Livestock water productivity in mixed crop–livestock farming systems of the Blue Nile basin: Assessing variability and prospects for improvement

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A B S T R A C T

Water scarcity is a major factor limiting food production. Improving Livestock Water Productivity (LWP) is one of the approaches to address those problems. LWP is defined as the ratio of livestock's beneficial outputs and services to water depleted in their production. Increasing LWP can help achieve more production per unit of water depleted. In this study we assess the spatial variability of LWP in three farming systems (rice-based, millet-based and barley-based) of the Gumera watershed in the highlands of the Blue Nile basin, Ethiopia. We collected data on land use, livestock management and climatic variables using focused group discussions, field observation and secondary data. We estimated the water depleted by evapotranspiration (ET) and beneficial animal products and services and then calculated LWP. Our results suggest that LWP is comparable with crop water productivity at watershed scales. Variability of LWP across farming systems of the Gumera watershed was apparent and this can be explained by farmers' livelihood strategies and prevailing biophysical conditions. In view of the results there are opportunities to improve LWP: improved feed sourcing, enhancing livestock productivity and multiple livestock use strategies can help make animal production more water productive. Attempts to improve agricultural water productivity, at system scale, must recognize differences among systems and optimize resources use by system components.

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1. Introduction

Water scarcity is highly evident in river basins like the Blue Nile where more than 160 million people dwell and agriculture is responsible for about 75% of annual fresh water withdrawal (Mason, 2003). The whole Nile River basin contains about 58 million Tropical Livestock Unit (TLU) but livestock's requirements for and impact on agricultural water uses have been largely ignored (CA; 2007; Peden et al., 2007; World Bank, 2006). Peden et al. (2008) suggested improving Livestock Water Productivity (LWP) as a strategy to address these problems. LWP is a new concept and theoretically defined as the ratio of livestock products and services to the amount of water depleted and degraded in producing them (Kurz et al., 2006; Peden et al., 2007). The management of each of the many species and breeds of domestic animals and their interaction with water (e.g. feed sourcing) vary in different farming systems due to farmers’ diverse livelihood strategies (i.e. livestock or crop focused livelihood) and the resources base. Understanding spatial and temporal variability of those interactions and circumstances which lead to unproductive water use and loss is important to enhance LWP (Peden et al., 2007; Peden et al., 2008).

Our study presents an analysis of spatial variability of LWP in three farming systems of the Blue Nile basin. As a case study site, Gumera watershed was selected for its diversity of farming

1 In this paper depletion is conceptualized as non process and process. Process depletion is the water transpired by crops plus that amount incorporated in to the plant, while the non-process depletion refers to water evaporated from soil and free water surface (Molden, 1997).

2 A TLU is equivalent to 250 kg live weight of tropical livestock.
systems and its role as a “hotspot” of water shortages where increased LWP can benefit poor farmers (Haileslassie et al., 2006b). We focused on the prominent rice-based, millet-based and barley-based mixed crop–livestock systems (Fig. 1).

The overarching objectives of this study were: (i) to describe the magnitude and spatial variability of LWP among the three farming systems in Gumera watershed, and (ii) to shed light on strategies that can improve LWP in crop–livestock mixed farming systems.

2. Materials and methods

2.1. Physical setting of the study area

The Gumera watershed covers an area of 1644 km² and drains into Lake Tana in Ethiopia (Fig. 1). The climate varies due to wide range of altitude from 1700 to 3704 m above sea level (EMA, 1980). FAO (1982) indicates that lower elevations have a warm climate with annual mean temperatures greater than 20 °C. The mountains are temperate, with mean annual temperature ranging between 10 °C and 20 °C. The highest mean monthly rainfall is recorded in July while the highest potential evapotranspiration (ET) is in May.

The variability of topography, climate, geology and land use has resulted in different pedogenic processes. Haplic luvisols cover a large proportion of the area especially on the upper slopes and Eutric vertisols are less extensive and found on lowland areas. Soil on the upper part of the watersheds is mainly volcanic origin, developed from basic and ultra basic rocks (e.g. basalt). Soils at the outlet of the drainage area are developed from undifferentiated and unconsolidated sediments (FAO, 1986, 1984).

