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Contents

Acronyms and Abbreviations

FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
LWP	Livestock Water Productivity
NRM	Natural Resource Management
SSA	Sub-Saharan Africa
TLU	Tropical Livestock Unit

Summary

In sub-Saharan Africa (SSA), the increasing competition for water between various sectors is aggravated by growing demands for water, climate change and environmental degradation. One of the major consumers of water is livestock keeping, which is an important livelihood strategy for smallholder farmers in Africa. The water consumption for livestock production is currently increasing with the growing demands for livestock products. On the other hand, current low returns from livestock, limit its contribution to livelihoods, threaten environmental health and aggravate local conflicts. The objectives of this review are to (1) bring together the available knowledge in the various components of the livestock and water sectors, (2) identify promising strategies and interventions to improve the situation using the "livestock water productivity" (LWP) concept, and (3) identify critical research and development gaps. Improvements in LWP can lead to a positive impact on poverty reduction, resilience and environmental health, provided that interventions are well-targeted, community innovation and empowerment is achieved and appropriate dissemination and communication lead to awareness and adoption. Promising interventions are grouped in two domains. In the biophysical domain, numerous interventions related to feed, water and animal management can be applied to increase LWP. These should be complemented and integrated with interventions in the socio-political-economic domain. Enhancing the capacity of local institutions, improving market incentives and facilitating socioeconomic arrangements form part of the institutional improvements. A conducive policy framework, taking into account equity and gender and geared towards problem-solving local policies, improvements in infrastructure, price signals and land tenure systems, is a prerequisite for the successful application of the LWP concept. However, for the LWP concept to be widely applicable, knowledge gaps have to be filled, in terms of methodologies for quantifying water productivity and integrating animal, herd, farm, water catchment and basin scales. This paper suggests approaches for the integration of technological, policy and institutional interventions that would contribute to making the LWP concept operational.

INTRODUCTION

By bringing together information that is available from the water and livestock sector and analyzing livestock-water interactions, this paper provides valuable insights that can be used to face up to the difficult challenge of increasing livestock productivity without using more water or causing further environmental degradation. The LWP concept, which was brought into the open by the work of Peden et al. (2007), addresses this challenge. Based on an analysis of the LWP concept and a framework for mixed crop-livestock systems, strategies and pathways for improving LWP are suggested and promising interventions are identified. Furthermore, this paper determines where gaps in our understanding of the LWP concept still impede sound progress and what kind of institutional and policy issues need to be tackled first.

Before investigating the interactions and relationships between livestock and water, we first set the scene in both sub-sectors separately. Then, the introduction to the LWP concept starts with a discussion of the debated relationship between livestock and the environment in general, before moving on to the specific interactions between livestock and water. After that, the LWP concept is explained and a LWP framework for mixed crop-livestock systems is proposed. Based on the framework, the different strategies and interventions that could improve LWP are discussed in more detail in the main body of the paper and practitioners can get an overview of the options available. The gap analysis at the end of the paper provides an outlook to where efforts should be directed in this area.

Although most issues are put in a global perspective, this review focuses on crop-livestock systems of smallholder farmers in SSA. In SSA, mixed farming systems are very important in terms of livestock population, geographical extent, livelihood provision and scope for improvements. In relation to changing markets and increasing population densities, these systems in Africa are also very dynamic and mostly intensifying, with common transitions from rangeland to mixed systems (Herrero et al. 2008).

LIVESTOCK SECTOR: IMPORTANCE AND TRENDS

Importance of the Livestock Sector

The livestock sector is the fastest growing agricultural sub-sector globally, employing 1.3 billion people (Steinfeld et al. 2006a) and supporting about 4 billion people worldwide (Thornton et al. 2002). Livestock production contributes approximately 40% of the gross value of agricultural production worldwide, with values of 30% in developing countries, 37% in East Africa and 25% in Southern Africa (Parthasarathy Rao et al. 2005). In SSA, the share of livestock in agricultural GDP increases with decreasing rainfall and increasing water scarcity and tends to be very important also in highland areas. Globally, 30% of the land surface is used for livestock production with 33% of arable land being used for growing livestock feed crops and 26% being used for grazing (Steinfeld et al. 2006a). Of the land area occupied by SSA countries, 37% is covered by rangelands and 25% by mixed rainfed crop-livestock systems (Thornton et al. 2002), which support the livelihoods of approximately 80% of the population. In terms of total output of animal products, small-scale mixed farming systems contribute more than grassland-based or industrial livestock systems (Seré and Steinfeld 1996).

In SSA, very high livestock densities are found in a band from Senegal to Ethiopia and from East Africa to Southern Africa (Thornton et al. 2002). These high densities of up to 40 tropical livestock units (TLU) (250 kilogram bodyweight) per square kilometer (km^2) often coincide with high population density, intensified agriculture, proximity to markets (Peden et al. 2006), and also with high incidences of poverty (Peden et al. 2007). In marginal environments and with resource-poor farmers, small ruminants are important, whereas cattle dominate the livestock herd in the highlands of Eastern Africa (Parthasarathy Rao et al. 2005). However, when considering the TLU, in particular, cattle are also very important in many rangeland grazing systems.

Livestock provide many different products and services to people (Thornton and Herrero 2001; ILRI 2002; Peden et al. 2007), thus making an important contribution to rural livelihoods; with particular economic and social importance for the majority of the world's poor (Misturelli and Heffernan 2001; Thornton et al. 2002; Parthasarathy Rao et al. 2005; World Bank 2007). Livestock production is an important factor for smallholders to move out of poverty (see, for example, Kristjanson et al. 2007; Burke et al. 2007). Besides that, the consumption of animal products can alleviate nutritional deficiency, which is still widespread in developing countries, and secure a better child physical and mental development (Delgado 2003; Speedy 2003). Apart from the obvious products like meat, milk and eggs, livestock also provide energy in the form of draught power for land preparation and threshing, transport and manure for fuel. Manure also fulfils another important role through nutrient cycling between and within farms, which enables the sustainable functioning of mixed farming systems of smallholders. Furthermore, livestock have an economic role to play as they are major sources of income. Animals also assume various sociocultural roles and are a means to store wealth (ILRI 2002). If animal herds are managed well, pastures and rangelands also provide ecosystem services in terms of maintaining soil and water resources.

Livestock are an important part of many types of farming systems around the world. The often used classification system developed by Seré and Steinfeld (1996), which was slightly modified by Thornton et al. (2002), differentiates the farming systems with livestock into four broad groups, namely (1) rainfed mixed systems, (2) irrigated mixed systems, (3) landless or industrial systems, and (4) livestock only, rangeland-based grazing systems. These groups are further subdivided according to agroecological characteristics. Mixed crop-livestock systems are widespread in semi-arid and sub-humid regions in the tropics (Steinfeld et al. 2006a), and with increasing population density and land scarcity, crop and livestock activities tend to integrate more intensively (Mclntire et al. 1992; Jagtap and Amissah-Arthur 1999; Thornton and Herrero 2001; Parthasarathy Rao et al. 2005). The integration of crop and livestock production offers possibilities for risk spreading (Ellis 2000), which makes these systems especially adapted to semi-arid conditions. Mixed crop-livestock systems are characterized by a strong complementarity in resource use, with outputs from one component being supplied to other components (Devendra and Thomas 2002). Crop-livestock interactions provide many benefits, such as the improvement of agronomic operations with animal traction or the use of crop residues as feed. Generally speaking, 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). However, when mixed systems are pushed beyond certain thresholds they are vulnerable to collapse, often because of failure to maintain healthy soils. Because of the complexity of the multiple components and their mutual interactions (see, for example, Thorne 1998; Dixon et al. 2001), and the influence of both biophysical and socioeconomic factors, mixed farming systems are still not fully understood (Thornton and Herrero 2001). This lack of understanding and the disregard of households as primary actors and decision-makers on input use, labor allocation, timing of operations, product marketing, etc., is often on the basis of poor adoption rates of so-called improved technologies (Amede et al. 2008).

Trends in the Livestock Sector

Population growth, urbanization, economic growth and flourishing markets all lead to the increasing demand for animal products (Delgado 2003; Costales et al. 2006; Steinfeld et al. 2006a, 2006b). Also, changing nutritional needs, driven by growing incomes and demographic transitions, result in an increase in the need for livestock products on a global scale (Speedy 2003; Steinfeld et al. 2006a, 2006b). Over the past few decades, the demand for animal products has increased two to three times faster in developing countries than in developed countries (Delgado 2003). According to Peden et al. (2007), the annual growth in consumption and production of animal products was 2-4% in developing countries, while it was only 0.5% in developed countries. However, if the transforming countries in Asia and Latin America are excluded from the group of developing countries, the overall growth in production is far less spectacular (Speedy 2003; World Bank 2007). Moreover, in the rural areas of the poorer African countries, population has increased faster than meat consumption, so that the per capita consumption of livestock products has declined. On the other hand, in rich countries, the trend of rising demand is stagnating, not only because of a small population growth (Delgado 2003), but also because of growing concerns on health, environment, animal welfare, ethical issues (Steinfeld et al. 2006a) and, more recently, also because of rising prices. On a global scale, Delgado et al. (1999) predicted a rise in meat production from 233 million tonnes in 2000 to 300 million tonnes in 2020, and a rise in milk production from 568 to 700 million tonnes over the same time span. From the group of animal products, the highest growth rates are achieved in poultry, pigs, eggs and milk production (Speedy 2003).

The livestock revolution (Delgado et al. 1999; Delgado 2003) offers a chance for smallholders to benefit from the rapidly growing market and raise their incomes. Besides being an opportunity for poverty alleviation (World Bank 2007), it can also lead to better nutrition and health, and to environmental preservation. However, an increase in livestock production could also have negative environmental, nutritional, social (if smallholders are out-competed by industrial producers) and health impacts if not managed well (Peden et al. 2002; Delgado 2003; Steinfeld et al. 2006a). Some policy measures should be taken in order to avoid these negative aspects, such as (1) vertical integration of smallholders with food processors, (2) removing market and trade distortions, and (3) institutional changes to improve property rights, install adequate market prices and correct for environmental externalities (Delgado 2003; Steinfeld et al. 2006a). Obviously, the increase in demand for animal products also leads to an increased pressure on environmental and water resources. Therefore, adapted technologies are also needed to allow for an increase in animal productivity that does not imply an increase in water use or further environmental degradation.

