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Constraints of small-scale irrigated fodder production and nutrition assessment for livestock feed, a case study in Ethiopia

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ABSTRACT

Livestock is an integral part of the agricultural system in sub-Saharan Africa, serving as a food source, income, fertilizer, and power for farming and transportation. However, the productivity of the livestock system has been hampered due to a lack of sufficient quantity and quality feed. This study evaluates the gaps and constraints of fodder and nutritional potential for livestock feed using small-scale irrigation (SSI). The study comprised of 30 randomly selected farmers from two different ecological zones in Ethiopia. Half of the farmers cultivated Napier grass (*Pennisetum purpureum*) in the Robit watershed in northern Ethiopia, and the other half cultivated mixed vetch (*Lathyrus cicera)* and oats *(Avena sativa)* in Lemo watershed in southern Ethiopia. The Soil and Water Assessment Tool (SWAT) and Agricultural Policy Environmental eXtender (APEX) were applied in an integrated manner to assess the impacts of SSI at the watershed and field-scale levels, respectively. The watershed-scale analysis showed that there is a substantial amount of surface runoff and shallow groundwater recharge that could be used for dry season fodder production using irrigation. Field data calibrated APEX model indicated that Napier yield could be maximized with 550 mm of water in Robit watershed. While in the Lemo watershed, maximum vetch and oats yield may be achieved with 250 mm of water. The major constraints for Napier and oats production in the study sites were soil fertility, especially nitrogen and phosphorus, and vetch production was limited by high temperature. Fodder samples were collected at the time of harvest to evaluate feed quality. The nutritional analysis indicated that Napier grass has a higher dry matter and ash (mineral) content compared to oats and vetch. However, vetch has higher crude protein content (18%) compared to Napier (10%) and oats (6%). Overall the study indicated that cultivating vetch provided superior performance in terms of providing quality feed and environmental services.

1. Introduction

Agriculture is the dominant economic sector in Ethiopia, contributing more than a quarter of the country's Gross Domestic Product and export earnings (Yami and Sileshi, 2001) while employing more than 80% of the workforce in Ethiopia (Diao et al., 2010; Chauvin et al., 2012). The agricultural practice is primarily a subsistence rain-fed system; however, frequent rainfall variability affects crop yields and thereby puts pressure on the agriculture-led economy. The agricultural sector is also heavily integrated with the livestock production system, which serves as a source of food, fertilizer, cash income, and farm power for plowing and transportation. The livestock systems account for about 40% of the agricultural GDP, and over 67% of the agricultural labor force (Declaration, 1996; Asresie and Zemedu, 2015). Livestock also serves as insurance in times of crop failure due to drought or dry spells (Thornton et al., 2003). Ethiopia has the largest livestock population in Africa, estimated at 60 million heads of cattle, 61 million small ruminants, 10.7 million equines, 1.2 million camels, 59.5 million poultry, and 6.2 million beehives (CSA, 2017). Some farmers living in areas that have a high potential for livestock production started cultivating

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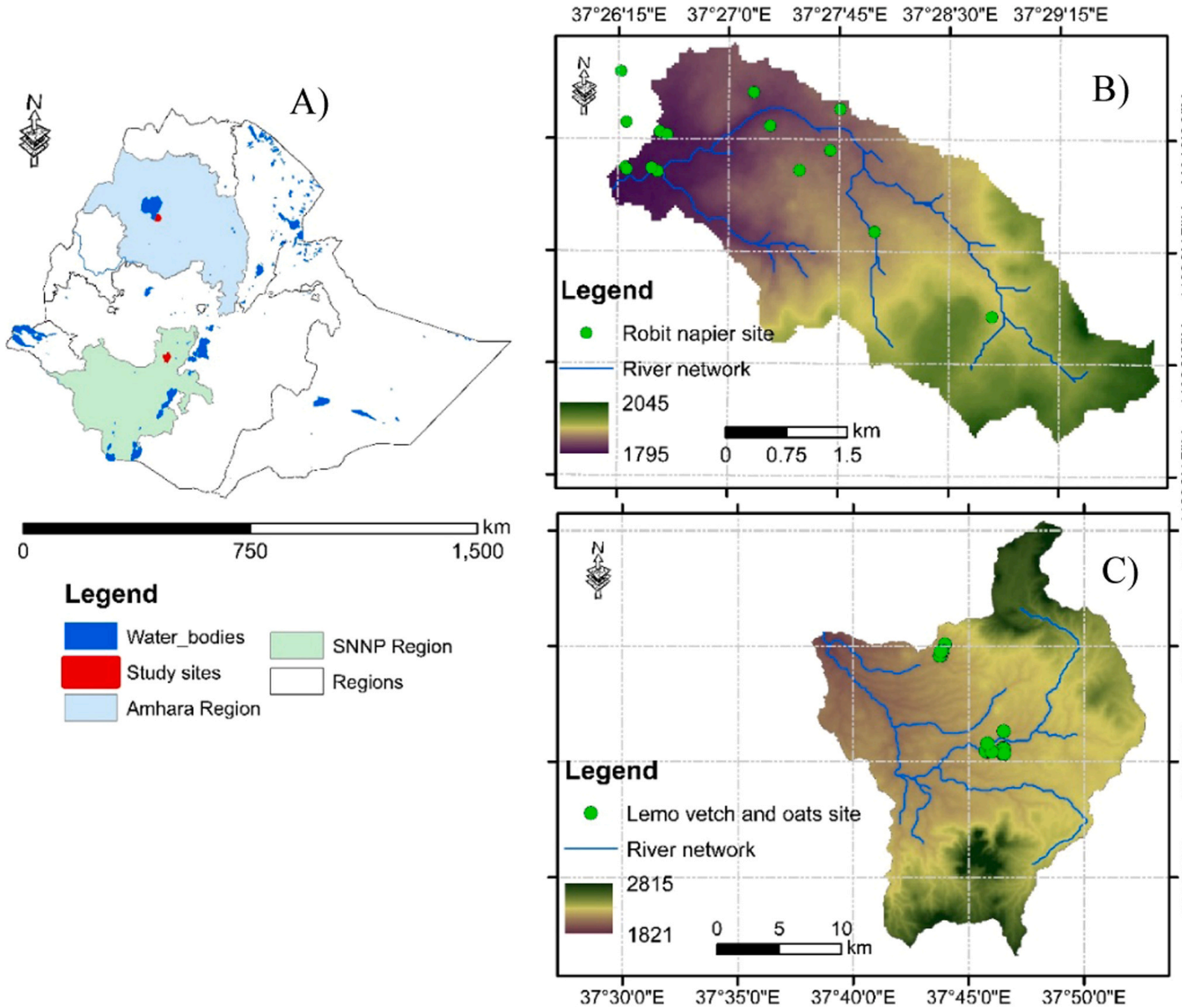