2.2. Farming systems

A farming system is defined as a group of farms which have a similar structure and function and can be expected to produce similar levels of production (Ruthenberg, 1980). Ethiopian farming systems consist mostly of mixed crop–livestock farming and agro-pastoralism or pastoralism (Assefa, 1986) and evolved in response to regional differences in climate, population density, diseases, economic opportunities and cultural practices (Stangel, 1993; Westphal, 1975). Mixed farming systems which integrate both crops and livestock are typical in the Gumera watershed. Farmers keep cattle (Bos indicus), sheep (Ovis aries), goat (Capra hircus), horse (Equus caballus) and donkey (Equus asinus). The relative importance of different livestock species in the farming systems is indicated in Table 1. Manure fulfills an important role through nutrient cycling between and within farms, which enables the sustainable use of smallholder plots. Crop and livestock enterprises are complementary and at the same time competitive. They are complementary in the sense that livestock are a source of traction power, and sources of organic fertilizer and cash for inorganic fertilizer, whilst crop residues provide up to 30% of livestock feed. Yet, they compete for land and water. Typical features of the three farming systems in the Gumera watershed (rice-based; millet-based and barley-based) are discussed in the following sections.

2.2.1. Rice-based farming system

Rice-based farming is located at lower altitudes (~1700–1806 masl; Fig. 1) where floods are frequent. Rice (Oryza sativa) and indigenous Niger seed (Guizotia abyssinica), are important crops. Rice production was introduced in the early 1980s using the X-Jigna variety.

Farmers usually practice relay cropping to make use of the residual moisture after the flood is over. For example pulses such as chickpea (Cicer arietinum) and grass pea (Lathyrus hirsutus) are commonly relayed with rice. Farmers also grow horticultural crops such as onion (Allium cepa), tomato (Lycopersicon esculentum) and garlic (Allium sativum) by means of irrigation (IFAD, 2005).

The rice-based system is well integrated with fish production (from Lake Tana) and cattle and crop production (on the plains). Farmers along the shoreline of Lake Tana are also fishers and use traditional ways of fishing using papyrus boats and nets (Gordon et al., 2007).

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Table 1

<table>
<thead>
<tr>
<th>Farming system characteristics</th>
<th>Farming systems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rice-based system</td>
</tr>
<tr>
<td>Altitude range (masl)</td>
<td>1700–1800</td>
</tr>
<tr>
<td>Mean annual rain fall (mm)</td>
<td>121</td>
</tr>
<tr>
<td>Mean daily minimum–maximum temperature (°C)</td>
<td>12–27</td>
</tr>
<tr>
<td>Population density (persons ha⁻¹)</td>
<td>2.4</td>
</tr>
<tr>
<td>Livestock density (TLU ha⁻¹)</td>
<td>0.8</td>
</tr>
<tr>
<td>Dominant livestock species (TLU%)</td>
<td>Bv: 96; Eq: 3</td>
</tr>
<tr>
<td>Cropping pattern (%)</td>
<td>R: 47; M: 24</td>
</tr>
<tr>
<td>Total land holding size (ha household⁻¹)</td>
<td>1.2</td>
</tr>
<tr>
<td>Total pasture land (ha household⁻¹)</td>
<td>0.07</td>
</tr>
</tbody>
</table>

TLU, Tropical Livestock Units; masl, metres above sea level; P, potato; B, barley; W, wheat; T, teff; M, millet; R, rice. Bv, Bovine; Eq, Equine; Sh, shoat.

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Fig. 1. Location map of Gumera watershed and the study farming systems.
In the rice-based system, farmers keep mostly cattle, donkeys and a few goats (Table 1). The major purposes of livestock keeping are traction power, transport and manure. Crop residues (except rice husk), stubble grazing and pasture are major animal feed sources. Feed supplements are not normally used. Feed shortage is a major problem, especially during seasonal flooding (MoA, 2002).