While a trend of geographical concentration, scale expansion, industrialization and vertical integration (of producers with food processors and retailers) is noticed and leads to cost reductions on a global scale, smallholders are often marginalized (Costales et al. 2006). For smallholders, expansion is constrained by market and production risks and different barriers, including limited access to land and credit, subsidies and market distortions, lack of technology transfer and transaction costs (Delgado 2003; Costales et al. 2006; Steinfeld et al. 2006a).

Historical intensification and industrialization of the livestock sector in developed countries have led to very high levels of livestock productivity, which is in sharp contrast to the low livestock productivity in SSA countries (Parthasarathy Rao et al. 2005; Steinfeld et al. 2006a). Intensification in developed countries was brought about by increased yields through the application of external inputs, increased cropping intensity, abandonment of marginal cropland and more efficient feeding with grains and concentrates. Besides that, more productive breeds through genetic improvement, better feed conversion, improvements in animal health, geographical concentration, access to input–

output markets as well as institutional support all contributed to this intensification. The shift to, and the industrialization of, monogastrics (poultry and pigs), which can profitably make use of high quality feeds also played a role (Steinfeld et al. 2006a; Costales et al. 2006). In developing countries, development of the livestock sector is dualistic. Near peri-urban areas, fast-growing, commercial and intensive systems are developing, whereas at the same time, smallholders are still relying on traditional, (semi)subsistence systems, characterized by low productivity and market access constraints (Parthasarathy Rao et al. 2005). In SSA, intensification of the livestock sector is nearly nonexistent. For example, feeding grain to livestock is a common practice in developed countries, where approximately 40% of the total cereals produced are fed to animals. In Africa, however, only 14% of the grains produced are fed to livestock (Speedy 2003), of which much is fed to poultry and does not meet human standards. Instead, smallholders prefer to grow dual purpose crops that meet both the needs for human food (grains) and animal fodder (crop residues like straw) consumption (Lenné et al. 2003). The primary causes for the low livestock productivity in SSA are the low quantity and quality of feed (Lenné et al. 2003; Benin et al. 2006; World Bank 2007), the predominance of indigenous, low-yielding breeds, the inadequate availability of water resources for drinking and the prevalence of diseases, and the high rates of livestock mortality (Negassa and Jabbar 2008). One explanation for the low quality and quantity of feed is that pastures are driven back to marginal land due to the expansion of cropland (Steinfeld et al. 2006a). Some so-called pastures are abandoned croplands that no longer support cultivation because of totally degraded soils. However, low pasture productivity is not only related to its unfavorable conditions (including climate, topography and soils), but is also due to the lack of infrastructure in these often remote areas and to the fact that many pastures are common property (Costales et al. 2006).

The above overview highlights the importance of mixed crop-livestock farming systems in SSA in terms of areal extent and its contribution to the economy and livelihoods. Given the dynamic market situation, offering strong incentives and opportunities to intensify and raise livestock productivity, smallholder farmers are also likely to profit from the livestock revolution. However, important risks exist with respect to natural resource degradation, in general, and to water resource depletion and scarcity, in particular. As explained in the next section, natural resources are already under huge pressure and solutions leading to an increase in livestock productivity, without using more water or causing further environmental degradation, are urgently required.

TRENDS IN WATER DEMAND AND AVAILABILITY

Land Degradation

The growing human population and intensification of human activities worldwide have placed a huge pressure on the Earth's natural resources. Unsustainable and improper land use and land cover changes are the major causes of land degradation (Bossio et al. 2007). Land degradation is closely related to the degradation of other natural resources, such as vegetation, biodiversity and water. With respect to the latter, land degradation negatively affects water productivity, temporal and spatial availability of water, and also water quality and storage (Bossio et al. 2007). On the other hand, inefficient water management is also an important cause of land degradation.

Depending on the definition and the assessment approach, estimates of the extent of land degradation vary widely (Eswaran et al. 2001). Oldeman et al. (1991) estimated that 1.9 billion hectares of soils are degraded, globally. By including the status of vegetation, Dregne and Chou (1994) came up with a far greater estimate of 3.6 billion hectares of degraded land in the drylands alone. According to FAO statistics in the TERRASTAT database (FAO 2007), the current extent of global land degradation amounts to 8.6 billion hectares or 66% of the Earth's surface. Following the definitions of the Global Assessment of human-induced Soil Degradation (GLASOD) study (Oldeman et al. 1991), 46% of the global land surface is moderately to very severely degraded (FAO 2007). In SSA, 65% of the total land surface is degraded and 42% is moderately to very severely degraded (FAO 2007). Consequences of desertification (i.e., land degradation in arid, semi-arid and dry sub-humid areas) are particularly severe in dryland areas of SSA, South and Southeast Asia (Dregne 2002; Geist and Lambin 2004). Effects in these areas are aggravated because ecosystem resilience (see Holling 1973, 1986) is threatened by the high climate variability, and many poor people are socially and politically marginalized (Millennium Ecosystem Assessment 2005).

The severity of land degradation in SSA complicates and undermines attempts to improve water productivity. Just as decisions on land use impinge upon decisions on water, appropriate water management can be instrumental to the rehabilitation of degraded and unproductive lands.

Water Scarcity, the Growing Demand and Competition for Water

With growing human populations, growing incomes and changing diets, more water is needed to meet the increasing food demand (Alcamo et al. 2000; Wallace 2000; Falkenmark 2007; Molden et al. 2007). The amount of water needed to produce an acceptable human diet varies between 2,000 and 5,000 liters per capita per day (Rijsberman 2006; Molden et al. 2007). This depends on the climate where the food is produced, the crop and livestock management system and the nature of the diet itself (e.g., whether the diet includes meat or not). According to Rijsberman (2006) and Falkenmark (2007), water requirements for human diets are about 70 times higher than the water needed for domestic supplies. Taking into account the projected population and income growth, food demand is estimated to grow by 70-90% by 2050 (Molden et al. 2007), which includes the increase in demand for livestock products. This would require an extra 5,000-6,000 cubic kilometers (km^3) of water per year, when compared to the 7,000 km^3 of water that is used globally per year, at present, to produce food and fodder (Falkenmark 2007). Other studies have predicted a 25% increase in yearly water demand from 4,000 to 5,000 km^3 between 2000 and 2025 (Shiklomanov 1998).

Alcamo et al. (2000) forecast that 4 billion people will live in countries facing high water stress by 2025, while Postel (2000) estimates this to be 3 billion people in the developing world alone, with the highest concentration in SSA and South Asia. Depending on the definition of water stress (see, for example, Rijsberman 2006), other estimates vary from 30% of the world's population facing water stress by 2030 (Rockström and Barron 2007) to 67% of the global population in that situation by 2050 (Wallace 2000). Along the same lines, Rijsberman (2006) concludes, from a number of studies, that over the next few decades, about two-thirds of the global population will be affected by water scarcity. Water will become the key limiting factor in food production and livelihood generation, particularly in rural areas of Africa and Asia. At present, 1.2 billion people already live in conditions of physical water scarcity. Another 1.6 billion people live in conditions of economic water scarcity, where water availability is limited due to aspects other than natural factors, such as human, institutional and financial constraints (Molden et al. 2007).

Competition for water between different uses and users is increasing (Bouman 2007) due to a number of factors. Due to urbanization, the share of water being diverted to the domestic and industrial sectors is expected to more than double in the next decade (Postel 2000). Nevertheless, agriculture will remain the largest user of water, accounting for approximately 75% of current human water use (Wallace 2000). Major trade-offs between agriculture and ecosystem services (see, for example, Lemly et al. 2000) are forecasted, including trade-offs between increasing food security, on the one hand, and safeguarding ecosystems, on the other (de Fraiture et al. 2007). Focusing solely on agriculture could result in freshwater shortages for wetlands and other aquatic ecosystems (Postel 2000), and it could also lead to degraded water quality, with serious impacts on terrestrial and aquatic ecosystems. With growing concerns about climate change, the production of biofuels has gained momentum, increasing the consumption of water for non-food production. Furthermore, the demand for restoring and maintaining environmental services are forecasted to increase with rising public awareness (de Fraiture et al. 2007). These demands will increasingly include water allocated to carbon sequestration.

The current over-exploitation of limited (blue) water resources (with blue water defined as the surface and subsurface flow of water in rivers and lakes, and groundwater (UN 1997)) in crop-livestock systems (Wallace 2000), will result in falling groundwater levels in aquifers, decreasing river flows, worsening water pollution, declining lake levels and deteriorating wetland systems (Postel 2000; Rosegrant et al. 2002; Rijsberman 2006; Rockström and Barron 2007). Together with increasing demands, the worsening water scarcity threatens biodiversity and impairs the supply of water for food production and other vital human needs (Pimentel et al. 2004), such as drinking and sanitation.

Coping with Water Scarcity

Different factors aggravate the current problems of water scarcity and potential solutions to the problems are complicated by several challenges (Gleick 2003). One important factor is that water is mostly considered as a free good, for which no price has to be paid. There is a huge loss of water in various agricultural and non-agricultural systems, which is associated with uncontrolled evaporation, water depletion through runoff, water pollution due to excessive use of chemicals and water contamination by industrial and agricultural activities. Water management interventions at farm, landscape and higher levels are often poorly adapted and implemented, which leads to high social and environmental costs (Molden et al. 2007). Policies have not given enough priority to improvements in the use and management of water, but have invested mainly to improve water supply and hydropower generation by building dams for irrigation and hydropower stations. The absence of adequate treaties and international arrangements dealing with shared water resources is likely to result in increasing water conflicts (Postel 2000; Postel and Wolf 2001), which will further undermine the future sustainable use of the limited water resources. Climate change puts extra pressure on sustainable water resources management (Molden et al. 2007), through probable increases in temperature, rainfall variability and the occurrence of extreme events, like droughts or floods (IPCC 2001). The remaining uncertainty on the actual characteristics and the extent of climate change, and its effect on water supply and agricultural production make it difficult to develop appropriate adaptive measures (Bruinsma 2003; Kurukulasuriya et al. 2006).

