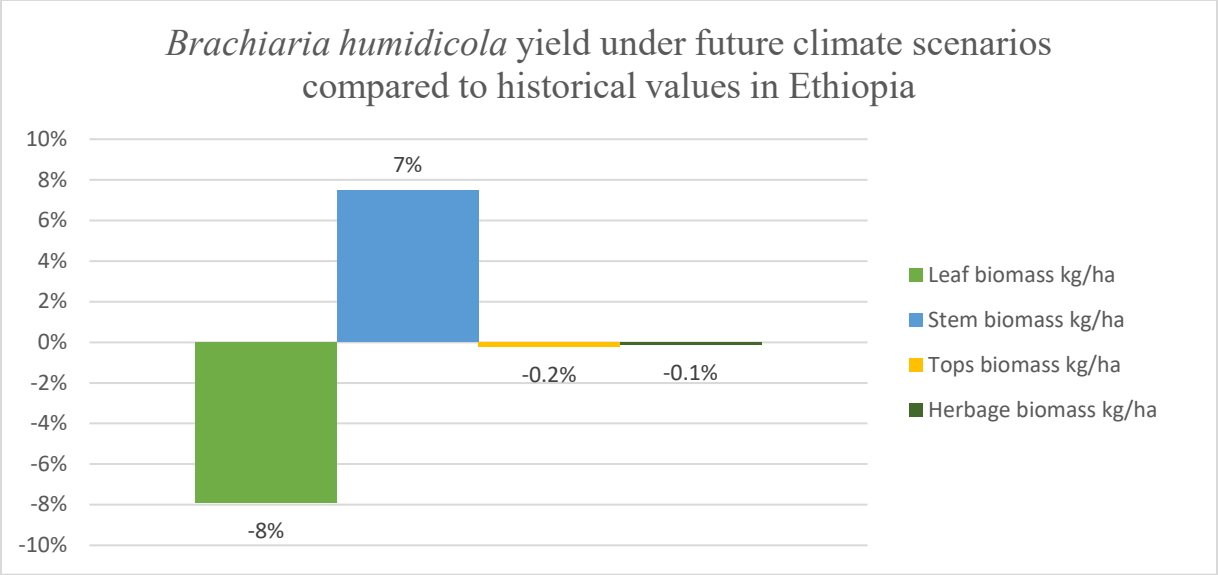


Figure 7.3. Yield gained/lost (compared to historical value) as simulated using CROGRO-PFM based on CORDEX Africa under RCP4.5, RCP8.5 for the future climate for Bako and Bishoftu.

7.4. Conclusion

The original CROPGRO-PFM model demonstrated good performance in simulating the growth and yield of *Brachiaria humidicola*. The results of the post-calibration simulation showed enhanced precision, with reduced RMSE values and a *d*-statistic closer to 1, indicating a close agreement between the simulated and observed data. Consequently, the calibrated model offers a reliable tool to assess the sustainability of forage development and predict the impacts of climate change on forage production in Ethiopia. Our findings suggest a projected increase in temperature and rainfall in the study regions, consistent with global climate change trends. However, these changes appear to remain within the suitable temperature range for *Brachiaria* grasses, highlighting their potential resilience to future climate scenarios. This study lays the foundation for future evaluations of *Brachiaria humidicola* yield under different representative concentration pathways, facilitating informed decision making for sustainable livestock farming practices in response to a changing climate.

Chapter 8: General Discussion, Conclusions and Recommendations

8.1. Discussion

Challenges such as feed scarcity, low-quality forage, and the additional pressures of climate change have underscored the need for improved forages like *Brachiaria* grasses. Integrating these grasses into farming systems presents a promising strategy for enhancing livestock productivity in Ethiopia (Cheruiyot *et al*., 2020). Their ability to thrive in sub-humid conditions and produce high biomass yields makes them suitable for broader adoption among farmers.

Beyond their biomass yield, *Brachiaria* grasses have been shown to enhance both milk and meat production (Djikeng *et al*., 2014; Njarui *et al*., 2021). In this regard, optimizing concentrate supplementation is crucial to maximizing the utilization of *Brachiaria* grass. Additionally, studies highlight their role in carbon sequestration, improved nitrogen use efficiency, and their remarkable resilience to changing climatic conditions, positioning them as a climate-smart forage option increasingly adopted across East Africa. To further explore this, assessing the impacts of climate change on *Brachiaria* grass productivity is essential.

This study highlights the remarkable potential of different *Brachiaria* and other grass species as sustainable forage solutions for enhancing livestock productivity in Ethiopia. Their adaptability, high biomass yield, superior nutritional value, and resilience from adverse climate make them viable alternatives, effectively addressing both feed shortages and climate change challenges.

To evaluate the adaptability and yield performance of *Brachiaria* (syn. *Urochloa*) and other grass cultivars, we assessed agronomic parameters such as herbage yield, plant height, and leaf-to-stem ratio, along with their nutritive values, under the central and western subhumid environmental conditions (**Paper I** and **Paper II**). To facilitate the integration of high-performing *Brachiaria* cultivars into feeding systems, we evaluated and optimized the level of concentrate supplementation for a basal diet of *B. mutica* hay, providing recommendations for smallholder livestock producers (**Paper III**). This involved

evaluating growth performance, feed conversion efficiency, carcass quality, and the balance between feed costs and productivity outcomes for yearling Arsi-Bale rams. These integrated approaches collectively highlight the value of *Brachiaria* species in advancing livestock productivity and feed sustainability in Ethiopia. Finally, to gain critical insights into the future of forage production under projected climate scenarios, we employed a simulation model. The CROPGRO-Perennial Forage Model effectively simulated yield dynamics for *B. brizantha*, *B. mutica* and *B. humidicola,* demonstrating their resilience to climate stressors, particularly in subhumid regions where such challenges are intensifying (**Paper IV, V** and **VI**).

8.1.1. Adaptability, yield performance, and nutritional value

Paper I examined the adaptability, yield performance, and nutritional profile of four *Brachiaria* (syn. *Urochloa*) species, along with Desho and Rhodes grasses, over three years under rainfed conditions in the central and western subhumid areas of Ethiopia. In contrast, **Paper II** focused solely on the central subhumid areas. Given the livestock sector's reliance on low-quality pastures and crop residues in mixed crop-livestock systems, this study assesses the potential of these grasses as sustainable forage options to improve Ethiopia's livestock feed supply. The introduction of high-quality forage species, such as *Brachiaria* (syn. *Urochloa*) species, is essential for enhancing livestock productivity and sustainability, especially in the face of climate change and its impact on traditional feed sources (Njarui *et al*., 2021).

The results revealed a significant interaction between cultivar performance and environmental conditions, with DM yield, CP yield, and plant height varying across locations and years (Table 2.2 and Table 3.2). This highlights the need for climate-resilient forage species tailored to specific regions (Vendramini *et al*., 2023). Notably, *B. mutica* exhibited broad adaptability, consistently producing high DM yields and CP content, followed closely by *B. brizantha*. Both cultivars outperformed Desho and Rhodes grasses across different environments, positioning them as superior forage alternatives for Ethiopian smallholders.

Beyond yield performance, the study also evaluated the nutritional quality of these grasses to determine their suitability as livestock feed. All tested grasses met the minimum CP requirements for ruminant maintenance, as noted Faji *et al*. (2022) citing Lonsdale (1984). Among them, *B. humidicola, B. mutica* and *B. brizantha* were classified as medium-protein sources. However, NDF content was consistently high, indicating lower forage quality. While NDF is essential for maintaining rumen function, excessive levels can reduce intake rates, underscoring the trade-off between forage quality and quantity (Van Soest, 1994). Despite this, *B. humidicola* showed superior digestibility due to its lower ADF content.

These findings suggest that *Brachiaria* species, particularly *B. mutica* and *B. brizantha*, can significantly enhance forage availability and nutritional quality. Their adaptability, high biomass yield, and superior digestibility make them promising alternatives to conventional forage species, offering a viable solution for improving livestock productivity and sustainability in Ethiopia's smallholder farming systems.

8.1.2. *B. mutica* hay basal diet supplementation for Arsi-Bale rams

Paper III evaluated the effect of supplementing *B. mutica* hay with graded levels of concentrate feed on the performance and economic returns of yearling Arsi-Bale rams. The study demonstrated that increasing concentrate supplementation significantly enhanced dry matter intake (DMI), nutrient digestibility, and feed conversion efficiency (FCE), growth performance, and carcass characteristics. Specifically, rams receiving 300 g of concentrate (T3) exhibited higher growth performance, with body weight gains and carcass yields statistically similar to those receiving 400 g (T4). These findings highlight the importance of crude protein-rich concentrates in improving growth rates and overall feed efficiency, aligning with previous studies on lamb fattening, which found that high-protein and energy diets facilitate superior growth (Gadissa *et al*., 2021; Kahsu *et al*., 2021).

However, the result suggest that beyond a certain threshold, additional concentrate supplementation does not provide proportionate benefits (Roba *et al*., 2022). Furthermore, the significant increases in digestibility coefficients for dry matter and nutrients across treatments reinforce the importance of concentrate feeds in meeting the nutritional requirements of growing rams. Nutritional deficiencies in traditional forage grass-based

systems are a well-documented constraint to livestock productivity in Ethiopia (Mekonnen *et al*., 2022; Tolera *et al*., 2012). This study suggests that strategic supplementation can mitigate such deficiencies, leading to improved growth performance and overall animal health.

The observed improvements in carcass yield and meat quality traits with higher concentrate supplementation align with previous studies emphasizing the role of protein supplementation in ruminant diets (Van Soest, 1994; NRC, 2007). These improvements are crucial for enhancing meat quality, which benefits both consumer health and market profitability (Muleta, 2022).

Beyond the biological benefits, the study also assessed the economic implications of different supplementation levels. Partial budget analysis revealed that moderate supplementation levels (200 &300 g) provided the highest financial returns. This finding emphasizes the need for smallholder farmers to balance feed costs with growth performance, as excessive supplementation may not be financially viable (Upton, 1973). These results support earlier research, which suggests that optimizing feed strategies can significantly enhances the economic viability of livestock production systems (AGP-LMD, 2013; Feyissa *et al*., 2015).

This research offers important insights into managing livestock nutrition, advocating for the combination of *B. mutica* grass hay with concentrate supplements to enhance productivity in smallholder systems.

8.1.2. Impacts of climate change on *Brachiaria* grasses

Papers IV, V and VI explored the potential of *Brachiaria* species (*B. brizantha, B. mutica* and *B. humidicola*) under present and future climate scenarios in the subhumid environments of Ethiopia using the CROPGRO-Perennial Forage Model. These studies underscore the critical role of simulation models in understanding perennial forage dynamics, particularly in regions where agricultural productivity is highly sensitive to climatic variability. The findings highlight *Brachiaria's* resilience as a forage species,

emphasizing its adaptability to varying climates and its importance in ensuring sustainable livestock production globally.

