



Adaptation opportunities for smallholder dairy farmers facing resource scarcity: Integrated livestock, water and land management

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ABSTRACT

Dairy intensification is a widely used means of achieving food security, improving farmer incomes and enhancing overall economic growth. However, intensification is dependent upon the availability and suitability of natural resources to sustain growth in production. Here, land and water footprints of milk production in three contrasting agro-ecological zones ranging from humid to semi-arid across nine counties of Kenya are quantified. Water and land use footprints across three potential intensification pathways are also outlined and evaluated against the baseline scenario, the currently prevailing practices or the S1 Futures scenario, treated as the benchmark. Intensification pathways focusing on improving livestock breeds, feed provisioning and milk output per cow and distinguished by contrasting management practices perform differentially across the three agro-ecological zones. Total water and land footprints increase for all scenarios relative to the baseline scenario. In particular, all the breed improvement scenarios, have much larger total water footprints than the baseline scenario. Improvement in breed to pure bred cattle across all production systems has the largest total water footprint across all the production systems. Across all the scenarios, the largest reduction in water footprint of milk production (75%) occurs with improvement in breed and feeding practices from two scenarios in the lowlands. Milk production by the cross-bred cattle is most efficient in the lowlands system whereas milk production by the pure breed Ayrshire is most land use efficient in the midlands system. Across the three agro-ecological zones, improving breeds, feed provisioning and milk production per cow may achieve production intensification but concurrently exacerbates resource limitation. Consequently, the heterogeneity inherent in resource availability across dairy production zones should be considered when developing strategies for increasing dairy production.

1. Introduction

Consumption and production trends for African countries have not followed the trajectory of exponential increase in meat and milk consumption witnessed in other continents (Alexandratos and Bruinsma, 2012; Bruinsma, 2003). Though this is true for most countries in the developing world, many developed countries have exhibited this growth pattern in demand and have transitioned into managing it with calls for reducing consumption of Animal Source Foods (ASFs) (Rask and Rask, 2011). Conversely, in many developing countries, the consumption of ASFs is not yet at the point that merits similar calls to reduce consumption of these foods (Gómez et al., 2013; Herrero et al.,

2014). However, consumption can be expected to increase in countries with accelerating urbanisation and economic development (Crosson and Anderson, 1994; Herrero et al., 2014; Regmi and Dyck, 2001; Schneider et al., 2011).

Many developing countries aim to increase production to meet both the growth in demand by the wealthy consumers and concurrently commit to poverty alleviation through implementing interventions that enhance smallholder farmers' engagement in market-oriented economic activities leading to improved livelihoods (Herrero et al., 2014; Schneider et al., 2011; Thorpe et al., 2000). Though intensification often requires increased investment by the smallholder farmers, thereby also increasing the risk of losing this investment if production fails (Udo

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et al., 2011), there are increasingly more incentives to encourage farmers to increase production to meet the growth in demand for ASFs (Conceição et al., 2016; FAO, 2017).

Production intensification almost certainly increases the demand and competition for limiting natural resources (Herrero et al., 2010). Increased production of meat and milk translates to increased demand for both water and land resources (Bosire et al., 2015; Mekonnen and Hoekstra, 2012). This is especially so for increased meat consumption due to the large resource footprint associated with meat production. However, though similarly categorized as a resource intensive product, milk production has a much lower natural resource demand than meat production (Falkenmark and Lannerstad, 2004; Jalava et al., 2014; Mekonnen and Hoekstra, 2012). Understanding this large differential in resource demand is important especially to discussions on establishing policies on food security that aim to ensure sustainability of production under varying levels of water and land availability. This is especially relevant for regions with large variations in climatic conditions and characterized by recurrent severe droughts or flooding.

To assess the implications for the environment of the increase in consumption of ASFs across contrasting ecological zones, water and land footprints can be used as indicators. The water footprint is an indicator of water use in relation to the production of consumer goods and is expressed in terms of the water volume evaporated or polluted (Hoekstra et al., 2011). The water footprint is composed of three components: the green, blue, and grey water footprints. This indicator is especially suitable for quantifying the water stress that would be expected if agricultural production were increased under both water scarcity and abundance scenarios (Chouchane et al., 2018; Fader et al., 2011; Mekonnen and Hoekstra, 2012). The land footprint is the 'actual land used' for producing consumer goods and services (Erb, 2004) and typically has two components: the cropland footprint and the grazing land footprint used in livestock production. This indicator is useful for assessing the pressure on land across heterogeneous landscapes and impacts at various scales (Fischer et al., 2011; Wirsenius et al., 2010).

Like in other developing countries, livestock production in Kenya is undergoing intensification driven by increasing demand for animal source foods and changing resource availability linked to widening variation in climatic conditions. For instance, under Kenya's Vision 2030 strategy it is envisaged that economic growth will be maintained at 10% per annum up to 2030 (Kenya, 2007). This would translate to wealthier citizens able to access diets with high-cost animal food sources (AFSS). On the production side, Kenya's Vision 2030 strategy envisions an increase in productivity of both crops and livestock. This would be achieved through such initiatives as seed improvement, testing, promotion and distribution of low-cost irrigation technologies, improvement of livestock breeding programmes and long-term arid and semi-arid land development programmes. So far, no comprehensive analysis of the extent to which this goal has been achieved has been undertaken, though irrigation schemes aimed at improving production have been implemented. Such strategies are aimed at attaining advances in productivity similar to those achieved in the developed countries (Tilman et al., 2002). The dairy sector contributes substantially to the overall water and land use in agricultural production in Kenya (Bebe et al., 2017). Under the dairy development strategy, the Kenya government aims to increase dairy production by 50% by the year 2030 to meet the growing demand for milk (GOK, 2010). By 2012, the national dairy consumption was estimated to have increased from 96 litres per person in 2009 to 106 litres person⁻¹ yr⁻¹ in 2012 and was expected to grow to 139 litres in 2022 (Fintrac, 2015). This would necessitate an increase in the intensity of the overall use of natural resources within the country as a large proportion of the milk consumed locally is produced within the country (Bebe et al., 2003; Bosire et al., 2017). However, the use of these resources, for example water in the arid and semi-arid regions and land in the humid areas, is projected to decrease mainly due to restrictions on the available arable land attributed to changing climate and increased production (El-Beltagy and

Madkour, 2012; Elliott et al., 2014; Hanjra and Qureshi, 2010; Harvey and Pilgrim, 2011). For smallholder farmers, it is thus important to invest in practices that facilitate adaptation to increasingly limited land resources and water scarcity. Failure to adapt would restrict their ability to produce the quantities of food demanded by the rising and urbanising populations.

Here, we quantify the water and land footprints of current livestock production systems in three agro-ecological zones in Kenya; zones that contrast strongly in terms of land availability and rainfall. The information is then used to evaluate the extent to which farmers can improve agricultural productivity in non-traditional and pre-commercial dairy areas in these zones. Because water availability and suitability of land resources for agricultural production are projected to decline, especially in the low rainfall regions of Kenya, it is important to understand the implications of interventions that aim to increase production in dairy systems on farmers' adaptation potential to climate-induced reduction in water availability and land usability. This is done by assessing options for intensifying fodder-based production best suited to particular regions with contrasting constraints on water and land availability.

2. Methods

2.1. Study area and agroecological zones

The study was conducted across nine counties in pre-commercial dairy areas in Kenya. In this study, dairy or milk production refers to raw milk production. The counties fall in three agroecological zones: semi-arid to semi-humid zone supporting predominantly mixed crop-dairy systems (Makueni and Kitui), semi-humid, sub-humid to humid midlands (Busia, Homa Bay, Kisumu, Migori, Siaya) dominated by rainfed mixed crop-livestock systems, and semi-humid to humid highlands (Taita Taveta and Vihiga) where rainfed mixed crop-livestock systems are the most common (Jaetzold and Schmidt, 1983a, 1983b).

The semi-arid to semi-humid zone supporting mixed crop-dairy systems is characterised by bimodal rainfall with an annual average ranging between 250 and 1000 mm. The counties falling in this zone are classified into two agro-ecological zones; semi-arid and sub-humid-humid and are prone to frequent droughts. The annual average temperature in these counties is quite high and ranges between 14 and 36 °C. The sub-humid to humid midlands, supporting predominantly rainfed mixed crop-livestock systems similarly experience bimodal rainfall that ranges between 700 and 2000 mm annually. The altitude in this zone averages 1000–1500 m above the sea level. The annual average temperatures in this zone range between 9 and 30 °C. The final zone, the semi-humid to humid highland zone, supports mostly rainfed mixed crop-livestock systems and encompasses two counties located in Eastern and Western Kenya. Rainfall is also bimodal in this zone with the average annual total ranging from 500 mm in the Taita Taveta lowlands to 2000 mm in the Taita Taveta and Vihiga highlands. The average annual temperature in this zone ranges between 18 and 23 °C.