Fig. 1. Location of study sites in Ethiopia with river networks and showing experimental plots. A) Map of Ethiopia with regional boundaries, B) Robit watershed showing of the location of Napier grass growing sites and, C) Lemo watershed showing the location of oats-vetch growing sites. The background image of the watersheds is a 30 m resolution DEM.

improved pasture and forage to feed their livestock through a cut and carry system and sell in the local market in the form of green fodder and/or hay. However, the productivity of the livestock sector overall has been constrained by availability, quality, and seasonality of feed, as well as lack of access to veterinary services (Ahmed et al., 2016; Tonamo, 2016).

The major sources of livestock feed in Ethiopia are open grazing on pasture land, crop residue left over after harvest, and weeds from arable land (Mengistu, 2006; Birhan and Adugna, 2014). Open grazing from pasture land contributes the largest share (Mengistu, 2004; Amede et al., 2005; Tegegne et al., 2011; Malede and Takele, 2014). The open pasture is often exhaustively grazed and therefore stored crop biomass is consumed before the rainfall season starts. It is a common phenomenon for feed shortage to occur during the dry season, posing a major challenge for overall feed quality and quantity (Yami et al., 2013; Dejene et al., 2014).

Different species of forage grasses, legumes, and trees are used as feeds for livestock in tropical and subtropical regions. In Ethiopia, Napier grass (*Pennisetum purpureum*), vetch (*Vicia villosa*), oats *(Avena sativa)*, alfalfa (*Medicago sativa*), and desho grass (*Pennisetum glaucifolium*) are some of the most widely used fodder crops used for livestock feed due to their high yield and easy management (Orodho, 2006; Getu, 2015). Besides cattle feed, these fodder crops are widely used for soil and water conservation, fuelwood supply, and input to biogas production (Orodho, 2006; Sawasdee and Pisutpaisal, 2014; Asudi et al., 2015). Fodder crops also serve for soil and water management by covering the soil they reduce evaporation and soil erosion serving as a cover crop in steep slope areas and enhance soil fertility through their ability to fix nitrogen and contribution to organic matter (Assefa et al., 2018; Belay et al., 2019).

Availability of quality feed determines the animal's ability to produce optimally within their genetic limits (Coleman and Moore, 2003). A assessment of the nutritional quality of available fodder can help to identify potential livestock nutritional deficits that must be addressed to provide a balanced diet that helps to maintain a healthy livestock production system. Fodder quality can be assessed using fodder dry matter, crude proteins, and minerals as indicators (Moreira, 1989; Lounglawan et al., 2014). However, there are limited studies in Ethiopia that identify and review environmental factors that limit the ability to produce optimal feed and access the nutritional quality of different fodder crops.

Therefore the objective of this study is to evaluate the potentials and constraints of growing Napier and mixed cropping of vetch and oats using Small-Scale Irrigation (SSI) to produce sufficiently nutritious feed to improve the livelihoods of the smallholder farmers. The study used data collected from 30 randomly selected farmers in two watersheds located in different agro-ecological zones in Ethiopia. The study watersheds, Robit and Lemo, are located in the Amhara Region and Southern Nations and Nationalities People Region (SNNPR), respectively. Fifteen farmers in the Robit watershed cultivated Napier; the remaining fifteen farmers in the Lemo watershed cultivated mixed oats and vetch. The study integrated the Soil and Water Assessment Tool (SWAT) and Agricultural Policy Environmental eXtender (APEX) models, which are part of the Integrated Decision Support System (IDSS, Clarke et al., 2017; Worqlul et al., 2018), to evaluate the gaps and constraints of fodder production in Ethiopia. SWAT is a physically-based model developed to assess the impact of land and water management practices on water, sediment, and agricultural chemical yields (e.g., fertilizer and pesticides) in large complex watersheds with varying soils, land uses, and management conditions over long periods (SWAT, Arnold et al., 1994). Likewise, APEX is also a physically-based model which is used to evaluate detailed crop management technologies and decisions that can affect agricultural production and environmental sustainability at the scales of individual fields, whole farms, or small watersheds (APEX, Williams et al., 1998). The SWAT model was used to estimate the potential water resource at the watershed scale, while the APEX model was used to identify optimal irrigation management practices and environmental sustainability at the field level. The feed quality of the fodder produced was evaluated using established quality matrices (Williams, 1984; AOAC., 1990).

2. Methodology

2.1. Study watersheds

Robit watershed is located in the Amhara Region between 11°37′00″ N, 37°26′00″ E, and 11°42′00″ N, 37°31′00 E. Lemo watershed is located in the Southern Nations, Nationalities, and People's Region (SNNPR) between 7°20′56.40″ N, 37°37′44.39″ E and 7°46′33.59″ N, 37°53′45.60″ E (Fig. 1). The catchment area for the Robit and Lemo watersheds are approximately 15 km^2 and 482 km^2, respectively. The elevation at Robit watershed varies between 1795 m and 2045 m, while the elevation of Lemo watershed ranges between 1821 m and 2815 m. The major types of livestock raised in these watersheds and the surrounding area are cattle, goats, sheep, donkeys, and mules. The main livestock outputs include meat, milk, and manure. Some of the livestock provide labor for plowing and transportation.

2.2. Experiment design

The field data were collected from 30 randomly selected experimental sites. The experimental sites were selected randomly, and on average, they are ~2 km and 3 km apart in Robit and Lemo watersheds, respectively. The data collected included planting dates, irrigation and fertilizer application dates and amounts, soil moisture content, crop height, and yields. Soil samples were collected for two layers of the top 60 cm, which were analyzed to determine soil physical and chemical properties such as texture, field capacity, available organic matter, pH, total nitrogen, available phosphorus, and electric conductivity. Napier biomass was harvested two times throughout the growing period. The first harvest was 110 days from the planting and the second harvest was after 30-days from the first harvest followed by a permanent killing to prepare the land for rainfed maize production. The fodder height was measured throughout the growing period, such as at the initial, crop development, and maturity growth stages.

