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Upgrading the smallholder dairy value chain: a system dynamics ex-ante impact assessment in Tanzania's Kilosa district

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Research Article

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Abstract

This paper examines ex-ante impacts of two policy interventions that improve productivity of local-breed cows through artificial insemination (AI) and producers' access to distant markets through a dairy market hub. The majority of cattle in Kilosa district in Tanzania are local low productivity breeds kept by smallholders and agro-pastoralists. Milk production is seasonal, which constrains producers' access to distant urban markets, constrains producers' incomes and restricts profitability in dairy processing. We developed and evaluated an integrated system dynamics (SD) simulation model that captures many relevant feedbacks between the biological dynamics of dairy cattle production, the economics of milk market access, and the impacts of rainfall as an environmental factor. Our analysis indicated that in the short (1 year) and medium (5-year) term, policy interventions have a negative effect on producers' income due to high AI costs. However, in the long term (5+ years), producers' income from dairy cattle activities markedly increases (by, on average, 7% per year). The results show the potential for upgrading the smallholder dairy value chain in Kilosa, but achievement of this result may require financial support to producers in the initial stages (first 5 years) of the interventions, particularly to offset AI costs, as well as additional consideration of post-farm value chain costs. Furthermore, institutional aspects of dairy market hub have substantial effects on trade-offs amongst performance measures (e.g. higher profit vs. milk consumption at producer's household) with gain in cumulative profit coming at the expense of a proportional and substantial reduction in home milk consumption.

Most poor rural households depend on agriculture for their livelihood (Townsend *et al*., 2013; Peña-López, 2016). Agriculture is particularly important as an employer of those with limited education and in locations with few off-farm employment opportunities (World Bank, 2006). In arid rural areas agriculture, and particularly livestock, may be the only viable income generating opportunity. A report by the International Livestock Research Institute (Njehu and Omore, 2018) confirmed Tanzanian rural households' reliance on agriculture for livelihoods and emphasized the importance of livestock, including in Kilosa district of the Morogoro region. The location of Kilosa and other surveyed districts are shown on the map of Tanzania (online Supplementary Fig. S1).

Tanzania has one of the largest cattle populations in Africa, at about 25 million head, 98% of which are indigenous breeds primarily the East African Shorthorn Zebu (*Bos indicus*) (Ministry of Livestock and Fisheries Development, 2015). Cattle make significant contributions to the economy of Tanzania, particularly its rural economy, although this is constrained by the low productivity associated with these breeds. Dairy production in Tanzania, particularly in its drier regions, features seasonal imbalances, and market access issues (whereby wet season surpluses are unable to be sold on markets beyond those available locally) and dry season shortages. These marketing conditions, characterized by seasonally low marketable surplus from unproductive cattle breeds, consign producers to remaining largely pre-commercial (Njehu and Omore, 2018), which in turn restricts investment in potential improvements.

Milk volumes are important aspects of marketing structures because of the cost implications of utilization of processing capacity. Njombe *et al.* (2011) reports that limited raw milk supply leads to underutilization of milk processing plants in Morogoro region where Kilosa district is located. Total capacity of milk processing plants in the region is about 7000 liters/d but on average just 17% of this capacity is utilized (Njombe *et al*., 2011). Such effects influence investment behavior in the dairy value chains and incentives for producer actions such as uptake of technology that would in turn raise marketable surplus. Organizational change to generate cost savings and enhance market access offers potential benefits to milk processors, small-scale milk traders and producers, as well as to households as milk consumers.

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The importance of improving livestock productivity, strengthening value chains and enhancing market access to improve income and nutrition of rural households has been widely recognized (IFAD, 2004; Townsend, 2015). Smallholders' capacity and willingness to invest in improved productivity often is limited, and has been shown to be constrained by low levels of marketable surplus (Hamza *et al*., 2014). Barrett (2008) also argued that producers' reliance on their own production and purchases in the market for nutrition, can override commercial considerations to the extent that price increases may not benefit smallholder producers in terms of income nor prompt market engagement.

In this study, we conduct ex ante analysis of technology adoption for enhanced productivity, and formation of smallholder dairy hubs to improve market access, in Kilosa district. The concept of producer cooperatives and hubs is discussed further in the online Supplementary File. These two improvements, and interactions between them, constitute a case of improved 'efficiency and effectiveness' as proposed by Jonathan and Kumburu (2016) that will orient collective action toward a contribution to development goals. The analysis contributes to policy formulation and the method employed advances analysts' understanding of interactions amongst economic and technical features of smallholder livestock systems. The objectives of this paper are to examine potential benefits of transition mechanisms for pre-commercial extensive smallholder dairy farmers to become commercial and semi-intensive, a market hub solution that improves Tanzania's extensive dairy systems with respect to improving cow's productivity and market access, and the implications of attempts to transition to more commercial semi-intensive system and market hub solution on producers' income for the case of Kilosa district, which features low productivity breeds, highly seasonal rainfall – and hence milk production – and associated difficulties with market access.

Analysis of the role of agriculture in development has frequently focused on *ex post* static macro-economic analysis of growth of agricultural GDP and its effects on poverty and rural households' income (World Bank, 2007; Diao *et al*., 2010; Valdés and Foster, 2010; Christiaensen *et al*., 2011). There is limited ex-ante dynamic microeconomic analysis of the impact of specific policies, and particularly those related to localized interventions such as organizational change and technological adoption. In the current study we expand on work by McRoberts *et al*. (2013) and Hamza *et al*. (2014) to develop and use a system dynamics approach to smallholder dairy households' livelihoods in Tanzania's Kilosa district. Moreover, we focus on the roles played by market hubs in market access as a pre-requisite to value chain-based development that explicitly considers rewards, incentives and actions at multiple points in the value chain. In particular, we evaluate market hubs and contract farming (organizational changes), artificial insemination (a technological change), and interactions amongst these interventions over time. In our model, cattle breed is improved by means of artificial insemination and using exotic breeds of bull.