2.2. Characterizing the livestock production systems

The livestock production systems were characterized based on information collected using household surveys. Respondents in these surveys were selected through a two-stage, stratified cluster random sampling, one at the ward (subdivided into locations, sub-locations and villages) level and the other at the household level, for each county (Auma et al., 2018). A random sample of wards is selected with probability proportional to the population size and number of households in each ward relative to the total population size in all the wards in the counties. The wards are selected randomly from a list of all wards in the counties. The counties represent the strata and when a ward is selected, all the households within the ward are also automatically selected, as in cluster sampling. For this study, a total of 169 households were selected

Table 1
Summary of the various parameters used to estimate the water and land footprints of milk production across three improved production scenarios in each of nine counties of Kenya.
Sources: 1, (GOK, 2010), 2, 4 and 5 (Auma et al., 2018), 3(Bouwman et al., 2005), 6 (ILRI, 2010).

Parameters	Production System										
	Mixed crop -dairy systems, lowlands						Rainfed mixed crop - livestock systems, midlands				
	Makueni	Kitui	Semi-Arid Futures	Semi-Local-Cross	Semi-Cross-AY-Pure	Busia	Homa Bay	Kisumu	Migori	Siaya	
Scenario	Current		S ¹	S ²	Pure S ^{3a}	S ^{3b}	Current				
Number of local cows ¹	62,172	68,419	130,591				36,975	90,756	45,998	92,436	71,984
Number of crossbred cows	9,107	22,567	31,674	162,265	162,265	162,265	5,040	3,005	7,057	4,152	1,668
Total milk production (tonne/year)	61,071	71,472	321,206	494,908	742,362	989,817	27,193	49,607	35,302	68,979	38,851
Livestock breed ²	Cross	Cross	Cross	Cross	Pure breeds	Pure breeds	Zebu	Zebu	Cross	Zebu	Zebu
Feed conversion ratio (kg feed DM /kg milk) ³	bred	bred	bred	bred					bred		
Milk yield (kg/year/local cow) ⁴	3.1	3.1	3.1	3.1	2.6	2.4	4.6	4.6	3.1	4.6	4.6
Milk yield (kg/year/crossbred cow) ⁵	540	270	1350		4,575	6,100	486	486	351	675	486
Weighted average milk production (kg/ animal/year)	3,020	2,349	4,575	3,050	4,575	6,100	1,830	1,830	2,715	1,586	2,318
Feed composition (%) ⁶	857	786	1,980	3,050	4,575	6,100	647	529	665	714	527
Pasture	30	26	10	30	20	20	35	50	5	32	30
Forages	51	56	50	33	45	45	38	40	53	39	66
Crop residues	9	10	10	32	5	5	15	9	3	28	4
Compounded and supplemental feeds	10	8	30	5	30	30	13	1	39	1	0

Parameters	Production System										
	Rainfed mixed crop - livestock systems, midlands						Rainfed mixed crop-livestock systems, highland				
	Midlands Futures (S ¹)	Midlands-Local-Cross (S ²)	Midlands-Cross-AY-Pure (S ^{3a})	Midlands-Cross-Fr-Pure (S ^{3b})	Midlands-Cross-Fr-Pure (S ^{3b})	Vihiga Current	Taita Taveta	Highlands Futures (S ¹)	Highlands-Local-Cross (S ²)	Highlands-Cross-AY-Pure (S ^{3a})	Highlands-Cross-Fr-Pure (S ^{3b})
Scenario	S ¹	S ²				Current					
Number of local cows ¹	338,149					27,009	31,574	58,583			
Number of crossbred cows	20,922	359,071	359,071	359,071	359,071	14,824	11,534	26,358	84,941	84,941	84,941
Total milk production (tonne/year)	520,313	1,095,167	1,642,750	2,190,333	2,190,333	58,617	51,024	199,675	259,070	388,605	518,140
Livestock breed ²	Cross	Cross	Pure breeds	Pure breeds	Pure breeds	Cross	Cross	Cross	Cross	Pure breeds	Pure breeds
Feed conversion ratio (kg feed DM /kg milk) ³	bred	bred	Pure breeds	Pure breeds	Pure breeds	bred	bred	bred	bred	Pure breeds	Pure breeds
Milk yield (kg/year/local cow) ⁴	3.1	3.1	2.6	2.4	2.4	3.1	3.1	2.6	2.6	2.6	2.4
Milk yield (kg/year/local cow) ⁴	1350					513	513	1350			
Milk yield (kg/year/crossbred cow) ⁵	3,050	3,050	4,575	6,100	6,100	3,020	3,020	4,575	3,050	4,575	6,100
Weighted average milk production (kg/ animal/year)	1,449	3,050	4,575	6,100	6,100	1,401	1,184	2,351	3,050	4,575	6,100
Feed composition (%) ⁶											
Pasture	10	50	20	20	20	2	48	20	20	20	20
Forages	50	20	45	45	45	49	33	45	45	45	45
Crop residues	10	20	5	5	5	14	0	5	5	5	5
Compounded and supplemental feeds	30	10	30	30	30	35	19	30	30	30	30

to represent all the six counties in Western Kenya. The household information on dairy production in Western Kenya was collected using the Rural Household Multiple Indicator Survey (RHoMIS) tool (Hammond et al., 2017). The RHoMIS survey tool is a set of carefully designed questionnaire modules, which are administered digitally using the ODK software platform, and an associated set of data extraction and analysis tools written in R (see also www.rhomis.org). The survey is designed to be both flexible enough to suit local contexts and sufficiently standardised to permit rapid deployment, analysis and comparison between multiple sites. Where possible industry standard pre-existing indicators were used, in this case the Household Food Insecurity of Access Scale (Coates et al., 2007) which measures the frequency and severity of hunger, the Household Dietary Diversity Score (Swindale and Bilinsky, 2006) which provides an indicator of household nutrition status, and the Probability of Poverty Index which is an asset-based scoring system to estimate the likelihood that a household is in poverty. These are combined with a comprehensive inventory of agricultural crops and livestock including yields, uses, sale prices and inputs, and an assessment of off farm incomes.

Similar information on household dairy production for the three counties in Lower Eastern Kenya were collected for 102 households under the Accelerated Value Chain Development Program (Auma et al., 2018). This is a development program funded by USAID and targeted food security and nutrition among pre-commercial dairy farmers in these regions. Variables or indicators from both datasets were used to estimate water and land use for each of the livestock production systems as described in Section 2.4. This information was combined with the county level information to derive total animal numbers and population density (CBS, 2010) used to derive the total land and water footprints for the different counties representing the three agro-ecological zones.

The two counties, Kitui (30,496 km²) and Makueni (8,034.7 km²), supporting the mixed crop-dairy systems in the arid to semi-humid zone, have the lowest population densities of 44 and 115 persons /km², respectively (CBS, 2010). In the semi-humid to humid midland zone dominated by rainfed mixed crop-livestock systems. Busia and Kisumu counties have the highest population density of 480 people /km². Migori and Siaya Counties have a similar population density of 350 people /km². Homa Bay County has the lowest population density of 342 people /km².

The average land size per household across all the nine counties is 1.7 ha (Auma et al., 2017). The average land holding is highest in Makueni (9.2 Ha) and Kitui (4.0 Ha) and smallest in Vihiga (0.97 Ha) and the highlands of Taita Taveta (1.0Ha). In Kisumu, Busia, Migori and Siaya, the reported average household land holding is 2.1, 1.2, 1.1 and 1.06 ha, respectively. Generally, farmers in the semi-arid to semi-humid zone in Makueni and Kitui counties own larger land sizes than those in the other zones. The large farm sizes per person are due to low human population density whereas low average rainfall supports mainly extensive livestock production in the agricultural areas.

Overall, a large proportion (63%) of the dairy cattle breeds owned in the nine counties are local breeds (Auma et al., 2017). Busia County has the highest proportion of local breeds of all the nine counties sampled followed by Siaya, Homa Bay and Migori, in decreasing order. On the other hand, while most of the sampled farmers in Busia (94%) kept local breeds, all the sampled beneficiaries in Taita Taveta kept improved breeds only. In Makueni, Kitui and Vihiga counties, most of the sampled households keep improved breeds. About a quarter of the sampled beneficiaries in these three counties kept both local and improved breeds. In Migori, about 37% of the farmers keep exclusively improved cattle and almost the same proportion (38%) exclusively own local breeds. The proportion of farmers keeping only improved breeds is the lowest in Busia (6.2%), Siaya (15%), Homa Bay (22.7%) and Migori (29.4%).