2.2.1. Robit Napier sites

Napier grass is a tall perennial grass that grows at an altitude ranging from 1500 to 2500 m (Ecocrop, 2000). Well-managed Napier grass produces a substantial amount of good quality feed and feedstock for biogas production (Sawasdee and Pisutpaisal, 2014). Although Napier grass thrives in high rainfall areas, it is also considered a drought-tolerant crop (Orodho, 2006; Mwendia et al., 2017). The optimal temperature for Napier grass growth ranges between 21 and 40 °C (Ecocrop, 2000).

Table 1
Land management practices for the Napier and mix of oats and vetch fields in the Robit and Lemo watersheds, respectively.

Operation	Napier	Vetch and oats
Planting	March 4–13	January 10–January 21
Urea (46–0–0) (200–400 kg/ha)	April 23–25	–
DAP (46–18–0) (50 kg/ha)	–	January 19–January 23
Harvesting date	July 07–28	April 05–May 19

The field data were collected from 15 farmsteads cultivating Napier grass using irrigation during the dry season (March to July). The source of water for irrigation was shallow groundwater from wells having depths between 6.5 and 17.2 m. The farming plots' size ranges from 50 to 140 m^2. Of the 15 sites, only data from six sites were used for this study. The data quality from nine sites were found poor to use for the analysis since the grass in the plots was lost after planting due to lack of proper management and/or grazing by animals. Table 1 shows a summary of the management practices in the six selected Napier sites.

2.2.2. Lemo vetch and oats sites

Commonly, oats and vetch are cultivated together to increase feed value and enhance soil fertility (Assefa and Ledin, 2001; Lithourgidis et al., 2006). Oat is a cereal crop that can be cultivated for grain and forage (Stevens et al., 2004). The optimal temperature for oat ranges from 16 to 20 °C (Ecocrop, 2000). Vetch is an annual legume cover crop used for haymaking; the optimal growing temperature ranges from 11 to 23 °C (Ecocrop, 2000). It grows taller when planted mixed with crops that offer structural support. Vetch has a taproot that can reach depths up to 1.5 m (Sattell et al., 1998).

Field data were collected from 15 sites in the Lemo watershed. Each site has an area of 50 m^2, growing mix of vetch and oats at a planting ratio of 3 vetches to 1 oat. Farmers used irrigation water from groundwater wells which have depths between 5.5 and 12 m. A summary of the land management practices for vetch and oats cultivation in the Lemo watershed is presented in Table 1. The biomass was harvested once at the end of the growing season.

2.3. Rainfall distribution in the fodder cultivation sites

Daily rainfall data from weather stations close to the watersheds were used to identify rainfall contribution to fodder crop water requirment during the cultivation season. The rainfall analysis was done based on the available data for the period 1994–2015. The long-term average monthly rainfall, the number of raining days, and the fodder growing period (March to mid-July) in Robit and Lemo watersheds, which were used to inform irrigation, are presented in Fig. 2a and b. For the studied period, the annual rainfall for Robit watershed varies between 1100 and 1900 mm. The total daily rainfall in the Robit site during the Napier cultivation period was ~400 mm (with a standard deviation of 75 mm). The majority of the rainfall occurred at the end of the cultivation period.

In Lemo watershed, the annual rainfall varies between 900 and 1500 mm. From March to June, the area receives rainfall for more than ten days, and from July to September, the rainy days exceed 15 days. The total rainfall amount during the vetch and oats growing period was ~320 mm with a standard deviation of 90 mm. Although the rainfall amount in both sites had a significant contribution to the total fodder crop water requirement in the dry season, it was not sufficient to meet the total crop water requirement for optimal fodder production, which indicated a need for supplemental irrigation.

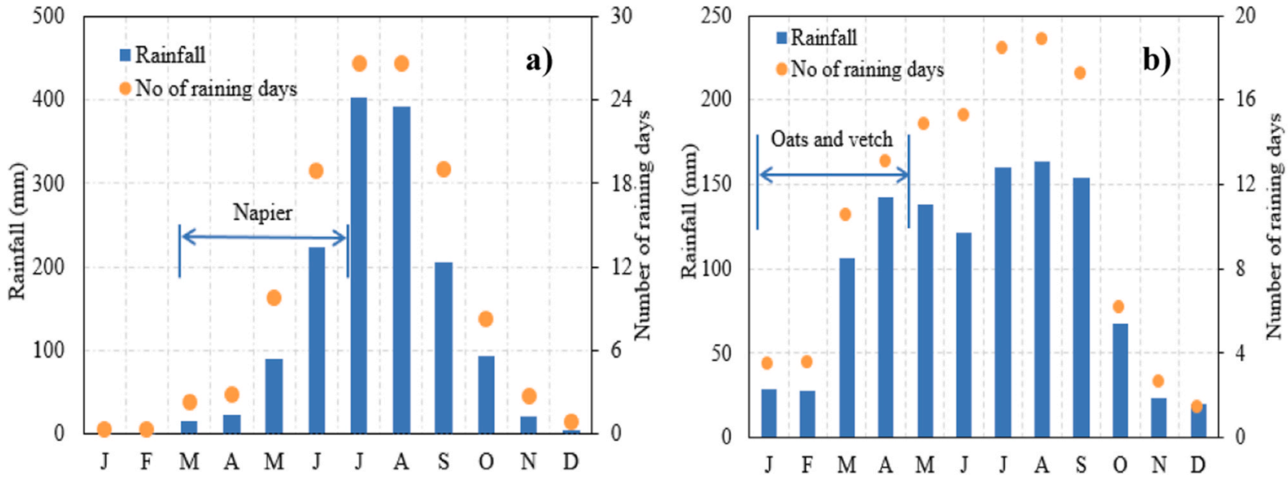

Fig. 2. Long-term monthly rainfall and number of raining days of the study sites (1994–2015). a) Robit watershed and b) Lemo watershed.

Table 2
SWAT and APEX model streamflow related calibration parameters, their description, and parameter calibration space.