Continuing in a business-as-usual mode will lead to a serious global water crisis (de Fraiture 2007). Wallace (2000) pleads for increasing agricultural productivity by producing more crop and livestock products on existing land and water resources. However, merely increasing water productivity will not solve the dual challenge of increasing food production and saving water (Bouman 2007). An interdisciplinary or even transdisciplinary approach is needed, as the challenge in integrated water management spans science, technology, policy and politics (Postel 2000).

A shift away, from actions merely focusing on the supply side or the ‘hard path’, is required (Gleick 2003; de Fraiture 2007). This previously widespread focus has led to many benefits, but has also caused enormous social, economic and ecological costs (Postel 2000). A new approach, applying integrated resource management concepts, should pay attention to factors beyond the water sectors that affect water use. Appropriate policies and institutions must be developed and local communities must be involved in decision-making (Gleick 2003; de Fraiture 2007). In order to alleviate water scarcity for agriculture, scientists and policymakers should not only focus on renewable, 'blue' water resources, but should also carefully consider 'green' water (as opposed to the tangible 'blue' water, 'green' water comprises the water retained by the soil) management and the interactions between the various sources of water (Rijsberman 2006). For countries where water is very scarce, the virtual import of water that comes with the import of staple foods can alleviate water scarcity considerably (Allan 1998, 2001; Hoekstra and Hung 2005). However, the social and political effects related to this issue need to be recognized as well.

Given the current alarming degree of environmental degradation and water scarcity, and the ever-increasing demand and competition for water, the challenge to reduce poverty and hunger is huge. Meeting this challenge not only requires considerable improvements in water productivity, but an integrated, multidisciplinary approach to water management is also required.

LIVESTOCK WATER PRODUCTIVITY

Livestock and the Environment

Livestock production systems have a serious impact on the environment. Land degradation is probably the most quoted negative effect of livestock production and livestock grazing, in particular (see, for example, Stroosnijder 1996; Mwendera and Saleem 1997; Asner et al. 2004; Savadogo et al. 2007). With respect to rangelands, Asner et al. (2004) identified three types of ecosystem degradation factors related to overgrazing, including desertification, woody plant encroachment and deforestation.

Global environmental evidence has led different reports (e.g., Steinfeld et al. 2006a; Costales et al. 2006) to conclude that the livestock sector has a strong negative impact on water depletion and pollution, the loss of biodiversity, the atmosphere and climate change. Concerning the latter, the livestock sector contributes 18% of the anthropogenic greenhouse gas emissions and 37% of the anthropogenic methane emissions to the atmosphere worldwide (Steinfeld et al. 2006a). However, these global estimates mask important regional differences, which are related to the degree of industrialization: recent evidence suggests that emissions from Africa only contribute 10% to the global methane emissions from enteric fermentation (Herrero et al. 2008). Caution is also needed with respect to pronouncements on water depletion: huge differences in water use exist, for example, between industrial livestock production systems using irrigated feedstuffs and mixed crop-livestock systems using crop residues as feed (Peden et al. 2007). Whereas industrial systems may lead to soil and water contamination from manure and wastewater mismanagement and the excessive use of chemicals, these issues are not problematic in smallholder, low-input farming systems as yet. Finally, the statement on the loss of biodiversity also needs some consideration, as grazing livestock also contribute to maintaining biodiversity in some circumstances (see, for example, Pykala 2003; Stammel et al. 2003; Hellström et al. 2005).

From the mechanisms identified by Steinfeld et al. (2006a) on how livestock production triggers and aggravates resource degradation, the following are widely applicable to crop-livestock systems in SSA. First, rangelands are degrading due to over-stocking, inadequate grazing and water point management. To a lesser extent, to satisfy increasing feed demand, pastures and arable land used for the cultivation of feed crops expand into and destroy natural ecosystems.

Livestock–Water Interactions

Access to water is probably the most important link between livestock, people and the environment, and a major influencing factor for the development of various livestock production systems. The distribution of water and land resources dictates herd composition and livestock distribution, livelihood strategies of people and their coping mechanisms. For instance, in SSA, where water is in short supply, farmers have adapted to these challenges through transhumant or nomadic lifestyles. On the other hand, in intensifying crop-livestock systems, where population density is on the rise, the farm size is declining, and competition for water among various sectors is increasing, the application of remedial interventions in land and water management is becoming a necessity.

Livestock convert water and feed resources into high value goods and services. At farm level, livestock-water relationships vary depending on the composition of the animal herds, the production objectives of farmers, livestock management practices, market links, and livestock health and productivity. In the Ethiopian Highlands, for instance, where draught power is an important animal output, farmers give priority to oxen for a high quantity and quality of feed. Hence, oxen are the major user of feed and water, but also exhibit invaluable outputs: farmers owning oxen can plough on time to capture early rainfall and plant early, which enables crops to escape droughts during the late season (Gryseels et al. 1986; Gryseels 1988). On the other hand, in dairy systems of Kenya (see, for example, Moll et al. 2007), lactating cows are the major consumers of feed and water, but in turn, they generate the highest income among the herd.

Although water for livestock drinking and servicing might be the most obvious user of water in livestock production systems, it constitutes only a minor part of the total water consumption (Peden et al. 2007). Recent reports indicated that the major water consumption in livestock systems is related to the transpiration of water for feed production, which is generally about 50 to 100 times the amount needed for drinking (Singh et al. 2004; Peden et al. 2007; Gebreselassie et al. 2008). Livestock systems that depend on grain-based feed, as is the case in the developed world, are more water intensive than systems that rely on crop residues and pasturelands, as is the case in SSA and South Asia. Assuming that the former case is valid everywhere, it is often too easily and commonly accepted that producing one kilogram of meat or milk requires huge amounts of water. In the Gujarat State in India, for example, a study estimated that, to produce one liter of milk, 1.96 to 4.6 cubic meters (m^3) of water are depleted, mainly to grow irrigated alfalfa feed (Singh et al. 2004), whereas the global average for this is approximately 0.9 m^3 of water (Chapagain and Hoekstra 2003). Estimates of water requirements for producing one kilogram of beef meat vary from 100 m^3 (Goodland and Pimentel 2000) to 12.2 m^3 of water (Chapagain and Hoekstra 2003). However, these estimates are usually made for intensive livestock systems based on feed grain or forage crops and, therefore, do not apply to many smallholder systems. In cases where livestock are fed crop residues, and graze rangelands, which are unsuitable for crop production anyway, livestock make a very efficient use of the available water (Peden et al. 2007). Moreover, as goats and sheep have a more efficient water metabolism than large ruminants (Wilson 1989), livestock systems dominated by small ruminants are found to be more water-efficient than those with large ruminants and equines.

Animals derive their water from different sources (Sileshi et al. 2003; McGregor 2004), such as water directly consumed by drinking and water consumption through feed intake. The amount of drinking water used varies from 20–50 liters per TLU per day and depends on the species, dry matter intake, composition of the feed, water content of the feed, live weight of the animal, level of milk and meat production, physiological status of the animal and the climate in which the livestock is managed (King 1983; Gigar-Reverdin and Gihad 1991).

When analyzing livestock–water interactions it is important to take into account the impact of livestock keeping on water resources at watershed and landscape scales. Ignoring it could lead to significant over-estimations of LWP. Livestock grazing does not only result in soil and vegetation degradation (see the section on *Livestock and the Environment*), it also affects the hydrological response of pastures and rangelands. Findings of different studies (e.g., Wilcox and Wood 1988; Mwendera and Saleem 1997; Mwendera et al. 1997a; Tadesse et al. 2002; Descheemaeker et al. 2006) indicate that increased grazing pressure leads to a combination of different, interrelated factors, such as decreased vegetation cover, decreased soil organic matter content, soil compaction through trampling, decreased soil structural stability, soil erosion, lower infiltration rates and, thus, higher runoff. On the other hand, underestimates of LWP might be related to the tendency of assigning all water lost in rangeland systems to livestock. This ignores the value of water for different kinds of ecosystem services.

The grazing pressure on the vegetation cover and the trampling effect of livestock is especially felt around the watering points, where land degradation can be severe (Brits et al. 2002). Moreover, if watering points are not well protected or managed, water contamination due to the inflow of faecal excretions can also make the water unsuitable for any other productive uses (Wilson 2007).

So far, apart from research on land degradation due to grazing and livestock water requirements for drinking, the research community has paid insufficient attention to livestock-water interactions (Peden et al. 2007). The resulting lack of understanding is reflected in the large variation in the reported values for feed water productivity, the uncertainty in feed intake estimates and the resulting variation in LWP estimates in the scientific literature. In general, the lack of knowledge and the insufficient understanding of livestock-water interactions impede sound decision-making and the implementation of targeted interventions to improve the often alarming situation. This leads to missed opportunities to reverse environmental degradation, low livestock productivity and smallholder poverty.

Livestock Water Productivity: The Concept

Water productivity, in general, is defined as the ratio of agricultural outputs to the amount of water consumed. It provides a robust measure of the ability of agricultural systems to convert water into food (Kijne et al. 2003). More specifically, LWP is the ratio of livestock-related products and services to the water depleted in producing these (Peden et al. 2007):

$$LWP = \frac{\sum \text{Net livestock products \& services}}{\sum \text{Water depleted \& degraded}} \qquad (1)$$

LWP can be expressed in different units, depending on the beneficial outcomes that are considered. If only livestock meat or milk is considered, this physical LWP could be expressed in kilograms per cubic meter of water or in liters per cubic meter of water, respectively. Other notations include food, expressed in kilocalories per cubic meter of water or the monetary value, expressed in US dollars per cubic meter of water. The non-economic benefits of water used by livestock production systems can be significant, but more difficult to assess due to the fact that unlike direct products they can comprise indirect benefits and environmental flows (Cook et al. 2008). However, the growing potential for payment for environmental services (see, for example, Sierra and Russman 2006; Pagiola and Platais 2007), offers scope to include non-economic benefits in assessments of water productivity. When comparing water productivity values, both the produced commodity and the water flow components included in the analysis should be clearly defined, as these can vary greatly with the scale of the analysis, the system concerned and the interests of stakeholders (Wesseling and Feddes 2006). The discussion is often confounded by the diverging definitions of water productivity (biomass:transpiration, biomass:evapotranspiration, biomass:water inflows, etc.) and the varying scales of analysis (Bouman 2007).