Dairy productivity varies widely across breeds, production systems and counties. On average, each local cow produces 480 litres of milk

per year, while an improved cow produces 2,410 litres per year (Auma et al., 2018). Annual milk yields are estimated as the weighted average of the milk yields from the local and crossbred cows. This allows us to account for the potential pulling of the overall average toward the average for the local breeds that are the most common breeds contributing to the total production in eight of the nine counties (Table 1). In the production systems on midlands, the proportion of local cows in the total dairy cow population is consistently over 70%, indicating a large potential gap that has to be bridged to achieve higher efficiency rates.

2.3. Description of scenarios representing improved production efficiency

Three scenarios are outlined based on pathways to improved productivity targets in the three production systems as summarised in Table 1. These scenarios are based on improvements to the current practices in the production systems. The first scenario, Scenario S¹, is linked to feed improvement targets and is defined as Semi-Arid Futures, Midlands Futures and Highlands Futures for semi-arid to semi-humid zone; semi-humid, sub-humid to humid midlands zone and; semi-humid to humid highlands respectively (see Table 1 for details). The Semi-Arid Futures, represents an improvement to total production through improved feeds. The dominant breed is retained as the local breed accounting for 67–85% of all the cows. The weighted average milk production per cow in this scenario increases from the current 821 kg cow⁻¹ year⁻¹ to 1,980 kg cow⁻¹ year⁻¹. There is also an improvement in the feed management through feed compositional changes to enhance fodder consumption. Feed conversion ratio is also lowered to achieve higher production per unit of feed consumed. Midlands Futures also focuses on improving the baseline in the midlands production system such that the milk production per cow is increased from a low of 530 kg cow⁻¹ year⁻¹ currently to an average of 1,450 kg cow⁻¹ year⁻¹. This value is lower than that for the lowlands due to the sampling design. This does not affect the outcome of the analysis as the midlands on average exhibit the largest production improvement gap (Auma et al., 2018). Feed composition is also changed such that the consumption of compounded and supplemental feeds increases by 20% to match the improved feed management practices in line with ratios proposed under improved feeding in the FEAST tool (ILRI, 2010). In the Midlands, local breeds dominate and constitute, on average, 94% of all the dairy cattle. In Siaya County, in particular, local breeds account for up to 98% of all the dairy cows. The third, Highlands Futures, also envisions improvement of milk production or lowering of feed conversion ratio. The breed composition in this scenario is dominated by crossbreeds (55%). The feed composition does not change drastically as the current feeding practices are considered sufficient.

The second scenario, Scenario S², also focuses on breed improvement, for the three production systems. Semi-Arid-Local-Cross, denotes a complete change in the breed from mostly local to fully crossbred. This represents a realistic outcome of interventions aimed at improving productivity through improved breeds. Midlands-Local-Cross is similarly linked to breed improvement through conversion of all the cows to crossbred animals with attendant changes in milk production, feed composition and conversion rates. The Highlands-Local-Cross, has similar breed improvement in which all the cows are improved to crosses. The current composition of the feed for cows in the highlands system is kept unchanged because it is considered to be sustainable and to represent good feeding practices.

The third scenario, Scenario S³, involves breed improvement by replacing the current animals with pure breeds. Feed, FCE and milk productivity are also improved. For all the systems, two different breed improvements towards exotic pure-bred cows is carried out. Firstly, the breed selected as the pure breed is Ayrshire because it is the best suited to the two systems due to its feed requirements and potential for sustainable management practices. This would generate the Semi-Arid-Cross-AY-Pure, Midlands-Cross-AY-Pure and Highlands-Cross-AY-Pure

outcomes and subsequently referred to as Scenario S^{3a}. The second breed improvement involves crossing of the breeds towards a fully Friesian herd, which is the preferred breed in the highlands system. This is denoted as Semi-Arid-Cross-Fr-Pure and Midlands-Cross-Fr-Pure and Highlands-Cross-Fr-Pure for the semi-arid, midlands and highlands systems, respectively, and is referred to as Scenario S^{3b}. This breed improvement would achieve the full potential of pure breed cows in the highlands system. In scenario S^{3b}, breeding is aimed at achieving a purely Friesian herd and the attendant increase in milk production.

2.4. Calculation of water and land footprint of dairy production

2.4.1. Estimating the total annual production of animal products

The water footprint of a product is the total amount of freshwater used to produce the good (Hoekstra et al., 2011). It consists of three components. The green water footprint refers to consumptive water use of rainfed soil moisture whereas the blue water footprint refers to the consumptive water use of groundwater and surface water. The grey water footprint refers to the volume of water required to dilute pollution. This study focuses on water consumption, not water pollution, and therefore on the analysis of green and blue water footprints. The land footprint of a product is the actual land used to produce a unit of the product. In this study, livestock production is considered as being associated with both grassland and cropland. The cropland is the most productive land use type and consists of the area required to grow all crop products categorized as animal feed, for instance maize, forage sorghum, wheat and fodder crops such as Napier, pigeon peas and sweet potato vines. Grazing land has lower productivity than the croplands and consists of grasslands – cultivated and natural – used to provide feed to animals (Borucke et al., 2013). The calculation of the water and land footprints of livestock follows Bosire et al. (2015). The total annual milk production (tonne) per animal for each production system was calculated as follows:

$$P_{milk}[a, c] = MY[a, c] \times DC[c] \quad (1)$$

where $P_{milk}[a, c]$ represents the production of milk per cow a in county c , $MY[a, c]$ (kg) is the milk yield per dairy cow a in county c and $DC[c]$ is the number of dairy cows in county c . The number of lactating cows is derived from their proportional contribution to the total herd of the improved and indigenous dairy animals in each county (KNBS, 2010; Waithaka et al., 2002). The yield estimate is derived by assigning the yield attributed to the predominant breed, i.e., Zebu, crossbreed or exotic, to the milk yield estimate for a specific county (Auma et al., 2018).

2.4.2. Volume and composition of feeds

Feed demand in each county is estimated by consolidating information on diet composition and quality, feed conversion efficiency and milk production per animal. Estimates of the quantities of feed, feed composition, sources of feed and feed yields per unit area within a county were derived from the literature and are summarised in Table 1.

To estimate the feed volume in each system, a relationship linking the feed conversion factor of the production system to the product output was developed (Greer and Thorbecke, 1986):

$$Feed[a, c] = FCR[a, c] \times P_{milk}[a, c] \quad (2)$$

$Feed[a, c]$ (tonne yr⁻¹) is the total amount of feed consumed per cow a in county c , $FCR[a, c]$ is the feed conversion ratio (kg dry mass of feed kg⁻¹ product) for cow a in county c and $P_{milk}[a, c]$ (kg yr⁻¹) is the amount of milk produced per cow a in county c . The feed conversion ratios per cow for each county were taken from (Bouwman et al., 2005) and verified with expert opinion.

Feed is partitioned into four classes: (i) pasture, which includes hay and silage; (ii) planted forage; (iii) crop residues; and (iv) compounded feed and supplements. The feed composition focusses on summaries from the FEAST tool for the nine study counties (ILRI, 2010).

2.4.3. Water footprints of milk production

This study focuses on dairy production by cattle. Estimating the water footprint of dairy cattle requires the water use of the animal per year, averaged over its lifetime, and incorporates the link between the annual water footprint of an animal and its average annual milk production (Mekonnen and Hoekstra, 2010). The water footprint of an animal can then be expressed in terms of m³ animal⁻¹ year⁻¹ and calculated using:

$$WF[a, c] = WF_{feed}[a, c] + WF_{drink}[a, c] + WF_{serv}[a, c] \quad (3)$$

where $WF_{feed}[a, c]$, $WF_{drink}[a, c]$ and $WF_{serv}[a, c]$ represent the water footprint of cow a in county c , related to feed, drinking water and service water consumption, respectively. The feed water footprint generally dominates the other components. Estimates of the water footprint for drinking and servicing were taken from (Mekonnen and Hoekstra, 2010).

2.4.3.1. Estimating the water footprint of feed (WF_{feed}). The water footprint of an animal related to the feed consumed consists of two parts: (i) the water footprint of the various feed ingredients; and (ii) the water that is used to mix the feed ingredients:

$$WF_{feed}[a, c] = \sum_{p=1}^n (Feed[a, c, p] \times WF_{prod}^*[p]) + WF_{mixing}[a, c] \quad (4)$$

where $Feed[a, c, p]$ is the annual amount of feed ingredient p consumed by animal a in county c (tonne yr⁻¹). $WF_{prod}^*[p]$ is the average water footprint of the various crops, roughages and crop by-products p (m³ tonne⁻¹) weighted over the production locations to account for variation in feed production systems across counties. $WF_{mixing}[a, c]$ is the volume of water consumed by mixing the feed for animal a in county c (m³ yr⁻¹ animal⁻¹). The crop yields and water footprints of feed components used in the analyses are summarized in Table 2. Other than supplemental and compounded feeds, all the other categories of feed are assumed to be produced and consumed within the production system. Supplemental and compounded feeds were further characterised as consisting of maize as the main cereal. Given that maize in Kenya originates from both domestic and foreign (imported) sources, an average value was calculated by weighting the domestic production and imports with their relative proportional contributions to the total (Mekonnen and Hoekstra, 2011). Finally, the water footprints of the various crops, roughages and crop by-products ($WF_{prod}^*[p]$, m³ tonne⁻¹) that are consumed by dairy cattle are then calculated following the method of Hoekstra and Chapagain (2008).

