Management practices and agro-ecological effects on crop water productivity in Meja watershed, Ethiopia
Management practices and agro-ecological effects on crop water productivity in Meja watershed, Ethiopia

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Abstract: Mixed crop–livestock farming system is a major livelihood strategy in most sub-Saharan African countries. Low water use efficiency and water scarcity characterize the dominant rainfed agricultural production system in the densely populated highlands of Ethiopia. Improving water productivity in the rainfed system is among the ways of overcoming the water scarcity challenge. This study was conducted in Meja watershed, located in Jeldu district, West Shewa in the Ethiopian part of the Blue Nile Basin to estimate economic crop water productivity based on agro-ecology and crop management practices. The watershed was classified into three landscape positions (local agro-ecologies) and major crops representing at least 70% of each landscape position were identified through discussion with farmers and development agents. Five farmers field were randomly selected for each major crop and crop management practices implemented by the farmers were monitored and yield (grain or tuber and straw) was measured at harvest. The local market value of the crops and the production cost was estimated based on the local market value for labour and other inputs. CROPWAT model was used to estimate effective precipitation based on weather data generated using NewLocClim and crop characteristics. The result indicated that the landscape positions, crop variety and management practices significantly influenced the net economic water productivity. The net economic crop water productivity for barley, wheat, tef, sorghum and maize grains and fresh potato tubers were 3.31, 2.45, 3.09, 3.01 and 5.20 ETB m⁻³, respectively. Similarly, physical water productivity of the crops ranged from 0.47 for teff to 9.98 kg m⁻³ for fresh potato tubers. Hence, farmers can enhance economic benefit from the land and water resources they are endowed with rainfed by using improved agronomic practices that could raise grain/tuber and biomass yield. Enhancing improved input use, improving access to market for outputs and integrating livestock with crops may further augment the benefit at system scale.

Key words: Meja watershed, Ethiopia, water use efficiency, water scarcity, crop management

Introduction

Mixed crop–livestock farming system, which is characterized by a strong complementarity in resource use (Devendra and Thomas 2002), is a major livelihood strategy in most sub-Sahara African (SSA) countries (Steinfeld et al. 2006) including Ethiopia and supported the livelihoods of approximately 80% of the population (Thornton et al. 2002). In
this system, achieving higher production and improved rural livelihoods is highly restricted by underdevelopment, rapid population increase, land degradation, climate uncertainty and associated water scarcity (Singh et al. 2011). Among others, the problem of water scarcity has been aggravated and seriously hampered crop productivity in rainfed agriculture mainly due to non-water related factors. Among water related factors, increasing competition for water among agricultural and other economic sectors as well as household consumption and environmental demand (Molden et al. 2007), increasing temporal and spatial variability of rainfall resulting in amplification of extreme events (IPCC 2007), poor land and inefficient rainwater management systems implemented by most smallholder farmers (Rockström and Steiner 2003; Wani et al. 2003; Zemadim et al. 2011) and decreasing potential of irrigation water withdrawals due to its stressing effect in many of the world’s major river basins (Molle et al. 2007). These factors reduced water available for agricultural sectors. Among non-water related factors, land degradation, poor soil fertility, soil salinity, lack of improved varieties, low rate of fertilizers used, poor weed management, unsecured land ownership, limited access to capital for investment, limited skill and abilities are the determinant factors for low crop productivity (Kijne et al. 2003; Mulugeta 2006; Singh et al. 2011). Generally speaking, water available for agricultural sector is continued to be reduced despite the increasing food demand (Kijne et al. 2003) due to increasing human population. One of the best solution to alleviate this problem lies on improving crop water productivity (Cai et al. 2010). Hence, technological interventions that could significantly increase crop water productivity and improve rural livelihoods in different landscape positions at farm and watershed levels are highly required. The Ethiopian Institutes of Agricultural Research (EIAR 2004) also recommended that water productivity improvements in crops, livestock and fishery can effectively address food insecurity and poverty. In line with this, the major objective of the study was to estimate net economic water productivity of major crops based on agro-ecology and management practices. Therefore, the study result would confidently serve as a valuable input for the concerned governmental, NGOs, policymakers and others at local, regional and country level to design and implement appropriate technological intervention strategies to the study area in particular and upper Blue Nile Basin in general so as to address the problem of water scarcity and food insecurity.