Materials and methods

We employed a dynamic value chain framework, using a system dynamics modeling approach, that measures the projected changes in, and performance of, smallholder dairy value chains within a network of market actors over time (Rich *et al*., 2011). Such primary industry networks have been depicted as systems (Xu, 2013), for the purposes both of management (Olson and Swenseth, 2014) and policy (Baker *et al*., 2017). A 'system' is defined as 'a collection of parts that interact with one another to function as a whole' (Maani and Cavana, 2007). System dynamics (SD) is a methodology that studies the dynamic interactions and feedback effects amongst components of a system (Sterman, 2000).

The central concepts of SD are stocks, flows and feedback loops. Stocks are accumulations (inventories, such as numbers of animals in a region) at a point in time. Stocks change by way of flows which alter the levels of stocks in a given time period (e.g. number of cattle entering (inflow to) or exiting (outflow from) a region over time). Flows are regulated by feedback loops in which a model element initiates changes which in turn modify one or more of its elements in future periods that eventually alters the element that induced initial change. There are two types of feedback loop: reinforcing (R) or positive; and balancing (B) or negative feedback loops. An example of R is where higher animal population leads to more births which further increases population, and this in turn leads to more births in subsequent periods. In contrast, B is a self-correcting loop: higher animal population leads to more deaths, which in turn lowers population (Sterman, 2000). The utility of SD in this assessment is profound in capturing the long delay time until the benefits of AI materializes. SD also facilitates the simulation of the dynamic impact of various policy options and counts for underlying feedbacks of production system. In a similar vein, SD approach facilitates to capture dynamic complexity of the system under study in which long-term effect of an intervention often differs from short- and medium-term.

Our model adapts concepts from Sterman (2000) while our general value chain structure draws on Kaplinsky and Morris (2001). We represent physical production (cattle herd dynamics, forage and feed resources, and milk production) and markets (milk) in Kilosa district. The model was constructed during multiple meetings, following Group Model Building (GMB) approach in Vennix (1996), over 5 d with International Livestock Research Institute (ILRI) researchers in Nairobi, Kenya. Participating ILRI researchers were selected for their expertise on Tanzanian smallholder dairy value chains and their knowledge of animal breeding, health and feeding technologies. The GMB process included sessions to familiarize users with SD and GMB, problem definition, model conceptualization, model evaluation, formalization and policy design and implementation. Then the results were communicated back to the participants in the subsequent periods (in late 2015 and early 2016) through workshops and meetings for further feedback. Model data and parametric specifications were drawn from an Njehu and Omore (2018) survey of four districts in Tanzania's Morogoro region. Kilosa district was selected for detailed analysis because it best exhibits extensive and pre-commercial smallholder production system out of the four districts.

The model features operational modules for (1) products, (2) markets, (3) feed inputs, and (4) policy and institutions. The latter module enables representation of scenarios examined using the model, and combinations of modules 1–3 mobilize the calculation of performance measures for the dairy value chain. Performance is defined as departures from corresponding baseline magnitudes. Performance measures include production, based on changes in milk production under policy interventions, cumulative profit (discounted over time), household milk consumption (including that given away to neighbors), achievement of a higher proportion of genetic potential (breed improvement), and milk traded *via* various channels.

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Model structure and data

The production (cattle, forage, and milk sector) and market (dairy market and profit generation) modules of the model illustrate the aggregate herd size, milk inventory and trading channels, respectively, of the cattle owners in Kilosa district (Fig. 1). Stocks (rectangles) reflect the state of the system at a given point in time, and represent an accumulation of services, goods, funds, or knowledge. For example, *Breeding cows* represents the number of breeding cows held by producers, whereas *Produced milk* represents the quantity (in liters) of milk (produced and) held by producers as inventories. Flows denote changes over time and regulate the inflow and output of goods or services from a stock. For example, *calving* represents number of claves delivered over time, whereas *milk production* represents quantity of milk produced over time. The connectors (thin arrows) represent information feedback loops – feedback loops are circular causalities that regulate flows through delayed circular causal (and often nonlinear) relationships among model components. The notation (//) denotes delays in the system due to biological cycles and causalities and the time between the arrival of information at a decision maker and that actor's making of a decision and implementing it. In the figure we show breeding cow stock as an aggregated producer's stock of lactating and dry cows to simplify model portrayal. In our model, we have separate stocks of dry and lactating cows in which cattle move in and out each stock as a result of calving and drying. In essence, at the background of stocks and flows, a set of integral ($\text{Stock}_t = \text{INTEGRAL}(\text{Inflow} - \text{outflow}) + \text{Stock}_{t-1}$) and differential equations ($d(\text{stock})/dt = \text{Net Change in Stock} = \text{Inflow}(t)\text{-Outflow}(t)$) operate the model (Sterman, 2000). A full list of model equations is available in online Supplementary Materials and Methods.

The stock and flow structure in the upper half of Fig. 1 represents categories of cattle in producers' stocks. At any point in time, the model calculates producers' stock of calves, pre-adults, adults, and breeding cows. In general, males are sold when they reach adult age, but females are kept for breeding and milking purposes. The breeding rate is a variable affected by a number of factors including male to female ratio and availability of resources, particularly forage. The model targets the flow of milk from producers to the market, which represents the part of producers' income that is from the dairy herd, and we concern ourselves with milk income only. Producers also gain income from other sources, such as cattle sales (culled breeding stock and surplus males). We did not include revenue from cattle sales in our model due to lack of data. Cattle herd structure is also depicted in the simplified portrait of the model.