	Parameter	Description	Parameter space
SWAT	r_CN2.mgt	SCS runoff curve number	−0.25–0.25
	v_ESCO.hru	Soil evaporation compensation factor	0.01–1.0
	v_ALPHA_BF.gw	Baseflow alpha factor (days)	0.00–1.0
	v_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0.0–5000
	v_GW_REVAP.gw	Groundwater "revap" coefficient	0.02–0.2
	r_SOL_AWC ().sol	Available water capacity of the soil layer	−0.25–0.25
	v_REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	−0.50–0.5
	v_CH_K2.sub	Effective hydraulic conductivity in main channel	0.01–0.3
APEX	v_PARM20	Runoff curve number initial abstraction	0.05–0.4
	v_PARM42	SCS curve number retention parameter	0.30–2.5
	v_PARM12	Soil evaporation coefficient	1.50–2.5
		Return Flow / (Return Flow + Deep Percolation)	0.05–0.98
		Groundwater residence time in days	0.00–50

Note: The parameter calibration for SWAT and APEX models were constructed based on "v_" and "r_" meaning a replacement and a relative change to the initial parameter value, respectively.

2.4. Modeling approaches

The study used the Soil and Water Assessment Tool (SWAT) and Agricultural Policy/Environmental eXtender (APEX) models to assess the gaps and constraints of fodder production. The SWAT model is a basin-scale distributed hydrological model. In SWAT, a watershed is divided into multiple sub-watersheds which may have multiple hydrologic response units (HRUs). HRUs are unique combinations of land use, soil, and slope. Most of the biophysical processes such as soil water content, surface runoff, sediment yield, and crop growth are simulated at the HRU level and then aggregated to each subbasin. The APEX model is a field or small watershed scale model in which a sub-watershed is assumed to have a single HRU, called *subarea*. The model can simulate detailed field conditions, including crop management and growth, nutrient and pesticide fate, hydrology, soil temperature, erosion-sedimentation, and costs and returns of the various management practices (Saleh and Gallego, 2007; Wang et al., 2011).

Although SWAT and APEX models operate at a different spatial scale and apply for different applications, they share several attributes. For example, they both require similar input data and most of their biophysical equations are similar (Arnold et al., 1994; Gassman et al., 1998; Williams et al., 1998). Spatial data used by both models include DEM, soil, and land use. The DEM was used to characterize the watershed physical characteristics such as slope, subbasin/subarea areas, longest flow path length, etc. For the SWAT model, land use and soil data were collected from the Ethiopian Ministry of Water, Irrigation, and Energy (EMWIE). The soil data contains the physical and chemical properties of the soils in the watersheds. Since the APEX model was set up at the field level, soil and land use information were collected at the field sites.

2.4.1. Model calibrations and evaluations

Streamflow calibration parameters for both SWAT and APEX were identified from the literature (Bitew and Gebremichael, 2010; Mengistu and Sorteberg, 2012; Worqlul et al., 2019). Table 2 presents the list of parameters selected and their respective parameter space. The SWAT model parameters were calibrated using the Sequential Uncertainty Fitting (SUFI-2) algorithm in the SWAT Calibration Uncertainty Procedures (SWAT-CUP) tool (Abbaspour et al., 2007). The model calibration period was from1995 to 2010 for Gumara and 2000 to 2010 for Bidru Awana watersheds and the model was validated for the period 2011–2016 and 2010–2015, respectively. The calibration of the APEX model was conducted using APEX-CUTE (auto-Calibration and Uncer-Tainty Estimator) (Wang et al., 2014). The fodder yield calibration was based on one-year multiple site field observations. Observed Napier yield was available for 2015, and vetch and oats yield were available for 2016.

Because of observed streamflow data limitation, the SWAT model in both watersheds was calibrated and validated using data from nearby watersheds. Robit watershed had daily streamflow observation since June 22, 2015; while there was no streamflow observation for the Lemo watershed. The selected nearby gauged watersheds have similar watershed characteristics as the study watersheds, which enabled reasonable model parameter transfers (Kokkonen et al., 2003; Booij et al., 2007; Wale et al., 2009). The watersheds selected to represent the Robit and Lemo watersheds were the Gumera and Bidru Awana watersheds, respectively. The transferred parameters for the Robit watershed were further fine-tuned using the available observed streamflow data at its outlet. The SWAT model, thereafter, was used to estimate the spatial and temporal distribution of available surface runoff and shallow groundwater recharge across the watersheds.

The APEX model was set up for the field plots where there were land management and fodder yield data for model setup and calibration. The

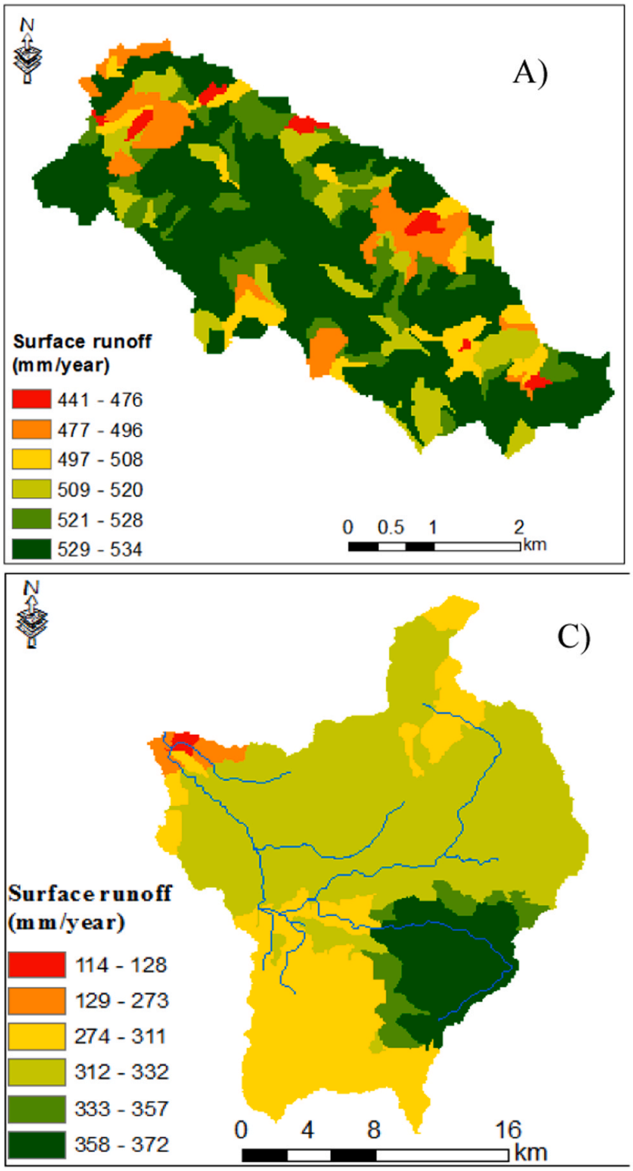

Fig. 3. Water resource potential of Robit and Lemo watershed (mm/year); (A) average annual surface runoff of Robit watershed and (B) shallow groundwater recharge of Robit watershed, (C) average annual surface runoff of Lemo watershed and (D) shallow groundwater recharge of Lemo watershed.

