Journal of Sustainable Development; Vol. 5, No. 7; 2012
ISSN 1913-9063 E-ISSN 1913-9071
Published by Canadian Center of Science and Education

Increasing Livestock Water Productivity under Rain Fed Mixed Crop/Livestock Farming Scenarios of Sub-Saharan Africa: A Review

Mengistu Alemayehu[1, 2], Tilahun Amede[3], Michael BÖhme[4] & Kurt J. Peters[1]

[1] Humboldt Universität zu Berlin, Berlin, Germany

[2] Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia

[3] International Livestock Research Institute/International Water Management Institute, Addis Ababa, Ethiopia

[4] Humboldt Universität zu Berlin, Berlin, Germany

Correspondence: Mengistu Alemayehu, Humboldt Universität zu Berlin, Philippstr. 13, Haus 9, Berlin 10115, Germany. E-mail: mengistualem@yahoo.com

Received: May 10, 2012 Accepted: June 4, 2012 Online Published: June 11, 2012

doi:10.5539/jsd.v5n7p1 URL: http://dx.doi.org/10.5539/jsd.v5n7p1

Abstract

Although water is a renewable natural resource, it has become insufficient at the global level. Unless the current efficiency level of water use can be increased, the trend of water shortages will become more serious. Among agricultural activities, livestock production is mostly considered an intensive water consuming operation although the knowledge and information related to livestock-water interaction appears to be limited in scope. The present review focused on the livestock-water interaction with the following objectives: 1) to strengthen the current understanding of the concept of livestock water productivity and relate it to life cycle assessment analysis framework; 2) to provide insights on the methodology of livestock water productivity estimation using water foot printing approach; 3) to assess the potential integrative intervention options towards improving livestock water productivity pertinent to the contexts of rain fed mixed farming. The concept of water accounting for livestock production is reviewed to reflect feasible options for improving animal productivity, income, livelihood and ecological benefits per unit of water input, especially the practical implications of these options for the rural poor in Sub-Saharan Africa. Utilising the rainfed mixed farming endowment as a relatively less competitive water scenario is also emphasised. In line with the intention for increased livestock water productivity, the likelihood of its negative impact on the environment and possible mitigating methods are outlined.

Keywords: livestock water productivity, sub-Saharan Africa, life cycle assessment, water footprint, mixed farming system

1. Introduction

Livestock production has a prominent position in satisfying the diverse needs of humans ranging from the provision of natural animal food products (highly nutritious) to rendering the associated benefits of economic, social, cultural and ecological domains (Thomas et al., 2002). Furthermore, livestock is considered an inflation-proof asset that can be converted into cash in difficult times for the poor livestock keepers in developing countries (Thomas & Sumberg, 1995). In Sub-Saharan Africa (SSA), the livestock component of mixed farming is highly significant in ensuring food security and reducing poverty (Thornton & Herrero, 2001; Thomas et al., 2002). The statistics indicate that approximately 144 million people (in SSA) located within mixed-farming systems often manage to draw their livelihoods from livestock (Thornton et al., 2002). However, livestock productivity is usually low because of inadequate feeding, ill health (ACIAR, 2003), less capital input, depleted natural resources, low genetic potential of local breeds and limited access to improved technological options.

Currently, the demand for livestock products in developing countries has increased by 6% to 8% per annum (ACIAR, 2003), which exceeds that of cereals (Steinfeld et al., 2006). The rising demand for livestock products has occurred following the rise in incomes that trigger an accelerated desire to eat nutritious foods (Delgado et al., 1999). While attempting to satisfy the increasing and changing demands for animal food products, keeping sustainability of the natural resource base (soil, water, air and biodiversity) at the same time is a key issue confronting the agriculture (Steinfeld, 2004), particularly in view of the present climate change and concern over animal welfare. Fresh water resources are fixed in abundance, yet the loss of water in both rainfed and irrigated agriculture systems often amounts to more than 70% (Wallace, 2000), highlighting the need for improving water use efficiency.

Although the largest part of fresh water is left for agricultural use (Wallace, 2000; Steinfeld, 2004; Molden et al., 2010), there is an increasingly growing demand and competition for this finite water resource required by municipal and industrial sectors for other indispensable uses. Among agricultural activities, livestock production is widely considered an intensive water consuming activity (Molden et al., 2010) but with a wide variability of potential for improvement (Peden et al., 2007). Globally, livestock farming is responsible for approximately 20% of the evapotranspiration (ET) in agriculture (de Fraiture et al., 2007), and this share is expected to considerably rise in an attempt to fulfil ongoing increments of demand for animal products. In addition, climate change may also induce rainfall reduction and alteration of its distribution pattern to cause frequent droughts in tropical regions (Zhang et al., 2007) and intra-seasonal dry spells (Rockstrom et al., 2002), which cause SSA to be vulnerable because its rainfed agriculture constitutes more than 95% of the agricultural land use (Rockstrom et al., 2004). These scenarios underscore the need for improving water management in rain fed agriculture to secure the water required for food production and to build resilience for coping with water scarcity (Rockstrom et al., 2010). Thus, improving the productivity of water in livestock production may substantially contribute to reducing future agricultural water needs. Capitalising on rain fed agriculture is a worthwhile consideration to lessen the competition for scarce water resources. Moreover, it may boost the potential for increasing water use efficiency of the rainfed system from its present low level of utilisation (less than 15% of rainfall) in field conditions of Africa (Rockstrom, 1999).

