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Addressing variation in smallholder farming systems to improve dairy development in Kenya

Salome Atieno Migose

Thesis

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Abstract

Mixed crop-livestock (MCL) systems with small herds of improved dairy cattle breeds produce the bulk of Kenya's milk. The adoption of interventions to achieve increased cow productivity and increased market orientation has been relatively low, which could be due to the fact that variation between MCL farming systems is not taken into account in development projects. Variation among farming systems is determined by their market quality for inputs and outputs, by their availability of production factors, and by their biophysical context. These aspects are associated with spatial variation, i.e. they differ among locations. Consequently, farming systems in different locations will be different, will have different constraints and different targeted interventions to overcome these constraints. Better understanding of the variation in these systems and the context they operate in can inform development interventions towards their market-orientation and productivity. The aim of this thesis was to understand the variation in farming system development, constraints for development and targeted interventions for development, in order to increase market-orientation and dairy cattle productivity of smallholder MCL system in Kenya. I concluded from my studies that in Urban Locations (UL), farm development was constrained by scarcity of fodder, replacement stock and hired labour, and the limited availability of production factors, while in Rural Locations (RL) farm development was constrained by low quality of concentrates and low prices of milk. In UL, most perceived positive deviant farmers (PDs), i.e. farmers that overcame constraints and/or were perceived successful for dairy production, were economic PDs. Results suggest that in UL, PDs overcame constraints by increasing herd size and intensity of production, whereas non-PDs lacked the skills and financial stability to increase herd size and milk production per cow. In RL, PDs overcame constraints by increasing herd size, whereas non-PDs lacked the skills and financial stability to increase herd size. A method was developed to estimate milk production per lactation (MPL) from recall data, which was used to assess the biophysical factors constraining milk production. Results suggest that the level of accuracy of estimating MPL based on recall data were acceptable. In all locations, feed was the most important biophysical constraint for increasing milk production and protein deficiency was a pervasive constraining factor during lactation. Therefore, supplementing lucerne, with or without concentrates, increased feed-limited milk production, suggesting that sourcing affordable protein supplements of good quality is a priority for increasing productivity. These results imply that

development interventions should address the different constraints in the farming systems. UL farmers and PDs are following the stepping-up livelihood strategy and relevant interventions should be tailored for commercial production including to develop and/or strengthen market-oriented fodder production and value chains, infrastructure, and training and extension. RL non-PDs are hanging-in and interventions should address both production function and subsistence function of cattle and should include improving farmers' financial stability, access to grazing areas, and skills as well as improving breeds. Future dairy development in Kenya will follow diverse pathways with mid-rural location (the location between UL and RL, about 15 to 50 km from the centre of UL) as the most promising optimal location for dairy development because of land availability and potential to develop formal dairy value chains and infrastructure and recycle nutrients.

Table of contents

Chapter 1

General introduction

Variation among farming systems

1.1 Overview of global dairy farming

1.1.1 Milk production and dairy development

Dairy farming is the practice of keeping animals to produce milk. Milk is a rich source of nutrients for humans, and about 75% of the global population consumes milk (FAO, 2016). As such, milk contributes to global food security (Pereira, 2014). The dairy industry, moreover, has a significant economic value, since the industry supports livelihoods and contributes substantially to the agricultural gross domestic products (GDP) of many countries (FAO, 2018a). Globally, the demand for milk has increased and is expected to further increase because of human population growth and increasing wealth (Andersson Djurfeldt, 2015; Kapaj and Deci, 2017). In response to the increase in demand, global annual milk production increased from 344 million tons in 1961 to 850 million tons in 2018 (Fig. 1; FAO, 2019). Milk production levels and their increase differ largely between regions. For example, Europe has a high milk production and a slow growth rate, Africa, Oceania, North America (the US and Canada) and the rest of America (the Caribbean, Central and South America) have low milk production levels and slow growth rates, whereas Asia has a high milk production and growth rate since 2005 (Fig. 1).

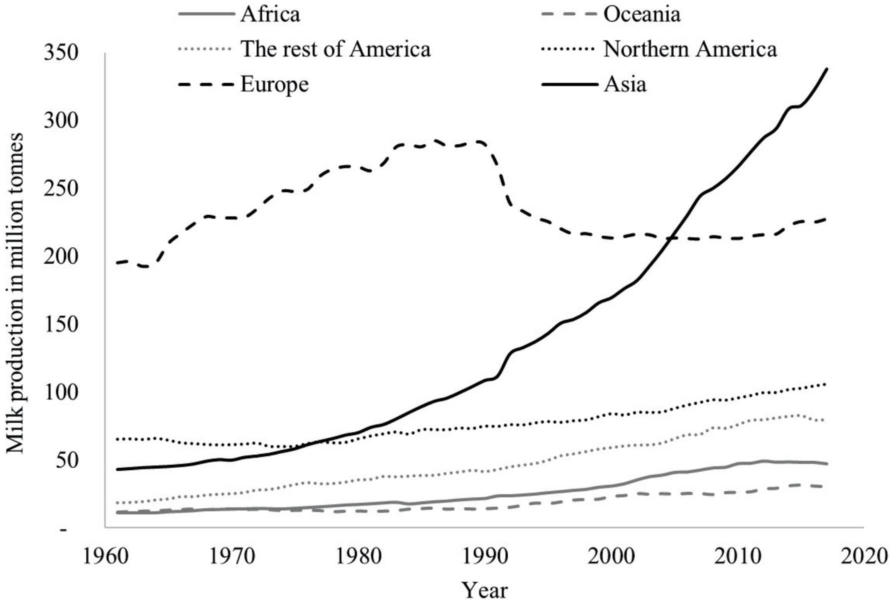

Figure 1. Global milk production trends by region, data source *(FAOSTAT, 2019)*

1.1.2 Dairy farming systems

Globally, dairy farming systems can be classified into three major categories: the mixed crop-livestock (MCL) system, the grazing system, and the landless system (Oosting et al., 2014; Seré et al., 1996).

The MCL system is generally found in agricultural regions with conditions that favour crop production, such as seasonal rainfall and fertile soils (Robinson et al., 2011). These conditions allow farmers in relatively densely populated regions to produce crops and livestock for subsistence. The majority of the MCL systems are small-scale. The MCL system supports livelihoods of about 3.4 billion people globally. In developing countries, moreover, smallholder MCL systems produce the majority of the food for households, including 75% of milk (Herrero et al., 2014, 2010; Thornton and Herrero, 2015). In most smallholder MCL system, crop production is the core objective, and it interacts with livestock production. Livestock feed on crops residues and provide manure and traction for crop production as well as food, savings and insurance functions for livelihoods (Oosting et al., 2014; Thornton and Herrero, 2015; Udo et al., 2011). Crop and livestock interactions increase security during crop failures, which enhances the resilience of the MCL system (Stark et al., 2018). Population density is high and often increasing in regions with MCL systems, and the latter are faced with pressure on land, which reduces farm sizes and communal grazing resources (Valbuena et al., 2012). The potential of the MCL system to change to market-oriented production with increased productivity of dairy cattle, and hence contribute to the rising global demand for milk, so far, appears limited because of the difficulty to change from subsistence to market-oriented production (Steinfeld et al., 2006).

The second category includes the grazing system in which the majority of the feed for cattle originates from grasslands, such as pastures and rangelands. Grasslands cover about two-thirds of the global agricultural soils (FAO, 2011). Grazing systems are found in agricultural regions where climatic conditions are unfavourable (e.g. too hot, too dry or both hot and dry) and land is less suitable for crop production (e.g. infertile) (Reid et al., 2008). The most significant global examples of grazing systems are pastoralism and rangeland production (Ayantunde et al., 2011; Campbell et al., 2000). Pastoralists move their livestock in search of feed and water to maintain their existence (Adriansen, 2008; Ayantunde et al., 2011; Tamou et al., 2018). Livestock provide food for own consumption, manure, are a store of wealth, and have an insurance function (FAO, 2018b; McDermott et al., 2010; Tamou et al., 2018). Herders move to crop-producing regions to feed their livestock on crop residues in dry seasons, which benefits crop farmers through deposits of livestock manure. Increased crop production, use of synthetic fertiliser, policies that restrict pastoralism, and infrastructure development challenge the relation between pastoralists and crop farmers (Ayantunde et al., 2011; Herrero et al., 2010; Tamou et al., 2018).

Rangeland production involves keeping ruminants in vast tracts of grasslands that are owned privately (Campbell et al., 2000), and is dominant in the Americas, but also occurs in Africa (Seré et al., 1996). Rangeland production aims at producing milk and meat for the market. This grazing system supports about 300 million people globally and contributes to about 7% of the global milk output (Herrero et al., 2010). Livestock production on rangelands may intensify through irrigation, fertilisation and use of improved breeds (Ayantunde et al., 2011). Pastoralism and rangeland systems, however, are currently threatened by increased production of crops (McCabe et al., 2010; Tamou et al., 2018).

The last category is the landless system, also referred to as the industrial system. Landless systems are dairy systems in which the majority of the feed is purchased. They are found in areas with high population densities, high land scarcity and well-developed infrastructures, such as markets for feed and milk. Peri-urban dairy farms are often land-limited or landless and are examples of this kind of farming system (Oosting et al., 2014). At present, this system is least important globally, as it produces only about 4% of the global milk (Herrero et al., 2010).

1.2 Dairy farming in Kenya

1.2.1 Status and farming systems

In Kenya, the dairy industry contributes to income and food of households as well as to the economic growth of the nation. It provides a livelihood to 25% of households and contributes 5% to the national GDP (GoK, 2019). Milk is generally consumed as a liquid in tea, but the consumption of processed products, such as yoghurt, cheese, butter, and ice cream, is increasing (Cornelsen et al., 2016; Njarui et al., 2011). The average Kenyan consumption of milk products of 115 kg/person/year is higher than the average of 37 kg/person/year in Africa (FAOSTAT, 2019). The national demand for milk in Kenya is increasing because of population growth (~2.5% per year) and rising incomes (GoK, 2013a). Milk production ideally increases in line with demand. So far, the estimated annual milk production increased from 699 thousand tons in 1961 to 3.6 million tons in 2017 (FAOSTAT, 2019). The present average milk production of dairy cattle in Kenya is 2000 kg per cow per year, whereas it was 1500 kg per cow per year in the 1990s (GoK, 2013b; Reynolds et al., 1996). The increase in national milk production, therefore, has been achieved mainly through an increase in the size of dairy cattle population and only to a small extent through an increase in dairy cattle productivity (Hemme and Otte, 2010). Increasing dairy cattle productivity, therefore, offers an opportunity to meet future demands for milk production (Brandt et al., 2018; Notenbaert et al., 2017).

In this thesis, I focus on increasing dairy cattle productivity in the smallholder MCL system, which is by far the most important dairy farming system in Kenya (Herrero et al., 2014). The MCL system is dominant in the highlands because of the favourable agro-ecological conditions, i.e. annual rainfall above 1000 mm and average daily temperatures below 20°C (Bebe et al., 2002; Herrero et al., 2014; Omore et al., 1999). In the Kenyan MCL system, smallholders grow food as well as cash crops. They, moreover, mainly keep dairy cattle, and, therefore, contribute to about 70% of the national milk production (Bebe et al., 2002; Omore et al., 1999). The dominant dairy cattle breeds are exotic, mainly Holstein Friesian and Ayrshire, originating from Europe, and their crosses with local breeds (Omiti et al., 2009; Omore et al., 1999). Cows in the MCL system are fed, to a great extent, with grass and fodder cultivated on private lands, while they also graze on communal lands (Lukuyu et al., 2011). Crop production is essential for dairy cattle as they provide crop residues for feeds (Castellanos-Navarrete et al., 2015; Duncan et al., 2016). Important functions of dairy cattle, besides milk production, are manure provision to support crop production, and to act as a capital asset (Udo and Cornelissen, 1998; Weiler et al., 2014).

The milk production in Kenya, is also relatively high, compared to other African countries (Bingi and Tondel, 2015; Odero-Waitituh J A, 2017; Udo et al., 2011). This relative high milk production in Kenya has resulted from a relatively high adoption rate of veterinary care (84%), improved breeds (51%), and improved feeding practices (21%) (Kebebe et al., 2017; Njarui et al., 2016). Nevertheless, dairy cattle productivity in Kenya is still lower than the 6000 kg per cow per year potential yield of the exotic breeds (Muasya et al., 2014; Njubi et al., 2009).

Before I will further describe the potential and constraints to increase milk production in smallholder MCL systems, I first give some historical background essential to better understand the current dairy sector and its context.

1.2.2 Historic development

Before colonisation of Kenya by the British government, which started around 1884, the native communities settled mostly in the non-arid lands (about 20% of the landmass in Kenya; Fig. 2) (Jedwab et al., 2017) and cultivated crops, such as millet and tubers while also keeping local cattle, sheep and goats, for subsistence

(Austin, 2008; Collier, 2010). Around 1895, the colonial government crowned part of these non-arid lands that belonged to the natives as the "white highlands" (Fig. 2). These white highlands were from that moment onwards reserved for British farmers, while the natives were relocated to the peripheries of the highlands. The British farmers produced crops, such as coffee, tea, tobacco and maize and established dairy herds and introduced exotic cattle breeds from Europe to upgrade the local cattle population (Conelly, 1998). The colonial government, however, prohibited natives to keep exotic and crossbred cows (Bates, 1987). Natives, also the ones working as labourers on British farms, therefore, only kept local cattle.

Dairy production by British farmers became more specialised and market-oriented, and butter was exported to Europe. After the first world war, around 1919, the demand for animal products increased, and ex-soldiers from Europe and the US, the so-called white settler farmers, also started settling in part of the white highlands. Consequently, the number of MCL farms owned by 'white settler' farmer increased, and, therefore, the population of cattle of exotic breeds and their crossbreds also increased. To reduce the transmission of tick-borne diseases from the local tolerant cattle to the susceptible exotic and crossbred cattle, the colonial government prohibited native labourers from keeping their local cattle on 'white settler' farms. This ban significantly reduced the number of local cattle in Kenya, while it increased the number of exotic and crossbred cattle.

To stimulate agricultural growth, the colonial government lifted the ban restricting native communities from keeping exotic cattle in 1955 (Conelly, 1998; Swynnerton, 1955). After independence in 1963, the post-colonial government subdivided the 'white settler' farms and redistributed the farms, often in small herds, to the natives (Thorpe et al., 2000). These historical events have resulted in the many smallholder MCL systems with exotic and crossbred cows, that are market-oriented.

The 'white settler' farmers and the colonial government, furthermore, developed an infrastructure for dairy production and marketing. They established research centres for tropical diseases and infrastructure for milk marketing in the formal dairy value chain through cooperatives. The government, on one hand, established semen production facilities, and delivered inputs and services, such as veterinary care, and artificial insemination (AI), at subsidised prices. The farmers, on the other hand, practised stall feeding and introduced high yielding fodder species, such as Rhodes and Napier grass, to improve grasslands and fodder availability and quality (Bebe et al., 2002; Conelly, 1998).

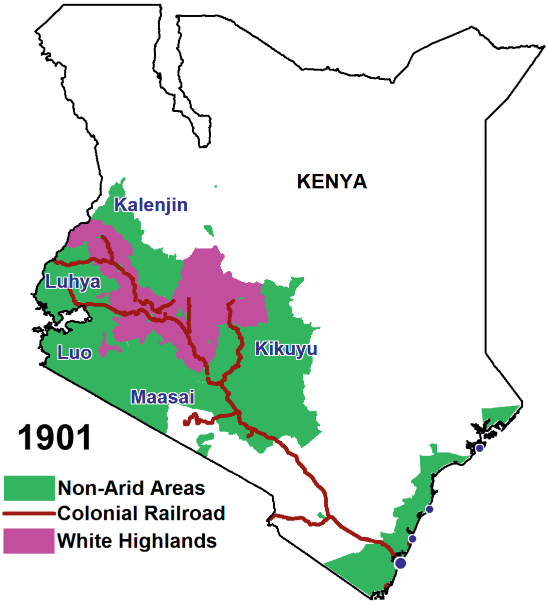

Figure 2. The White Highlands in Kenya during the colonial era (Jedwab et al., 2017)

The policies of the colonial government were directed at selling of milk through quota and contract pricing via cooperatives (1957). Prices of milk were offered to farmers according to quantities of milk supplied: if farmers produced more, they received a higher price per kg of milk. The post-colonial government, furthermore, improved value chains for inputs, such as veterinary care and AI, and milk and provided extension services and credit programmes to native farmers (Muriuki, 2011; Waller, 2004), which increased adoption of innovations among the native farmers post-colonisation.

From the 1970s onwards, several policy changes occurred: the government support and subsidies programmes became too expensive and unsustainable, and started to reduce. In 1971, the milk pricing policy was revised and the quota and contract pricing were abolished and replaced by uniform and fixed pricing independent of the season and amount of milk produced. This fixed pricing implied that cooperatives (i.e. the formal value chain) provided higher prices during months of surplus and lower prices during months of milk shortages than the informal dairy value chains. Farmers responded by supplying milk more through these informal than formal dairy value chains, especially in the dry period. In the 1990s, moreover, some support activities were withdrawn and markets for extension services, veterinary care and semen production were liberated. This market liberation was followed by the collapse of the formal dairy value chains through cooperatives, which contributed further to the increase of milk supply through the informal dairy value chain (Owango et al., 1998; Staal and Shapiro, 1994). These informal dairy value chains remained 'illegal' until 2004 but currently still exist and supply about 80% of the milk (GoK, 2013b; Kebebe et al., 2017).

1.3 Constraints to market-oriented dairy production and increased productivity of dairy cattle in Kenya

To meet the increasing domestic demand for milk production, the present government policies aim to increase market-oriented dairy production of the MCL system and to double the productivity of dairy cattle in the system. These policies comprise promoting farming as a business, favouring formal dairy value chains, and improving access to markets for inputs and outputs. In addition, policies support research, and training and extension services, in order to increase innovations and transfer of knowledge on improved technologies for dairy farming (GoK, 2019, 2013b). Increased and market-oriented dairy production in MCL systems and increased productivity of dairy cattle need higher production per ha and per cow on more specialised farms, which is complex and these farms face many constraints (Burke et al., 2015; Olwande et al., 2015; Oosting et al., 2014; Udo et al., 2011). The next paragraphs explain these constraints, subdivided into biophysical, economic, and social constraints.

1.3.1 Biophysical constraints

Biophysical constraints that hinder the transition from subsistence to market-oriented dairy farming and increased productivity of dairy cattle in Kenya are related to climate, quality of soils on which feeds are produced, breeds and disease prevalence (van der Linden et al., 2015). At farm level such biophysical constraints relate to the management regarding breeding, feeding, housing and health.

First, genetics can be a constraint. Presently, 49% of farmers keep cattle of local breeds and such local breeds are of low genetic potential for milk. Artificial insemination (AI) with semen from exotic breeds is an intervention to improve cattle genetics. The adoption of AI technology, however, is only about 13%, and breed improvement is not occurring everywhere (Kebebe et al., 2017; Ojango et al., 2016). Moreover, improved breeds may have adaptation problems to the production environment in smallholder herds (Kim and Rothschild, 2014; Muasya et al., 2014). Finally, inbreeding, which potentially could limit milk production of exotic cattle, is often reported in large scale herds (Gorbach et al., 2010).

Second, the quantity and quality of fodders available in smallholder farms are lower than required for meeting maintenance and production of the relatively high genetic potential of the improved breeds (Lukuyu et al., 2009). Fodder availability is insufficient because of high temperatures, inadequate rainfall and limited nutrient supply from the soils (Notenbaert et al., 2017; Tittonell et al., 2005a, 2005b). Fodder scarcity is most severe in the dry season (Lukuyu et al., 2009). At the same time, several technologies for improving quantity and quality of fodders are available, such as improved fodder species, technologies for conserving fodder, ration formulation, and chemical treatments, such as using urea or ammonia, or biological treatment using fungi and bacteria to improve quality of straws (Kashongwe et al., 2017b; Kebebe et al., 2017; Lukuyu et al., 2011; Musalia et al., 2016; Thornton and Herrero, 2015). The adoption rate of feeding technologies by smallholders, however, is low, i.e. 21% in Kenya (Kebebe et al., 2017; Lukuyu et al., 2009).

Third, although the climatic conditions in the highlands are relatively favourable for improved breeds, housing is still important to provide protection from cold or hot temperatures, to confine animals in stall feeding systems, and to allow ease of control and management (van Laer et al., 2014). Few large-scale farms have well-constructed barns for housing dairy cattle, but 50% of smallholder farms have zero-grazing barns for cattle (Njarui et al., 2016). These zero-grazing barns are neither optimally built, nor ideal for welfare and health of cows and optimal production (Batz et al., 1999; Vaarst et al., 2019).

Last, the improved breeds of dairy cattle are highly susceptible to diseases, such as tick-borne diseases (e.g. east coast fever), foot and mouth disease, mastitis, and helminths (Okuthe and Buyu, 2006). The adaption of veterinary care by farmers is relatively high, but disease control still is ineffective and economic losses from diseases, therefore, stay high (Karanja-Lumumba et al., 2015; Kebebe et al., 2017; Patel et al., 2019). These economic losses have two major causes. First, diseases cause losses in milk yield and, therefore, in milk revenues. Second, costs for veterinary care are high.

1.3.2 Economic constraints

The various biophysical and associated technological constraints, discussed above, are linked and together they contribute to economic constraints. The aim of market-oriented dairy production and increased productivity of dairy cattle is to obtain economic gains from milk production and marketing. For economic gains to occur, farmers need to increase milk output per farm and be commercially viable. Increased output and commercial viability require, first, adequate use of production factors, such as land and labour. In countries where population pressures and urban employment are high such as in Kenya, land and labour are scarce (Jayne et al., 2014). Scarcity of land and labour limit milk production in large quantities because dairy production competes with crop cultivation for these production factors (Herrero et al., 2014). Allocation of land and labour to dairy production may compete, also, with non-farm work, such as construction of buildings, employment and engagement in trade. Farmers, transitioning from subsistence farming to market-oriented dairy farming and increased productivity of dairy cattle, therefore, should reallocate land and shift family labour from crops and off-farm activities to dairy farming (Bosire et al., 2019; Willy et al., 2019). Reallocating land to dairy farming, however, is limited when opportunity costs of land and labour are higher for crop cultivation and off-farm activities than for dairying. To cope with scarcity of land and labour, external inputs e.g. purchase of feed and mechanisation, which require functional markets and value chains, are sourced (Bebe et al., 2003; Bebe, 2008).

Markets and dairy value chains for inputs and services, such as concentrates, AI, purchased heifers, hired labour and veterinary care, are often not fully functional, i.e. prices may be too high and inputs may be of too low quality in some places (Omore et al., 1999). Poorly functioning dairy value chains for inputs and services contribute to sub-optimal use of inputs, which contributes to low production and low benefits from the dairy activity (Baltenweck et al., 2011).

Because of increased milk output per farm, local production (of a village or a whole region) may exceed local consumption. Markets in urban areas become necessary, in that case, for the marketing of the milk (Burke et al., 2015; Oosting et al., 2014). These urban markets, often, are located far from farms, and functional value chains for milk marketing are required to connect farms to these urban markets. In the Kenyan highland, the informal dairy value chain accounts for about 80% of marketed milk, but this informal dairy value chain is unreliable; its milk price fluctuates and is highly dependent on quantity of milk supplied (USAID, 2015). Formal dairy value chains for milk marketing are limited and offer low prices, in part, because of high transaction costs (Kilelu et al., 2017a; Makoni et al., 2015; Rao et al., 2016).

1.3.3 Social constraints

MCL systems traditionally produce milk for subsistence. If the dairy component of the MCL system has to evolve to become a market-oriented one with high productivity of dairy cattle, the style of farming will change and farmers will have to adapt to practices for entrepreneurship (Kostov and Lingard, 2002;

Oosting et al., 2014; Reynolds et al., 1996). Entrepreneurship requires curiosity, risk-taking and business mindedness (Coppola et al., 2018; Schreiber, 2002). The levels of curiosity, risk-taking and business mindedness of the MCL smallholders are low and farmers, often, remain risk-averse (Nyikal and Kosura, 2005). The lack of entrepreneurship and risk averseness of MCL farmers, in part, can be explained by a sub-optimal enabling environment.

An optimal enabling environment is one that allows innovations and that facilitates farmers' behaviour (i.e. entrepreneurship and risk-taking) to innovate (Kebebe, 2019; Kilelu et al., 2013; McKague et al., 2014; Schut et al., 2016). Such an enabling environment comprises policies that favour markets and trade, and institutions and infrastructure that facilitate provision of inputs and marketing of outputs (Kebebe et al., 2015). The public sector, non-governmental organisations, farmers' groups and private sector may be stakeholders providing an enabling environment. Most of these stakeholders, however, are associated with the formal dairy value chain. Most of the milk is marketed in, and most of the farms are connected to, the informal dairy value chain, which is, by default, not under government policies and connected to institutions. Hence, the major enabling environment for the informal dairy value chain is the infrastructure. The formal dairy value chain has strong connections to policies, institutions and private sector and examples of enabling environments associated with the formal dairy value chain are plenty: markets for input, micro-insurance for protection against risks and credit for financing (banks), research for new technologies, inventions and innovation (national agricultural research institutes), capacity building by transfer of knowledge about technical perspectives and about management and organisation of businesses (training institutes and government extension services), and regulations, standards and quality assurance (Kenya dairy board, Kenya bureau of standards, and ministry of public health) (Kilelu et al., 2017b; Makoni et al., 2014). Despite these examples, the enabling environment for the formal dairy value chain could be integrated and be better accessible to smallholders to catalyse and stimulate market-orientation and increased productivity of dairy cattle (Giuliani et al., 2005; Juma et al., 2013; Kilelu et al., 2017b; USAID, 2015).

1.4 Knowledge gap and aim

The constraints for market-orientation of smallholder MCL farmers and increased productivity of dairy cattle in their farms presented above have been well documented and studied. In addition, various options have been formulated to overcome these constraints, such as importing exotic breeds, using improved fodders, establishing dairy value chains, and strengthening institutions and policies, and interventions have been implemented by many development projects (Herrero et al., 2014; McDermott et al., 2010; Rufino et al., 2009). So far, however, the adoption rate of these interventions remained low (Kebebe et al., 2017; Staal et al., 2002). I hypothesize here that the low adoption of interventions is, at least in part, due to insufficient understanding of the MCL farming systems and the context they operate in and the fact that variation among farming systems is not taken into account in projects. As a consequence, interventions are often proposed for a wide array of farmers while they are only relevant for a few (Baltenweck et al., 2003; Tarawali et al., 2011).

Variation among farming systems is determined by their market quality for inputs and outputs, by their availability of production factors, and by their biophysical context (Duncan et al., 2013; Herrero et al., 2014; Staal et al., 2002; van de Steeg et al., 2010; van de Ven et al., 2003; van der Lee et al., 2018). These aspects are associated with spatial variation, i.e. they differ among locations. Market quality, which is the "attractiveness and reliability of input procurement arrangements and output market chains" (adapted from Duncan et al. (2013)), depends, among others, on distance to markets (Staal et al., 2002; van der Lee et al., 2018). Availability of production factors, such as land and labour, depends on population pressure and levels of urbanisation (Bilsborrow, 1987; Jayne et al., 2014; Muyanga and Jayne, 2014; Satterthwaite et al., 2010). Biophysical conditions may favour dairy production more in one location than in another (van de Steeg et al., 2010). Hence, variation in farming systems is associated with spatial variation, i.e. farming systems differ among locations if locations have different characteristics. Moreover, farming systems in different locations will have different constraints and different targeted interventions to overcome these constraints. However, the number of scientific studies relating spatial variation to variation in farming system development, constraints for development and targeted interventions for development, is limited (van de Steeg et al., 2010; van der Lee et al., 2018).

The aim of this thesis, therefore, is to understand the variation in farming system development, constraints for development and targeted interventions for development, in order to increase market-orientation and dairy cattle productivity of smallholder MCL system in Kenya.

By better targeted interventions, milk output of Kenyan dairy farming may increase to meet the increasing demand for milk, while relatively poor smallholder MCL farmers can benefit from the increasing market opportunities for milk. This objective of this thesis will be met through studying diverse farming systems at different locations.

A spatial framework was applied to select locations with different MCL farming systems. I hypothesize that distance to the urban market influences farm development and determines the prevailing constraints. Subsequently, I hypothesize that farming systems also differ within these locations, and I studied how different farmers overcome local and generic constraints and how they address different biophysical constraints. To explore these differences among farming systems, we needed accurate estimates of dairy cow productivity.

The main research questions of this thesis, therefore, are:

i. How does the distance to urban markets influence the development of smallholder dairy farming systems in Kenya? (Chapter two);
ii. How do positive deviant farmers overcome dairy production constraints in urban and rural locations? (Chapter three);
iii. How accurate are the estimates of milk production per lactation from limited number of records from smallholder dairy farms? (Chapter four); and
iv. Which are the most limiting biophysical constraints and what are the improvement options to overcome these constraints in urban and rural locations? (Chapter five).

1.5 Outline of the thesis

1.5.1 Order of chapters

Fig. 3 provides the arrangement of chapters of this thesis. In **Chapter two**, I study the influence of farm location on farm development and determine the prevailing constraints for different locations. In **Chapter three**, I identify successful strategies for overcoming production constraints in different locations. In **Chapter four**, I assess the accuracy of estimates of milk production per lactation from recall data. In **Chapter five**, I analyse yield gaps of dairy cattle to identify and prioritise biophysical limitations to milk production in order to determine relevant improvement options for different locations. In **Chapter six,** I synthesise the findings of all chapters of the thesis and conclude on the factors that contribute to increased market-oriented production of MCL farmers and increased the productivity of dairy cattle in their farms.