Table 2

Summary of the various parameters used to estimate the water and land footprints of milk production across the production systems.

Sources: 1 (De Leeuw and Tothill, 1990; Orodho, 2006; Olwande, 2012; Omoyo et al., 2015), 2 Estimated by authors

Parameters	Feed Type			
	Pasture	Forages	Crop residues	Compounded and supplement feeds
Crop yields (tonne/ha) ¹				
Semi-Arid	15.6	14.2	3.5	3.5
Semi-humid	19.5	18.9	4.4	4.4
Humid	28	28.4	6.2	6.2
Water footprint of feed (m ³ /tonne) ²				
Semi-arid				
Green	456.79	471.91	0	1081.05
Blue	0.00	0.65	0	1.45
Semi-humid				
Green	428.38	439.30	0	1091.13
Blue	0.00	1.27	0	3.47
Humid				
Green	292.96	309.06	0	786.94
Blue	0.00	0.42	0	0.90

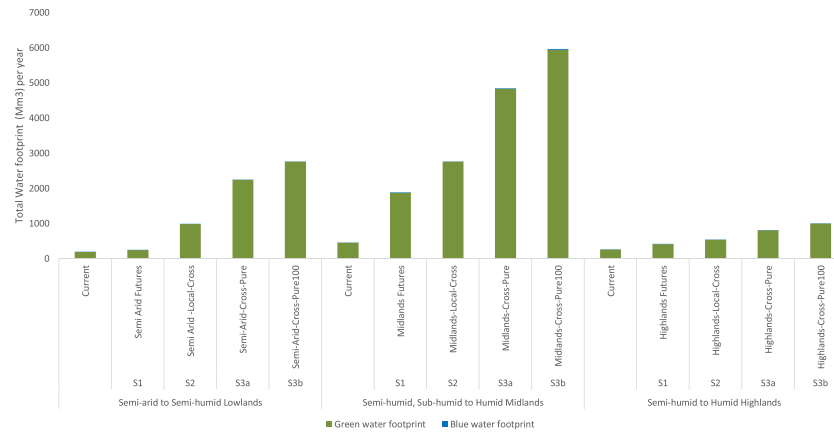


Fig. 1. Total water footprint of milk production across seven improved production scenarios in three production systems.

2.4.4. Land footprints of milk production

Estimation of land use for dairy production in the nine counties is dependent on the feed consumed per animal, county-specific yields and domestic production and import of the different feed crops. Land use associated with grass production is based on grassland production and corresponding yield in the counties. Using local yields ensures that the calculated area is representative of the actual area used for production in each county as outlined by van Vuuren and Smeets (2000). The land use (ha) within a county is estimated based on the land used for domestic production minus those related to exports plus those related to imports (Bosire et al., 2015). For all categories of feed except compounded feed and supplements, it is assumed that there is no import or export of these feed components from the production system. For the category of supplemental and compounded feeds that only considers maize germ as the main cereal in the feed, import and export values are used in the calculation by extending Eq. (5) as follows:

$$LF_{milk}[a, c] = \frac{Prod_{p,c}}{Y_{p,c}} + \sum_{n_e} \frac{IMP_{p,n_e}}{Y_{p,n_e}} - \frac{EXP_{p,c}}{Y_{p,c}^*} \quad (5)$$

where $LF_{milk}[a, c]$ (ha) is the land area associated with the production of feed product p for cow a in county c , IMP_{p,n_e} (tonne yr^{-1}) is the imported quantity of feed product p from exporting nation or county n_e , $EXP_{p,c}$ (tonne yr^{-1}) is the quantity of feed product p exported from county c , $Y_{p,c}$ (tonne ha^{-1}) is the annual yield of product p in county c , Y_{p,n_e} (tonne ha^{-1}) is the yield of product p in the exporting country n_e and $Y_{p,c}^*$ (tonne ha^{-1}) is the weighted average of the local production and import yields. The imported component of the feed is mainly associated with the compounded and supplemental feed through maize that is the main constituent of this feed component. There is however a low proportion of this feed type in the feed composition in most of the

counties (Table 1).

3. Results

The total water and land footprints of milk production in the agro-ecological zones are presented. This is followed by the total water and land use values for the current production practises and under scenarios S^1 , S^2 , S^{3a} and S^{3b} . Finally, production efficiencies are evaluated by quantifying the water and land use required to produce a tonne of milk.

3.1. Total water footprint of production

The total water footprint of production is dominated by the green water footprint, with the blue water footprint making a minor contribution (Fig. 1). The green water footprint represents 98–99% while the blue water footprint represents the remaining 1–2% of the total water footprint of production. The large green water footprint is due to the rainfed production of feed used in these systems. There is no irrigated production of feed in these systems. The blue water footprint is determined by the drinking and servicing water for dairy production and is much smaller than the water needed for fodder production. Among the three production systems, the midlands production system has the largest water footprint because it has the largest number of cows (Fig. 1).

The total water footprint increases for scenarios S^1 , S^2 and S^3 relative to the baseline scenario (Fig. 1). In particular, all the breed improvement scenarios, S^2 and S^3 , have much larger total water footprints than the currently prevailing practices (baseline) or the S^1 Futures scenario. The S^3 scenario has the largest total water footprint across all the production systems. The increase in water footprint in this scenario relative to the baseline is caused by the larger feed quantity per animal

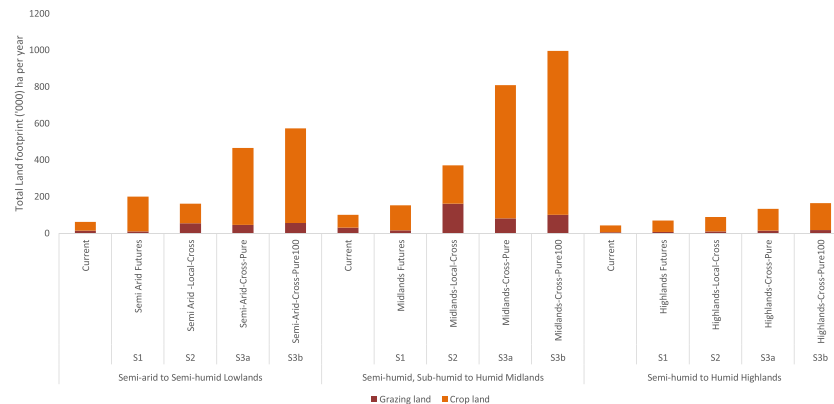


Fig. 2. Total land footprint of milk production across seven improved production scenarios in three production systems.

required to achieve the higher milk yields. The midlands-cross-pure and the midlands-cross-pure100 improvement in scenario S³ have the largest total water footprint of all the scenarios. A complete improvement of dairy cows in both the semi-arid and midlands systems to pure breed cows would translate to an almost four-fold increase in the total water footprint relative to the current production practices. The large increase in the total water footprint is linked to replacing the current breeds with pure breeds and the associated increase in the total feed consumed by improved cattle breed in the S³ scenario.

The total water footprint showed the largest relative increases in the S³ scenarios for both the semi-arid and midlands production systems, with about 92% larger water footprint of milk production than the levels under the current production practices. However, relative to the current water footprint, this semi-arid production system also exhibits the smallest expected increase in the total water footprint of milk production of only 24% under the Semi-Arid Futures in the S¹ scenario. This implies that increasing feed quantities does not necessarily always lead to higher water footprints. This may be because the feed is mainly composed of crop residues and much less produced fodder.

Among the nine counties, the total water footprint of milk production was the largest for Vihiga County at 150 Mm³ yr⁻¹, followed closely by Taita Taveta and Kisumu counties both of which had annual water footprints of 110 Mm³ yr⁻¹. Each of these three counties has a higher proportion of crossbreed cattle and compounded and supplemental feed in the feed composition than the six others. This translates to a higher water footprint associated with the feeding regime.

3.2. Total land footprint of production

The total land footprint of milk production across the production systems shows a similar trend to that for the water footprint. The estimated total land footprint is the largest for the midlands system, intermediate for the lowlands system and the smallest for the highlands system (Fig. 2). This pattern reflects the relatively larger number of cows in the midlands system and a better feed conversion efficiency despite higher consumption in the highlands system.