By analogy with the spatial scales (plant – field – agricultural landscapes) identified for crop water productivity (e.g., Bouman 2007), the relevant spatial scales for LWP are animal, field, herd, farming system, catchment and basin scale. From a socioeconomic point of view, production systems can be analyzed at farm, community, region and country scale. The temporal scale at which livestock production systems are analyzed also matters (Cook et al. 2008). A logical starting point for assessing agricultural water productivity is one crop cycle. This is extended to one year to also account for nonproductive water flows taking place outside the crop cycle. For livestock systems, which are adapted to strong fluctuations in water availability, it is useful to extend the analysis over several years in order to average out related fluctuations in livestock productivity.

The Livestock Water Productivity Framework

It is hypothesized that increased LWP contributes to improving livelihoods and reducing poverty in smallholder farming systems, while reversing land degradation and safeguarding environmental resilience.

Given the complex nature of livestock systems, a conceptual framework (Peden et al. 2002) was developed in order to analyze LWP. This framework allows accounting for the multiple benefits from livestock production, the different water flows that are involved and the various factors (not only biophysical but also institutional and socioeconomic factors) influencing LWP. The adapted framework for mixed crop-livestock systems in Figure 1 was built upon the original by Peden et al. (2002, 2007) and integrates production systems, hydrology, economics, ecosystems and various natural resources, so that it offers a way to systematically analyze livestock–water interactions and increase our understanding of mixed farming systems and their water use.

Water inflow into the system can comprise precipitation, surface water and groundwater. Virtual water is taken into account only when feed is imported. The water flowing into the system is used for biomass production, drinking, and processing and servicing. It allows the system to produce animal outputs by using the different feed types and relying on other natural resources and inputs. Animal outputs then contribute to livelihoods and environmental services. This contribution is positive if managed well, but could also be negative if managed badly. The effect on environmental services creates feedback loops because of the influence on feed production, on other natural resources such as soils and vegetation and on the water inflow itself. The water that flows into the system also flows out one way or another. This outflow comprises much more than the water contained in animal urine or faeces. Transpiration, evaporation, contaminated water and degraded runoff water all form part of depleted water flows, which cannot be used by the system anymore. On the other hand, non-degraded discharge and deep percolation out of the root zone flow out of the system, but might be used by other systems downstream or after recycling.

The LWP concept and its framework can be used to determine strategies and well-targeted interventions to increase LWP. The framework deals with the systems level, so that strategies are not only directed at animal or crop level, but also at herd, household and wider community

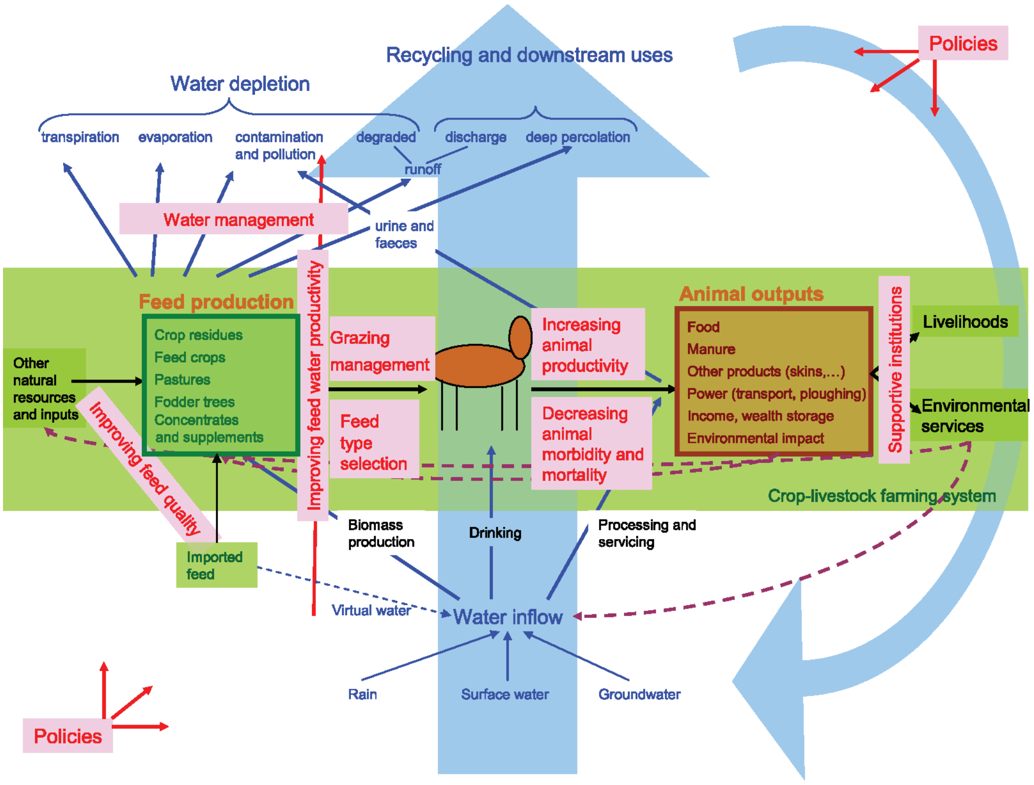

FIGURE 1. The livestock water productivity framework for mixed crop-livestock farming systems. The horizontal area represents the livestock component of crop-livestock farming systems. Vertical arrows indicate the different water inflows and outflows constituting the water balance. Dashed arrows indicate feedback loops, such as the use of animal outputs for feed production or the impact of livestock on environmental services. Technical strategies that could improve LWP are located on the interface between the crop-livestock production system and the water balance (text boxes highlighted in pink). Strategies involving policies and extension and capacity are located at the outer boundaries (text boxes highlighted in pink), illustrating that they potentially influence all flows and interactions. *Source:* built upon Peden et al. 2002, 2007.

levels. A total of nine strategies have been identified to increase LWP based on the framework, including water management, feed type selection, improving feed quality, improving feed water productivity, grazing management, increasing animal productivity, decreasing animal morbidity and mortality, supportive institutions and enabling policies (Figure 1). The strategies can be clustered into two main categories, as they are either directed at the biophysical components of the farming system or at sociopolitical and socioeconomic issues (see the section on *Interventions for Improving Livestock Water Productivity*). The first category of technical strategies can be further subdivided into three groups related to feed management (improving feed quality, improving feed water productivity, feed type selection and grazing management), water management and animal management (increasing animal productivity and decreasing animal morbidity and mortality). For each of the nine strategies, several interventions for improving LWP will be discussed in more detail in the next section. It needs to be stressed that these groups are somewhat artificial, as certain strategies could also be classified in other groups. For example, although grazing management is classified under feed management, it also contributes to and benefits from water management.

INTERVENTIONS FOR IMPROVING LIVESTOCK WATER PRODUCTIVITY

Improving LWP includes several challenges, located on different fronts and usually not straightforward to meet. First, given the growing water scarcity and the rising demand for animal products (as discussed above), appropriate water allocation is needed in order to satisfy both these demands and also safeguard environmental services of ecosystems at the same time. As the latter is also largely dependent on water, meeting these competing demands is very challenging and raising water productivity of livestock production systems alone will probably not be sufficient (Bouman 2007). Sustaining and safeguarding environmental services in SSA cannot be realized without controlling the expansion of grazing land and cropland into natural ecosystems, and limiting and reversing rangeland degradation. Insufficient integration of water and livestock development in the past led to poverty aggravation, environmental degradation and missed opportunities for investment in both the livestock and the water sub-sectors (Peden et al. 2006, 2007). Interdisciplinary development planning and management of natural resources is therefore necessary to turn this vicious cycle into a positive one. When aiming at increasing LWP, it is important not only to improve individual outcomes, but also to pay attention to improving collective outcomes and equity in terms of gender, wealth and age groups (Mapedza et al. 2008). Adequate water distribution and recognition of the multiple uses of water could help in this matter (van Koppen et al. 2006; Tulu et al. 2008). Intensification and vertical integration of different components in the product chain usually lead to higher productivity, but tend to marginalize smallholders. To avoid this, appropriate safety nets are necessary (Parthasarathy Rao et al. 2005). Besides the domestic reforms and policy adjustments that are needed, there also exist international challenges, for example, in reducing trade and market distortions (Costales et al. 2006).

Farming systems, in general, and, therefore, also mixed crop-livestock systems are influenced by both their biophysical and socio-political-economic conditions. Therefore, interventions to increase LWP should be sought after within both spheres of influence. The latter are not mutually exclusive, but interact at different scales (Figure 2) and interventions in one domain will have their impact on the conditions in the other. Interventions always have an impact on labor costs for the household or for certain members of the household (Mapedza et al. 2008). It is important to take this into account, because higher labor costs might be a reason for non-adoption or might cause gender inequality. On the other hand, certain interventions free up time for farmers which can lead to improvements in other production components (van Koppen et al. 2005). Based on the concept of interacting spheres of influence, the two main entry points to increase LWP are suggested as (Figure 2):

(1) the animal and natural resource components of farming systems and their environment (biophysical sphere of influence); and

(2) the policies and institutions (socio-political-economic sphere of influence).

The LWP strategies identified in the framework (Figure 1) are categorized according to these entry points, with strategies directed at feed, water and animals representing the biophysical entry point and comprising mainly technological interventions. Supportive institutions and enabling policies belong to the second entry point.