Paper IV focused on simulating the growth and yield of *Brachiaria brizantha* under current and future climate conditions in Ethiopia's subhumid regions. Given Ethiopia's livestock feed dependence on low-quality natural pasture feeds, this study assessed the potential of *B. brizantha* as a climate-resilient forage species for livestock production. The model was successfully calibrated and evaluated using field data from two agricultural research centers Bako and Bishoftu, refining parameters related to nitrogen stress, senescence, and biomass partitioning to improve simulation accuracy. Post-calibration, the model demonstrated a strong agreement with observed field data for shoot, herbage, stem and leaf biomass.

Future climate projections under RCP 4.5 and RCP 8.5 indicated increased biomass accumulation, particularly in shoot and herbage biomass, despite an anticipated decline in leaf biomass and crude protein content. This suggests a shift in forage quality and quantity, with potential implications for livestock nutrition and feed management. These findings reinforce the resilience of *B. brizantha* to climate variability and its potential role in Ethiopia's livestock sector (Djikeng *et al*., 2014; Wassie *et al*., 2018).

Paper V calibrated and evaluated CROPGRO-PFM model for simulating the growth and yield of *B. mutica,* using adaptation parameters from *B. brizantha* (Pequeno *et al*., 2014) and field data from Bako and Bishoftu. The study assessed the model's predictive performance and examined the potential impacts of future climate scenarios on *B. mutica* productivity.

Initial simulation using the default *B. brizantha* model exhibited moderate predictive capability but underestimated biomass accumulation, particularly for shoot, herbage, and stem biomass. This discrepancy highlighted the need for adjustments to key parameters related to refining dormancy, senescence and biomass partitioning parameters. Post-calibration, RMSE values decreased, and improvements in Willmott's d and r-squared values confirmed enhanced predictive accuracy. However, crude protein percentage

simulations remained inconsistent, suggesting the need for further refinement in modeling forage quality.

Future climate simulations under RCP 4.5 and RCP 8.5 suggest a general decline in biomass production and crude protein content throughout the 21st century. While slight biomass increases were observed under near-future RCP 8.5 projections, mid-century and end-century predictions show substantial reductions, likely due to elevated temperatures and increased evapotranspiration stress (Izaurralde *et al*., 2011).

Specifically, *B. mutica* shoot biomass is projected to decline by up to 24% by the end of the century under RCP8.5, while herbage biomass may decrease by as much as 31%. Additionally, crude protein content is expected to decline by 14–20%, negatively impacting forage quality and livestock nutrition. These findings underscore the vulnerability of *B. mutica* to climate change, aligning with expectations that rising temperatures and altered precipitation patterns will pose significant challenges to forage production (Muzzo *et al*., 2024).

Paper VI explored the calibration and evaluation of the CROPGRO-PFM for simulating the yield of *B. humidicola* under future climate scenarios in the subhumid environments of Ethiopia. The study reinforced the importance of crop simulation models in assessing forage sustainability and predicting climate change impacts.

The model calibration process refined key parameters associated to vegetative partitioning, senescence, and nitrogen stress, leading to improved predictive accuracy, as evidenced by enhanced d-statistics and reduced RMSE values. These improvements suggest that the model can reliably simulate *B. humidicola* growth dynamics, making it a valuable tool for forage management strategies.

Future climate projections under RCP 4.5 and RCP 8.5 indicate that *B. humidicola* will undergo biomass allocation shifts, with a decrease in leaf biomass and an increase in stem biomass. This adaptation suggests that *B. humidicola* may optimize resource allocation in response to elevated temperatures and altered precipitation patterns (Brunetti *et al*., 2021). Despite these changes, its overall production is expected to remain stable or even improve

in certain biomass aspects, reinforcing its resilience to climate change and its potential role in sustaining livestock productivity.

8.2. Conclusion

Papers I and **II**: The studies conclude that *B. mutica* and *B. brizantha* are excellent candidates for adoption in subhumid Ethiopia due to their high biomass yield and superior feed quality. These findings highlight the potential of *Brachiaria* as an improved forage species that can strengthen the livestock feed base of Ethiopia. Assessing livestock performance when fed these grasses appears to be the next key step in research on these forages, with the goal of optimizing the diets of livestock owned by smallholders. Additionally, evaluating the resilience of *Brachiaria* grass against climate change and variability is essential for maximizing its benefits. Based on these research priorities, the subsequent studies (Papers III, IV, and V) were conducted.

Paper III: This study concludes that supplementing *B. mutica* hay with 300 g of concentrate is an effective strategy for improving growth performance, carcass yield, and economic efficiency in smallholder sheep production systems in Ethiopia. This approach has the potential to enhance livestock productivity and, in turn, improve the livelihoods of smallholder farmers.

Paper IV, V and VI: These research highlights the CROPGRO-PFM model as a valuable tool for predicting *Brachiaria* forage yield and supporting strategic livestock feed planning in Ethiopia, particularly in the context of climate change challenges. The findings demonstrate both the potential and limitations of crop models in simulating forage production dynamics. While the model accurately simulated biomass yield, it showed inconsistencies in crude protein content. Overall, the study underscores the climate resilience of *Brachiaria* species in Ethiopia's subhumid regions. Specifically, *B. brizantha* and *B. humidicola* exhibited resilience to projected climate stressors, whereas *B. mutica* appeared more vulnerable, requiring additional management interventions to sustain productivity.

Further research is needed to refine model predictions for crude protein content and to develop sustainable management strategies that enhance forage resilience under changing climatic conditions. These findings reinforce the importance of continued research on forage adaptation strategies to ensure sustainable livestock production and food security in the face of future climate challenges.

8.3. Recommendations

These findings offer valuable insights for farmers, policymakers, and researchers aiming to develop a high-biomass, high-quality and climate-resilient forage production systems and it emphasize the importance of forage species selection.

Future Research Priorities

1. Evaluate the effects of feeding value of alternative forage, *B. brizantha*, and determine the optimum supplementation levels for wide utilization and productivity.

2. Investigate on-farm supplementation strategies using *B. mutica*-based diets across different sheep breeds to enhance the sustainability and applicability of feeding systems.

3. Assess environmental impacts, particularly methane emissions from *B. mutica*-based diets, as this remains a critical but unexplored aspect of climate-smart livestock systems.

4. Expand field trials across diverse agroecological zones to refine species selection and validate model simulations under varying environmental conditions.

5. Enhance crop simulation models by incorporating additional forage species and diverse management practices to improve predictive accuracy.

6. Explore adaptive strategies such as fertilization, irrigation, and climate-smart agronomic practices to mitigate the projected decline in forage yield and quality under future climate scenarios.

Policy and Management Recommendations

1. Integrate forage modeling results into national livestock development programs to support resilient and sustainable feed systems.

2. Investigate the long-term benefits of forage-based systems, focusing on carbon storage and nitrogen-use efficiency.

By implementing these strategies, forage production can be sustained, contributing to improved livestock productivity, enhanced rural livelihoods, and greater resilience to climate change.

References

Abdallah, A., Zhang, P., Elemba, E., Zhong, Q., & Sun, Z. (2020). Carcass characteristics, meat quality, and functional compound deposition in sheep fed diets supplemented with Astragalus membranaceus by-product. *Animal Feed Science and Technology*, *259*, 114346. https://doi.org/10.1016/j.anifeedsci.2019.114346

Abdollahy, H., Hasani, S., Zerehdaran, S., Shadparvar, A. A., & Mahmoudi, B. (2012). Determination of economic values for some important traits in Moghani sheep. *Small Ruminant Research*, *105*(1–3), 161–169. https://doi.org/10.1016/j.smallrumres.2012.01.008

Adnew, W., Tsegay, B. A., Tassew, A., & Asmare, B. (2021). Combinations of *Urochloa* hybrid Mulato II and natural pasture hays as a basal diet for growing Farta lambs in Ethiopia. *Tropical Grasslands-Forrajes Tropicales*, *9*(2), 206–215. https://doi.org/10.17138/tgft(9)206-215

AGP-LMD, (Agricultural Growth Project-Livestock Market Development). (2013). *Livestock Market Development Value Chain Analysis for Ethiopia: Meat and Live Animals, Hides, Skins, Leather and Dairy. Expanding Livestock Markets for the Small-holder Producers* (p. 160).

An, J., Li, Y., Zhang, C., & Zhang, D. (2022). Rapid Nondestructive Prediction of Multiple Quality Attributes for Different Commercial Meat Cut Types Using Optical System. *Food Science of Animal Resources*, *42*(4), 655–671. https://doi.org/10.5851/kosfa.2022.e28

Andrade, A. S., Santos, P. M., Pezzopane, J. R. M., de Araujo, L. C., Pedreira, B. C., Pedreira, C. G. S., Marin, F. R., & Lara, M. A. S. (2015). Simulating tropical forage growth and biomass accumulation: An overview of model development and application. *Grass and Forage Science*, *71*(1), 54–65. https://doi.org/doi: 10.1111/gfs.12177

AOAC, A. of O. A. C. (1990). *Official Methods of Analysis. 15th Edition, Association of Official Analytical Chemist* (15th ed., Vol. 1).

Arango, J., Moreta, D., Núñez, J., Hartmann, K., Domínguez, M., Ishitani, M., Miles, J., Subbarao, G., Peters, M., & Rao, I. (2014). Developing methods to evaluate phenotypic variability in biological nitrification inhibition (BNI) capacity of

Brachiaria grasses. *Tropical Grasslands-Forrajes Tropicales*, *2*(1), 6–8. https://doi.org/10.17138/tgft(2)6-8

Asmare, B., Demeke, S., Tolemariam, T., Tegegne, F., Haile, A., & Wamatu, J. (2017). Effects of altitude and harvesting dates on morphological characteristics, yield and nutritive value of desho grass (Pennisetum pedicellatum Trin.) in Ethiopia. *Agriculture and Natural Resources*, *51*(3), 148–153. https://doi.org/10.1016/j.anres.2016.11.001

Asmare, B., Demeke, S., Tolemariam, T., Tegegne, F., Wamatu, J., & Rischkowsky, B. (2016). Evaluation of desho grass (Pennisetum pedicellatum) hay as a basal diet for growing local sheep in Ethiopia. *Trop Anim Health Prod*, *48*(4), 801–806. https://doi.org/10.1007/s11250-016-1031-8

Asresie, A., & Zemedu, L. (2015). *Contribution of Livestock Sector in Ethiopian Economy: A Review*. *29*, 79–91.

Assefa, G., Mengistu, S., Feyissa, F., & Bediye, S. (2016). Animal Feed Resources Research in Ethiopia: Achievements, Challenges and Future Directions. *Ethiop. J. Agric. Sci.*, *2605*(special), 139–153.