A comparison of the total land footprint across the improved productivity scenarios shows that the improvements outlined for scenarios S² and S³ would result in larger total land footprints relative to the contemporary production practices. The increase in the total land footprint expected under scenarios S^{3a} and S^{3b} relative to the current

production practices is the largest for the midlands system (88% and 90%), middling for the semi-arid system (87% and 89%) and the least for the highlands system (68% and 72%). In all the scenarios, the cropland footprint made a far greater contribution to the total land footprint than the grazing land footprint. In both the lowlands and midlands systems, the grazing land footprint is expected to decline by 35% and 85%, respectively, under the S¹ Futures scenario relative to the contemporary practices. Despite this decrease in the grazing land footprint, the total land footprint of the S¹ scenario for the lowlands system is anticipated to be 70% larger than that for the same system under the current production practices. This is associated with the reduction of pasture use in the feed composition and increase in the forage and crop residue consumption in the feed composition with changes in the S¹ scenario. Whereas improved feed practices in this scenario result in a relatively small increase in the total water footprint (~24%), they lead to a more substantial increase in the land footprint in these production systems (70%).

Among the nine study counties, the estimated total land footprint is the largest for Kitui and Makueni counties, third largest for Vihiga County and fourth largest for Kisumu County. The large total land footprint is mainly due to a larger number of animals in Kitui and Makueni counties than in the other counties. Additionally, the lower land productivity in these counties, Table 2, leads to more expansive use of the land. Vihiga and Kisumu counties are the third and fourth ranked, respectively, due to the large proportion of compounded and supplemental feeds required to feed the animals. This leads to a large cropland and subsequently to a large total land footprint despite the lower number of dairy cows in both Vihiga and Kisumu Counties. These two counties also have larger cropland footprints because feeds derived from crop lands make the greatest contribution to the total feed.

3.3. Water footprint per unit of milk production

As expected, the highest level of improvement in the efficiency of water use in milk production across all the systems is exhibited by the highlands system (Fig. 3). The water footprint per tonne of milk produced in this system ranges from 1,940 m³ to 2,530 m³. The water use efficiency is highest in this system due to relatively higher milk production associated with the pure breed Ayrshire and Friesian cows as well as a low crop water use for feed production. Overall, the total water footprint in the lowlands is generally the largest across the

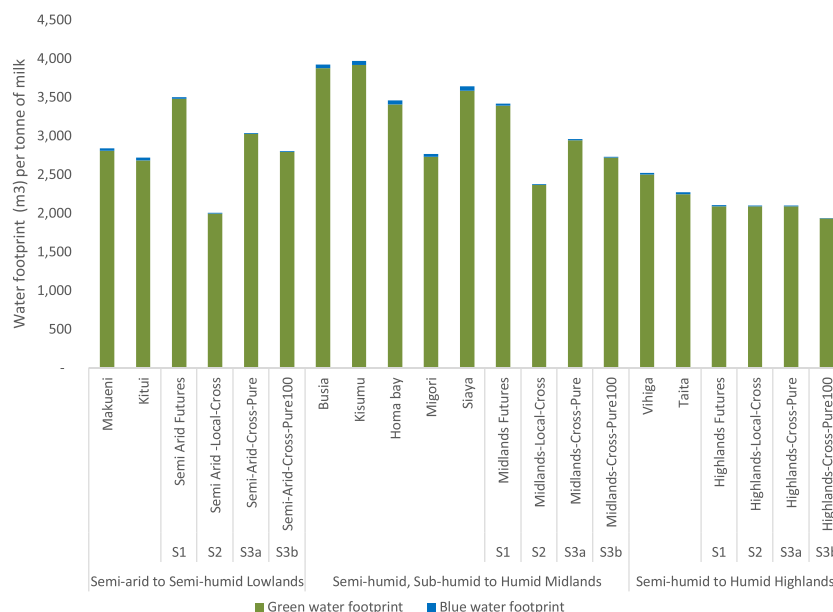


Fig. 3. The water footprint per tonne of milk produced across nine counties and across three improved production scenarios in three production systems.

production systems due to the high crop water use in producing animal feed. But the higher proportion of cross breeds leads to higher milk production per cow and hence a slightly lower water footprint per unit milk than for the midlands system.

Across all the scenarios, the largest reduction in water footprint of milk production (75%) occurs with the improvement of breed and feeding practices from S^1 to S^2 in the lowlands. This is due to the more than doubling of production output per cow that occurs with this change of breed in this system and a 20% increase in total feed provisioning. Similarly, an improvement in breed and feed from scenario S^1 to S^2 in the midlands system translates to a 40% improvement in water footprint. The efficiency gains are not as large as those estimated for the lowlands system due to the need to quadruple the total feed provided to cows to sustain the increased milk production. Improvement of the breeds in scenario S^1 to pure breed Ayrshire and Friesian cows as described for scenario S^{3a} and S^{3b} translates to an increase in the water footprint by between 10 and 34% for both the lowlands and midlands systems. This implies that the water footprint per tonne of milk produced under scenario S^3 is less resource efficient in these two systems. Overall, it appears that the improvements described for scenario S^2 are the most suited for ensuring water use efficiency gains in the drier lowlands and midlands systems. The water footprint of milk production with improvement of breeds and feeding practices across scenarios S^1 , S^2 and S^3 for the highlands system only improves efficiency by 10% at most. This is because improvement of breeds and feeding practices from the current, mainly crossbred cows to pure Ayrshire or Friesian breeds, leads to limited efficiency gains.

Among the nine counties, the largest water footprints of milk production are for Kisumu, Busia, Siaya and Homa Bay counties where water footprints are all above $3,000 \text{ m}^3$. The reason for these rather large water footprints per unit milk production is the low milk production per cow for these counties. In Migori, Makueni and Kitui counties, the water footprint of milk production ranges between 2760 and $2840 \text{ m}^3 \text{ tonne}^{-1}$ of milk. These counties also have quite similar amounts of milk produced per animal. Vihiga and Taita Taveta Counties represent the counties with the lowest freshwater requirements to produce a tonne of milk at 2530 and 2270 m^3 , respectively. This is due mainly to the much larger proportion of improved breeds and therefore a higher milk production per cow in Vihiga and Taita Taveta counties than in the other seven counties (Fig. 3).

3.4. Land footprint of milk production

Overall, the aggregated land footprint of milk production for the semi-arid and midlands systems is larger than that for the highlands system. This ranges from 0.33 to $0.73 \text{ ha tonne}^{-1}$ and is dominated by the cropland footprint. This is because a large proportion of animal feed constitutes low yielding cultivated forage, compounded and supplemental feed as opposed to natural pasture (Fig. 4).

Improved resource use efficiency in the proposed scenarios is evidenced by the reduced land footprint associated with the production of one tonne of milk. This is especially noteworthy for the breed and feed improvements from Scenario S^1 to S^2 in the lowlands system where the land demand reduces by more than half. On the other hand, within the midlands production system, production under scenario S^{3a} results in the smallest land footprint of milk production. For these two systems, milk production by the cross-breed cattle is most efficient in the lowlands system while milk production by the pure breed Ayrshire is most land use efficient in the midlands system. Breed and feed improvements, as described for all the scenarios, lead to an increase in the land footprint in the highlands system of between 19% and 23%. Through improvements to Friesian cows, scenario S^{3b} is only 7% more resource efficient than improvements to Ayrshire cows contemplated for scenario S^{3b} , in these highland systems.

Fig. 4 shows that land use per tonne of milk varies greatly across the nine counties under current conditions, with the largest land footprint being $0.7 \text{ ha tonne}^{-1}$ for Kisumu County and is dominated by the cropland footprint (98%). This is due to high feed provision in the form of forages and, compounded and supplemental feeds and low milk production per animal. Busia County's land footprint of $0.6 \text{ ha tonne}^{-1}$ is the second largest and is closely followed by the footprint associated with milk production in Makueni, Kitui and Vihiga counties of 0.48, 0.45 and $0.43 \text{ ha tonne}^{-1}$. The smallest land footprint of $0.33 \text{ ha tonne}^{-1}$ is associated with milk production in Migori county. Low land footprints are associated with low feed provision and output per animal.