Online Supplementary Table S1 presents the values used for the model's main variables and their initial values (upper section) and parameters (lower section).

In Kilosa district, feed for cattle is predominantly from pasture (with small recourse to crop residues) and is referred to here as an aggregated quantity of 'forage' – measured in aggregated kg of feed (dry matter). The stock and flow structure along the bottom of Fig. 1 depicts forage production: seasonal rainfall determines the growth rate of forage and forage mass on the area of pasture land. Hence, producers' cattle stocks interact not only with the market, but also with the environment by way of forage mass. In an adaptation of Helldén (2008) our model considers the environmental constraints of livestock based on rainfall, which affects vegetation cover which in turn influences forage mass on pasture lands and so its constraints (i.e. the interaction and switching dominance between B1 and R1 feedback loops). The interaction between total animal population and environmental constraints introduces dynamic changes to cattle mortality and reproduction: as the ratio of cattle population to feed resources rises, fecundity declines and mortality increases (this is introduced to the model through a set of non-linear variables that normalizes feed consumption per cattle (i.e. feed consumption per cattle/initial (feed consumption per cattle)) and then transforms this ratio to a non-linear – power function – variable that affects fecundity and mortality parameters), and vice versa. Similarly, as feed per cattle (i.e. feed to desired feed ratio) declines, milk yield declines and vice versa.

Milk production is determined by lactating cows held as producer stocks, forage mass, and supplementary feed: with productivity governed by genetic potential and subject to change in model scenarios. This is particularly important in Tanzania because the total quantity of milk produced has been rising over time due to increases in herd size rather than in productivity (Njombe *et al*., 2011). The more breeding (lactating) cows in a producer's herd the more milk is produced, and vice versa, but the model recognizes that increased cattle population at a given environmental constraints would reduce cows' productivity, all other things being equal.

The majority of smallholder producers in Tanzania follow a traditional dairy system where the majority of produced milk is consumed at home. Only 10% of milk produced by the traditional dairy system in Tanzania is sold to urban markets and the remainder is retained for household consumption, calves or non-commercial uses (Njombe *et al*., 2011). Specifically, our survey results in Kilosa district revealed that about 62% of milk produced is consumed at home, 15% is sold to local traders, and 23% is sold to local consumers (mostly neighbors) (Njehu and Omore, 2018).

The stock and flow structure in the lower right-hand side of Fig. 1 represents producers' market channels for milk. It also features alternative or new market channels (stocks of *dairy market hub center* and *processors* and flows of *milk sales rate to market hub*, *milk sales rate to processors*, *selling to individual buyers*, and *selling to consumers*) based on structural changes of the value chain introduced through policy intervention. Similarly, artificial insemination affects the model in two ways. First, it increases production costs. Second, it affects breeding rate of local breed (i.e. a successful AI will reduce breeding rate of local breed and increase breeding rate of mixed-breed). Multiple feedback loops govern the model structure (Fig. 1), including R1, R2, B1, B2, B3, and B4:

> *Reinforcing feedback loop 1 (R1)* regulates cattle breeding and reproduction. A higher breeding cattle population leads to more reproduction and a higher cattle production. This in turn increases, albeit after some time lag – biological delay, breeding cattle population in subsequent periods which then further accelerates cattle reproduction.
>
> *Balancing feedback loop 1 (B1)* regulates cattle production by taking into account forage mass constraints. A higher cattle population lowers forage mass per cattle and dry matter intake which in turn limits reproduction rate. This leads to a lower cattle population in subsequent periods which in turn increases forage mass per cattle, and raises reproduction rate.
>
> *R2* governs the feedback loop whereby producers' profit influences cattle production. Higher numbers of breeding cattle increase milk production, which leads to more milk sales. This in turn increases producers' profit which, after a time