Knowing that the challenge of water scarcity will continue in the years to come, it is worthwhile to consider every option for optimising the use of water. There is limited knowledge on livestock-water interactions (Peden et al., 2007; Descheemaeker et al., 2010) and the limited available information largely refers to industrial livestock production systems. A conceptualised livestock-water interaction is the focus of the present review in the context of rain fed mixed farming systems of SSA. Therefore, the objectives of this review were 1) to strengthen the current understanding of the concept of livestock water productivity and relate it to life cycle assessment (LCA) framework, 2) to provide insights on the methodology of livestock water productivity estimation using water foot printing approach, and 3) to assess the potential integrative intervention options for improving livestock water productivity.

2. Understanding Livestock - Water Interactions

The provision of water is critically important in all animal production systems because most livestock have to drink at least every other day to remain productive and have to drink every few days to survive (King, 1983). As the production level intensifies, the need for water by a productive animal increases. Thus, water constraints severely affect the productivity of livestock. King (1983) stated that the greatest threat to life on land is the danger of dehydration. In a tropical ruminant, 99% of all the molecules in the body are water (King, 1983), which forms approximately 65% to 80% of the body weight of the animal (Lillywhite & Navas, 2006).

Animals obtain their water not only from drinking but also from their feed, metabolic processes within the animal and other sources. While access to adequate water is essential for livestock production, drinking water is only of minor significance (50 l/day for a TLU) in terms of livestock water budgets in a farming system or watershed as compared to the amount of water depleted for feed production, which can reach 5,000 l/day for a TLU or 100 times that amount directly consumed (Peden et al., 2003). Nonetheless, the daily drinking water requirement of livestock and its regular provision should not be neglected. The metabolic function of water in the animal body is a highly determinant factor for maintaining the normal physiological process and healthy production state of the animal despite its small proportional amount as indicated above.

In arid areas with annual precipitation below 600 mm, most common crops do not have good yields, and isohyets near this magnitude delineate the natural limit between animal and crop production (Wilson, 2007). In such environments, raising livestock represents the only feasible agricultural activity under rainfed conditions for utilising the extensive natural grasslands of marginal areas in the world, which are estimated to cover approximately 21 million km^2 (Mack, 1996). Consequently, the pastoral livestock system can be considered the best traditional strategy in utilizing this scarcely available water, which is normally obtained from erratic rainfall sources that would have otherwise remained non-beneficial (Cook et al., 2009).

2.1 Water Accounting for Livestock Production

In the past, the growth in agricultural production has heavily relied on increasing water withdrawals for farming (Humboldt Forum for Food and Agriculture, 2010). In the face of the present trend of critical water deficit for satisfying multiple uses (Molden et al., 2007; Descheemaeker et al., 2010; Rockstrom et al., 2010), the growth of future food production is highly influenced by water shortage unless the efficiency of its use is dramatically increased in all respects (Wallace, 2000). It is thus necessary to have a clear description of the water input depletion in the course of agricultural production to arrive at appropriate option for improving agricultural water management (Bastiaanssen et al., 2008).

2.2 Livestock Water Productivity (LWP)

With regard to water productivity, its implication goes beyond the direct effect of simply increasing total farm outputs and farm income (Bossio et al., 2010; Namara et al., 2010). Because water productivity plays a pivotal role in improving land productivity, increasing labour productivity, safeguarding the ecosystem, encouraging the use of more inputs, providing employment opportunity and fostering equitable economic growth (Harrington et al., 2009), it needs to involve and intersect the complex matters associated with social, economic, organisational, policy and technical issues (Amede et al., 2009).

Water productivity is generally defined as output per unit of water depleted in the production process where the output can be measured in physical terms or values. It is considered to serve as a partial measure of productivity (Harrington et al., 2009) because of its limitation in accounting for all types of benefits. With the present empirical formula of water productivity, it is widely variable in space and time scale even in areas with apparently similar agro-ecologies (Harrington et al., 2009). It is more useful to emphasize on selective priority areas where profound increases in water productivity are possible (Molden et al., 2010). The identified scenarios include the following areas where: 1) poverty is high and water productivity is low; 2) competition for water is high due to its scarcity; 3) high returns from additional water use can make a substantial difference; and 4) water-driven ecosystem degradation occurs, such as falling groundwater tables and river desiccation. SSA is of particular concern because the intended changes can be comprehended with the application of appropriate interventions. The progress can be evaluated by monitoring the extent of improvement in water productivity.