APEX model crop parameters were calibrated to capture the observed fodder height and yield. After calibrating the model for observed crop yield and height, the model was used to understand the constraints and gaps of fodder production in the watersheds. The calibrated model was also used to estimate the water and fertilizer production of the study fodder crops.

Fodder yield samples were collected from the fields for fodder nutritional quality analysis. A total of 70 samples of Napier and 22 samples for oat and vetch were collected for nutritional quality analysis. The nutrient indicators analyzed included percent of dry matter, ash, organic matter, nitrogen, crude protein, natural detergent fiber, acid detergent fiber, acid detergent lignin percent on dry matter, and metabolizable energy.

The performance of the daily simulated streamflow, soil loss, crop height, and yield were evaluated using multiple statistics such as coefficient of determination (R-Squared), root mean square error (RMSE), percent bias (PBIAS), and Nash-Sutcliff Efficiency (NSE). Generally, R-squared values can range between zero and one, where zero indicates no correlation and one represents perfect association between simulated and observed variables. RMSE refers to the standard deviation of the prediction error. PBIAS calculates the relative volume difference between simulated and observed volume. A negative value indicates over-prediction, and a positive value indicates under-prediction of simulation. NSE is the normalized statistic that describes the relative magnitude of residual variance compared to the observed variable variance. NSE values can range between negative infinite and one. An NSE value of one indicates a perfect fit between the simulated and observed variable, and negative NSE values mean that use of an average of observed variable is better than the simulated variable. According to Moriasi et al. (2007), the model performance is assumed "very good" if R-square is >0.5, NSE is >0.75 and PBIAS is $\leq 10\%$.

2.4.2. Water and fertilizer use efficiency of fodder crops

The calibrated APEX model was used to study the water and fertilizer use efficiency of fodder crops in both sites. Water use efficiency was determined by simulating the model multiple times by varying irrigation amounts at two-day irrigation intervals paired with sufficient nutrients. This approach helps to disentangle the impacts of different irrigation amount levels on crop yield while avoiding other limiting conditions like nutrient stress. The nutrient limitation was avoided by automatically

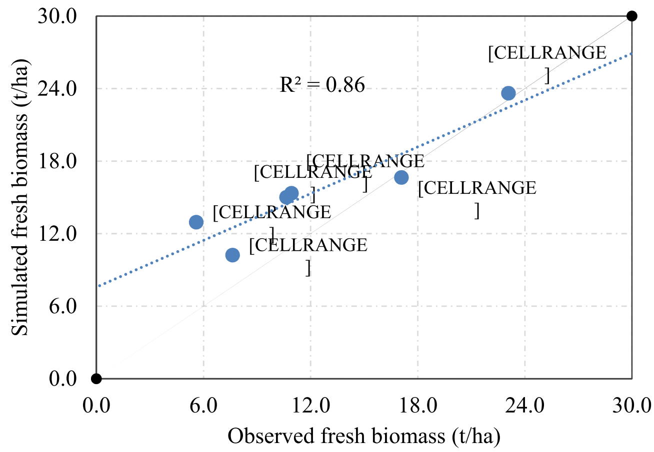

Fig. 4. Comparison of simulated vs. observed yield of Napier in Robit sites. The labels across the point represent the plot identification number.

applying DAP (diammonium phosphate) fertilizer for vetch and oats, and a combination of urea and DAP fertilizers for Napier. Urea fertilizer consists mainly of nitrogen with N-P-K (nitrogen-phosphorus-potassium) ratio of 46–0–0, while the DAP fertilizer is a source of P and N with N–P–K ratio of 18–46–0. The scenarios of water productivity analysis were achieved by applying water between 100 and 850 mm over the growing period. The amount of water per irrigation event was calculated based on the number of growing days from planting to harvest and irrigation intervals. For example, Napier grass was set at a two-day irrigation interval with a per-event irrigation amount of 4.1 mm, for a total of 250 mm irrigation for a growing period of 122 days.

2.4.3. Fodder nutritional quality analysis

The nutritional quality of collected fodder samples was analyzed at the Animal Nutrition Laboratory of the International Livestock Research Institute (ILRI) in Addis Ababa, Ethiopia. The samples were dried at 65 °C for 48 h in a forced draft oven and then ground to pass through 1 mm mesh sieve. Near-infrared reflectance spectroscopy (NIRS) prediction was employed for the analysis using equations calibrated and validated for each fodder type with data obtained from standard wet chemistry analysis (Williams, 1984; AOAC., 1990). The NIRS instrument used was a FOSS Forage Analyzer 5000 with software package WinISI II. Analyzed quality variables were dry matter, ash, crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), and in vitro organic matter digestibility (IVOMD) and metabolizable energy (ME).

3. Results and discussion

3.1. Water resources potential of Robit and Lemo watersheds

The performance of the SWAT models for the Gumara and Bidru Awana watersheds were acceptable with NSE of 0.83 and 0.60 and PBIAS of 5.4% and 8.5% during the calibration period, respectively. The models' performance was also validated with an independent period of data and provided NSE of 0.84 and 0.55 and PBIAS of 15.3% and 10.6% for Gumara and Awana watersheds. The SWAT calibrated parameters with Gumera and Bidru Awana watersheds were used to estimate the surface and groundwater recharge at Robit and Lemo watersheds, respectively, which is presented in Fig. 3.

The average annual surface runoff of Robit watershed was between 440 and 535 mm, and the average annual groundwater ranges between 250 and 320 mm (Fig. 3a and b). While in the Lemo watershed, the average annual surface runoff ranged between 115 and 370 mm (Fig. 3c), and the average annual groundwater recharge varied between 80 and 400 mm (Fig. 3d). The analysis showed that when the available

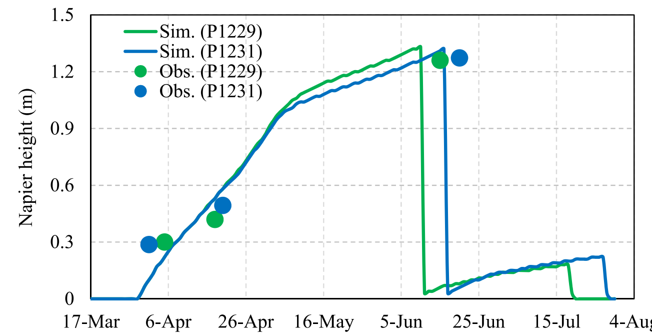

Fig. 5. Simulated versus observed Napper height of plot P1231 and P1229. The plots numbers are shown in Fig. 1.