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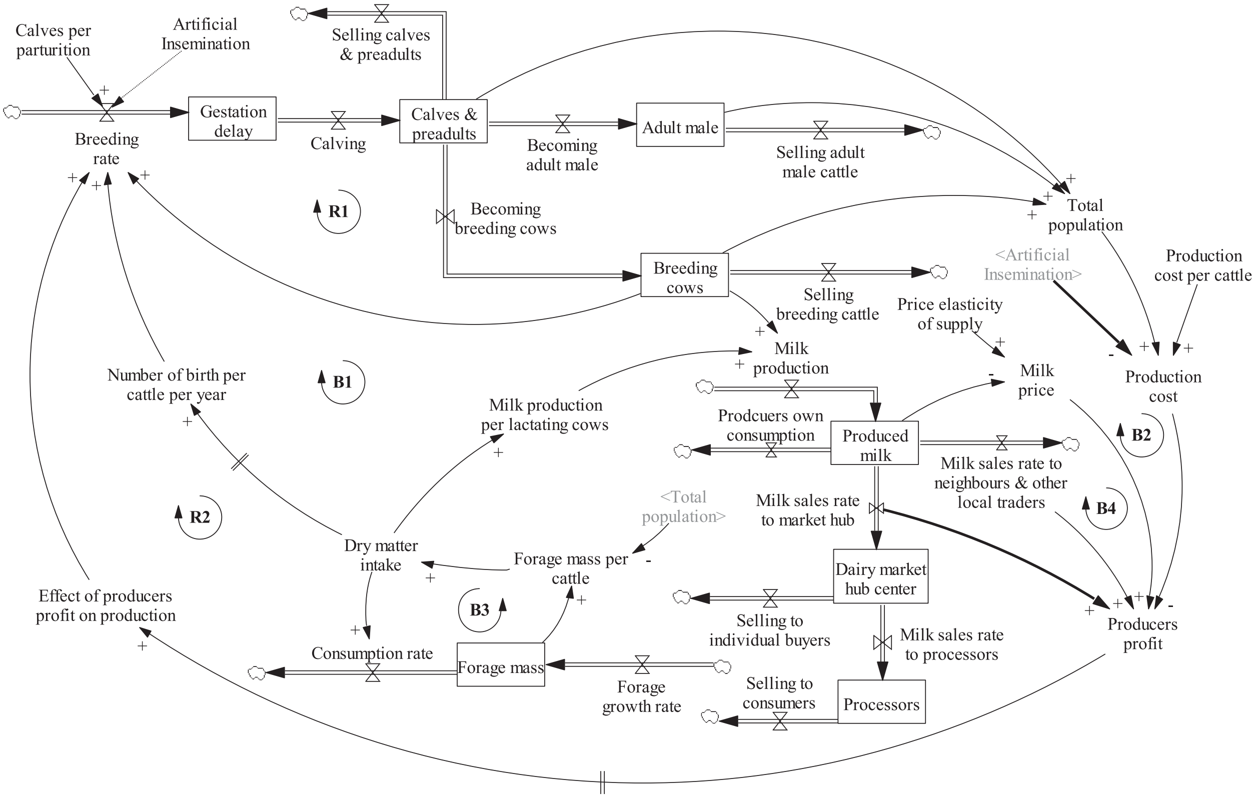

Fig. 1. Main model components and feedback interactions. Stocks (rectangles) reflect the state of the system at a given point in time, and represent an accumulation of services, goods, funds, or knowledge. Flows denote changes over time and regulate the inflow and output of goods or services from a stock. The connectors (thin arrows) represent information feedback loops and the notation (//) denotes delays in the system due to, for example, biological cycles.

lag, motivates cattle producers to increase cattle production. This in turn further increases breeding cattle stock in subsequent periods. The intuition behind this feedback loop is implicit herd management practice in which higher profit encourages producers to better manage their herd, while lower profit discourages proper management.

B2 constrains growth in cattle population by way of production cost, which increases with higher cattle population and reduces producers' profit. This in turn reduces, albeit after a time lag, producers' incentives to increase cattle production which lowers cattle population in subsequent periods.

B3 governs forage mass per head of cattle. Its balancing loop mechanism is that higher forage mass increases forage mass per head which in turn increases dry matter intake. This then lowers forage mass in subsequent periods.

B4 regulates milk price based on changes in milk production. An increase in milk supply leads to a decline in milk price which in turn lowers producers profit than what it would normally be (we used price elasticity of supply of −0.0653 (Twine, 2016)). This in turn balances investment in cattle production which lowers, after some time lag, milk production and hence increases price in subsequent periods.

Baseline and intervention scenarios

Our model describes a number of performance measures in a baseline scenario. We then ran the model on two intervention scenarios (described fully in Table 1): implementing an artificial insemination (AI) to improve cows' milk productivity, and collective action to establish a dairy market hub. We measured producers' profit over time (at weekly intervals to show the short term effect of AI) and cumulative profit over the simulation time horizon (10 and 20 years). Here we report the baseline (business as usual) scenario and then compare it with performance measures derived from the alternative intervention scenarios. Desirable future extensions of the model include the addition of processed dairy products; inclusion of input and service providers' actions in intensification of production; inclusion of the costs of establishing and operating the dairy market hub and inclusion of processors' and retailers' profits so as to measure whole-chain profits.

Results and analysis of simulation

We ran the model over a twenty-year time horizon (1040 weeks) from 2015 to 2035. Policy interventions (AI and market hub) began at year 2018. We report model results to compare impacts of each scenario relative to the baseline (scenario 1). We report results of milk production over time, producers' profit over time, and indicators of genetic progress and household milk consumption in each scenario. In all figures, trend line 1 represents scenario 1 (baseline), 2 represents scenario 2 (AI), and 3 represents scenario 3 (AI and market hub). We conducted several SD model evaluation procedures as suggested in Sterman (2000) and Forrester and Senge (1996). The results of each evaluation test are presented in the online Supplementary File Appendix 2.

Milk production in scenario 1 is seasonal in nature because of seasonal rainfall and hence forage mass (Fig. 2a) (i.e. B1 and B3

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Table 1. Baseline and policy intervention scenarios description

Scenarios	Description
Scenario 1: baseline	Parameterized using actual data collected from predominantly pre-commercial cattle producers in Kilosa district. About 62% of milk produced is consumed at home, 15% is sold to local traders, and 23% is sold to local consumers (mostly neighbors).
Scenario 2: artificial insemination (AI)	Producers use AI to achieve higher genetic potential of dairy cows' milk productivity. Producers inseminate 50% of their breeding cows with AI each year, commencing in 2018 (week 156 in the model). The cost of AI per service is 18 USD, and its success rate is 60%. From each successful AI service, a (female) newborn calve will be a higher-producing crossbred that produces more milk than its local breed dam – baseline data records that such improved dairy cows produce 3.7 times more milk than do local breeds. Cross-bred cattle death rates is about 20% lower than death rate parameters of local cows (see figures reported in Supplementary Table S1) and cross-bred cattle calving interval is about 14 months (calving interval of local breed is about 18 months). Cross breed production cost is 50% (100% more in case of lactating cross-bred cows) more than local breed to meet extra energy need to ensure higher productivity.
Scenario 3: AI and dairy market hub	Includes AI intervention (scenario 2). We implement establishment and operation of a dairy market hub to collect and transport milk to local consumers, processors, and to urban markets. Any milk that is neither consumed at home nor traded through existing channels (neighbors and local markets) will be delivered to dairy market hubs. This milk appears as additional volume due to AI. As an operating assumption[a], the dairy market hub collects milk to trade to individual consumers (20% of milk collected) and peri-urban and urban processors (80%). We also test this policy under a simulated more commercial contract farming situation in which producers sell a specified percentage of their milk to the dairy market hub. This allows us to evaluate how performance indicators changes when producers are under contractual agreement to supply milk.