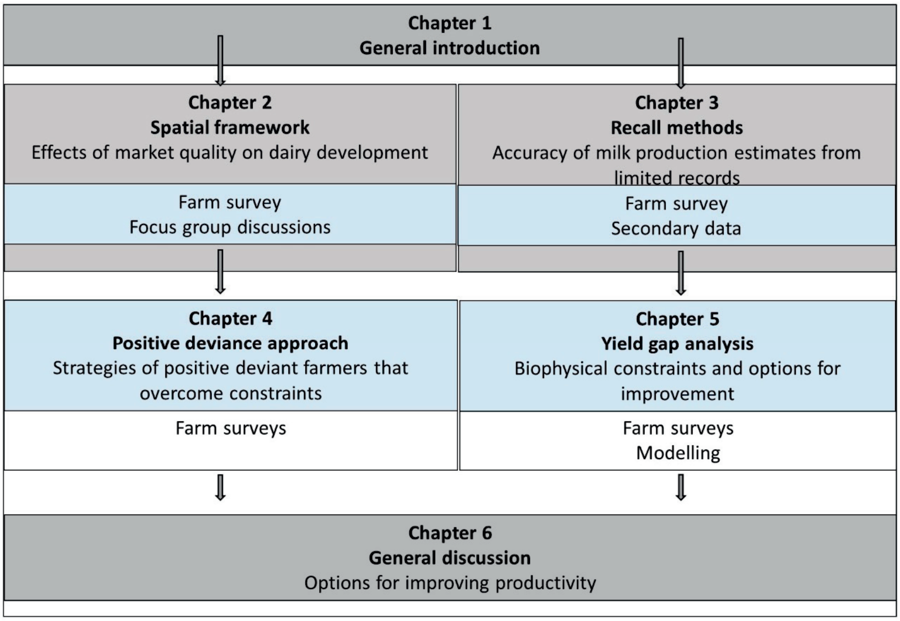

Figure 3. Overview of the chapters and structure of the thesis

1.5.2 Study sites

The study was conducted in Nakuru County (Fig. 4). The county covers 7495 km^2 and has about 4 million inhabitants, 45% of which live in towns and trading centres along tarmac roads. The main urban area and the capital of the county is Nakuru town. Infrastructures (e.g. roads, electricity and water) and social amenities are better in Nakuru town than in the smaller towns, trading centres and rural areas within the county (County Government of Nakuru, 2017). The county has two major agro-ecological conditions: highlands with an average annual rainfall above 1400 mm and latosolic and planosolic soils of moderate to high fertility, and semi-arid areas with an average annual rainfall of 500 mm and deposits of alluvial and lacustrine soils of low to moderate fertility (County Government of Nakuru, 2018, 2017). The average annual temperature ranges from 12°C to 20°C (MoALF, 2016). The highlands favour MCL farming, which is practiced by about 71% of farmers, and they produce food crops (e.g. maize, wheat, Irish potato, beans and vegetables), cash crops (e.g. tea, flowers and vegetables) and keep livestock (e.g. cattle, sheep, goats and chicken) (Nakuru County Government, 2018). The semi-arid areas, in contrast, are dominated by pastoralists on communal lands and privately-owned rangelands with farms keeping large herds.

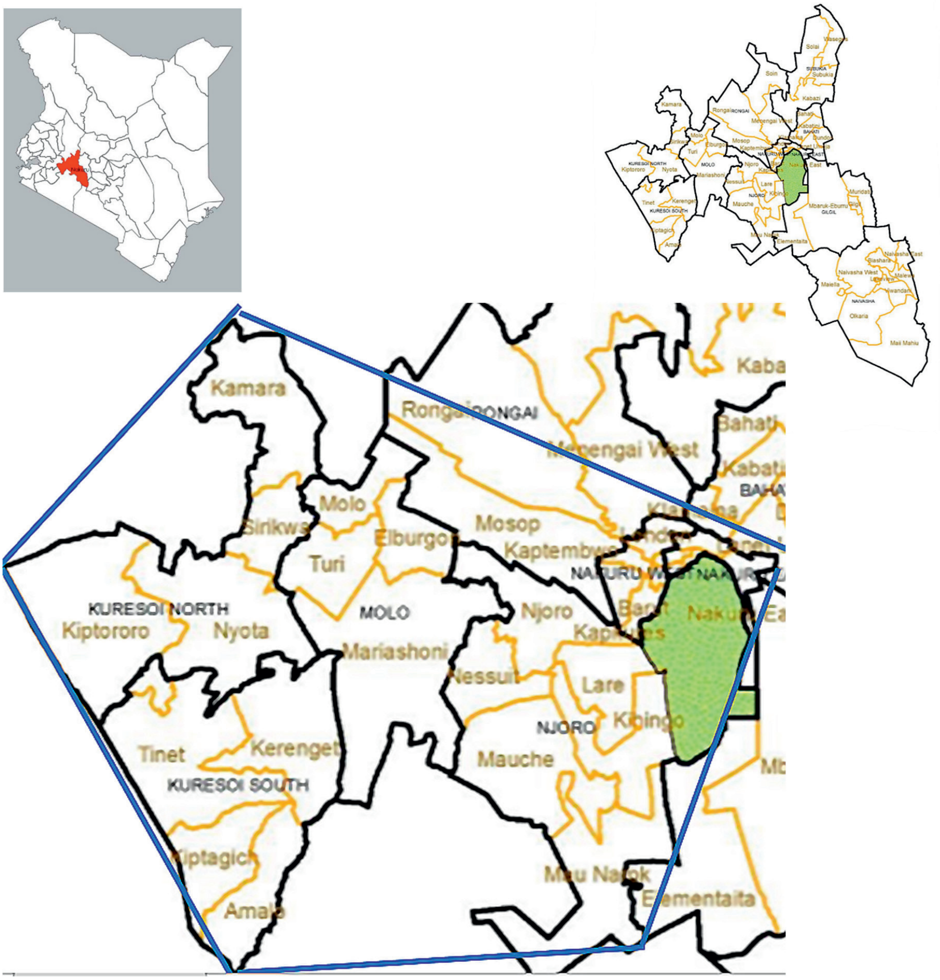

Figure 4. The sub-counties in Nakuru County (right inset) in Kenya (left inset) sampled for data collection, source (County Government of Nakuru, 2017)

The study locations were selected in the highlands and cover five sub-counties, i.e. Nakuru, Rongai, Njoro, Molo and Kuresoi (Fig. 4). I chose Nakuru county to conduct this study for a number of reasons. First, it is a major milk-shed, with a high density of dairy cattle and smallholder dairy farmers (van de Steeg et al., 2010). Second, it has an agro-ecological environment with bimodal rainfall and low temperatures, which is favourable for dairy production (Jaetzold and Schmidt, 1983). Third, dairy production is a source of livelihood in (peri)-urban and rural areas (Foeken and Owuor, 2008; Kashongwe et al., 2017a). Fourth, Nakuru town, located within the county, is rapidly urbanising and provides an urban market for dairy products (County Government of Nakuru, 2018).

Chapter 2

Influence of distance to urban markets on smallholder dairy farming systems in Kenya

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Farms in urban location, mid-rural location and extreme rural location in that order

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Abstract

We studied influence of distance to urban markets on smallholder dairy farming system development. Farms were chosen from three locations that varied in distance to the urban market of Nakuru Town in the Kenyan highlands: urban location (UL, $n = 10$) at less than 15 km distance, mid-rural location (MRL, $n = 11$) in between 20 and 50 km west of Nakuru and extreme-rural location (ERL, $n = 9$) beyond 50 km west and south-west of Nakuru. In-depth interviews with farmers and focus group discussions with eight groups of stakeholders were held to collect narratives and data about market quality, production factors, farm performance and functions of dairy cattle. We applied thematic content analysis to qualitative information by clustering narratives according to predefined themes and used ANOVA to analyse farm data. In UL, markets were functional, with predominantly informal market chains, with a high milk price (US $ 45.1/100 kg). Inputs were available in UL markets, but prices were high for inputs such as concentrates, fodder, replacement stock and hired labour. Moreover, availability of grazing land and the high opportunity costs for family labour were limiting dairy activities. In UL, milk production per cow (6.9 kg/cow/day) and per farm (20.1 kg/farm/day) were relatively low, and we concluded that farm development was constrained by scarcity of inputs and production factors. In rural locations (MRL and ERL), markets were functional with relatively low prices (average US $ 32.8/100 kg) for milk in both formal and informal market chains. Here, concentrates were relatively cheap but also of low quality. Fodder, replacement stock and labour were more available in rural locations than in UL. In rural locations, milk production per cow (average 7.2 kg/cow/day) and per farm (average 18.5 kg/farm/day) were low, and we concluded that farm development was constrained by low quality of concentrates and low price of milk. In all locations, production for subsistence was valued since income generated was used for non-dairy expenses. A tailor-made package of interventions that targets the above constraints is recommended for farm development.

Keywords: market quality, production factors, farm performance, cattle functions

2.1 Introduction

Demand for milk is increasing globally because of rapid population growth, urbanisation and shifts in dietary patterns (Gerland et al., 2014). Milk demand in East Africa, for instance, is projected to increase by 43% in 2050 over the 2005/2007 base (Ugo et al., 2013). Because more than 70% of the future world population will live in cities by 2050, demand for milk will be concentrated largely around urban areas (Valin et al., 2014). This increased demand for milk in urban areas may influence dairy farming (Swain and Teufel, 2017).

Our theoretical framework is that distance of farms to urban markets influences smallholders' benefits from the increasing demand for milk. This is because distance to urban markets affects market quality for farm inputs and outputs (Chamberlin and Jayne, 2013), and availability of production factors (Jiang et al., 2013), and therefore, influences levels of inputs and outputs (Staal et al., 2002). Market quality is defined as "the attractiveness and reliability of input procurement arrangements and output market chains" (adapted from (Duncan et al., 2013)) and is reflected in availability of inputs of good quality, reliability of suppliers and opportunities to sell products at favourable prices.

In urban location (UL), a high market quality is expected because of high demand and low transaction costs for outputs and inputs. Low transaction costs result, among others, from a well-developed and reliable infrastructure, such as roads and electricity supply (Chamberlin and Jayne, 2013). Moreover, production factors, such as land and labour, are expected to be scarce and expensive because of high pressure on land for urban expansion and the availability of alternative well-paid labour opportunities (Jiang et al., 2013). Farms in UL, therefore, are expected to become intensive, i.e. to maximise profit per unit land or labour, with high levels of inputs and outputs. High input levels are reflected in use of improved exotic breeds, good-quality fodder (i.e. hay, maize silage or Napier (*Pennisetum purpureum*)) and concentrates and proper veterinary care (i.e. drugs, e.g. anthelmintic and acaricides, and treatment services). Because of high input and output levels, it is expected that farms will enter into formal value chains with specialised and efficient farming system designs and dairy cattle functions will be more oriented towards the production of milk at such high input-high output farms than at subsistence farms (Oosting et al., 2014).

In rural locations, in contrast, market quality is expected to be low, i.e. high input prices, because of low availability of inputs, unreliable supply and low output prices. This could be attributed to low demand and high transaction costs because of underdeveloped and unreliable infrastructure (Chamberlin and Jayne, 2013; Gollin and Rogerson, 2014). Moreover, production factors, land and labour, are relatively abundant and cheap because of lower population pressure and less job opportunities, respectively, than in urban areas (Jiang et al., 2013). Farms in rural locations, therefore, are expected to remain relatively extensive with low input-low output levels (Van Veenhuizen and Danso, 2007). Because of low input-low output levels, farms are diversified and dairy cattle functions are manifold, such as production of manure, draught power, banking and insurance besides providing small daily income for household expenses (Oosting et al., 2014; Weiler et al., 2014). Specialisation under rural conditions involves risks and farms may remain subsistence to be resilient (ibid).

There is a knowledge gap on the influence of distance to urban markets on development of smallholder dairy farming systems. (Duncan et al., 2013) studied effects of market quality on dairy intensification in India and Ethiopia and concluded that intensification was high when the market quality was high. This study of Duncan et al. (2013) classified market quality based on expert knowledge and functioning of formal and informal market chains, but did not analyse distance of farms to urban markets. Extent of importance of formal and informal market chains for milk marketing in urban and rural locations, besides, is unknown.

In the Kenyan highlands, smallholders produce milk in mixed crop-livestock systems (van Leeuwen et al., 2012). The aim is subsistence and cattle in these systems have multiple functions: next to milk production, cattle also produce manure and traction and serve as a capital stock (Oosting et al., 2014; Weiler et al., 2014). Milk, exceeding household’s needs, is sold predominantly in informal market chains, directly to consumers or indirectly through retailers, such as vendors, brokers, middlemen and shopkeepers (Berem et al., 2015). Farms are distributed spatially and distances to urban markets are variable (van de Steeg et al., 2010).

We use distance to urban markets as proxy for market quality with the objective to determine the influence of distance to urban markets on smallholder dairy farming system development. This is achieved through analysis of market quality, production factors, farm performance and dairy cattle functions. Results will inform designs of intervention packages to enhance benefits that the smallholder dairy farmers can obtain from the growing demand for milk in urban areas.

2.2 Materials and methods

2.2.1 Study area

Nakuru County was selected for this study because of four reasons. First, it is a major milk-shed, with high density of dairy cattle and smallholder dairy farmers (van de Steeg et al., 2010). Second, it has an agro-ecological environment with bimodal rainfall and low temperatures, which is favourable for dairy production (Jaetzold and Schmidt, 1983). Third, dairy production is a source of livelihood in (peri)-urban areas (Kashongwe et al., 2017a). Fourth, Nakuru town, located within the county, provides an urban market for dairy products. Three locations were chosen that varied in distance to Nakuru Town: the urban location (UL) at less than 15 km distance, the mid-rural location (MRL) at a distance between 20 and 50 km west of town and the extreme rural location (ERL) at a distance beyond 50 km, west and south-west of town.

2.2.2 Data collection

We conducted a cross-sectional survey to collect information at farm level. Subsequently, to complement the survey, we held focus group discussions (FGDs) with stakeholders to collect information at location level. To ensure a fair representation of smallholder dairy farms, we selected villages with a high proportion of smallholder dairy farms in UL ($n = 10$), MRL ($n = 11$) and ERL ($n = 9$). In each village, we selected one farm to represent the average smallholder dairy farm in the village (Creswell, 2015). A small sample size was targeted, purposively, suit the narrative methodology and to allow individual farmers to provide in-depth information about their perceptions on dairy farming. Each farm was visited once and in-depth interviews (IDIs), which lasted from 60 to 90 minutes, were conducted at the farmers' homesteads (Creswell, 2015).

For the FGDs, we established parallel groups, either consisting of farmers also involved in the survey and of non-farmer stakeholders. Each stakeholder group consisted of 7–10 members. In UL and ERL, we had one farmers' group and one non-farmers' group, whereas in MRL, we had two farmers' and two non-farmers' groups. The non-farmers' group of stakeholders included representatives of government extension offices, agricultural research and training institutes, milk marketing groups, input suppliers, livestock non-governmental organisations and financial institutions. Each focus group met once and FGDs, which lasted for 6 h, were held at meeting venues located within the sub-county government offices.

A guide, with semi-structured questions, was developed and used to guide the process of data collection. The following topics were included in the guide: farm characteristics, such as farm size, land use and labour availability; management of dairy production, i.e. feeding, breeding and veterinary care; technical and economic performance; and dairy cattle functions. For the FGDs, participants were asked to discuss the topics and generalise responses for the whole location. FGDs were held to get stakeholder perception on dairy farming to corroborate, validate and put information from IDIs in a broader context. The IDIs and FGDs were conducted by the first author, assisted by livestock extension officers, who translated responses and facilitated selection of villages, farms and stakeholders. Audios and field notes were used to record interviews and discussions.

Data were collected between April and August 2013, under permit from the National Commission for Science, Technology and Innovation.

2.2.3 Data analysis

The unit of analysis was the farm household for IDIs and the location for FGDs. Audio records of both IDIs and FGDs were transcribed and analysed qualitatively. Thematic content analysis (TCA) was applied to the narratives reflected in the transcripts (Boréus and Bergström, 2017). The TCA had the following procedure: the narratives were read and elements of it were labelled by the first author using a predetermined thematic framework Table 1. Each theme corresponded with questions in the interview guide, i.e. (i) market quality, (ii) production factors, (iii) farm performance and (iv) dairy cattle functions. Within each theme, we clustered responses according to issues that emerged. We made a summary of issues and used the summary to compare locations.

Quantitative data collected during IDIs, furthermore, were used for assessment of input and output prices, production factors and farm performance. Numerical variables were converted to universal standard units: 88 Kenya shillings was 1 US Dollar ($), 2.5 acres was 1 hectare (ha), 1 cattle of 250 kg was 1 tropical livestock unit (TLU) (Castellanos-Navarrete et al., 2015). Land size was calculated for land within location allocated to crops, fodder and non-farm activities and land outside the location. Communal grazing land was not included. The herd sizes comprised of cows (after first parturition, lactating and dry, av. 400 kg) and non-cows (heifers between 1 and 2 years, av. 200 kg, young stock between 4 and 12 months, av. 100 kg, and calves below 4 months, av. 50 kg). Milk yield was expressed in kg/cow/day, kg/herd/day, and kg/ha/day. Milk yield (kg/cow/day) was averaged by dividing total milk yield per farm (kg/herd/day) by the number of adult lactating cows and dry cows per herd. Milk consumed was included in the estimates of the yield per herd and dry cows were given zero yields. Milk yield (kg/ha/day) was calculated by dividing total milk yield per farm by total land size within the location per farm. Land outside the location was included only when it was used for fodder production. Communal grazing land could not be quantified. Dairy gross margins were calculated as dairy benefits (milk sold (kg/farm/day) × milk price (US $/kg) × 30 days) minus monthly production costs (feeds, hired labour, veterinary care and breeding). Milk consumed and opportunity cost for on-farm inputs (land, family labour, fodder, replacement heifers and bulls) were excluded. The aim was to get a cash flow.

Variables were tested for normal distribution using QQ plots. A one-way ANOVA was used to test the location effect, followed by Fisher's least significant difference (LSD) post hoc test to compare differences between means. Statistical analyses were done in the SAS software, v9.3©.

2.3 Results

Issues emerging from TCA were price and quality of inputs and outputs, scarcity of production factors, quality and quantity of input use, level of output and gross margin and subsistence functions of dairy cattle (Table 1).

2.3.1 Urban location

2.3.1.1 Market quality

Individual farmers and FGD participants perceived milk and input markets as functional throughout the year. Morning and evening milk were sold, mainly via the informal market chains, direct to consumers or to shopkeepers and vendors. Milk prices were higher in the informal than formal market chain and in the lean season (i.e. season with the lowest milk production, which is towards the end of the dry season) than the flush season (i.e. the season with highest milk output in the beginning of the rainy season), when supply of milk from rural locations was in surplus. Only one farmer sold surplus milk through the formal market chain

Table 1. Issues that emerged from thematic content analysis for market quality, production factors, farm performance and dairy cattle functions

Theme	Issues
market quality	functionality of milk and inputs markets
production factors	land use for non-dairy activities
	family labour use for non-dairy activities
farm performance	quality and quantity of inputs used
	milk output level
	economic performance
function of dairy cattle	importance of daily cash income for daily subsistence

to a processor in the flush season. The assessment of output prices showed significantly higher prices of milk in UL than in rural locations (MRL and ERL) (Table 2).

Inputs, such as AI, veterinary care, concentrates, fodder, hired labour and replacement stock, were available. Prices were perceived as high for high-quality inputs, specifically, high-quality concentrates and fodder in the dry season were expensive. The assessment of input prices revealed significantly higher prices of concentrate in UL than in rural locations (Table 2).

2.3.1.2 Production factors

Land and family labour were considered as scarce production factors, since farmers preferred to allocate them to crops and off-farm activities. Only one farmer allocated more land to fodder than crops. Some farmers constructed rental housing on their land to get income. Total land size (owned or rented) and cropland size per farm available within the location were smaller in UL than in rural locations (Table 2). Some UL farmers owned or rented land in rural areas

Table 2. Price of milk and inputs, land size and herd size for farms in the in-depth interviews

Parameters	**Urban location ($n = 10$)**	**Mid-rural location ($n = 11$)**	**Extreme rural location ($n = 9$)**	**RMSE**[1]
price				
milk (US$/100 kg)	45.1^{a}	34.0^{b}	31.7^{b}	4.62
AI[2] (US$/straw)	11.9 ($n = 8$)	11.0 ($n = 10$)	12.0 ($n = 7$)	1.75
concentrates (US$/100kg)	33.6^{a} ($n = 6$)	26.0^{b} ($n = 6$)	27.9^{b} ($n = 8$)	4.83
land within location (ha/farm)				
crops	0.4^{a}	1.7^{b}	1.7^{b}	1.03
fodder	0.4	1.4	1.2	1.47
non-farm	0.2	0.5	0.5	0.54
total	1.0^{a}	3.6^{b}	3.4^{b}	2.14
land outside loc. (ha/farm)[3]	5.3	–	–	7.67
herd size (TLU)[4]				
lactating cows	3.4	4.5	3.2	3.24
dry cows	0.3	0.9	0.2	0.93
heifers (1–2 years)	0.5	0.9	0.5	0.92
young stock (< 1 year)	0.3	0.4	0.4	0.32
total cattle	4.5	6.7	4.2	3.77

[a] Values with different superscript are significantly different at $P < 0.05$

[1] *RMSE* root-mean-square error;

[2] *AI* artificial insemination;

[3] Land outside the location was allocated to fodder (0.8 ha) in only one farm;

[4] 1 tropical livestock unit (TLU) is 250 kg (Castellanos-Navarrete et al. 2015), hence, 1 cow was 1.6 TLU, heifer was 0.8 TLU and young stock was 0.3 TLU

for crop production (on average 5.3 ha/farm) (Table 2). Family labour was available and was used for dairy activities but also for off-farm income-earning activities since six farms had at least one family member engaged in an off-farm job. Some farmers expressed that they hired labour for dairy activities while they had their family members working in an off-farm job. The herd size of cows and non-cows were considered as small, which was attributed to land and fodder scarcity. Herds were large (> 5 TLU, i.e. about three cows) in six farms. The herd sizes did not differ among locations (Table 2).

2.3.1.3 Farm performance

FGD participants mentioned that use of inputs, i.e. AI, high-quality concentrates and fodder, was high. In most farms, concentrates of high quality, veterinary care, fodder of low quality (crop residues and roadside grasses) and replacement stock from breeders were not used. Drug resistance and chronic cases of East Coast fever (ECF) were reported in some other farms, because of bad management. Moreover, use of expired drugs, unqualified veterinarians, conception failures and increased chances of bull calves due to late insemination were reported in some farms, which were attributed to poor delivery of services, such as veterinary care and AI. In some farms, however, high-quality inputs, such as hay, imported semen, replacement stock and hired labour, were used.

Use of replacement stock of high genetic potential was discouraged by scarcity, high price and inability to achieve anticipated yields. Labour (family, hired or both) used was considered as of low quality because turn-over rate for hired semi-skilled labourers was high. Concentrates (see Table 3) and fodder were used in small quantities.

Individual farmers and FGD participants perceived milk yield as low and attributed the relatively low milk production per cow to use of low-quality inputs in low quantities and to diseases, which they perceived to result in long lactation lengths and culling of cows when too old. Individual farmers and FGD participants perceived production costs as high because of high prices of inputs, such as feeds, water and hired labour, and high costs of breeding (repeated AI (see Table 3), flushing, hormone treatment) and veterinary care. Dairy benefits were perceived as low because of small herd sizes and low milk yield.

The farm assessment of performance, however, showed no differences among locations in input use, milk production and economic performance, except for milk yield per hectare, which was higher in UL than in rural locations (Table 3). Although average milk production was about 6.9 kg/cow/day, a production of

Table 3. Mean value for input use, milk production and economic performance of farms involved in the in-depth interviews

Performance	**Urban location (*n* = 10)**	**Mid-rural location (*n* = 11)**	**Extreme rural location (*n* = 9)**	***RMSE*[1]**
input use				
AI (straw/cow/conception)	1.9	1.0	2.0	1.19
concentrates (kg/cow/day)	1.7	1.2	1.4	1.11
milk production				
yield (kg/cow/day)	6.9	5.6	8.7	3.85
yield (kg/herd/day)	20.1	20.1	16.8	17.96
yield (kg/ha/day)[3]	68.6^a	5.6^b	8.7^b	65.84
economic performance				
production cost (US$/month)	102.8	74.4	39.0	69.61
dairy benefits (US$/month)	210.6	136.1	87.8	174.89
dairy gross margin (US$/month)	107.8	61.8	48.8	127.41

[a] Values with different superscript are significantly different at $P < 0.05$;

[1] *RMSE* root-mean-square error;

[2] *AI* artificial insemination;

[3] Total land per farm comprised of land for crops, fodder and non-farm land

30 kg/cow/day at peak lactation was reported by one farmer. Production costs, for example, ranged from US $ 24 to 225 per month, dairy benefits from US $ 0 to 682 per month and dairy gross margins from US $ − 92 to 457 per month.

2.3.1.4 Dairy cattle functions

FGD participants mentioned that both commercial and subsistence functions were valued, and dairy cattle generated daily cash income needed for daily household expenses. Only on some farms, the dairy income was used to purchase dairy inputs. Delivering milk to the formal market chain would give the farmer lower milk prices and would also mean that payment for milk would only be made weekly or monthly, which was not appreciated.

2.3.2 Mid-rural location

2.3.2.1 Market quality

Individual farmers and FGD participants perceived milk and input markets as functional throughout the year, though road conditions during the rainy season sometimes limited access to markets. Morning and evening milk were sold, about equally distributed among formal and informal market chains at about same price. Some farmers could not sell their evening milk in the flush season, because the processor did not collect evening milk. Individual farmers and FGD participants perceived prices as low for milk in the flush and lean seasons, in both formal and informal market chains (see also Table 2), milk price in MRL lower than in UL). AI with semen produced within the country, concentrates, hired labour, fodder and replacement stock were perceived as available at low and acceptable prices. Hired labour for crop activities was scarce during cropping seasons. The assessment of input prices showed significantly lower concentrate prices in MRL than in UL (Table 2).

2.3.2.2 Production factors

Land and family labour were considered as scarce production factors, since farmers preferred to allocate more land to crops than to fodder. Seven farmers had grazing land but only two allocated more land to fodder than to crop farming. Some farmers rented land for crop production within MRL. Land size was larger in MRL than in UL (Table 2). Family labour was available but inadequate for dairy activities for some farmers. Family labour, besides, was spent more on crop than dairy activities, especially during cropping seasons, and cows that were not stall-fed or grazed on paddocks were tethered. Two farmers provided off-farm labour. The herd sizes were considered as small, which was attributed to scarcity of land for fodder. Herds were large in five farms.

2.3.2.3 Farm performance

FGD participants mentioned that use of concentrates and AI was high. Most farmers used small quantities of low-quality concentrates, inseminated cows with semen of local bulls and grazed cows. Moreover, replacement rates were low and replacement heifers were of zebu-exotic crossbreds. Veterinary care was infrequent, and the quality of drugs and treatment services were low. Additionally, inadequate labour (of low quality because of lack of knowledge and old age), were reported by most farmers. Farmers attributed low levels of input use to scarcity, high price and insecurity and political unrest.

Individual farmers and FGD participants perceived milk yield per cow as low, which was blamed on use of inputs of low-quality and in low quantities. FGD participants perceived production costs as high because of high prices of concentrates and high costs of breeding (of repeated AI, three farmers used bulls to reduce AI costs). Dairy benefits were considered as low because of small herd sizes, low yields, low quantities of milk sold and low prices of milk. Dairy gross margins were perceived as low because of high production costs and low dairy benefits.

The assessment of farm performance, however, showed no differences among locations with regard to input use, milk production and economic performance, except for milk yield per hectare, which was lower in MRL than in UL (Table 3).

Production costs ranged from US $ 10 to 306 per month, dairy benefits from US $ 0 to 511 per month and dairy gross margins from US $ − 22 to 216 per month.

2.3.2.4 Dairy cattle functions

FGD participants mentioned that the use of daily or weekly earning of a small amount of cash to supplement income from crops for household expenses was an important function of dairy cattle. In three farms, the dairy income was invested fully in dairy inputs. Additionally, delivering milk to the formal market chain not only gave low milk prices but also meant that payment for milk occurred monthly (instead of daily or weekly in the informal market chain), which was not appreciated. Generally, the formal market chain for milk was perceived as a more reliable chain than the informal one. Manure and cash income were used to support crop cultivation.

2.3.3 Extreme-rural Location

2.3.3.1 Market quality

FGD participants perceived milk and input markets as functional throughout the year, though some farms did not sell their evening milk because the processor did not collect milk in the evening and because they preferred to consume the milk or to use it to rear calves. Market chains were mainly formal, and FGD participants perceived the milk price as low, specifically during the flush season. Most farmers purchased AI, concentrates and veterinary care, but fodder, replacement stock and labour were purchased only on some farms (e.g. four of the sampled farms) for two reasons. First, because own inputs were used and second, because fodder was scarce (e.g. hay for sale was scarce and Napier did not perform when temperatures were low), and experienced theft of replacement stock. FGD participants mentioned that prices of inputs were low for inputs of low quality. Access to markets was poor during rainy seasons because of bad roads and poor means of transport. The price assessment showed lower prices of milk and concentrates in ERL than in UL (Table 2).

2.3.3.2 Production factors

FGD participants mentioned that land and labour were scarce in ERL since they were allocated to cropping, but some farms allocated land to fodder production and some grazing occurred on communal lands. Only one farm allocated more land to fodder than crops. Non-farmer FGD participants, however, indicated that in some parts of the ERL (about 50%), land was available. Land size was larger in ERL than in UL (Table 2). Family labour was available for dairy activities, despite youth migrating to urban areas, use of labour for crop production and for employment as motorbike taxi driver. Only a few farms hired labour for dairy activities. The herds were considered as small, which was attributed to scarcity of grazing land. Herds were large only in two farms.

2.3.3.3 Farm performance

FGD participants mentioned that use of inputs was low, partly because of low availability and high prices. In most farms, low-quality concentrates (e.g. high bran content), veterinary care, grazing, unproven bulls and crossbred replacement heifers were used. The quantities of concentrates given were small and fodder was inadequate. The frequency of administration of anthelmintic drugs and spraying with acaricides were low. In most farms, cases of drug resistance, chronic conditions of ECF and death of animals were reported.