Materials and methods

Description of the study area

Meja watershed is located in Jeldu district, West Shewa in the Ethiopian part of the Blue Nile Basin. Mixed crop–livestock farming system is the most common livelihood strategy in the area (Zemadim et al. 2011). It was estimated that about 4769 households were living in the watershed from which 16% were females and the average family size of the district was six. The watershed was predominantly characterized by subsistence, low yielding rainfed agriculture, lack of appropriate soil and water conservation practices and increasing human and livestock population pressure (Berhanu Ayana 2011). The watershed covers an area of about 85.36 km² with an altitude ranging from 2440 to 3200 masl (Zemadim et al. 2011). Barley is the dominant crop cultivated followed by wheat, potato and enset (false banana), respectively. Farmers used both traditional and improved farm inputs to treat soil fertility problem and enhance crop yield. Cattle, sheep and equines were the dominant livestock species reared by farmers (Berhanu Ayana 2011). Small-scale irrigation through traditional diversion of the major river is common along the downstream regions. The area receives bimodal rainfall pattern with main rain from June to September and short rain from March to May having mean annual rainfall varies from 900 to 1350 mm (Zemadim et al. 2011). The mean maximum and minimum annual temperature ranges from 17°C to 22°C. Farmers obtained income mainly from the sale of barley, potato, green maize, eucalyptus and livestock products.

Sampling, data collection methods and determination of crop yield

The watershed was classified into three landscape positions (local agro-ecologies) and major crops representing at least 70% of each landscape position were identified through discussion with farmers and development agents in the district. Five farmers field were randomly selected for each major crop and crop management practices implemented by the farmers were monitored and yield (grain/tuber and straw) was measured at harvest. The sampled crop fields were continuously monitored in 10–20 days intervals and detailed data on crop management and agronomic practices including tillage frequency, crop rotation patterns, types of precursor crops, planting dates, seeding rates, types and
rates of fertilizer applied, methods of sowing, weed control method, date to flowering, date of maturity and harvesting dates were recorded. Above ground biomass and grain yield were also estimated using quadrat sampling technique at the time of harvesting. Samples for grain and straw were brought to laboratory and forced to dry in the oven at 65°C for 24 hours and grain moisture content was adjusted to 12%. Finally, average productivity of each crop in kg ha⁻¹ was determined.

Simulating effective precipitation
The other input data required for CWP analysis is amount of rainwater consumed to produce crop products. Weather data required for simulation of crop water requirement was generated by using New-LocClim model from FAO data base due to absence of weather station in the area. Effective precipitation (m³) was simulated by CROPWAT model using imported weather data and both crop and soil water characteristics of the study area. According to Singh et al. 2011, rainfed crops use infiltrated rainfall that forms soil moisture in the root zone which accounts for most of the crop water consumption in agriculture. As compared to other components of water, effective precipitation is more affected by crop management practices. As a result of this, effective precipitation was preferable to be utilized for CWP analysis of this particular study.