aThis assumption is consistent with field notes which indicate that during high production seasons, sometimes, milk remains unsold. However, when more milk is produced, there will be extra milk traded at diminishing rate to existing trading channels and producers increase their own household milk consumption rate. Any milk surplus left will be traded to dairy market hub which in turn sells milk to individual consumers and processors.

feedback loops are dominating the seasonal pattern of milk production). Scenarios 2 and 3 display similar seasonal milk production, but milk production increases steadily after about 2023 due to the use of AI after 2018 and consequent increases in milk productivity. Milk production in scenarios 2 and 3 increases at an increasing rate from 2023 to 2033 as an increasing number of cross bred cattle reach productive age over time. However, from 2033 onwards, feed constraints limit further growth in milk yield because an increasing cattle population reduces forage mass, effectively encountering the system's production capacity due to a feed constraint that becomes binding with increased production (i.e. B1 feedback loop dominates the behavior which limits its further growth in milk yield).

From 2015 to 2018, all three scenarios generate the same profit over time (Fig. 2b). From 2018 to 2025, scenarios 2 (AI) and 3 (AI and market hub) have lower profit over time than the baseline (scenario 1) because of the costs of AI (B2 feedback loop becomes stronger due to high AI costs). From 2026 onwards, profits in scenario 2 (AI) slightly exceed those of the baseline scenario because AI intervention increases milk production and trading. Similarly, from 2024 and onwards, profit over time of scenario 3 (AI and market hub) greatly exceeds baseline scenario because the additional milk production due to the AI intervention is able to be sold on distant markets in urban and peri-urban areas by the activation of the dairy market hub (B2 feedback loop loses dominance as more milk is produced and traded due to increased number of cross-bred cows). From 2025 onwards, scenario 3 generates more profit over time than does scenario 2 because surplus milk (unsold milk in scenarios 1 and 2) is traded to processors and consumers.

In addition to improving profit performance, the AI intervention (scenarios 2 and 3) provides extra milk for household nutrition. In the baseline, the model allocates milk to different outlets based on predefined exogenous parameters. In scenario 2, the model allocates milk to similar market channels but at a different rate (i.e. when milk yield under policy intervention scenarios exceeds the maximum yield per time unit under baseline, the following equation is used to adjust milk allocation to exiting trading channels: baseline milk yield/scenario milk yield multiplied by exogenous parameter, smoothed by about a month to allow for milk trading to adjust). Any extra milk left will be considered surplus that will be dissipated to non-commercial channels. This is consistent with the observation that a large proportion of milk is either consumed at home or wasted (surplus) in rural, milk producing, areas of Tanzania (Njombe *et al.*, 2011). In scenario 3, the model allows the surplus milk to be traded, through a market hub, to distant markets (an assumption is that the volume of surplus must be at least 700 liters/time unit (week) (i.e. about at least 100 liters/d) for this new trading channel to be active). The seasonal pattern of milk production has a strong effect on producer households' milk consumption (Fig. 2c). During the high production season, more milk is consumed, and vice versa.

The extent and timing of changes in key model variables (Fig. 2) are indicative of the short-term effect of the policy interventions. Cumulative changes throughout the simulation (2025 and 2035) offer indicators of longer-term effects of policy interventions (Table 2).

By the year 2025 (over a 10-year period), cumulative milk increase in scenarios 2 (AI) and 3 (AI and market hub) is 4% more than in the baseline (Table 2). This indicates that AI intervention is effective in increasing milk productivity. However, increase in milk production does not necessarily mean increased profitability because existing milk trading channels in local markets in Kilosa district are at or near saturation, particularly during high production seasons. An increase in milk production will also lead to lower milk price which reduces producers profit to less than what it would normally be (switching dominance to B4 feedback loop). Indeed, the cumulative profit in scenario 2 is 14% less than that in the baseline, which indicates that producers do not

