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Enhancing farming system water productivity through alternative land use and water management in vertisol areas of Ethiopian Blue Nile Basin (Abay)

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ABSTRACT

Until recently, the Ethiopian government's investment did not systematically target high potential areas for agricultural intensification, limiting the potential productivity gains. Waterlogged vertisols, which cover about 2.7 million hectares in the Ethiopian part of the Blue Nile Basin, are among the high potential soils where management interventions could result in positive impacts. This study utilized soil, climate, crop and livestock productivity data and models to demonstrate intensification strategies which can increase crop-livestock system productivity. To understand the effects of alternative land use and water management interventions on water productivity, the areas have been classified into three drainage status depending on slope classes. Accordingly, non-drainable (0–2%), drainable (2–5%) and naturally drained (>5%) respectively, represented areas where artificial drainage is not feasible, where drainage using broad bed and furrows (BBF) is recommended, and areas where waterlogging is not a problem and no intervention is needed. Early planting of wheat (*Triticum* spp.) on BBF instead of the traditional late planting on flat beds in drainable areas and rice (*Oryza sativa*) cultivation instead of the traditional extensive grazing or growing grass-pea (*Lathyrus sativus*) on the flat areas provide viable alternative cropping options. Yield data of the crops and biomass of the native grass were obtained from research stations in the area while the effective rainfall and crop water requirement were estimated using CROPWAT Model. The value of the native grass and crop straw as livestock feed was estimated based on previous works. With respect to effective rainfall, the water productivity increase due to BBF over the control ranged from 5% to 200%, with an average increase of 57%. Despite higher water consumption of rice, feeding its residues to livestock enhanced the overall economic water productivity of the system as compared to the natural grazing or grass-pea cultivation. This can be accounted for by higher rice biomass productivity and the greater demand for its grain. The study demonstrated that draining the excess water when the slope allows, growing suitable high value crops on non-drainable areas, and integration of livestock into improved land and water management enhance overall agricultural system water productivity.

1. Introduction

The Ethiopian part of the Blue Nile Basin, locally known as *Abay*, covers about two thirds of the country's landmass and contributes nearly 40% of its agricultural products and 45% of its surface water. The mean annual rainfall ranges from 800 to 2200 mm in the north-eastern and southwestern parts respectively, making it favorable for rainfed agriculture. However, rainfed agricultural productivity remains low (Erkossa et al., 2009), mainly due to management rather than physical limitation (Benites et al., 1998). Traditionally, extensification was the major response to increased demand for food and feed. However, the availability of 'new' land suitable for cultivation is limited (Erkossa et al., 2011). The predominant low capital investment and limited technical capacity also imply that a wide-ranging transformation of traditional small scale rainfed agriculture to irrigated agriculture is unlikely to occur soon. Rainfed agriculture will remain the major source of livelihood in the foreseeable future. Therefore, increased food and feed production and rural livelihood enhancement must come from sustainable intensification of existing rainfed crop and livestock production system.

Intensification of the rainfed system requires the generation and adoption of integrated land, water, crop and livestock management alternatives. However, the extreme biophysical variations such as soil and climate of the basin pose daunting challenges to

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widespread adoption of technologies that were tested under specific conditions. The waterlogged vertisols that cover about 2.7 million hectares in the Abay Basin are among the high potential sites where intensification can significantly improve productivity as well as agricultural system resilience to shocks (Erkossa et al., 2009). One major impediment to intensification in the area is the hydrological properties of the soils, manifested by their slow internal drainage, with infiltration rates between 2.5 and 6.0 cm day^{-1} (Erkossa et al., 2004). According to Debele (1985), the Ethiopian vertisols occur on landscapes with a general slope ranging from 0 to 8%, but the majority have a 0–2% slope range, which restricts surface drainage and leads to seasonal inundation.

The traditional response to these drainage related problems includes planting of local cultivars with low productivity at the end of the rainy season after the major part of the water has evaporated, or leaving the land for native pasture to establish. This is common in the low lying areas which represent valuable grazing during the dry season. Empirical evidence suggests that the traditional management significantly reduces the length of the effective growing period, maximizes evaporation loss, exposes crops to terminal moisture stress and thus reduces water productivity of crops (Erkossa et al., 2011).

Studies conducted in various agro-ecologies in Ethiopia and India have shown that surface drainage of vertisols allows early sowing, enabling the utilization of the potentially available growing period (El-Swaify et al., 1985; Astatke and Kelemu, 1993) while suppressing evaporative losses (Erkossa et al., 2011). Broad bed and furrows (BBF) made by the Broad Bed Maker (BBM) developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India (El-Swaify et al., 1985), have been modified to fit the smallholder systems in the Ethiopian Highlands and are now widely adopted (Astatke et al., 1995; Erkossa et al., 2011; Haque et al., 1996; Muhamed-Saleem and Astatke, 1996). However, application of the BBF is limited to areas having slope of 2–5% as it requires a slope steep enough for drainage while avoiding erosion. Most vertisol areas in the Abay Basin occur on slopes of less than 2% necessitating the use of other options such as high yielding waterlogging tolerant crops. Depending on the growing season temperature, rice (*Oryza sativa*), tef (*Eragrostis tef*) and forage crops can be grown in these areas. Several authors argue that rice is one of the best and cheapest ways of using the flooded and waterlogged soils by small-scale farmers in Ethiopia (e.g. Seyoum et al., 2011; Tadesse et al., 2013). Currently, rice cultivation is expanding into the Fogera, Metema, and Pawe plains, areas which are known for their extensive vertisols coverage (Gebrekidan and Seyoum, 2006). The replacement of extensive grazing with crops such as rice may provide grain for food and crop residues for animal feed, thereby increasing system water productivity.

Crop water productivity (CWP) is a measure of beneficial output of a crop or cropping system in relation to the water actually consumed (ETa) (Eq. (1)) or delivered (effective rainfall for rainfed system (eff)) (Eq. (2)) (Rockström and Barron, 2007):

$$\mathrm{CWP}_{\mathrm{ETa}} = \frac{Y(\mathrm{kg}, \$)}{\mathrm{ETa}} \tag{1}$$

in which CWP stands for crop water productivity, *Y* for grain yield in kg or its value (USD) and ETa for water actually consumed by the crops, and

$$\mathrm{CWP}_{\mathrm{eff}} = \frac{Y(\mathrm{kg}, \$)}{\mathrm{eff}} \tag{2}$$

in which CWP and *Y* are same as in Eq. (1) and eff stands for effective rainfall during the growing period.