Individual farmers and FGD participants perceived milk yield as low and attributed the low milk production to use of inputs of low qualities and in small quantities, which contributed to diseases, prolonged lactations and culling of too old cows. FGD participants perceived production costs as high because of high prices of concentrates, and high cost of breeding (repeated AI), and of prevention and treatment of diseases. Dairy benefits were perceived as low because of small herd sizes, low yields, low quantities of milk sold and low prices of milk. Dairy gross margins were perceived as low because of high production costs and low dairy benefits. Production costs ranged from US $ 7 to 113 per month, dairy benefits from US $ 31 to 225 per month and dairy gross margins from US $ − 1 to 112 per month.

The assessment of farm performance showed no differences among locations with regard to input use, milk production and economic performance, but milk yield per hectare was lower in ERL than in UL (Table 3).

2.3.3.4 Dairy cattle functions

Individual farmers and FGD participants mentioned that the earning of a small amount of cash used to supplement crop income for household expenses was an important function of dairy cattle. Crop income was received after 4 months for potatoes and after 1 year for maize, while milk income from processors was received monthly. The dairy income was invested fully in dairy inputs on two farms only. Manure and cash income were used to support crop cultivation.

2.4 Discussion

In Kenya, milk is produced predominantly by smallholder dairy farmers in the highlands, with a favourable climate for exotic breeds (van Leeuwen et al., 2012). Milk, however, is sold to consumers mainly in major urban areas and in areas where sufficient milk production does not occur (GoK, 2010). Formal market chains are expanding because they provide an improved delivery of services and inputs at relatively low prices and are platforms for empowering farmers (Kilelu et al., 2013). Although, formal market chains are preferred in the national dairy master plan, the bulk (80%) of milk produced is sold through informal market chains. In this study, farmers were predominantly engaged in informal market chains, although we observed differences between locations. The informal market chains for milk were more important in UL than in rural locations because they offered high prices because of low transaction costs (explained in the introduction), i.e. low costs of transport and processing, mostly paid by buyers.

We determined the influence of distance to urban markets of smallholder dairy farming system development. Our theoretical framework was that distance to urban markets influences market quality and the availability of production factors, and which, therefore, influences levels of inputs and outputs. The low input-low output systems with quantities of inputs used and milk yields per cow being low in all locations, either close or far from urban markets was contrary. Signs of intensification, such as use of inputs of high-quality and high milk yield per hectare in response to land scarcity, however, were expected in UL.

Results for milk market were in line with our theoretical framework. Purchase of concentrates of higher quality at a higher price than those in rural locations may explain the price differences. Lack of differences in market quality between the rural locations is because shops that supplied inputs were present in local trading centres. In UL, however, market quality for inputs was negatively affected by lack of fodder, replacement stock and hired labour, also, reported in other studies (Duguma et al., 2017; Gillah et al., 2012). Variation in quality of inputs is a common observation in Kenya (Njoroge et al., 2015).

The observation of differences in production factors between UL and rural locations is in line with our framework and indicates that land and labour have high opportunity costs because of alternative uses (Jayne et al., 2014; Jiang et al., 2013). Lack of difference in production factors between rural locations, probably, is because the differences in distance between both rural locations to the urban market were not large enough to create variations in land holding and opportunity cost of labour.

Based on our observations that market quality and production factors differed among locations, we expected farming system development to differ between UL and rural locations such that UL farms become intensive high input-high output systems and farms in rural locations remain extensive. Results do not match our expectations. Low input use in UL is contrary to our expectations and to results from some studies in (peri)-urban areas in East African conditions (e.g. in Tanzania, Ethiopia, Kenya and Uganda) (Duncan et al., 2013; Gillah et al., 2012) but within range reported for peri-urban of Nakuru (Kashongwe et al., 2017a). A higher milk yield per hectare in UL than in rural locations reflects land scarcity and is in line with our framework (Jayne et al., 2014). Lack of differences in milk yield per cow among locations is contrary to our framework but agrees with results from Ethiopia and India (Duncan et al., 2013). Low yield in UL was unexpected and a milk yield of on average 6.9 kg/cow/day in UL (Table 3), is at the bottom end of the range of 6 to 20 kg/cow/day for dairy cattle in East African peri-urban smallholder farms (Gillah et al., 2012). Milk yield, however, varied widely (range 0 to 14.5 kg/cow/day) among farms. Dairy development policies often have the objective to develop relatively specialised, market-oriented high input-high output smallholder dairy farming systems. The UL farming systems in the present study are specialised and market oriented, but they have not become the high input-high output farming systems which we expected to develop (Oosting et al., 2014; Weiler et al., 2014). Possible reasons for this are several:

First is inadequate use of inputs, such as fodder, replacement stock and labour, because of scarcity in line with literature (Kashongwe et al., 2017b; Richards et al., 2016). On-farm production of inputs was limited by land and labour scarcity and trade of inputs was limited by high transaction costs (Gollin and Rogerson, 2014). Other reasons for inadequate input availability may be related to low production for commercial purposes, seasonal availability and challenges related to conservation and storage of fodder. Fodder limitation was not mitigated by use of concentrates because in UL, as generally in Kenya, concentrates are used in minimal quantities because of perceived high prices and variability in nutritional content (Njagi et al., 2013). Crop residues and non-conventional feeds, usually used to supplement or substitute concentrates and fodder during feed scarcity, might be of low quality (Castellanos-Navarrete et al., 2015; Duguma et al., 2017). Poor husbandry and management might have occurred because of labour scarcity and inadequate capacity. Replacement stock used might have been of low genetic potential because smallholder farmers do not participate in genetic improvement programmes or due to unmet nutritional and management demand of high genetic potential (Ojango et al., 2016). High yields were observed for some individual cows but differences in daily yield among cows within farms, however, was not known because we calculated daily cow yield as herd yield divided by the total number of cows including dry cows with zero.

Second is diseases and reproductive problems, which prolong lactation lengths and calving intervals. Long calving intervals, further, contributed to few replacement stock and are associated with low replacement rates and culling at too old age (Baur et al., 2017). Farmers and stakeholders indeed reported a low milk yield due to long lactation lengths and milking of too old cows because of conception failures and associated low replacement rates. Veterinary care might have been inadequate for exotic cattle. Nevertheless, veterinary care is well adopted in Kenya (Kebebe et al., 2017).

Third is lack of opportunities to sell additional milk through informal market chains at high prices. Farms development to high input-high output systems, for example, moving from the current 20 to 40 kg/farm/day, would lead to saturation of informal market chains and force farmers to formal market chains (Duguma et al., 2017; Oosting et al., 2014).

Fourth is that the development of dairy into high output systems is at the expense of other cattle functions. In UL, cash income from daily sales of milk was valued for livelihood support. When faced with trade-offs, farmers are likely to prioritise livelihood over dairy investment. Current cash benefits are low and may be inadequate to satisfy both household needs and dairy investment. Additional or external sources of financing may be necessary to support family livelihood in order to save resources for purchase of inputs. Multi-functionality of dairy cattle is in line with literature (Weiler et al., 2014).

Other reasons reported by farmers and other studies might include old age of farmers which impairs physical and cognitive ability to adopt dairy improvement technologies; little knowledge which hinders use of correct inputs and husbandry management for improved breeds; and insecurity, such as theft and loss of property during political unrest, which interfere with management and use of replacement stock (Gillah et al., 2012).

Hence, in UL, high output is limited by scarcity of inputs, reproductive problems and saturation of informal market chains for milk and subsistence function of dairy cattle. Such multiple reasons imply that development into high output systems require a package of interventions including efficient input supply chains, formal market chains for milk with favourable prices and external financial sources (Oosting et al., 2014). Opportunities to improve fodder production and marketing, include established fodder markets and formal market chains for milk as well as regulated standards for nutritional content of inputs in UL.

In rural locations, the observed level of milk yield was within expectations (Kashongwe et al., 2017a). The relatively low yield could possibly be attributed to use of zebu-crossbred cows of relatively low to medium genetic potential for milk. Grazing on communal land and crop fields after harvesting, besides, is providing only low-quality feeds (Kashongwe et al., 2017b). In rural locations, in addition, the low price of milk did not make it attractive for farmers to invest in dairy. Moreover, formal market chains were unable to collect evening milk, and dairy cattle was valued to support crop cultivation. Multifunctional benefits from dairy, such as manure and daily cash income, are important for farmers (Weiler et al., 2014). Specialization, which often is a consequence of higher input use and higher production may cause a reduction of such multifunctional values and farmers may perceive this as negative (Oosting et al., 2014). Market quality for milk and inputs should be enhanced, either by establishing or strengthening producer organisations, to reduce transaction costs, secure milk delivery possibilities and increase empowerment of farmers (Kilelu et al., 2013).

2.5 Conclusion

We related increased demand for milk in urban areas to smallholder dairy development at different distances from the urban market and found that, despite differences of milk prices and farm characteristics among locations, farms remained low input-low output and production for subsistence was valued in all locations. Farm development was constrained by scarcity of inputs and production factors in UL and low price of milk in rural locations. Dairy development interventions targeting high input-high output should address the key constraints.

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Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

Chapter 3

A positive deviant approach to understanding key factors to successful smallholder dairy farming in Kenya

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A positive deviant farm and non-positive deviant farm in urban location

A positive deviant farm and non-positive deviant farm in rural location

To be submitted

Abstract

Dairy farming in Kenya is hampered by many constraints, and farmers who successfully overcome such constraints are the so-called positive deviants (PDs). The objective of the present study was to identify strategies that PD farmers deploy to overcome dairy production constraints. A total of 60 farmers in urban and rural locations in Nakuru county (our case area in the Kenyan highlands) were classified as PDs and non-PDs, based on either experts' and/or peers' perception or on economic performance, i.e. on the gross margin of dairy activities. All these farmers were also interviewed to determine farm and household characteristics. In urban location, most of the perceived PDs were classified as economic PDs. The main factors distinguishing such PDs from non-PDs were relatively large herd size, high milk yield per cow and good cost control (achieving such input costs that maximize the gross margin of dairy activities). For good cost control, PDs required good dairy husbandry regarding feeding, breeding and veterinary care, which was facilitated by input use, i.e. level, quality and cost control, milk marketing with a high price of milk, knowledge, and skills, and having financial stability. In rural location, most of the perceived PDs were economic non-PDs (nine out of 13 perceived PDs). The PDs in rural location had large herds since maintaining a large herd contributes to non-economic functions (particularly store of wealth and insurance) and to economic functions (farm milk output) of the dairy activity of the farm. The productivity of cows in these herds was relatively low, and input use in rural farms has the risk of too high costs since many of the perceived PDs were economic non-PDs because of this reason. The results imply that interventions for urban locations should be tailored for commercial production, with high input use and high output, and high productivity per cow. Interventions for rural locations should be tailored for multiple functions, with low input use and low output and large herd sizes, in the absence of reliable markets.

Keywords: perceived deviance, economic deviance, production strategy, constraint analysis, Kenyan highland

3.1 Introduction

Dairy farming is an important agricultural activity in Kenya. The sector accounts for 6 to 8% of the national gross domestic product (Odero-Waitituh, 2017). Smallholder farmers own the majority of the cattle, and produce about 80% of all milk (Odero-Waitituh, 2017). The country is experiencing a growing demand for milk due to population growth, urbanization and rising incomes (Bosire et al., 2016). This growing demand provides opportunities for smallholder dairy farmers to benefit through increased milk production for the domestic markets.

At present, however, the average technical and economic performance of smallholder dairy farmers is below the potential (Moran and Chamberlain, 2017). In a previous study, we observed that despite this generally low farm performance, there was a high variability in performance among individual farms (Migose et al., 2018). In part, this variation among farms can be explained by location. Availability of production factors and quality of supply and output markets differ among rural and (peri)-urban locations (Migose et al., 2018). In (peri)-urban locations, for example, land, high quality fodder and replacement stock were scarce, whereas in rural locations high quality labour was scarce (Migose et al., 2018). In both (peri)-urban and rural locations, however, some farmers, referred to as positive deviants (PDs), more successfully developed their farms into productive and profitable businesses than others. This high production and profitability was achieved at such farms because bio-physical and socio-economic constraints, such as scarcity of fodder, replacement stock and labour, and importance of dairy cash for daily subsistence, were overcome (Migose et al., 2018). Studying the strategies of such PDs will yield insight and provide avenues for successful interventions.

We, therefore, use a PD approach to explore why some farmers use innovative strategies to overcome constraints and achieve better performance than others (Amankwah, 2013; Birhanu et al., 2017; Herington and van de Fliert, 2018; Lentes et al., 2010; Sternin, 2017). Such better performance can either be a better economic or technical performance, which is assessed through measurements (Amankwah, 2013; Mertens et al., 2016), whereas it can also be judged subjectively by experts or peers (Mertens et al., 2016). Based on knowledge of such strategies, interventions can be designed that lead to successful smallholder dairy farming.

Studies that use the PD approach to understand pathways of success in smallholder dairy farming in the Kenyan context are rare, to our knowledge. The objective of the present study was to identify strategies that PD farmers deploy to overcome dairy production constraints.

3.2 Materials and methods

3.2.1 Study area

The study was conducted in Nakuru county in the highlands of Kenya. This county has an agro-ecological environment favourable for dairy farming with a high density of smallholder dairy farmers. Nakuru town is the county's capital, which is a major urban market for dairy products. Within the county, three locations were chosen that differed in distance to urban market of Nakuru town: urban location (UL), mid rural location (RL), and extreme RL. The study locations have been described in detail in Migose et al. (2018).

3.2.2 Selection of farmers

We distinguished PDs and non-PD farmers in two ways. The first way was based on experts' and/or peers' perception (Mertens et al., 2016). In each of the locations, we asked a government dairy extension officer or a peer, i.e. a fellow farmer, to recommend one smallholder dairy farmer, whom they perceived as successful (i.e. PD) and one whom they perceived as non-successful (i.e. non-PD, control). In the second step, the PDs and non-PDs, recommended by extension officers, were asked to recommend their peers through a chain referral "snowballing" technique (Biernacki and Waldorf, 1981). We asked the farmers for their reasons to perceive a peer as a PD or non-PD. A total of 60 farmers were sampled (Table 1).

The second way was to distinguish PD and non-PD farmers based on economic performance (Amankwah, 2013; Herington and van de Fliert, 2018; Mertens et al., 2016). The gross margin of dairy activities was estimated for each of the farms of the selected perceived PDs and perceived non-PDs. The gross margin was calculated as the difference between milk revenues, which is the milk yield per farm per month multiplied by the unit price of milk, and the production costs, which is the monthly costs of feeds, breeding, labour and veterinary care. We distinguished farmers into economic PDs and non-PDs using a fixed threshold: economic PDs, gross margin (US Dollar ($)/farm/month) ≥ 300; and economic non-PDs, gross margin < 300 US $/farm/month.

A gross margin higher than 300 US $/farm/month was considered a reasonable income from a farming activity at the time of the study since it is equivalent to the minimum wage of, for example, drivers or cashiers (Wageindicators.org, 2015).

Table 1 . Number (n) of perceived positive deviants (PDs) and non-PDs sampled by extension officers and peers in urban, mid-rural and extreme-rural locations

Class	Urban location		Mid rural location		Extreme rural location	
	extension officers	peers	extension officers	peers	extension officers	peers
perceived PDs	2	5	2	5	2	4
perceived non-PDs	4	8	5	10	5	8

3.2.3 Data collection

Farms were visited and in-depth interviews (IDIs) were conducted with farmers. Semi-structured guides were used to collect quantitative farm data and qualitative data to explore PD and non-PD behaviour in farm practices (Creswell and Creswell, 2018). Questions were asked about farm performance characteristics, i.e. markets, availability of production factors, performance levels, output, and economic indicators, as well as routine farm practices, i.e. feeding, breeding, veterinary care, labour, and milk marketing (Table 2). Audios and field notes were used to record interviews. Data were collected between April 2013 and September 2014 under the permit from the National Commission for Science, Technology, and Innovation.

3.2.4 Data analysis

Table 2 shows themes and factors within themes used for analysing differences among the various classes of deviants. A factor is a specific element of a theme and a combination of themes constitutes a strategy.

For quantitative analyses, numerical variables were converted to standard units: 88 Kenya shillings was 1 US Dollar ($), 2.5 acres was 1 hectare (ha), 1 head of cattle of 250 kg was 1 tropical livestock unit (TLU) (Castellanos-Navarrete et al., 2015). The herds comprised cows (after first parturition, lactating and dry, with an average bodyweight of 400 kg) and young stock (heifers within 1 and 2 years of age with an average bodyweight of 200 kg, and calves of 0 to 12 months, with an average bodyweight of 100 kg).

Quantile-quantile (QQ) plots were used to test for normal distribution of continuous variables. A one-way ANOVA was used to test differences between economic PDs and non-PDs. Statistical analyses were done in SAS software, v9.3© (SAS Institute Inc., Cary, NC, USA).

Qualitative data were analyzed using thematic content analysis (Boréus and Bergström, 2017). The first author read the transcripts, generated from audio

Table 2. Themes and factors within themes used to analyse differences among positive and non-positive deviants

Theme	Factor	Reference
scale	herd size (n milking cows)	(Cortez-Arriola et al., 2015)
	land on fodder	(Cortez-Arriola et al., 2015)
intensity	production (milk/cow)	(Hammond et al., 2017)
input use	quantity	(Baur et al., 2017; Maleko et al., 2018)
	quality	(Buza et al., 2014; Chagunda et al., 2016)
	cost control[1]	(Shadbolt, 2012)
dairy husbandry	breeding	(Saraswat and Purohit, 2016)
	feeding	(Birhanu et al., 2017; Richards et al., 2016)
	health	(Karanja-Lumumba et al., 2015)
resource endowment	land	(Amankwah, 2013; Cortez-Arriola et al., 2015; Ellis, 2000)
	physical capital (livestock, equipment, and assets)	(Amankwah, 2013; Cortez-Arriola et al., 2015; Ellis, 2000)
	financial resources (financial stability, savings, other income)	(Cortez-Arriola et al., 2015)
knowledge and skills	education level	(Baur et al., 2017; Birhanu et al., 2017)
	access to training and extension services	(Birhanu et al., 2017; Chagunda et al., 2016)
	experience	(Mazvimavi and Twomlow, 2009)
household characteristics	age of the farmer	(Baur et al., 2017)
	family size	(Baur et al., 2017)
milk marketing	price of milk	(Baur et al., 2017)

[1] Achieving such input costs that maximize the gross margin of the dairy activities

records and field notes, and identified and labelled narratives and phrases associated with factors listed in Table 2. Labelled factors were clustered and were analysed for differences among PDs and non-PDs.

3.3 Results

Results did not differ much between mid RL and extreme RL and, therefore, we presented them as one location, i.e. RL. In UL, most of the perceived PDs were classified as economic PDs, whereas in RL, nine out of 13 of the perceived PDs were classified as economic non-PDs (Table 3).

3.3.1 Perceived positive deviance in dairy farming

In UL, factors that were most often mentioned by peers for perceiving a farmer as being a PD were large volumes of milk sold per day, large land sizes used for fodder production, financial stability, cost control and good prices of milk (Table 4). In RL, factors that were most often mentioned by peers for perceiving a farmer

Table 3. Number (n) of economic positive deviants (PD) and non-PDs for perceived PDs and non-PDs in urban and rural locations

Class (n)	Urban location (UL)		Rural location (RL)	
	perceived PDs	perceived non-PDs	perceived PDs	perceived non-PDs
economic PDs	5	0	4	0
economic non-PDs	2	12	9	28

Table 4. Frequency (n) of factors mentioned by peers for perceiving a farmer as being a positive deviant in urban and rural locations

Theme	Factor	Urban location (n=9)	Rural location (n=24)
scale	large herd size of milking cows	2	5
	large volume of milk sold per day	5	0
	large land size for fodder production and grazing	4	3
	selling of fodder	0	1
	bulk purchase fodder	3	0
intensity	high productivity (milk production per cow)	2	4
input use	high yielding breeds (Friesian)	2	4
	artificial insemination	0	21
	supplementing concentrate, minerals	3	13
	zero grazing	2	7
	high labour use	1	0
	cost control[1]	4	4
dairy husbandry	good overall management	1	10
	good breeding	0	2
	good feeding	2	3
	good health care	0	2
resource endowment	financial stability	5	7
	non-dairy income	2	1
knowledge and skills	education level	3	0
	training	0	2
	access to extension services	0	2
milk marketing	price of milk (good markets)	4	3
	own a milk bar	3	1

[1] Achieving such input costs that maximize the gross margin of the dairy activities

as being a PD were the use of artificial insemination (AI), concentrate and mineral supplement, good overall management, zero grazing, and financial stability (i.e. having sufficient capital to cover sudden and expected financial needs). Household characteristics were not mentioned as a factor for perceiving someone as a PD in both locations.

3.3.2 Economic deviance in dairy farming

Land size did not differ between economic PDs and non-PDs in both locations (Table 5). The number of milking cows was higher for economic PDs than for economic non-PDs in both locations. In UL, concentrate use per cow per year and milk yield per cow per day, was higher for economic PDs than for economic non-PDs, whereas in RL concentrate use, and milk yield per cow did not differ between economic PDs and non-PDs.

The prices of inputs and milk did not differ between economic PDs and non-PDs in both locations. Average prices of inputs and milk are presented in supplementary material (Table 6).

Table 5. Mean values of physical farm performance measures for economic positive deviants (PD) and non-PDs in urban and rural locations

Variable	**Urban location**			**Rural location**		
	economic PDs	economic non-PDs	P-value	economic PDs	economic non-PDs	P-value
sample (n)	5	14		4	37	
land size (ha)	1.7	0.8	0.19	3.9	3.5	0.89
herd composition						
milking cow (n)	3.8	1.9	0.00	5.8	2.2	0.00
dry cow (n)	0.2	0.8	0.33	0.3	0.6	0.52
young stock (TLU)[1]	1.0	0.8	0.58	2.5	1.2	0.03
total herd size (TLU)	7.4	4.9	0.03	12.1	5.6	0.01
farm technical performance						
concentrates (kg/cow/day)	4.3	2.1	0.01	0.9	1.3	0.49
milk yield (kg/cow/d)	14.2	7.0	0.00	9.1	7.1	0.33

[1] 1 tropical livestock unit (TLU) is 250 kg; hence, 1 cow was 1.6 TLU, and young stock was 0.6 TLU

Table 6. Mean prices of inputs and milk for economic positive deviance (PD) and non-PD classes in urban and rural locations

Variable	**Urban location**			**Rural location**		
	economic PD	economic non-PD	P-value	economic PD	economic non-PD	P-value
sample (n)	5	14		4	37	
input						
concentrates (US$ /100 kg)	31.8	32.8	0.52	31.9	26.3	0.12
artificial insemination (US$ /straw)	24.8	14.0	0.05	9.8	15.8	0.29
labour (US$/man-day)	2.3	1.7	0.10	1.4	1.3	0.92
milk (US$ /100 kg)	47.7	47.4	0.91	34.4	35.0	0.82

Table 7. Economic variables that describe farm performance for economic positive deviants (PD) and non-PDs in urban and rural locations.

Variable	Urban location			Rural location		
	economic PDs	economic non-PDs	P-value	economic PDs	economic non-PDs	P-value
sample (n)	5	14		4	37	
total cost (US$/month)	313.6	177.8	0.07	171.0	88.6	0.07
wet season feed	165.9	90.7	0.04	101.4	46.7	0.06
dry season feed	208.0	123.1	0.14	128.3	62.6	0.10
concentrates	168.2	56.7	0.00	59.4	34.1	0.24
hired labour	59.1	23.4	0.01	58.2	20.3	0.03
veterinary care	37.0	12.8	0.00	17.2	10.7	0.30
artificial insemination	7.7	5.6	0.46	8.5	4.0	0.10
revenue (US$/month)	725.0	233.8	0.00	540.9	136.5	0.00
gross margin (US$/month)	411.4	56.0	0.00	369.8	47.7	0.00
gross margin (US$/100 kg milk)	24.7	11.9	0.05	23.8	5.0	0.05
cost (US$/100 kg milk)	17.9	28.3	0.19	10.0	19.7	0.18

Costs of inputs, such as concentrate, hired labour, and veterinary care, were higher for economic PDs than for non-PDs, whereas the cost of AI did not differ between economic PDs and non-PDs in UL (Table 7). Costs of feeds, veterinarycare and AI did not differ between economic PDs and non-PDs whereas the cost of labour was higher for economic PDs than for non-PDs in RL. Costs per kg of milk did not differ between economic PD and non-PDs in both locations. Revenue and gross margin were higher for economic PDs than for non-PDs classes in both locations. Gross margin per kg of milk did not differ between economic PDs and non-PDs in UL, but it was higher for economic PDs than for non-PDs in RL.

3.3.3 Perceived and economic positive deviance

In UL, perceived PDs who were also economic PDs had good dairy husbandry. Among others, good feeding practices regarding fodder quality and quantity were important. The PDs produced or purchased adequate fodder, e.g. Napier grass (*Pennisetum purpureum*), hay of Rhodes grass (*Chloris gayana*) and maize silage or they harvested Kikuyu grass (*Pennisetum clandestinum)* from communal fields, and they supplemented with minerals. Moreover, PDs kept Holstein Friesian or Ayrshire genotypes, controlled parasites, treated sick cows, and vaccinated cows against diseases, such as Food and Mouth Disease and East Coast Fever. In UL, three PDs had sophisticated milk marketing, e.g. they sold milk in their own milk bar, and one of them used multiple channels (including hotel supply and processor cooperatives). In UL, many of the PDs had non-dairy income and wealth, among others, permanent houses, houses for rental income, personal cars, and poultry farms. Three PDs had land and produced fodder on-farm. In addition, the PDs had more than 7 years of experience while four PDs had advanced education.

In RL, perceived PDs with economic PD also had good dairy husbandry regarding feeding, breeding, and veterinary care. Three PDs used paddocks of kikuyu grass for grazing and supplemented grazing with Napier grass, concentrate and minerals. The PDs in RL kept Holstein Friesian or Ayrshire genotypes, used AI (except 1), controlled parasites, treated sick cows, while one PD vaccinated cows against East Coast Fever. In RL, the PDs had non-dairy income and wealth, among others, permanent houses, houses for rental income, personal cars, business enterprises, land, and sheep. In addition, the PDs had more than 7 years of experience. There was one perceived PD with economic deviance in RL who did not use concentrate and AI.

In UL, one perceived PD was an economic non-PD because he had sold part of his herd to meet financial needs and another perceived PD was an economic non-PD because he had high cost of inputs, among others because he had limited land and purchased expensive feeds and hired expensive land for fodder production.

In RL, three perceived PDs were economic non-PD because they had a low milk yield per cow, either because they had many dry cows per farm or because input use or livestock management were sub-optimal. Two of the perceived PDs in RL were economic non-PD because they had a relatively small herd size; one had sold part of his milking herd to meet financial needs and the other one was having a milk bar for sale of milk, which was probably the major reason he was perceived as a PD. In addition, three of the perceived PDs in RL were economic non-PD because of the high cost of inputs per cow, among others because of repeated inseminations and expensive inputs such as sexed semen, concentrate and hire of labour. In RL, one perceived PD was an economic non-PD because he had a small productive herd and a large herd of non-productive heifers (for which reason he was perceived as a PD).

3.4 Discussion

In this study, we compared farmers perceived by peers as PDs and as non-PDs. The comparison of the economic performance of both groups showed that in UL, most of the perceived PDs were also economic PDs. Perceived non-PDs were all economic non-PDs. This indicates that in UL, factors contributing to being perceived as a PD were often also contributing to good economic performance. In UL, farmers were perceived as being PDs for having high farm milk production, and being better than their peers regarding milk marketing, and input use i.e. level, quality and cost control. The economic analyses showed that PDs in UL achieved high productivity. Hence, the strategy of PDs in UL consisted of a combination of the themes scale, intensity, input use, and milk marketing. Underlying factors that facilitated PDs in UL to follow such a strategy were their financial stability and their level of skills and knowledge. Conditions in UL, i.e. land and labour scarcity, and relatively high milk prices and good opportunities for milk marketing, make high-input high-output strategies with high productivity, per cow and per hectare of land, a rational strategy (Herrero et al., 2014; Migose et al., 2018; Oosting et al., 2014) and the present study corroborates this.

In RL, many farmers were perceived as PDs while not being economic PDs. This implies that non-economic functions of dairy activities at a farm are important in these RL communities (Hänke and Barkmann, 2017; Moll et al., 2007; Weiler et al., 2014). Having a large herd size, using AI and feed supplements, such as concentrate and minerals, and having financial stability were important factors that made farmers to be perceived as PDs in RL.

The economic analysis showed that economic PDs in RL had a larger herd size than economic non-PDs. Hence, being perceived as a successful dairy farmer is associated with wealth and financial stability, which is determined by having assets, e.g. permanent houses, houses for rental income, business premises personal cars, as well as sheep (Ellis, 2000; Udo et al., 2011). Large herd size is a sign of wealth, but it also enables households to cope with sudden financial needs (Hänke and Barkmann, 2017; Moll et al., 2007). This so-called insurance function of livestock (Hänke and Barkmann, 2017; Moll et al., 2007) was one reason why some of the perceived PDs in RL were economic non-PDs, since they had to sell part of their herd to cover sudden expenses. Having large herds could also have the aim to sell live animals for commercial purposes (Moll et al., 2007; Vaarst et al., 2019). This function of large herds was not assessed in the present study. Use of AI and supplementation feeding was done by perceived PDs in RL, but this did not result in good economic performance. This can partly be explained by the fact that some of the perceived PDs in RL did not have appropriate cost control: they spent too much on inputs for breeding and feeding. In RL, milk prices are relatively low, whereas input prices are relatively high and markets for inputs and outputs are not always reliable (Migose et al., 2018). This high ratio between input and output prices and the unreliable markets and the fact that land and labour are relatively cheap in RL trigger low-input low-output strategies for economic farming (Andersen et al., 2007). Hence, farmers that follow a high input strategy to achieve high productivity may not have the highest gross margin. In contrast, large scale and relatively low productivity seems to be the most rational economic strategy. The additional benefit of this strategy is that in an unreliable market situation (high input prices, and low milk prices), farmers can choose for subsistence strategies (in which livestock has a role of wealth store, insurance asset, status function, manure supply, and a small income for daily expenses), whereas in a reliable market situation they might choose for more market-oriented strategies (maximization of the gross margin for milk production). A large herd size appears central to both these objectives of a rural farm (Hänke and Barkmann, 2017; Migose et al., 2018).