In Figure 3, a number of strategies are grouped under technologies and institutions. Policies are also included as an influence to all other factors. The figure clarifies the vision that improved LWP can contribute to poverty alleviation, resilience and environmental health. However, first,

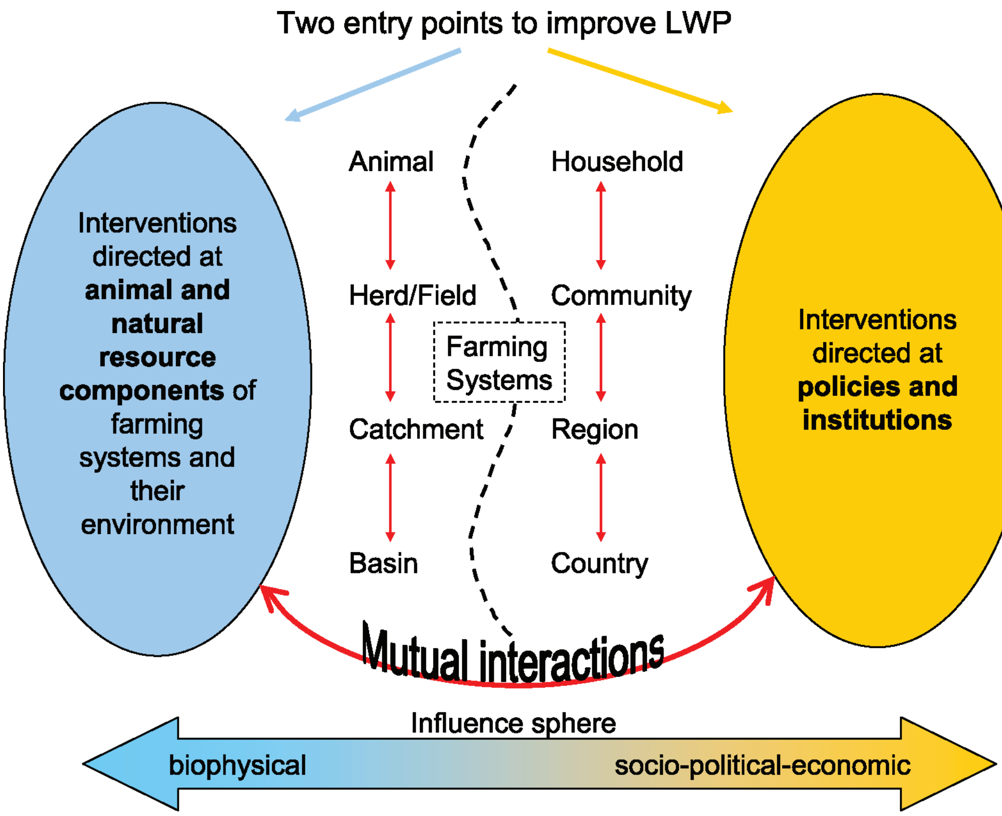

FIGURE 2. Integrating biophysical and socioeconomic interventions to improve LWP in their respective spheres of influence, acting at various scales.

besides technological interventions, there is also the need for enabling policies and institutions in order to achieve improvements in LWP. Second, to ensure that improvements in LWP really have a positive impact, other prerequisites for good development practices have to be met. These include adequate targeting and dissemination to achieve the adoption of interventions, promoting community innovation and empowerment, and awareness and capacity building (DFID 2007; Haileslassie et al. 2008; Amede et al. 2008). Feedback loops to the interventions (Figure 3) illustrate that this is an iterative process.

In what follows, an overview will be given of promising interventions that contribute to the different LWP strategies. For the technological interventions, the three main groups of strategies (feed management, water management and animal management), which arose from the framework, will be treated separately. Institutional and policy options will also be discussed at that stage. Although it is clear from the above frameworks (figures 1 to 3) and rationale that technological interventions have to go hand in hand with efforts in the socio-political-economic domains, the following overview of interventions turns out to be much more extensive for the former. The fact that more examples have been found of LWP interventions in the biophysical sphere of influence reflects the need for more attention to the other dimensions. This will also become apparent from the institutional and policy gap analysis later in this report.

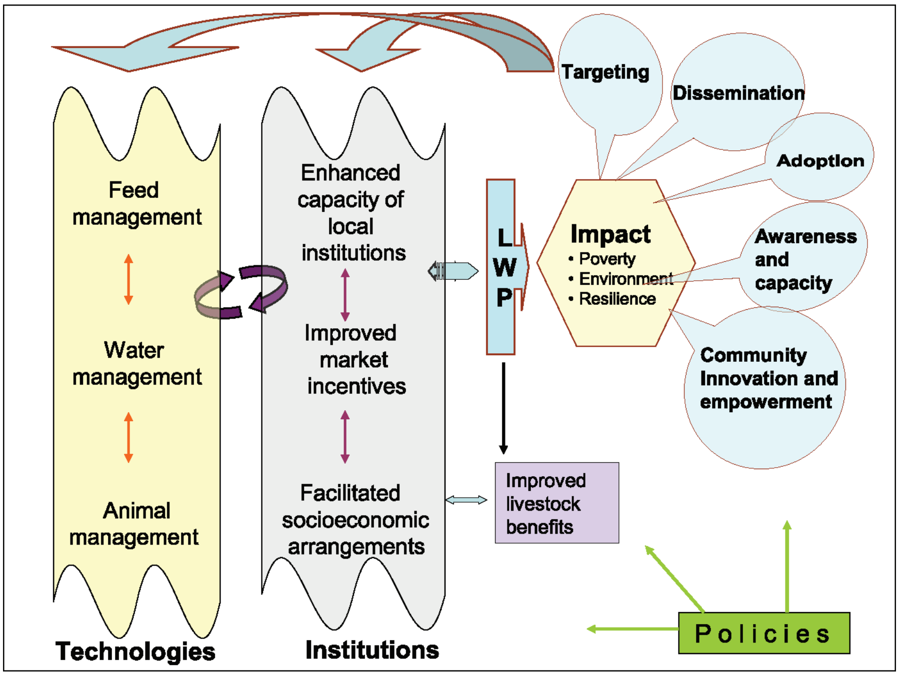

FIGURE 3. Scheme of strategies to improve LWP.

In general, several studies have demonstrated that multifaceted and integrated approaches taking on board interventions in different domains (biophysical as well as socio-political-economic) have great potential to improve LWP (Faki et al. 2008; Mpairwe et al. 2008; Amede et al. 2008)

Feed Management

Feed comes forward as an important component in the LWP framework, as on the one hand livestock depend on it for production and on the other it consumes water for growth (Figure 1). From the framework (Figure 1) some feed-related strategies could be readily inferred, such as feed type selection, improving feed quality and improving feed water productivity. Grazing management could be considered as forming part of other strategies, such as water management, improving feed quality, feed type selection and even supportive institutions. However, as grazing primarily contributes to feeding, it is discussed here as a separate paragraph.

Feed Type Selection

When selecting a feed type to improve LWP, it is not only the water productivity of the feed that must be considered, but also the feed requirements of the animals. The latter implies that the digestibility and nutrient content of the feed needs to be matched with the requirements of the livestock in different physiological conditions in order to achieve maximum livestock productivity. As the consumption of water for feed production can vary tremendously (Peden et al. 2007), a strategic choice of feed types can clearly benefit LWP.

In mixed crop-livestock systems and, especially, with resource-poor smallholders, crop residues are a major source of fodder for ruminants (Devendra and Thomas 2002). In these systems, dual purpose crops or food-feed crops are very common as the grain can be used for human consumption and the residues for livestock feed (Lenné et al. 2003). Because crop residues and other by-products do not consume any additional water, they present a huge opportunity to increase feed water productivity and, therefore, also LWP (Peden et al. 2007; Alemayehu et al. 2008). However, there is a trade-off for soil quality as crop residues are also needed to maintain soil fertility and soil structure. Another reason for not using crop residues as the only source of feed is their generally low nutritional quality (Coleman and Moore 2003; Blümmel et al. 2003).

Within the land use mosaic of crop livestock farming systems in SSA, pastures and rangelands contribute an important part of the feed requirements. They are usually located on marginal land, unsuitable for crop production (Steinfeld et al. 2006a). Therefore, making use of the available natural resources in these areas increases overall system productivity. However, being located on fragile, marginal land, rangelands and pastures can be degraded if subjected to inappropriate grazing management (for example, see Alemayehu et al. 2008). In such cases a lot of water is lost as runoff, leading to lower LWP as a result. Careful grazing management is, therefore, mandatory (see the section on *Grazing Management*), but not evident in these usually communally owned lands (Gebremedhin et al. 2004).

By making use of fodder trees within agroforestry systems, different benefits can be obtained simultaneously. Besides providing biomass for fodder, appropriate multi-purpose trees stabilize the land, decrease erosion, improve soil structure and fertility, and increase ecosystem stability (see, for example, Roothaert and Franzel 2001; Mekoya et al. 2008).

Although very little information is available on the water productivity of different forages, concentrates and supplements (Peden et al. 2007), adding these sources of nutritive fodder to the animal diet improves animal productivity. Forage legumes like cowpea (*Vigna ungulata*) (e.g., Tarawali et al. 1997; Singh et al. 2003) or lablab (*Lablab purpureus)* (e.g., Nyambati et al. 2003; Kabirizi et al. 2007) not only lead to higher animal performance, but also contribute to soil fertility through the fixation of atmospheric N and are an excellent food source. Easy to establish and fast growing grasses like Napier grass *(Pennisetum purpureum*, also called elephant grass) not only provide a lot of biomass for fodder but also have the capacity to stabilize land and gullies (e.g., Magcale-Macandog et al. 1998), thereby leading to water conservation as well. This dual purpose of water conservation and fodder production can contribute to improving LWP. However, because of the high water consumption of Napier grass, which might lead to competition for water with adjacent crops, not all locations are suitable for the cultivation of this type of forage. This should be taken into account when planning the incorporation of fast growing forages.

For countries or regions experiencing severe water stress, importing feed, and as such bringing in virtual water (Allan 1998, 2001), can be a viable option to increase LWP. Imported feed enables livestock production without using water resources for feed production within the system. However, water costs have to be taken into account when considering the larger scales that include the regions where the feed is produced.

It is clear from the above that the selection of a particular feed type has important implications for the amount of water that is used or lost and, therefore, also for LWP. However, there is not much of a choice when it comes to feed types for many smallholder farmers operating at subsistence level. Rather, feeding is a matter of using everything that is available to secure the herd’s survival. Often, that means resorting to crop residues and grazing.