Assefa, S., Duguma, B., & Worku, Z. (2024). Assessment of livestock husbandry practices and production constraints among smallholder mixed crop-livestock production systems in the Majang zone, southwest Ethiopia. *Heliyon*, *10*(19), e37400. https://doi.org/10.1016/j.heliyon.2024.e37400

Atsbha, K., Gebremariam, T., & Aregawi, T. (2021). Slaughter performance and meat quality of Begait breed lambs fattened under different diets. *Heliyon*, *7*(5), e06935. https://doi.org/10.1016/j.heliyon.2021.e06935

Atumo, T. T. (2022). Repeated cuttings under farmer management effect on growth and yield performance of Pennisetum glaucifolium varieties in major agro-ecological zones of Ethiopia. *Heliyon*, *8*(4), e09344. https://doi.org/10.1016/j.heliyon.2022.e09344

Ayele, S., & Urge, M. (2019). Productive and Reproductive Performances of Indigenous Sheep in Ethiopia: A Review. *Open Journal of Animal Sciences*, *09*(01), 97–120. https://doi.org/10.4236/ojas.2019.91009

Ayele, S., Urge, M., Animut, G., & Kurtu, M. Y. (2018). Comparative Evaluation of Proximate Chemical Composition and Eating Quality of Meat from Three Selected Ethiopian Sheep Breeds in Different Levels of Concentrate Supplement. *East African Journal of Veterinary and Animal Sciences*, *2*(2), 99–106.

Bachewe, F., Minten, B., Tadesse, F., & Taffesse, A. S. (2018). *The Evolving Livestock Sector in Ethiopia: Growth by heads, not by productivity.* (IFPRI-ESSP Working Paper 122, p. 26). International Food Policy Research Institute/Ethiopia Strategy Support Program (IFPRI/ESSP).

Bantihun, A., Asmare, B., & Mekuriaw, Y. (2022). Comparative Evaluation of Selected Grass Species for Agronomic Performance , Forage Yield , and Chemical Composition in the Highlands of Ethiopia. *Advances in Agriculture*, *2022*, 13.

Begna, R., Urge, M., Negesse, T., & Animut, G. (2023). Performances, carcass characteristics, and economic benefit of yearling Hararghe highland rams fed diet containing concentrate mixtures and sugarcane bagasse or rice husk treated with *Trichoderma viride* and effective microorganisms. *Food Science & Nutrition*, *11*(12), 7686–7697. https://doi.org/10.1002/fsn3.3687

Behnke, R. (2010). *The Contribution of Livestock to the Economies of IGAD Member States: Study Findings, Application of the Recommendations for Further Work* (Issue 02, pp. 1–45). IGAD Livestock Policy Initiative.

Bender, F. D., Cuadra, S. V., Dias, H. B., Silva, L. E. A., Gravina De Oliveira, M. P., Lamparelli, R. A. C., Cabral, O. M. R., Nogueira, S. F., Pezzopane, J. R. M., Bosi, C., De Freitas, H. C., & Magalhães, P. S. G. (2024). A new perennial forage module coupled with the ECOSMOS terrestrial ecosystem model: Calibration and evaluation for Urochloa (syn. Brachiaria) brizantha. *European Journal of Agronomy*, *159*, 127253. https://doi.org/10.1016/j.eja.2024.127253

Bezerra, L. S., Barbosa, A. M., Carvalho, G. G. P., Simionato, J. I., Freitas, J. E., Araújo, M. L. G. M. L., Pereira, L., Silva, R. R., Lacerda, E. C. Q., & Carvalho, B. M. A. (2016). Meat quality of lambs fed diets with peanut cake. *Meat Science*, *121*, 88–95. https://doi.org/10.1016/j.meatsci.2016.05.019

Boler, D. D. (2014). Species of Meat Animals. In *Encyclopedia of Meat Sciences* (pp. 363–368). Elsevier. https://doi.org/10.1016/B978-0-12-384731-7.00079-9

Bosa, R., Faturi, C., Vasconcelos, H. G. R., Cardoso, A. M., Ramos, A. F. O., & Azevedo, J. C. D. (2012). Intake and apparent digestibility with different inclusion levels of coconut meal for sheep feeding. *Acta Scientiarum. Animal Sciences*, *34*(1), 57–62. https://doi.org/10.4025/actascianimsci.v34i1.11936

Bosi, C., Sentelhas, P. C., Pezzopane, J. R. M., & Santos, P. M. (2020). CROPGRO-Perennial Forage model parameterization for simulating Piatã palisade grass growth in monoculture and in a silvopastoral system. *Agricultural Systems*, *177*(102724). https://doi.org/10.1016/j.agsy.2019.102724

Brunetti, H. B., Boote, K. J., Santos, P. M., Pezzopane, J. R. M., Pedreira, C. G. S., Lara, M. A. S., Moreno, L. S. B., & Hoogenboom, G. (2021). *Improving the CROPGRO Perennial Forage Model for simulating growth and biomass partitioning of guineagrass*. *113*, 3299–3314. https://doi.org/10.1002/agj2.20766

Brychkova, G., Kekae, K., McKeown, P. C., Hanson, J., Jones, C. S., Thornton, P., & Spillane, C. (2022). Climate change and land-use change impacts on future availability of forage grass species for Ethiopian dairy systems. *Scientific Reports*, *12*(1), 20512. https://doi.org/10.1038/s41598-022-23461-w

Budiman, Soetrisno, R. D., Budhi, S. P. S., & Indrianto, A. (2012). Morphological characteristics, productivity and quality of three napier grass (Pennisetum purpureum Schum) cultivars harvested at different AGE. *Journal of the Indonesian Tropical Animal Agriculture*, *37*(4), 294–301. https://doi.org/10.14710/jitaa.37.4.294-301

Changshun, W., Fandong, M., Xin'e, L., Lili, J., & Shiping, W. (2014). Factors affecting plant primary productivity of grasslands: A review. *Acta Ecologica Sinica*, *34*(15).

Chen, H., Wang, C., Huasai, S., & Chen, A. (2021). Effects of dietary forage to concentrate ratio on nutrient digestibility, ruminal fermentation and rumen bacterial composition in Angus cows. *Scientific Reports*, *11*(1), 17023. https://doi.org/10.1038/s41598-021-96580-5

Cheruiyot, D., Aura, C., Midega, O., Berg, J. Van Den, & Pickett, J. A. (2018). Genotypic Responses of Brachiaria Grass (Brachiaria spp.) Accessions to Drought Stress. *Journal of Agronomy*, *17*(3), 136–146. https://doi.org/10.3923/ja.2018.136.146

Cheruiyot, D., Midega, C. A. O., Pittchar, J. O., Pickett, J. A., & Khan, Z. R. (2020). Farmers' perception and evaluation of brachiaria grass (Brachiaria spp.) genotypes for smallholder cereal-livestock production in East Africa. *Agriculture (Switzerland)*, *10*(7), 1–13. https://doi.org/10.3390/agriculture10070268

Cheruiyot, D., Midega, C. A. O., Ueckermann, E. A., Berg, J. Van Den, Pickett, J. A., & Khan, Z. R. (2018). Genotypic response of brachiaria (Urochloa spp.) to spider mite (Oligonychus trichardti) (Acari: Tetranychidae) and adaptability to different environments. *Field Crops Research*, *225*, 163–169. https://doi.org/10.1016/j.fcr.2018.06.011

CIAT. (1992). Tropical pastures target environments. In *Pastures for the Tropical Lowlands: CIAT's Contribution*.

Claffey, N. A., Fahey, A. G., Gkarane, V., Moloney, A. P., Monahan, F. J., & Diskin, M. G. (2018). Effect of forage to concentrate ratio and duration of feeding on growth and feed conversion efficiency of male lambs. *Translational Animal Science*, *2*(4), 419–427. https://doi.org/10.1093/tas/txy071

Coblentz, W. K., Akins, M. S., Kalscheur, K. F., Brink, G. E., & Cavadini, J. S. (2018). Effects of growth stage and growing degree day accumulations on triticale forages: 1. Dry matter yield, nutritive value, and in vitro dry matter disappearance. *Journal of Dairy Science*, *101*(10), 8965–8985. https://doi.org/10.3168/jds.2018-14868

Conway, D., & Schipper, E. L. F. (2011). Adaptation to climate change in Africa: Challenges and opportunities identified from Ethiopia. *Global Environmental Change*, *21*, 227–237. https://doi.org/10.1016/j.gloenvcha.2010.07.013

CSA, (Central Statistical Agency). (2022). *Livestock and Livestock Characteristics (Private Peasant Holdings) 2021/2022 (2014 E.C.)* (No. 594; Agricultural Sample Survey). Ethiopian Statistical Service.

CSA, (Central Statistical Agency). (2021). *Agricultural Sample Survey 2020/21 [2013 E. C .] Volume II: Report on livestock and livestock characteristics (Private Peasant Holdings).: Vol. 589 Bullet* (p. 199). FDRE Central Statistical Agency.

da Silva, E. A., da Silva, W. J., Barreto, A. C., Junior, A. B. de O., Paes, J. M. V., Ruas, J. R. M., & Queiroz, D. S. (2012). Dry matter yield, thermal sum and base

temperatures in irrigated tropical forage plants. *Revista Brasileira de Zootecnia*, *41*(3), 574–582.

Da Silva, P. C. G., Brandão Ferreira Ítavo, C. C., Vinhas Ítavo, L. C., De Nadai Bonin Gomes, M., Dias Feijó, G. L., Monteiro Ferelli, K. L. S., Da Silva Heimbach, N., Da Silva, J. A., De Melo, G. K. A., & Filgueira Pereira, M. W. (2020). Carcass traits and meat quality of Texel lambs raised in *Brachiaria* pasture and feedlot systems. *Animal Science Journal*, *91*(1), e13394. https://doi.org/10.1111/asj.13394

Damene, S., Bahir, A., & Villamor, G. B. (2020). The role of Chomo grass (Brachiaria humidicola) and exclosures in restoring soil organic matter , total nitrogen , and associated functions in degraded lands in Ethiopia. *Regional Environmental Change*, *20*(92).

De Carvalho, G. G. P., Rebouças, R. A., Campos, F. S., Santos, E. M., Araújo, G. G. L., Gois, G. C., De Oliveira, J. S., Oliveira, R. L., De A. Rufino, L. M., Azevedo, J. A. G., & Cirne, L. G. A. (2017). Intake, digestibility, performance, and feeding behavior of lambs fed diets containing silages of different tropical forage species. *Animal Feed Science and Technology*, *228*, 140–148. https://doi.org/10.1016/j.anifeedsci.2017.04.006

Dereje, F., Mengistu, A., Geleti, D., Diba, D., & Feyissa, F. (2024). Herbage Yield and Nutritive Value of Selected Grasses in Subhumid Agroecological Environments in Ethiopia. *International Journal of Agronomy*, *2024*, 1–8. https://doi.org/10.1155/2024/6170361

Desta, A. G. (2024). Seasonality, balance and copying mechanisms of livestock feed in Northwestern Ethiopia. *Cogent Food & Agriculture*, *10*(1), 2343895. https://doi.org/10.1080/23311932.2024.2343895

Diba, D., Mekasha, Y., Urge, M., & Tolera, A. (2015). Carcass Yield and Composition of Supplementing Hararghe Highland Sheep with Ficus sur (cv. Forssk.) Fruits to a Basal Diet of Natural Pasture Hay. *Science, Technology and Arts Research Journal*, *4*(4), 09–17.