The changes expected under the proposed scenarios would result in varied outcomes in terms of efficiency of use of both grazing land and cropland across all the nine counties. If animal breeds and feeds are improved as proposed in the S^3 scenario, then the land footprint of milk production will increase for the nine counties. On the other hand, the changes prescribed by scenario S^2 would reduce the land footprints of

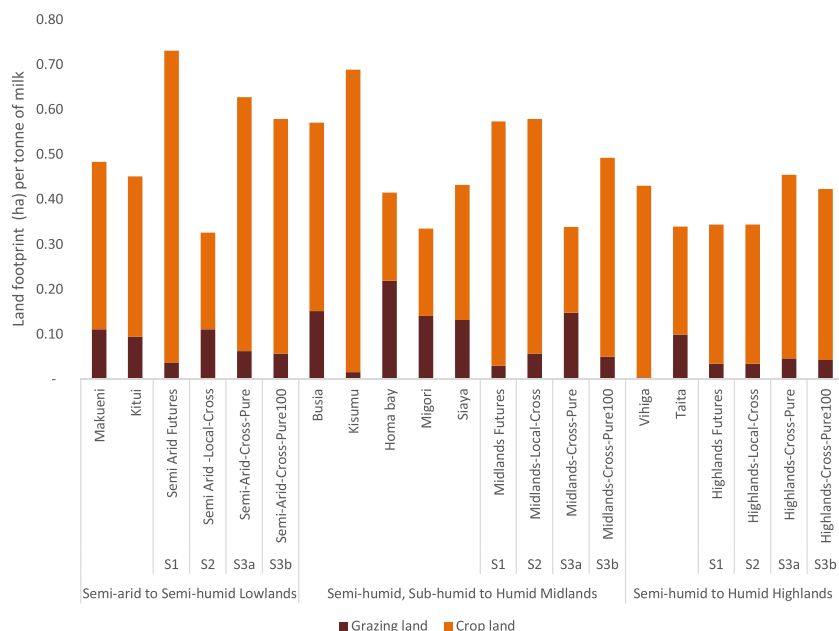


Fig. 4. The land footprint per tonne of milk produced in three production systems across nine counties and across seven improved production scenarios.

milk production for Makueni, Kitui, Kisumu and Vihiga counties. The largest efficiency gains in grazing land use is expected for Homa Bay county where a nine-fold reduction is expected to occur with changes in feed composition in scenario S^1 . This is followed by Busia, Migori, Siaya, Makueni, Kitui and finally Taita Taveta County, in order of diminishing reduction in grazing land. For Vihiga and Kisumu counties, grazing land use would increase by 92% relative to the current practices if milk production were to be improved as proposed under scenarios S^1 , S^2 and S^3 .

4. Discussion

This work contributes to the continued focus on studying interaction between agricultural systems and their biophysical environment. Recent work on this topic includes Navarrete-Molina et al. (2019) on improving breeds, feed production in different geographical locations and feed and manure management; Fan et al. (2018) which focuses on use of wetlands to mitigate the impact of animal waste especially in terms of manure production in industrial farms; and the value of biodiversity in dairy farming (Alary et al., 2019; Palm et al., 2014; Pierik et al., 2017). All this work opens up the exciting opportunity to take an integral perspective of agro-ecosystems and their interactions with the environment, and quantification of ecosystem services.

The options for intensifying fodder-based production best suited to three regions with contrasting constraints on water and land availability in Kenya are assessed. This is done by defining and comparatively analysing three scenarios of feed, breed and milk production improvements in three distinct production systems relative to the contemporary practice taken as the baseline scenario.

The land and water footprints of milk production in three contrasting agro-ecological zones in Kenya were quantified. The specific agro-ecological zones comprised semi-arid to semi-humid lowlands zone, semi-humid, sub-humid to humid midlands zone, and semi-humid to humid highlands zone. The analyses showed that intensification pathways focused on improving breeds, feed provisioning and milk output per cow and scenarios based on management practices produce contrasting outcomes for these zones. Under the dairy development strategy, the government of Kenya aims to increase dairy production by 50% (GOK, 2010) and this study quantified what some of the environmental consequences of this can be under three intensification scenarios. It should be noted that climate change imposes increasing constraints on water availability by increasing both the frequency and intensity of droughts (Bartzke et al., 2018). The success and sustainability of production intensification under the various scenarios would thus be contingent upon developing efficient water management and harvesting technologies. This implies that even though improving dairy production may achieve the intensification objective, it does not make the best use of limiting land and water availability across the three representative agroecological zones. Therefore, it is more appropriate to use a tailored approach that focuses on ensuring the water and land resources are used optimally in dairy production. This will facilitate adoption of appropriate intensification pathways by the farmers in each of the zones and therefore adaptation to the available land resources and water scarcity. Failure to adapt will restrict the farmers' ability to produce the quantities of food demanded by the rising and urbanising populations within the constraints imposed by the rapidly changing environments.

Across all the production systems, there is currently a consistently lower total milk production in the baseline production scenario. This is mainly due to the low productivity associated with the large proportion of local breeds in the production systems and sub-optimal feeding practices. As the breed improves across the feed basket scenarios in each production system, the total milk production more than doubles, which shows the potential for closing the milk yield gaps. This is also consistent with findings of other studies (e.g., Herrero et al. (2016)). However, the anticipated increases have not been achieved in the past

because of low investment in dairy production in the study counties, the apparent inability of the farmers to take up dairy farming in the drier regions in which the counties fall (Fintrac, 2015). There are also only a few Artificial Insemination (AI) service providers due to persistently low demands for the service in the region given the currently low population of dairy cows (Auma et al., 2018). However, increasing milk yields by improving cattle breeds is associated with substantial increases in the water and land footprints. The magnitude of these increases vary widely across the three scenarios and for each scenario across the three production systems.

4.1. The water footprint of milk production

All intensification scenarios lead to substantial increases in the total water footprint, while improving the water footprint per unit milk produced. Higher water use efficiency and hence smaller water footprints per tonne of milk produced than under the baseline practices across all the production systems can be achieved by improving cattle through breeding and better feeding practices. Such improved breeding and feed management practices can jointly improve the efficiency of consumptive water use in milk production, leading to a decline in water footprint per tonne of milk. From a water use efficiency perspective, scenario S^2 , representing a first step up in terms of breed improvement, is the most appropriate for the semi-humid, sub-humid to humid midland system. The crossbred animals have relatively low water footprints in these systems because the total water footprint does not increase too dramatically when mostly local breeds are replaced with cross bred cows, while production increases substantially. For the highlands systems, there is a smaller change in the water footprint with similar improvements between crossbred to pure bred cows and the most efficient production is under the S^{3b} scenario. Across all the systems, the change to pure breed results in low improvement in the water footprint per unit of milk. It follows that, given the large increase in the total amount of inputs required for intensification to pure breeds of Ayrshire and Friesian, it is not advisable to encourage farmers facing resource constraints to intensify to the pure breeds. This finding reinforces the recommendation of Dairy Genetics East Africa project (DGEA) that stabilizing crosses for most non-traditional dairy areas should recognize that beyond 75% exotic blood, there are no substantial productivity gains.

The more than doubling of the total water footprint of milk production in the semi-arid and the midlands systems, where water is scarce, is a major challenge to achieving the most intensive dairy improvement outcomes envisioned under the feed and breed improvement scenarios S^{3a} and S^{3b} . Improvements in water footprint in the semi-arid and midlands production systems per tonne of milk do not justify the very high water footprints per animal for these water scarce systems nor the need to improve the local breeds to pure Friesian or Ayrshire breeds. This suggests that a tailored approach, in which improvements take specific environmental contexts into account, such as agro-ecological zones, is the best. This is because in the highland based agro-ecological zone, where water scarcity is less limiting, the water footprint under scenarios S^{3a} and S^{3b} does not increase as dramatically as it does in the water scarce systems, thus providing the opportunity to meet the increased demand for feed production locally.

Overall, the increase in total water footprint in the arid and semi-arid counties raises a fundamental question about the sustainability of intensification of dairy production in water stressed systems. Because it is hard to quantify the total available water, the water requirements for each scenario relative to the total available water was evaluated against a baseline scenario taken as the benchmark and the most efficient pathway to achieving dairy intensification identified for each county. Consequently, the practices outlined under scenarios $S^{3a,b}$ for the semi-arid lowlands and midlands systems are not recommended whereas the scenario S^2 is suggested as the one most likely to yield the smallest increase in total demand for water resources because of its relatively

lower water footprint. This scenario also yields the largest gains in water productivity and so can permit intensification by enabling both increased production and lowered negative environmental impacts. Satisfying both constraints is necessary for intensifying production in water deficient systems. Most of the nine counties are included in at least one of the Kenya government's programs to increase irrigation coverage by 700,000 acres (GOK, 2018). The programs aim to achieve this by expanding the existing and launching new irrigation projects and completing the infrastructure for about 290 stalled small projects. When completed and operationalized, these irrigation projects, could relax the water constraints and promote intensification.

4.2. The land footprint

The land and water footprints show similar overall patterns, but the land footprint shows much larger differences across scenarios and counties than the water footprint. The intensification of milk production increases land use and the total amount of land needed for milk production except in two scenarios; the change to cross bred cows in the semi-arid lowlands and the change to Ayrshire cows in the midlands. These land footprints have different implications to the water footprints of each scenario across the different agro-ecological zones. Whereas water is the most limiting factor in the semi-arid to sub humid system, land is the most limiting factor in the humid Highlands system with the highest human population densities. So, whereas the water footprint shows that intensification up to scenarios S^{3a} and S^{3b} is the most appropriate for the highland zone, the land footprint shows that this would also increase the land footprint. As land has a fixed area and is often intensively used in the highland system, the pressure on land is likely to increase tremendously with progressive intensification of dairy production due to increased demand for feeds derived from croplands in the form of forages, supplemental and compounded feeds. In Kenya, the amount of high potential land has shrunk from 0.42 ha per person in 1962 to just under 0.12 ha in 2015 (World Bank, 2016). These high potential areas are also the traditional dairy production regions, so it would seem difficult to achieve further production intensification unless fodder production per unit area is further increased through more intensive use of inputs like mineral fertilizer, higher yielding varieties, use of dual purpose crops and irrigation. It also highlights the need to invest in other areas where, unlike in the high potential lands, dairy farming experiences less competition with basic grain food and cash crop production.