Water productivity can be used as an indicator for sustainable agricultural intensification, especially in areas where water is scarce. It can be expressed in physical or economic terms. The objective of this study was to assess the impacts of alternative land, water and crop management practices on water productivity of the mixed crop-livestock system in the vertsol areas of the Blue Nile Basin.

2. Materials and methods

2.1. The study areas: location and biophysical settings

This study was conducted on the vertisol areas in the Ethiopian part of the Blue Nile Basin (Fig. 1). The Basin is characterized by highly rugged topography with altitudes ranging from 490 m to over 4250 masl (meters above sea level). Rainfall in the Basin generally increases with altitude but due to interference caused by local or extensive 'rain-shadow' effects, windward slopes receive higher rainfall than the leeward slopes. Although the main rainy season from June to September–October contributes 50–90% of the annual rainfall, its onset and secession is often uncertain.

Due to the variation in landscape and other soil forming factors like climate and vegetation, the soils of the Basin are highly variable and are severely degraded because of the prevailing poor management (Haileslassie et al., 2005). Four soil types, nitisols, leptosols, luvisols and vertisols, cover over 80% of the Basin (Erkossa et al., 2009). The vertisols are considered to have high potential due to their good inherent fertility and their location on flat to gentle slopes. About 90% of the vertisols in the Basin are located on a nearly flat (0–2%) slopes.

2.2. The farming systems

The farming systems of the Basin can be broadly categorized into the mixed farming of the highlands and the pastoralism/agro-pastoralism of the lowlands (Erkossa et al., 2009). Over 90% of the cultivated area is covered by the cereal based farming system, which encompasses *single cropping*, *double cropping* and *shifting cultivation* sub-systems (Erkossa et al., 2009). The productivity of the major crops grown on vertisols in the mid to highlands, such as wheat, is hampered mainly by waterlogging. Traditionally, wheat is planted in late August on flat beds toward the end of the growing season to avoid the waterlogging problem. The use of broad bed and furrows (BBF) to drain the excess water during the early growing season allows early sowing and enables the utilization of the available growing period (Erkossa et al., 2011). However, suitability of BBF is limited mainly by slope gradient, as major parts of the soils are situated on nearly flat areas where drainage is impossible without significant earth moving. Traditionally, the flat vertisol areas in the Basin are left for grazing as they are extremely waterlogged and cropping is often practiced late in the season after the standing surface water has evaporated. Grass-pea is favored, mainly because of its tolerance to the inevitable moisture stress induced by the late planting practice and its high biomass yield. Recently, both upland and flooded rice were introduced and expanding in the low and mid altitude areas as the daily minimum temperature is limiting in the highlands (Gebrekidan and Seyoum, 2006).

2.3. Analytical framework, tools and data source

2.3.1. Analytical framework and the alternative land use

Depending on the slope gradient, the landscape position on which vertisols are located was divided into (Fig. 2):

i. non-drainable (0–2% slope);
ii. drainable (2–5% slope);
iii. steep enough to drain passively (>5%), for which no assessment was made in this paper.

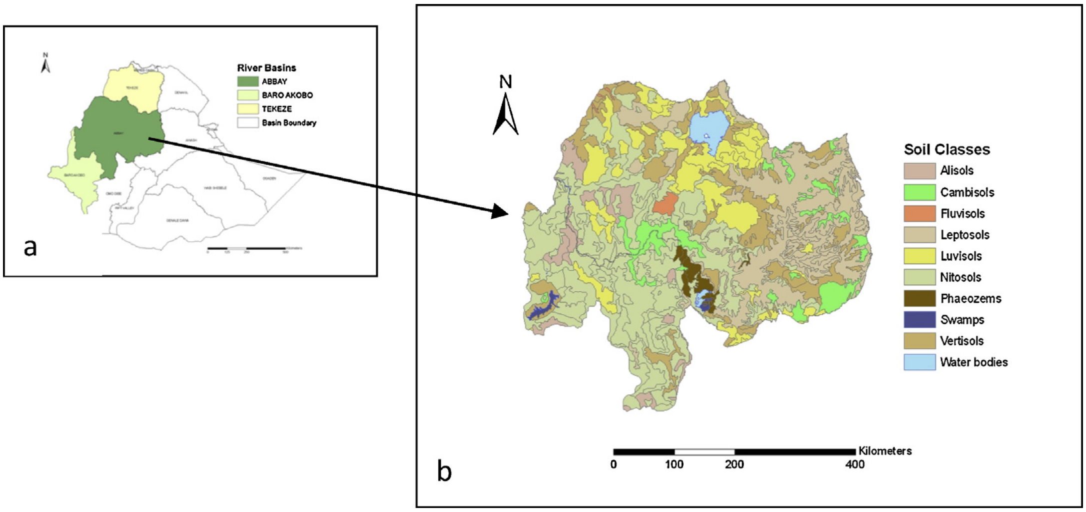

Fig. 1. Location (a) and soil types of the Abay Basin (b).

Alternative land and water management interventions were proposed for vertisols depending on slope gradient, landscape position and temperature. The interventions included early sowing of wheat using BBF for the drainable areas and rice cultivation for the non-drainable areas, provided that the daily minimum temperature ($T_{\min}$) during the growing season remains above 10 °C. The traditional practices, i.e. late sowing of wheat on flat beds for the drainable and growing grass-pea (*Lathyrus sativus*) or natural pasture for the non-drainable areas, were treated as controls.

Initially, crop and livestock water productivities were assessed separately and then aggregated to system scale. Fig. 2 provides details of the analytical framework. Grain and feed production and water depleted under both the traditional and improved management practices were quantified following the procedures detailed in the next sections, together with details of data sources and tools used to estimate the crop and livestock water productivities.