The determination of LWP followed the concept of water productivity as described by Peden et al. (2009). LWP is a ratio of total benefits in terms of outputs and services obtained from livestock per total water depleted in livestock production. Wide variations have been noticed in reported values of LWP (from case studies in Ethiopian highlands) such as 0.4 USD m^{-3} volume of water by Haileselassie et al. (2009) against 0.07-0.09 USD m^{-3} by Mekonnen et al. (2011) for similar subsistence based mixed faming systems. This may indicate that there is a strong need to refine and standardize the methodology for estimating LWP. The numerator takes the total sum of benefits obtained from livestock over the complete period of productive herd life including their insurance value. In SSA, keeping livestock serves as live banking to accumulate asset. The denominator represents the amount of water depleted for producing feeds, consumed by the animals (expressed as evapo-transpiration), and for drinking over the entire lifetime of the herd being assessed based on the water foot printing concept (Hoekstra et al., 2009) and applying the frame of LCA (Beauchemin et al., 2010; Koehler, 2008). To represent this relationship, a computational model was adapted from Peden et al. (2009) and modified as follows:

$$LWP = \frac{\sum_{i=1}^{n}(O_i * P_i) + \sum_{j=1}^{n} SC_j - \sum_{j=1}^{n} M_j}{\sum_{k=1}^{n} ET_k + \sum_{j=1}^{n} D_j + \sum_{l=1}^{n} S_l + \sum_{m=1}^{n} DGm} \quad (1)$$

Where O_i=quantity of the i^{th} livestock output or service type obtained over the productive life span, P_i=local market price (USD) of the i^{th} output or service type, SC_j=stock capital (USD) of a breeding herd/flock of the j^{th} livestock species towards the end of productive life span, Mj=loss of monetary value (USD) due to mortality of the j^{th} livestock species, ET_k=water depleted (m^3) in evapotranspiration to produce k^{th} feed type consumed by livestock species kept at the farm over the productive life span or until off take being assessed using water-foot printing concept in LCA frame, D_j=drinking water consumed (m^3) by the j^{th} livestock species kept at the farm over the productive life span or until off take being assessed using water foot printing concept in LCA frame, S_l=water used (m^3) in l^{th} service type such as cleaning of barn, milking parlour and milk utensils, DG_m=degraded water due to contamination for livestock production in m^{th} water source like dipping and spraying in veterinary services.

2.3 LCA and Water Foot Printing

Agriculture today must follow a sound path to sustain the environment and the ecology. It is expected to increasingly maintain public values e.g. positive landscape image and appropriate animal welfare (Haas et al., 2001). Emphasizing on fresh water resource use and its allocation, Koehler (2008) reported the need for assessing the use of agricultural water by applying the LCA framework. LCA is a method that can be applied to compile inventory and evaluate agricultural production system for assessing its impact on natural resource management in a defined system boundary (Haas et al., 2001). To estimate LWP at farm level, LCA within the boundary of cradle to farm gate, enables us to enfold the entire herd life in accounting for water. It invokes the whole continuum from birth/growing period to end of the productive age of a herd.

The water footprint of a product is conceptualized as the amount of freshwater used to produce the product, measured over the full supply chain. Hoekstra and Chapagain (2008) have shown that visualizing the hidden water use behind products can help in understanding the global character of freshwater and in forming the foundation for a better management of the globe's freshwater resources. Truncating the boundary of the water foot printing to a livestock farm gate, the volume of water consumed by livestock can be quantified from birth to end of productive age or off-take in the breeding cycle. The water foot print accounting is based on the LCA frame of livestock production. It considers the subsequent growth stages of livestock as: i) birth to weaning, ii) weaning to maturity and iii) production to culling. Nutrient requirement of an animal varies depending on its growth and productive stage and hence quantifying the feed demand over lifespan of the animal must take care of all this.

The water used for producing animal feeds comprises the majority of the physical water needed for determining the extent of LWP (Molden et al., 2007; Peden et al., 2007; Peden et al., 2009). To calculate ET and crop water requirements, the CROPWAT model of FAO (1998) and the Penman-Monteith equation (FAO, 2005) are employed. Of all the forms of water depletion, transpiration is preferable (Peden et al., 2009) for its contribution towards increasing biomass production, thereby improving the nutrition of animals, which is the most serious limitation to increasing livestock productivity.

In mixed farming systems, the utilization of crop residues as animal feed is currently a prominent practice. In these systems, farmers appreciate the nutritional values of crop residues and hence they play a role in choosing the type or variety of crops. Considering market price of grain and crop residue as a partitioning factor helps to allocate the total ET between the two components.