The UL PD strategy of intensity and the RL PD strategy of scale can only be successful if costs are aligned with revenues (Shadbolt, 2012). For good cost control, good dairy husbandry is required. So, the results of the present study imply that first, providing training and extension services to farmers improves their ability to provide good feeding, breeding, and veterinary care, as well as to acquire entrepreneurial skills to market milk and to control costs (Bebe et al., 2016). Second, the development of reliable markets for inputs and milk with good prices is important as an intervention for dairy and smallholder development (Chagwiza et al., 2016; Kilelu et al., 2017). Third, poor households should be facilitated with credits for investments or for the purchase of inputs, because the present study has shown, as many other studies, that resource endowed households do better in dairy farming than poor households (Ellis, 2000; Udo et al., 2011). Cooperatives and dairy hubs are suggested as avenues for improved provision of inputs and services, such as credit facilities, milk marking, and training and extension services (Chagwiza et al., 2016; Kilelu et al., 2017).

3.5 Conclusion

This study indicates that scale, intensity and input use are important themes contributing to successful smallholder dairy farming. Strategies differ between UL and RL. In UL, economic objectives of strategies are predominant. In UL, therefore, productivity, which is the major factor describing intensity in the present study, is one of the most important elements of the strategy because it has a strong economic driver. In RL, non-economic objectives are important besides economic objectives. Hence, in RL large herd size, which is the major factor describing scale in the present study, is one of the most important elements of the strategy. Interventions should be tailor made. In urban locations, with labour and land scarcity, focusing on high-input high-output strategies with high productivity, per cow and per hectare, appears rational, whereas in rural locations, maintaining a large herd size is needed as long as reliable markets are absent.

Declarations of interest

None.

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Chapter 4

Accuracy of estimates of milk production per lactation from limited test-day and recall data collected at smallholder dairy farms

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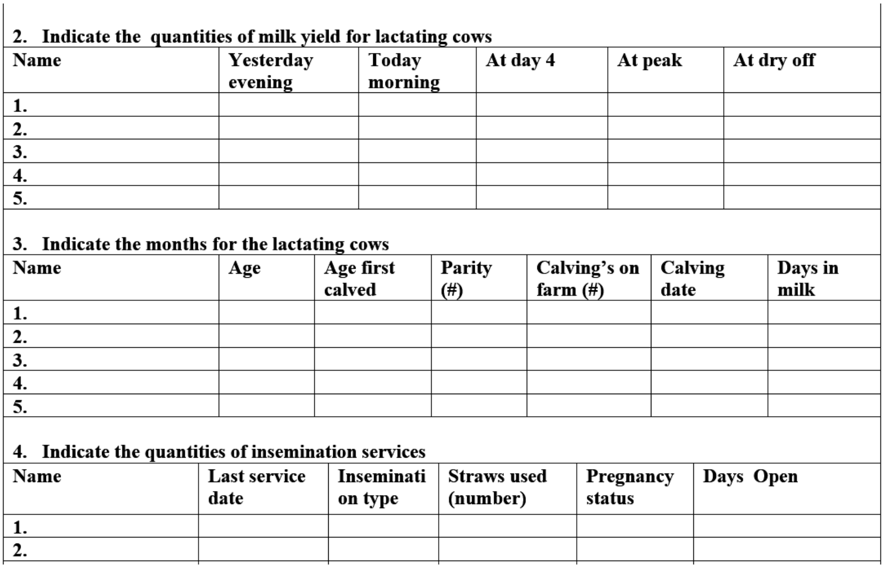

2. Indicate the quantities of milk yield for lactating cows

Name	Yesterday evening	Today morning	At day 4	At peak	At dry off
1.					
2.					
3.					
4.					
5.					

3. Indicate the months for the lactating cows

Name	Age	Age first calved	Parity (#)	Calving's on farm (#)	Calving date	Days in milk
1.						
2.						
3.						
4.						
5.						

4. Indicate the quantities of insemination services

Name	Last service date	Insemination type	Straws used (number)	Pregnancy status	Days Open
1.					
2.					

A section of the questionnaire used to collect recall data

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Abstract

Milk production per lactation (MPL) is a key metric of dairy farms. Accurate estimation of MPL requires regular recording, which is laborious and costly. In smallholder systems in the tropics, therefore, generally very few records are available to estimate MPL. Cross-sectional studies collect only one single record per lactation, and even longitudinal studies usually yield only a limited number of records per lactation. Such data recording methods, therefore, are sometimes extended with records recalled by farmers. The accuracy of MPL-estimates based on such limited and imperfect data, however, is unknown. The aim of the present study was to assess the accuracy of MPL-estimates from a single record and a limited number of records per lactation, obtained from smallholder dairy farms in Nakuru County, Kenya. Test-day records from a milk recording scheme for 114 smallholders were used to prepare three datasets with: i) a complete number of test-days (CTD, 5803 records), ii) a limited number of test-days (LTD, 1583 records), and iii) a single test-day (STD, 471 records). In addition, farmers' recall data from a survey of 29 farms with 56 lactations were used to prepare two datasets with: i) a limited number of recall moments per lactation (LRM, 200 records), and ii) a single recall moment per lactation (SRM, 56 records). These five datasets were used to derive MPL-estimates, at individual cow level or at herd level. The latter was done to mimic a situation without individual cow data, but only herd data (i.e. yield and size). MPL-estimates for CTD were set as a benchmark to quantify the accuracies, based on the relative mean absolute error (RMAE) and root mean square error (RMSE), of MPL-estimates for LTD and STD. As a benchmark dataset was absent for recall data, we computed a virtual benchmark to quantify the accuracies of MPL-estimates for LRM and SRM. At cow level, accuracy of MPL-estimates was highest for LTD (RMAE 15%), and lowest for SRM (RMAE 28%), while accuracies for STD and LRM were intermediate (RMAEs ~ 20%). At herd level, accuracy was higher for STD (RMAE 13%) than for SRM (RMAE 25%). We also showed that to detect a difference of, for example, 100 kg in MPL we need 3002 cows for CTD, and between 3620 and 5003 cows when using alternative data collection methods. Hence, depending on the study objective, alternative data recording methods provide labour-saving and cost-effective ways to estimate MPL in data-scarce smallholder dairy systems.

Keywords: accuracy, cattle, data scarcity, developing countries, tropics

4.1 Introduction

Accurate estimates of milk production per lactation (MPL) are key to evaluate the performance of dairy farms (Pica-Ciamarra et al., 2014). MPL is generally estimated from several measurements of milk production at specific moments in time (t) during the lactation (MP_t). The most accurate estimates of MPL are obtained through regular longitudinal recording of MP_t throughout the lactation. Such longitudinal records are obtained from automatic milking systems or through repeated recording of milk production throughout the lactation by farmers, researchers or extension officers (ICAR, 2017; Zezza et al., 2016; Ojango et al., 2019). In smallholder systems in developing countries, however, longitudinal records are generally scarce due to multiple constraints, including infrastructure, skills and level of organization required to collect reliable records, and farmers perceive little value in collecting records (Desiere et al., 2016; Pica-Ciamarra et al., 2014; Rege et al., 2011; Zezza et al., 2016). Lactation data are often incomplete and based on recall instead of on measurement, what can be termed as 'imperfect data' (Fraval et al., 2018). Besides, other indicators, such as feeding regime and parity, can be used to improve predictions of MPL, but such indicators are often not recorded at smallholder farms. In addition, the feeding regime (i.e. feed availability and feed quality at smallholder farms) is highly variable from season to season, but even from week to week. Estimating MPL based on imperfect data is thus a challenge.

Only a small proportion of farms in developing countries keeps frequent longitudinal records on milk production. In the Kenyan highlands, where resource-limited smallholder farming is dominant, less than one percent of all farms participates in test-day (TD) recording programs (Kosgey et al., 2011; Trivedi, 1997). Full participation of a farmer in a TD recording program implies that MP_t is measured at least eight times at regular intervals throughout a lactation (ICAR, 2017). These TD data are used in breeding programs to estimate breeding values of MPL (Muasya et al., 2014). The scarcity of frequent longitudinal milk production records has driven the search for alternative data recording methods that estimate MPL based on less records per lactation. This can be through a limited number of TD records per lactation, but it can be done also by using farmer recall data, where farmers rely on memory and recollection to give information for events in the past (Kong et al., 2018; McGill et al., 2014; Zezza et al., 2016). Ideally, farmers participating in recall surveys provide information about MP_t at several distinctive days in the past from their memory. However, in many surveys, farmers are asked to recall the MP_t on the day of a farm visit only. Moreover, farmers can be asked to recall milk production of individual cows, but also of the herd in total. The average production of individual cows is then estimated by dividing the whole farm production by the number of adult cows (Zezza et al., 2016).

It is likely that estimates of MPL from alternative data recording methods using imperfect data have a lower accuracy than estimates using data from a full TD program. Few studies have explored the accuracy of estimates of MPL that are based on methods using a limited number of TD-records (Berry et al., 2005; Duclos et al., 2008; Flores et al., 2013; McGill et al., 2014; Vanraden, 1997) or using recall data (Zezza et al., 2016). So far, however, none of these studies compared the accuracy of MPL-estimates based on alternative data recording methods with MPL-estimates based on full data from TD recording programs. Our aim, therefore, was to assess the accuracy of MPL-estimates based on four alternative data recording methods i.e. a limited number of TDs per lactation, a single TD per lactation, a limited number of recall records per lactation, and a single recall record per lactation. Knowledge of the accuracies of these alternative methods is relevant to design cost-effective approaches for, among others, evaluation of breeding programs, the impact of feeding strategies on milk production, or economic performance of resource-limited smallholder farms.

4.2 Material and methods

4.2.1 Data collection

Test-day and recall data were collected to assess the accuracies of MPL using different alternative methods for data recording, namely; collecting i) a limited number of TDs per lactation, ii) a single TD per lactation, iii) a limited number of recall records per lactation, and iv) a single recall record per lactation. Test-day data were obtained from the Livestock Recording Centre, a department of the Ministry of Agriculture, Livestock and Fisheries of Kenya. The Livestock Recording Centre obtains TD data from the national performance recording scheme operated by the Dairy Recording Services of Kenya (DRSK). According to the standard monthly TD recording procedure, farmers submitted their milk production records for individual cows on the 4th evening and the 5th morning after calving, and thereafter on the 14th evening and the 15th morning of the month, until drying-off (ICAR, 2017). The MP_t for each TD was calculated as the sum of the milk production records for the evening and morning of the TD (ICAR, 2017), as described in detail in Wasike et al. (2011) and Muasya et al. (2014). In addition to milk production records, the DRSK records included unique farm identification number, cow identification number, parity, calving date, and breed. Farmers submitted records for exotic dairy breeds, i.e. breeds that are non-native to tropical countries, and for their crossbreds with native breeds (>75% exotic genotypes). Holstein-Friesian and Ayrshire are the main exotic breeds recorded in the scheme (Kosgey et al., 2011; Njubi et al., 2009). The scheme does not record information about feeding regime. The TD records are submitted by smallholder farms as well as by medium- and large-scale farms (n = 457) from all parts of Kenya. We selected 242 farms out of the total of 457 farms in the scheme, based on the criterion that they submitted records for maximally ten cows per year. This resulted in 9872 TD records that represented 988 cows and 1234 lactations. These selected TD data were recorded between November 2002 and April 2015. The majority of smallholder farms that submitted TD records were within Nakuru County, located in the Kenyan highlands (Kosgey et al., 2011).

Smallholder dairy farming in Nakuru County has been described in Migose et al. (2018). In brief, most smallholder dairy farms have less than ten cows, mainly Holstein-Friesian or Ayrshire cattle, or crosses of Holstein-Friesian or Ayrshire cattle with native breeds. Like in the other parts of the highlands, cows are mostly kept in (semi)-intensive or extensive systems and fed on grass pasture and supplemented with Napier grass, maize stover and concentrate (Ojango et al., 2019). Breeding is by artificial insemination or by bulls. Cows calve year-round and can lactate beyond one year. Cows are generally milked by hand and milking is done in the morning and evening. The moment of drying-off varies among farms and cows and can range from 30 to 90 days prior to calving. However, the average drying-off of 2 months (60 days) prior to calving is recommended in extension advisory and was thus assumed for this study (ILRI, 2015; Njubi et al., 1992).

Recall data were collected through a cross-sectional survey conducted in Nakuru county. Stakeholders, such as extension agents, inseminators and milk transporters, were asked to refer smallholder farmers whom they interacted with, and the referred farmers also referred new farmers. Farms were visited once between December 2014 and April 2015. Interviews were conducted with each farmer. The identification name of each lactating cow was recorded. For each cow, farmers were asked to recall the date of the last calving, the date of the last service, the pregnancy status, the parity, and the MP_t for four moments in time, i.e. at the day of the farm visit (MP_r), the start (MP_s) and peak (MP_p) of the lactation, and the day of drying-off (MP_d). The MP_s corresponded to MP_t for the first week after calving, and the MP_p was defined as the highest MP_t in a lactation, assumed to occur around 55 days in milk (Muasya et al., 2014). For multiparous cows that were not in peak lactation yet, the future MP_p was assumed to correspond with the recalled MP_p in the previous lactation. The MP_d was recalled from the MP_t at drying-off in the previous lactation also. For primiparous cows, MP_s and MP_r were recalled, and MP_p was recalled if the cow had reached peak production already. The MP_d is not available for lactating primiparous cows yet. Only for MP_r, the evening and morning milk was recalled separately and summed to calculate MP_t for the day, for the other three moments, an average daily milk production was recalled. None of the farms surveyed was participating in the TD recording scheme. In the survey no data were collected about the feeding regime. Data were collected under permit from the National Commission for Science, Technology, and Innovation, Kenya.

4.2.2 Preparation of datasets

We prepared three datasets from the data collected through TD recording: the first had records for a complete number of TDs (CTD), including at least eight TDs per lactation; the second had records for a limited number of TDs (LTD), including three or four TDs per lactation; and the third had records for a single TD (STD) per lactation. We prepared two datasets from the recall data collected through the survey: the first had records for a limited number of recall moments (LRM), i.e. three or four moments per lactation, and the second had records for a single recall moment (SRM), i.e. one moment per lactation. Recall data included a maximum of four milk production moments per lactation, and therefore a dataset with a complete number of recall moments, equivalent to CTD, was unavailable for this study (Table 1).

4.2.2.1 Complete test-day dataset

Lactations were excluded from the TD data based on the following criteria: if less than eight TDs were available per lactation, if records were missing for three consecutive TDs before the eighth TD, if the MP_t at two consecutive TDs differed by more than 50% (ICAR, 2017), and if the first TD was submitted earlier than five days after calving. Farmers did not always submit TD records for the

Table 1. The number of complete, limited and single records for farms, cows, lactations, and milk production records in the datasets for test-day (TD) and recall data

Dataset[1]	**Test-day dataset**				**Recall dataset**			
	farms	cows	lactations	milk production	farms	cows	lactations	Milk production
complete	114	386	532	5803	-	-	-	-
limited	112	354	471	1583	29	56	56	200
single	112	354	471	471	29	56	56	56

[1] Datasets consisting of a limited number of TDs and a single TD per lactation were constructed ten times to avoid bias due to selection of a random TD. Values indicate the averages for the ten datasets

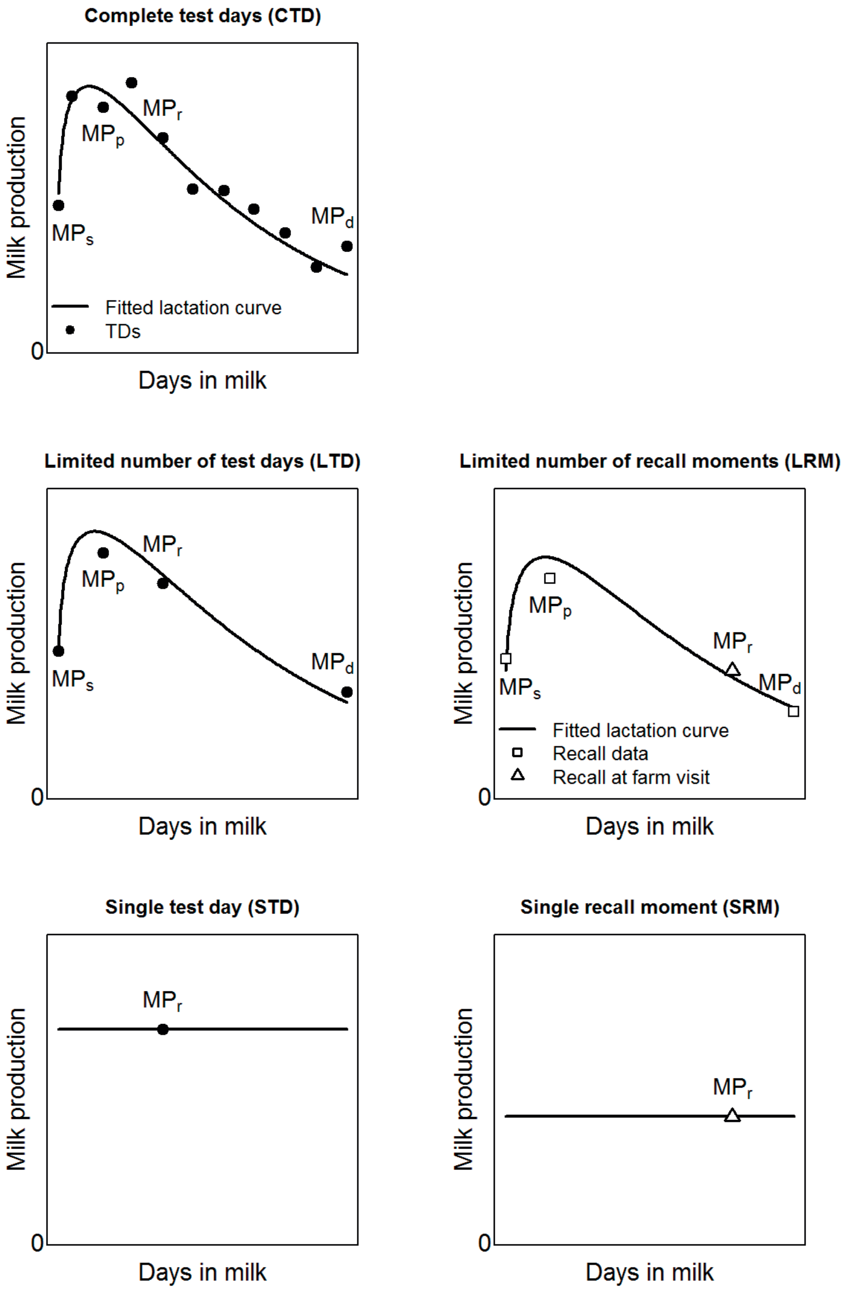

Figure 1. An overview of the five datasets created to estimate the accuracy of milk production per lactation. MP_s = milk production at the start of the lactation (5-8 days in milk), MP_p = milk production at peak lactation (55 days in milk), MP_r = milk production at a random day in the lactation, corresponds to farm visit, MP_d = milk production at drying-off, TD = test-day

specified monthly recording date, i.e. the evening of the 14th and the morning of the 15th. As a result, some TDs were not available for the specified recording date or were recorded more than once per month. In such occasions, the TD closest to the specified monthly recording date was adopted. The last TD recorded in a lactation was assumed to be the TD at drying-off. In total, the CTD dataset contained 5803 records from 532 lactations (average: 10.9 records per lactation) of 386 cows that were kept on 114 farms (Table 1).

4.2.2.2 Limited number of test-day and single test-day datasets

The LTD dataset was constructed from the CTD dataset and included three or four TDs per lactation, which mimicked the four moments of collecting milk records in the recall survey, i.e. MP_s, MP_p, MP_r and MP_d. These four TDs were selected as follows: the first TD (5-8 days) corresponds to MP_s and the last TD corresponds to MP_d, the third TD (39-68 days in milk, average 55 days in milk) corresponds to the MP_p, and finally, one TD was randomly selected from all available TDs to mimic MP_r (Fig. 1). Because MP_r was collected on the day of the farm visit and farm visits occurred at random moments during a lactation, the TD that corresponds with MP_r was selected randomly. To this end, we used the 'sample' function in R (R core Team, 2018). If the randomly chosen MP_r corresponded to either MP_s, MP_p or MP_d, the TD was only included once, which resulted in three records per lactation. Only lactations with three or four records per lactation were included in the LTD dataset. The MP_d was available for all lactations due to the assumption that drying-off corresponded to the last TD. Seven lactations were excluded because both MP_s and MP_p were missing, resulting in two records per lactation only. On several occasions, either MP_s or MP_p was missing and MP_r corresponded to one of the two available records, which resulted in having only two records per lactation (MP_d and either MP_s or MP_p). These lactations (n = 54) were excluded from the LTD datasets as well. The estimates for MPL from the LTD dataset were assumed to be affected by the randomly selected TDs. Therefore, the LTD dataset was created ten times with different random TDs and the ten LTD datasets contained, on average, 1583 records from 471 lactations and 354 cows that were kept at 112 farms (Table 1). In addition, the STD was created from the LTD by selecting the random TD that corresponds to MP_r (Fig. 1). Because the LTD was created ten times, the STD was selected ten times as well.

4.2.2.3 Limited number of recall moments and single recall moment datasets

The recall data comprised of MP_t records for maximally four moments per lactation, i.e. MP_s, MP_p, MP_r and MP_d (Fig. 1). Cows included in the LRM dataset had records for at least three moments out of the four moments, whereas cows with records for two or less moments were excluded. The time at drying-off was calculated as the expected date of the next calving minus 60 days (average dry period (Njubi et al., 1992)). The expected date of the next calving was calculated as the date a cow was served plus the average gestation period, i.e. 285 days. In addition, cows without an expected date of calving were excluded, because this date is essential to calculate MPL.

The LRM dataset comprised of 200 records from 56 lactations of 56 cows that were kept in 29 farms (average: 1.9 cows per farm) (Table 1). Finally, the SRM dataset comprised of 56 records that corresponded to MP_r in the LRM (Fig. 1).

The five datasets were used to estimate MPL at cow level, where individual lactations are the unit of measurement, and at herd level, where the farm is the unit of measurement (Table 1). This was done because often only the total MP_t per herd is recalled in cross-sectional surveys. From this farm-MP_t, the average MP_t per cow is calculated and these average MP_ts are multiplied by the average length of the lactation or the average length of the calving interval (dependent on whether dry cows are excluded or included in the estimation of the average MP_t) to calculate MPL (Migose et al., 2018; Zezza et al., 2016).

4.2.3 Accuracy of MPL-estimates from limited records per lactation

4.2.3.1 MPL-estimates

We estimated MPL by fitting lactation curves to the data in CTD, LTD and LRM. Lactation curves can be either typical, i.e. show an initial increase in milk production after calving, up to peak production, and subsequently, a gradual decline up to drying-off, or atypical, i.e. lactation curves with an intercept and a slope, which is either decreasing, constant, or increasing. MPL for typical lactation curves is best described by non-linear equations, whereas atypical curves are best described by either a linear equation. To describe the lactation curves, therefore, we used both a non-linear and a linear equation.

The non-linear equation is based on the commonly used Wood's equation. We, however, used the modified Wood's equation, as specified by Jenkins and Ferrell (1984), which requires only two instead of three parameters (Eq. 1). This equation is better suited, therefore, to estimate MPL if only a limited number (at least three data points) of sparsely distributed lactation data is available (Landete-Castillejos and Gallego, 2000; Sawyer et al., 1994). The equation was developed for crossbred beef cattle in the tropics (Adediran et al., 2007; Jenkins and Ferrell, 1984).

$$Y(t) = t \times (a \times e^{kt})^{-1} \qquad (1)$$

where *Y(t)* is daily milk production on the t^{th} week after calving (kg/day), *t* is the number of weeks after calving, and *a* and *k* are scaling parameters that determine the curvature of the lactation curve.

The linear equation contains one parameter for the slope and one for the intercept. The slope was considered to be decreasing if it was significantly lower than zero, increasing if it was significantly higher than zero, and constant if it was not significantly different from zero. Significant deviations of the slope from zero were determined with a t-test.

The JF-equation and linear equation were fitted to the data in CTD, LTD and LRM datasets. Parameters of both equations were fitted in such a way that the difference between the actual and the estimated milk production represented by the root mean squared error (RMSE), was minimized (Bennett et al., 2013). For the LTD, the equations were fitted to all ten datasets and the RMSE was averaged. The equation (either the linear or JF) that resulted in the lowest RMSE was considered to fit best. MPL is integral of the fitted lactation curves from calving up to drying-off for the CTD, LTD and LRM. MPL for STD and SRM was calculated by multiplying MP_r and the lactation length.

For curves that were best fitted by a linear equation, we also determined the suitability of the JF-equation to estimate their MPL by quantifying the difference between MPL-estimates by both equations. This difference was expressed as the mean absolute error (MAE), relative MAE (RMAE), mean squared error (MSE) and RMSE (Bennett et al., 2013). The MSE was decomposed into the bias, slope, and random component using the method of Theil and Rey (1966) and Bibby and Toutenburg (1977). The bias component of the MSE indicates the overall bias in MPL between two equations, the slope component indicates differences in variability in MPL between two equations, and the random component indicates the random variation (Bellocchi et al., 2011).

We derived MPL-estimates at herd level, by averaging MPL-estimates of all individual lactations recorded per farm. The average MPL-estimate per cow was calculated for each farm and for each of the five datasets, as described in the previous paragraphs. The sum of MP_r data for all lactating cows in a herd (i.e. STD and SRM) was assumed to correspond to farmers' estimates of the daily milk production of a farm in the cross-sectional survey (Table 1).

4.2.3.2 Accuracy of MPL-estimates from alternative data recording methods

MPL-estimates from CTD were assumed to closely resemble the actual MPL at farms. CTD was used, therefore, as the benchmark for the MPL-estimates based on LTD and STD. Differences in MPL-estimates between this benchmark and the alternative data recording methods LTD and STD were derived at cow and at herd level. The MPL-estimates were calculated for the 10 sets of LTD and STD and then averaged. Since the benchmark was assumed to resemble the actual MPL, differences from the benchmark were considered to be errors, which were expressed as the MAE, relative MAE, MSE, and RMSE (Bennett et al., 2013). The MSE was decomposed to its bias, slope, and random components, as described before. The larger these errors, the lower the accuracy of the MPL-estimates.

A benchmark dataset equivalent to CTD was absent for recall data (Fig. 1), which does not allow to calculate errors between MPL-estimates from LRM or SRM and a benchmark, as was done for TD data. We assumed, therefore, that the proportions in errors of limited and single records relative to a benchmark of complete records were the same for TD and recall data. We assumed, also, that recall bias did not affect the proportions in the errors. Given these assumptions, we calculated the errors for the LRM and SRM using a two-step approach. First, SRM was benchmarked to LRM, and STD was benchmarked to LTD. The error between LRM and SRM was divided by the error between LTD and STD, which resulted in a dimensionless ratio (Eq. 2). For example, the RMAE between LRM and SRM for individual lactations was 30.7%, and the RMAE between LTD and STD was on average 22.6% for the 10 datasets, which resulted in a ratio of 1.36. Second, this ratio was multiplied by the error for LTD to get the error for LRM, and by the error for STD to get the error for SRM (Eqs 3 and 4). This implies, for example, that the RMAE for the LRM is 1.36 times the RMAE between the benchmark CTD and the alternative data collection method LTD.

$$Ratio = Error_{LRM\text{-}SRM} / Error_{LTD\text{-}STD} \tag{2}$$

$$Error_{LRM} = Ratio \times Error_{CTD\text{-}LTD} \tag{3}$$

$$Error_{SRM} = Ratio \times Error_{CTD\text{-}STD} \tag{4}$$

Where the *Error* is expressed as the MAE, RMAE, MSE, and RMSE. The procedure to calculate the error for LRM and SRM was conducted for individual animals and for herds. For herds, the errors were linked to the number of lactations per herd. Using the STD dataset, herds were grouped according to number of lactations, i.e. all herds with one lactation were put in a group. The average RMAE was calculated for each group as the sum of RMAEs per group divided by the number of lactations per group.

4.2.3.3 Effective sample sizes

The accuracy of MPL-estimates determines the effective sample size of cows or farms with milk production records required to detect significant effects of interventions on MPL. Less accurate methods require larger effective sample sizes to detect significant effects (Kanyongo et al., 2007; Mason et al., 2018; Phillips and Jiang, 2016). We determined effective population sizes for each method of data recording. The reliability coefficient, which is similar to the coefficient of determination (R^2) of the regression between the benchmark and each alternative method, was quantified and the resulting R^2 value was incorporated in the formula described in Cohen (1988) to calculate the effective sample sizes (Eq. 5).

$$n = \frac{2\delta^2}{(d)^2} \tag{5}$$

where n is the effective sample size, δ is the critical value of t at $t_{1-\alpha}$ and $t_{1-\beta}$, and d is the standardized effect size. The formula is described in detail in the appendix A. We calculated the sample sizes required to detect significant differences ranging from 1 to 1500 kg of milk per lactation. All analyses in the present study were performed in R (R Core Team, 2018).