Diba, D., Mekasha, Y., Urge, M., & Tolera, A. (2018). Effect of Different Proportions of Fig (Ficus sur) Fruits and Oats (Avena sativa) Grain Supplementation on Feed Intake , Digestibility , Nitrogen Retention and Live Weight Change of Hararghe

Highland Sheep Fed Natural Pasture Hay Based Diets. *Eth. J. Anim. Prod.*, *18*(1), 20–35.

Djikeng, A., Rao, I. M., Njarui, D., Mutimura, M., Caradus, J., Ghimire, S. R., Johnson, L., Cardoso, J. A., Ahonsi, M., & Kelemu, S. (2014). Climate-smart Brachiaria grasses for improving livestock production in East Africa. *Tropical Grasslands−Forrajes Tropicales*, *2*, 38–39.

Ebrahim, H., & Alemayehu, K. (2024). Dietary Supplements Improve the Growth Performance and Carcass Yields of Indigenous Sheep in Ethiopia: A Systematic Review and Meta-Analysis Study. *Veterinary Medicine and Science*, *11*(1), e70129. https://doi.org/10.1002/vms3.70129

Ecker, M., Kelley, D., & Sato, H. (2020). Modelling the effects of CO2 on c3 and c4 grass competition during the mid-Pleistocene transition in South Africa. *Scientific Reports*, *10*(16234). https://doi.org/10.1038/s41598-020-72614-2

Ehsan, M. A., Tippett, M. K., Robertson, A. W., Almazroui, M., Ismail, M., Dinku, T., Acharya, N., Siebert, A., Ahmed, J. S., & Teshome, A. (2021). Seasonal predictability of Ethiopian Kiremt rainfall and forecast skill of ECMWF's SEAS5 model. *Climate Dynamics*, *57*(11–12), 3075–3091. https://doi.org/10.1007/s00382-021-05855-0

Ergon, Å., Seddaiu, G., Korhonen, P., Virkajärvi, P., Bellocchi, G., Jørgensen, M., Østrem, L., Reheul, D., & Volaire, F. (2018). How can forage production in Nordic and Mediterranean Europe adapt to the challenges and opportunities arising from climate change? *European Journal of Agronomy*, *92*, 97–106. http://dx.doi.org/10.1016/j.eja.2017.09.016

Eshetie, T., Hussien, K., Teshome, T., & Mekonnen, A. (2018). Meat production, consumption and marketing tradeoffs and potentials in Ethiopia and its effect on GDP growth: A review. *Journal of Nutritional Health & Food Engineering*, *8*(3). https://doi.org/10.15406/jnhfe.2018.08.00274

Faji, M., Kebede, G., Feyissa, F., Mohammed, K., & Mengistu, G. (2022). Yield, Yield Components , and Nutritive Value of Perennial Forage Grass Grown under Supplementary Irrigation. *Hindawi Advances in Agriculture*, *2022*, 11. https://doi.org/10.1155/2022/5471533

FAO, (Food and Agriculture Organization). (2018). *Ethiopia Report on feed inventory and feed balance 2018*(p. 160). Food and Agriculture Organization of the United Nations.

Fekadu, D., Bediye, S., & Sileshi, Z. (2010). Characterizing and predicting chemical composition and in vitro digestibility of crop residue using near infrared reflectance spectroscopy (NIRS). *Livestock Research for Rural Development*, *22*(2), 29.

Feyissa, F., Assefa, G., Kebede, G., Ababa, A., & Geleti, D. (2015). Cultivated Forage Crops Research and Development in Ethiopia: In A. u Yami, G. Assefa, & L. Gizachew (Eds.), *Pasture and Rangeland Research and Development ni Ethiopia* (pp. 89–118). Ethiopian Society of Animal Production, ESAP.

Feyissa, F., Kebede, G., Gelete, D., Assefa, G., & Mengistu, A. (2022). Improved Forage Crops Research and Development in Ethiopia: Major Achievements, Challenges and the Way Forward. *OMO International Journal of Sciences*, *5*(2), 36–69. https://doi.org/10.59122/135BE51

Gadissa, S., Eshetu, M., Urge, M., Tolera, A., & Feyissa, F. (2021). Effects of dietary energy and protein levels on nutrient intake, digestibility, and body weight change in Hararghe highland and Afar sheep breeds of Ethiopia. *Journal of Advanced Veterinary and Animal Research*, *8*(2), 185–194. https://doi.org/10.5455/javar.2021.h501

Gebremariam, T., & Belay, S. (2021). Chemical Composition and Digestibility of Major Feed Resources in Tanqua-Abergelle District of Central Tigray, Northern Ethiopia. *The Scientific World Journal*, *2021*. https://doi.org/10.1155/2021/5234831

Gebremichael, S. G. (2008). *Sheep resources of Ethiopia: Genetic diversity and breeding strategy*. Wageningen University.

Gijsman, A. J., Hoogenboom, G., Parton, W. J., & Kerridge, P. C. (2002). Modifying DSSAT Crop Models for Low-Input Agricultural Systems Using a Soil Organic Matter–Residue Module from CENTURY. *AGRONOMY JOURNAL*, *94*, 462–474.

Gizaw, S., Tegegne, A., Gebremedhin, B., & Hoekstra, D. (2010). *Sheep and goat production and marketing systems in Ethiopia: Characteristics and strategies for improvement* (Improving Productivity and Market Success (IPMS) of Ethiopian Farmers Project No. Working Paper No. 23; p. 58). ILRI.

González, C., Schiek, B., Mwendia, S., & Prager, S. D. (2016). *Improved Forages and Milk Production in East Africa. A case study in the series: Economic foresight for understanding the role of investments in agriculture for the global food system* (p. 48). Centro Internacional de Agricultura Tropical (CIAT).

Habermann, E., Dias De Oliveira, E. A., Contin, D. R., Costa, J. V. C. P., Costa, K. A. D. P., & Martinez, C. A. (2022). Warming offsets the benefits of elevated CO2 in water relations while amplifies elevated CO2-induced reduction in forage nutritional value in the C4 grass Megathyrsus maximus. *Frontiers in Plant Science*, *13*, 1033953. https://doi.org/10.3389/fpls.2022.1033953

Habermann, E., Dias De Oliveira, E. A., Contin, D. R., Delvecchio, G., Viciedo, D. O., De Moraes, M. A., De Mello Prado, R., De Pinho Costa, K. A., Braga, M. R., & Martinez, C. A. (2019). Warming and water deficit impact leaf photosynthesis and decrease forage quality and digestibility of a C4 tropical grass. *Physiologia Plantarum*, *165*(2), 383–402. https://doi.org/10.1111/ppl.12891

Habte, M., Eshetu, M., Maryo, M., Andualem, D., & Legesse, A. (2022). Effects of climate variability on livestock productivity and pastoralists perception: The case of drought resilience in Southeastern Ethiopia. *Veterinary and Animal Science*, *16*, 100240. https://doi.org/10.1016/j.vas.2022.100240

Hadgu, G., Tesfaye, K., & Mamo, G. (2014). Analysis of climate change in Northern Ethiopia: Implications for agricultural production. *Theor Appl Climatol*. https://doi.org/DOI 10.1007/s00704-014-1261-5

Hart, E. H., Christofides, S. R., Davies, T. E., Rees Stevens, P., Creevey, C. J., Müller, C. T., Rogers, H. J., & Kingston-Smith, A. H. (2022). Forage grass growth under future climate change scenarios affects fermentation and ruminant efficiency. *Scientific Reports*, *12*(1), 1–14. https://doi.org/10.1038/s41598-022-08309-7

Hassan, H., Beyero, N., & Bayssa, M. (2020). Estimation of major livestock feed resources and feed balance in Moyale district of Boran Zone , Southern Ethiopia. *International Journal of Livestock Production*, *11*(1), 43–51. https://doi.org/10.5897/IJLP2019.0623

Hoogenboom, G., H. Porter, C., J. Boote, K., & Shelia, V. (2020). The DSSAT crop modeling ecosystem. In *Advances in crop modelling for a sustainable agriculture* (First, pp. 173–216). Burleigh Dodds Science Publishing.

Hoogenboom, G., Porter, C. H., Shelia, V., Boote, K. J., Singh, U., White, J. W., Hunt, L. A., Ogoshi, R., Lizaso, J. I., & Koo, J. (2017). *Decision support system for agrotechnology transfer (DSSAT) version 4.7 (https://DSSAT. net). DSSAT Foundation, Gainesville, Florida*. USA.

Huang, Y., Liu, L., Zhao, M., Zhang, X., Chen, J., Zhang, Z., Cheng, X., & Ren, C. (2023). Feeding regimens affecting carcass and quality attributes of sheep and goat meat—A comprehensive review. *Animal Bioscience*, *36*(9), 1314–1326. https://doi.org/10.5713/ab.23.0051

ICPALD, (IGAD Centre for Patoral Areas and Livestock Development). (2013). *The Contribution of Livestock to The Ethiopian Economy [ICPALD/CLE/8/2013]: POLICY BRIEF* (ICPALD 5/CLE/8/2013, p. 4). IGAD Centre for Patoral Areas and Livestock Development (ICPALD).

IPCC, (Intergovernmental Panel on Climate Change). (2007). *Climate Change 2007: Synthesis Report* (Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (Eds.)], p. 104). IPCC, Geneva, Switzerland.

IPCC, (Intergovernmental Panel on Climate Change). (2014). *Climate Change 2014: Synthesis Report* (Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)], p. 151) [Synthesis Report]. IPCC.

IPCC, (Intergovernmental Panel on Climate Change). (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Working Group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (p. 3676).

ISRIC. (2013). *World Soil Information-Soil property maps of Africa at 1 km. Available for download at www.isric.org.*

Izaurralde, R. C., Thomson, A. M., Morgan, J. A., Fay, P. A., Polley, H. W., & Hatfield, J. L. (2011). Climate impacts on agriculture: Implications for forage and rangeland production. *Agronomy Journal*, *103*(2), 371–381. https://doi.org/10.2134/agronj2010.0304

Jabessa, T., Bekele, K., & Amare, Z. (2021). Evaluation of Desho Grass for Their Agronomic Performances and Nutritive Values in Highland and Midland Areas of Guji Zone, Southern Oromia, Ethiopia. *Science Research*, *9*(3), 35–40. https://doi.org/10.11648/j.sr.20210903.11

Jank, L., Barrios, S. C., Do Valle, C. B., Simeão, R. M., & Alves, G. F. (2014). The value of improved pastures to Brazilian beef production. *Crop and Pasture Science*, *65*(11), 1132. https://doi.org/10.1071/CP13319

Jemberu, W. T., Li, Y., Asfaw, W., Mayberry, D., Schrobback, P., Rushton, J., & Knight-Jones, T. J. D. (2022). Population, biomass, and economic value of small ruminants in Ethiopia. *Frontiers in Veterinary Science*, *9*, 972887. https://doi.org/10.3389/fvets.2022.972887

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., & Ritchie, J. T. (2003). The DSSAT cropping system model. *Europ. J. Agronomy*, *18*, 235–265.