2.4 Livestock Outputs and Services

The production goal of a farm dictates the type of livestock output. For instance the output of a dairy farm is majorly milk, and of a cow-calf beef ranch is meat. In typical mixed crop/livestock faming systems of SSA, livestock have multi-functions and give many outputs and services. Ordinarily, a smallholder farmer keeps mixture of livestock species such as cattle, sheep/goat and equine. It needs to model the herd structure of a farm and quantify the different outputs and services of each livestock species by age class over the productive lifetime of a herd or until off-take time. Using manure for replenishing soil fertility and draught oxen for land cultivation have considerable values in such system. Keeping livestock in the mixed farming of SSA also has the merit of asset accumulation and insurance, which this to be considered in the valuation like the case quantified by Bebe (2003). Each output or service needs to be converted into monetary value. The monetary unit is more convenient and comprehensible for combining the values of diverse benefits as they are derived from multiple livestock species and are variable in terms of quality. Animal mortality is a serious problem in livestock production scenarios of SSA where livestock diseases are rampant. It is necessary to account for the monetary loss due to livestock mortality in determining the value of LWP.

3. Strategies to Enhance LWP

Increased LWP reverses land degradation and safeguards environmental resilience in addition to improving food security and livelihoods (Descheemaeker et al., 2010). The volume of water needed to produce 1 kg of meat or milk is estimated to range from 3,000 l to 15,000 l (Molden et al., 2007) depending on the type of husbandry, the type of feedstuff, the processing system and the conversion efficiency of animals. Improvement in LWP can be realized by adjusting each of these factors. Research results have shown that proper management can improve the return from water by more than two-folds (Oweis, 1997). Various experiences reveal that there is considerable scope for increasing livestock productivity in both physical and economic water productivity (ILRI, 2006; Peden et al., 2007; Molden et al., 2010). Strategies to enhance LWP include improving feed components, improving grazing management, enhancing animal productivity, improving water management, strengthening livestock marketing, improving animal health, and reducing negative environmental impacts, such as water pollution. The compatibility of the intervention and its environmental friendliness to the specific local context should be considered with caution, as the adoption of a well-proven technology can often be stalled by the coevolving changes that entail intensive labour demand, gender inequality, additional cost, mode of utilisation and cultural implication. Thus, increasing water productivity demands thorough understanding of the biophysical, socioeconomical and environmental aspects at field, farm and basin scale (Amede et al., 2009; Descheemaeker et al., 2010; Molden et al., 2010).

4. Impacts of Livestock on Environment

Currently, the quick rises in demand for animal food products in developing countries are placing unprecedented stress on the resources used in livestock production (Delgado et al., 1999; Steinfeld, 2004). Livestock production is blamed for its strong association to land degradation, water pollution, green house gas emission and the erosion of biodiversity (de Haan et al., 1997). However, the negative role attributed to livestock is frequently a result of other pressures and distorted policies (de Haan et al., 1997; Boyazogulu, 1998).

Land degradation is considered a major threat to future agriculture in SSA because it reinforces poverty (Steinfeld, 2004). The impact is substantiated by the reports of case studies on the trends of soil erosion in the highlands of Ethiopia, showing that land degradation can reduce per capita incomes of the residing people by 30% (FAO, 1986). Livestock production is believed to be among the key causes of land degradation (Hurni, 1988; Mwendra et al., 1997a; Mwendra et al., 1997b; Tadesse, 2001; Steinfeld, 2004). Grazing systems set the direct interface between livestock and land, water and biodiversity, which represent a significant part of the natural resources of the earth (de Haan et al., 1997). Livestock grazing inflicts change on watershed ecosystem by altering the plant cover and causing physical damage (Blackburn, 1983). The mechanical pulverisation effect on the soil and the denudation of the vegetation cover eventually lead to serious land degradation (Tadesse, 2001). The tradeoffs between the need to improve livestock productivity and the desire to sustain natural resources should be scrutinised to keep them compatible (Bellaver & Bellaver, 1999).

Ruminant livestock are labelled as significant contributors to global warming through the emission of greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) (Schils et al., 2007). In Europe, emissions from ruminant livestock account for 55% of the total agricultural emissions (Freibauer, 2003). These gas emissions are assumed to be higher in developing countries because of the higher number of livestock and the dominant use of fibrous and less digestible feedstuffs. The goal of lowering these agriculture-related greenhouse gas emissions in Europe (to an approximate 10% reduction level by 2004) was achieved through a strategy targeted at reducing livestock population (Schils et al., 2007). This perhaps entails a shift in human food habits towards vegetarianism at least in the developed world where the concern or awareness of dietary health has already been developed. The use of higher concentrate proportions in the diet of ruminants or an increase in the digestibility of forages may contribute to reducing methane emissions (RuMeth International, 2001).

In rural areas, agricultural activities result in surface water and groundwater pollution (Zhang et al., 2009). Water is vulnerable to contamination from livestock farms. A case report shows that drinking water was contaminated by effluents from livestock agriculture causing illness of local people in Canada (Burton, 2009). In SSA, water sources are commonly used for multiple uses. Hence, the extent of the problem from water contamination would be worse in the rural areas of SSA, leading to an increased risk of human health. The challenge of water pollution from a nitrate source further compounds the problem (Hooda et al., 2000). To address this problem, a convenient device for isolating the access to livestock drinking water must be developed.