4.3 Results

4.3.1 Lactation curves

Majority of lactations derived from CTD and LTD datasets were best described by a linear equation and thus showed an atypical curve (Table 2), whereas the

Table 2. Percentages (%) of lactations best fitted by a Jenkins and Ferrell (JF) equation (typical) or a linear equation (atypical) in the complete test-days (TDs) dataset, limited number of TDs dataset and limited number of recall moments dataset

Lactation curve[1]	Complete TDs (n = 532)	Limited number of TDs (n = 471)[2]	Limited number of recall moments (n = 56)
typical	17.1	28.8±0.5	66.1
atypical decreasing	69.4	24.0±0.4	14.3
atypical constant	12.8	46.7±0.6	19.6
atypical increasing	0.8	0.5±0.1	0.0

[1] Curves best fitted by JF equation for typical and a linear equation for atypical lactation;

[2] The limited number of TDs dataset was derived from the complete TDs dataset, using the milk production at the start, peak, drying-off, and a random TD in the lactation; the random TD for each lactation was selected ten times and consequently lactation curves were fitted ten times, values represent average percentages and standard errors of ten repeated analyses

majority of lactations derived from LRM were best described by a non-linear equation and thus showed typical curve. The atypical curves derived from CTD were mostly decreasing, whereas atypical curves from LTD were mostly constant. A generic equation is preferred, however, to estimate MPL in a universal way that can be recommended to others for the collection of milk production data on farms. It was tested, therefore, whether the JF-equation was also suitable as a generic equation for atypical lactations best described by the linear equation, by exploring the differences in MPL-estimates between the fitted JF-equation and the fitted linear equation. The RMAE was 4% of MPL for CTD (Table 3) and estimates derived from both equations were quite similar (Fig 2). The average RMAE was 13% of MPL for the LTD, and 14% of MPL for the LRM (Table 3). Linear and non-linear estimates of MPL based on LRM differed from each other as shown by the deviation from the x = y line in Fig. 2. Thus, the JF-equation estimated MPL for atypical curves in CTD with a small RMAE and, also, for LTD, since LTD was part of CTD. Though the JF-equation applied to the atypical curves in LRM resulted in an error for some animals, the majority of

Table 3. Milk production per lactation (MPL) and error variables for Jenkins and Ferrell (JF) equation and linear equation used for estimating MPL for atypical lactation curves in the complete test-day (TD) dataset, limited number of TDs dataset, and limited number of recall moments dataset

variable	**complete TDs (n=441)**	**limited number of TDs (n=336)**[1]	**limited number of recall moments (n = 19)**
MPL - Linear, kg	4939	4995	3943
MPL - JF, kg	4764	5143	2744
mean absolute error, kg	184	636	1273
relative mean absolute error, %	3.7	12.7	13.8
root mean square error, kg	244	1010	1922
bias, % of MSE[2]	51.4	2.3	38.9
slope, % of MSE[2]	5.7	36.3	13.8
random, % of MSE[2]	42.9	61.5	54.1

[1] Limited number of TDs dataset was derived from the complete TDs dataset, using the milk production at the start, peak, drying-off, and a random TD in the lactation; the random TD for each lactation was selected ten times and consequently lactation curves were fitted ten times; values represent average percentages and standard errors of ten repeated analyses;

[2] Bias = MSE decomposed into error due to the overall bias of prediction; Slope = MSE decomposed into error due to the deviation of the regression slope from unity; Random = MSE decomposed into error due to the random variation

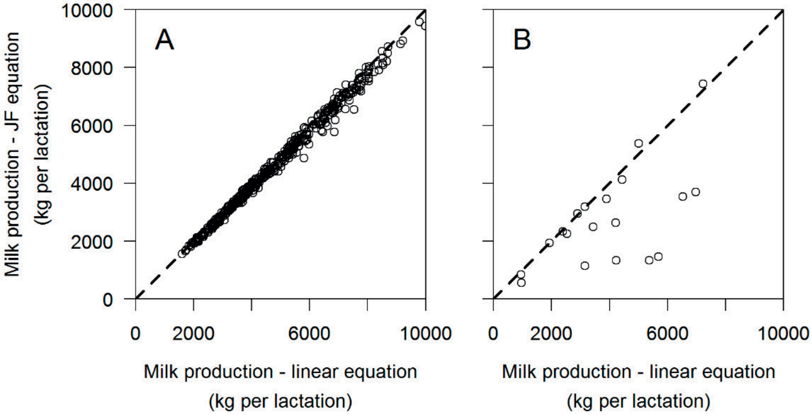

Figure 2. Relation between milk production per lactation estimated by the Jenkins and Ferrell (JF) equation and by a linear equation for the complete test-day (CTD) dataset (A) and the limited number of recall moments (LRM) dataset (B). The dashed line is the x = y line

curves in LRM were best described by a JF-equation (

Table 2). Hence, we conclude that it is justified to use the JF-equation to estimate MPL for both TD and recall data.

4.3.2 Accuracy of MPL-estimates from limited records per lactation

The RMAE for STD derived at herd level was 13%, and the RMAE for LTD derived at cow level was 15%. These two RMAEs were the lowest among the RMAEs for all alternative methods (Table 4), and consequently, these two methods for estimating MPL were most accurate. The RMAEs for STD (20%) and LRM (20%) derived at cow level and for SRM derived at herd level (21%) were intermediate. The RMAE for SRM derived at cow level was the highest (Table 4), which implies that using this method to estimate MPL is the least accurate of the alternative methods assessed. The random component of MSE for STD derived at herd level was 77%, and the bias and slope components of MSE were 23% together, which suggest that most of the RMSE was related to random variation (Table 4).

Random variation is expected to decrease at herd level if more lactations are recorded per herd, and RMAEs are expected to decrease with an increasing number of lactations recorded per herd. The RMAEs for STD decreased indeed with increasing number of lactations per herd(Fig. 3). Herds with one or two

Table 4. Mean milk production per lactation and estimation errors for various datasets from test-day (TD) and recall data at cow and herd level

Variables	**Cow level**				**Herd level**	
	limited number of TDs (n = 471)	single TD (n = 471)	limited number of recall moments (n = 56)	single recall moment (n= 56)	single TD (n = 112)	single recall moment (n = 29)
milk production per lactation[1], kg	5210	5060	4115	4000	4738	3810
mean absolute error[2], kg	715	973	772	1051	590	775
relative mean absolute error[2], %	14.8	20.2	20.2	27.5	12.8	21.4
root mean squared error[2], kg	1116	1359	1195	1456	833	1061
bias, % of MSE[3]	10.4	1.6			3.0	
slope, % of MSE[3]	37.1	35.0			20.5	
random, % of MSE[3]	52.4	63.4			76.6	

[1] Milk production per lactation (standard deviation) for complete test-days (TDs) dataset (benchmark for limited number of TDs dataset and single TD dataset) was 4814 (1955) kg per lactation at cow level (n = 471) and 4637 (1748) kg per lactation at herd level (n=112); the virtual benchmark value for limited number of recall moment, and single recall moment at cow level was 3821 kg and for single recall moment at herd level was 3621 kg (only one virtual benchmark per recall dataset);

[2] Errors are expressed relative to the milk production per lactation from the benchmark datasets;

[3] The components of the mean squared error (MSE) were not calculated for recall datasets due to the missing benchmark for recall data

lactations had RMAEs that were higher than the average RMAE for all herds (13%). The RMAE was approximately half or even less for herds that submitted records for 13 or more lactations (Fig. 3).

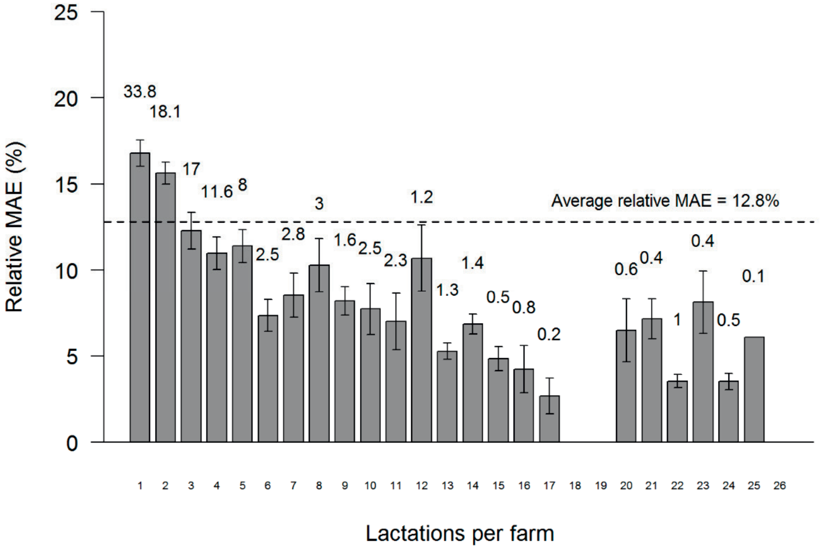

Figure 3. Relative mean absolute error (MAE) for single test-day records relative to complete test-day records in smallholder dairy farms with 1 up to 25 lactations. Numbers above bars indicate the average number of farms in each class (averaged across 10 repeated analyses)

4.3.3 Effective sample sizes

We calculated the effective sample size, for the benchmark, given a coefficient of determination (R^2) of 1.0, and for the alternative methods of estimating MPL, using the following R^2s: 0.83 for LTD, 0.72 for LRM, 0.69 for STD and 0.60 for SRM at cow level, and 0.83 for STD and 0.62 for SRM at herd level. The effective sample sizes decreased with increasing differences in MPL to be discriminated and with increasing value of coefficient of determination (Fig. 4). To detect small differences in MPL, i.e. <100 kg, we need an effective sample size of more than 3000 cows and 2400 farms (Fig. 4). For example, a detectable difference in MPL of 100 kg required 3002 cows for CTD, and between 3620 and 5003 cows for alternative methods, whereas a detectable difference of 600 kg required 85 cows for CTD and between 102 and 141 cows for alternative methods. The effective sample sizes were slightly smaller for farms than for cows: at a similar detectable difference, the effective sample size using CTD at the farm level was 80-81% of the effective sample size using CTD at the cow level.

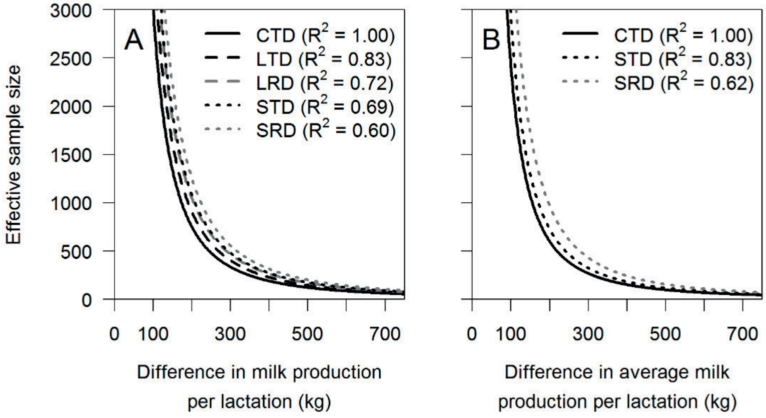

Figure 4. The relation between effective sample sizes of cows (A) and farms (B) and detectable differences in milk production per lactation

4.4 Discussion

4.4.1 Complete records of the lactation

The most accurate measure of MPL is obtained from the aggregation of daily milk production records, which are often not available in smallholder systems. Taking records at regular intervals in a lactation, referred to in the present study as CTD with a minimum of 8 records per lactation, has a high correlation with true MPL (Flores et al., 2013; Norman et al., 2009; Quist et al., 2007). Estimation of MPL through such CTD is mostly done in systems with limited day-to-day and limited seasonal variation, i.e. large-scale farms with exotic breeds, and good management. A study that explored the correlation between MPL estimated from CTD and other datasets with limited number of TDs was based predominantly on large-scale farms (Wasike et al., 2011). It is unknown, however, what the accuracy is between true MPL and MPL estimated from CTD on smallholder farms in the tropics. For the present study, we assumed that CTD allows to estimate MPL accurately enough to serve as a benchmark for the alternative methods of MPL estimation.

Most CTD-lactations had atypical, decreasing lactation curves (Table 2). Previous studies about lactations of cows in smallholder farms in Kenya have reported atypical curves, too, and attributed a mild peak or even no peak to a negative energy balance (Katiku et al., 2011; Muraguri et al., 2004; Omore et al., 1996; Staal and Omore, 1998). The JF equation estimated MPL adequately for both typical and atypical curves (Fig. 2).

4.4.2 Limited records per lactation

Accuracy of MPL-estimates based on limited records were expected to be lower than that those based on CTD, because the accuracy of MPL-estimates decreases with a decrease in number of records per lactation (Berry et al., 2005; Duclos et al., 2008; Flores et al., 2013; Kong et al., 2018; McGill et al., 2014; Otwinowska-Mindur et al., 2014; Zezza et al., 2016, 2016). The accuracy of the LTD method was higher than that of the LRM method (Table 4). For LRM, part of the lower accuracy compared to LTD can be attributed to the so-called recall bias (Godlonton et al., 2018; Zezza et al., 2016). Recall bias is a systematic error caused by differences in the completeness of recollections retrieved by farmers on past events or experiences (Godlonton et al., 2018; Zezza et al., 2016). The magnitude of recall bias is variable and over-reporting of estimates of 30% has been demonstrated when recall is used instead of ledger books (De Mel et al., 2009). Recall bias may be associated with several factors, including memory failures, farmers' high expectations, illiteracy and conditions at the time of the interview (e.g. duration) (Beegle et al., 2012; de Nicola and Giné, 2014; Deininger et al., 2012). To estimate MPL from LRM, we had to make assumptions about gestation length, length of the dry period, and the moment of peak production. Moreover, in contrast to TD data, which are often obtained through actual weighing or volume recording, recall estimates are subjective. While the accuracy is higher for LTD compared to LRM, we realize that collection of LTD data requires more efforts: multiple farm visits to record the daily milk production of individual lactating cows at different moments during a lactation or organizing farmers to submit three or four TD records for each lactating cow. For LRM, on the other hand, only a single farm visit is required.

4.4.3 Single record per lactation

Accuracies of MPL-estimates based on single records were lower than those based on a limited number of TDs (Table 4), which is in line with literature (Liu et al., 2000; Macciotta et al., 2002; Otwinowska-Mindur et al., 2014). When only a single record of the lactation is used to estimate MPL, it is assumed that the random daily milk production is representative for the average daily milk production throughout the lactation, implying that variation in daily milk production throughout the lactation is not accounted for. In our study, errors were higher for SRM than for STD and this could potentially be attributed to recall bias, which may be caused by the several factors, already mentioned in the previous paragraph (Beegle et al., 2012; de Nicola and Giné, 2014; Deininger et al., 2012). However, it is likely that recall bias was limited since farmers only had to recall the production for the last 24 hours. Nevertheless, wishful thinking associated with the subjective estimation of the milk quantity could be a source of error. Data of a single record per lactation require minimal efforts to collect, but they estimated MPL with a relatively low accuracy, except at herd level, which will be discussed in the next section.

Errors for LRM and SRM datasets, relative to the virtual benchmark, were quantified using a ratio, i.e. errors of SRM when benchmarked to LRM divided by errors of STD when benchmarked to LTD, that relates recall data to TD data. This is a rough assumption and has limitations; it assumes no differences in relative errors between TD and recall data and no effect of recall bias on errors. Ideally, the datasets should contain the same farms, the same cows, and the same lactations for the TD records and recall data, but such data were not available for Nakuru country. In this study, recall data were not related to TD data because farms in the survey were not participating in the TD- scheme. As a result, MPL-estimates based on the LRM and SRM datasets, therefore, could not be benchmarked directly to CTD.

4.4.4 Single records of the herd

If all lactation stages are represented uniformly at a farm, at any random day, the total milk production per farm divided by the number of adult (lactating and dry) cows represents the average daily milk production of a cow during calving interval (Pica-Ciamarra et al., 2014; Zezza et al., 2016). Hence, multiplication of this daily milk production times the average length of the calving interval gives MPL. The more adult cows on a farm, the more accurate the estimation of this average daily milk production (Zezza et al., 2016). This theoretical hypothesis is confirmed by our results (Fig. 3) and in line with Pica-Ciamarra et al. (2014) and Zezza et al. (2016). The SRM had a lower number of lactations per farm (1-4) than STD (1-25), which explains part of the lower accuracy for SRM than for STD at herd level. The recall bias has likely contributed too (Zezza et al., 2016). Recall data were available only for lactating animals and calculations were based on lactating animals only. Milk production per lactation at herd level was calculated as milk production per day multiplied by the average lactation length. In actual farms, dry cows are part of the herd and MPL per herd is calculated by multiplying the average daily milk production by the average calving interval (Pica-Ciamarra et al., 2014; Zezza et al., 2016). Hence, MPL can be calculated from the lactation length when lactating cows are considered, or from the calving interval when both lactating and dry cows are considered. Estimating MPL using

SRM at herd level, however, neglects variation among cows and the estimates cannot be used for interventions that target individual cows.

4.4.5 Effective sample sizes

The increase in effective sample sizes with decreasing detectable differences in MPL-estimates (Fig. 4) has the following implications: a large sample size is required to detect small differences in MPL-estimates, whereas a relatively small sample size is required to detect large differences in MPL. A breeding intervention, such as sire evaluation in Kenya, for example, which in the case of Muasya et al. (2014) has a detectable difference of about 100 kg milk per lactation, would require approximately 3000 cows for CTD and up to 5000 cows for alternative methods. An intervention, such as concentrate feeding in Kenya, however, is likely to increase daily milk production by approximately 2 kg per day, equivalent to 600 kg per lactation (e.g. Mwendia et al., 2018; Richards et al., 2016). Detecting such an effect size would require 85 cows for CTD and between 102 and 141 cows for the alternative methods. The practical implication of the present study is that, to quantify relatively large effect sizes, relatively simple methods of data collection can be done: a single farm visit can be used to collect individual cow records directly or via recall, and even a method where the whole farm production is recorded and divided by the total number of adult cows at a farm gives a reasonable estimates for MPL.

4.4.6 Limitations of estimating MPL using recall data

In the present study, for recall data, we included records for the ongoing lactations only, and without knowing the drying-off date, we estimated the lactation length by assuming a fixed length of the gestation period and a fixed length of the dry period. Hence, a possible bias of this approach is this assumed absence of variation in lengths of the gestation and of dry period. Although variation in gestation lengths are low for cattle (Norman et al., 2009), variations of the length of the dry period can be large (Drackley, 1999). Lactation lengths and lengths of the calving intervals are important parameters for estimation of MPL in all approaches. Hence, records of the last calving date and the predicted next calving date are essential. Cows that are not pregnant yet should be excluded from the datasets because no estimate of the calving interval can be made. Alternatively, it may be assumed that the average length of the calving interval of the other cows at the same farm resembles the calving interval for the cows for which no estimate can be made. In the present study, we estimated MPL for herds based on lactating cows only. The method can include dry cows also by assessing total herd production and dividing this by the number of adult cows

(cows having calved at least once including the dry cows) and MPL is calculated by multiplying the average MP_t per cow by the number of days in the calving interval.

In smallholder system in developing countries, where these alternative methods are targeted, data for assessment of farm performance are incomplete and imperfect (Desiere et al., 2016; Fraval et al., 2018; Pica-Ciamarra et al., 2014; Rege et al., 2011; Zezza et al., 2016). Lack of information about the feeding regime is part of the imperfectness and incompleteness as is the lack of knowledge about parity. Including feeding data next to milk production records to predict MPL would hamper, therefore, the adoption and application of the alternative methods.

4.5 Conclusion

We assessed the accuracy of MPL-estimates from alternative data recording methods with a limited number of TD or recall records or a single TD or recall record per lactation. For MPL-estimates derived at cow level, the accuracy was highest for LTD (RMAE, 15%), and lowest for SRM (RMAE, 28%), while accuracies for STD and LRM were intermediate. For MPL-estimates derived at herd level, the accuracy was higher for STD (RMAE, 13%) than for SRM (RMAE, 20%). Methods based on a limited number of TD and on farmers' recall data required larger effective sample sizes to detect significant effects when compared to the benchmarks. Dependent on the objective of studies, however, alternative data recording methods provide labour-saving and cost-effective ways to estimate MPL in data-scarce smallholder dairy systems.

Conflict of interest

The authors declare that there is no conflict of interest for this study.

Acknowledgements

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Appendix A

The formulas described in Cohen (1988) were used to calculate the effective sample sizes (Eqs A1-A3). $\delta = (t_{1-\alpha} - t_{1-\beta})$ *(A1)*

$$d = \frac{m_A - m_B}{\sigma} \qquad (A2)$$

$$d = d * \sqrt{r_{yy}} \qquad (A3)$$

where δ is the critical values of t at $t_{1-\alpha}$ and $t_{1-\beta}$, α is the probability of a type I error, β the probability of a the type II error, d is the standardized effect size, m_A and m_B are the means of populations A and B, respectively (e.g. before and after an intervention), σ is the population standard deviation, r_{yy} is the reliability coefficient (R^2). The two populations were assumed to have equal variances and an equal reliability coefficient, α was set at $P = 0.05$ (one-tailed), and β at $P = 0.20$.

Chapter 5

Yield gap analysis of dairy cow production at smallholder dairy farms in the Kenyan highlands

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Breeds of cattle: Holstein-Friesian (HF), Ayrshire and Kenyan zebu and exotic crossbreds

To be submitted

Abstract

Smallholder dairy farms contribute substantially to global food supply, but cattle productivity in these farms is generally low. Identification of options for improving cattle productivity in smallholder farms requires insights into biophysical constraints, which can be gained by an analysis of yield gaps. The objective of this study was to identify biophysical factors that constrain milk production of dairy cattle in order to explore improvement options that contribute to mitigating yield gaps in smallholder systems in the Kenyan highlands. The model LiGAPS-Dairy (Livestock simulator for Generic analysis of Animal Production Systems – Dairy) was used to analyse yield gaps. To collect data for actual milk production and feed utilisation, we conducted a survey at three farms types: farms in urban locations with exotic cattle breeds (ULE, n=10), farms in rural locations with exotic cattle breeds (RLE, n=6) and farms in rural locations with crossbred cattle (Kenyan zebu and exotic crosses) (RLCB, n=6). Weather data were obtained from on-station and online databases, while data on genotypes and feed quality were obtained from literature. Potential, feed-quality limited, feed-limited (i.e. combined feed quality and quantity limited) milk production and growth were simulated. Yield gaps were quantified relative to potential production, and further partitioned according to the limiting factors feed quality and feed quantity, and reducing factors diseases and stress. The most frequently constraining factors throughout the calving interval were simulated to explore improvement options. Farm types ULE and RLE had a higher potential, feed quality limited, and feed-limited production than farm type RLCB. Farm type RLE had the lowest actual production. Yield gaps were large in all farm types, namely 57% of potential production in ULE, 82% in RLE and 47% in RLCB. Feed quality was the main factor limiting milk production. It explained 47% of the yield gap in ULE, 34% in RLE, and 63% in RLCB. Detailed analysis of feed quality limitation indicated that protein deficiency was the most frequent constraining factor during the lactation. To overcome this protein deficiency, we explored feed supplementation. Supplementing lucerne, (dependent on context with or without concentrates), increased feed-limited milk production by 32% for ULE, 45% for RLE and 88% for RLCB. Therefore, we concluded that protein supplementation was relevant to increase productivity of exotic and crossbred cattle and livelihoods of smallholder dairy farmers.

Keywords: exotic cattle, biophysical factor, feed-limited production, protein deficiency, lactation

5.1 Introduction

Dairy farming contributes to global food supply and supports the livelihoods of rural households (FAO, 2016). Estimated global milk production in 2018 was 843 million tons, out of which 505 million tons was from cattle (FAOSTAT, 2019). Moreover, about three-quarters of the global population consumes milk and milk-derived products (FAO, 2016). Milk production and consumption are expected to increase further due to population growth and rising incomes (Andersson Djurfeldt, 2015; Kapaj and Deci, 2017), also in Africa. At present, average milk consumption in Africa is only 37 litres per capita per year, which is lower than the global average of 104 litres per capita per year. It, moreover, varies across countries within Africa. In Kenya, for example, average milk consumption per capita is 115 litres per capita per year, whereas it is only 3 litres per capita per year in Liberia (FAOSTAT, 2019). This high milk consumption in Kenya is supported by a vibrant smallholder dairy sector comprising of 4.3 million cattle (Odero-Waitituh, 2017). These dairy cattle are mainly exotic breeds of European origin and crossbreds resulting from their crosses with Kenyan zebu (Gorbach et al., 2010; Kim and Rothschild, 2014). On average, dairy cattle in Kenya have a milk production of approximately 10 kg cow^{-1} day^{-1} (Migose et al., 2019, 2018; Odero-Waitituh, 2017). This low productivity results, among others, from constraints related to genotypes, climate, feeds, diseases, and farm management (Migose et al., 2019, 2018; Odero-Waitituh, 2017). To sustain the current as well as to meet the future demand for milk, there is a need to get insights into constraints in order to devise options for increasing productivity of dairy cattle in the smallholder farming systems in Kenya.

One way to get insights into biophysical constraints and options for improving the productivity of cattle is to apply yield gap analysis (van der Linden et al., 2019a). Following the so-called concepts of production ecology, three levels of livestock production are distinguished to analyse yield gaps: (1) potential production, which is the maximum theoretical production obtained under ideal management, and determined by the defining factors genotype and climate only; (2) limited production, which is determined by the limiting factor feed quality, available feed quantity and drinking water, in addition to the genotype and climate; and (3) actual production, which is the production realised on-farm (van de Ven et al., 2003). This actual production, in addition to genotype, climate, feed quality, feed quantity and water, is determined by the reducing factors diseases and stress. Yield gaps are generally defined as the difference between potential and actual production (van de Ven et al., 2003). Thus, the limiting factors, i.e. feed quality, feed quantity, and drinking water, and the reducing factors, i.e. diseases and stress, attribute to yield gaps. The defining, limiting and reducing factors are (exclusively) biophysical factors. Socio-economic, cultural, and legislative factors determine how farmers deal with these biophysical factors and to which extent yield gaps can be mitigated.

Several studies, based on various methods, have highlighted that the scope to increase dairy production in Africa and Kenya is considerable (Bosire et al., 2016; Henderson et al., 2016; King et al., 2006; Mayberry et al., 2017; Rufino et al., 2009). However, only few of these studies have allowed identifying the biophysical factors contributing to the yield gaps or the few that could, could only do so to a limited degree. The objective of the present study, therefore, was to identify to which extent the various biophysical factors define and limit milk production of dairy cattle in order to explore improvement options that contribute to mitigating yield gaps in smallholder systems in the Kenyan highlands. To achieve this objective, we first quantified yields gaps relative to potential milk production using a dynamic mechanistic model for dairy cattle (Van der Linden et al., in preparation). We then identified and analysed the biophysical factors attributing most to yield gaps and subsequently, we quantified changes in milk production after implementing interventions that were specified based on yield gap analyses. For this analysis, we considered differences among farm types and phases of a lactation.

5.2 Materials and methods

To conduct a yield gap analysis, we require data of actual production as well as input data for modelling potential and feed-limited production. Actual production data were obtained from farm surveys (section 2.1), whereas potential production, feed-quality limited production and feed-limited production were simulated using a mechanistic model (section 2.2). Feed-limited production included both feed quality and feed quantity limitations.

5.2.1 Farm survey

We conducted a cross-sectional farm survey in Nakuru County, which is located in the Kenyan highlands. The county has diverse climatic conditions. Annual precipitation ranges from 500 mm to 1400 mm and above, and average temperature ranges from 12°C to 29°C (Nakuru County Government, 2018). Areas with precipitation levels higher than 1000 mm and average temperatures lower than 20°C are dominated by smallholder farmers having mixed crop-livestock systems. These farmers keep exotic and crossbred cattle and produce milk for home consumption and the market (Nakuru County Government, 2018). The primary urban market for milk is Nakuru town. Distance to the market in

Nakuru town influences the magnitude of socio-economic constraints that dairy farmers face and consequently milk production. Farms in urban locations (<15 km radius from the town centre) are linked to markets of higher quality, and have better access to inputs and services such as artificial insemination, feeds, veterinary care and labour than farms in rural locations (>50 km from the town centre) (Migose et al., 2018).

To understand yield gaps, we purposively selected three contrasting farm types. We selected farms in urban locations with exotic cattle (ULE), farms in rural locations with exotic cattle (RLE), and farms in rural locations with crossbred cattle (RLCB). ULE farms used artificial insemination for the exotic cattle and represented the most intensive type of farms. RLE and RLCB farms applied natural mating, and RLCB farms represented the most extensive farms. A chain referral "snowballing" technique was used to select farms (Biernacki and Waldorf, 1981). Stakeholders, including extension agents and artificial inseminators, were asked to refer smallholder farmers whom they interacted with, and the referred farmers further referred their peers. Farmers stated or recalled information for the farm about herd size, feed supply to the herd (feed types, quantities and duration of use) and daily grazing time in the wet season (April-November) and the dry season (December-March). For individual cows in milk, farmers were asked to recall information about the breed, age, dates of calving and insemination, pregnancy status and milk production for at least three of the following four moments: start, peak, end of the previous lactation, and at the day of the farm survey (Migose et al., 2020). Total body weight (TBW, kg) of adult cows was measured using a Rondo tape (Wangchuk et al., 2017).

We surveyed a total of 42 farms, 22 in urban locations and 20 in rural locations. The inclusion criteria of farms for further analysis was firstly that farmers were able to recall milk production for at least three out of the four moments of the lactation. Nine farmers in urban locations and eight farmers in rural locations could not recall the milk production for at least three moments in a lactation. Secondly, the average milk production of a herd and the feed supply per herd had to be consistent with each other in both the wet and dry season. Therefore, farms with milk production but a feed supply below maintenance requirements were excluded, i.e. three farms in urban locations (Supplementary Material SM-E). Hence, 10 farms in urban locations and 12 farms in rural locations remained for yield gap analysis. At some farms, farmers could only recall information for part of the herd. In that situation we assumed that the average of the whole herd was similar to the average of the cows for which we had the recall information. We estimated the actual milk production per lactation for each cow for which we had data by fitting the three or four milk production records per lactation to the equation of Jenkins and Ferrell (1984) as described in Migose et al. (2020).

5.2.2 Simulation

5.2.2.1 Model

To quantify and analyse yield gaps, we used a dynamic mechanistic model for dairy cattle named LiGAPS-Dairy (Livestock simulator for Generic analysis of Animal Production Systems – Dairy (Van der Linden et al., in preparation). LiGAPS-Dairy is derived from the model LiGAPS-Beef and likewise consists of three sub-models that describe thermoregulation, feed intake and digestion, and energy and protein utilisation (van der Linden et al., 2019c, 2019b, 2019a). The model uses a one-day time step and simulates growth and milk production throughout the life span of an individual animal. Data collected at farms were used as input for LiGAPS-Dairy. Model simulations were conducted for the average cow in the herd of each farm, because data on feed supply were only available at the herd level, and not per individual animal. Within the simulation results, we focussed on the calving interval where cows were in at the time of the farm survey. However, no data were available for the initial conditions of the cows at the previous calving, such as body weights and body conditions scores. We simulated, therefore, the animals from birth up to the end of the dry period that marked the end of the calving interval the farm survey was conducted in.