Estimating crop water productivity
Both physical and economic water productivity with respect to effective precipitation were determined as a ratio of unit mass of agricultural output (kg ha⁻¹) and economic return in ETB to effective precipitation (m³) (Kijne 2003; Steduto et al. 2007) using the following procedures:

- WP of GY or FTY (kg m⁻³) = GY or TY (kg ha⁻¹) / Effective Precipitation (m³ ha⁻¹) (A)
- WP of SY (kg m⁻³) = SY (kg ha⁻¹) / Effective Precipitation (m³ ha⁻¹) (B)
- EWP of Grain (ETB m⁻³) = GY (ETB) / Effective Precipitation (m³ ha⁻¹) (C)
- EWP of Straw (ETB m⁻³) = SY (ETB) / Effective Precipitation (m³ ha⁻¹) (D)

The net economic crop water productivity was determined by subtracting costs of production (ETB) from monetary values of BM, GY or FTY through the following course of action:

- GEWP (ETB m⁻³) = above ground BM for cereals and total BM for potato in kg ha⁻¹, Effective Precipitation (m³ ha⁻¹) or (C + D) (E)
- Net economic crop WP = GEWP (ETB m⁻³) – Q (ETB) (F)

Where WP, EWP, GEWP, ETB, Q, BM, GY, FTY, SY refer to Water productivity, economic water productivity, gross economic water productivity, Ethiopian birr, Costs of Production, Biomass, grain yield, fresh tuber yield and straw yield, respectively.

Data analysis
In order to test whether there is significant mean net economic biomass, grain or tuber water productivity difference among the three agro-ecological zones or not, comparison of means was employed. The null hypotheses for such test would be: $H_0: x_1 = x_2 = x_3 = \ldots = x_k$ where $x_1$ to $x_k$ represent sample means of the 1 to k groups (Storck et al. 1991) and the most appropriate statistical technique to test such hypothesis is the analysis of variance (Norusis 1987). Analysis of variance is used to examine the degree of variability in the mean net economic biomass and grain or tubers water productivity results. Based on the variability, some conclusions about the means were drawn. Again,
one-way analysis of variance (multiple comparisons) test was also applied to justify the differences among mean net economic biomass and grain or tubers water productivity magnitudes of the major crops with respect to each local agro-ecology. In addition to this, several management practices that could affect crop water productivity in the study watershed were considered to test their degree of association with net economic biomass and grain or tuber water productivity. The Pearson’s correlation analysis was employed to test the existence and strength of relationships between the selected crop management practices and net economic biomass, grain or tuber water productivity across the three local agro-ecological zones by using SPSS software. Based on the results and level of significance, the possible effects of those management practices on EWP magnitude of each crop was presumed.

Results and discussion

Physical crop water productivity

Productivity is a ratio between a unit of output and a unit of input and the term water productivity is used exclusively to denote the amount (physical) or value (economic) of product over volume of water depleted or diverted (Renault and Wallender 2000; Kijne 2003; Steduto et al. 2007). For this particular study, the amount of product and individual net monetary value over volume of effective precipitation was considered. Hence, the average rainwater productivity result of barley grain was 0.78 kg m\(^{-3}\) while that of wheat (0.83 kg m\(^{-3}\)) in the upper zone and 0.98 kg m\(^{-3}\) in the middle zone. WP of teff in the lower zone (0.64 kg m\(^{-3}\)) was more than twice of that of middle zone (0.29 kg m\(^{-3}\)). Similarly, the WP of sorghum in the lower zone (0.71 kg m\(^{-3}\)) was better by 17% than that of the middle zone (0.52 kg m\(^{-3}\)). WP of maize was 1.14 kg m\(^{-3}\) and that of fresh potato tuber was 9.98 kg m\(^{-3}\) in the upper zone (Table 1). These cereal crops WP results are strongly agreed with research output by Droogers et al. (2001) and Cai and Rosegrant (2003), in that the value of WP index for cereals ranged from 0.50 to 1.50 kg m\(^{-3}\) depending on variety, soil, climate and management. According to FAO (2011), the world average WP of barley, wheat and fresh potato tubers range from 1.20 to 1.40 kg m\(^{-3}\), 1 to 1.20 kg m\(^{-3}\) and 4 to 11 kg m\(^{-3}\), respectively. Likewise, the average WP of sorghum at global level also ranges from 0.80 to 1.30 kg m\(^{-3}\). Thus, the average WP results of barley, wheat and sorghum were by far lower than that of the global average while that of fresh potato tubers falls within the range of world average. There is no well-defined study on teff WP in Ethiopia and elsewhere in the world except Araya et al. 2010 and Alemtsehay et al. 2011, who tried to estimate normalized WP test to use in AquaCrop simulation. However, its average WP result (0.47) was extremely lower even as compared to all other cereal crops considered for this study. Therefore, WP of the dominant food crops like barley, wheat, teff and sorghum needs to be improved so as to bring sustainable livelihood improvement in the area and beyond.