2.2.2. Millet-based farming system

The millet-based farming system (1800–2300 masl) covers the largest area in the watershed and has the most crop diversity compared to the rice-based or barley-based systems (MoA, 2002 (Fig. 1)). Maize (Zea mays) and finger millet (Eleusine coracana (originally native to the Ethiopian highlands)) are dominant. Also common are teff (Eragrostis tef) which is native to the Ethiopian highlands and wheat (Triticum durum and Triticum aestivum). In the millet-based farming system, irrigation of horticultural crops is also important at lower elevations (IFAD, 2005). Wheat, teff and oil crops are major cash crops. In contrast to rice-based farming, the millet-based farming system experiences severe soil erosion and land degradation.

Livestock are an important component of the millet-based system (Table 1). As in other two systems, livestock and crop production complement each other (Haileslassie et al., 2006a; Haileslassie et al., 2007). Feed shortage, low livestock production (<31 day⁻¹ of milk) and overstocking are major problems.

2.2.3. Barley-based farming system

Barley-based farming system is located in the high mountains between ~3200 and 3700 masl (Fig. 1) where temperatures range between 10 °C and 16 °C. This system is the smallest in terms of area coverage of the Gumera watershed (MoA, 2002). Cereals like barley (Hordeum vulgare) and faba bean (Vicia faba) are most common. Potatoes (Solanum tuberosum) are often relayed with barley. In contrast to other two systems, cash crops are few and the landscape is less suitable for cultivation due to very steep slopes and rugged topography.

Similar to millet-based system, the barley-based systems experience severe soil erosion and land degradation. Haileslassie et al. (2006b) reported erosion rates ranging between 33 and 84 Mg ha⁻¹ yr⁻¹. This is the major sediment source for the fertile soils deposited on the rice-based system.

Livestock serve as important sources of farmers’ cash income in addition to providing transport and traction services. Small ruminants are more important than in the rice and millet-based systems (Table 1). Like the millet-based system, low productivity, feed shortage and overstocking are major problems.

2.2.4. Water productivity: concept and the model

The productivity of water refers to the benefits derived from use of water. The numerator then has a physical or economic term expressing the benefit. The denominator is usually the volume of water (e.g. m³; Kijine et al., 2003; Molden, 1997; Molden et al., 2007) or the value of water.

LWP, like its counterpart Crop Water Productivity (CWP), is based on principles of water accounting (e.g. Molden, 1997; Peden et al., 2007) and takes the values of livestock products and services as a numerator and evapo-transpiration (ET) associated with feed production as the denominator. If the purpose of analysis is to compare different agricultural enterprises, the numerator of LWP can be expressed as monetary units such as dollars (Peden et al., 2008). Depending on the scale, the denominator of LWP may include degraded water and downstream discharge because it may be impossible or too costly to purify or recapture lost water for reuse (Peden et al. 2007). This relation can be presented as follows:

\[
LWP = \frac{\sum_{j=1}^{n} O_j P_j - CP}{\sum_{j=1}^{n} D_p + \sum_{j=1}^{n} D_g}
\]

where \(O_j\) is the beneficial outputs of type \(j\) (e.g. milk, meat, manure and traction); \(P_j\) is the price of output \(j\); \(CP\) is cost of production; \(D_p\) is ET water for production of animal feed sources type \(j\) (e.g. on grazing land, crop residues); \(D_g\) is water degraded as results of poor livestock management (Peden et al., 2006). In this study only ET water was considered as a denominator.

Estimation of CWP has a well established method (e.g. Donald and Hamblin, 1976). We used the economic dry matter yield (grain and tuber) in the numerator and depleted water (ET) in the denominator. Finally we calculated each system’s agricultural water productivity using the same water accounting principle, i.e., as the ratio of gross livestock and crop returns to total ET water in producing livestock feeds and crops.

2.2.5. Estimating values of agricultural products and services

Livestock are important components of global agriculture: providing meat, milk, hides, manure, farm power and transportation. They also have cultural values and provide ecosystem services outputs (Kaufmann and Saleem, 2000). However, we considered only traction, transportation, meat, milk, manure, skin and hides in this study. To quantify those outputs total livestock populations in each farming system were estimated from regional and national agricultural survey data (MoA, 2002) and these were updated through focus group discussions held in December 2007. We converted the different livestock populations to TLUs using a conversion factor of 0.79 TLU/head for cattle, 0.1 TLU/head for sheep and goats, and 0.66 (TLU/head) for equines (FAO, 2002). The beneficial outputs and services were estimated as follows:

- **Fertilizer values of manure:** dung production of livestock is affected by a number of factors including type, age, season and feed. Relevant data are not available in the study area. We used dry weight daily dung production of 3.3 kg day⁻¹ TLU⁻¹ for cattle and 2.4 kg day⁻¹ for equines and shotts to estimate total dung produced in different farming systems (Haileslassie et al., 2006a). The nutrient content of dung (e.g. Nitrogen, Phosphorus and Potassium) was estimated based on average chemical composition for Ethiopia of 18.3 g N kg⁻¹, 4.5 g P kg⁻¹ and 21.3 g K kg⁻¹ on a dry weight basis (Lupwayi et al., 2000; Haileslassie et al., 2006a). This was converted to fertilizer equivalent monetary values using the current local price of fertilizer. We did not consider the beneficial value of urine because reliable data on volume of production and nutrient concentration were not available. We also did not consider the value of manure as a replenisher of soil organic matter.

- **Milk production:** reports on Ethiopian indigenous cattle breeds indicated that milk yield ranged between 500 and 700 l with less than 150 days of lactation period, under average to good management conditions (Kebede 1984; Mukasa-Mugerwa, 1989). For this study the annual milk production was estimated as a function of the number of lactating cows, lactation period and milk production in liters day⁻¹ cow⁻¹ in the study area. Finally, this was converted to monetary values based on the current market price of milk in the different farming systems of the Gumera watershed.

- **Meat value:** we estimated meat production using parameters such as off-take rate, carcass weight and average slaughter age for different livestock species (FAO, 1999) and applied a similar procedure to estimate the values of hides and skins.

- **Value of livestock services:** we estimated the value of livestock traction services from data collected on the daily cost of hiring draft animals such as oxen and equines and the number of working days per year in each farming system.
• Crop outputs: grain and tuber yields of crops and their market values in the different farming systems were estimated from focus group discussions and district level surveys.

In estimating LWP and CWP, we considered both the net and gross value of products in the numerator. The variable cost breakdown for the livestock included herding, feed collection, manure management, milking and milk processing, watering, and marketing of products. The variable costs for crop production included land preparation, seed, fertilizer, weeding, harvesting and marketing. For both enterprises, fixed costs, other than land, were assumed to be insignificant and thus not considered. We used land rental cost to estimate the current land values and the monetary value of crop residues was considered to be a cost of livestock production.

2.2.6. Water used by livestock and crops: depleted water

The major component of livestock and crop water use is the ET water which is used in producing animal feed and crop (e.g. Peden et al., 2007). To calculate ET we used the reference evapotranspiration (ET\textsubscript{0}, mm day\textsuperscript{-1}) and crop coefficient (K\textsubscript{c}) approaches (FAO, 1998; Eq. (2)). We used the Penman-Monteith method to estimate ET\textsubscript{0} and applied Angstrom’s Coefficients of 0.25 and 0.5 as presented in New LocClim (version 1.06 (FAO, 2005)). We used climatic data (temperature, wind speed, precipitation) recorded inside or adjacent to each farming systems (Bahir-Dar and Debre Tabor stations). We used literature values for crop coefficients, the dimensionless ratios of ET to ET\textsubscript{0}, to relate crop ET, (meter day\textsuperscript{-1}) to ET\textsubscript{0} and calculated ET from land use β (m\textsuperscript{2}) as given in (Eq. (2)).

\[
\text{ET}\textsubscript{0} = K\textsubscript{c} \times \text{ET}\textsubscript{0} \beta
\]  

(2)

We assumed a composition of 50% grasses and legumes on grazing lands and applied mean Kc values of known legumes and grasses growing in the study areas. The length of growing period was also estimated using New LocClim (version 1.05 (FAO 2005)) and adjusted based on local knowledge. In all parts of the Gumera watersheds, crop residues are important animal feed. We used harvest indices (the ratio of dry weight grain or tuber yields to above ground biomass dry matter yield) to allocate the total ET between the grain and crop residues. The residue used by animals was calculated based on use factors as reported in MoA (2002). Then the water in the residue portion was factored into LWP while the grain portion was factored into the estimation of CWP (FAO, 1986; Donald and Hamblin, 1976; MoA, 2002).