5.2.2.2 Potential production

Under potential production, the genotype and climate define growth and milk production of dairy cows (van de Ven et al., 2003; van der Linden et al., 2015). The genotype was represented by the cattle breeds in the farms surveyed. Cattle breeds were classified as Holstein-Friesian, a mixture of Holstein-Friesian and Ayrshire (if both breeds present in the herd on a farm), Ayrshire, and crossbreds between exotics and local Kenyan breeds. Genetic parameters for these breeds were retrieved from literature (Supplementary Material SM-A, Table S1). Among the genetic parameters were fat and protein contents of milk, maximum milk production per lactation and maximum adult TBW. Genetic parameters for mixed Holstein-Friesian and Ayrshire herds were averages of parameters for the Holstein-Friesian and Ayrshire breeds. Genetic parameters for crossbreds were averages of parameters for Holstein-Friesian breed and local Kenyan breed or averages for Ayrshire and local Kenyan breeds.

The equation of Yan et al. (2011) was used to compute fat- and protein-corrected milk (FPCM) from the maximum milk production and the fat and protein percentages of milk (Eq.1)

$$FPCM\ (kg) = Milk\ production\ (kg) \times (0.337 + 0.116 \times Fat\% + 0.06 \times Protein\%) \qquad (1)$$

For each breed and for the mixed Holstein-Friesian and Ayrshire herds, the maximum genetic potential for FPCM production in a 305 day-lactation was used to fit the lactation curve developed by Wood (1967). Values for the three parameters of the Woods curve were assumed to be the same for each breed in the urban and rural locations.

LiGAPS-Dairy uses daily weather data to include the defining factor climate (Van der Linden et al., 2019a). We combined weather data for Nakuru County (0.16ºS, 36.6ºE) from the "WeatherOnline" database (www.weatheronline.co.uk), the Kenya Meteorological Department (www.meteo.go.ke) and the Global Yield Gap Atlas (www.yieldgap.org) to construct the required input files for LiGAPS-Dairy (Supplementary Material MS-B).

Under potential production, energy and protein deficiencies are assumed to be eliminated by *ad libitum* intake of high-quality feeds (van der Linden et al., 2015). Hence, the diet fed *ad libitum* under potential production consisted of soybean meal (19.5%), wheat (31.8%) and hay (48.6%). The ME content of this diet is 11.6 MJ kg^{-1} DM, and its CP content is 225 g kg^{-1} DM (Van der Linden et al., in preparation). Net energy requirements for grazing were included under potential production if grazing occurred in actual farms. We assumed a net energy use of 70 kJ kg$^{-0.75}$ day^{-1} for physical activity during grazing of dairy cows (CSIRO, 2007).

5.2.2.3 Feed-quality limited production and feed-limited production

Two additional production levels were simulated similarly to potential production, but with information on the actual diets fed in practice. Under feed-quality limited production, the availability of fodder and grazed grass, as offered on each farm under actual production, was assumed to be available *ad libitum* for lactating and dry cows, whereas the availability of concentrates offered was fixed at the actual level for lactating cows and zero for dry cows. Concentrates were set to zero for dry cows, because dry cows are usually not fed with concentrates in smallholder farms in Kenya (Muraguri et al., 2004). Under feed-limited production, the feed quality and available feed quantity both corresponded to those under actual production. Following concepts of production ecology, the differences between feed-limited production and actual production were assumed to be due to effects of diseases and stress (van de Ven et al., 2003; van der Linden et al., 2015).

Farmers provided estimates of the feed quantity available to a herd for the wet season (8 months per year) and the dry season (4 months per year). The daily quantity of each feedstuff per season was calculated per tropical livestock unit (TLU) on a farm. A cow equals 1 TLU, a heifer 0.5 TLU and a weaner calf 0.25 TLU (Castellanos-Navarrete et al., 2015). In the present study, TLU was a cow of 400 kg. Concentrates were supplied only to cows during the lactation period (Muraguri et al., 2004). The duration of the lactation period was calculated as the difference between the duration of the average calving interval for an average cow at a farm and the dry period, which was assumed to be 60 days (Njubi et al., 1992) for all farms. Therefore, a dimensionless concentrates allocation factor (*CAF*) was used, eventually, to calculate concentrates availability per cow day of the lactation relative to the average intake of concentrates in the calving interval (Eq. 2).

$$CAF = \frac{CI - DP}{CI} \tag{2}$$

where, *CI* is the average duration of the calving interval per farm (days), and *DP* is the duration of the dry period (60 days). The quantity of concentrates offered (*CO*) per lactating cow per day was calculated for each farm based on the *CAF* (Eq.3):

$$CO = \frac{CY}{365 \times n \times CAF} \tag{3}$$

where *CY* is the amount of concentrates (kg DM) available per farm per year, *n* is the total number of cows per farm (dry and lactating).

Quantities of feedstuffs available per season were recalled by farmers, except for grazed grass. In farms where cattle grazed on pastures, grazing was assumed to occur year-round. The average daily duration of grazing from the farm survey was used to estimate DM intake from grazing, which was calculated as multiplicative of the grazing time (in hours per day) and the grass intake per unit of time (in kg DM per hour). Grazing time was capped at 8 hours per day as longer grazing usually does not increase intake (Oosting, 1993). Grass intake was assumed to be higher in the wet season than in the dry season due to a higher grass quality and quantity. The assumed grass intake was 1.0 kg DM per hour for the wet season and 0.8 kg DM per hour for the dry season (Ongadi et al., 2010).

Feed quality was represented by the metabolizable energy content (ME, MJ kg^{-1} DM) and the crude protein content (CP, g kg^{-1} DM). The DM, ME and CP contents of feeds in the survey were obtained from literature and online databases (Supplementary Material SM-C, Table S2). The DM, ME and CP content of all feeds were assumed to be constant throughout the year, without differences between the wet and dry season. The quality of tropical grasses often differs between seasons in the tropics. In Nakuru county, however, the difference in climatic conditions between the dry season (December-March) and the wet season (April-November) affects the DM yields of grasses, but their quality only to a limited extent (Kerfoot, 2018). Average ME and CP contents of total diets were calculated for the wet and the dry season as weighted averages of the ME and CP contents of individual feeds. The ME content of total diets fed on each farm were used to calculate the heat increment of feeding (MJ kg^{-1} DM) and the fill units kg^{-1} DM (van der Linden et al., 2019a).

5.2.3 Yield gaps, yield gap analysis and improvement options

Yield gaps were partitioned according to limiting factors (feed quality, feed quantity), and reducing factors (diseases and stress). The part of the yield gap explained by feed quality is the difference between potential and feed-quality limited production. The part of the yield gap explained by feed quantity is the difference between feed-quality limited production and feed-limited production. Reducing factors explain the difference between feed-limited and actual production (van der Linden et al., 2019a).

Besides partitioning of the yield gaps, the most constraining biophysical factor for milk production and growth was investigated at a daily basis to explore improvement options. The defining factor climate was split up into heat stress and cold stress to allow a more detailed analysis. Heat stress occurs if an animal reduces its feed intake to prevent that heat production from metabolic processes from exceeding heat release from the animal's body (Turnpenny et al., 2000). Cold stress occurs if an animal increases its feed intake to prevent that heat release from the animal's body from exceeding heat production from metabolic processes (Young, 1983). The factors feed-quality and feed quantity limitation are not providing much concrete information to explore improvement options, so these were further detailed to indicate whether milk production was limited by the animal's digestion capacity, energy deficiency or protein deficiency. Limitation in milk production and growth due to digestion capacity occurs if the maximum digestion capacity of an animal is met while the energy and protein requirements are not met (Jarrige et al., 1986; van der Linden et al., 2019c, 2019a). The digestion capacity of an animal is affected by the fill units kg^{-1} DM of a particular diet in LiGAPS-Dairy. Limitation in milk production due to energy deficiency occurs if the amount of energy from the available feed does not meet the energy requirements. Limitation in milk production due to protein deficiency occurs if the amount of protein is inadequate to meet the protein requirements. Protein deficiency can concur with heat stress, cold stress, reaching maximum digestion capacity.

For each farm in the survey, milk production and growth of an average cow was simulated for each day of the calving interval, which consists of the lactation period and the dry period. The lactation period was divided into two phases according to milk production level: 1 to 100 days in milk (1-100 DIM) to represent the phase with high milk production, and 101 DIM up to drying-off (>101 DIM) to represent the phase with low milk production. For each day of the calving interval, the model identified the most constraining factor under feed-limited production, because this production level corresponds most to the actual production, and therefore, it is most suited to identify improvement options. The most constraining factors were either the genotype, cold stress, heat stress, digestion capacity, energy deficiency or protein deficiency. For 1-100 DIM, >101 DIM and the dry period, the number of days each factor was most limiting was summed and expressed as a percentage of the total number of days in milk in that period. We averaged the percentages for each farm type.

The relative occurrence of the most constraining biophysical factors allows to specify improvement options. The factors that constrained milk production most were used to explore which options were promising to mitigate yield gaps. Besides biophysical considerations, improvement options were selected after accounting for socio-economic factors, to make sure they are practically feasible and have scope for adoption by smallholder farmers (Oosting et al., 2014; Udo et al., 2011; Van Ittersum et al., 2013). Inputs of LiGAPS-Dairy, such as feed intake at farms, were adjusted according to the selected improvement options. Milk production per lactation was simulated with the improvement options, and the percentage increase in milk yield relative to feed-limited production were quantified.

5.2.4 Statistical analysis

We tested differences among farm types regarding feed offered and feed quality, and between actual production and feed-limited production using ANOVA and Fishers' Least Significant Difference for normally distributed data and Kruskal Wallis test if data were not normally distributed. We tested normality using Shapiro-Wilk tests (Shapiro and Wilk, 1965).

5.3 Results and discussion

5.3.1 Breeds and feeds in farm types

Breeds differed among farm types (Table 1). In ULE farms, mostly Holstein-Friesian (HF) cattle were kept, whereas in RLE farms mostly HF and Ayrshire cattle were kept together. In RLCB farms all had crosses of HF with local Kenyan breeds as well as crosses of Ayrshire with local Kenyan breeds.

Table 1. Number of farms with Holstein-Friesian, Holstein-Friesian and Ayrshire, Ayrshire, and crossbred cattle in urban and rural locations

Breeds	**Urban locations (n = 10)**	**Rural locations (n = 12)**
Holstein-Friesian (HF)	7	2
HF and Ayrshire	2	4
Ayrshire	1	0
crosses of HF or Ayrshire with local Kenyan breeds	0	6

Patterns of fodder supply differed among farm types and between seasons (Supplementary Material SM-D, Table S3). In the wet season, ULE farmers mainly provided hay and Napier (fed as cut and carry), whereas RLE farmers provided Napier and their cows were allowed to graze in pastures, and RLCB farmers provided Napier, stover, weeds and grazing. In the dry season, most ULE farmers provided hay and stover, whereas RLE and RLCB farmers provided Napier, stover and grazing. Patterns of concentrates supply differed among farms but did not differ between the wet and dry season. Most ULE farmers provided concentrates consisting of bran, molasses, maize germ, cotton seedcake and dairy meal (a commercially available concentrates), whereas concentrates used in RLE and RLCB farms mainly consisted of dairy meal.

The quantity of fodder offered did not differ significantly among farm types in both seasons, but the quantity, digestibility, ME and CP of concentrates offered were significantly lower for RLE and RLCB farms than for ULE farms in both seasons (Table 2). The ME of fodder was significantly higher for RLE and RLCB farms than for ULE farms in the wet season, and significantly higher for RLE farms than for ULE and RLCB farms in dry season. The CP of total feed offered was significantly higher for ULE and RLE farms than for RLCB farms in both seasons. The ME and CP contents of feeds were comparable to those reported for the region (Klapwijk et al., 2014). The differences in feeding strategies among farm types can be explained by the differences in contexts. Land is scarce, but markets for inputs and outputs are good in urban locations (Foeken and Owuor, 2008; Migose et al., 2018). Land scarcity makes grazing impossible for ULE (Bosire et al., 2016), and fodder and concentrates have to be imported into the systems (Lukuyu et al., 2011). The higher quality and the ease of transport give concentrates an advantage over the lower quality and more bulky fodder. Land is less scarce in rural locations than in urban locations, and fodder availability is higher in rural locations (Migose et al., 2018). The quality to price ratio of concentrates is lower in rural locations than in urban locations, and concentrates, therefore, are a less appreciated substitute of fodder in rural locations(Migose et

Table 2. Quantity and quality of feeds types offered in wet and dry seasons for farms in urban location with exotic cattle (ULE, n=10), farms in rural locations with exotic cattle (RLE, n=6) and farms in rural locations with crossbred cattle (RLCB, n=6)

	Fodder			**Concentrates**			**Total diet**[1]		
	ULE	**RLE**	**RLCB**	**ULE**	**RLE**	**RLCB**	**ULE**	**RLE**	**RLCB**
wet season									
feed offered, kg DM cow^{-1} day^{-1}	14.6	13.7	27.6	6.2^a	0.8^b	1.5^b	22.0	14.5	29.1
digestibility, g kg^{-1} DM	555	615	565	781^a	630^b	689^b	628	615	579
metabolisable energy, MJ kg^{-1} DM	8.4^b	9.3^a	8.5^b	11.8^a	9.5^b	10.4^b	9.4	9.3	8.6
crude protein, g kg^{-1} DM	85	129	89	192^a	129^b	129^b	124^a	129^a	89^b
dry season									
feed offered, kg DM cow^{-1} day^{-1}	14.9	15.7	24.5	6.0^a	0.8^b	1.5^b	20.9	16.5	26.0
digestibility, g kg^{-1} DM	531	611	558	786^a	630^b	689^b	604	612	566
metabolisable energy, MJ kg^{-1} DM	8.0^b	9.2^a	8.4^b	11.9^a	9.5^b	10.4^b	9.1	9.2	8.5
crude protein, g kg^{-1} DM	70	129	83	194^a	129^b	125^b	116^a	128^a	84^b

Different superscripts within a row and within feed type indicate significant differences among farm types ($P < 0.05$);

[1] Total diet values for digestibility, metabolisable energy and crude protein are weighted averages based on the relative occurrence of feed types in the diet. The total diet is supplied during lactation only

al.,2018; Mutua et al., 2010). RLE farmers provided no stovers and weeds to their crossbred cattle, whereas RLCB farmers did (see Supplementary Material SM-D, Table S3). It is not known why RLE farmers did not provide stovers and weeds to their exotic cattle.

5.3.2 Actual, feed-limited and potential production and yield gaps

Farm types also differed regarding actual production: ULE farms had the highest and RLE farms the lowest actual milk production (Table 3). Potential production was highest for RLE and ULE, farms and lowest for RLCB farms. Relative yield gaps were 82% of potential production for RLE farms, 57% for ULE farms, and 47% for RLCB farms. These results imply that, from a biophysical perspective, milk yields can be more than quadrupled in RLE farms, and can almost be doubled in ULE and RLCB farms. Hence, we consider (relative) yield gaps to be very high in RLE farms, and high in ULE and RLCB farms. Relative yield gaps of 40-60% were considered high for maize in African smallholder farms (Tittonell and Giller, 2013).

Feed-quality was an important limiting factor for all farm types. The yield gap was explained for 47% by feed quality in ULE farms, by 34% in RLE farms, and by 63% in RLCB farms. Feed quantity was limiting to a lesser extent in ULE and RLCB farms than in RLE farms (Table 3 and Fig. 1). Feed-limited and actual milk production did not differ significantly for ULE and RLCB farms, which may suggest that diseases and stress were of restricted importance. However, these reducing factors were of importance in RLE farms, which could be related to the

Table 3. Milk production and yield gaps for farms in urban locations with exotics (ULE), rural locations with exotics (RLE) and rural locations with crossbreds (RLCB) (means ± SE)

	ULE (n = 10)	**RLE (n = 6)**	**RLCB (n = 6)**
milk production (kg FPCM cow^{-1} lactation^{-1})[1]			
potential	10220 ± 315	10697 ± 569	6240 ± 401
feed-quality limited	5380 ± 535	7040 ± 876	2346 ± 719
feed-limited	4674 ± 627	3486 ± 570	2262 ± 694
actual	4383 ± 535	1871 ± 378	3293 ± 788
yield gap[2]			
absolute (kg FPCM cow^{-1} lactation^{-1})	5837 ± 666	8826 ± 752	2947 ± 527
relative (%)	56.6 ± 5.5	82.3 ± 3.8	47.2 ± 10.2

[1] FPCM = Fat- and protein-corrected milk; 1 kg FPCM = 1 kg milk × (0.337 + 0.116 × Fat% + 0.06 × Protein%);

[2] Yield gap = Potential - actual production. The relative yield gap is expressed as a percentage of potential production

fact that exotic breeds were less adapted to the harsh conditions in the rural location (Burrow, 2012). Moreover, farmers in rural locations keep exotics for non-production reasons as well, such as insurance, banking function and status (Migose et al., 2019; Oosting et al., 2014; Udo et al., 2011). Farmers in rural locations, therefore, may offer their exotics fodder of relatively high quality (reflected in the higher ME content, Table 2) but in an insufficient amount for high milk production, but enough for non-production functions.

Actual production was higher than feed-limited production in 9 of the 22 farms, and this resulted in partially negative yield gaps (Fig. 1). Partially negative yield gaps may occur if the feed quantities are underestimated by farmers or if the actual milk production is overestimated by farmers. Both underestimation and overestimation of feed supply and milk production may have occurred, because farmers had to recall feed and milk production levels. In addition, negative yield gaps may occur due to underestimation of feed quality values. We, also, cannot rule out the imperfections in the model LiGAPS-Dairy, although model evaluation indicated that its performance was satisfactory, since the values simulated under feed-limited production for TBW, feed intake, and milk production per day were comparable with the actual values for the day of the farm visit (See Supplementary Material SM-E, Table S4).

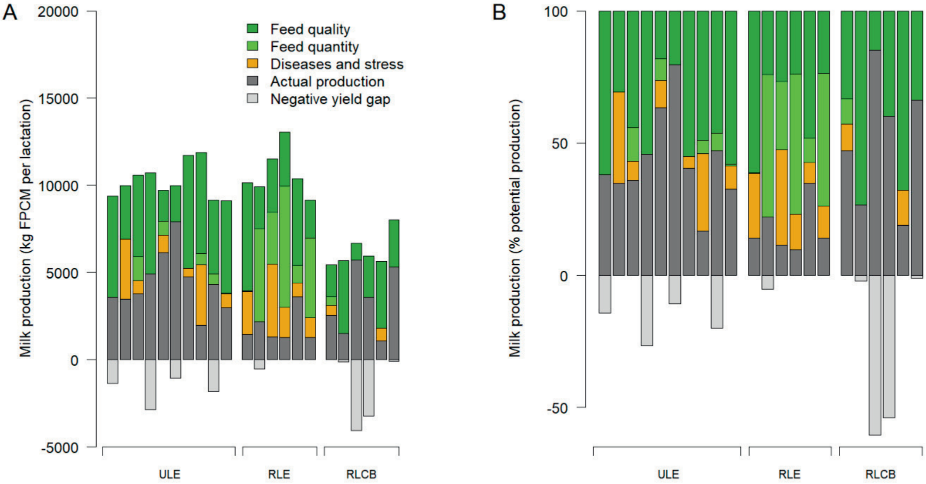

Figure 1. Absolute (A) and relative (B) actual production and yield gaps for farms in urban locations with exotics (ULE), farms in rural locations with exotics (RLE) and farms in rural locations with crossbreds (RLCB). Yield gaps are the difference between potential and actual milk production, due to feed quality, feed quantity, diseases and stress and partially negative yield gaps. Partially negative yield gaps occur if feed-limited production or feed-quality limited production is lower than actual production. Each bar represents a farm

5.3.3 Biophysical factors constraining milk production most

The relative importance of factors that define, limit or reduce production can help prioritise designs of improvement options for mitigation of yield gaps (Van Ittersum et al., 2013). For instance, if heat stress is found to be a defining factor for milk production, milk production can be increased by changing to breeds that are heat tolerant, by improving feed quality to reduce heat production, or by housing animals in stables with cooler ambient temperatures. If dietary protein content, for example, is found to be limiting in a specific period, milk production and growth can be increased by increasing the protein content of the diet during that period. We could not model improvement options regarding diseases and stress because these reducing factors are not included in LiGAPS-Dairy (van der Linden et al., 2019a)

The percentage of days in a phase of a calving interval on which a particular biophysical factor constrained, i.e. defined or limited, milk production and growth most are presented in Table 4. For 1-100 DIM, the two most important constraining factors were protein deficiency and heat stress for ULE and RLCB farms, and protein deficiency and genotype for RLE farms. For >101 DIM, the two most important constraining factors were protein deficiency and genotype for ULE farms, genotype and protein deficiency for RLE farms, and protein deficiency and heat stress for RLCB farms. For the dry period, the two most important constraining factors were genotype and digestion capacity for ULE farms, genotype and energy deficiency for RLE farms, and energy deficiency and genotype for RLCB farms.

The genotype was an important defining factor for milk production and growth, except for RLCB farms. A lack of genotype effects in RLCB farms implies that the genetic potential for milk production of crossbreds was not utilised yet. Hence, upgrading the Kenyan zebu to pure or almost pure exotic breeds may not contribute to increased milk production in the rural location given the feed quality in RLCB farms. Besides, subsistence-oriented farmers who appreciate non-production functions of cows may not be interested in genetic interventions with the objective of additional milk production, since the latter is not their priority (Notenbaert et al., 2017).

Table 4 shows that protein deficiency is the constraining factor that occurs most during lactation. The CP content of total diets varied from 84 to 129 g kg^{-1} DM (Table 2). These values are below the recommended level for milk production (Moran, 2005a). Moreover, heat stress, digestion capacity and energy deficiency

Table 4. Proportion (%) of days in a phase of a calving interval that a particular biophysical factor defined or limited milk production and growth most under feed-limited production for farms in urban locations with exotics (ULE), farms in rural locations with exotics (RLE) and farms in rural locations with crossbreds (RLCB)

Phase in lactation	**Most constraining biophysical factor**	**ULE (n=10)**	**RLE (n=6)**	**RLCB (n=6)**
1 to 100 days in milk (DIM)	genotype	2.0	35.3	0.0
	heat stress[1]	26.9	11.5	57.3
	digestion capacity	12.2	5.3	9.2
	energy deficiency	0.0	0.0	0.0
	protein deficiency[2]	85.8	59.3	90.8
> 101 DIM	genotype	23.5	56.4	0.1
	heat stress[1]	9.1	4.4	49.3
	digestion capacity	19.3	19.3	25.4
	energy deficiency	0.0	0.1	0.2
	protein deficiency[2]	57.6	24.7	74.7
dry period	genotype	80.0	83.3	33.3
	heat stress[1]	0.0	0.0	0.0
	digestion capacity	20.0	0.0	0.0
	energy deficiency	0.0	16.7	50.0
	protein deficiency[2]	0.0	0.0	16.7

[1] In line with expectations, the factor cold stress did not define milk production and growth;
[2] Protein deficiency can concur with the occurrence of heat stress, which explains why the total percentage of all factors is more than 100% in some phases and farm types

were constraining milk production and growth also. Heat stress, is partly determined by the ambient climate, and partly by feed digestibility, since heat increment of feeding is negatively correlated with digestibility. At the same time, feeds with a higher digestibility generally have a lower number of fill units per unit DM, and consequently these feeds are less likely to limit feed intake, milk production, and growth (Conte et al., 2018). During the dry period, cows restore their body condition and gain weight. Constraining factors for this growth were genotype and energy deficiency. In practice, most farmers will not aim for maximum growth during the dry period to avoid excess weight at calving, which may cause birth problems (Muraguri et al., 2004). They feed cows less concentrates, which reduces the overall quality of the diet.

5.3.4 Options for mitigating protein deficiency

Protein deficiency limited milk production in most days of the lactation, while heat stress, digestion capacity and energy deficiency were also important constraints for milk production and growth (Table 4). We explored options to mitigate these factors concomitantly. We opted, therefore, for supplementing cattle diets with fodder legumes and with more concentrates than actually fed because of their high CP content and digestibility, and relatively low number of fill units kg^{-1} DM. In addition, reallocation of the available amount of concentrates among the phases in lactation was explored, as well as supplementing fodder legumes and (more) concentrates in early lactation only or in the whole lactation.

These improved feeding strategies are considered feasible for smallholder dairy farmers in the Kenyan highlands (Brandt et al., 2018; Ericksen and Crane, 2017; Richards et al., 2016; Rufino et al., 2009). In the actual situation, farmers supply concentrates at a flat rate from the start to the end of lactation (Romney et al., 2000). Feeding a flat rate could imply underfeeding during early lactation and overfeeding during late lactation. In the first improvement option, therefore, we redistributed the total actual concentrates supplied for the whole lactation in such a way that it was fed proportionally to the genetic potential for daily milk production, which is represented by the Woods curve. With this reallocation of concentrates, milk production per lactation increased only slightly for RLE and decreased for ULE and RLCB (Table 5). The dietary composition of the fodder and crop residues is of such low quality that feeding concentrates is important to sustain milk production, also during late lactation. Moving from a flat rate to proportional feeding according to the genetic potential shifts part of the supply of concentrates in late lactation to the period around peak lactation. This reallocating of supply of concentrates from late to early lactation resulted in a

Table 5. Relative change in feed-limited milk production (%) for five improvement options for farms in urban location with exotic cattle (ULE), farms in rural locations with exotics (RLE) and farms in rural locations with crossbreds (RLCB)

Improvement option	**ULE (n = 10)**	**RLE (n = 6)**	**RLCB (n = 6)**
concentrates proportional[1]	-0.8 (-4.5 – 2.7)	4.9 (-2.1 – 20.1)	-1.3 (-6.5 – 0.1)
lucerne 100 days[2]	9.1 (1.6 – 18.2)	12.6 (6.5 – 24.6)	25.5 (4.8 – 85.0)
concentrates full lactation[3]	23.0 (10.5 – 45.3)	32.5 (5.5 – 63.4)	34.3 (-0.4 – 131.8)
lucerne full lactation[4]	26.0 (9.2 – 47.5)	39.4 (21.3 – 60.0)	87.9 (17.4 – 292.4)
lucerne + concentrates[5]	32.4 (17.0 – 61.2)	44.6 (13.1 – 86.1)	60.6 (3.9 – 222.1)

[1] Concentrates is fed proportional to the genetic potential for daily milk production instead of a flat rate throughout lactation, leaving the total amount of concentrates fed per lactation constant;

[2] Additional lucerne is fed at 2 kg DM cow^{-1} day^{-1} for 1 to 100 days in milk;

[3] Additional concentrates is fed at 2 kg DM cow^{-1} day^{-1} for the whole lactation;

[4] Additional lucerne is fed at 2 kg DM cow^{-1} day^{-1} for the whole lactation;

[5] Additional lucerne is at fed 2 kg DM cow^{-1} day^{-1} for 1 to 100 days in milk, and additional concentrates is fed at 2 kg DM cow^{-1} day^{-1} for the whole lactation

loss of milk production in late lactation, which was only just (RLE) or not (ULE and RLCB) compensated by increased production in early lactation. This improvement option thus has limited practical scope. Feeding proportional to daily milk production requires specific management for individual cows or for groups of cows in a similar lactation stage, which is likely to be more laborious than feeding at a flat rate. The actual farmers' practice of feeding concentrates at a flat rate may therefore be regarded as a labour-saving practice.

Second, we explored the option of supplying additional fodder in early lactation. We added 2 kg DM of lucerne *(Medicago sativa)* to the actual daily ration per cow for 1-100 DIM. Lucerne is a fodder legume and its CP content was assumed to be224 g kg^{-1} DM. The legume can be sown in pastures in the rural locations to improve dietary quality. Lucerne also adds nitrogen to pastures through symbiotic nitrogen fixation (Mayberry et al., 2017). This option increased milk production per lactation on average by 9 to 26%, depending on the farm type (Table 5).

Third, we explored options for increasing feed supply in the whole lactation. Therefore, we added 2 kg DM concentrates (129 g CP and 9.5 MJ ME kg^{-1} DM) per cow to the actual daily ration throughout the whole lactation (same quality as supplied by farmers). This option increased milk production per lactation on average by 23 to 34%, depending on the farm type (Table 5).

The fourth improvement option was to add 2 kg DM of lucerne to the actual daily ration for the whole lactation. This option increased milk production on average by 26 and 88%, depending on the farm type (Table 5). This option had the highest scope for RLCB because farming systems in RCLB are mostly affected by the constraining factors protein deficiency, heat stress, digestion capacity and energy deficiency (Table 4). Finally, we added to 2 kg DM of lucerne per cow to the daily ration for 1-100 DIM and 2 kg DM of concentrates per cow for the whole lactation. This option increased milk production per lactation on average by 32 to 61%, depending on the farm type (Table 5). This option had the highest scope for ULE and RLE, however, only if economically feasible. Brandt et al. (2018) investigated a comparable feed intervention and the model results showed an increase of milk production by 38%.

In all the feeding options investigated in this study, values varied considerably within farm types, indicating that increases were small in some farms and large in others (Table 5). A wide range of values implies that all options are sensitive to farm contexts. Hence, an option that increases milk production for an average farm may fail for an individual farm. For instance, when concentrates or fodder supply is already relatively high in practice, additional concentrates supply does not increase milk production much further. For such farms, either yield gaps are small or other factors, such as diseases and stress, reduce milk production most, and therefore, such factors should be addressed instead of feed limitation. Options for yield gap mitigation, therefore, should be fine-tuned to the contexts of each farm.