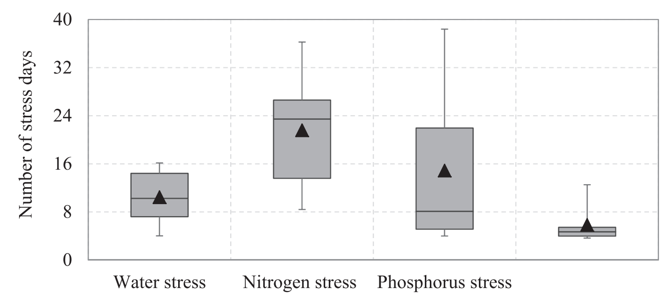

Fig. 6. Boxplot of Napier yield-limiting factor averaged for six sites for the period 1995–2015. The rectangle box represents the first and third quartile; the median is represented by a segment inside the rectangle, and the whiskers above and below represent minimum and maximum. The triangle represents the average number of stress days.

water resources are used for SSI in combination with the rainfall in the dry season, both watersheds can produce sufficient amount of fodder.

3.2. APEX fodder yield simulation and yield-limiting factors

3.2.1. Napier yield simulation and yield-limiting factors

The field data indicated a strong linear relationship between Napier yield and the amount of water applied; the water applied captured 77% of the yield variability (R-Square = 0.77), while the fertilizer applied (urea) captured 66% of the yield variability. The APEX model was set up and calibrated at six Napier sites using the observed fodder yield data. The model simulated well the observed fodder yield with 0.86 coefficient of determination, and 0.6 t/ha root mean square error (Fig. 4).

The performance of the APEX model simulated crop height was also validated using the observed fodder height (Fig. 5). The simulated fodder height captured the observed average fodder height reasonably well with R-square of 0.95. Fig. 5 showed that the observed fodder height (in dots) and the daily simulated daily Napier height (line graphs) showing the model performed well in capturing the observed fodder height.

The calibrated APEX model was further used to understand the major yield-limiting factors. Fig. 6 presents the major yield-limiting factors in the six simulated sites. The simulation results indicated that nitrogen and phosphorus were the major yield-limiting factors, followed by water and temperature stress. Due to its fast growth and higher yield, Napier requires a regular application of nutrients (N and P). Recommend annual nitrogen and phosphorous application rates vary from 200 to 460 kg/ha and 50 to 100 kg/ha, respectively; it varies based on soil type and fertility (Orodho, 2006; Pontes et al., 2016; Yang et al., 2016). In the Robit site, Napier was cultivated with nitrogen fertilizer application rates of between 92 and 184 kg/ha and without phosphorus based on local recommendations. This caused Napier yield limitation due to nitrogen and phosphorous absence by an average of 23 and 15 stress days, respectively (Fig. 5). Actual daily growth of plant in the APEX model is

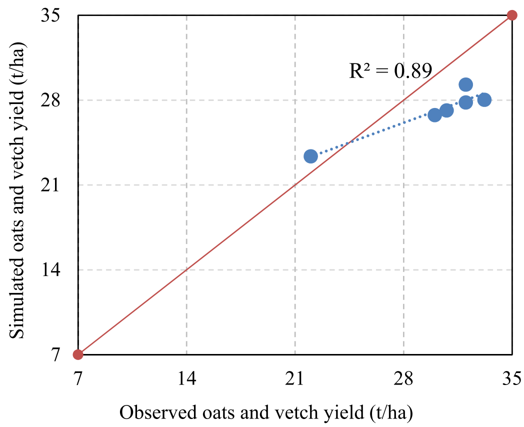

Fig. 7. Comparison of simulated and observed oats and vetch yield (2016).

constrained by nutrient, water and temperature stresses. The number of stress days were estimated counting the number (fraction) of days in which the available soil nutrients, water and/or temperature was outside the demand for optimal crop growth. For example, the number of nitrogen stress days is counted as 0.1 days if the available root zone soil nitrogen meets 90% of the crop nitrogen requirement for optimal growth.

3.2.2. Oats and vetch simulation and yield-limiting factors

The amount of water applied throughout the growing season of oats and vetch as a mixed crop varies between 100 and 140 mm. The calibrated APEX model based on the six selected sites captured the observed yield very well with an average difference of 13% for oats and 6% for vetch (Fig. 7). The model performance was also validated using the observed fodder height. The result indicated an acceptable performance with an R-square of 0.89. Fig. 8 presented the number of stress days that the yield of both oats and vetch was limited by water, nitrogen, phosphorus, and temperature. The result showed that oats yield was limited by nitrogen and water while vetch yield was limited by water and temperature. Simulations showed that oats and vetch yield can be optimized by adding more nitrogen fertilizer and water as well as by increasing the vetch proportion in the planting mix. Increasing the vetch proportion contributed to soil fertility since it has the ability to fix nitrogen. This assertion was, in fact, validated using the calibrated APEX model. The model was applied to simulate oat yield as a single crop to understand the effect of vetch on the cropping mix. The singly cultivated oat was simulated with a similar amount of fertilizer and irrigation amounts as the mixed cropped oats and vetch simulation. The result showed a significant oat yield reduction when planted as a single crop compared to the mixed cultivation. The reduction in yield ranged from 17% to 43% depending on the site. The reduction in yield was mainly related to nitrogen stress. The vetch increased the soil nitrogen by symbiotically fixing atmospheric nitrogen through nitrogen-fixing bacteria; the simulation indicated that vetch can contribute soil nitrogen up to 30 kg/ha. Some studies reported that vetch can contribute more than 100 kg of nitrogen per hectare in a single growing period (Ku et al., 2018).

3.3. Water and fertilizer use efficiency of fodder crops

The calibrated APEX model was further used to estimate the water use efficiency of Napier and oats and vetch mix. Since the study focused on assessing the optimal water use efficiency level, the model was supplied unlimited urea and DAP fertilizer rates to meet crop nitrogen and phosphorus requirement.