It is plausible that grazing alters the botanical composition of a pasture. De Haan et al. (1997) indicated that heavy grazing for a longer period causes the disappearance of desirable plant species and the subsequent dominance of other, less desirable, herbaceous species. The same report showed that the total absence of grazing also reduces biodiversity in some cases because a thick canopy of shrubs and trees develops, and results in overprotected plant communities that are susceptible to natural disasters. However, previous studies illustrated that moderate grazing maintains watershed conditions and utilises the feed resource base for optimal return (Blackburn, 1983).

In general, livestock production with good management can also make a positive contribution to the natural resource base by enriching soil quality, keeping plant biodiversity and others (Cunningham, 1999). Therefore, policies and technologies that favour good management need to be identified and implemented to overcome the negative environmental impact in an attempt to satisfy the increasing demand for livestock products.

5. Implications of LWP on Rain Fed Mixed Crop/Livestock Farming

Smallholder farming in SSA occurs in diverse conditions of soil, climate and socio-economic structure. The development of these systems is strongly affected by the limited availability of key resources, like land, plant nutrients, cash and labour (van Wijk et al., 2009). In mixed farming systems, the ways of utilizing these resources and the decisions of farmers pertaining to the allocation of the resources have immense implications to the farm livelihood (van Wijk et al., 2009). Hence, there is a wide variation in level of development of the mixed farming systems across the world depending on their specific contexts (resource use efficiency, productivity of the integral components, sustainability of the agroecological system and socioeconomic/governance complexes).

The evolutionary trend of mixed farming systems has shown that as the pressure on land increases, herds are restricted to smaller grazing areas during the cropping season to avoid crop damage (Powell & Williams, 1995), which poses nutritional problems for the livestock and increases the risk of overgrazing. During dry seasons when low-lying areas are transformed into irrigated gardens, traditional grazing lands may become inaccessible, giving few alternatives for livestock that otherwise have to depend on aftermath grazing and crop residues. Strategies directed at raising the productivity of a specific mixed faming system need to consider the stage of development of the target area and the nature of the crop/livestock interactions (Jagtap & Amissah-Arthup, 1999).

Under crop residue grazing, animals remove greater amounts of biomass and nutrients disproportionate to the manure return (Powell & Williams, 1995). This nutrient removal by livestock may lead to the spread of animal voiding in the landscapes, which is usually concentrated around watering points, resting places and along trekking paths (Stoorvogel & Smalling, 1990). As a result, nutrient balance has become negative for many farming systems in SSA. Increasing population pressures on fixed land resources of poor soil fertility have turned the arable lands to barely provide the basic food needs (Wilson, 2007). The present and future trends of water availability prove that rain fed agriculture will continue to have a significant role in securing food and livelihoods of an increasing world population (Rockstrom et al., 2010). However, supporting rainfed agriculture with supplemental irrigation schemes by enforcing water harvesting and storage mechanisms becomes an indispensable necessity to mitigate terminal water stress that nowadays occurs more frequently (because of climate change). The integration of livestock with crop farming contributes to the optimal utilisation of farm resources (Harrington et al., 2009).

6. Conclusions

Satisfying the growing demands for livestock products while simultaneously sustaining the natural resource base (soil, water, air and biodiversity) is a key issue confronting the future farming practices. Alleviating malnutrition and food insecurity in developing countries will require reducing the existing wide gap between actual and maximal yields. Improving productivity is the most plausible way to meet the demand for agricultural products.

Investigating the concept of livestock-water interactions and water accounting may help to better understand the wider dimension and complexity of water uses in a given domain. The in-depth understanding of these interactions and water accounting in LCA framework will help to explore alternative options for improving the use of this scarce water resource. Because LWP is a function of both livestock outputs and water input, there is a need to consider practical avenues for enhancing livestock outputs by combining them with water use efficiency in a manner more compatible to the specific local contexts.

Capitalising on rain fed agriculture may have a key role in lessening the competition for scarce water resources. Moreover, emphasis on virtual water trading would also contribute to increase water use efficiency from global perspective. Integrating crop and livestock in mixed farming systems is a better and more synergistic way of utilising farm resources. Livestock can make use of the crop by-products and a portion of the non-process water depletion (such as weeds and green biomass that grow along farm paths between crop fields) to convert this fibrous matter into useful animal products with higher food value, thereby contributing to increasing water productivity.

Acknowledgements

The first author thanks the CGIAR Challenge Program on Water and Food (CPWF) for financially supporting his PhD study under project number PN37. He extends his gratitude to the International Livestock Research Institute (ILRI) for providing him graduate fellowship and the Ethiopian Institute of Agricultural Research (EIAR) for offering him study leave.