Feed Quality

It is not only the quantity or the availability of feed that influence livestock productivity, but also its quality or nutritive value (Lenné et al. 2003). The nutritive value of the feed depends on its nutrient composition, its digestibility (i.e., the availability of energy and nutrients) and the efficiency of nutrient and energy utilization (Coleman and Moore 2003). Different opportunities to enhance feed quality exist, including feed crop genetic enhancement, chemical and biological treatment, supplementation and crop management interventions (Lenné et al. 2003). Besides choosing improved varieties, the options for farmers mainly lie in appropriate crop management ensuring an optimal, non-stressed plant growing environment. When low quality crop residues are fed to animals, the nutritive value can be improved by adding high quality legume feed (see, for example, Singh et al. 2003) or by urea treatment of the residues (see, for example, Sundstol et al. 1977; Schiere et al. 2000).

As overgrazing of pastures often leads to bush encroachment and the prevalence of less palatable plant species (Milchunas and Lauenroth 1993), appropriate grazing management (see the section on *Grazing Management*) and watershed management, in general, are necessary to obtain high quality feed from these areas. Simultaneously, the latter will lead to better water conservation.

Feed Water Productivity

As feed production is the largest consumer of water in crop-livestock systems (Singh et al. 2004; Peden et al. 2007), interventions to increase feed water productivity will help to increase LWP. From the location and direction of the arrow representing this strategy in the LWP framework (Figure 1) it is clear that it embraces both water flows and feed biomass production.

For smallholders, opportunities mainly lie in reducing water losses in feed production and reducing un-productive water depletion from the systems. This can be achieved by ensuring ideal conditions for crop production and choosing adapted, water-efficient crops. Given the worsening water scarcity and increasing demand for food, a lot of research and efforts are directed at increasing crop water productivity, which is reflected in the high number of scientific publications on this topic. Recent comprehensive overviews on how to improve crop water productivity are given by, for example, Kijne et al. (2003), Bouman (2007) and Rockström and Barron (2007). Interventions to improve feed water productivity can be grouped under three categories: crop management, soil management and water management.

The choice of a certain cropping system can influence water productivity as it affects the quantity and quality of forages and crop residues from cropland, fallow land and grazing areas. Agroforestry systems, like alley cropping with fodder trees (see e.g., Young 1989; Sanchez 1995), produce high quality fodder, while reducing losses in runoff (through improved soil cover and soil physical properties) and deep percolation (as the deep roots of the perennial vegetation pump up water). Besides that, intercropping and agroforestry are known to create a favorable microclimate and thereby reduce the vapor pressure deficit at plant level, so that transpiration efficiency is increased (Rockström and Barron 2007). Through their influence on the vegetative soil cover, cropping patterns (e.g., close row spacing), cropping systems (e.g., intercropping and agroforestry) and the crop (variety) choice (e.g., crops with early development of a closed canopy) can reduce un-productive water losses like evaporation and runoff (Wallace 2000; Bouman 2007).

As the timing of operations like tilling and weeding has a clear effect on crop performance and yields, it also influences crop water productivity. If tillage is delayed due to the lack of draught animals, the ideal planting period might be missed so that the crop cannot respond to rainfall at the start of the rainy season and good crop development is compromised (Rockström and Barron 2007). This link between animal and crop productivity is an important feature of mixed crop-livestock systems (Figure 1).

Soil, with its physical, chemical and biological characteristics dictating productivity at farm, landscape and higher scales, is one of the most important natural resources for feed production. Soil organic matter plays a key role in the maintenance of soil structure and, therefore, water holding capacity and infiltration. Mulching or leaving plant residues on the field after harvesting protects the soil against erosion while at the same time improving its physical and chemical properties through the increase in organic matter content (Vanlauwe et al. 2002). By covering the soil, mulches also minimize evaporative water losses. So, whereas mulching can improve water productivity through these mechanisms, it entails a reduced availability of crop residues for feed, which could lead to lower animal productivity. Especially in situations of feed scarcity, the decisions made by smallholder farmers on resource use will often prioritize animal survival above longer-term soil improvements.

Fertilizing, either by inorganic fertilizers or manure improves soil fertility, with manure having the additional advantage of improving the soil physical characteristics (Bationo et al. 2004). Manure application is usually a vital feature of complementarity between the crop and livestock components of mixed systems (Figure 1). However, this feedback loop can get lost when farmers are forced to fall back on dried dung for fuel in case of wood scarcity.

Various erosion control measures are effective in preventing loss of valuable soil resources, such as nutrients and soil organic matter, while at the same time improving the soil water regime in different environments (for overviews refer to, for example, Morgan 1986; Hudson 1991; WOCAT 2007).

Water management for improving feed water productivity comprises, first, of in situ water conservation measures that decrease water losses from the fields and rangelands where feed biomass is produced. Eliminating crop water stress through irrigation can decrease yield losses, and if water is used efficiently this will improve water productivity (see section, *Water Management*, for details).

In general, agronomic measures directed at healthy, vigorously growing crops favor transpirational and productive water losses over un-productive losses. Taking away water stress will only improve water productivity if other stresses (nutrient deficiencies, weeds and diseases) are also alleviated or removed (Bouman 2007), i.e., water management should go hand in hand with nutrient management, soil management, pest management, etc. (Rockström and Barron 2007).

Grazing Management

Appropriate grazing management is primarily intended to maintain a sufficient vegetative ground cover and to preserve and contribute to healthy, productive pastures and rangelands that not only provide biomass for fodder but also to environmental services such as biodiversity conservation and protection of downstream water uses (Gibon 2005; Hadjigeorgiou et al. 2005). Rangeland degradation is to be avoided, as severe erosion from these lands result in sedimentation of reservoirs and rivers, destruction of downstream aquatic ecosystems, disruption of the hydraulic characteristics of water channels, eutrophication, etc. (Steinfeld et al. 2006a).

A proactive and stimulating rangeland grazing management can be achieved through appropriate, adaptive stocking density and herd composition, as these measures influence vegetative ground cover, net primary production and species composition of rangelands (Milchunas and Lauenroth 1993; Mwendera et al. 1997b; Hadjigeorgiou et al. 2005; Navarro et al. 2006). Stocking density should be adjusted according to water and biomass availability, thus taking into account climate variations and their effects on plant production. The effects of over-stocking can be influenced by restricting access to grazing lands. Totally closing rangelands for a certain period (exclosure) allows them to recover and produce more biomass (Asefa et al. 2003; Descheemaeker et al. 2006). While it has been demonstrated that overgrazing leads to degraded, un-productive rangelands (e.g., Asner et al. 2004), it must be recognized that moderate grazing intensities can favor high pasture production and more diversified species composition (Milchunas and Lauenroth 1993; Asefa et al. 2003; Rowntree et al. 2004; Hadjigeorgiou et al. 2005). Watering point management, regulating traveling distances and animals' access to watering points, should be part and parcel of proactive grazing land management. Besides that, zero-grazing with cut and carry of grasses is a technique that can release grazing pressure on pastures (WOCAT 2007). In this system, a limited number of animals can be kept and well fed near the homestead, which also results in decreased energy losses and easier manure collection.

Wherever grazing management requires the regulation of rangeland access, strong institutions are mandatory (see the section on *Supportive Institutions*), which illustrates the links between the biophysical and socio-political-economic spheres of influence (Figure 2).

Water Management

Water conservation, which involves decreasing the un-productive water losses (runoff, evaporation, conveyance losses and deep percolation) from a system but also increasing the water use efficiency of the respective system components, has the potential to increase overall water productivity. Water conservation is often achieved through integrated interventions, which simultaneously lead to soil conservation and land management, as they are often designed to reduce the energy of the surface water flows and thereby enhance infiltration of the surface water. Within the group of soil and water conservation measures (see, for example, WOCAT (2007) for an overview), a distinction can be made between physical structures on the one hand and vegetation management on the other. Vegetation has a direct impact (through its effect on surface roughness and soil protection) and an indirect impact (through its effect on soil organic matter and soil structure) on rainwater infiltration and runoff (Descheemaeker et al. 2006). As changes in vegetation cover also influence soil temperature, evaporation and transpiration, the overall impacts on the hydrological cycle are quite complex (see, for example, Le Maitre et al. 1999; and Bruijnzeel 2004 for extensive overviews). Generally, increasing the vegetation cover will result in higher biomass production and a higher ratio of productive water losses over un-productive losses.

Irrigation is an effective way to eliminate crop water stress and decrease yield losses during dry spells, thereby increasing crop production. Especially in drought-prone areas, supplemental (i.e., applying small amounts of irrigation at critical times of the growing season) and deficit (i.e., applying less irrigation than is needed for maximal crop production) irrigation, both aiming at optimal rather than maximal yields, are known to strongly increase crop water productivity (Oweis and Hachum 2006). In irrigation, non-productive water losses can be reduced by improvements in irrigation water management, which includes among other things, minimizing conveyance and drainage losses through various techniques (refer to, for example, Hussain et al. 2007; Jensen 2007; Faurès et al. 2007 for comprehensive information on improving water productivity in irrigated agriculture). Integration of livestock production systems in both small- and large-scale irrigation schemes holds important opportunities to improve overall system productivity (Ayalneh 2004; Elzaki et al. Forthcoming). However, irrigation schemes often suffer from poor institutional arrangements, e.g., with respect to water user rights (Awulachew et al. 2005), which again demonstrates the importance of institutional interventions to backup the biophysical interventions (Figure 2).

Water harvesting, defined as concentrating and diverting runoff from one area and storing it for subsequent beneficial use in another area (Oweis and Hachum 2006), enhances the temporal distribution of water and leads to important improvements in water productivity. This water stored can be applied to crops or forages to bridge dry spells and can be used for domestic uses or for human and animal drinking.