3.3.1. Water and fertilizer use efficiency of Napier

The simulated Napier yield and average number of water stress days over 21 years are shown in Fig. 9. The result showed that when 100 mm of water was applied, the fertilizer uptake of Napier grass was very low, and yield was limited by water stress. For 100 mm of water application, the amount of nitrogen and phosphorous uptake was 81 kg/ha and 21 kg/ha, respectively. As the amount of water applied increases, the water stress level reduced, and the fertilizer requirement increased due to an increase in plant nutrient uptake and nutrient losses through

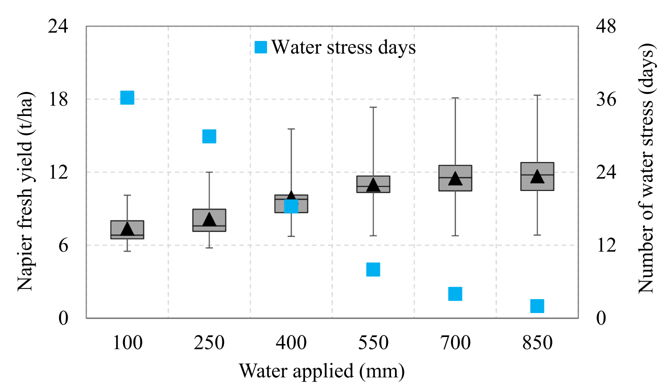

Fig. 9. Boxplot of singly cultivated Napier simulated yield with different amount of irrigation at two days irrigation interval for the period 1995–2015. Unlimited urea and DAP fertilizers were applied to avoid nutrient stress. The rectangle box represents the first and third quartile; the median is represented by a segment inside the rectangle, and the whiskers above and below represent minimum and maximum.

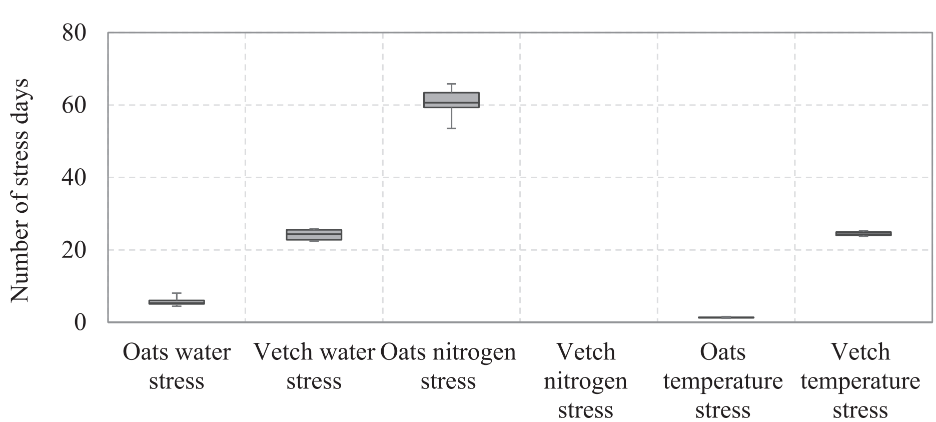

Fig. 8. Boxplot of vetch and oats major yield-limiting factors averaged for six sites (1995–2016). The rectangle box represents the first and third quartile, the median is represented by a segment inside the rectangle, and whiskers above and below represent minimum and maximum.

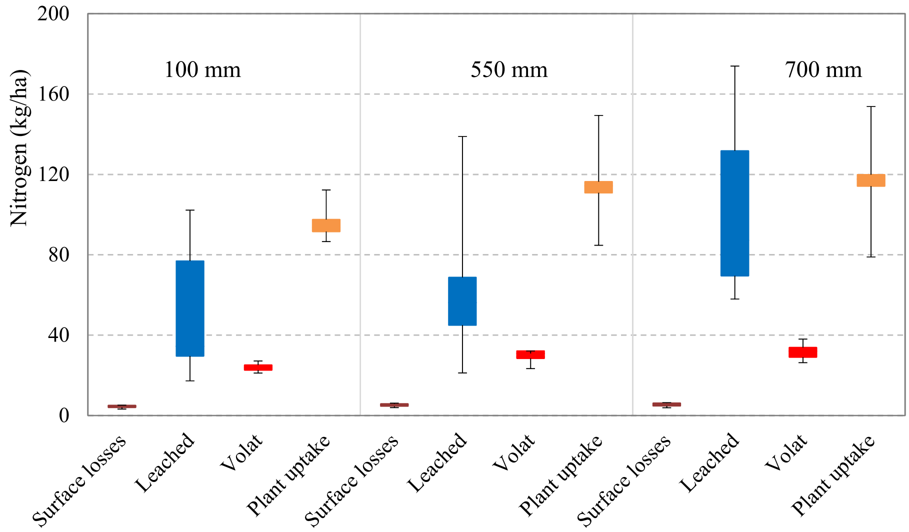

Fig. 10. Simulated nutrient components of irrigation scenarios simulated with 100, 550, and 700 mm of water.

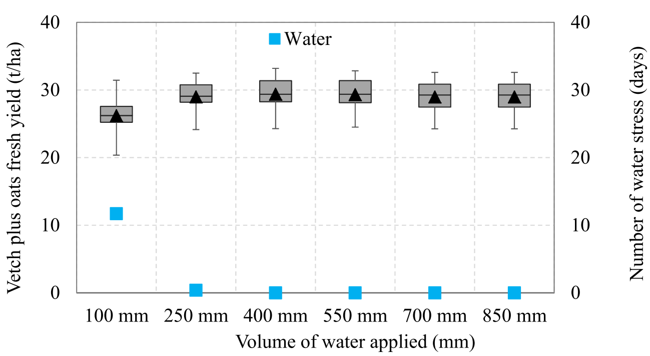

Fig. 11. Boxplot of simulated vetch and oats yield with different amount of irrigation at two days irrigation interval (1995–2015). Unlimited DAP was applied to avoid nutrient stress and estimate optimal water and nutrient requirement. The rectangle box represents the first and third quartile; the median is represented by a segment inside the rectangle, and the whiskers above and below represent minimum and maximum.