2.3.2. Crop water productivity

The crop water requirements (CWRs) under the traditional and alternative crop management practices were estimated using the CROPWAT 8.0 model. CROPWAT requires climate, soil and crop data as inputs (FAO, 1998). Monthly rainfall data were obtained from the rain gauges nearest to the locations where the crop data were

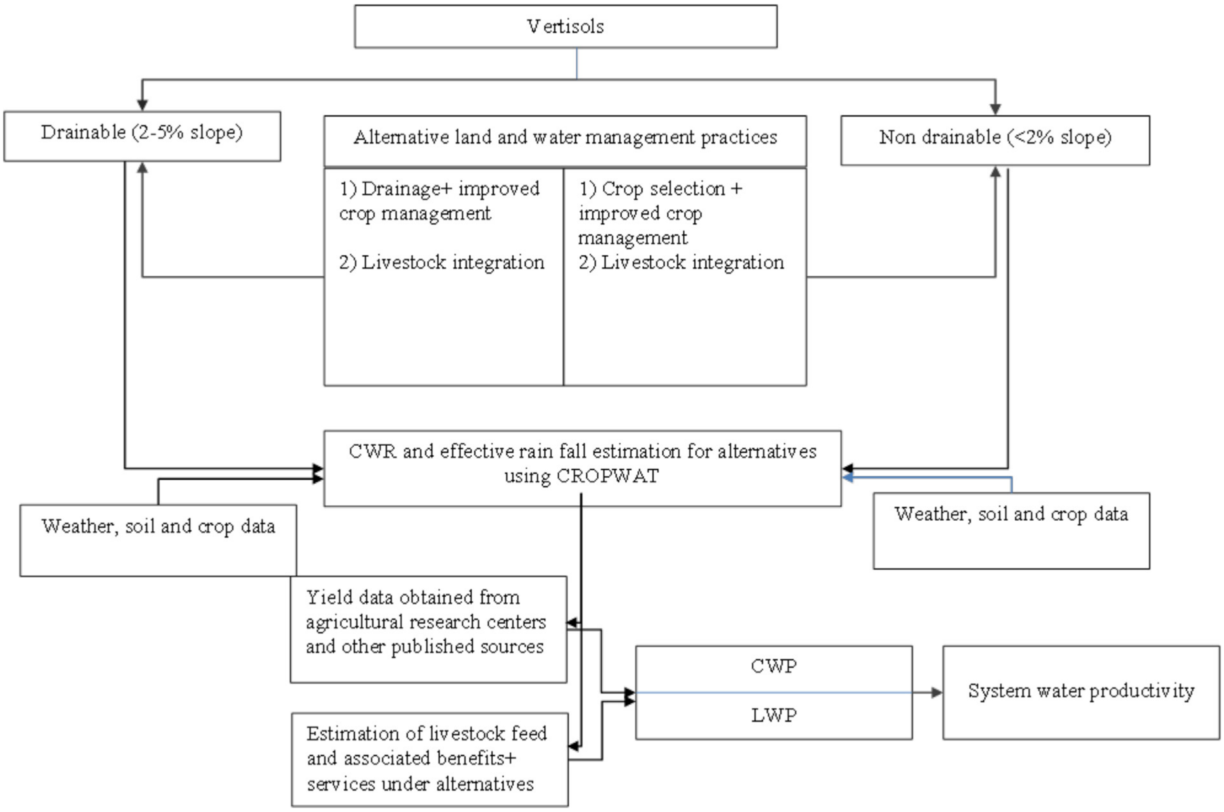

Fig. 2. Conceptual framework for assessing impacts of selected land and water management on water productivity.

Table 1
Length of growing period (LGP) of the study sites.

Location	Growing season		
	Begin date	End date	LGP (days)
Enewari	04 June	02 October	121
Dogollo	12 June	30 October	114
Dejen	08 may	01 October	147
Bahir Dar	16 May	23 October	161
Merawi	10 May	09 November	184
Bichena	08 May	09 November	147
Enewari	04 June	02 October	121
Fogera	01 June	09 October	131
Pawe	01 May	07 November	191

obtained. As the stations do not record temperature, average reference evapotranspiration (ET0) was estimated for the stations using FAO NewLocClim (Grieser et al., 2006).

Soil texture, depth and organic matter content for the areas were obtained from the soil profile data of the Ministry of Water Resources (MoWR, 1998). The soil water characteristics were estimated using a pedotransfer function (Saxton and Rawls, 2006). Crop phenological data were obtained from field monitoring of selected crops on farmers' fields during the growing season of 2011, published and unpublished documents from Amhara Regional Agricultural Research Institute (ARARI), and the CROPWAT data base. The grain yield of wheat grown under traditional and improved management practices was obtained from published literature (Table 1). The straw yield was estimated using an average harvest index of 0.41 (Birhanu, 2010). Similarly, the grain yield of rice was obtained from demonstration fields whereas the straw yield was estimated using a harvest index of 0.44 (Seyoum, 2006). The common wheat and rice varieties, HAR2029 and X-JIGNA respectively, were used. The farm-gate prices of the grains for the year 2012 were obtained through an informal survey conducted across the study areas.

CWP was estimated as a ratio of the crop yield or its equivalent gross economic value to the actual evapotranspiration (Eq. (1)) or the effective rainfall (Table 2) (Eq. (2)). Both the effective rainfall and crop water requirement were estimated using the CROPWAT 8. USDA-SCS curve number method built in CROPWAT 8 was used to estimate effective rainfall while crop water requirement was estimated by multiplying ET_0 with crop coefficient (K_c) at the different growth stages of the crops. The water deficit which was estimated as the irrigation requirement by CROPWAT 8 was deducted from the ETc to get the actual amount of water consumed (ETa).

The following assumptions were applied in computing these relationships:

i. The yield data obtained from the research stations and demonstration sites represent a near optimal yield level;
ii. BBF drains all the excess water and aeration is not limiting;
iii. All crop straws are used as livestock feed.

2.3.3. *Livestock water productivity*

Livestock are important agricultural system components in the Ethiopian Blue Nile Basin and their water requirements for feed production is reported as high (Peden et al., 2007). Similar to that of crops, livestock water productivity (LWP) is a factor of beneficial outputs and services from livestock and water depleted in the process of livestock feed production (ETa), or water available for depletion, depending on the interest of analysis (Eq. (3)):

$$\mathrm{LWP} = \frac{\sum_{j=1}^{n} O_j P_j}{\sum_{j=1}^{n} K_c \times \mathrm{ET}_0(G_j) + \sum_{j=1}^{n} K_c \times \mathrm{ET}_0(\beta_j)} \tag{3}$$

in which LWP is livestock water productivity, K_c, is crop coefficient and ET_0 is reference evapotranspiration; O_j is the beneficial outputs of type j; P_j is the price of output j; G_j and β_j are grazing and arable land types of j from where livestock feed is harvested, respectively.