Kahsu, A., Tikabo, G., & Teferi, A. (2021). Feed intake, digestibility and growth performance of Begait sheep kept under different feeding options. *African Journal of Agricultural Research*, *17*(3), 378–386. https://doi.org/10.5897/AJAR2020.15053

Kassahun, M., Ture, K., & Nedaw, D. (2023). Evaluation of CORDEX Africa regional climate models performance in simulating climatology of Zarima sub-basin northwestern Ethiopia. *Environmental Systems Research*, *12*(1), 41. https://doi.org/10.1186/s40068-023-00325-4

Kebebe, E. (2015). *Understanding factors affecting technology adoption in smallholder livestock production systems in Ethiopia: The role of farm resources and the enabling environment.* Wageningen University.

Kebede, G. (2015). Optimum Dietary Crude Protein Level for Fattening Yearling Arsi-Bale Lambs. *World Journal of Agricultural Sciences*, *11*(2), 101–106. https://doi.org/10.5829/idosi.wjas.2015.11.2.1847

Kebede, G., Feyissa, F., Faji, M., Mohammed, K., Dejene, M., Mengistu, G., Geleti, D., Assefa, G., Alemayehu, M., Mengistu, S., Mengistu, A., & Tsegahun, A. (2023). Dry matter accumulation dynamics, morphological characteristics and nutritive value of desho (*Pennisetum glaucifolium*) grass varieties in the central Highlands of Ethiopia. *Journal of Agriculture and Environmental Sciences*, *8*(1), 110–123. https://doi.org/10.4314/jaes.v8i1.8

Kebede, G., Mengistu, A., & Animut, G. (2020). *Performances of Arsi-Bale Lambs Fed Diets Based on Sugarcane Tops Silage and Hay as a Partial Substitute for Natural Pasture Hay*. *30*(3), 177–190.

Korir, J., Ordóñez, L., Hoogenboom, G., Boote, K., Paul, B., & Nyawira, S. S. (2021). *Simulating forage yields and soil organic carbon under Brachiaria hybrid cv. Cayman in Tanzania with the CROPGRO perennial forage model* (No. CIAT Publication No. 522; p. 26). International Center for Tropical Agriculture.

Lara, M. A. S., Pedreira, C. G. S., Boote, K. J., Pedreira, B. C., Moreno, L. S. B., & Alderman, P. D. (2012). Predicting Growth of Panicum maximum: An Adaptation of the CROPGRO–Perennial Forage Model. *Agron. J.*, *104*(3), 600–611. https://doi.org/10.2134/agronj2011.0272

Legese, G., & Fadiga, M. (2014). *Small ruminant value chain development in Ethiopia: Situation analysis and trends* [ICARDA/ILRI Project Report]. International Center for Agricultural Research in the Dry Areas/International Livestock Research Institute.

Lenth, R. V. (2016). *Least-Squares Means: The R Package lsmeans*. *69*(1). https://doi.org/doi: 10.18637/jss.v069.i01

Maass, B. L., Midega, C. A. O., Mutimura, M., Rahetlah, V. B., Salgado, P., Kabirizi, J. M., Khan, Z. R., Ghimire, S. R., & Rao, I. M. (2015). Homecoming of Brachiaria:

Improved Hybrids Prove Useful for African Animal Agriculture. *East African Agricultural and Forestry Journal*, *81*(1), 71–78. https://doi.org/10.1080/00128325.2015.1041263

Maina, K. W., Ritho, C. N., Lukuyu, B. A., & Rao, E. J. O. (2020). Socio-economic determinants and impact of adopting climate-smart Brachiaria grass among dairy farmers in Eastern and Western regions of Kenya. *Heliyon*, *6*(6), e04335. https://doi.org/10.1016/j.heliyon.2020.e04335

Maino, R., & Emrullahu, D. (2022). *Climate Change in SubSaharan Africa's Fragile States: Evidence from Panel Estimations* (IMF Working Paper No. WP/22/54; p. 31). International Monetary Fund.

Management Entity, 2021. (2021). *Ethiopia's Livestock Systems: Overview and Areas of Inquiry* [Feed the Future Innovation Lab for Livestock Systems].

McDonald, P., Edwards, R. A., Greenhalgh, J. F. D., Morgan, C. A., Sinclair, L. A., & Wilkinson, R. G. (Eds.). (2010). *Animal nutrition* (7th ed). Prentice Hall/Pearson.

McNamara, K., & McKune, S. (2018). *Looking beyond productivity: Barriers to animal source food consumption in Ethiopia* [Feed the Future Innovation Lab for Livestock Systems].

Mekonnen, K., Bezabih, M., Thorne, P., Gebreyes, M. G., Hammond, J., & Adie, A. (2022). Feed and forage development in mixed crop–livestock systems of the Ethiopian highlands: Africa RISING project research experience. *Agronomy Journal*, *114*(1), 46–62. https://doi.org/10.1002/agj2.20853

Mekuriaw, Y., & Asmare, B. (2018). Nutrient intake, digestibility and growth performance of Washera lambs fed natural pasture hay supplemented with graded levels of Ficus thonningii(Chibha) leaves as replacement for concentrate mixture. *Agriculture & Food Security*, *7*(1), 30. https://doi.org/10.1186/s40066-018-0182-4

Melese, G., Mengistu, U., Getachew, A., & Dereje, T. (2017). Slaughter performance and meat quality of intact and castrated Washera sheep kept under feedlot condition. *African Journal of Agricultural Research*, *12*(41), 3072–3080. https://doi.org/10.5897/AJAR2017.12679

Mengistu, A., Kebede, G., Feyissa, F., & Assefa, G. (2017a). Overview of Improved Forage and Forage Seed Production in Ethiopia: Lessons from Fourth Livestock Development Project. *Inter J Agri Biosci*, *6*(4), 217–226.

Mengistu, A., Kebede, G., Feyissa, F., & Assefa, G. (2017b). Review on Major Feed Resources in Ethiopia: Conditions, Challenges and Opportunities. *Academic Research Journal of Agricultural Science and Research*, *5*(3), 176–185. https://doi.org/10.14662/ARJASR2017.013

Mengistu, G., & Assefa, G. (2022). Supplementation of Mulberry (Morus indica) and Vernonia (V. amygdalina) leaves as protein source on morphometric measurement, weight change, and carcass characteristics of sheep. *CABI Agriculture and Bioscience*, *3*(1), 69. https://doi.org/10.1186/s43170-022-00137-z

Mganga, K. Z., Ndathi, A. J. N., Wambua, N. A., Stephen M., Bosma, L., Kaindi, E. M., Kioko, T., Kadenyi, N., Musyoki, G. K., Steenbergen, F. van, & Musimba, N. K. R. (2021). Forage value of vegetative leaf and stem biomass fractions of selected grasses indigenous to African rangelands. *Animal Production Science*, *61*, 1476–1483. https://doi.org/10.1071/AN19597

Moore, C. E., Meacham-Hensold, K., Lemonnier, P., Slattery, R. A., Benjamin, C., Bernacchi, C. J., Lawson, T., & Cavanagh, A. P. (2021). The effect of increasing temperature on crop photosynthesis: From enzymes to ecosystems. *Journal of Experimental Botany*, *72*(8), 2822–2844. https://doi.org/10.1093/jxb/erab090

Moreno, L. S. B., Pedreira, C. G. S., Boote, K. J., & Alves, R. R. (2014). Base temperature determination of tropical Panicum spp. Grasses and its effects on degree-day-based models. *Agricultural and Forest Meteorology*, *186*(2014), 26–33. http://dx.doi.org/10.1016/j.agrformet.2013.09.013

Moreta, D. E., Arango, J., Sotelo, M., Vergara, D., Rincón, A., Ishitani, M., Castro, A., Miles, J., Peters, M., Tohme, J. O. E., Subbarao, G. V, & Rao, I. M. (2014). Biological nitrification inhibition (BNI) in Brachiaria pastures: A novel strategy to improve eco-efficiency of crop-livestock systems and to mitigate climate change. *Tropical Grasslands – Forrajes Tropicales*, *2*, 88–92.

Muinga, R. W., Njunie, M. N., Gatheru, M., & Njarui, D. M. G. (2016). The effects of Brachiaria grass cultivars on lactation performance of dairy cattle in Kenya. In D.

M. G. Njarui, E. M. Gichangi, S. R. Ghimire, & R. W. Muinga (Eds.), *Climate Smart Brachiaria Grasses for Improving Livestock Production in East Africa – Kenya Experience. Proceedings of the workshop held in Naivasha, Kenya,14—15 September* (pp. 229–237). KALRO.

Muleta, B. G. (2022). Perception of Stakeholders for Meat Qualities among Value Chain Actors in Ethiopia. *Veterinary Medicine International*, *2022*, 1–10. https://doi.org/10.1155/2022/1247459

Muzzo, B. I., Ramsey, R. D., & Villalba, J. J. (2024). Changes in Climate and Their Implications for Cattle Nutrition and Management. *Climate*, *13*(1), 1. https://doi.org/10.3390/cli13010001

Mwangi, P. M., Eckard, R., Gluecks, I., Merbold, L., Mulat, D. G., Gakige, J., Marquardt, S., & Pinares-Patino, C. S. (2024). Supplementation of a tropical low-quality forage with Calliandra calothyrsus improves sheep health and performance, and reduces methane emission. *Frontiers in Animal Science*, *5*, 1296203. https://doi.org/10.3389/fanim.2024.1296203

Namazzi, C., Sserumaga, J. P., Mugerwa, S., Kyalo, M., Mutai, C., Mwesigwa, R., Djikeng, A., & Ghimire, S. (2020). Genetic Diversity and Population Structure of Brachiaria (syn. Urochloa) Ecotypes from Uganda. *Agronomy*, *10*(8), 1193. https://doi.org/10.3390/agronomy10081193

Nazarenko, L., Schmidt, G. A., Miller, R. L., Tausnev, N., Kelley, M., Ruedy, R., Russell, G. L., Aleinov, I., Bauer, M., Bauer, S., Bleck, R., Canuto, V., Cheng, Y., Clune, T. L., Del Genio, A. D., Faluvegi, G., Hansen, J. E., Healy, R. J., Kiang, N. Y., … Zhang, J. (2015). Future climate change under RCP emission scenarios with GISS ModelE2. *Journal of Advances in Modeling Earth Systems*, *7*, 244–267.

Negassa, W., Getaneh, F., Deressa, A., & Dinsa, B. (2007). Integrated Use of Organic and Inorganic Fertilizers for Maize Production. *Tropentag*, 1–8.

Negewo, T., Melaku, S., Asmare, B., & Tolera, A. (2019). Effect of Graded Levels of Concentrate Supplementation on Carcass Yield and Characteristics of Local Sheep Fed Urea Treated Maize Cob as a Basal Diet. *Animal Science and Biotechnologies*, *52*(1).

Njarui, D. M. G., Gatheru, M., & Ghimire, S. R. (2021). Brachiaria Grass for Climate Resilient and Sustainable Livestock Production in Kenya. In *African Handbook of Climate Change Adaptation* (pp. 755–776). Springer International Publishing. https://doi.org/10.1007/978-3-030-45106-6_146

NRC, (National Research Council). (2007). *Nutrient requirements of small ruminants: Sheep, goats, cervids, and New World camelids*. The National Academies Press.