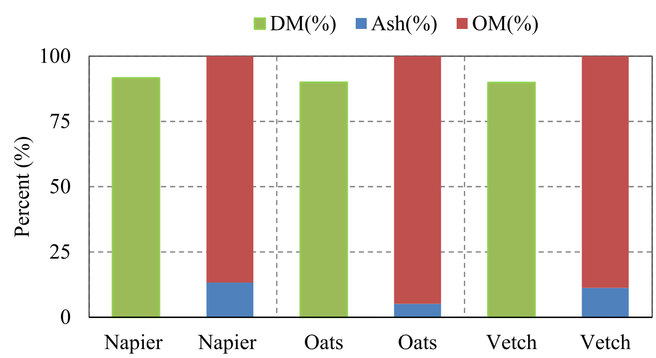

Fig. 12. Percentage of dry matter (DM, the fraction of dry and fresh weight of fodder), organic matter (OM), and Ash for Napier, vetch, and oats.

surface runoff and deep percolation. Maximum Napier yield was obtained when 550 mm of water and 145 kg/ha of nitrogen, and 25 kg/ha phosphorus were applied. After that, any increase in the amount of irrigation and fertilizer did not improve the yield.

The nitrogen components (i.e.,. plant nitrogen uptake (kg/ha), soluble nitrogen lost in surface runoff (kg/ha), leached nitrogen, and nitrogen loss in the form of volatilization and denitrification (kg/ha)) for the different amount of irrigation application were estimated and presented in Fig. 10. The nitrogen uptake of Napier grass increased until 550 mm of irrigation, and thereafter it did not change significantly. However, as the amount of water applied increases, the nitrogen loss through percolation increased significantly, while a minor increase was observed in volatilization and denitrification (Fig. 9). The simulation indicated very little phosphorous loss in the soil since phosphorous is less soluble compared to nitrogen. However, over-application of phosphorous could lead to a build-up of phosphorus in the soil.

3.3.2. *Water and fertilizer use efficiency of vetch and oats*

Similar to the simulations for Napier in the Robit watershed, simulations for the vetch and oats showed that nutrient uptake increased with increased irrigation up to a limited extent. The result indicated that when 100 mm of water is applied, the fertilizer requirement of vetch and oats was very low, and the yield was limited by water. For 100 mm of irrigation, the phosphorous uptake was 52 kg/ha. As the amount of irrigation applied increases to 250 mm and above, the water stress reduced significantly, and the fertilizer requirement did not change much. Maximum simulated vetch and oats yield was obtained at 250 mm of irrigation, and phosphorus uptake was 52 kg/ha (Fig. 11). Irrigation beyond 250 mm did not significantly increase the phosphorus uptake as well as the yield. Fig. 10 presents the simulated vetch and oats yield, and the number of water stress days for six scenarios of irrigation over a simulation period of 21 years (1995–2015).

3.4. *Nutritional value of Napier, vetch, and oats*

The feed nutrition analysis indicated that DM (fraction of dry and fresh weight) content of Napier was slightly higher than vetch, and oats (Fig. 12). Napier DM is approximately 2% higher than oats and vetch. However, there was no significant difference in DM between vetch and oats. DM of the feed contains energy, protein, fiber, vitamins, and minerals. The analysis also indicated a higher proportion of Ash (mineral) in Napier (13%), followed by vetch and oats (11% and 5%, respectively). These results were similar to those previously reported by Galyean (1989). Vetch has the highest crude protein content (18%) compared to Napier (10%) and oats (6%). CP is considered as a good determinant of feed quality.

The detergent fiber component (NDF, ADF, and ADL) estimated for the fodder crops is shown in Fig. 12. NDF is a good measure of feed quality and plant maturity. Higher NDF in the feed decreases intake and increases chewing activity. The NDF content was higher in oats and

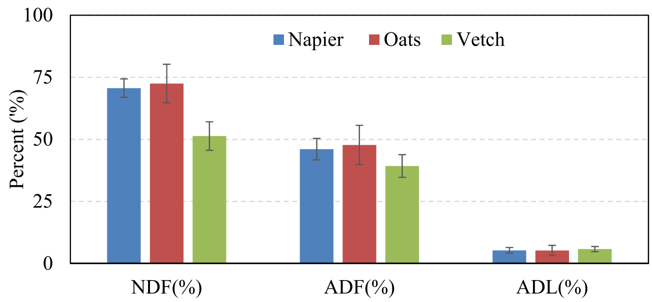

Fig. 13. The detergent fiber (NDF, ADF, and ADL) component of Napier, vetch, and oats. The error bars represent the standard deviation of the observed variable. NDF, ADF and ADL represent neutral detergent fiber, acid detergent fiber, and acid detergent lignin, respectively.

Napier compared to vetch (Fig. 13), which is consistent with the findings of Fulkerson et al. (2007) and Ergon et al. (2016). The average ADF (lignin and cellulose) component was lower in vetch at 39% compared to Napier (46%) and oats (47%). ADF is a subset of the NDF, which contains the poorly digestible (insoluble in a weak acid) cell wall components (lignin and cellulose) (Van Saun, 2006). The ADL component between the three fodders was similar at 5% (Fig. 13). Vetch contained 11 MJ/kg DM metabolizable energy, a higher energy content than oats and Napier, which is at 7 and 8 MJ/kg, respectively. Overall, the feed quality analysis indicated a superior performance of vetch in terms of digestibility and feed quality.

4. Conclusion

Integrating field data with two biophysical models (APEX and SWAT), this study explored the opportunities, gaps, and constraints of fodder production in two different agro-ecological zones in Ethiopia. The study also examined the nutrition components of the cultivated fodder to identify fodder types that provides balanced diet to livestock. The findings showed that there is a substantial amount of water resources in both watersheds to produce fodder production using small-scale irrigation. The modeling results showed that the average optimal amount of water required to cultivate Napier and a mix of oats and vetches is ~550 and 250 mm, respectively. The application of irrigation beyond the optimal amount for the respective fodder crops increased surface runoff and percolation that cause nutrient losses. Moreover, the study indicated that poor soil fertility limited optimal fodder production in both watersheds. For example, phosphorous was one of the major yield-limiting factors for vetch production, although nitrogen was not a limiting factor as vetch is a legume crop. The fodder nutrition assessment indicated that Napier has a higher dry matter content compared to oats and vetch. Napier also has a higher mineral content, while vetch contains the most crude protein and energy content. Overall, vetch provides a superior nutrition performance as a livestock feed. Besides providing high biomass, dry matter content, crude protein, and energy for livestock, fodder crops such as vetch provided other environmental services. For example, vetch crop can symbiotically fix atmospheric N through nitrogen-fixing bacteria and thereby improve soil fertility. This study concludes that fodder production using small-scale irrigation can help to produce high quality fodder (like vetch) that could improve Ethiopia's livestock sector and its contribution to the country's economy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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