3. Results

3.1. Livestock production

Our result showed that the beneficial livestock products and services varied among the three farming systems (Table 2). The highest, intermediate, and lowest values of total livestock production occurred in the millet-based, barley-based and rice-based farming systems respectively.

The mean values (both gross and net return in USD ha\textsuperscript{-1} yr\textsuperscript{-1}) for the barley-based system was higher than the millet and the rice-based systems (Fig. 2). These results are clearer when the total beneficial outputs are disaggregated by the type of livestock products (Table 2). Fertilizer, milk and traction services from livestock showed the highest gross return per hectare, but returns from hides and skin were insignificant. Unlike productivity of livestock per hectare, productivity per TLU did not show strong differences among the different farming systems (Fig. 2).

3.2. Crop water productivity

Estimates of evapotranspired water (m\textsuperscript{3} ha\textsuperscript{-1} yr\textsuperscript{-1}) and water productivity of crops and animal feed are shown in Table 3. ET varied between 3500 m\textsuperscript{3} ha\textsuperscript{-1} yr\textsuperscript{-1} and 5500 m\textsuperscript{3} ha\textsuperscript{-1} yr\textsuperscript{-1} for grasslands and most crops, except for rice with an ET estimate 8678 m\textsuperscript{3} ha\textsuperscript{-1} yr\textsuperscript{-1}. Potatoes, onions, wetlands, and maize all exhibited ET values exceeding 5000 m\textsuperscript{3} ha\textsuperscript{-1} yr\textsuperscript{-1}. The lowest ET (<4000 m\textsuperscript{3} ha\textsuperscript{-1} yr\textsuperscript{-1}) was associated with barley and millet.

Biomass water productivity of human food and livestock feeds showed similar trends and varied from a low of about ~0.2 kg m\textsuperscript{-3} for rainfed grains to a high of ~1.8 kg m\textsuperscript{-3} for irrigated oranges (Table 3). In general, rainfed grains and pulses had low crop water productivity (WP), but potatoes and irrigated horticultural crops had high WP. Grassland and wetland WP was higher than that observed for most non-irrigated crops.

ET in the Gumera watershed consumes about 20% of the total precipitation while 41% of the water remains in the watershed (i.e. precipitation – discharge). The percentage of ET water (from the total rain input) varies across the study systems. The highest

![Livestock productivity across different farming systems (gross return for production year 2006/2007).](image)

Table 2

<table>
<thead>
<tr>
<th>Farming systems</th>
<th>TLU (ha\textsuperscript{-1})</th>
<th>ET (‘000000 m\textsuperscript{3} yr\textsuperscript{-1})</th>
<th>Values in USD ha\textsuperscript{-1} yr\textsuperscript{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice-based system</td>
<td>0.79</td>
<td>48.99</td>
<td>318</td>
</tr>
<tr>
<td>Millet-based system</td>
<td>2.56</td>
<td>228.91</td>
<td>875</td>
</tr>
<tr>
<td>Barley-based system</td>
<td>2.20</td>
<td>20.93</td>
<td>921</td>
</tr>
<tr>
<td>All</td>
<td>2.27</td>
<td>298.85</td>
<td>799</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Milk</th>
<th>Fertilizer</th>
<th>Hides</th>
<th>Skins</th>
<th>Meat</th>
<th>Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>71</td>
<td>167</td>
<td>0.01</td>
<td>0.57</td>
<td>15</td>
<td>65</td>
</tr>
<tr>
<td>Rice-based system</td>
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<td>544</td>
<td>0.35</td>
<td>3.02</td>
<td>67</td>
<td>140</td>
</tr>
<tr>
<td>Millet-based system</td>
<td>219</td>
<td>467</td>
<td>0.46</td>
<td>1.67</td>
<td>41</td>
<td>130</td>
</tr>
<tr>
<td>Barley-based system</td>
<td>219</td>
<td>467</td>
<td>0.46</td>
<td>1.67</td>
<td>41</td>
<td>130</td>
</tr>
</tbody>
</table>

Services are transportation and traction power; slaughterhouse by-products (e.g. offal, hoofs and horn) are not included; for manure fertilizer values of N, P and K are considered; TLU, Tropical Livestock Unit; ET is for water used for feed production at system scale.