References

ACIAR-Australian Centre for International Agricultural Research. (2003). Meeting rising demand for animal protein: 1.4. Researching profitable crop-livestock systems for developing crops. *Internal Report of ACIAR*.

Amede, T., Geheb, K., & Douthwaite, B. (2009). Enabling the uptake of livestock water productivity interventions in the crop-livestock systems of sub-Saharan Africa. *The Rangeland Journal, 31*, 223-230. http://dx.doi.org/10.1071/RJ09008

Bastiaanssen, W. G. M., Binfang, W., Liping, J., & Olson, D. (2008). *The need for ET management of closed river basins with irrigated agriculture*. Water Front, World Water Council, Stockholm, Sweden.

Beauchemin, K. A., Janzen, H. H., Little, S. M., McAllister, T. A., & McGinn, S. M. (2010). Life cycle assessment of green house gas emissions from beef production in western Canada: A case study. *Agricultural Systems, 103*, 371-379. http://dx.doi.org/10.1016/j.agsy.2010.03.008

Bebe, B. O. (2003). *Herd dynamics of smallholder dairy in the Kenyan highlands*. PhD Thesis, Wagningen University, The Netherlands.

Bellaver, C., & Bellaver, I. H. (1999). Livestock production and quality of societies' life in transition economies. *Livestock Production Science, 59*, 125-135. http://dx.doi.org/10.1016/S0301-6226(99)00021-4

Blackburn, W. H. (1983). Livestock grazing impacts on watersheds. *Rangelands, 5*, 123-125.

Bossio, D., Geheb, K., & Critchley, W. (2010). Managing water by managing land: Addressing land degradation to improve water productivity and rural livelihoods. *Agricultural Water Management, 97*, 536-542. http://dx.doi.org/10.1016/j.agwat.2008.12.001

Boyazoglu, J. (1998). Livestock farming as a factor of environmental, social and economic stability with special reference to research. *Livestock Production Science, 57*, 1-14. http://dx.doi.org/10.1016/S0301-6226(98)00193-6

Burton, C. (2009). Reconciling the new demands for food protection with environmental needs in the management of livestock wastes. *Bioresource Technology, 100*, 5399-5405. http://dx.doi.org/10.1016/j.biortech.2008.11.018

Cook, S., Anderson, M., & Fisher, M. (2009). Assessing the importance of livestock water use in basins. *The Rangeland Journal, 31*, 195-205. http://dx.doi.org/10.1071/RJ09007

Cunningham, E. P. (1999). The application of biotechnologies to enhance animal production in different farming systems. *Livestock Production Science, 58*, 1-24. http://dx.doi.org/10.1016/S0301-6226(99)00007-X

De Fraiture, C., Wichelns, D., Rockstrom, J., & Kemp-Benedict, E. (2007). Looking ahead to 2050: scenarios of alternative investment approaches. In D. Molden (Ed.), *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture* (pp. 91-145). London, UK: Earthscan; Colombo, Sri Lanka: IWMI.

De Haan, C., Steinfeld, H., & Blackburn, H. (1997). *Livestock and the environment: Finding a balance*. FAO/USAID/World Bank. WRENmedia, Eye, Suffolk, UK. Retrieved from http://www.fao.org/WAIRDOCS/LEAD/X6137E/X6137E00.HTM

Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S., & Courbois, C. (1999). Livestock to 2020: the next food revolution. *Food, agriculture and the environment discussion paper 28*. FAO, Rome, Italy. Retrieved from http://www.ifpri.org/publication/livestock-2020

Descheemaeker, K., Amede, T., & Haileselassie, A. (2010). Improving water productivity in mixed crop–livestock farming systems of sub-Saharan Africa. *Agricultural Water Management, 97*, 579-586. http://di.doi.org/10.1016/j.agwat.2009.11.012

FAO (2005). *Local climate estimator (New LockClim 1.06)*. FAO, Rome, Italy.

FAO (1998). *Crop evapotranspiration–guidelines for computing crop water requirements*. FAO, Rome, Italy.

FAO (1986). *Ethiopian Highland Reclamation Study* (pp. 37- 46). Final report. FAO, Rome, Italy.