<table>
<thead>
<tr>
<th>Agro-ecology</th>
<th>Crop</th>
<th>Grain</th>
<th>Straw</th>
<th>Biomass</th>
<th>Fresh Tuber</th>
<th>Effective Precipitation (m(^3))</th>
<th>Physical WP (kg m(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Zone</td>
<td>Barley</td>
<td>3487</td>
<td>5397</td>
<td>9424</td>
<td>–</td>
<td>4463</td>
<td>2.11</td>
</tr>
<tr>
<td></td>
<td>Wheat</td>
<td>3629</td>
<td>10544</td>
<td>14173</td>
<td>–</td>
<td>4364</td>
<td>3.25</td>
</tr>
<tr>
<td></td>
<td>Potato</td>
<td>–</td>
<td>1360</td>
<td>54600</td>
<td>53240</td>
<td>5334</td>
<td>10.24</td>
</tr>
<tr>
<td>Middle Zone</td>
<td>Teff</td>
<td>3569</td>
<td>7167</td>
<td>10735</td>
<td>–</td>
<td>3947</td>
<td>2.72</td>
</tr>
<tr>
<td></td>
<td>Sorghum</td>
<td>3050</td>
<td>17435</td>
<td>20485</td>
<td>–</td>
<td>5878</td>
<td>3.49</td>
</tr>
<tr>
<td>Lower Zone</td>
<td>Teff</td>
<td>1631</td>
<td>3799</td>
<td>5430</td>
<td>–</td>
<td>2550</td>
<td>2.13</td>
</tr>
<tr>
<td></td>
<td>Sorghum</td>
<td>3802</td>
<td>20799</td>
<td>24601</td>
<td>–</td>
<td>5391</td>
<td>4.56</td>
</tr>
<tr>
<td></td>
<td>Maize</td>
<td>5986</td>
<td>22129</td>
<td>28115</td>
<td>–</td>
<td>5274</td>
<td>5.33</td>
</tr>
</tbody>
</table>

Source: Field measurement 2011, CROPAT model and own calculation.

Net economic crop water productivity

Water productivity calculated in terms of net value output gives better picture of the net gain from a unit of water in production than gross value output (Mulugeta 2006). The results also help to make comparison of economic benefit
of one crop with other crops and also assist farmers to make proper decision to invest on more valuable crops at the expense of others. Economic value of the crops and production costs i.e. seed, fertilizers, labour, agrochemicals and other inputs were determined based on their local market value. The result indicated that potato has extremely high cost of production (ETB 25,551 ha⁻¹) as compared to other cereal crops whereas sorghum has the least cost of production (Figure 1B). The net economic water productivity of sorghum, teff, wheat, barley and maize grains were ETB 3.10, 3.27, 3.49, 3.73 and 5.54 m⁻³, respectively, while that of fresh potato tubers was ETB 15.17 m⁻³ (Figure 1A).