Osman, A., Osafo, E. L. K., Attoh-Kotoku, V., & Yunus, A. A. (2023). Effects of supplementing probiotics and concentrate on intake, growth performance and blood profile of intensively kept Sahelian does fed a basal diet of *Brachiaria decumbens* grass. *Journal of Applied Animal Research*, *51*(1), 414–423. https://doi.org/10.1080/09712119.2023.2211652

Osman, A., Osafo, E. L. K., Attoh-Kotoku, V., Yunus, A. A., Simpa Anim-Jnr, A., Yawo Akwetey, W., & Antwi, C. (2023). Carcass characteristics and meat quality of adult Sahelian does fed a basal diet of Brachiaria decumbens grass supplemented with probiotics and concentrates. *Cogent Food & Agriculture*, *9*(1), 2225259. https://doi.org/10.1080/23311932.2023.2225259

Pannier, L., Pethick, D. W., Geesink, G. H., Ball, A. J., Jacob, R. H., & Gardner, G. E. (2014). Intramuscular fat in the longissimus muscle is reduced in lambs from sires selected for leanness. *Meat Science*, *96*(2), 1068–1075. https://doi.org/10.1016/j.meatsci.2013.06.014

Pedreira, B. C., Pedreira, C. G. S., Boote, K. J., Lara, M. A. S., & Alderman, P. D. (2011). Field Crops Research Adapting the CROPGRO perennial forage model to predict growth of Brachiaria brizantha. *Field Crops Research*, *120*(3), 370–379. https://doi.org/10.1016/j.fcr.2010.11.010

Pequeno, D. N. L., Pedreira, C. G. S., & Boote, K. J. (2014). Simulating forage production of Marandu palisade grass (Brachiaria brizantha) with the CROPGRO-Perennial Forage model. *Crop & Pasture Science*, *65*, 1335–1348. http://dx.doi.org/10.1071/CP14058

Pequeno, D. N. L., Pedreira, C. G. S., Boote, K. J., Alderman, P. D., & Faria, A. F. G. (2017). Species-genotypic parameters of the CROPGRO Perennial Forage Model:

Implications for comparison of three tropical pasture grasses. *Grass and Forage Science*, 1–16. https://doi.org/10.1111/gfs.12329

Perelli, C., Cacchiarelli, L., Mupenzi, M., Branca, G., & Sorrentino, A. (2024). 'Unlock the Complexity': Understanding the Economic and Political Pathways Underlying the Transition to Climate-Smart Smallholder Forage-Livestock Systems: A Case Study in Rwanda. *Economies*, *12*(7), 177. https://doi.org/10.3390/economies12070177

Ponnampalam, E. N., Holman, B. W. B., & Scollan, N. D. (2016). Sheep: Meat. In *Encyclopedia of Food and Health* (pp. 750–757). Elsevier. https://doi.org/10.1016/B978-0-12-384947-2.00620-6

Ponnampalam, E., Priyashantha, H., Vidanarachchi, J., Kiani, A., & Holman, B. (2024). Effects of Nutritional Factors on Fat Content, Fatty Acid Composition, and Sensorial Properties of Meat and Milk from Domesticated Ruminants: An Overview. *Animals*, *14*(6), 840. https://doi.org/10.3390/ani14060840

Poorter, H., Niklas, K. J., Reich, P. B., Oleksyn, J., Poot, P., & Mommer, L. (2012). Biomass allocation to leaves, stems and roots: Meta-analyses of interspecific variation and environmental control. *New Phytologist*, *193*, 30–50. https://doi.org/10.1111/j.1469-8137.2011.03952.x

Puche, N. J. B., Kirschbaum, M. U. F., Viovy, N., & Chabbi, A. (2023). Potential impacts of climate change on the productivity and soil carbon stocks of managed grasslands. *PLoS ONE*, *18*(4). https://doi.org/10.1371/journal.pone.0283370

Rao, I. M., Ishitani, M., Peters, M., & Tohme, J. (2014). Climate-smart crop-livestock systems for smallholders in the tropics: Integration of new forage hybrids to intensify agriculture and to mitigate climate change through regulation of nitrification in soil. *Tropical Grasslands – Forrajes Tropicales*, *2*, 130–132. https://doi.org/10.17138/TGFT(2)130-132

Renvoize, S. A., Clayton, W. D., & Kabuye, C. H. S. (1996). Morphology, taxonomy and natural distribution of Brachiaria (Trin.) Griseb. In J. Miles, B. Maass, & C. B. do Valle (Eds.), *Brachiaria: Biology, Agronomy and Improvement* (pp. 1–15). Centro International de Agricultura Tropical.

Ritchie, J. T. (1972). Model for Predicting Evaporation from a Row Crop with Incomplete Cover. *Water Resources Research*, *8*(5), 1204–1213.

Roba, R. B., Letta, M. U., Aychiluhim, T. N., & Minneeneh, G. A. (2022). Intake, digestibility, growth performance and blood profile of rams fed sugarcane bagasse or rice husk treated with Trichoderma viride and effective microorganisms. *Heliyon*, *8*(12), e11958. https://doi.org/10.1016/j.heliyon.2022.e11958

Rufino, L. M. A., Batista, E. D., Rodrigues, J. P. P., Valadares Filho, S. C., Paulino, M. F., Costa E Silva, L. F., & Detmann, E. (2020). Effects of the amount and frequency of nitrogen supplementation on intake, digestion, and metabolism in cattle fed low-quality tropical grass. *Animal Feed Science and Technology*, *260*, 114367. https://doi.org/10.1016/j.anifeedsci.2019.114367

Rymph, S. J., Boote, K. J., Irmak, A., Mislevy, P., & Evers, G. W. (2004). Adapting the CROPGRO model to predict growth and composition of tropical grasses: Developing physiological parameters. *Annual Proceedings Soil and Crop Science Society of Florida*, *63*, 37–51.

Santos, M. L. dos, Menezes Santos, P., Boote, K. J., Pequeno, D. N. L., Barioni, L. G., Cuadra, S. V., & Hoogenboom, G. (2022). Applying the CROPGRO Perennial Forage Model for long-term estimates of Marandu palisadegrass production in livestock management scenarios in Brazil. *Field Crops Research*, *286*. https://doi.org/10.1016/j.fcr.2022.108629

Santos, M. G., Boote, K. J., Faria, R. T., & Hoogenboom, G. (2019). Simulation of productivity and soil moisture under Marandu palisade grass using the CSM-CROPGRO-Perennial Forage model. *Crop & Pasture Science*, *70*, 159–168. https://doi.org/10.1071/CP18258

Schiek, B., Gonzalez, C., Mwendia, S. W., & Prager, S. D. (2018). Got forages? Understanding potential returns on investment in Brachiaria spp. For dairy producers in Eastern Africa. *Tropical Grasslands-Forrajes Tropicales*, *6*(3), 117–133. https://doi.org/10.17138/tgft(6)117-133

Schumacher, M., DelCurto-Wyffels, H., Thomson, J., & Boles, J. (2022). Fat Deposition and Fat Effects on Meat Quality—A Review. *Animals*, *12*(12), 1550. https://doi.org/10.3390/ani12121550

Seid, W., Tsega, W., & Demisse, E. (2021). Growth Performance of Arsi-Bale Sheep Fed Desho Grass (Pennisetum pedicellatum) Hay Supplemented with Different Concentrate Levels. *Ethiopian Journal of Agricultural Sciences*, *31*(4).

Shapiro, B. I., Gebru, G., Desta, S., Negassa, A., Nigussie, K., Aboset, G., & Mechale, H. (2017). *Ethiopia livestock sector analysis.* (p. 127) [ILRI Project Report.]. International Livestock Research Institute (ILRI).

Smith, H. D., Wilson, C. H., Rymph, S. J., Santos, E. R. S., & Boote, K. J. (2023). Adapting the CROPGRO Perennial Forage model to predict growth and development of Pensacola bahiagrass. *Field Crops Research*, *302*, 109095. https://doi.org/10.1016/j.fcr.2023.109095

Sollenberger, L. E., Vendramini, J. M. B., Pedreira, C. G. S., & Rios, E. F. (2020). Warm-Season Grasses for Humid Areas. In K. J. Moore, M. Collins, C. J. Nelson, & D. D. Redfearn (Eds.), *Forages: The Science ofGrassland Agriculture: Vol. II* (Seventh, pp. 331–345). John Wiley & Sons Ltd. https://doi.org/10.1002/9781119436669.ch18

Tadesse, D., Urge, M., Animut, G., & Mekasha, Y. (2016). Growth and carcass characteristics of three Ethiopian indigenous goats fed concentrate at different supplementation levels. *SpringerPlus*, *5*(1), 414. https://doi.org/10.1186/s40064-016-2055-2

Tafesse, D., & Esayas, A. (2003). *Soils of Debre Zeit Agricultural Research Center and its sub-centers: Vol. Technical*.

Taiz, L., & Zeiger, E. (2002). *Plant Physiology* (3rd ed.). Sinauer Associates. https://doi.org/10.1093/aob/mcg079

Tedeschi, L. O., Molle, G., Menendez, H. M., Cannas, A., & Fonseca, M. A. (2019). The assessment of supplementation requirements of grazing ruminants using nutrition models. *Translational Animal Science*, *3*(2), 811–828. https://doi.org/10.1093/tas/txy140

Tegegn, A., Kyalo, M., Mutai, C., Hansen, J., Assefa, G., Appolinare, D., & Ghimire, S. (2019). Genetic diversity and population structure of Brachiaria brizantha (A.Rich.) Stapf accessions from Ethiopia. *African Journal of Range & Forage Science*, *36*(2), 129–133. https://doi.org/10.2989/10220119.2019.1573760

Tekliye, L., Mekuriaw, Y., Asmare, B., & Mehret, F. (2018). Nutrient intake, digestibility, growth performance and carcass characteristics of Farta sheep fed urea-treated rice straw supplemented with graded levels of dried Sesbania sesban leaves. *Agriculture & Food Security*, *7*(1), 77. https://doi.org/10.1186/s40066-018-0226-9

Tesfaye, A., Asmare, B., Abiso, T., & Wamatu, J. (2023). Effect of Nutritional Flushing Using Long-Term Energy and Protein Supplementation on Growth Performance and Reproductive Parameters of Doyogena Ewes in Ethiopia. *Veterinary Sciences*, *10*(6), 368. https://doi.org/10.3390/vetsci10060368

Tesfaye, M., & Tessema, L. (2023). An overview of the status, productivity and determinants of improved forage technology adoption in Ethiopia: A review. *CABI Agriculture and Bioscience*, *4*(1), 47. https://doi.org/10.1186/s43170-023-00189-9

Tibebu, M. Z., Ashenafi, M. W., Adugna, T. Y., & Geert, H. G. (2019). Carcass and meat quality characteristics of two hair type breed lambs fed tef (Eragrostistef) straw ensiled with effective micro-organisms and supplemented with concentrates. *International Journal of Livestock Production*, *10*(4), 110–121. https://doi.org/10.5897/IJLP2018.0565

Tilley, J. M. A., & Terry, R. A. (1963). A TWO-STAGE TECHNIQUE FOR THE IN VITRO DIGESTION OF FORAGE CROPS. *Grass and Forage Science*, *18*(2), 104-111.