A feasible solution could be to turn to the medium potential land in the midlands or even in the lowlands where land availability is less constrained. Similarly, to the sustainability of the water footprint, the increase in land footprint with intensification is also optimised to ensure both improved production and higher land use efficiency. Production under scenario S^2 in which breeds, feeding practices and other livestock husbandry practices are tailored to yield the best outcomes for farmers, is indicative of sustainable practices for farmers and optimal water and land demands. By importing fodder from the medium potential areas into the dairy production systems in the highlands, a part of the land footprint can be exported, while the water footprint does not have to increase unsustainably. Additionally, the interaction between fodder yields and extent of fodder production should be considered. For instance, across the agro-ecological zones, the propensity to grow fodder would be higher in the semi-humid midlands than in the lowlands. Yet, fodder yields are expected to be lower than in the highlands. Therefore, it is anticipated that farmers growing fodder in the midlands would have to dedicate more land to feed production. In the highlands, yields are higher but have to compete with other land uses with possibly better returns. In the lowlands the probability of engaging in fodder production is much lower but this can be enhanced especially when the fodder varieties and crops used in feeding are of drought-tolerant varieties that require less water to produce. Additionally, the feed may also be largely composed of crop

residues and rely less on production of fodder.

Enhancing the use of such medium potential lands (for example in Tana River County) therefore holds the key to reducing competition for the land resources required to produce dairy feeds for enhanced production as contemplated in the proposed intensification scenarios. This is already being promoted and is at initial stages of implementation where there are initiatives to promote fodder production. The farmers planting the fodder are linked to milk aggregation units (cooperatives) for onward sale to members of the cooperatives. However, most of these areas and other medium potential lands are also vital biodiversity repositories and so it is critical to carefully balance the need for intensification against that for nature conservation and protection of essential ecosystem services.

Overall, it is not the difficulty of achieving the proposed technological advances but rather historical marginalisation and indifference to dairy production in the drier environments that mainly constrain intensification. Adopting appropriate technologies is essential to alleviating limitations to the uptake of improved breeds. Moreover, such interventions as the introduction of ECF vaccine would make it possible to rear improved cattle breeds where people previously kept off these breeds. ECF is responsible for up to 80% mortality of improved calves and is one of the most expensive diseases to treat for farmers rearing improved cows. The high likelihood of losing animals to this disease therefore previously discouraged the risk averse smallholder farmers from adopting improved dairy cattle breeds. Consequently, the low uptake of improved dairy breeds heightens the cost of dairy production by limiting the number of dairy-related businesses; Animal health advisors, Artificial Insemination service providers and suppliers of dairy inputs. The high costs in turn discourage uptake of improved cows, completing a vicious cycle of low density and high cost of production. To surmount these limitations, development projects such as AVCD and KCDMS are providing incentives for private sector actors to move into these regions. These projects are also implementing breeding innovations aimed at rapidly increasing the density of improved cows to attract more dairy businesses and therefore reduce the cost of production.

5. Conclusion and recommendation

Studies of dairy intensification often do not adequately articulate how intensive farming interacts with the environment, nor critically explore the consequences of such intensification. It is however necessary to tightly link intensification with the local context. Not doing so often underlies the general failure of programs or policies aimed at enhancing farmers' resilience through intensification of production and can lead to otherwise avoidable and unintended negative environmental consequences. In many cases, intensification initially increases production but decreases it in the long run. This is because intensification of small-holder dominated production systems often weakens the very ecological conditions necessary for supporting their resilience. Consequently, it is advisable to conduct cross-sectional analyses, including socio-economic analyses, and use detailed local knowledge and available adaptation options to generate pluralistic and locally adaptive approaches to intensification and not use a "one-size-fits-all" approach. Such analyses would do well to also factor in the cost of intensification to natural biodiversity and essential ecosystem services in water stressed but biodiversity rich environments.