Table 3 summarizes the output from six LWP studies in twelve agricultural systems, where characterization and entry points to improve LWP studies were undertaken over the last couple of years. One of the major challenges of LWP studies is quantification of the beneficial outputs from the livestock. Studies included in Table 3 report beneficial outputs and services in terms of milk, meat, manure and traction. Disaggregation of agricultural water into grain and residues is also a major hurdle to estimate the water components of the LWP equation. In this regard a number of studies (Haileslassie et al., 2011, 2009a,b) have used the harvest index and ratio of Metabolizable Energy of grain and residues to estimate the volume of water that should be accounted to livestock production.

The two approaches to calculate system LWP include:

(i) Partitioning water between grain and residues and use the proportion of water allocated to residues as the denominator and the livestock beneficial outputs as the numerator to calculate water productivity separately for system components (crop and livestock) and use the weighted sum of the components to estimate system water productivity;
(ii) Aggregating the beneficial outputs of crop and livestock (in monetary value) and use the total agricultural water (ETa) as denominator.

The farming systems from previous work included in Table 3 represent production systems where vertisols are dominant. From these data sources, we assumed a typical livestock herd composition and structure model, and we established values of livestock outputs and services per Tropical Livestock Unit (TLU), clustered into $\mathrm{USD/TLU}^{-1}$. Based on these data sources we estimated a typical smallholder's herd structure model Metabolizable Energy (ME) requirement per TLU per year, considering energy for maintenance and additional energy for the effect of standing and walking, milk production, body weight gain and traction service.

The feed biomass (crop straws) productivity from the traditional and alternative land and water management were converted to ME in $\mathrm{MJ\,kg^{-1}}$ using literature values on energy content. The number of TLU that the energy per hectare can support under the traditional practices and the alternatives were estimated and linked to the benefit per TLU, to calculate total livestock outputs and services per hectare.

2.3.4. *System water productivity*

Approaches to estimate system water productivity (SWP) are relatively new and gaps exist in terms of estimating benefits from system components and their interactions. For this study we followed an approach suggested by Haileslassie et al. (2009b) (eq. 4):

$$\mathrm{SWP} = \frac{\sum_{i=1}^{n} B_i P_i + \mu_i P_i}{\mathrm{eff}} \tag{4}$$

where SWP is system water productivity; B_i is output of crop i and P_i is the financial value of the product of crop i; u_i is benefit and services of livestock type i and P_i is financial value of the product of livestock type i; and eff is as defined under Eq. (1).

Table 2
Grain and straw yield (kg ha^{-1}) of wheat grown at different vertisols locations under BBF and traditional flat seedbeds.

Location and year	Grain (kg ha^{-1})			Straw (kg ha^{-1})		
	BBF	Flat	% Increase due to BBF	BBF	Flat	% Increase due to BBF
Enewari (1986)	1105	1072	3	1590	1543	3
Dogollo (1986)	1844	1258	47	2654	1810	47
Dejen (1987)	1263	918	38	1817	1321	38
Bahir Dar (2007)	2600	2000	30	3741	2878	30
Merawi (2007)	1700	600	183	2446	863	183
Bichena (1997)	1600	900	78	2302	1295	78
Average	1685	1125	63	2425	1618	63

Source: Demissie et al. (1999); Rutherford (2008); Gezahegn Ayele (Not dated).
BBF, Broad bed and furrows.

3. Results and discussion

3.1. *Impact of land and water management alternatives on water productivity of system components*

3.1.1. *Crop water productivity on drainable areas*

Early sowing of wheat on BBF increased average biomass yield by over 63% as compared to the traditional late sowing on flat seedbeds, though the magnitude of the effect varied over locations and years (Table 1). The highest increase (183%) in both grain and straw yield was at Merawi in 2007, while the least (3%) was at Enewari in 1986. The increased grain yield may enhance the food security and livelihoods of the households both through improved food availability and increased income through sale of the products. The benefits of additional straw production depends on how it is used, which can include: direct incorporation into the soil; feed to the livestock and return the manure to the soil; use as soil mulch, building material, household energy or sell it to generate income. Depending on the decision of the household on the type of use, the increased biomass production may enhance agro-ecological sustainability through the increased soil organic matter or improve household livelihoods as a direct benefit.

The effective rainfall during the growing period ranged from the highest of 7900 m^3 ha^{-1} at Pawe to the lowest of 4770 m^3 ha^{-1} at Enewari. Pawe exhibited the longest length of growing period (LGP) of 191 days, as opposed to Dogollo that had the shortest (114 days) (Table 2). On the other hand, the highest (3161 m^3 ha^{-1}) and the lowest (2804 m^3 ha^{-1}) actual water consumption for wheat (ETa) were at Dogollo and Bahir Dar, respectively. Evidently, advancing the sowing date of wheat using BBF increased consumptive use of water over the traditional late planting on flat beds irrespective of the locations, but the magnitude of the increase varied with location and time, ranging from the lowest (15%) at Bahir Dar to the highest (177%) at Bitchena and Enewari. This may be related to the extended growing period (184 days) at the latter site (Table 2), which led to less effective consumption of water by the crop.

Early sowing of wheat on BBF increased the crop water productivity (CWP) with respect to effective rainfall, as compared to late sowing on flat beds, but it was reduced with respect to ETa, indicating that higher water productivity with respect to consumed water does not necessarily mean higher crop yield (Table 4). While the average increase in CWP due to BBF was about 57%, it ranged between 5% at Enewari in 1986 and 200% at Merawi in 2007. This corroborates with Erkossa et al. (2011) who reported that the yield advantage of BBF over flat beds varies over space and time, and that it often increases with increased seasonal rainfall. Therefore, advancing the sowing date of wheat on vertisols using BBF increased the productive use of the potentially available water, most of which would have otherwise been lost to evaporation (Erkossa et al., 2011). The spatial and temporal variation in the effect suggests the need for targeting interventions to optimize the return to available water. However, targeting requires sufficient information on biophysical and socio-economic factors, including soil and weather, which are highly variable in space and time. Therefore, comprehensive characterization of the soil and timely provision of reliable weather information are crucial inputs in planning the use of BBF to grow wheat or other crops sensitive to water logging. Besides, advising farmers to use the BBF technology requires understanding the socio-economic determinants of adoption in the area.