Timlin, D., Paff, K., & Han, E. (2024). The role of crop simulation modeling in assessing potential climate change impacts. *Agrosystems, Geosciences & Environment*, *7*(1), e20453. https://doi.org/10.1002/agg2.20453

Tolera, A., Yami, A., & Alemu, D. (2012). *Livestock Feed Resources in Ethiopia: Challenges, Opportunities and the Need for Transformation*. Ethiopian Animal Feeds Industry Association.

Tsega, W., Seid, W., & Demisse, E. (2021). Growth Performance and Carcass Characteristics of Arsi-Bale Sheep Fed Various Levels of Sugarcane Bagasse Contained Ration. *Journal of Veterinary Medicine and Animal Sciences*, *5*(1), 1093.

Upton, M. (1973). *Farm Management in Africa: The Principles of Production and Planning*. Oxford University Press. https://books.google.com.et/books?id=q6UPAQAAIAAJ

Van Soest, P. J. (1994). *Nutritional ecology of the ruminant* (Second Edition). Cornell University Press.

van Soest, P. J., & Robertson, J. B. (1985). *Analysis of Forages and Fibrous Foods*. CRC-Press. https://books.google.com.et/books?id=Rg18AAAACAAJ

Vega-Britez, G. D., Retore, M., Sousa, A. M. D., Silva, A. L. A. D., Costa, C. M., Souza, C. G. D., Souza, M. R. D., & Vargas Junior, F. M. D. (2024). Effects of Using Different Concentrate Supplementation Levels in Diets of Lambs Fed Tropical Aruana (Megathyrsus maximus) or Marandu (Brachiaria brizantha) Grass: Performance, Digestibility, and Costs of Production. *Grasses*, *3*(1), 19–34. https://doi.org/10.3390/grasses3010003

Vendramini, J. M. B., Silveira, M. L., & Moriel, P. (2023). Resilience of warm-season (C4) perennial grasses under challenging environmental and management conditions. *Animal Frontiers*, *13*(5), 16–22. https://doi.org/10.1093/af/vfad038

Wang, Q., Zeng, Y., Zeng, X., Wang, X., Wang, Y., Dai, C., Li, J., Huang, P., Huang, J., Hussain, T., Zhu, M., & Yang, H. (2021). Effects of Dietary Energy Levels on Rumen Fermentation, Gastrointestinal Tract Histology, and Bacterial Community Diversity in Fattening Male Hu Lambs. *Frontiers in Microbiology*, *12*, 695445. https://doi.org/10.3389/fmicb.2021.695445

Wassie, W. A., Tsegay, B. A., Wolde, A. T., & Limeneh, B. A. (2018). Evaluation of morphological characteristics , yield and nutritive value of Brachiaria grass ecotypes in northwestern Ethiopia. *Agriculture & Food Security*, *7*(89), 1–10. https://doi.org/10.1186/s40066-018-0239-4

Wheeler, T., & Reynolds, C. (2013). Predicting the risks from climate change to forage and crop production for animal feed. *Animal Frontiers*, *3*(1), 36–41. https://doi.org/10.2527/af.2013-0006

Willmott, C. J., Robeson, S. M., & Matsuura, M. (2011). Short Communication: A refined index of model performance. *International journal of climatology*. https://doi.org/10.1002/joc.2419

Worku, A., Urge, M., Animut, G., & Asefa, G. (2020). Comparative Slaughter Performance and Meat Quality of Rutana, Gumuz and Washera Sheep of Ethiopia Supplemented with Different Levels of Concentrate. *Open Journal of Animal Sciences*, *10*(01), 48–63. https://doi.org/10.4236/ojas.2020.101005

Yadete, G. K. (2019). *Sugarcane Byproducts as Feed Resources and Performance Of Sheep Fed On Sugarcane Tops Based Diets*. Addis Ababa University.

Yang, J. M., Yang, J. Y., Liu, S., & Hoogenboom, G. (2014). An evaluation of the statistical methods for testing the performance of crop models with observed data. *Agricultural Systems*. http://dx.doi.org/10.1016/j.agsy.2014.01.008

Yirgu, T., Mengistu, S., Shanku, E., & Ijara, F. (2017). Desho Grass (Pennisetum pedicellatum) Lines Evaluation for Herbage Yield and Quality under Irrigation at Wondogenet. *American-Eurasian J. Agric. & Environ. Sci.*, *17*(5), 427–431. https://doi.org/10.5829/idosi.aejaes.2017.427.431

Zarei, A., Chemura, A., Gleixner, S., & Hoff, H. (2021). Evaluating the grassland NPP dynamics in response to climate change in Tanzania. *Ecological Indicators*, *125*, 107600. https://doi.org/10.1016/j.ecolind.2021.107600

Zeleke, M., Wamatu, J., & Mengistu, S. (2022). *Indigenous Forages of Ethiopia Species. Evaluation and Variety Development: A Historical Perspective*. ILRI.

Zheng, Y., Li, F., Hao, L., Ali Sheday, A., Guo, L., Ma, C., Huang, B., & Xu, M. (2018). The optimal CO2 concentrations for the growth of three perennial grass species. *BMC Plant Biology*, *18*(27). https://doi.org/DOI 10.1186/s12870-018-1243-3

Zheng, Y., Li, F., Yu, J., Guo, L., Zhou, H., Ma, C., Zhang, X., & Xu, M. (2019). Elevated CO2 concentration induces photosynthetic down-regulation with changes in leaf structure, non-structural carbohydrates and nitrogen content of soybean. *BMC Plant Biology*, *19*(255). https://doi.org/10.1186/s12870-019-1788-9

Annexes/Appendices:

Appendix 1. List of publications, accepted and submitted manuscripts

1. Dereje, Fantahun, Mengistu, Ashenafi, Geleti, Diriba, Diba, Diriba, Feyissa, Fekede, Herbage Yield and Nutritive Value of Selected Grasses in Subhumid Agroecological Environments in Ethiopia, *International Journal of Agronomy*, 2024, 6170361, 8 pages, 2024. https://doi.org/10.1155/2024/6170361

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Research Article

Herbage Yield and Nutritive Value of Selected Grasses in Subhumid Agroecological Environments in Ethiopia

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The introduction of improved forage varieties could play a crucial role in meeting the growing demand for livestock and livestock products in Ethiopia. However, different cultivars exhibit varied performance. Therefore, this study aimed to assess the performance of *Brachiaria* cultivars and other grass cultivars in two subhumid agroecological areas of Ethiopia. Four *Brachiaria* cultivars (*B. brizantha* (DZF-13379), *B. humidicola* (DZF-9222), *B. decumbens* (DZF-10871), and *B. mutica* (var. DZF-483), and two local grass cultivars, Rhodes grass (*Chloris gayana* var. Massaba) and Desho grass (*Pennisetum glaucifolium* var. Kindu Kosha), were evaluated in Bako and Bishoftu for three years during the rainy season. The experiment was carried out using a completely randomized block design. Results indicated that both cultivars and years had significant ($P < 0.001$) effects on herbage dry matter (DM) yield, crude protein (CP) yield, and plant height, whereas location only affected DM yield. Significant cultivar × year interactions were observed for DM yield, CP yield, and plant height, while cultivar × location interactions had a significant effect on all parameters except for CP yield. Additionally, cultivars significantly ($P < 0.001$) impacted the in vitro dry matter digestibility (IVDMD) as well as the nutritional content (CP, ash, acid detergent lignin (ADL), neutral detergent fiber (NDF), and acid detergent fiber (ADF). Overall, all cultivars demonstrated potential as alternative ruminant feeds, with *B. mutica*, followed by *B. brizantha*, showing superior performance in the subhumid agroecological areas of Ethiopia.

2. Dereje, F., Mengitsu, A., Geleti, D., Diba, D., Feyissa, F., Beriso, Y., Tesfaye, B., & Dejene, M. (2024). Agronomic performance and nutritive value of Urochloa species, Desho and Rhodes grass grown in sub-humid central Ethiopia. *Tropical Grasslands-Forrajes Tropicales*, *12*(3), 154–161. https://doi.org/10.17138/tgft(12)154-161

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Research Paper

Agronomic performance and nutritive value of *Urochloa* species, Desho and Rhodes grass grown in sub-humid Central Ethiopia

Desempeño agronómico y valor nutritivo de las especies de Urochloa*, pastos Desho y Rhodes cultivados en en la zona Central subhúmeda de Etiopía*

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Abstract

Improved forage grasses with high quality and biomass are a crucial additional feed source for cereal-livestock farming in Ethiopia. This study compared the performance of 4 *Urochloa* species [*U. brizantha* (DZF-13379), *U. humidicola* (DZF-9222), *U. decumbens* 'Basilisk' (DZF-10871) and *U. mutica* (DZF-483)] with other 2 commonly used grasses, Rhodes grass (*Chloris gayana* 'Massaba') and Desho grass (*Pennisetum glaucifolium* local variety Kindu kosha), over 3 years during the main rainy season in Bishoftu in a sub-humid area of Ethiopia. The experiment was conducted using a completely randomized block design. There was significant variation among species for agronomic parameters. The species × year interaction was significant for dry matter yield, plant height, and plot cover but not significant for leaf-to-stem ratio. Nutritional value [ash, acid detergent fiber (ADF), crude protein (CP) and in vitro dry matter digestibility (IVDMD)] was significantly different among species with no differences for neutral detergent fiber (NDF) and acid detergent lignin (ADL). All species showed potential as alternative ruminant feeds with *U. mutica* and *U. brizantha* the highest yielding in the sub-humid environment.

Keywords: Dry matter yield, grass species, leaf-to-stem ratio, plant height, quality.

3. Dereje, F., Mengistu, A., Geleti, D., Diba, D., Feyissa, F., Pequeno, D., & Tesfaye, B. (2025). Simulating the growth and yields of Brachiaria Brizantha using the CROPGRO-perennial forage model under present and future climate conditions in subhumid environments of Ethiopia. *Agricultural and Forest Meteorology*, *371*, 110605. https://doi.org/10.1016/j.agrformet.2025.110605

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Simulating the growth and yields of *Brachiaria Brizantha* using the CROPGRO-perennial forage model under present and future climate conditions in subhumid environments of Ethiopia

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Brachiaria brizantha
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Simulation
Ethiopia

ABSTRACT

Brachiaria is a crucial forage crop in tropical and subtropical regions, but there is limited research on its response to climate change in Ethiopia. This study aimed to (1) calibrate and evaluate the performance of the CROPGRO-Perennial Forage model and (2) assess the impact of climate change on future Brachiaria brizantha yield in the subhumid environments of Ethiopia. Field data from Debre Zeit (Bishoftu) and Bako Agricultural Research Centers were used to calibrate and evaluate the model for accurately simulating rainfed growth and biomass yield. Weather data, including rainfall, temperature, and solar radiation, were obtained from Bishoftu and Bako weather stations. Historical and future climate scenarios for the near future, mid-century, and end of the 21st century were derived from the CORDEX Africa outputs under Representative Concentration Pathways (RCPs; RCP4.5 and RCP8.5). The calibration process involved refining parameters related to senescence and dormancy, vegetative partitioning, and N stress to improve the model's performance. Simulation results for future climate scenarios indicated an expected increase in biomass accumulation, with positive responses in the shoot, herbage biomass, and stem. However, leaf biomass and crude protein percentage of herbage are expected to decline. Overall, the production of B. brizantha is anticipated to increase in subhumid Ethiopian environments. Using simulations of CROPGRO-PFM can account for uncertainties about the impact of future climate change on Brachiaria grass. Further studies on Brachiaria forage responses under different management practices are advisable, to provide comprehensive information to policymakers and planners.