Regarding economic benefit of food crops, potato tuber has the highest economic value followed by maize, barley and wheat while that of sorghum has the least value in the study district. In terms of net economic BM water productivity (food and feed), barley, wheat, teff, sorghum, maize and potato has ETB 4.77, 4.78, 4.97, 6.63, 7.09 and 13.56 m⁻³, in that order (Figure 1A). Here, potato again ranks first followed by maize, sorghum and teff whereas barley was the lowest. Thus, it is possible to say that potato is the most appropriate crop in economic water productivity than all other crops in the upper zone of the study watershed. Similarly, wheat is more appropriate in the middle zone and that of teff in the lower zone. Generally speaking, net economic benefit obtained from BM (food and feed) is by far better than that of food crop indicating the need to integrate crop with livestock. Several research results confirmed that crop–livestock interactions increase productivity and the income of farmers and improve system resilience and environmental sustainability (Devendra and Thomas 2002; Parthasarathy Rao et al. 2005). Therefore, if farmers integrate crop with livestock, they will generate better economic benefit from available land and water they are endowed with rainfed and also bring sustainable livelihood improvement in the long run.

**Figure 1.** Net economic water productivity of biomass, grain and fresh tuber yield in ETB m⁻³(A) and costs of production in ETB ha⁻¹ (B).

**Effect of agro-ecology on physical and net economic CWP**

The ANOVA test result indicated that there was significant mean of both physical and net economic CWP variation (at \( p = 0.014 \) and \( P = 0.001 \), respectively) between the three local agro-ecological zones. However, one way ANOVA (multiple comparisons) test result showed that the variation was significant for both variables only in between upper and middle and upper and lower zone indicating that treating the middle and lower agro-ecological zones independently is not necessary but rather treating them as one. Therefore, the three local agro-ecological systems arbitrarily classified by the local people should be corrected to only two zones (upper and middle) having no lower zone and the whole watershed, except few areas around the outlet, fall in the upper zone. Ecologically, the upper zone was highly degraded and more populated than the other two zones. The severity of land degradation due to high human and livestock population pressure, poor land and water management practices (Berhanu Ayana 2011 and Zemadim et al. 2011) increased surface runoff and reduced infiltration resulting in low water productivity. In addition, barley was a dominant crop in the district in general and in the watershed in particular but, its total BM water productivity was found to be the lowest. Therefore, technological interventions that could increase soil water availability, improve productivity and enhance economic benefit are required mainly here. Most of the soil and soil nutrients washed away by erosion from the upper zone deposit in the middle and lower zones. This aspect was
Rainwater management for resilient livelihoods in Ethiopia

Effects of management practices on physical and net economic CWP

The aspects like physical and economic crop water productivity in a system depend on many factors and the management practices prevailing in the watershed is one.

Several management practices were considered and investigated their relationship with both physical net economic WP. The result showed that rate of UREA and DAP application, seeding rate, crop variety, precursor crop, method of sowing and harvesting date significantly affected both parameters (Table 2) indicating that improving rate of application of both types of fertilizers, using improved method of sowing and proper seeding rate based on crop type, variety, location in a landscape position and other physiographic conditions could considerably increase CWP in the area. This finding strongly agreed with research outputs of Toung 1999; Rockstrom and Steiner 2003; Kijne et al. 2003; Molden et al. 2003 and Mulugeta 2006 in that any management practices used to enhance crop yield significantly increased crop WP. Hence, farmers should implement improved management and agronomic practices so as to increase CWP.

Table 2. Some management and agronomic practices and their degree of association with CWP