The supply of feeds was increased by 2 kg DM cow^{-1} day^{-1}, to ensure that interventions are practical and feasible for adoption within the contexts of smallholder farms in the Kenyan highlands where fodder is scarce and adoption of concentrates is low (Kashongwe et al., 2017; Lukuyu et al., 2009; Migose et al., 2018). In general, fodder production is constrained by availability of seeds, land, labour, capital, and skills, while feed marketing is constrained by unfunctional value chains (Ericksen and Crane, 2017; Lukuyu et al., 2013; Migose et al., 2018; Mutoko et al., 2014; Romney et al., 2003). Fodder supply can be improved by improving farmers' skills through training and extension, and by improving access to credit facilities, seeds and markets (Ericksen and Crane, 2017; Klapwijk et al., 2014; Odhong' et al., 2019). As a rule of thumb, the addition of 1 kg DM of concentrates of good quality is expected to increase milk production by 2 kg, and it is always economical to use concentrates to increase productivity if the price of milk is good and farmers can sell the milk (Moran, 2005b). If farmers have different objectives of dairy production, i.e. non-production functions, additional concentrates supply may be unfavourable (Migose et al., 2019, 2018).

The present study focused on biophysical constraints of milk production and growth in the lactation period and growth in the dry period (Table 4). Non-production functions of the dairy activity were not addressed, such as banking functions, insurance functions and status (Migose et al., 2018; Oosting et al., 2014; Udo et al., 2011). These non-production functions are positively correlated to herd size and less or not to milk productivity. Hence, if feed supply increases farmers could use the additional feed to keep more animals instead of feeding more per head. If so, herd size increases (Mayberry et al., 2017; Migose et al., 2019), which increases greenhouse gas emissions (Gerber et al., 2011) and competition for land (Brandt et al., 2018; Herrero et al., 2014; Ortiz-Gonzalo et al., 2017).

We chose improved supply of concentrates and lucerne as options since this concomitantly addressed the constraining factors protein deficiency, heat stress, digestion capacity and energy deficiency. However, some farmers treat crop residues, with urea or ammonia, to increase the protein content of diets

(Kashongwe et al., 2017; Romney et al., 2003). It was reported, however, by Oosting (1993) that the effect of this treatment on feed intake and digestibility is limited, and for this reason we did not explore this option in our study. We also did not explore silage making as an improvement option, since it does not increase the CP content, digestibility or fill units of the diet, but it adds to feed availability in the dry season. However, feed supply did not differ much between the wet and dry season in the present study (Table 2), and silage making is therefore not a priority improvement option in Nakuru county.

5.3.5 General discussion

The present study only focuses on interventions to increase milk production by mitigating biophysical constraints, in particular by improving feed quality and feed quantity offered. Adoption of these feed interventions, however, may be hampered because of two reasons. First, social and economic constraints may hinder production or marketing of feeds, such as technical capacity constraints, limited availability of land and labour or institutional and policy constraints. Second, in many cases, feed-related constraints may be associated with socio-economic constraints. Some authors, therefore, suggest that interventions should come in packages that address biophysical and socio-economic constraints (Ericksen and Crane, 2017; Kebebe et al., 2015). For example, in Ethiopia the genetic potential of the dairy cattle population, diseases and feed quality and quantity constrain dairy development (Mayberry et al., 2017; van der Lee et al., 2018), but also policy and institutional environments (Kebebe et al., 2015). The present study shows, however, that the genetic potential for exotics and crossbreds in Kenya is not a constraining factor for milk production, which is in line with literature (Marshall, 2014; van der Lee et al., 2018). Diseases are known to affect milk production in Kenya (Bebe et al., 2003; Odhong et al., 2015) as does feed (Duncan et al., 2016; Lukuyu et al., 2011, 2009; Odero-Waitituh, 2017; Richards et al., 2016) and market quality and institutional environment (Kilelu et al., 2017; Migose et al., 2018; van der Lee et al., 2018). The present study found feed-related constraints as the most important biophysical ones. For Kenya, therefore, we recommend interventions combining disease control and feed improvement to increase milk production (VanLeeuwen et al., 2012) accompanied by a strong enabling environment i.e. policies to improve market quality and institutional support.

The biophysical constraints and interventions to overcome constraints have cultural, legislative and ethical aspects. For example, smallholders who are subsistence-oriented may not consider cattle productivity as a major priority and therefore may not want to invest in the interventions presented in the present study. Moreover, future dairy policies in Kenya may also include legislation concerning animal welfare and environmental issues, e.g. greenhouse gas emissions (Thornton, 2010), which will restrict or facilitate certain developments.

Cattle are generally effective in utilising grassland unsuitable for crops and crop by-products (van Zanten et al., 2016). In Kenya, the area of marginal grasslands is decreasing, and crop by-products are of lower quality than those required to increase milk production for dairy cattle (Bosire et al., 2016; Lukuyu et al., 2011, 2009). Hence, use of cultivated forages and concentrates ingredients is a likely future development in the dairy sector. Such a development will imply, however, that land suitable for production of food crops will be used for feed production. Sourcing of agro-industrial by-products with good feeding value, development of food crops with high value stovers and a reduction in the number of non-productive cattle may be options to limit competition for land between food and feed production. A benefit of such measures to increase productivity is that it lowers the emission of greenhouse gases per kg of milk produced (Gerber et al., 2011).

5.4 Conclusions

This study used yield gaps analysis to identify and prioritise biophysical factors that constrain milk production for dairy cattle in smallholder farms in urban and rural location in the highlands of Kenya. Yield gaps were large (47-82% of potential production), which shows scope for improvements. Feed quality limitation was the major constraints since it explained 47%, 34% and 63% in ULE, RLE and RLCB, respectively. Protein deficiency was the most constraining factor while genotype, heat stress, digestion capacity and energy deficiency also constrained milk production to some extent. Interventions such as supplementing lucerne and (more) concentrates increased feed-limited milk production per lactation on average by 9 to 88%, depending on farm location (urban or rural) and the cattle breed kept on farm. The effect of interventions depends on the quality of the baseline diets and the lactation. Feasibility and adoption of feed interventions will depend on social and economic context of smallholders.

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Supplementary Material SM - from A to E

SM-A. Genetic parameters

Table S6. The maximum genetic potential values for the Holstein Friesian (HF) cows, Ayrshire cows, and crossbreds of these breeds with local zebu cattle

Parameter	Holstein Friesian	Ayrshire	Mixed herd[1]	Crossbreds[1]
milk production (kg FPCM per cow per lactation)[2]	9800[a]	8100[bc]	8950	5000[d]
woods 1[3]	21.32	17.62	19.47	10.88
woods 2	0.2024	0.2024	0.2024	0.2024
woods 3	0.00368	0.00368	0.00368	0.00368
fat content in milk (%)	3.6[e]	4.0[e]	3.8	4.0[e]
protein content in milk (%)	3.2[e]	3.4[e]	3.3	3.5[e]
maximum adult total body weight (kg)	700[d]	600[d]	650	500[d]
reflection coat (%)	30[e]	30[e]	30	35[e]

[1] For a farm where both HF and Ayrshire are present, the values of the two breeds were averaged;

[2] Milk production is based on a standard lactation of 305 days and is corrected for fat and protein;

[3] Parameters Woods equation: Woods 1 × $\mathrm{DIM}^{\mathrm{Woods\ 2}}$ × exp $^{(-\mathrm{Woods\ 3}\times\mathrm{DIM})}$; where DIM is days in milk;

[a] Estimated using data from Dairy Recording Services of Kenya (DRSK);

[b] Rufino et al. (2009);

[c] Amimo et al. (2007);

[d] Kahi and Nitter (2004);

[e] Karugia et al. (2002);

[e] Estimated from the coat colour of the breed based on da Da Silva et al. (2003);

SM-B. Weather variables

Weather variables required as input for LiGAPS-Dairy (Van der Linden et al., in preparation) were solar radiation (kJ m^{-2} day^{-1}), minimum and maximum temperatures (°C), vapour pressure (kPa), wind speed (m s^{-1}) and precipitation (mm day^{-1}).We obtained these weather data for Nakuru county (0.16°S, 36.6°E, 1901 meters above sea level) for the years 2014 and 2015 in which the farm survey was conducted. Weather data, except for precipitation data, were retrieved from the “WeatherOnline” database (https://www.weatheronline.co.uk), whereas the Kenya Meteorological Department (http://www.meteo.go.ke) provided precipitation data. Data were either recorded weekly or at 10-day intervals. We interpolated these data to daily intervals. Cloud cover and a conversion factor for solar radiation from a horizontal surface to coat surface calculated from solar radiation and vapour pressure according to van der Linden et al. (2019).

For model simulations, we required an estimate of the body fat percentage and total body weight (TBW) of the average cow in a farm at the start of the lactation in which the farm survey took place. Body fat percentages and TBW were estimated, therefore, based on the feeding strategies before this lactation. To do this, we required a time series of weather data before 2014. We used these data to simulate growth and milk production of cows from birth up to the lactation in which the farm survey took place. In addition, we needed to simulate the time after 2015, because some lactations extended in the year 2016. We retrieved weather data for the years before and after the survey from the Global Yield Gap Atlas (GYGA, www.yieldgap.org), except for the year 2013, which was missing in the GYGA. As a consequence, we ignored the year 2013 in the simulation.

SM-C. Feed quality

Table S7. Dry matter (DM), metabolizable energy (ME) and crude protein (CP) content of feed types fed to dairy cows in smallholder farming systems in the Kenyan highlands

Feed type	**Scientific name**	**DM (g kg^{-1} fresh matter)**	**ME (MJ kg^{-1} DM)**	**CP (g kg^{-1} DM)**	**Reference**
banana trunk, fresh	*Musa sp*	69	9.9	35	(Feedipedia, 2019)
barley chaff	*Hordeum vulgare*	909	6.5	86	(Feedipedia, 2019)
barley head	*Hordeum vulgare*	871	12.4	118	(Feedipedia, 2019)
bone meal	-	750	12.0	60	(Feedipedia, 2019)
brewers waste (barley)	*Hordeum vulgare*	907	12.0	270	(Feedipedia, 2019; Lukuyu et al., 2012)
cabbage waste	*Brassica oleracea*	10	12.2	119	(Nkosi et al., 2016)
sugarcane molasses	*Saccharum officinarum*	750	9.6	55	(Feedipedia, 2019; Lukuyu et al., 2012)
chicken waste (manure and poultry litter)	-	876	9.1	265	(Feedipedia, 2019; Lukuyu et al., 2012)
commercial concentrates (Dairy meal)[1]	-	880	9.5	129	(Feedipedia, 2019; Lukuyu et al., 2012)
cottonseed cake	*Gossypium spp*	920	10.2	340	(Feedipedia, 2019; Lukuyu et al., 2012)
fish meal[2]	*Rastreneobola argentea*	920	14.5	600	(Feedipedia, 2019; Lukuyu et al., 2012)
pasture (Kikuyu grass)	*Pennisetum clandestinum*	200	9.7	150	(Feedipedia, 2019)
lucerne	*Medicago sativa*	300	13.5	165	(Feedipedia, 2019; Lukuyu et al., 2012)
maize flour	*Zea mays*	900	13.6	112	(Feedipedia, 2019; Lukuyu et al., 2012)
maize germ	*Zea mays*	880	16.2	226	(Feedipedia, 2019)
maize silage	*Zea mays*	300	10.5	80	(Feedipedia, 2019; Lukuyu et al., 2012)
maize stover	*Zea mays*	880	7.6	37	(Feedipedia, 2019; Lukuyu et al., 2012)
maize thinning	*Zea mays*	233	9.6	79	(Feedipedia, 2019; Lukuyu et al., 2012)

rhodes hay	*Chloris gayana*	864	8.1	101	(Feedipedia, 2019)
soybean meal	*Glycine max*	907	14.5	470	(Feedipedia, 2019; Lukuyu et al., 2012)
sunflower cake	*Helianthus annus*	890	9.1	290	(Feedipedia, 2019; Lukuyu et al., 2012)
sweet potato vines	*Ipomea batatas*	160	13.5	165	(Feedipedia, 2019; Lukuyu et al., 2012)
weeds[2]	-	200	9.7	150	(King et al., 2006)
wheat bran	*Triticum aestivum*	880	11.0	165	(Feedipedia, 2019; Lukuyu et al., 2012)
wheat pollard	*Triticum aestivum*	880	12.0	160	(Feedipedia, 2019; Lukuyu et al., 2012)
wheat straws and cane molasses[3]	-	909	6.5	80	(Feedipedia, 2019)
wilted Napier grass	*Pennisetum purpureum*	300	8.2	80	(Feedipedia, 2019; Lukuyu et al., 2012)

[1] Pre-packaged by manufacturers;

[2] Weeds were assumed to have the same nutrient contents as pasture grass (Kikuyu grass);

[3] average quality of protein and ME, treating wheat straw with molasses increases CP to 7%, and reduces DM to 60 for molasses (Sarwar et al., 2006)

SM-D. Feed utilisation

Table S8. Number of farms in the urban and rural location feeding particular types of fodder and concentrates for urban location with exotics (ULE), rural location with exotics (RLE) and rural location with crossbreds (RLCB) in the wet and dry season

Feed type	Wet season			Dry season		
	ULE (n=10)	RLE (n=6)	RLCB (n=6)	ULE (n=10)	RLE (n=6)	RLCB (n=6)
fodder						
hay	6	0	0	6	0	0
lucerne	3	0	0	1	0	0
silage	2	0	0	3	0	0
straw	1	0	0	2	0	0
sweet potato vine	1	0	0	0	0	0
cabbage	0	0	0	1	0	0
banana stem	0	0	0	1	0	0
napier	7	5	5	4	3	5
stover	3	1	4	7	5	3
cut grass[1]	1	1	1	0	0	1
weeds	1	0	4	1	1	0
grazing	0	6	5	0	5	6
maize thinning	0	1	1	1	0	0
concentrates						
bran	8	0	0	8	0	0
sugarcane molasses	8	0	0	8	0	0
maize germ	7	0	0	7	0	0
cotton seedcake	5	0	0	5	0	0
dairy meal	5	5	3	5	3	5
maize flour	3	0	1	3	1	0
sunflower cake	4	0	0	4	0	0
fishmeal	4	0	0	4	0	0
chicken waste	3	0	0	2	0	0
pollard	2	0	0	2	0	0
soy bean meal	2	0	0	2	0	0
bone meal	0	0	0	1	0	0

[1] Harvested grass from communal areas (e.g. roadside, uncultivated public land)

SM-E. Evaluation of the model

The accuracy of model results is to be evaluated thoroughly before model application (Bellocchi et al., 2011; Bennett et al., 2013). The performance of the model LiGAPs-Dairy (Livestock simulator for Generic analysis of Animal Production Systems – Dairy) has been evaluated for Holstein-Friesian (HF) cows in the Netherlands (Van der Linden et al., in preparation), but not for HF cows in Kenya, and neither was the model performance evaluated for Ayrshire or crossbred cows. We evaluated, therefore, the model LiGAPS-Dairy with data from the farm survey. Data collected during the farm survey represent cows under actual production, and the simulated production level closest to the actual production is the feed-limited production (van de Ven et al., 2003). Simulated feed-limited production and actual production at the day of the farm visit were plotted against each other to do an exploratory evaluation of the model performance. Linear regression was used to assess whether the slope of the regression line was equal to one, and whether its intercept was equal to zero. Furthermore, the mean absolute error (MAE) and the relative MAE were calculated (Bennett et al., 2013).

In general, the simulated TBW, feed supply and milk production corresponded reasonably well to the actual values at the day of the farm survey, especially because recall bias may have affected the results for the actual feed intake and milk production (Fig. 2). Simulated TBWs were higher than actual TBWs, except for two farms where the simulated TBWs were below 300 kg (Fig. 2A). The low TBWs in these two farms are explained by feeding a basic ration of low quality in one farm ((ME) content 6.7 MJ kg^{-1} (DM)), and feeding a basic ration of low quantity in the other farm (4.76-5.40 kg DM per cow per day).

Feed intake under feed-limited production often equalled the quantity of feed offered, because the actual amount of feed offered is the maximum amount of feed offered under feed-limited production (van de Ven et al., 2003; van der Linden et al., 2015).

In general, the simulated feed-limited milk production and the actual milk production at the day of the farm visit corresponded broadly to each other (Fig. 2C). The mean absolute error (MAE) and relative MAE for the simulated TBW, feed intake, and milk production under feed-limited production were relatively large due to outliers (Fig. 2, Table S9). For the same reason, regression between simulated and actual values indicated that the simulated values were significantly different from the actual values, except for feed intake (Table S9).

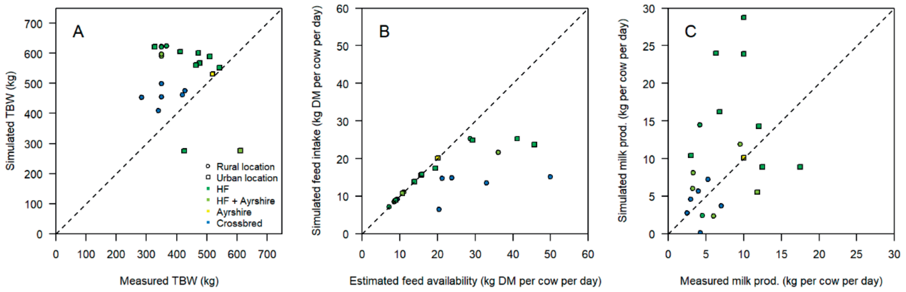

Figure 2. Simulated feed-limited values and actual values for total body weight (TBW) (A), feed intake (B), and milk production (C) at the days of the farm survey. Milk weight is expressed as fat- and protein-corrected milk (FPCM). FPCM = Milk production (kg) × (0.337 + 0.116 × Fat% + 0.06 × Protein%). Dotted lines indicate the 1:1 line. HF = Holstein Friesian

Table S9. Evaluation of model results under feed-limited production with the total body weights, feed intake (simulated) or feed offered (measured) and milk production obtained from the farm survey. The intercept and slope of the regression line refer to the regression line between simulated values and actual values from the farm survey

Values	**Total body weight (kg)**	**Feed intake or feed offered (kg DM cow^{-1}day^{-1})**	**Milk production (kg cow^{-1} day^{-1})[1]**
average actual values[1]	411	21.7	7.13
average simulated values[1]	527	15.1	10.03
average difference[1]	-115	6.6	-2.90
mean absolute error[1]	159	6.6	5.77
relative mean absolute error (%)	38.8	30.6	81.3
intercept regression line equal to 0 (*P*-value)[2]	<0.001	0.066	<0.001
slope regression line equal to 1 (*P*-value)[2]	<0.001	0.084	<0.001

[1] fat- and protein-corrected milk (FPCM)= Milk production (kg) × (0.337 + 0.116 × Fat% + 0.06 × Protein%);

[2] *P*-values lower than 0.025 indicate that the intercept of the regression line between actual and simulated values is significantly different from zero, and that the slope is significantly different from one

Chapter 6

General discussion

Rural location non-PD farms and farmers

Urban location and positive deviant farms and farmers

Field work (interviews, observations and challenges)

6.1 Background

In Kenya, the average consumption of milk products is about 115 kg/person/year, which is higher than the average of 37 kg/person/year in Africa (Cornelsen et al., 2016; FAOSTAT, 2019; Njarui et al., 2011). Nevertheless, the national demand for milk in Kenya is increasing, because of population growth (~2.5% per year) and rising incomes. Consequently, the increase in milk demand (~3 to 4 %) is higher than the increase in milk production (GoK, 2013b). The majority of milk in Kenya is produced in mixed crop-livestock (MCL) systems with small herds of improved dairy cattle breeds (GoK, 2013b). To meet the increasing demand for milk production, the present government policies aim to double productivity of dairy cattle by 2030 and to increase market-oriented dairy production in smallholder MCL farming systems (GoK, 2013b; GoK, 2007). Increasing dairy cattle productivity and market-oriented production in smallholder MCL farming systems, however, face many biophysical, economic and social constraints (Burke et al., 2015; Olwande et al., 2015; Oosting et al., 2014; Udo et al., 2011). Various options have been formulated to overcome these constraints, such as using exotic breeds and improved fodders, and strengthening dairy value chains, institutions and policies (Bosire et al., 2019; Brandt et al., 2018; Ericksen and Crane, 2017; Kebebe et al., 2015; Kilelu et al., 2017b). Interventions have been implemented by many development projects, but so far the adoption rate of these interventions remained low (FAO, 2017; Herrero et al., 2014; Kebebe et al., 2017; Klapwijk et al., 2014; McDermott et al., 2010).

In the introduction of this thesis, I hypothesized that the low adoption rate of interventions is, at least in part, due to the limited understanding of the variation in MCL farming systems and the context they operate in, and the fact that variation between MCL farming systems is not taken into account in development projects. Variation among MCL farming systems is determined by their market quality for inputs and outputs, their availability of production factors (e.g. land and labour), and their biophysical context (Duncan et al., 2013; FAO, 2001; Herrero et al., 2014; Rufino et al., 2009; Tittonell et al., 2009; van de Steeg et al., 2010). These aspects are associated with spatial variation, i.e. they differ among locations. Consequently, farming systems in different locations will have different constraints and different targeted interventions to overcome these constraints. The number of scientific studies relating spatial variation to variation in farming system development, constraints for development and targeted interventions, however, is limited (Duncan et al., 2013; van der Lee et al., 2018).

The aim of this thesis, therefore, is to understand the variation in farming system development, constraints for development and targeted interventions, in order to increase market-orientation and dairy cattle productivity of smallholder MCL farming systems in Kenya. This chapter starts with a discussion about the variation in farming systems development and their specific constraints. Subsequently, some methodological challenges around data collection are addressed. Finally, implications for dairy development in Kenya are presented, and an overview of the conclusions of this thesis is given.

6.2 Variation in the MCL farming system development and their constraints

Variation in farming systems is determined by their market quality for inputs and outputs, their availability of production factors, and their biophysical context (Duncan et al., 2013; Tittonell et al., 2010; van de Steeg et al., 2010). Market quality for inputs and outputs and availability of production factors are associated with spatial variation, i.e. they differ among locations (Jiang et al., 2013; Staal et al., 2002). In Chapter two, I hypothesized that spatial variation regarding distance to an urban market influences farm development in terms of input use, dairy cattle productivity and economic performance. To study this hypothesis, I used a spatial framework, and I selected MCL farming systems in the urban location (UL), mid-rural location (MRL) and extreme-rural location (ERL). I held in-depth interviews with farmers and organized focus group discussions with groups of stakeholders to collect narratives and data about market quality, availability of production factors, farm performance and functions of dairy cattle.

In UL, markets were functional, implying that markets for inputs and for selling of milk were available. Informal market chains with high milk prices milk were predominant. Inputs like fodder, replacement stock and labour were scarce, whereas high-quality concentrates were costly. Furthermore, the availability of grazing land was limited, and the opportunity costs for family labour were high. Consequently, milk production, per cow and per farm, was relatively low, and farm development was constrained by the scarcity of fodder, replacement stock and hired labour, and the availability of production factors, such as land and family labour.

In rural location (RL), which comprised of MRL and ERL, markets were also functional. We, however, found both formal and informal market chains with relatively low milk prices. Inputs like fodder, replacement stock and labour were available, whereas low-quality concentrates were cheap. Furthermore, the availability of grazing land was adequate, and the opportunity costs for family labour were low. Consequently, milk production, per cow and per farm, was relatively low, and farm development was constrained by the low quality of concentrates and low prices of milk.

Variation in farming systems also results from variation in biophysical conditions, such as prevailing climate, genotypes, quantity and quality of available feeds and diseases (van de Ven et al., 2003). In Chapter five, I conducted a yield gap analysis to determine the variation regarding these biophysical conditions among farming systems within locations. I selected farms with exotic cattle in UL (ULE) and RL (RLE), and farms with crossbred cattle in RL (RLCB). Results of Chapter five show that feed was the most important biophysical constraint for increasing milk production per cow in all farm types. The analysis showed that feed quality limitation explained 34% of the yield gap in RLE, 47% in ULE, and 63% in RLCB. Detailed analysis of feed quality limitation indicated that protein deficiency was the most frequently occurring constraining factor during the lactation. Supplementing lucerne, with or without concentrates, increased feed-limited milk production by 32% for ULE, 45% for RLE and 88% for RLCB. Therefore, I concluded that supplementation with lucerne and concentrates was relevant to increase the productivity of exotic and crossbred cattle. Sourcing affordable protein supplements of good quality is thus a priority for increasing productivity.

Finally, I hypothesized that farming systems within a specific location also differ, because of the different ways farmers cope with constraints. To study this hypothesis, I conducted a positive deviance (PD) study to analyse how some farmers overcome local and generic constraints, whereas others do not. I classified farmers in UL and RL as PDs and non-PDs, based i) on experts' and/or peers' perception and ii) on economic performance. All farmers were interviewed to determine farm and household characteristics. In UL, five out of seven (71%) of the perceived PDs were classified as economic PDs. The main factors distinguishing economic PDs from non-PDs were relatively large herd size, high milk yield per cow and good balance between costs and revenues, which enabled PDs to realise higher gross margins than non-PDs. PDs achieved better control of cost with good animal husbandry practices, such as feeding, breeding and veterinary care. Input use (i.e. level, quality and cost), high milk price, good level of knowledge and skills, and financial stability enabled PDs to practice good animal husbandry. I concluded that PDs in UL overcame constraints by increasing herd size and intensity of production, whereas non-PDs lacked the skills and financial stability to increase herd size and milk production per cow.

In RL, 4 out of 13 (31%) perceived PDs were economic PDs. Economic PDs in RL had large herds since maintaining a large herd contributes to non-economic functions (particularly store of wealth and insurance) and to economic functions (farm milk output) of the dairy activity of the farm. The cows of RL economic PDs attained low productivity because of low input use. The inputs for increasing productivity, such as high-quality concentrates, were too expensive relative to the low price of milk, presenting economic risks to farmers. Therefore, many of the perceived PDs were economic non-PDs because of low productivity and high cost of production. I concluded that PDs in RL overcame constraints by increasing herd size, whereas non-PDs lacked the skills and financial stability to increase herd size.

In summary, the research chapters of this thesis show that the following aspects could constrain dairy development of smallholder MCL farming systems: fodder quality and availability, market quality (underdeveloped forage market in UL, low price of milk and low quality of concentrates in RL), farmers' financial stability and farmers' skills (required for cost reduction). These results are in agreement with results of previous studies, which I will discuss in the next paragraphs.

First, fodder quality and availability are commonly reported constraints to dairy development in the East African highlands, and are caused mainly by land scarcity which makes cultivation of sufficient quantities of high quality fodders unfeasible (Bosire et al., 2016; Brandt et al., 2018; Klapwijk et al., 2014; Mayberry et al., 2017). Specifically in urban locations, fodder quality and availability are shown to be major constraints to dairy development (Duguma et al., 2017; Gillah et al., 2012; Kashongwe et al., 2017; Lukuyu et al., 2011, 2009). Moreover, my observation that, within the feed related constraints, protein deficiency was the most limiting factor for increasing milk production per cow concurs with Rufino et al. (2009).

Second, market quality also limits dairy development in Ethiopia and India (Duncan et al., 2013); farmers in areas with good market quality fed larger quantities of concentrates per cow and had larger herd sizes than farmers in areas with poor market quality. In urban locations in Ethiopia, moreover, undeveloped forage markets were shown to constrain dairy development (Duguma et al., 2017; Duguma and Janssens, 2016). In contrast to our findings, others found that genetic potential of the dairy cattle population and diseases constrained dairy development in Ethiopia and India (Ericksen and Crane, 2017; Mayberry et al., 2017; van der Lee et al., 2018). This difference can be explained by the fact that unlike in Ethiopia and India, the Kenyan dairy herd consists to a large extent of exotic cattle (Kebebe et al., 2015). The fact that disease was not a major constraint in my study could be due to the high level of adoption of veterinary care in Kenya (Kebebe et al., 2017).

Third, low milk price is a documented concern for dairy development in rural areas in Kenya (Staal et al., 2003). The low price of milk is attributable to an undeveloped infrastructure, such as roads and electricity supply (Gollin and Rogerson, 2014; Holloway et al., 2000). Poor roads and electricity supply limit development of formal dairy value chains that need collection and cooling centres or processing plants for milk (Kilelu et al., 2017a; van der Lee et al., 2018). Where milk price is low, farmers may be unwilling to invest in inputs and choose to remain subsistence, using low quality concentrates (Lukuyu et al., 2011; Mutua et al., 2010; Staal et al., 2003), a phenomenon I observed in RL in the present study.

Fourth, farmers' financial stability and resource endowment are important supportive factors for dairy development (Cortez-Arriola et al., 2015; Tittonell et al., 2009; Udo et al., 2011). Financial stability and resource endowment ease access to land to produce fodder, to physical capital (livestock, equipment and assets), and to savings needed to acquire necessary inputs (Cortez-Arriola et al., 2015; Tittonell et al., 2009; Udo et al., 2011). Positive deviant small ruminant farmers in west Africa, for example, were the ones keeping large herds as an accumulation of wealth (Amankwah, 2013). Odhong' et al. (2019) reported that the majority of smallholder dairy farmers in Kenya face financial capacity constraints.

Fifth, success in economic performance, as a result of good management and balance between costs and revenues, is attributed to knowledge and skills of farmers (Birhanu et al., 2017; Chagunda et al., 2016; Kilelu et al., 2013). Farmers acquire knowledge and skills through education, training and extension services and experience (Bebe et al., 2016). Studies of MCL farming systems have indicated that the level of education and access to training and extension services is generally low (Birhanu et al., 2017; Chagunda et al., 2016; Kilelu et al., 2013). Moreover, farmers who access extension services have shown better productivity and economic performance than those who do not (Bebe et al., 2016).

Besides all constraints mentioned above, lack of an enabling environment, i.e. weak policies and institutions to support dairy development is an important constraint for dairy development (Kebebe et al., 2015).

The findings in this thesis demonstrate that variation in MCL farming systems between and within locations cause multiple, context-specific constraints to dairy development. This conclusion has development implications since it supports the need for interventions for dairy development that come as a package addressing multiple constraints concomitantly and that are tailor-made to target a group of farmers that have a specific context. Before I will elaborate these development implications of my research findings, I will first reflect on the methodological aspects of my study.

6.3 Methodological challenges

I used a spatial framework to study the variation in farming systems between locations. Van der Lee et al. (2018) applied a comparable spatial framework and obtained results consistent with mine.