Fig. 2. Livestock productivity across different farming systems (gross return for production year 2006/2007).
was estimated for millet, followed by the rice-based system (Fig. 3).

### 3.3. Economic livestock and total agricultural water productivity

Livestock and crop water productivities in the Gumera watershed are presented in Table 4. Because of the need to integrate multiple crop and animal based benefits, monetary values are shown. Gross and net farm return of both LWP and CWP varied among farming systems (Table 4). At a watershed scale, LWP and CWP were 0.42 m$^{-3}$/C0 and 0.29 USD m$^{-3}$/C0 respectively. The difference between net LWP and net CWP was even greater. Within the watershed, there were notable and contrasting differences in water productivity among farming systems. Gross LWP increased with altitude with values of 0.15 USD m$^{-3}$, 0.45 USD m$^{-3}$, and 0.69 USD m$^{-3}$ in the rice-based, millet-based, and barley-based farming systems respectively. In contrast, gross CWP decreased with altitude and was 0.34 USD m$^{-3}$, 0.25 USD m$^{-3}$, and 0.19 USD m$^{-3}$ in the rice-based, millet-based, and barley-based farming systems respectively. Net LWP and net CWP showed similar trends.

#### 4. Discussion and conclusions

#### 4.1. Variability of livestock water productivity across farming systems

Livestock water productivity varies among farming systems in the Gumera watershed being lowest in the low altitude rice-based farming system and highest in the higher altitude barley-based farming system (Table 4). This variation is closely related to differences in farmers’ livelihoods strategies. Asrat et al. (2006, unpublished) estimated LWP ranging from 0.2–0.6 USD m$^{-3}$ of water for mixed farming system in the Ethiopian Blue Nile. Gebreselassie et al. (2008) also reported LWP values of 0.3–0.7 USD m$^{-3}$. These authors suggest that feed, age, breed and herd structure account for variability in LWP. These studies and ours suggest that LWP is higher than CWP especially in rainfed mixed farming systems that occupy most of the Gumera watershed. Our results were in disagreement with Chapagain and Hoekstra (2003) who state that animal production requires more water than crops (kg m$^{-3}$). We argue that the global livestock production systems are diverse and often provide multiple benefits making global generalizations problematic. Within sub-Saharan Africa, LWP has not been estimated for many products, services and farming systems, and

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Crop and feed ET and physical water productivity for typical land use in Gumera watershed (production year 2006/2007).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farming systems</td>
<td>Crop groups</td>
</tr>
<tr>
<td>Rice-based system</td>
<td>Rice</td>
</tr>
<tr>
<td></td>
<td>Teff</td>
</tr>
<tr>
<td></td>
<td>Pulses</td>
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<tr>
<td></td>
<td>Onion</td>
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<td></td>
<td>Garlic</td>
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<td></td>
<td>Grasslands</td>
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<tr>
<td></td>
<td>Wetlands</td>
</tr>
<tr>
<td>Millet-based system</td>
<td>Sorghum</td>
</tr>
<tr>
<td></td>
<td>Millet</td>
</tr>
<tr>
<td></td>
<td>Teff</td>
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<tr>
<td></td>
<td>Maize</td>
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<td></td>
<td>Wheat</td>
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<td></td>
<td>Potato</td>
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<td>Grasslands</td>
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<td>Wetlands</td>
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<tr>
<td>Barley-based system</td>
<td>Barley</td>
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<tr>
<td></td>
<td>Wheat</td>
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<td></td>
<td>Triticale</td>
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<tr>
<td></td>
<td>Pulse</td>
</tr>
<tr>
<td></td>
<td>Potato</td>
</tr>
<tr>
<td></td>
<td>Grasslands</td>
</tr>
</tbody>
</table>