<table>
<thead>
<tr>
<th>Variable</th>
<th>Net EWP WP of grains or fresh tubers</th>
<th>Physical WP of grains or fresh tubers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pearson’s corr. coeff. (r)</td>
<td>Significance (p-value)</td>
</tr>
<tr>
<td>UREA (kg ha⁻¹)</td>
<td>+0.562** 0.000 0.000</td>
<td>+0.681** 0.000 0.000</td>
</tr>
<tr>
<td>DAP (kg ha⁻¹)</td>
<td>+0.740** 0.000 0.000</td>
<td>+0.849** 0.000 0.000</td>
</tr>
<tr>
<td>Seeding rate (kg ha⁻¹)</td>
<td>+0.851** 0.000 0.000</td>
<td>+0.950** 0.000 0.000</td>
</tr>
<tr>
<td>Crop type</td>
<td>– – –0.377** 0.011 0.011</td>
<td></td>
</tr>
<tr>
<td>Crop variety</td>
<td>–0.359 0.016 0.010</td>
<td>–0.382** 0.003 0.003</td>
</tr>
<tr>
<td>Precursor crop</td>
<td>–0.434** 0.003 0.003</td>
<td>–0.438** 0.003 0.003</td>
</tr>
<tr>
<td>Tillage frequency</td>
<td>– – +0.302** 0.044 0.044</td>
<td></td>
</tr>
<tr>
<td>Method of sowing</td>
<td>+0.706** 0.000 0.000</td>
<td>+0.671** 0.000 0.000</td>
</tr>
<tr>
<td>Harvesting date</td>
<td>–0.577** 0.000 0.000</td>
<td>–0.531** 0.000 0.000</td>
</tr>
</tbody>
</table>

*Significant at the 0.05 level and ** at the 0.01 level (2-tailed).

Conclusions and recommendations

The study revealed that farmers tried to implement different crop management practices which were not appropriate such as inappropriate crop rotation systems, maximum tillage, inadequate rainwater management systems, improper seeding rates, inappropriate fertilizer rate, traditional methods of sowing (88%) and harvesting (100%), delayed harvesting, poor weed control methods were mostly practised. Among this, rate of fertilizers applied, seeding rate, crop variety, types of precursor crops, method of sowing and harvesting date as well as landscape positions significantly affected both physical and net economic water productivity of food crops. Water productivity results in kg m⁻³ of barley, wheat and sorghum grains were by far lower than that of the global average while that of fresh potato tubers falls within the range of world average. Even though there is no well-defined study on teff water productivity in Ethiopia and elsewhere in the world, its average water productivity result (0.47kg m⁻³) was the least as compared to all other cereal crops under study. Therefore, water productivity of the dominant food crops like barley, wheat, teff and sorghum needs to be improved so as to bring sustainable livelihood improvement in the area and beyond. In terms of economic benefit (ETB m⁻³) of food crops, fresh potato tuber has the highest economic value followed by maize, barley and wheat while that of sorghum has the least value in the study district. With respect to net economic biomass water productivity (food and feed) maize, sorghum and teff were the leading whereas barley was the least. Thus, it is possible to say that potato is the most appropriate crop in both economic and physical water productivity than all other crops in the upper zone of the study watershed; wheat is more appropriate in the middle zone and that of teff in the lower zone. Generally, net economic benefit obtained from biomass (food and feed) is by far better than net economic benefit of that of food crop. Therefore, if farmers integrate crop with livestock, they will generate better economic benefit from available land and water they are endowed with rainfed and also bring sustainable
livelihood improvement in the long run. In addition to this, the one way ANOVA (multiple comparisons) test result shows that there was significant variation of both variables only in between upper and middle and upper and lower zone indicating that treating the middle and lower agro-ecological zones independently is not necessary but rather treating them as one. Therefore, the three local agro-ecological systems arbitrarily classified by the local people should be corrected to only two zones (upper and middle) having no lower zone and the whole watershed, except few areas around the outlet, fall in the upper zone.

Hence, some of the recommendations include implementing improved technology at both farm and watershed level such as using improved crop varieties, improving rate of fertilizers use, using improved crop ration, appropriate seeding rate, improve method of sowing and timely harvesting, diversifying rainwater management systems, crop diversification and integrating crop with livestock could significantly improve both the quantity and economic values of crops. Moreover, given the high current and potential productivity of potato in the upper part of the watershed and poor market linkage, all local and regional actors need to facilitate the development of value chain for this essential product. Furthermore, scaling up and implementing these findings to the whole basin could help to address the problem of water scarcity and food insecurity so as to bring sustainable livelihood improvement in the long run.

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