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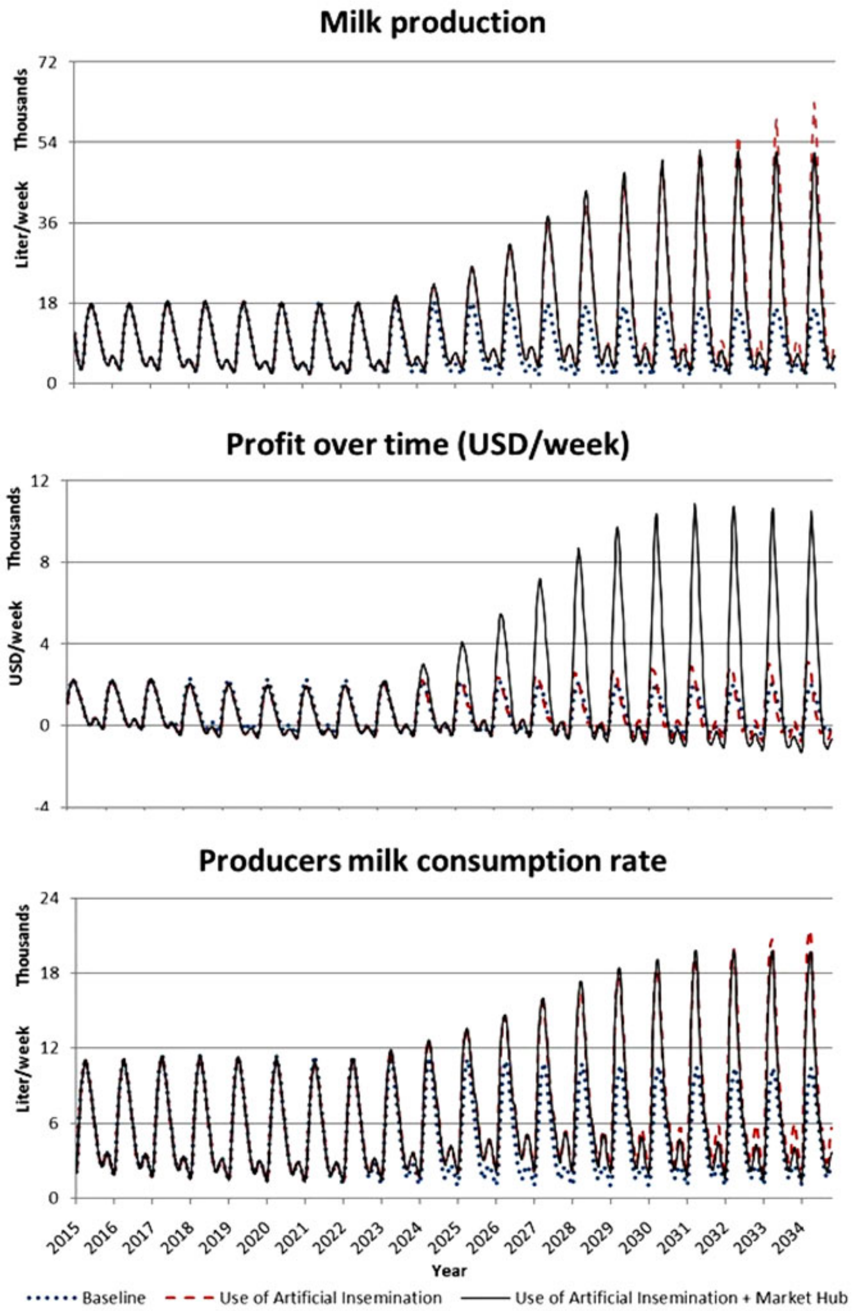

Fig. 2. Milk production (2a, top panel), producer's profit (2b, middle panel) and producer's milk consumption rate (2c, bottom panel) over time

recover investment costs of AI by 2025. The cumulative profit from scenario 3 is 11% less than that of the baseline because activating the dairy market hub facilitates access to new markets that can absorb milk surplus produced in Kilosa district, but the costs of AI are still not offset in the 10 year simulation period presented in Table 2 due to high AI costs and biological delays between the intervention and the payoff in dairy cattle production systems. These results indicate that it is unlikely for producers to receive any positive returns to investment in the short (1 year) and mid (5 year) term. Even where marketing activities can dispose of a milk surplus, the 10-year time horizon analysis shows that there is a negative return on any investment by producers.

Both scenarios 2 (AI) and 3 (AI and market hub) increased producers' cumulative household milk consumption by 4% (i.e. on average, one tenth of 4% per year – about 30 ml of milk/person/d). This indicates that increasing milk production motivates producers to consume more milk which improves household nutrition – our results show very limited impact (30 ml of milk/person/d) in the first 10 years (see Pereira (2014) for chemical composition and nutrition of cow milk). Both scenarios 2 and 3 also increased the proportion of improved (crossbred) cows in smallholder cattle herds from 0 to 31%.

Table 2 also shows the same result set extended to a 20-year time horizon so as to enable evaluation of longer-term effects of policy interventions. The results are more pronounced than those presented for 10 years. This is because the full potential, within the dynamic system's feed constraints, of the policy interventions is delivered. Indeed, cumulative milk production over the 20-year

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Table 2. Cumulative changes of producer's profit and other key variables (2025 and 2035)

Scenarios[a]	Milk production (%)	Cumulative profit (%)	Milk consumption[b] (%)	Improved cross breed (%total population) (%)	milk traded to market hub (liter)	Milk traded to processors (liter)
Percentage change in cumulative (by the end of 10 years simulation in 2025)						
2 *vs*. 1	4	−14	4	31	No change	No change
3 *vs*. 1	4	−11	4	31	29 166	23 339
Percentage change in cumulative (by the end of 20 years simulation in 2035)						
2 *vs*. 1	67	1	34	73	No change	No change
3 *vs*. 1	57	133	30	67	2 523 843	2 019 263

[a] Scenario1: Baseline; Scenario2: Artificial insemination; Scenario 2: Artificial Insemination + Market Hub.

[b] Consumption includes consumption at producer households and given away (non-commercial).

time horizon in scenarios 2 (AI) and 3 (AI and market hub) is 67 and 57% more than in the baseline, respectively (Table 2).