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References

- Alary, V., Moulin, C.H., Lasseur, J., Aboul-Naga, A., Sraïri, M.T., 2019. The dynamic of crop-livestock systems in the Mediterranean and future prospective at local level: a comparative analysis for South and North Mediterranean systems. *Livest. Sci.* 224, 40–49. <https://doi.org/10.1016/j.livsci.2019.03.017>.
- Alexandratos, N., Bruinsma, J., 2012. World Agriculture Towards 2030/2050: the 2012 Revision. Retrieved from .
- Auma, J., Kidoido, M., Rao, J., Kariuki, E., 2017. Retrieved from Nairobi. AVCD dairy component annual monitoring report. Retrieved from Nairobi.
- Auma, J., Rao, J., Kariuki, E., 2018. Report of the Annual Monitoring Survey of Beneficiaries in Western and Eastern Kenya. Retrieved from Nairobi, Kenya.
- Bartzke, G.S., Ogutu, J.O., Mukhopadhyay, S., Mtui, D., Dublin, H.T., Piepho, H.-P., 2018. Rainfall trends and variation in the Maasai Mara ecosystem and their implications for animal population and biodiversity dynamics. *PLoS One* 13 (9), e0202814.
- Bebe, B.O., Rademaker, C., van der Lee, J., Kilelu, C., Tonui, C., 2017. Sustainable Growth of the Kenyan Dairy Sector. Retrieved from .
- Bebe, B.O., Udo, H.M.J., Rowlands, G.J., Thorpe, W., 2003. Smallholder dairy systems in the Kenya highlands: cattle population dynamics under increasing intensification. *Livest. Prod. Sci.* 82 (2–3), 211–221. [https://doi.org/10.1016/S0301-6226\(03\)00013-7](https://doi.org/10.1016/S0301-6226(03)00013-7).
- Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., et al., 2013. Accounting for demand and supply of the biosphere's regenerative capacity: the National Footprint Accounts' underlying methodology and framework. *Ecol. Indic.* 24, 518–533.
- Bosire, C.K., Lannerstad, M., de Leeuw, J., Krol, M.S., Ogutu, J.O., Ochungo, P.A., Hoekstra, A.Y., 2017. Urban consumption of meat and milk and its green and blue water footprints—Patterns in the 1980s and 2000s for Nairobi, Kenya. *Sci. Total Environ.* 579, 786–796.
- Bosire, C.K., Ogutu, J.O., Said, M.Y., Krol, M.S., Leeuw, J., Hoekstra, A.Y., 2015. Trends and spatial variation in water and land footprints of meat and milk production systems in Kenya. *Agric. Ecosyst. Environ.* 205 (0), 36–47. <https://doi.org/10.1016/j.agee.2015.02.015>.
- Bouwman, A.F., Van der Hoeck, K.W., Eickhout, B., Soenar, I., 2005. Exploring changes in world ruminant production systems. *Agric. Syst.* 84 (2), 121–153. <https://doi.org/10.1016/j.agsy.2004.05.006>.
- Bruinsma, J., 2003. World Agriculture: Towards 2015/2030: an FAO Perspective. Earthscan.
- CBS, 2010. Population by Administrative Units. Retrieved from Nairobi, Kenya.
- Chouchane, H., Krol, M.S., Hoekstra, A.Y., 2018. Expected increase in staple crop imports in water-scarce countries in 2050. *Water Res.* X 1, 100001. <https://doi.org/10.1016/j.wroa.2018.09.001>.
- Coates, J., Swindale, A., Bilinsky, P., 2007. Household Food Insecurity Access Scale (HFIAS) for measurement of food access: indicator guide. food and nutrition technical assistance project, academy for educational Development, Washington, DC, pp. 34.
- Conceição, P., Levine, S., Lipton, M., Warren-Rodríguez, A., 2016. Toward a food secure future: ensuring food security for sustainable human development in Sub-Saharan Africa. *Food Policy* 60, 1–9. <https://doi.org/10.1016/j.foodpol.2016.02.003>.
- Crosson, P., Anderson, J.R., 1994. Demand and supply – trends in global agriculture. *Food Policy* 19 (2), 105–119.
- El-Beltagy, A., Madkour, M., 2012. Impact of climate change on arid lands agriculture. *Agric. Food Secur.* 1 (1), 3.
- Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., et al., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proc. Natl. Acad. Sci.* 111 (9), 3239–3244.
- Erb, K.-H., 2004. Actual land demand of Austria 1926–2000: a variation on ecological footprint assessments. *Land Use Policy* 21 (3), 247–259.
- Fader, M., Gerten, D., Thamm, M., Heinke, J., Lotze-Campen, H., Lucht, W., Cramer, W., 2011. Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. *Hydrol. Earth Syst. Sci.* 15 (5), 1641–1660.
- Falkenmark, M., Lannerstad, M., 2004. Consumptive water use to feed humanity? Curing a blind spot. *Hydrol. Earth Syst. Sci. Discuss.* 1 (1), 7–40.
- Fan, X., Chang, J., Ren, Y., Wu, X., Du, Y., Xu, R., et al., 2018. Recoupling industrial dairy feedlots and industrial farmlands mitigates the environmental impacts of milk production in China. *Environ. Sci. Technol.* 52 (7), 3917–3925. <https://doi.org/10.1021/acs.est.7b04829>.
- FAO, 2017. The Future of Food and Agriculture. Trends and Challenges. FAO, Rome.
- Fintrac, I., 2015. USAID-KAVES Dairy Value Chain Analysis. Retrieved from Nairobi, Kenya.
- Fischer, G., Hitznik, E., Prieler, S., Wiberg, D., 2011. Scarcity and Abundance of Land Resources: Competing Uses and the Shrinking Land Resource Base. FAO SOLAW Background Thematic Report-TR02, pp. 34.
- GOK, 2010. Kenya National Dairy Master Plan. Volume 1: a Situational Analysis of the Dairy Sub-Sector. Government Printers, Nairobi, Kenya.
- GOK, 2018. Irrigation Projects in Kenya. Retrieved from. <https://nib.or.ke/index.php/projects/flagship-projects/mwea-irrigation-development-project#>.
- Gómez, M.I., Barrett, C.B., Raney, T., Pinstrip-Andersen, P., Meerman, J., Croppenstedt, A., et al., 2013. Post-green revolution food systems and the triple burden of malnutrition. *Food Policy* 42, 129–138. <https://doi.org/10.1016/j.foodpol.2013.06.009>.
- Greer, J., Thorbecke, E., 1986. A methodology for measuring food poverty applied to Kenya. *J. Dev. Econ.* 24 (1), 59–74. [https://doi.org/10.1016/0304-3878\(86\)90144-6](https://doi.org/10.1016/0304-3878(86)90144-6).
- Hammond, J., Fraval, S., van Etten, J., Suchini, J.G., Mercado, L., Pagella, T., et al., 2017. The Rural Household Multi-Indicator Survey (RHoMIS) for rapid characterisation of households to inform climate smart agriculture interventions: description and applications in East Africa and Central America. *Agric. Syst.* 151, 225–233. <https://doi.org/10.1016/j.agsy.2016.05.003>.
- Hanjira, M.A., Qureshi, M.E., 2010. Global water crisis and future food security in an era of climate change. *Food Policy* 35 (5), 365–377.
- Harvey, M., Pilgrim, S., 2011. The new competition for land: food, energy, and climate change. *Food Policy* 36, S40–S51.
- Herrero, M., Havlik, P., McIntire, J., Palazzo, A., Valin, H., 2014. African Livestock Futures: Realizing the Potential of Livestock for Food Security, Poverty Reduction and the Environment in Sub-Saharan Africa. Retrieved from Geneva, Switzerland.
- Herrero, M., Henderson, B., Havlik, P., Thornton, P.K., Conant, R.T., Smith, P., et al., 2016. Greenhouse gas mitigation potentials in the livestock sector. *Nat. Clim. Change* 6, 452. <https://doi.org/10.1038/nclimate2925>.
- Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., et al., 2010. Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science* 327 (5967), 822–825. <https://doi.org/10.1126/science.1183725>.
- Hoekstra, A., Chapagain, A., Aldaya, M., Mekonnen, M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard. Earthscan, London, UK.
- Hoekstra, A.Y., Chapagain, A.K., 2008. The global component of freshwater demand and supply: an assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. *Water Int.* 33 (1), 19–32. <https://doi.org/10.1080/02580600801927812>.
- ILRI, 2010. East African Dairy Development Project Baseline Survey: Feeds and Feeding Practices. Retrieved from .
- Jaetzold, R., Schmidt, H., 1983a. Farm Management Handbook of Kenya (Vol. II, Part A): Natural Conditions and Farm Management Information, West Kenya. Ministry of Agriculture and German Agency for Technical Cooperation (GTZ), Nairobi, Kenya.
- Jaetzold, R., Schmidt, H., 1983b. Farm Management Handbook of Kenya (Vol. II, Part C): Natural Conditions and Farm Management Information, East Kenya. Ministry of Agriculture and German Agency for Technical Cooperation (GTZ), Nairobi, Kenya.
- Jalava, M., Kumm, M., Porkka, M., Siebert, S., Varis, O., 2014. Diet change—a solution to reduce water use? *Environ. Res. Lett.* 9 (7), 074016.
- Kenya, 2007. Kenya Vision 2030. Government of the Republic of Kenya.
- KNBS (2010). Nairobi: Ministry of Finance and Planning.
- Mekonnen, M.M., Hoekstra, A.Y., 2010. The Green, Blue and Grey Water Footprints of Farm Animals and Animal Products. The Value of Water Research Report Series Vol. 48 UNESCO-IHE Institute for Water Education, Delft.
- Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* 15 (5), 1577–1600. <https://doi.org/10.5194/hess-15-1577-2011>.
- Mekonnen, M.M., Hoekstra, A.Y., 2012. A global assessment of the water footprint of farm animal products. *Ecosystems* 15 (3), 401–415.
- Navarrete-Molina, C., Meza-Herrera, C.A., Ramirez-Flores, J.J., Herrera-Machuca, M.A., Lopez-Villalobos, N., Lopez-Santiago, M.A., Veliz-Deras, F.G., 2019. Economic evaluation of the environmental impact of a dairy cattle intensive production cluster under arid lands conditions. *Animal*. <https://doi.org/10.1017/S175173111900048X>.
- Palm, C., Blanco-Cañqui, H., DeClerck, F., Gater, L., Grace, P., 2014. Conservation agriculture and ecosystem services: an overview. *Agric. Ecosyst. Environ.* 187, 87–105.
- Pierik, M.E., Gusmeroli, F., Marianna, G.D., Tamburini, A., Bocchi, S., 2017. Meadows species composition, biodiversity and forage value in an Alpine district: relationships with environmental and dairy farm management variables. *Agric. Ecosyst. Environ.* 244, 14–21. <https://doi.org/10.1016/j.agee.2017.04.012>.
- Rask, K.J., Rask, N., 2011. Economic development and food production—consumption balance: a growing global challenge. *Food Policy* 36 (2), 186–196. <https://doi.org/10.1016/j.foodpol.2010.11.015>.
- Regmi, A., Dyck, J., 2001. Effects of Urbanization on Global Food Demand. Changing Structure of Global Food Consumption and Trade. pp. 23–30.
- Schneider, U.A., Havlik, P., Schmid, E., Valin, H., Mosnier, A., Obersteiner, M., et al., 2011. Impacts of population growth, economic development, and technical change on global food production and consumption. *Agric. Syst.* 104 (2), 204–215. <https://doi.org/10.1016/j.agsy.2010.11.003>.
- Swindale, A., Bilinsky, P., 2006. Development of a universally applicable household food insecurity measurement tool: process, current status, and outstanding issues. *J. Nutr.* 136 (5), 1449S–1452S.
- Thorpe, W., Muriuki, H., Omere, A., Owango, M., Staal, S., 2000. Dairy Development in Kenya: the Past, the Present and the Future.
- Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. *Nature* 418 (6898), 671–677.
- Udo, H.M.J., Akilu, H.A., Phong, L.T., Bosma, R.H., Budisatria, I.G.S., Patil, B.R., et al., 2011. Impact of intensification of different types of livestock production in smallholder crop-livestock systems. *Livest. Sci.* 139 (1–2), 22–29. <https://doi.org/10.1016/j.livsci.2011.03.020>.
- van Vuuren, D.P., Smeets, E.M.W., 2000. Ecological footprints of Benin, Bhutan, Costa Rica and the Netherlands. *Ecol. Econ.* 34 (1), 115–130. [https://doi.org/10.1016/S0921-8009\(00\)00155-5](https://doi.org/10.1016/S0921-8009(00)00155-5).
- Waithaka, M., Nyanganga, J., Staal, S., Wokabi, A., Njubi, D., Muriuki, K., et al., 2002. Characterization of Dairy Systems in the Western Kenya Region.
- Wirsenius, S., Azar, C., Berndes, G., 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? *Agric. Syst.* 103 (9), 621–638. <https://doi.org/10.1016/j.agsy.2010.07.005>.
- World Bank, T., 2016. World Bank Open Data. The World Bank Group.