ET is evapotranspired water; CWP is physical crop water productivity; **values are this study’s estimate and *national average for Ethiopia as reported in Hoekstra and Hung, 2002.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Livestock water productivity (LWP) and crop water productivity (CWP) for Gumera watershed (USD m$^{-3}$ (production year 2006/2007)).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farming systems</td>
<td>WP (USD m$^{-3}$)</td>
</tr>
<tr>
<td>Rice-based system</td>
<td>0.26</td>
</tr>
<tr>
<td>Millet-based system</td>
<td>0.39</td>
</tr>
<tr>
<td>Barley-based system</td>
<td>0.43</td>
</tr>
<tr>
<td>All systems</td>
<td>0.38</td>
</tr>
</tbody>
</table>

The total evapotranspired water is shared between residues and grain, based on harvest index; SAWP, Systems’ Agricultural Water Productivity; NLWP, Net Livestock Water Productivity; NCWP, Net Crop Water Productivity.

Fig. 3. Magnitude of water depleted through evapotration for food-feed production across different farming systems in the Gumera watershed (production year 2006/2007).
et al., 2008; Peden et al., 2007). Therefore estimating LWP only from meat and milk production (in kg m\(^{-3}\)) could result in clear underestimation of LWP. Tulu et al. (2008), also showed that financial LWP is significantly higher than the CWP and lower than the domestic water use productivity. Our study supports this argument but suggests that LWP and CWP values are dependent on site specific natural biophysical conditions and the way people manage land, livestock and water as revealed in Table 4.

LWP depends on the quantity and quality of livestock beneficial outputs and the water productivity of animal feed (e.g. Gebreselassie et al., 2008). From the perspectives of current low feed water productivity (e.g. grass major feed sources, 0.55 kg m\(^{-3}\) in rice-based system (Table 3)) and very low livestock beneficial out puts (e.g. 0.5–1.5 kg milk day\(^{-1}\)) and a very short lactation period (6–9 months (Astatke and Saleem, 1996)) opportunities to improve LWP exist. Peden et al. (2007) and Gebreselassie et al. (2008), suggested enhancing LWP by increasing animal productivity, optimising herd structure, providing continuous access to quality drinking water, selecting and breeding cattle for improved feed conversion efficiency, providing veterinary services, adding value to animal products, and selecting of water-productive feeds. The following sections discuss how differences in livestock productivity and CWP cause variations in LWP, and on how feed- and livestock-focused interventions can help improve LWP.

4.2. Influence of beneficial outputs on LWP

The magnitude of livestock production varied with farming systems. It was highest in the barley-based area likely due to the higher livestock density (Table 2), while overall animal production was low (<500 USD TLU\(^{-1}\) yr\(^{-1}\)) in all three farming systems (Fig. 2). This pattern can be partly explained by the fact that barley-based farmers focus more on animal production and use species, breeds, and husbandry practices that provide higher farm income because barley and potatoes, the major crops in the cool highlands, have low market value (Habtemariam, 2003). Relative differences between economic water productivity of crops and livestock among the three farming systems may motivate farmers to choose options that lead to higher cash income. Farmers in the barley-based farming systems confirm that they hold livestock because it is the major source of cash.

A key difference between intensified animal production in developing countries and small holder production in the Gumera watershed is that farmers keep livestock for multiple purposes rather than focusing on one animal product as the beneficial output. Such diversity leads to increased LWP (Panin and Brokken, 1993; Peden et al., 2007). For example, the climate of the barley-based system is suitable to keep sheep breeds for both wool and meat production enabling multiple benefits from water use. Smith (1981) also suggested use of multipurpose cows that provide benefits from traction and milk and calf production: an option that allows for timely slaughter of males that leads to better income generation with similar amount of water input. This strategy reduces the required herd size and the water, land and feed resources required to maintain it. Although there is some concern on effects of using cows for traction power on milk yield, research concludes that dual purpose breeds showed no drop in milk yield if they are kept in good condition (Matthewman et al., 1993). Some barley-based farmers are currently using dual purpose cows, but this practice needs to be scaled out and improved to sustainably enhance LWP and improve poor farmers’ income.