In water scarce environments, animals are often forced to walk long distances to reach watering points, and thus spending a lot of the energy acquired from feed. Although the amount of water needed for drinking is small compared to the amount needed to produce feed, providing this small volume is a strategic choice (Peden et al. 2007). It enables animals to access feed (Faki et al. 2008) and convert it into animal products, thereby making a large difference to the overall LWP. The provision of sufficient watering points is important not only to maintain animal productivity, but also to avoid the concentration of too many animals around one watering point, causing soil and vegetation degradation, and water contamination (Brits et al. 2002; Mati et al. 2005; Solomon et al. 2007; Wilson 2007; Faki et al. 2008). Good watering point management, taking into account access restrictions, leads to improved water conservation and, therefore, higher LWP.

This section on water management encompassed interventions directed at different components of the LWP framework (Figure 1). Water conservation as well as the efficient use of water for feed production and animal drinking all contribute to better water management for an improvement in LWP. In the framework (Figure 1), the water management strategy is superimposed on the water outflow arrows, symbolizing the effect of good water management on shifting un-productive water depletion (runoff, evaporation, contamination) to productive water depletion (transpiration).

Animal Management

Increasing Animal Productivity

Improving animal productivity is primarily the domain of the conventional animal sciences (Peden et al. 2007). Animal breeding for better feed conversion, higher milk and meat production, lower energy requirements, etc., has been very successful globally, but the use of improved breeds in the tropics has been limited up to now, as these breeds are often less resistant to harsh conditions or prevailing diseases (Parthasarathy Rao et al. 2005). Therefore, especially in SSA countries, there is still a huge potential to increase animal productivity through genetic improvements. The spread of artificial insemination techniques can be an important driver in this matter (Steinfeld et al. 2006a). Selection should not be directed at productivity alone, but must also take into account the adaptation of species and breeds to the prevailing environmental conditions.

The choice of the animal species itself can influence overall livestock productivity. For instance, monogastric species (pigs, poultry) are characterized by a higher feed conversion rate than ruminants. This lies at the basis of the shift towards monogastrics in many developing industries and developed countries (Parthasarathy Rao et al. 2005; Costales et al. 2006; Steinfeld et al. 2006a). Taking advantage of the multiple-use function of certain animals, like wool-meat sheep, is also promising.

Decreasing Animal Morbidity and Mortality

In some places, animal mortality is so high (Negassa and Jabbar 2008) that it seriously undermines all other efforts to increase LWP. High livestock mortality rates are caused by a number of interrelated factors such as drought and high stocking rates, which negatively affect system stability and vulnerability (Desta 2001). The prevalence of animal diseases and the low capacity of veterinary health services to respond to disease outbreaks also play a role. Even if they don't die, diseased or stressed animals lead to lower productivity as they consume feed and water but do not deliver outputs or services as they should. Consequently, their market value is also lower. Therefore, investing in veterinary services and disease control can have significant benefits (Hüttner et al. 2001; Scoones and Wolmer 2006; Perry and Sones 2007; Faki et al. 2008). Adequate herd management and animal husbandry, comprising decisions on type and number of animals, offtake rates, slaughtering age and reproduction rates are equally necessary.

Although often ignored in the past, animal productivity can be strongly improved by applying different animal production technologies together. For instance, investing in improved health without tackling feed constraints, water scarcity or weak market institutions will not have the desired impact. On the contrary, when different measures are included simultaneously, they can be synergistic. This, again, is a plea for an integrated approach taking into account different strategies and entry points (refer also to figures 1 to 3).

Supportive Institutions

Institutions are formal or informal rules on who makes decisions, according to which procedures, what actions are permitted, what information must be provided and what payoffs will be assigned to individuals. Institutions also include formal and informal organizations, laws, customs and social practices that influence the behavior of people in a society (Ostrom 1990, 2005). Institutions may either include or exclude an actor group (e.g., individual, households and ethnic groups) from access to resources. Formal institutions constitute the written or codified rules such as the constitution, judiciary laws, organized markets and property rights. Meanwhile, informal institutions are the rules governed by behavioral norms in society, family, and community, and include sanctions, taboos, traditions and codes of conduct (North 1990).

The institutionalization of natural resource management (NRM) encompasses behavioral and structural adjustments that can lead to conceptualizing and implementing interventions in NRM by mobilizing appropriate capacities at various scales (Yasmi 2007). Interventions for institutional improvements are especially needed where environmental ethics are lacking and in the case of common property natural resources.

Conflicts in water and land use are pervasive, widespread and sometimes extremely destructive (Buckles 1999), particularly in pastoral and agropastoral systems in Africa (Turner et al. 2006). Strong institutions are fundamental to minimize and resolve conflicts through promoting equity among various groups, transferring information about policy and program objectives, and introducing improved resource management practices.

With respect to livestock and water, enabling institutions are necessary to provide support in different areas, such as community resource management, but also in credit facilities and value adding facilities (e.g., butter production), which are important for the income of smallholders (Parthasarathy Rao et al. 2005). Institutional development should take into account the establishment of markets for both input and output commodities. Fair prices and easy market access for smallholders are necessary to ensure the link between producers and traders and to avoid smallholders being out-competed (Delgado 2003; Costales et al. 2006). Keeping livestock as a means to store wealth or reduce risks, often results in large numbers of animals exceeding the carrying capacity of the land. Institutions that offer farmers a new way of insuring their assets or securing their savings, can lead to decreased herd sizes and as such contribute to alleviating pressure on land and water resources.

Regulations can only be enforced if institutions are in place to establish standards, monitor the necessary variables (e.g., water quality, groundwater depletion), issue permits and fine violations. Also, in conflict management and communication between different stakeholders or land users (e.g., crop cultivators and pastoralists), well-functioning and respected institutions play an important role (Steinfeld et al. 2006a).

For institutions to contribute to sustainable improvements in LWP, formal governance structures at (inter)national levels should integrate with institutions at regional level and with local, more informal institutions that are well-known and respected by the local population. Another prerequisite for development in the livestock sector, without jeopardizing water and other natural resources, is the integration of livestock issues in other sectoral institutions.

In general, institutions need to be functioning well and respected by the local population for improvements in LWP to really materialize and have a positive impact on the environment and livelihoods (Figure 1). This, again, reflects the fact that the interactions between the biophysical and the socio-political-economic domains of farming systems (Figure 2) cannot be ignored.

Enabling Policies

In many cases, the absence of a sound policy framework, which is conducive to practices benefiting both agricultural productivity and the environment, is an obstacle for increasing LWP and results in negative environmental impacts (Steinfeld et al. 2006a). To reverse this situation, the policy framework should take on board different issues. Policies should be directed at developing infrastructure (Amede et al. 2008), as this is necessary to secure access to markets, veterinary services, training services, etc. Appropriate land use should be based on land suitability for different agricultural activities (see, for example, FAO 1976, 2003). Besides that, given the high impact of livestock production systems on the environment, limiting the land requirements for livestock production systems through promoting intensification is warranted (Steinfeld et al. 2006a). Price signals and research and development of new technologies (Amede et al. 2008) can result in the intensification that is needed. Land titling and secure access to land and water have an effect on LWP, as they are necessary incentives for smallholders to maintain the long-term productivity of natural resources (see, for example, Owoyesigire et al. 2008). A change in this direction is certainly needed for grazing lands, which are often communally owned. As highlighted by Gebremedhin et al. (2004), private land ownership is not the only solution, as land rights devolved to local communities can result in successful community resource management as well. Land taxes and lease rates could encourage more intensive and more productive land use, whereas grazing fees and equitable access could result in more responsible rangeland management.

Natural resources are often seriously underpriced, because of overt subsidies and the fact that externalities are not taken into account (Steinfeld et al. 2006a). This leads to inefficient uses, and mis-allocation and degradation of land and water resources. An appropriate pricing policy is, therefore, mandatory and can include different tools. Water pricing is advocated as a useful tool to stimulate water conservation, proper allocation of water to ensure its use to highest value and cost recovery (Johansson et al. 2002). With appropriate water rights and water prices defined, water markets can encourage the efficient use of water resources (Norton 2003, cited in Steinfeld et al. 2006a). This does not apply exclusively to the use of water for crop production, but can also include charging for livestock drinking water at watering points.

As the removal of agricultural subsidies and trade liberalization lead to more realistic prices of both inputs and outputs (Costales et al. 2006), these measures also contribute to reducing the negative environmental impact of livestock production systems.

Payment for environmental services (Pagiola and Platais 2007), e.g., for improved management of upstream watersheds which may result in improved water quality and quantity to downstream users, can have a positive impact on environmental conditions as it may be an incentive for farmers to adjust their practices (see, for example, Sierra and Russman 2006; Pagiola et al. 2007). As an example, in order to preserve the environmental services, rangeland users may decide to shift from high intensity grazing with large herds to zero grazing with a limited number of animals kept nearby the homestead and fed by cut grasses from the rangeland. However, for such payment schemes to be operational, environmental services have to acquire a proper price reflecting their real value. As such, markets can be established, where beneficiaries pay to providers (Richmond et al. 2007).

Besides the above-mentioned concrete options, a more general prerequisite for policies to lead to sustainable improvements in LWP is to take into account equity and gender issues in all efforts (van Hoeve and van Koppen 2005). Understanding the effects of interventions on gender-specific labor costs can contribute to adapted policies (Mapedza et al. 2008). Leaving behind top-down approaches and allowing participatory management of watersheds are necessary for community empowerment, adoption of interventions and innovations to materialize (Amede et al. 2008).

As policies determine the enabling or disabling overall framework for the application of all types of interventions (figures 1 and 3), they should be given due attention and policymakers should be involved in the realization of LWP concepts.

GAP ANALYSIS

Knowledge Gaps

Water productivity is not a new concept in the crop sector, where it has been successfully used for many years (Kijne et al. 2003; Bouman 2007; Rockström and Barron 2007). Plant breeders and agronomists have applied concepts of genetics and plant physiology to develop varieties which are adapted to drought-prone regions and responsive to irrigation inputs. They have also identified phenotypic traits that could be used to identify appropriate inbred lines and gene pools to extract the desired genes and transfer them to the ideotypes and preferred crop varieties (Amede 1998). On the other hand, LWP is a new concept that is still under development (Peden et al. 2007) and much of the above-mentioned interventions have not been applied yet or evaluated in its context.