Changes in cumulative profit (producer-level) are also magnified in this longer term analysis relative to the mid-term (Table 2). Producers' cumulative profit in scenario 2 and 3 increased by 1 and 133% (i.e. on average, one twentieth of 1 and 136% per year), respectively, relative to baseline (in scenario 2, B2 and B4 feedback loops dominant the behavior of the model which limits the potential benefits of AI intervention relative to scenario 3). This indicates that there is a marked improvement in return on investment in the long term, or alternatively that a minimum period is apparent, within which a return on such investments will not appear. Scenario 3 (AI and market hub) demonstrates greater cumulative profit than does scenario 2 (AI) because in scenario 3 producers have access to distant markets in urban and peri-urban areas through a dairy market hub. Similarly, milk consumption by producers' households in scenarios 2 and 3 increased by 34 and 30%, respectively, relative to baseline. The proportion of improved crossbred cattle in the total population in scenarios 2 and 3 increased by 73 and 67%, respectively, relative to baseline.

Over the 10-year simulation time horizon (from 2015 to 2025), about 29 166 and 23 339 liters of milk were traded and processed through dairy market hub and processors, respectively (Table 2). The longer time horizon entails greatly increased milk sales through dairy market hubs and processors (2 523 843 and 2 019 263 liters, respectively). Milk processors' securing additional milk is an important simulation result because of concerns about underutilization of processing capacity, and specifically its effect on processors' profitability and sustainability.

Further research is needed to evaluate costs of establishing a dairy market hub. Moreover, milk production volume and seasonality of milk supply, are among the challenging aspects of realizing dairy market hub development. Producer sales *via* the dairy market hub and onwards to processors begin after 2018 and then grow at an increasing rate because cattle of improved breed reach productive age (Fig. 3). However, distribution of milk trading to market hub and processors varies significantly over time and this puts substantial pressure on both the market hub and processors because of idle capacity issues during low milk production periods. This suggests that investment in supplementary feed (and water availability during dry seasons) is needed to achieve more uniform seasonal milk production to support market hub.

Further research should evaluate supplementary feed not only in terms of producers' profits, but also in terms of whole chain or system performance – for example by evaluating impacts on dairy market hubs and processors. In particular, analysis would target the identification of price levels throughout the chain for milk for processing which would cover the costs (including feed) at various production levels, the costs of market hub operation, and the logistic cost of year-around milk delivery. A more constant within-year production profile would also enable larger volumes to be processed, and this may or may not be able to be achieved given the constraints of genetics, feed, management and marketable volumes.

Such co-ordination issues were examined in the current study, in terms of contracting for supply (i.e. change to the allocation rules for household milk production). Results of an extension to scenario 3 (AI and market hub) shows various constructed contractual agreements for supply of milk to the dairy market hub (Table 3). Results are expressed relative to scenario 3's ad hoc (i.e. only trading milk surplus to the market hub) supply results.

An increase in trading to market hub under contract agreement leads to a proportional decline in milk consumption at producers' households and in volumes sold through local trading channels (Table 3). As expected, higher percentage sales of milk to the dairy market hub leads to more accumulated profit: by 38, 20, 8, and 3% relative to scenario 3 when producers trade 50, 37, 23, and 10%, respectively. This gain in cumulative profit comes at the expense of a proportional and substantial reduction in home milk consumption. It should be noted that here that our analysis uses cash income analysis rather than full household income (i.e. we only measure income based on product sold).

A surprising result is that as contracted milk sales to the dairy market hub increase, milk production declines (e.g. 50% of producers milk supply to dairy market hub leads to 8.8% reduction in milk production – i.e. on average, one twentieth of −8.8% per annum). This is because increased milk sales to the dairy market hub leads to a substantial increase in producers profits, which in turn increases investment in cattle production, which leads to a reduction in productivity per cow due to feed constraints (i.e. switching dominance from R1 and R2 feedback loops at early stages to B1 at later stages as cattle population grows).

Another notable result is that the percentage of crossbred cows in the herd declines slightly (−0.3 to −0.6%) as milk sales rate to the dairy market hub increases. This is because all the contract scenarios presented lead to higher producers' profit and hence a larger cattle herd. This lowers the proportion (percent of total population), but not number, of improved cattle relative to scenario 3 (AI and market hub). These results suggest that institutional aspects of the dairy market hub have a substantial impact

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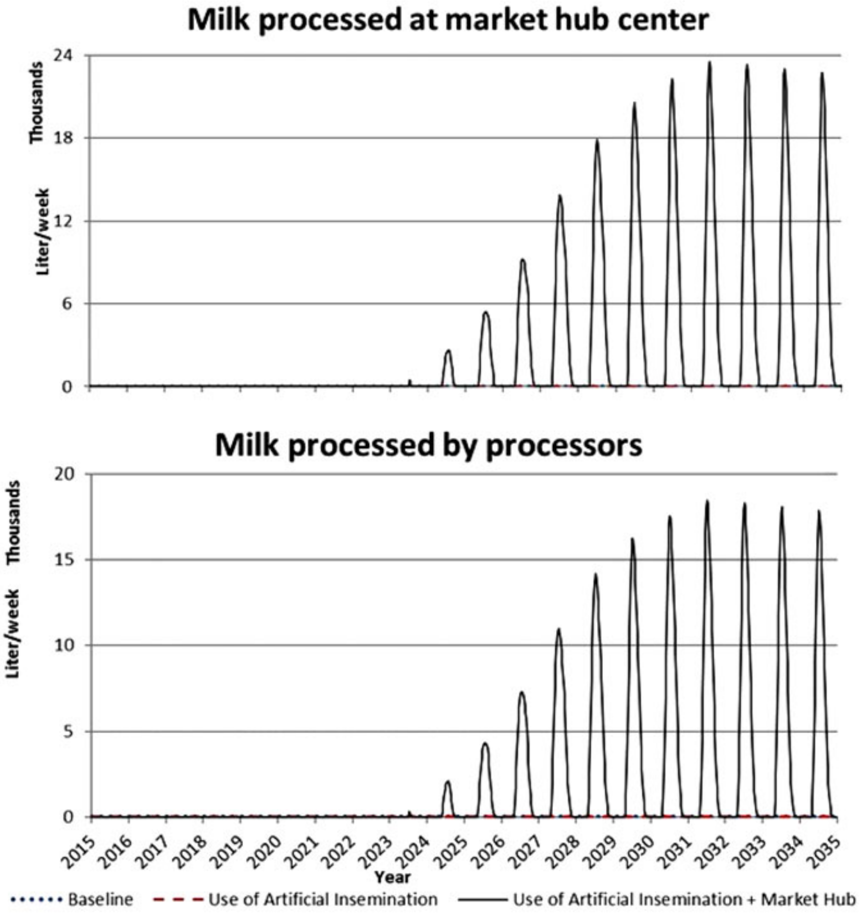