4.3. Influences of evapotranspiration and crop water productivity on LWP

Our results fall within global ranges of ET required to produce crop dry matter and animal feeds (Hoekstra and Hung, 2002; Table 3). However, even in a relatively small but diverse area such as the Gumera watershed, ET is variable (Table 3). Differences in climate and cropping patterns affect ET. For example, rice cultivation depleted more than 8000 m\(^3\) of water ha\(^{-1}\) yr\(^{-1}\) while barley depleted only 3640 m\(^3\) of water ha\(^{-1}\) yr\(^{-1}\) (Table 3). Differences in ET coupled with biomass productivity determine LWP.

Our estimate of physical CWP (kg m\(^{-3}\)), for different farming system, was in the lower range of the reported values (e.g. Cai and Rosegrant, 2003 (Table 3)). For example water productivity of grassland and wetlands (used for grazing) yielded less than 1 kg of biomass per m\(^{3}\) of water depleted. Elsewhere reported values of water productivity for animal feed ranges between 6 and 8 kg m\(^{-3}\) for irrigated sorghum (Gezira) and 0.1–0.7 kg m\(^{-3}\) in range lands (Saeed and El-Nadi 1998). Among the Gumera farming systems, physical CWP ranged between 1.7 and 2.0 kg m\(^{-3}\) for the rice-based system, 0.2–1.5 kg m\(^{-3}\) for millet, and 1.5–2.0 kg m\(^{-3}\) for barley. The overall system’s physical CWP was higher for rice- and barley-based systems compared to millet-based farming. Cereal crops, which are major components of the different land uses, were generally in the lower ranges of CWP values (Table 3) and indicative of low yields and poor water management. The question is, what does this imply for potential and actual LWP and ultimately for poor farmers’ livelihoods.

In all farming systems crop residues are important livestock feed. The current low level of CWP has implication for LWP. Several authors on LWP in sub-Saharan African suggested that it can be improved by selecting and using water productive feeds (Mark and Sarah, 2004; Peden et al. 2007). Our results indicated also that increasing biomass yields can increase CWP and crop residue production for animal feeds (Fig. 5). However the question is does water productivity of feed always contribute to higher LWP. For example the nutritive values of some crop residues are generally low in Ethiopia (PANESA, 1988). The author reported that residues of crops like maize and barley have low digestible protein (18 g kg\(^{-1}\)). In contrast, some grass species, which are native to eastern highlands of Ethiopia, and pulses, have about 87 g kg\(^{-1}\) and 40 g kg\(^{-1}\) of protein respectively. However, those grasslands are less water productive and degrading because of overstocking and inappropriate management (Evaldson, 1970; Gebreselassie et al. 2008), also suggested that feeds with higher water prod-

![Fig. 4. Relation between physical (kg m\(^{-3}\)) and gross financial (USDm\(^3\)) crop water productivity (production year 2006/2007).](image-url)
tivity and nutritional values have significantly higher LWP. Therefore, some of the major challenges are increasing water productivity and nutritive values of residues to maximizing livestock outputs and thereby LWP. In view of the current cropping pattern and grazing land management, opportunities exist to mix legumes with grass in pastures and rehabilitate degraded lands for improved biomass yields and nutritional values. Simply providing a small amount of higher quality supplemental feed can also help animals use poor quality feed in their diets more efficiently.

4.4. Optimizing resource use for higher agricultural water productivity

Increasing agricultural water productivity requires more effective use of land, water and labor, and selecting opportunities based on appropriate crop and animal species and varieties and husbandry practices to enhance their production. Analysis revealed a significant positive correlation between economic and physical CWP at a watershed scale (Fig. 4). However, this situation differs on appropriate crop and animal species and varieties and hus-
tive use of land, water and labor, and selecting opportunities based on relative and absolute terms. Attempts to improve agricultural water productivity in farming systems must recognize their unique structure and context, and will need to involve the effective use of natural resources and technology, while at the same time taking advantage of opportunities that farmers have to market their produce.

In conclusion, our results suggest that livestock water productivity varies among farming systems depending on farmers' livelihood options and prevailing climatic and natural resources conditions. At this scale of study, it appears that improved feed sourcing, enhanced livestock productivity, and multiple livestock use can help animal production become more water productive in relative and absolute terms. Attempts to improve agricultural water productivity in farming systems must recognize their unique structure and context, and will need to involve the effective use of natural resources and technology, while at the same time taking advantage of opportunities that farmers have to market their produce.

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