On average, the use of BBF increased the gross return (GR) from wheat grain by 50% as compared to the flat beds (Table 5), where the highest GR of 1282 USD ha^{-1} was achieved at Bahir Dar in 2007 under BBF. The lowest GR of 296 USD ha^{-1} was obtained at Merawi during the same year with a flat seedbed. The use of BBF increased the Gross Economic WP (GEWP) with respect to effective rainfall by up to 183% at Merawi in 2007, despite its increased water consumption as discussed earlier. Overall, every cubic meter of water

Table 3
Values of livestock (mixed herd) outputs and services and respective Metabolizable Energy (ME) requirement under current management condition of smallholder farmers in different farming systems of the basin.

Districts	Farming system	Values of outputs and services USD TLU^{-1} yr^{-1}				ME requirement (MJ TLU^{-1} yr^{-1})			
		Mean	StdDev	Minimum	Maximum	Mean	StdDev	Minimum	Maximum
Diga	Tef-Millet	97 (424)	33	14	165	20734	16359	9353	104853
	Maize-Sorghum	116	36	51	253	17745	13102	9101	99539
Jeldu	Barley-Potato	107 (418)	44	16	226	18159	11496	9366	78731
	Tef-Wheat	105	32	43	199	17700	10419	9145	83976
	Sorghum-Tef	111	28	56	178	18131	12299	9426	103612
Fogera	Rice-Pulse	112 (341)	47	14	237	20001	12880	9397	70121
	Tef-Millet	124	30	59	204	22444	17000	9353	98483

Source: Abebe (2012) and Eba (2012); mean values in brackets are output and services (USD TLU^{-1} yr^{-1}) reported earlier from the same site (Haileslassie et al., 2009a).
TLU, Tropical Livestock Unit.

Table 4
Land preparation methods effects on water productivity of wheat grain.

Location	Growing season eff. rainfall (m^3 ha^{-1})	ETa (m^3 ha^{-1})		Grain WP with respect to eff. rainfall (kg m^{-3})			Grain WP with respect to ETa (kg m^{-3})	
		BBF	Flat	BBF	Flat	% Increase due to BBF	BBF	Flat
Enewari (1986)	4770	3005	1086	0.23	0.22	5	0.37	0.99
Dogollo (1986)	5740	3161	2582	0.32	0.22	45	0.58	0.49
Dejen (1987)	5640	3000	1200	0.22	0.16	38	0.42	0.77
Bahir Dar (2007)	7570	2804	2429	0.34	0.26	31	0.93	0.82
Merawi (2007)	5720	3135	1206	0.30	0.10	200	0.54	0.50
Bichena (1997)	4770	3005	1086	0.34	0.19	79	0.53	0.83
Average	5876	3040	1669	0.33	0.24	57	0.66	0.89

Table 5
Gross economic water productivity of wheat grain as affected by land preparation methods.

Location	Gross return (USD ha^{-1})[a]		Grain WP with respect to effective rainfall (USD m^{-3})		
	BBF	Flat	BBF	Flat	% Increase due to BBF
Enewari (1986)	545	529	0.12	0.11	3
Dogollo (1986)	910	621	0.16	0.11	47
Dejen (1987)	623	453	0.11	0.08	38
Bahir Dar (2007)	1282	986	0.17	0.13	30
Merawi (2007)	839	296	0.15	0.05	183
Bichena (1997)	789	444	0.16	0.09	78
Average	831	555	0.14	0.09	56

BBF, broad bed and furrows.

[a] Wheat grain price estimated @ 0.4932 USD kg^{-1}.

resulted in an average gross return of 0.14 USD from the wheat sown early on BBF, a 36% increase on the previous 0.09 USD gross return obtained when the crop was sown late on flat beds.

3.1.2. *Impacts on livestock benefits and services*

As calculating livestock water productivity using the same water input to crop production is effectively double accounting of water invested (Peden et al., 2007), we present only the change in values of livestock outputs and services as the result of the alternative land and water management on drainable vertisol areas. One of the major limitations for Ethiopian livestock sector productivity and service provision is dwindling feed availability. Several studies suggest that Metabolizable Energy (ME) availability from the different land uses barely covers maintenance requirement of the livestock in the study areas (Eba, 2012). This, coupled with low availability of crude protein, has impacted both livestock productivity and long term ecosystem services of the production system.

Table 6 depicts the impacts on livestock benefits and services of advancing the planting date of wheat using BBF to drain the excess water from drainable vertisols. Under the present level of productivity and ME demand, the alternative land and water management practices on drainable vertisols significantly improved the value of livestock products and services. The highest value was estimated for Merawi, which is in line with the effect on biomass production. In fact, this is not the maximum exploitable value of benefits and services from livestock, as we used here only the mean values of benefits and services provided in Table 3. However, variation between and within systems indicates opportunities to improve the benefits from the livestock sector, while conserving water. To improve livestock productivity, availing sufficient Metabolizable Energy is only part of the equation. To achieve major impacts and close the productivity gap, investment in supplementary feeding and improved breed and livestock herd management is important (Gebreselassie et al., 2009). A critical question is whether smallholder farmers under their current economic setting and livestock management objectives are able to accomplish such interventions (Haileslassie et al., 2009a). For example, Abebe (2012) demonstrated that the current primary farmers' livestock management objective is traction and transportation, a service which is less than 150 days per year. Year-round supplementary feeding and breed improvement for traction services may not be economically feasible and also will not lead to closing the productivity gap. Therefore one major area of focus in addition to the supply of sufficient feed is transforming the production objectives of the farmer through creation of alternative market opportunities.

3.1.3. *Crop water productivity on non-drainable areas*

As shown in Table 7, replacing the native grass by grass-pea or rice increased the total biomass productivity by 400% and 190%, respectively. Even the straw yield of both grass-pea and rice exceeded the total dry biomass yield of the native grass. Considering the high demand for biomass in the area, particularly for livestock feed, the likelihood of adoption of interventions that increase this valuable product is high. The question is which of the two options is economically feasible and environmentally sound. In other words, how does such change in land use affect the economic productivity and availability of water for other uses. Growing rice instead of grass-pea on the flat areas increased the gross return and water productivity attributable to grain. The GEWP of rice with respect to effective rainfall exceeded that of grass-pea by 22% when only grain yield was considered (Fig. 3). Given the shortage of livestock feed that might be exacerbated by land use change from native pasture to food crops, the likelihood of using crop residues as feed instead of using it for other purposes increases. Consequently, the economic benefits that can be generated by feeding the residues to the livestock are considered in the following section.