There were some challenges in terms of data collection. A large-scale household survey covering hundreds or thousands of households was impossible because of time and resource limitations (Hammond et al., 2017). To overcome these challenges, multiple sources of data were used in this study to validate and cross-verify the results, a technique that is referred to as triangulation (Mathison, 1988). In Chapter two, in addition to data collected via surveys, data were collected from focus group discussions with stakeholders in the dairy value chain. I, therefore, used results obtained from focus group discussions to triangulate results from survey data. In Chapter three, both quantitative and qualitative data were collected, and results of qualitative data were used to triangulate results of quantitative data. Results of these two Chapters are consistent with the study hypothesis and with literature.

Besides spatial variation, temporal variation is also found in farming systems, such as seasonal variation in feed availability or quality (Maleko et al., 2018), and, variation in daily milk production throughout a lactation (Zezza et al., 2016). Hence, data from longitudinal surveys from many farms would be ideal (Ojango et al., 2019). However, conditions in many developing countries make frequent farm visits cumbersome and expensive, which results in many studies being cross-sectional (only one measurement in time) (Kosgey et al., 2011; Ojango et al., 2019; Opoola et al., 2019; Zezza et al., 2016). There are recent attempts to standardize survey tools to allow for combination of data from different studies that use a similar design (Fraval et al. 2018). However, these studies still cannot address temporal bias. Regular recording of milk production at farms by farmers can be a way to collect data to get insight into the temporal variation among farming systems (Ojango et al., 2019). Smallholders in MCL farming systems, generally, do not do regular recording of milk production (Opoola et al., 2019). For this thesis, longitudinal surveys or farm monitoring of milk production and feed utilisation was not conducted. Recall methods, i.e. asking farmers to recall performance data for the recent past, e.g. one year till present, can be applied in absence of regular records.

Due to a lack of regular longitudinal records, I had to use such recall data in all the chapters of this thesis. Recall methods are associated with the so-called recall bias, which may be caused by subjective estimation, and also memory failure (de Nicola and Giné, 2014; Godlonton et al., 2018). In Chapter four, the levels of accuracy of milk production in a lactation estimated from recall data were tested, and the levels of inaccuracy were found to be acceptable, i.e. relative mean absolute errors were 20% for records of limited recall moments per lactation and 25% for records of a single recall moment per lactation compared to 15% for records of limited test-days per lactation and 20% for records of a single test-day per lactation. Hence, I used recall data in this thesis.

Recall data may be adequate to estimate actual lactation production. However, to get insight into the potential and feed-limited lactation production I simulated milk production in the yield gap analysis in Chapter 5 using the model LiGAPS-Dairy (Van der Linden et al., in preparation). Simulation of reality through modelling is a robust tool to predict effects and to analyse the actual situation (Maria, 1997). For simulation of potential or feed limited production, recall data about both lactation production and feed intake are needed. Because of accumulation of errors the simulated feed-limited milk production was in some cases lower than the estimated actual milk production, which is impossible in reality.

Results of the various research chapters in this thesis, in general, are consistent in the way that they all show similar differences in constraints between and within locations, and the importance of feed, market for inputs and milk, skills and resources as constraints (Cornelsen et al., 2016; FAOSTAT, 2019; Njarui et al., 2011). It seems, therefore, justified to conclude that, by using multiple research methods, my studies have resulted in consistent findings despite the imperfect data.

6.4 Implications for dairy development in Kenya

In section 2 of this general discussion, I concluded that constraints for dairy development differ between and within locations. Different constraints imply different interventions. Hence, interventions differ between urban and rural locations, and between PDs and non-PDs. Nevertheless, it is unlikely that all farmers will be reached by interventions, even when targeted to specific groups.

Dorward et al. (2009) identified three main development pathways for smallholder farmers: 'hanging in', 'stepping up' and 'stepping out'. 'Hanging in' implies that farmers maintain livelihoods based on their socio-economic circumstances. 'Stepping up' implies that farmers invest in assets to expand activities to increase production and income, and in the process, they improve their livelihoods. 'Stepping out' implies farmers engage in current activities to accumulate resources required to engage in other activities that require more resources than the current activities. 'Stepping out' farmers were not considered in this thesis because I only studied farms presently farming.

Non-PDs are 'hanging in'. They are predominantly subsistence and not very motivated or capable to increase production (Oosting et al., 2014; Udo et al., 2011). Hence, non-PDs are relatively difficult to target for interventions aimed to increase market orientation and may not enter into formal dairy value chains. The PDs, on the other hand, may be following the 'stepping up'-pathway. They are commercial, market-oriented and motivated to increase production (Amankwah, 2013; Oosting et al., 2014). Hence, PDs are more likely to uptake interventions and enter into formal dairy value chains and will require functional dairy value chains and access to fodders and concentrates of high quality. These PDs will also be more likely to be farmers with exotic cattle. UL farmers, even the non-PDs, have no choice and need to become market-oriented because they lack conditions, most of all land, for subsistence farming. So, 'hanging in' is no choice for UL farmers and they either have to step-out or follow a 'stepping up' strategy. So, all UL farmers, PD and non-PDs can be addressed with interventions that help them 'stepping up'.

In the next section, I will first describe intervention strategies for farmers in the 'stepping up'-pathway, i.e. farmers in UL and PDs. This will be followed by a description of interventions for famers in the 'hanging in'-strategy, i.e. non-PDs in RL.

6.4.1 Interventions for UL and PDs

Urban locations, generally, have a good market quality for milk and concentrates, but fodder availability is a major constraint. In RL, the quality of fodder and concentrates and market quality for milk are the major constraints. Fodders cannot be easily produced in UL because the opportunity cost for land is too high for fodder production. Besides, intensive methods of fodder production under land scarcity, such as hydroponics, may be too costly or technologically challenging for smallholder farmers (Naik et al., 2015). Since land is less scarce in RL, and, consequently, the opportunity cost is low, forage production could be organised in RL to be marketed in UL (Lukuyu et al., 2011, 2009). Hence, developing market-oriented fodder production, for example of lucerne in rural locations and strengthening the value chain and markets for fodder are potential interventions (Duguma et al., 2011; Lukuyu et al., 2011). In both locations, availability and quality of fodder will improve, whereas an additional cash crop (i.e. the fodder) is creating additional income opportunities for rural farmers. The private sector should be involved in the fodder value chain development (Ayele et al., 2012). Such a fodder value chain will link rural to urban locations and vice versa. Private feed companies could build on such fodder value chains to improve and diversify the supply of concentrates in all locations at a fair price-quality ratio. Independent institutions should control quality of feeds being traded in feed value chains (Mutua et al., 2013, 2010).

Linking of rural locations to urban locations depends on quality of the infrastructure, such as roads and electricity supply (Von Braun, 2007). Developing roads eases transport of inputs and milk and consequently reduces transaction costs (Von Braun, 2007; Wasike, 2001). Improving electricity supply enhances development of formal dairy value chains because processors and cooperatives can establish collection, cooling and processing centres for milk (Kirubi et al., 2009). Such centres could serve multiple purposes: they could become a dairy hub even operated by farmer organisations or cooperatives of which farmers are members, where milk and fodder are collected, and where services and inputs can be acquired by farmers (Kilelu et al., 2017b; van der Lee et al., 2018). Development of roads and electrification requires public resources and long-term planning, which may require support from international development agencies and financiers (Wasike, 2001).

In addition to resources, non-PDs in UL need to develop skills to achieve good husbandry, optimal input use and to balance costs and revenue (Chapter three). Good husbandry practices, such as feeding, breeding and veterinary care, are facilitated by knowledge which is obtained through education and training. Moreover, to balance production costs and revenues, farmers require entrepreneurial skills for financial planning, for development of controlled cost strategies, for improving efficiency and for selling milk at maximum profit. These production and entrepreneurship skills could be achieved through extension services and innovation platforms (Bebe et al., 2016; Van Paassen et al., 2014). Such services and innovation platforms could be supplied by the aforementioned dairy hubs, farmer organisations and cooperatives (Kilelu et al., 2017b; van der Lee et al., 2018).

Results of this thesis imply that interventions for UL and PDs should be tailored for commercial production. PDs and UL farmers are market-oriented, and if the fodder constraint is elevated, they may have high input use and high output per cow and per farm.

6.4.2 Interventions for RL and non-PDs

In RL, specifically for non-PDs, relatively low input use is likely, and output per cow will be relatively low, but farmers maintain relatively large herds. These large herds meet many objectives of subsistence farmers, i.e. manure, and capital store, whereas income from milk is only of secondary importance. Feed and market interventions may not easily reach such subsistence non-PDs because the interventions address more the production function than the subsistence functions of cattle. Interventions for RL and non-PDS, therefore, should address production function and subsistence function of cattle both.

One intervention that could address both production and subsistence functions is to improve the financial stability of farmers, to facilitate the aspiring non-PDs to step up and to allow the very poor non-PDs to subsist. Financial stability of non-PDs can be achieved through access to affordable and favourable credit facilities under check-off arrangements administered by cooperatives (where credits are recovered from milk revenues) (Odhong' et al., 2019). In addition, since financial stability and capability to acquire inputs are related, the cooperative movement by organising the check-off system, facilitates access to high-quality inputs, such as concentrates, improved fodder seeds, artificial insemination, and veterinary care (Kilelu et al., 2017a; Odhong' et al., 2019). Credit facilities, also, can be affordable and favourable if loans offered by banks, micro-finance institutions or savings and credit cooperatives (SACCOs) are packaged to have favourable interest rates and terms of repayment, among others (Markelova et al., 2009; Odhong' et al., 2019). Finance institutions could offer multiple services: asset-based financing that combines credit facilitation, livestock insurance and farmers' financial training.

In addition, livestock farmers could improve their financial stability by benefiting from government social protection programs that seek to enhance the capacity of the poor and the vulnerable to improve and sustain their livelihoods and welfare. These could be in the form of cash transfer, grants, input waivers or subsidies, among others (Aliber and Hart, 2009; Klapwijk et al., 2014; Markelova et al., 2009; Odhong' et al., 2019).

An alternative option for an intervention for poor non-PDs livestock farmers will be to enhance their resource endowment. Two main resources required for substance livestock production are grazing areas and breeding stock for establishing herds (Klapwijk et al., 2014). Traditionally, grazing was communal and accessible to even the very poor farmers. At present, land is private and communal grazing lands are scarce; farmers owning little land have their cattle grazing along roadsides or illegally in forest reserves. To intervene for these poor subsistence dairy cattle farmers, projects could be established that improve farmers access to grazing areas. Such projects could develop strategies for sustainable and integrated management of forest grazing. Here, subsistence farmers could be allowed to have small herds grazing in the forest whiles they manage the forest by planting trees (for timber and fodder) and grasses. In this way, fodder availability and cow productivity will increase. In addition, projects could be established that have breeding and selection programs with local breeds: maintaining the disease tolerance and low feed requirements and increase cow productivity. Alternatively, projects could have programs for crossbreeding that cross exotic cattle and F1 exotic-zebu crossbreds back to zebu cattle (Kahi and Nitter, 2004). Locally adapted zebu cattle or zebu-exotic backcrosses with limited exotic genes are having high disease tolerance and low feed requirement (Rege, 2001).

An additional intervention that targets dairy cattle production and subsistence functions is to develop farmers' skills. RL and non-PDs who aim to step up need to develop skills for dairy husbandry, e.g. good feeding, breeding and veterinary care in order to maintain or increase productivity and to prevent mortality. In addition, non-PDs could benefit from commercial fodder production as small progress towards 'stepping up'. Projects could establish Farmer Field Schools to empower farmers with skills for dairy husbandry and fodder production (Davis et al., 2012).

6.4.3 Spatial distribution of future milk production in Kenya

Dairy production in the UL is currently economically viable because the informal markets provide favourable prices for milk and consumers prefer low cost over high quality of milk. Developing dairy in UL, thus, implies developing informal markets. Informal markets have low quality milk, which is not favoured by the existing government policies due to food safety concerns (GoK, 2010; Nyokabi et al., 2018). The government may be unable to restrict informal milk markets and consumers may not demand for milk of high quality. Therefore, developing formal dairy value chains in UL could be difficult and the informal milk markets in UL could persist. However, formal dairy value chains may develop if the government restricts informal milk markets and milk quality may improve if consumers demand for it. If the formal dairy value chains establish in UL, UL-farmers will lose the price advantage of the informal dairy value chain but still have higher production costs. Combined with the land and labour scarcity, UL farming systems then will be outcompeted by rural farms or may be forced to develop to intensive industrial systems with high productions per farm (Oosting et al., 2014). Because of the feed import at such farms from outside, nutrient accumulation may occur, which will lead to environmental pollution and introduce challenges with waste management in UL and soil mining in RL (Clay et al., 2019; Novotny, 1999). Hence, the sustainable development of UL dairy requires considerations of environmental issues.

In MRL, which is an intermediate zone between UL and ERL, farmers and other commercial producers can organise fodder production (Lukuyu et al., 2011, 2009; Wambugu et al., 2011). Simultaneously, in MRL, formal dairy value chains are developed and infrastructure is likely to develop further; hence, transaction costs will reduce and milk price may increase. In MRL, besides, nutrients can be recycled between livestock and crop production and environmental pollution and soil mining can be minimised (Thorne and Tanner, 2002). Therefore, MRL could be the optimal zone for dairy development.

The ERL is the zone at the greatest distance from urban markets and, therefore, it has the least developed infrastructure and highest transaction costs (Gollin and Rogerson, 2014; Von Braun, 2007). Given the high transaction costs, intensified dairy production will likely not be feasible in ERL, which makes the zone less suitable for dairy development when compared to MRL (Von Braun, 2007). ERL, thus, could be prioritised for production of food crops, such as maize and potatoes, and to some extent, cash crop, such as tea or feed crops, but also fodder legumes and feed grains. By focusing on multiple functions, farmers in ERL can maintain large herd sizes of exotic or crossbred cattle in a low input and low output production system. These systems can still give a reasonable gross margin in ERL, as long as the price of milk is favourable and the opportunity cost of land and labour for other farming activities are low.

6.5 Conclusions

The aim of the thesis was to understand the variation in farming system development, constraints for development and targeted interventions for development, in order to increase market-orientation and dairy cattle productivity of smallholder MCL system in Kenya. From the findings, the main conclusions reached are summarised as follows.

- In urban locations, farm development was constrained by the scarcity of fodder, replacement stock and hired labour, and the availability of production factors, such as land and family labour whereas in rural locations, farm development was constrained by the low quality of concentrates and low milk prices.
- Supplementation of diets of dairy cattle with lucerne and concentrates was relevant to increase productivity of exotics and crossbreds, thus, sourcing affordable protein supplements of good quality is a priority for increasing productivity.
- In urban locations, positive deviants overcame constraints by increasing herd size and intensity of production for market orientation whereas, in rural locations, positive deviants overcame constraints by increasing herd size for multiple functions. In urban locations, besides, non-positive deviants lacked skills and financial stability to increase herd size and intensity of production whereas, in rural locations, non-positive deviants lacked skills to increase herd size.
- For urban locations and positive deviants, interventions could address rural-urban value chains with development of infrastructure to ease market access, whereas, for rural locations and non-positive deviants, interventions could address production and subsistence functions of dairy cattle.

Summary

Mixed crop-livestock (MCL) systems with small herds of improved dairy cattle breeds produce the bulk of Kenya's milk. Kenyan dairy policies aim to increase the national milk production by stimulating the milk production at smallholder MCL farming systems through increasing productivity per cow and market orientation. Many development programmes and projects have suggested interventions to achieve increased cow productivity and increased market orientation. However, the adoption of such interventions has been relatively low. This low adoption of interventions could be due to the fact that variation between MCL farming systems is not taken into account in development projects and this could be due to the limited understanding of the variation in MCL farming systems and the context they operate in. Our hypothesis was that variation between MCL farming systems is determined by variation in market quality for inputs and outputs, variation in availability of production factors, and variation in biophysical context. These aspects are associated with spatial variation. Consequently, farming systems in different locations will be different, will have different constraints and different targeted interventions to overcome these constraints. However, the number of scientific studies relating spatial variation to variation in farming system development, constraints for development and targeted interventions is limited.

The aim of this thesis was to understand the variation in farming system development, constraints for development and targeted interventions for development, in order to increase market-orientation and dairy cattle productivity of smallholder MCL system in Kenya.

The first step to study this objective was to get insight into the spatial variation in farming systems. Chapter two had the objective to determine the influence of distance to urban markets on smallholder dairy farming system development. I used a spatial framework, and I selected MCL farming systems in urban location (UL, <15 km from the urban market of Nakuru town), mid-rural location (MRL, in between 20 and 50 km west of Nakuru) and extreme-rural location (ERL, > 50 km west and south-west of Nakuru). I held in-depth interviews with 30 farmers and organized 8 focus group discussions with groups of stakeholders to collect narratives and quantitative data about market quality, availability of production factors, farm performance and functions of dairy cattle. In UL, markets for inputs and for selling of milk were available and functional. Informal market chains with relatively high milk prices were predominant. Inputs like fodder, replacement stock and labour were scarce, whereas high-quality

concentrates were costly. Furthermore, the availability of grazing land was limited, and the opportunity costs for family labour were high. Consequently, milk production per cow and per farm were relatively low. In rural location (RL), which comprised MRL and ERL, markets were also functional. Here, I found both formal and informal market chains with relatively low milk prices. Inputs like fodder, replacement stock and labour were available, whereas low-quality concentrates were cheap. Furthermore, the availability of grazing land was adequate, and the opportunity costs for family labour were low. In RL, milk production per cow and per farm were relatively low.

I concluded that in UL, farm development was constrained by scarcity of fodder, replacement stock and hired labour, and the limited availability of production factors, such as land and family labour while in RL, farm development was constrained by the low quality of concentrates and low prices of milk.

Second, I looked at how different farmers within a location cope with constraints. I distinguished so-called positive deviants (PDs), which are farmers that overcame constraints and/or were perceived successful for dairy production and non-PDs, that were farmers that had not overcome these constraints. Chapter three had the objective to identify strategies that PD farmers deploy to overcome dairy production constraints. I classified farmers in UL and RL as PDs and non-PDs, based i) on experts' and/or peers' perception and ii) on economic performance. All farmers were interviewed to determine farm and household characteristics. In UL, five out of seven (71%) of the perceived PDs were classified as economic PDs. The main factors distinguishing economic PDs from non-PDs were relatively large herd size, high milk yield per cow and good balance between costs and revenues, which enabled PDs to realise higher gross margins than non-PDs. PDs achieved better control of cost with good animal husbandry practices, such as feeding, breeding and veterinary care. Input use (i.e. level, quality and cost), high milk price, good level of knowledge and skills, and financial stability enabled PDs to practice good animal husbandry. In RL, 4 out of 13 (31%) perceived PDs were economic PDs. Economic PDs in RL had large herds, since maintaining a large herd contributes to non-economic functions (particularly store of wealth and insurance) and to economic functions (farm milk output) of the dairy activity of the farm. The cows of RL economic PDs attained low productivity because of low input use. The inputs for increasing productivity, such as high-quality concentrates, were too expensive relative to the low price of milk, presenting economic risks to farmers. Therefore, many of perceived PDs were economic non-PDs because of low productivity and high cost of production. Results suggest that in UL, PDs overcame constraints by

increasing herd size and intensity of production, whereas non-PDs lacked the skills and financial stability to increase herd size and milk production per cow. In RL, PDs overcame constraints by increasing herd size, whereas non-PDs lacked the skills and financial stability to increase herd size.

Third, to study variation among farming systems regarding their potential milk production given their biophysical context, accurate estimates of milk production in a lactation (MPL) are essential. Chapter four had the objective to assess this accuracy of MPL-estimates for four alternative data recording methods i.e. a limited number of test-days (TDs) per lactation, a single TD per lactation, a limited number of recall records per lactation, and a single recall record per lactation. At cow level, the relative mean absolute errors (RMAEs) for test-day data were 15% for records of limited TDs per lactation and 20% for records of a single TD per lactation. The RMAEs for recall data were 20% for records of limited recall moments per lactation and 25% for records of a single recall moment per lactation. At herd level, the RMAEs were 13% for records of a single test-day per lactation and 25% for records of a single recall moment per lactation. The results of chapter four suggest that the level of accuracy of estimating MPL based on recall data are acceptable.

Finally, Chapter five had the objective to identify to which extent the various biophysical factors define and limit milk production of dairy cattle in order to explore improvement options that contribute to mitigating yield gaps in smallholder systems in the Kenyan highlands. I selected farms with exotic cattle in UL (ULE) and RL (RLE), and farms with crossbred cattle in RL (RLCB). Actual feed and lactation data were collected through questionnaires administered in 42 farms, 22 in UL and 20 RL. Not all farms met criteria for inclusion and I did the YGA with 22 farms, 10 in UL and 12 in RL. I simulated potential and feed limited MPL, calculated the potential and feed limited yield gaps, and partitioned yield gaps according to biophysical factors. Feed was the most important biophysical constraint for increasing milk production per cow in all farm types and feed quality limitation explained 34% of the yield gap in RLE, 47% in ULE, and 63% in RLCB. Protein deficiency was the most frequently occurring constraining factor during the lactation and supplementing lucerne, with or without concentrates, increased feed-limited milk production by up to 32% for ULE, 45% for RLE and 88% for RLCB. Results of Chapter five suggest that supplementing feeds was necessary to increase productivity of exotic and crossbred cattle. Sourcing affordable protein supplements of good quality is thus a priority for increasing productivity.

In Chapter six, implications of variation in farming systems between and within locations for increasing productivity per cow and market orientation in Kenya are discussed. Difference in constraints for dairy development were found between UL and RL and between PDs and non-PD implying that different interventions should be addressed to the different farming systems. UL farmers and PDs likely are following the stepping-up livelihood strategy while RL non-PDs are hanging-in. For stepping-up, relevant interventions could include: i) developing market-oriented fodder production in RL and market the fodder in UL by strengthening the value chain and markets for fodder, ii) develop infrastructure to develop formal dairy value chains, and iii) develop training and extension aimed at farmers but also at other value chain actors to improve animal husbandry, marketing and entrepreneurial skills. Interventions for RL non-PDs should address both production function and subsistence function of cattle. The reason is that such farmers likely will only gradually transition from subsistence farming objectives to market-oriented farming objectives. Such interventions could include: i) improve the financial stability of farmers, e.g. organise and improve the access to affordable credit facilities, ii) improve farmers access to grazing areas, and iii) to breeding and selection programs with local breeds or crossbreeding, and iv) establish Farmer Field Schools to enhance farmers' skills for dairy husbandry and fodder production. In summary, interventions for UL and PDs should be tailored for commercial production, since PDs and UL farmers are market-oriented, and if the fodder constraint is elevated, they may have high input use and high output per cow and per farm while interventions for RL non-PDs should be tailored for production and subsistence functions with large herds of dairy cattle.

The future dairy development in Kenya will follow diverse pathways. UL farming systems linked to the informal dairy value chain will persist unless government policies aimed at increasing milk quality for consumers forces UL farmers into formal dairy value chains. If this happens, UL farming systems will be faced with lower milk prices and be likely outcompeted by RL farming systems or may be forced to develop to intensive industrial systems with high productions per farm and as such, their sustainability will require considerations of environmental issues. MRL seems an optimal location for dairy development because land availability allows for fodder production, which could be further developed, formal dairy value chains are present and could be further developed, and also the infrastructure can and will be developed further. In MRL, moreover, livestock is coupled to land, hence nutrients can be recycled between livestock and crop production, and environmental pollution and soil mining can be minimised. In ERL, because of high transaction costs, intensive dairy production will likely not be feasible but the location could be prioritised for production of food, cash and feed crops with a focus on large herds for multiple functions.

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Salome Migose

Wageningen, the Netherlands, 10 March 2020

About the author

Salome Atieno Migose was born on June 12 1977 in Siaya, Kenya. She completed her KCPE in Rageng'ni Primary School in 1991, and her KCSE in Lwak Girls high school in 1995. She joined Egerton University to study a BSc in Animal Production at the Faculty of Agriculture in 1997 and graduated in 2004. She enrolled for MSc in Animal Science in the same University. During her MSc study, she evaluated the genetic aspects of growth of Sahiwal cattle in semi-Arid Kenya. She graduated in 2011. Between 2007 and 2011, she was employed in private organisations as a trainee manager in insect production, project coordinator in HIV-AIDs prevention, and program administrator. In 2011, she was employed by the government of Kenya as a livestock production officer. In 2012, she was selected as a beneficiary of the fellowship from the Netherlands Organisation for International Cooperation in Higher Education (NUFFIC) under the project "Build capacity to deliver competent graduates for enhanced competitiveness in the dairy value chain", a collaboration between Egerton University and Wageningen University. She started her PhD study at the Animal Production Systems group of Wageningen University in 2012. Her PhD study focused on understanding smallholder farming systems to improve dairy development in Kenya. Results of her work have been presented at the 66th Annual meeting of European Federation of Animal Production (EAAP) in 2015, at Tropentag in 2015 and at the WIAS Science day in 2019. Two manuscripts related to the chapters of her PhD thesis are published and two manuscripts are submitted to peer-reviewed scientific journals. While doing her PhD, in 2014, she joined the University of Embu as tutorial fellow in the Department of Agricultural Resource Management, the School of Agriculture, where she lectures till to date. Her areas of specialisation are Livestock production systems, Animal breeding, Analysis of livestock value chains, and Matching breeding practices with production systems.

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Publication list

Peer -reviewed journal publications

Migose, S.A., Bebe, B.O., de Boer, I.J.M., Oosting, S.J., 2018. Influence of distance to urban markets on smallholder dairy farming systems in Kenya. Tropical Animal Health and Production 50, 1417-1426

Migose, S.A., van der Linden, A., Bebe, B.O., de Boer, I.J.M., Oosting, S.J., 2020. Accuracy of estimates of milk production per lactation from limited test-day and recall data collected at smallholder dairy farms. Livestock Science 232, 103911. https://doi.org/10.1016/j.livsci.2019.103911

Migose, S.A., Bebe, B.O., de Boer, I.J.M., Oosting, S.J., 2019. A positive deviant approach to understanding key factors to successful smallholder dairy farming in Kenya. Submitted

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Abstracts in conference proceedings

Migose, S.A., de Boer, I.J.M., Bebe, B.O., Oosting, S.J., 2019. A positive deviant approach to understanding key factors of smallholder dairy development in Kenya, in: WIAS Science Day 2019. Wageningen University & Research, pp. 23–23

Migose, S.A., Bebe, B.O., Oosting, S.J., 2015. Sustainable dairy intensification in Kenya: Typologies of production systems and breeding practices, in: Book of Abstracts 66th Annual Meeting of the European Federation of Animal Science. p. 342

Migose, S.A., Bebe, B.O., Oosting, S.J., de Boer, I.J.M. (2015). Sustainable dairy development in the Kenyan highlands: Effect of market quality on smallholder farming systems. Abstract from Tropentag 2015, Berlin, Germany

Education Certificate

Competed training and supervision plan[1]

The Basic Package (3 ECTS)
WIAS introduction course, Wageningen, October 2012
Ethics and Philosophy in Life Sciences Wageningen, November 2015

International conferences (2.4 ECTS)
Annual Meeting of the European Association for Animal Production, Warsaw, August 2015
Tropentag, Berlin, September 2015

Seminars and workshops (1.5 ECTS)
Food in Africa, Wageningen, October 2012
Dairy Value chain project stakeholder workshop, February 2015
Departmental seminars, University of Embu, 2015
KLV seminar on agricultural extension in sub-Saharan Africa, June 2015
WIAS Science Day, Wageningen, February 2016
WIAS Science Day, Wageningen, March 2019

Presentations (4 ECTS)
Oral presentation at Annual Meeting of the European Association for Animal Production (2015)
Poster presentation at Tropentag (2015)
Poster presentation at WIAS Science Day (2016)
Oral presentation at WIAS Science day (2019)

In-Depth Studies (10.5 ECTS)
WIAS Advanced Statistics Course Design of Experiments, October 2012
Genetic Improvement of Livestock (MSc course), November-December 2012
Tropical livestock farming system research and development, February 2013
Animal breeding and sustainable food security, October-November 2014

Professional Skills Support Courses (4.6 ECTS)
Information Literacy including EndNote Introduction (ILP), December 2012
Project and Time Management (P&TM), January- February 2013
Pedagogy, Embu University, September 2014
Techniques for Writing and presenting a scientific paper, October 2015
Training on effective examination setting and processing (January 2018)

Research Skills Training (6 ECTS)
Preparing own PhD research proposal, July 2013

Didactic Skills Training (2.1 ECTS)
Lecture BSc students on: Principles of Animal Production, Livestock Production Systems (October 2013- May 2018)
Organizing a workshop for farmer in Nakuru and Embu (2015, 2016)

Total 34.1 ECTS

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[1] With the activities listed, the PhD candidate has complied with the requirements set by the Graduate School of Wageningen Institute of Animal Sciences (WIAS). One ECTS equals a study load of 28 hours.

Colophon

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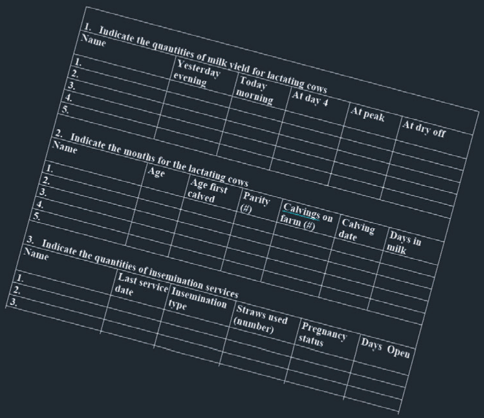

1. Indicate the quantities of milk yield for lactating cows

Name	Yesterday evening	Today morning	At day 4	At peak	At dry off
1.					
2.					
3.					
4.					
5.					

2. Indicate the months for the lactating cows

Name	Age	Age first calved	Parity (#)	Calvings on farm (#)	Calving date	Days in milk
1.						
2.						
3.						
4.						
5.						

3. Indicate the quantities of insemination services

Name	Last service date	Insemination type	Straws used (number)	Pregnancy status	Days Open
1.					
2.					
3.