Freibauer, A. (2003). Regionalized inventory of biogenic greenhouse gas emissions from European agriculture. *European Journal of Agronomy, 19*, 135-160. http://dx.doi.org/10.1016/S1161-0301(02)00020-5

Haas, G., Wetterich, F., & Köpke, U. (2001). Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. *Agriculture, Ecosystems and Environment, 83*, 43-53. http://dx.doi.org/10.1016/S0167-8809(00)00160-2

Haileselassie, A., Peden, D., Gebreselassie, S., Amede, T., & Descheemaeker, K. (2009). Livestock water productivity in mixed crop–livestock farming systems of the Blue Nile basin: Assessing variability and prospects for improvement. *Agricultural Systems, 102*, 33-40. http://dx.doi.org/10.1016/j.agsy.2009.06.006

Harrington, L., Cook, S., Lemoalle, J., Kirby, M., Taylor, C., & Woolley, J. (2009). Cross-basin comparisons of water use, water scarcity and their impact on livelihoods: Present and Future. *Water International, 34*, 144-154. http://dx.doi.org/10.1080/02508060802661584

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2009). *Water footprint manual. State of the art 2009* (p.127). Water Footprint Network, Enschende, The Netherlands. Retrieved from http://www.waterfootprint.org

Hoekstra, A. Y., & Chapagain, A. K. (2008). *Globalization of water: Sharing the planet's freshwater resources*. Blackwell Publishing, Oxford, UK. Retrieved from http://www.waterfootprint.org

Hooda, P. S., Edwards, A. C., Anderson, H. A., & Miller, A. (2000). A review of water quality concerns in livestock farming areas. *The Science of the Total Environment, 250*, 143-167. http://dx.doi.org/10.1016/S0048-9697(00)00373-9

Humboldt Forum for Food and Agriculture-HFFA. (2010). *Water will be decisive for global food security*. International Press Conference, Berlin, Germany, 14 January, 2010. Retrieved from http://www.humboldtforum.org

Hurni, H. (1988). Degradation and conservation of soil resources in the Ethiopian highlands. *Mountain Research and Development, 8*, 123-130. http://www.jstor.org/stable/3673438

ILRI (2006). *Livestock water an effective use of water in developing countries*. International Livestock Research Institute, Nairobi, Kenya. Retrieved from http://www.ilri.cgiar.org/enews/view/default.htm

Jagtap, S., & Amissah-Arthur, A. (1999). Stratification and synthesis of crop-livestock production system using GIS. *Geo Journal, 47*, 573-582. http://dx.doi.org/10.1023/A:1006995824626

King, J. (1983). Livestock water needs in pastoral Africa in relation to climate and forage. *ILCA Research Report 7,* Addis Ababa, Ethiopia.

Koehler, A. (2008). Water use in LCA: Managing the planet's freshwater resources. *International Journal of Life Cycle Assessment, 13*, 452-455. http://dx.doi.org/10.1007/s11367-008-0028-6

Lillywhite, H., & Navas, C. (2006). Animals, energy, and water in extreme environments: Perspectives from Ithala 2004. *Physiological and Biochemical Zoology, 79*, 265-273. http://dx.doi.org/10.1086/499987

Mack, S. (1996). Pastures-the overstocking issue. *World Animal Review, 87*, 6-14.

Mekonnen, S., Descheemaeker, K., Tolera, A., & Amede, T. (2011). Livestock water productivity in a water stressed environment in northern Ethiopia. *Experimental Agriculture, 47*(SI), 85-98. http://dx.doi.org/10.1017/S0014479710000852

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M., & Kijne, J. (2010). Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management, 97*, 528-535. http://dx.doi.org/10.1016/j.agwat.2009.03.023

Molden, D., Frenken, K., Barker, R., de Fraiture, C., Mati, B., Svendsen, M. … Finlayson, C. M. (2007). Trends in water and agricultural development. In D. Molden (Ed.), *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture* (pp. 57-89). London, UK: Earthscan; Colombo, Sri Lanka: IWMI.

Mwendra, E. J., Mohamed Saleem, A. M., & Zerihun, W. (1997). Vegetation response to cattle grazing in the Ethiopian Highlands. *Agriculture, Ecosystem and Environment, 64*, 43-51. http://dx.doi.org/10.1016/S0167-8809(96)01128-0

Namara, R. E., Hanjra, M. A., Castillo, G. E., Ravnborg, H. M., Smith, L., & Van Koppen, B. (2010). Agricultural water management and poverty linkages. *Agricultural Water Management, 97*, 520-527. http://dx.doi.org/10.1016/j.agwat.2009.05.007

Oweis, T. (1997). *Supplemental irrigation: A highly efficient water-use practice*. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

Peden, D., Taddesse, G., & Haileslassie, A. (2009). Livestock water productivity: Implications for sub-Saharan Africa. *The Rangeland Journal, 31*, 187-193. http://dx.doi.org/10.1071/RJ09002

Peden, D., Tadesse, G., & Misra, A. (2007). Water and livestock for human development. In D. Molden (Ed.), *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture* (pp. 485-514). London, UK: Earthscan; Colombo, Sri Lanka: IWMI.

Peden, D., Tadesse, G., & Mammo, M. (2003). Improving the water productivity of livestock: an opportunity for poverty reduction. *Proceedings of a Workshop on Integrated Water and Land Management Research and Capacity Building Priorities for Ethiopia held on 2-4 December 2002* (pp.57-65), Addis Ababa, Ethiopia.