Changing land use from native grass to rice or grass-pea increased crop water consumption by 152% and 10%, respectively. This is attributed to the fact that rice consumes more water per day for a longer duration (148 days) as compared to grass-pea that was sown late and required only 90 days to mature. Consequently, the biomass WP with respect to effective rainfall was 0.4, 1.0 and 1.8 kg m^{-3} for native grass, rice and grass-pea, respectively (Table 7).

Despite its high biomass production and water productivity, grass-pea can be risky both as food and feed due to its high content of anti-nutritional agents, especially β-ODAP neurotoxin, which

Table 6
Impacts of land and water management on Metabolizable Energy (ME) productivity and associated beneficial outputs.

Location	Wheat straw				TLU that can be supported (TLU ha^{-1})		Value of livestock outputs (USD ha^{-1})		% Increase in benefit (USD ha^{-1}) due to the use of BBF
	DM (kg ha^{-1})		ME (MJ ha^{-1})		BBF	Flat	BBF	Flat	
	BBF	Flat	BBF	Flat					
Eneway	1590	1543	13356	12961	0.69	0.67	136	132	3
Dogollo	2654	1810	22294	15204	1.16	0.79	227	155	47
Dejen	1817	1321	15263	11096	0.79	0.58	155	113	38
Bahir-dar	3741	2878	31424	24175	1.63	1.25	320	246	30
Merawi	2446	863	20546	7249	1.07	0.38	209	74	183
Bichena	2302	1295	19337	10878	1.00	0.56	197	111	78
Average	2425	1618	20370	13591	1.06	0.71	207	138	63

DM, dry matter; TLU, Tropical Livestock Unit; BBF, Broad bed and Furrows.

Table 7
Water requirement and physical water productivity of rice[a], grass-pea and extensively grazed grass grown on vertisols.

Crop type	Location	Year	Yield (kg ha^{-1})		Average eff. rainfall (m^3 ha^{-1})	Actual ETc (m^3 ha^{-1})	Grain WP (kg m^{-3}) with respect to		Biomass WP with respect to eff. rainfall
			Grain	Straw			Eff. rain	Actual ETc	
Rice	Fogera	2007	3510	4467	6330	5259	0.55	0.67	1.3
		2011	3744	4765	6330	4233	0.59	0.88	1.3
	Pawe	2007	3644	4638	7900	4953	0.46	0.74	1.0
		2008	3547	4514	7900	5857	0.45	0.61	1.0
		Average	**3608**	**4592**	**7272**	**5141**	**0.50**	**0.72**	**1.1**
Grass-pea	Fogera	2007			6330	3130			
		2011			6330	3130			
	Pawe	2007			7900	4930			
		2008			7900	4860			
		Average	**4662**	**9558**	**7115**	**4012**	**0.59**	**0.95**	**1.8**

Crop type	Location	Year	Biomass (kg ha^{-1})	Eff. rainfall (m^3 ha^{-1})	CWR (m^3 ha^{-1})	Biomass WP (kg m^{-3}) with respect to ETa	Biomass WP with respect to eff. rainfall
Grass	Fogera	2011	2793	6330	1940	1.44	0.44

CWR, crop water requirement; WP, water productivity.
[a] Planted on June 10.

can lead to a disease known as lathyrism (Sharma et al., 2003), if consumed beyond a limited quantity. Despite this apparent problem, farmers continue to grow the crop as there has been no alternative that provides high biomass for both food and fodder. Rice is an alternative that can be sown early in the rainy season as it tolerates waterlogging and can be harvested when the soil is still moist so that some legumes including forage crops can be grown on residual moisture.

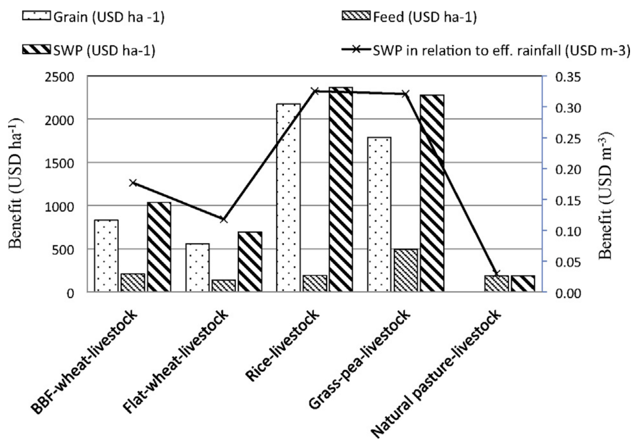

Fig. 3. Effect of the alternatives on system water productivity in relation to effective rainfall. SWP: system water productivity.

3.1.4. *Impacts on livestock benefits and services*

The impacts of the alternative land and water management practices on feed resources availability and associated livestock beneficial outputs and services are depicted in Table 8. These improvements as the result of the alternative land and water management practices (taking the natural pasture as the base scenario) are illustrated in Table 9. There was improvement in beneficial outputs and services as a result of the alternative practices. This can be accounted for by the high biomass yield from grass pea and also its relatively high energy density (Haileslassie et al., 2011). The lowest value was recorded for the scenario where non-drainable vertisols were used for rice in Pawe and improvement in livestock products and services. One of the major reasons for the marked gain in livestock products and services as the results of these interventions is related to the current low level of dry matter yield recorded on natural pasture (Haileslassie et al., 2009b). However, recent work by the International Livestock Research Institute (ILRI) in Fogera plain demonstrated that, when properly managed, traditional pasture land can yield as much as 10 Mg ha^{-1} yr^{-1} dry matter (unpublished), a value which is close to the dry matter biomass yield from grass pea. But when the combined farm benefits from grain and livestock products were considered, the overall benefit from integrating food-feed crops (like grass pea) exceed the benefit of improving pasture management. In contrast to the grass pea, livestock-related gains from rice intervention were not remarkable (Table 9). Thus for higher return, the possibility of succeeding rice by grass pea as a second crop to grow on residual moisture may need to be explored.

Table 8
Feed resources from alternative land use types on un-drainable Vertisoils.