4. Dereje, F., Mengistu, A., Geleti, D., Feyissa, F., Diba, D., Pequeno, D., & Tesfaye, B. (2024). Calibration and evaluation of a CROPGRO Perennial Forage Model for *Brachiaria humidicola* yield simulation under future climate in subhumid environments of Ethiopia. *African Journal of Range & Forage Science*, *41*(4), 235–243. https://doi.org/10.2989/10220119.2024.2380699

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Calibration and evaluation of a CROPGRO Perennial Forage Model for *Brachiaria humidicola* yield simulation under future climate in subhumid environments of Ethiopia

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Crop simulation models can be employed to assess the impacts of climate change and aid in strategic planning and decision making regarding forage strategies. This study focused on calibrating and assessing the performance of the CROPGRO Perennial Forage Model in simulating *Brachiaria humidicola* yield under projected future climates for high and moderate representative concentration pathway (RCP) scenarios in the central and western subhumid regions of Ethiopia. The model was calibrated to accurately represent rainfed growth and biomass yield, using field data from the Debre Zeit and Bako Agricultural Research Centers. Climatic data, including rainfall, temperature and solar radiation, were sourced from weather stations, whereas future climate scenarios for the near future, mid-century and end-of-century periods were derived from the CORDEX Africa outputs under RCP 4.5 and RCP 8.5. The calibration process refined species parameters related to vegetative partitioning, and enhanced the *d*-statistic and reduced the root mean square error (RMSE) for herbage, leaf, stem and total biomass accumulation. Despite projected decreases in leaf biomass, stem biomass is projected to increase. In addition, there are projected increases in herbage and total biomass accumulation under elevated greenhouse gas concentrations and warmer temperatures. Ultimately, the projected climate under both RCPs had no significant effect on *Brachiaria humidicola* grass production in Ethiopia.

Keywords: climate change; DSSAT; simulation models

Appendix 2. Ethical certificate



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ADDIS ABABA UNIVERSITY
College of Veterinary Medicine
and Agriculture
Bishoftu

Animal Research Ethical Review Committee

Ethical clearance certificate

Certificate Ref. No: VM/ERC/06/01/15/2023

Name and affiliation of applicant: **Fentahun Dereje (MSc in Anim Production, PhD student)**
Department of Animal Production Studies, College of Veterinary Medicine and Agriculture, Addis Ababa University

Title of the project: *Evaluation of forage field, nutritional quality, and feeding value and simulation of the growth and yield of Brachiaria species under varying locations in Central and Western Oromia, Ethiopia*

Date of application:	**December, 2022**
Nature of the project:	**Experimental feeding trial**
Target animal species:	**Sheep**
Number of animals involved:	**28**
Study area:	**Bishoftu Research Station, Ethiopia**

Minutes No. and date of review: **VM/ERC/01/15/022, 16/12/2022**

The Animal Research Ethical Review Committee of the College of Veterinary Medicine and Agriculture of Addis Ababa University has reviewed the above research project and unanimously approved the application of **Fentahun Dereje** provided that:

1. All procedures and conditions stipulated in the proposal are respected, minor comments are corrected and any deviation or changes be reported to the committee
2. The project activities be open for occasional supervision by the committee when deemed necessary

The Federal Democratic Republic of Ethiopia
Addis Ababa University
College of Veterinary Medicine and Agriculture

Professor Getachew Terefe (DVM, PhD)
Chairman

Signature

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Appendix 3. Statistical analysis

```
Type III Analysis of Variance Table with Satterthwaite's method
          Sum Sq Mean Sq NumDF DenDF  F value    Pr(>F)
Loc        61.60   61.60     1    82  13.5104 0.002805  **
Year     1575.99  787.99     2    82 174.5420 < 2.2e-16 ***
Trt       243.54   48.71     5    82  17.5774 7.845e-09 ***
Loc:Trt    37.65    7.53     5    82   2.7230 0.0411821 *
Loc:Year   21.82   10.91     2    82   2.3881 0.0713487 .
Year:Trt  391.26   39.13    10    82   9.7781 1.487e-10 ***
---
Signif. codes:  0 â€***â€™ 0.001 â€**â€™ 0.01 â€*â€™ 0.05 â€˙â€™ 0.1
â€˜â€™ 1

> lsm4<-lsmeans(model4, ~Trt|Loc, adjust = "sidak", )
> cld4 = cld(lsm4, Letters = "abcd", decreasing = TRUE)
> cld4
Loc = Bako:
 Trt lsmean    SE   df lower.CL upper.CL .group
 T4   12.84 0.667 9.66    10.65     15.0  a
 T1   11.23 0.667 9.66     9.04     13.4  ab
 T6    9.67 0.667 9.66     7.47     11.9  ab
 T3    9.53 0.667 9.66     7.34     11.7   b
 T5    8.31 0.667 9.66     6.12     10.5   b
 T2    8.19 0.667 9.66     6.00     10.4   b
Loc = Bsftu:
 Trt lsmean    SE   df lower.CL upper.CL .group
 T4   13.57 0.667 9.66    11.37     15.8  a
 T6   12.94 0.667 9.66    10.75     15.1  a
 T1   11.46 0.667 9.66     9.26     13.7  ab
 T3   11.19 0.667 9.66     9.00     13.4  ab
 T5   11.11 0.667 9.66     8.91     13.3  ab
 T2    8.57 0.667 9.66     6.37     10.8   b
Results are averaged over the levels of: Year
Degrees-of-freedom method: kenward-roger
Confidence level used: 0.95
Conf-level adjustment: sidak method for 6 estimates
P value adjustment: tukey method for comparing a family of 6
estimates
significance level used: alpha = 0.05
NOTE: If two or more means share the same grouping symbol,
      then we cannot show them to be different.
      But we also did not show them to be the same.
Loc = Bako:
 Trt lsmean    SE   df lower.CL upper.CL .group
 T4   12.84 0.667 9.66    10.65     15.0  a
 T1   11.23 0.667 9.66     9.04     13.4  ab
 T6    9.67 0.667 9.66     7.47     11.9  ab
 T3    9.53 0.667 9.66     7.34     11.7   b
 T5    8.31 0.667 9.66     6.12     10.5   b
 T2    8.19 0.667 9.66     6.00     10.4   b
```

```
Loc = Bsftu:
 Trt lsmean    SE   df lower.CL upper.CL .group
 T4   13.57 0.667 9.66    11.37     15.8  a
 T6   12.94 0.667 9.66    10.75     15.1  a
 T1   11.46 0.667 9.66     9.26     13.7  ab
 T3   11.19 0.667 9.66     9.00     13.4  ab
 T5   11.11 0.667 9.66     8.91     13.3  ab
 T2    8.57 0.667 9.66     6.37     10.8   b
Results are averaged over the levels of: Year
Degrees-of-freedom method: kenward-roger
Confidence level used: 0.95
Conf-level adjustment: sidak method for 6 estimates
P value adjustment: tukey method for comparing a family of 6
estimates significance level used: alpha = 0.05
NOTE: If two or more means share the same grouping symbol,
      then we cannot show them to be different.
      But we also did not show them to be the same.

> lsm444<-lsmeans(model4, ~Trt|Year, adjust = "sidak")
> cld444 = cld(lsm444, Letters = "abcd", decreasing = TRUE)
> cld444
Year = 2020:
 Trt lsmean    SE   df lower.CL upper.CL .group
 T6    8.78 0.817 9.84   6.1004    11.45  a
 T5    7.87 0.817 9.84   5.1914    10.54  ab
 T4    6.82 0.817 9.84   4.1482     9.50  ab
 T3    4.04 0.817 9.84   1.3660     6.72   bc
 T1    2.59 0.817 9.84  -0.0837     5.27    c
 T2    2.20 0.817 9.84  -0.4753     4.88    c
Year = 2021:
 Trt lsmean    SE   df lower.CL upper.CL .group
 T4   17.20 0.817 9.84  14.5202    19.87  a
 T6   14.66 0.817 9.84  11.9803    17.33  ab
 T3   14.65 0.817 9.84  11.9716    17.32  ab
 T1   14.64 0.817 9.84  11.9673    17.32  ab
 T5   12.24 0.817 9.84   9.5603    14.91   b
 T2   11.38 0.817 9.84   8.7028    14.05   b
Year = 2022:
 Trt lsmean    SE   df lower.CL upper.CL .group
 T1   16.80 0.817 9.84  14.1228    19.47  a
 T4   15.59 0.817 9.84  12.9190    18.27  ab
 T3   12.40 0.817 9.84   9.7197    15.07   bc
 T2   11.56 0.817 9.84   8.8849    14.24    c
 T6   10.48 0.817 9.84   7.8050    13.16    c
 T5    9.03 0.817 9.84   6.3523    11.70    c
Results are averaged over the levels of: Loc
Degrees-of-freedom method: kenward-roger
Confidence level used: 0.95
Conf-level adjustment: sidak method for 6 estimates
P value adjustment: tukey method for comparing a family of 6
estimates significance level used: alpha = 0.05
NOTE: If two or more means share the same grouping symbol,
      then we cannot show them to be different.
      But we also did not show them to be the same.
```

```
> lsm44<-lsmeans(model4, ~Trt, adjust = "sidak")
> cld44 = cld(lsm44, Letters = "abcd", decreasing = TRUE)
> cld44
 Trt lsmean    SE   df lower.CL upper.CL .group
 T4   13.20 0.471 8.75    11.61    14.80  a
 T1   11.34 0.471 8.75     9.75    12.94  ab
 T6   11.30 0.471 8.75     9.71    12.90  ab
 T3   10.36 0.471 8.75     8.77    11.95   bc
 T5    9.71 0.471 8.75     8.12    11.30   bc
 T2    8.38 0.471 8.75     6.79     9.97    c
Results are averaged over the levels of: Loc, Year
Degrees-of-freedom method: kenward-roger
Confidence level used: 0.95
Conf-level adjustment: sidak method for 6 estimates
P value adjustment: tukey method for comparing a family of 6
estimates
significance level used: alpha = 0.05
NOTE: If two or more means share the same grouping symbol,
      then we cannot show them to be different.
      But we also did not show them to be the same.
```