Powell, J. M., & Williams, T. O. (1995). An overview of mixed farming systems in sub-Saharan Africa. In J. M. Powell, S. Fernandez-Rivera, T. O. Williams & C. Renard (Eds.), *Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa* (pp. 21-36). Volume II: Technical papers. ILCA, Addis Ababa, Ethiopia.

Rockstrom, J., Karlberg, L., Wani, S. P., Barron, J., Hatibu, N., Oweis, T. … Qiang, Z. (2010). Managing water in rain fed agriculture-the need for a paradigm shift. *Agricultural Water Management, 97*, 543-550. http://dx.doi.org/10.1016/j.agwat.2009.09.009

Rockstrom, J., Folke, C., Gordon, L., Hatibu, N., Jewitt, G., Penning de Vries, F. … Schulze, R. (2004). A watershed approach to upgrade rain fed agriculture in water scarce regions through water system innovations: an integrated research initiative on water for food and rural livelihoods in balance with ecosystem functions. *Physics and Chemistry of the Earth, 29*, 1109-1118. http://dx.doi.org/10.1016/j.pce.2004.09.016

Rockstrom, J., Barron, J., & Fox, F. (2002). Rainwater management for increased productivity among small-holder farmers in drought prone environments. *Physics and Chemistry of the Earth, 27*, 949-959. http://dx.doi.org/ S1474-7065(02)00098-0

Rockstrom, J. (1999). On-farm green water estimates as a tool for increased food production in water scarce regions. *Physics and Chemistry of the Earth, 24*, 375-383. http://dx.doi.org/10.1016/S1464-1909(99)00016-7

RuMeth International. (2001). *International opportunities for reducing methane emissions*. Global Change Division, US Environmental Protection Agency, Washington D.C., USA.

Schils, R. L. M., Olesen, J. E., Del Prado, A., & Soussana, J. F. (2007). A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. *Livestock Science, 112*, 240-251. http://dx.doi.org/10.1016/j.livsci.2007.09.005

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., & de Haan, C. (2006). *Livestock's long shadow: Environmental issues and options*. Food and Agriculture Organization (FAO), Rome, Italy.

Steinfeld, H. (2004). The livestock revolution-a global veterinary mission. *Veterinary Parasitology, 125*, 19-41. http://dx.doi.org/10.1016/j.vetpar.2004.05.003

Tadesse, G. (2001). Land degradation: A challenge to Ethiopia. *Environmental Management, 27*, 815-824. http://dx.doi.org/10.1007/s002670010190

Thomas, D., Zerbini, E., Parthasarathy Rao, P., & Vaidyanathan, A. (2002). Increasing animal productivity on small mixed farms in South Asia: a systems perspective. *Agricultural Systems, 71*, 41-57. http://dx.doi.org/ 10.1016/S0308-521X(01)00035-X

Thomas, D., & Sumberg, J. (1995). A review of the evaluation and use of tropical forage legumes in sub-Saharan Africa. *Agriculture, Ecosystems and Environment, 54*, 151-163.

Thornton, P. K., Kruska, R. L., Henninger, N., Kristjanson, P. M., Reid, R. S., Atieno, F., Odero, A., & Ndegwa, T. (2002). *Mapping poverty and livestock in the developing world* (p. 124). International Livestock Research Institute, Nairobi, Kenya.

Thornton, P., & Herrero, M. (2001). Integrated crop–livestock simulation models for scenario analysis and impact assessment. *Agricultural Systems, 70*, 581-602. http://dx.doi.org/10.1016/ S0308-521X(01)00060-9

Van Wijk, M., Tittonell, P., Rufino, M., Herrero, M., Pacini, C., de Ridder, N., & Giller, K. (2009). Identifying key entry-points for strategic management of smallholder farming systems in sub-Saharan Africa using the dynamic farm-scale simulation model NUANCES-FARMSIM. *Agricultural Systems, 102*, 89-101. http://dx.doi.org/10.1016/j.agsy.2009.07.004

Wallace, J. S. (2000). Increasing agricultural water use efficiency to meet future food production. *Agriculture, Ecosystems and Environment, 82*, 105-119. http://dx.doi.org/10.1016/ S0167-8809(00)00220-6

Wilson, R. T. (2007). Perceptions, practices, principles and policies in provision of livestock water in Africa. *Agricultural Water Management, 90*, 1-12. http://dx.doi.org/10.1016/j.agwat.2007.03.003

Zhang, X., Huang, G. H., & Nie, X. (2009). Optimal decision schemes for agricultural water quality management planning with imprecise objective. *Agricultural Water Management, 96*, 1723-1731. http://dx.doi.org/10.1016/j.agwat.2009.07.011

Zhang, X., Zwiers, F. W., Hegerl, G. C., Lambert, F. H., Gillett, N. P., Solomon, S., Stott, P. A., & Nozawa, T. (2007). Detection of human influence on twentieth-century precipitation trends. *Nature, 448*, 461-466. http://dx.doi.org/10.1038/nature06025