The assessment of LWP is not straightforward because:

(1) it comprises different components both at the numerator and the denominator side of the ratio (Equation (1)),

(2) it is strongly scale-dependent, and

(3) it depends on the socioeconomic group, the agroecological zone and the type of livestock production system that is considered in the analysis (Cook et al. 2008; Peden et al. 2002).

Besides that, the strong interaction between livestock and water on the one hand and other natural resources (vegetation, soil, ecosystems and climate) on the other shapes the interpretation of LWP. The multiple products and services (the numerator of Equation (1)) obtained from livestock production systems can be of a physical, economic, environmental and sociocultural nature (refer to the animal outputs in Figure 1). Livestock produce food (including proteins, fat, minerals, micronutrients and vitamins), energy (including draught power for land preparation and threshing, transport, fuel from manure) and enable nutrient cycling. Animals provide farmers with a source of income and the possibility of storing wealth, risk spreading and insurance against difficult (drought) periods. With respect to sociocultural roles, livestock are often considered a status symbol and exchanged as dowry (ILRI 2002). Finding a common unit so that both quantifiable and non-quantifiable benefits can be analyzed together is a challenge on its own. Furthermore, depending on the system and the conditions, farmers also rank the various products and benefits differently, and this needs to be taken into account. To determine the denominator of the LWP equation (Equation (1)), the amounts of water consumed, depleted, and degraded by the livestock production system need to be assessed. The water accounting principle (Molden 1997) helps to determine water inflow (comprising rain, changes in water storage, groundwater, surface and subsurface water, and virtual water), water outflow (comprising evaporation, transpiration, surface and subsurface outflow, and deep percolation) and other ways of rendering water unavailable for further use (such as water pollution and degradation) (refer to the water flows in Figure 1).

Even for similar mixed crop-livestock systems in the Ethiopian Highlands, reported LWP values largely vary from US$0.06–0.08 per cubic meter of water (Alemayehu et al. 2008) over US$0.3–0.6 per cubic meter of water (Ayalneh 2004; Haileslassie et al. 2008; Gebreselassie et al. 2008) to US$4.8 per cubic meter of water (Tulu et al. 2008). This variation is indicative of the impact of scale and the use of different methodologies, accounting varying livestock benefits and water flows. As such, differences in reported LWP values do not always point to differences in actual livestock productivity. Therefore, to be able to draw conclusions and recommendations from studies on LWP, it is extremely important to always take into account the scale and the methodology of the study.

Water and livestock interactions have been investigated mainly from the perspective of drinking water uses (constituting less than 5% of the total water consumption in crop-livestock systems) and runoff in relation to grazing pressure. As such, knowledge gaps and lack of reference points in different domains hamper the analysis of LWP:

(1) There is limited knowledge on the amount of water used by the different types of feed originating from various system niches and influenced by management practices, climatic conditions and landscape positions. Values for feed water productivity reported in the literature vary with a factor 70 (Peden et al. 2007), which is mainly due to inconsistent methods and definitions;

(2) There is insufficient knowledge on the conversion efficiency for the different types of feed under intensive and extensive livestock production systems and across species and breeds;

(3) The impact of livestock on land and water resources across various livestock systems, agroecology and land characteristics is not fully understood;

(4) It is difficult to assess the amount of water and other resources used from a particular watershed in transhumant systems and systems with open grazing;

(5) The amount and quality of feed varies with animal type, household, season and productive objectives; and

(6) Partitioning the amount of depleted or lost water between livestock, crop or other farm-related practices is difficult.

Policy Gaps

As observed by Norse and Tschirley (2000), in many cases, policymakers don't know what kind of information they can reasonably expect or ask for from the research and development community to improve system components. For example, the majority of political leaders and policymakers in Uganda were not aware of the existing bylaws and NRM policies, their regulations and implementation mechanisms, and the process of formulating bylaws (Sanginga et al. 2006). Thus, a proactive role is essential in assessing the information needs of policymakers and thereby developing effective communication strategies for guiding and informing the policy process.

Crude estimations indicate that animal density follows human population density (Thornton et al. 2002), availability and access to land and water resources, and is commonly high in high rainfall and irrigated systems (Peden et al. 2006). These are also the systems that usually attract the attention of policymakers in investing on market infrastructure, institutional development and extension services. In SSA, where food security is a priority on the agenda, there is a growing interest in developing irrigation schemes and promoting agricultural technologies. However, most of the development planners have been biased towards the crop sector to date and policymakers have usually considered the livestock sector as subsidiary to the crop sector (Scoones and Wolmer 2006). Despite the growing market incentives for livestock products, nearly all extension packages in this region are crop-based. However, livestock are serving households and systems through a variety of products and benefits and also serve as a risk aversion strategy when crops fail.

The policy gaps related to livestock-water interactions can be summarized as follows:

(1) Policies that promote livestock productivity through improved access to drinking water are often lacking;

(2) Policies directed at providing veterinary services to improve animal health are inadequate in many cases;

(3) The livestock agenda is usually not integrated with irrigation development, and investments in biofuel and reafforestation. For instance, an increase in the production of ethanol from second generation biofuels will strongly compete with the availability of feed in the form of crop residues and other biomass, but this is rarely mentioned in energy and other policy documents;

(4) Local and regional policies that can enable local communities to respond to climatic and man-made shocks are lacking.

(5) The current strategy of most governments and NGOs with respect to poor livestock keepers is inclined towards post-disaster intervention rather than investing in early warning systems and introducing adaptive mechanisms.

In general, the policies required for poor livestock keepers are those directly or indirectly affecting the different components of LWP (Figure 1). Policies facilitating the integration of crop, livestock, land and water management initiatives are crucial to improving water productivity at farm, landscape and higher levels. Besides that, policies directed at environmentally friendly intensification of the crop-livestock systems can allow smallholders to take advantage of the dynamic market situation and cash improvements in LWP.

Institutional Gaps

It is often unclear how institutions assigned to manage land and water resources are enacted at the community level. The level of awareness of the rules and regulations enacted at various levels of government institutions (including bylaws) can greatly vary and the same applies to the level of compliance of communities with NRM regulations. There is a general consensus that institutions are key to the sustainable management of livestock, water and land resources, if communities could be convinced to comply with regulations. However, some of the institutional variables are beyond reach of the communities, but influence enactment, awareness of and compliance with regulations.

In SSA, livestock, land and water resource management are usually governed by both formal and informal institutions, whereby the formal institutions are setting the roles and the responsibilities of the various actors at national and district levels while the informal institutions are usually overseeing access and day-to-day management of communal and privately owned land and water resources. Local informal institutions encompass many different types of indigenous organizations and functions including resource governance, resource mobilization, conflict resolution, self-help arrangements and other fundamental village level issues. Although the action of formal institutions is strongly facilitated by the policies and the bureaucratic arrangements of the system, it is more common that the informal institutions are strongly respected by the respective communities.

Institutional arrangements for sharing livestock benefits (offspring, milk, manure and traction) can contribute to matching feed availability with livestock ownership (Amede et al. Forthcoming). In farming systems where feed resources are limited and ownership of livestock doesn’t necessarily correlate with resource distribution, these types of institutions can allow for a relatively higher level of LWP.

The major gaps from the formal institutional perspective are:

(1) A platform among organizations working on the different components of LWP is lacking. Coordinated institutional efforts between the departments of agriculture and water resources on the one hand and community-based organizations on the other, could be effective in improving water productivity of crop-livestock systems. As there are no institutions explicitly working on LWP, the latter should be considered as a tool to achieve human and environmental development goals;

(2) The agendas of specialized institutions should be enhanced and broadened to move from discipline–oriented development towards system-oriented engagement in research and development. However, as long as issues related to livestock-water interactions are not incorporated in the agenda of the ministries of finance, investments for improving LWP cannot materialize;

(3) Local institutions should be strengthened or formed where such institutions are not available. Capacity building activities amongst farmer groups could play a big role in the farmer institutional development. Local groups could be developed as farmer institutions and adjusted accordingly to meet the changing circumstances and the evolving roles of poor livestock keepers. The more developed a community group, the more likely it is to determine its own direction and form sustainable local institutions.

CONCLUSIONS

Increasing global water scarcity and competition for water on the one hand and the growing demand for (animal) food on the other, provide a strong impetus for the scientific community to come up with solutions that can increase (animal) food production without depleting more water while safeguarding the environment. Given the difficulty of the challenge in mixed crop-livestock systems in SSA, it is clear that technological innovations alone will not be sufficient. Integrated measures, which also take on board social, institutional and policy issues, are required.

The proposed concept and framework of LWP offer a way to analyze mixed crop-livestock production systems so that strategies and interventions can be identified and their impact analyzed. It is hypothesized that improvements in LWP can have a positive impact on livelihoods, environmental health and resilience if other prerequisites for adoption, awareness raising and community empowerment are also fulfilled.

This paper has identified various interventions within three ‘technical’ areas of LWP: feed management, water management and animal management. Strategies directed at the biophysical components of mixed crop-livestock systems include feed type selection, improving feed water productivity, improving feed quality, grazing management, water management, increasing animal productivity, and decreasing animal morbidity and mortality. Besides technological interventions, the paper has also indicated the way forward in institutional and policy issues.

The identified institutional and policy gaps demonstrate that concerted efforts in integrating all components of the LWP concept will be necessary to achieve improvements. Huge opportunities also lie in integrating the different agricultural sectors with the water sector.

For the LWP concept to be widely and successfully applied, important gaps in our knowledge and understanding of LWP need to be filled. Among other things, future research should be directed primarily at establishing reference points for the different LWP domains, clarifying the influence of scale on the analysis and coming up with a universal unit for quantifying the different livestock benefits.

Although this paper is specifically dealing with improving LWP of mixed crop-livestock systems, the ultimate aim is to improve overall agricultural water productivity at different scales. Moving beyond LWP is, therefore, mandatory. However, the LWP concept and framework presented here have proved to be very useful for identifying promising entry points and interventions to improve livelihoods and environmental health. Putting livestock and water interactions on the agenda of policymakers remains a high priority.

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