Location and feed type	Year	Biomass (DM kg ha^{-1})	ME (MJ ha^{-1})	TLU that can be supported (TLU ha^{-1})	Beneficial outputs (USD ha^{-1})	% increase (USD ha^{-1}) over natural pasture
Rice straw – Fogera	2007	4765	34785	1.80	198.53	4
Rice straw – Fogera	2011	4765	34785	1.80	198.53	4
Rice straw – Pawe	2007	4638	33857	1.76	193.24	2
Rice straw – Pawe	2008	4514	32952	1.71	188.07	1
Average		4592	33522	1.74	191.32	2
Grass-pea (Fogera and Pawe average)		9558	86022	4.46	490.96	101
Natural pasture – Fogera	2011	2973	32703	1.70	186.65	

DM, dry matter; TLU, Tropical Livestock Unit; ME, Metabolizable Energy.

Table 9
Potential impact of combined land, water and improved livestock management on water productivity of livestock (e.g. milk).

	ME (MJ kg^{-1})	Kl	Ev1	ME-L^{-1} milk	ME ha^{-1}	Total milk ha^{-1}	USD benefit ha^{-1}	% Improvement in benefit (USD ha^{-1})
BBF-wheat	8.4	0.580	3.59	6.19	20370	3289	2322	50%
Flat-wheat	8.4	0.580	3.59	6.19	13591	2194	1549	
Rice	7.3	0.559	3.59	6.43	33522	5217	3683	−2%
Grass-pea	8	0.572	3.59	6.28	86022	13707	9675	159%
Natural pasture	8.5	0.582	3.59	6.17	32703	5298	3739	

Milk price@ 0.71 USD L^{-1}; ME, Metabolizable Energy; Kl, efficiency of utilization of ME for milk; EV1, energy value of milk.

3.2. System water productivity

As shown in Fig. 3, all proposed alternative technologies showed higher system water productivity compared to the traditional practices at system level. Despite having the highest water consumption, the highest gross return and system water productivity was recorded under the rice-livestock based system, closely followed by the grass-pea–livestock system. This can be explained mainly by the high value of rice grain on the Ethiopian market, and the fact that the straw can be fed to the livestock. A number of studies argue that sustainable water use through improved water productivity focus on producing more agricultural products using the same or lower quantity of water input (e.g. Haileslassie et al., 2011). More crop and livestock products from the same or less amount of water usually means the same or less area of land used. Given the significant coverage of the vertisols in Africa (approximately 80 million hectares) and the severity of their constraints that they are considered agriculturally marginal and their use is limited to natural pasture (Jutzi et al., 1987), adoption of such integrated approach with necessary adaptation to the local circumstances could be far reaching in terms of increasing water and land productivity and environmental sustainability. The benefit could extend beyond the vertisol landscapes where the technologies are used, since water and land is likely to be left elsewhere for other purposes (Garnett et al., 2013), including reduction of encroachment to forested areas.

The decision on whether to go for high value but water depleting crops or a lower value crop which depletes less water is one with economic and political dimensions. However, in this particular situation, the opportunity cost of the extra water consumed by rice is insignificant as it is largely lost to evaporation under the traditional system. The BBF-wheat system also increased both the gross return and water productivity at system scale, confirming the previous findings in which it was recommended as a profitable alternative (Erkossa et al., 2006), even when water consumption is considered.

4. Conclusion

Based on primary and secondary data and model outputs, this study has demonstrated the potential for significant agricultural water productivity enhancement in both the crop and livestock components as well as overall system scales in environmentally constrained areas. Improving crop productivity on soils which are hydro-physically constrained such as vertisols, either using surface drainage technologies where the slope gradient is suitable, or growing hydrophilic crops such as rice in areas where drainage is limited by topography, have been demonstrated to be superior both in terms of gross return and efficiency of water use. The profitability is even higher when livestock is integrated into the system through using the dry matter as feed, the productivity of which was increased due to the use of the improved options. The utilization of crop residues as livestock feed not only enhances overall system productivity, but also improves nutrient recycling in the system, which can increase soil fertility and system resilience. Evidently such interventions improve the livelihoods of subsistence farmers and enhance resilience of their environment. Further refining the alternative soil, water, crop and livestock-related technologies and promoting enabling policy and institutional interventions that stimulate the wider adoption of improved management practices, may allow exploitation of the high system water productivity potential with positive impacts both for the livelihoods of local people and the integrity of their environment.

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References

Abebe, A., 2012. Study of Small-holder Farms Livestock Management Practices and Their Implications on Livestock Water Productivity in Mixed Crop-Livestock Systems in the Highlands of Blue Nile Basin: A Case Study from Fogera, Diga, Jeldu Districts (Ethiopia) University. Hawasa University, Ethiopia (M.Sc. Thesis).

Astatke, A., Kelemu, F., 1993. Modifying the traditional plough-maresha for better management of Vertisols. In: Mamo, T., Astatke, A., Srivastava, K.L., Dibabe, A. (Eds.), Improved Management of Vertisols for Sustainable Crop-livestock Production in the Ethiopian Highlands, Synthesis Report 1986–1992. Technical

Committee of the Joint Vertisol Project, Addis Ababa, Ethiopia, International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia, pp. 85–101.

Astatke, A., Muhamed-Saleem, M.A., ElWakeel, A., 1995. Soil water dynamics under cereal and forage legume mixtures on drained vertisols in the Ethiopian Highlands. Agricultural Water Management 27, 17–24.

Benites, J., Chuma, E., Fowle, R., Kienzle, J., Molapong, K., Manu, J., Nyagumbo, I., Steiner, K., VanVeenhuizen, R. (Eds.), 1998. Proceedings from an International Workshop. Harare, 22–27 June, 1998, Part 1, Workshop Report.

Birhanu, B., 2010. Assessment of Bread Wheat Production, Marketing and Selection of N-Efficient Bread Wheat (*Tritium aestivum* L.) Varieties for Higher Grain Yield and Quality in North Western Ethiopia, A Thesis Submitted to the Faculty of Agricultural and Environmental Sciences. Department of Plant Sciences, School of Graduate Studies, Bahir Dar University, Bahir Dar, Ethiopia, pp. 102.

Debele, B., 1985. The Vertisols of Ethiopia: Their properties, classification and-management. In: 5th meeting of the eastern African soil correlation and land evaluation sub-committee. 4-10 December 1983, Wad Medani. World soil resources report. FAO, Rome, 56, 31-54.

Demissie, M., Efrem, B., Bemnet, G., 1999. Evaluation of durum wheat using broadbed and flat drainage systems on Ethiopian Highland and vertisol soils. In: 10th Regional Wheat Workshop for Eastern, Central and Southern Africa, Stellenbosch (South Africa), 14–18 September, 1998, ISBN 92-9146-058-3, p. 603.

Eba, B., 2012. Study of Smallholder Farms Livestock Feed Sourcing and feeding Strategies and Their Implication on Livestock Water Productivity in Mixed Crop-livestock Systems in the Highlands of the Blue Nile Basin, Ethiopia. Haramaya University, Ethiopia (M.Sc. Thesis).

El-Swaify, S.A., Pathak, P., Rego, T.J., Singh, S., 1985. Soil management for optimized productivity under rained conditions in the semi-arid tropics. In: Stewart, B.A. (Ed.), Advances in Soil Science, vol. 1. Springer-Verlag, New York, pp. 1–64.

Erkossa, T., Gizaw, A., Stahr, K., 2004. Land preparation methods efficiency on the highland vertisols of Ethiopia. Irrigation and Drainage 53, 69–75.

Erkossa, T., Michael, M., Getnet, D.B., 2011. Effects of bed width and planting date on water productivity of wheat grown on vertisols in the Ethiopian Highlands. Irrigation and Drainage, http://dx.doi.org/10.1002/ird.608.

Erkossa, T., Awulachew, S.B., Hagos, F., 2009. Characterization and productivity assessment of the farming systems in the upper part of the Nile Basin. Ethiopian Journal of Natural Resources 11 (2), 149–167.

Erkossa, T., Stahr, K., Gaiser, T., 2006. Soil tillage and crop productivity on a vertisol in Ethiopian Highlands. Soil & Tillage Research 85, 200–211.

FAO, 1998. Crop evapotranspiration. In: Allen, R., Pereira, L.A., Raes, D., Smith, M. (Eds.), FAO Irrigation and Drainage Paper No. 56. FAO, Rome.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray, H.C.J., 2013. Sustainable Intensification in Agriculture: Premises and Policies, Policy Forum, Referred to a paper Downloaded from www.sciencemag.org on 29.06.13.

Gebrekidan, H., Seyoum, M., 2006. Effects of mineral N and P fertilizers on yield and yield components of flooded lowland rice on vertisols of Fogera Plain, Ethiopia. Journal of Agriculture and Rural Development in the Tropics and Subtropics 107 (2), 161–176.

Gebreselassie, S., Peden, D., Haileslassie, A., 2009. The factors affecting livestock water productivity: animal scale analysis using previous cattle feeding trials in Ethiopia. Range Land Journal 31, 251–258.

Grieser, J., Gommes, R., Bernardi, M., 2006. New LocClim – the local climate estimator of FAO. Geophysical Research Abstracts 8, 08305.

Haileslassie, A., Blümmel, M., Murthy, M.V.R., Samad, M., Clement, F., Anandan, S., Sreedhar, N.A., Radha, A.V., Ishaq, S., 2011. Assessment of livestock feed and water nexus across mixed crop livestock system's intensification gradient: an example from the Indo-Ganaga Basin. *Experimental Agriculture* 47, 113–132.

Haileslassie, A., Peden, D., Gebreselassie, S., Amede, T., Wagnew, A., Taddesse, G., 2009a. Livestock water productivity in the Blue Nile Basin: assessment of farm scale heterogeneity. Range Land Journal 31, 213–222.

Haileslassie, A., Peden, D., Gebreselassie, S., Amede, T., Descheemaeker, D., 2009b. Livestock water productivity in mixed crop–livestock farming systems of the Blue Nile Basin: Assessing variability and prospects for improvement. Agricultural system 102, 33–40.

Haileslassie, A., Priess, J., Veldkamp, E., Teketay, D., Lesschen, J.P., 2005. Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. Agriculture, Ecosystems and Environment 108 (1), 1–16.

Haque, I., Lupwayi, N.Z., Luyindula, N., 1996. Inoculation and phosphorus effects on *Desmodium intortum* and *Sesbania sesban* in the Ethiopian Highlands. Agriculture, Ecosystems and Environment 56, 65–72.

Jutzi, S.C., Haque, I., Mclntire, J., Stares, J.E.S., 1987. Management of vertisols in sub-Saharan Africa. In: Proceedings of a Conference held at ILCA, Addis Ababa, Ethiopia, 31 August–4 September, 1987.

Ministry of Water Resources (MoWR), 1998. Abbay River Basin Integrated Development Master Plan Project Report. Ministry of Water Resources, Addis Ababa, Ethiopia.

Muhamed-Saleem, M.A., Astatke, A., 1996. Options to intensify cropland use for alleviating smallholder energy and protein deficiencies in the East African highlands. Field Crops Research 48, 177–184.

Peden, D., Tadesse, G., Misra, A.K., 2007. Water and livestock for human development. In: Molden, D. (Ed.), Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. Earthscan/International Water Management Institute, London/Colombo, pp. 485–514.

Rockström, J., Barron, J., 2007. Water productivity in rainfed systems: overview of challenges and analysis of opportunities in water scarcity prone Savannahs. Irrigation Science 25, 299–311.

Rutherford, A.S., 2008. Broad Bed Maker Technology Package Innovations in Ethiopian Farming Systems: An Ex-post Impact Assessment, Research Report 20. ILRI (International Livestock Research Institute), Nairobi, Kenya, pp. 89.

Saxton, K.E., Rawls, W.J., 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Science Society of America Journal 70, 1569–1578.

Seyoum, M., 2006. Uptake and Response of Rice (*Oryya sativa* L.) to Nitrogen and Phosphorus Fertilization Under Rainfed Lowland Condition of the Forgera Plain, Northern Ethiopia. Alemaya University, Ethiopia (M.Sc. Thesis).

Seyoum, M., Alamerew, S., Bantte, K., 2011. Evaluation of upland RERICA rice (*Oryza sativa* L.) genotypes for grain yield and yield components along an altitude gradient in Southwest Ethiopia. Journal of Agronomy 10 (4), 105–111.

Sharma, A., Kalia, M., Malhotra, S.R., 2003. Effect of antinutritional factors in khesari seeds (*Lathyrus sativus*) on the biological performance of chicks. Lathyrus Lathyrism Newsletter 3, 41–43.

Tadesse, T.F., Dechassa, N.R., Bayu, W., Gebeyehu, S., 2013. Impact of rainwater management on growth and yield of rainfed lowland rice. Wudpecker Journal of Agricultural Research 2 (4), 108–114.