Fig. 3. Milk trading to dairy market hub and to processors over time

Table 3. Results of producer and dairy market hub contract agreement to supply milk relative to scenario 3 – dairy market hub – specifications (i.e. contract Vs. ad-hoc milk surplus supply to market hub)

	Percentage change in cumulative (by the end of simulation, 2035)					
Scenarios	Milk production	Cumulative profit	Milk consumption	Improved cross breed (% total population)	Milk traded to market hub (liter)	Milk traded to processors (liter)
Sce 3 – cumul.	13 187 901	1 354 633	6 749 864	67%	2 523 843	2 019 263
10%[a] *vs*. Sce 3	−2%	3%	−10%	−0.3%	26%	26%
23%[a] *vs*. Sce 3	−8.5%	8%	−24%	−0.6%	64%	64%
37%[a] *vs*. Sce 3	−8.5%	20%	−36%	−0.5%	105%	105%
50%[a] *vs*. Sce 3	−8.8%	38%	−46%	−0.5%	150%	150%

[a] Means 10% of milk produced over time is sold to dairy market hub under contractual agreement. 10% means from 2018 and on, 10% (relative to only trading surplus in scenario 3 of produced milk over time will be allocated to market hub over time).

on the value chain performance achieved by policy interventions. That is, as more milk is traded under contract agreement to a dairy market hub, milk consumption at household level declines. However, ad hoc organization of the dairy market hub does not increase producers' profit as much as does a contractual agreement, but it leaves milk consumption at producers' household intact. This result is indicative of the need to select performance measures that are appropriate to purpose of a policy analysis: notably a profitability measure needs to be traded off against a nutrition measure. Where a social performance measure is being traded off against a private performance measure in the same value chain, we could encounter the 'chain failure' phenomenon identified by Mounter *et al.* (2016).

Sensitivity analysis

We report sensitivity analysis results for changes (±20% of initial price) in milk price in all milk trading channels. Price is an important variable in the model that affects incentives throughout the value chain. Among the results listed in online Supplementary Appendix 3 is the result that producers' cumulative profit is more sensitive (standard deviation = 26%) to changes in milk price than

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is any other variable (e.g. milk production and milk consumption with a standard deviation of 2%). This is because changes in milk prices directly affect producers' profits, but indirectly affect milk production and consumption.

An increase in milk price increases producers' profits, which motivates producers to invest in enlarged cattle herds, and this increases total cattle population (i.e. R2 feedback loop becomes stronger relative to other feedback loops). However, changes in cattle population and milk price do not necessarily mean proportional changes in milk production and consumption. This is to say that an increase in cattle population lowers productivity of dairy cows due to constraints such as forage mass per cow (i.e. switching dominance to B1 feedback loop). In a similar vein, an increase in number of lactating cows balances higher milk prices through increasing the dominance of B4 feedback loop that lowers price as milk supply increases, and vice versa. Therefore, the standard deviation of milk production and milk consumption in the baseline scenario is substantially lower than that of producers' cumulative profit. This suggests that changes in milk price have a marked effect on producers' income, but minor impacts on total milk production and home consumption of milk (this is because lower profit reduces the dominance of R2 feedback loop which lowers cattle population than what it would normally be. This in turn increases forage mass per cattle which offsets any milk production loss due to reduced cow population through increasing milk yield per lactating cow). This finding is of methodological interest as conventional comparative static modeling would normally impose a positive supply response on the analysis of price change. Further details of the sensitivity analysis are presented in online Supplementary File Appendix 3.

Discussion and conclusion

Upgrading dairy production systems to include more productive, crossbred, cattle is a step towards moving from extensive to intensive dairy production systems to upgrade dairy value chains in Kilosa district. The combined effect of AI and dairy market hub collaborative action potentially facilitates the transition from extensive non-commercial to intensive semi-commercial/commercial dairy value chains in Kilosa district. However, more research is needed to evaluate supplementary feed and animal health service needs to make a sustainable transition to intensive dairy value chains given the seasonal nature of milk production.

This paper presented a dynamic model of the smallholder dairy value chain in Kilosa district of Morogoro region, Tanzania. Its results highlight the importance of artificial insemination (AI) and market re-organization by way of a dairy market hub to improve smallholder dairy producers' access to the market, in increasing producers' profits and home milk consumption. Both AI and the dairy market hub improve producers' profits significantly in the long term (10+ years). In the shorter term, benefits do not offset the costs of investment in AI in either scenario.

Essential feature of the dynamic nature and biological basis of the smallholder dairy value chain is well captured by our SD model. Milk production not only interacts with the environment (i.e. forage mass in our modular specification), but also with producers' performance across a range of measures. Similarly, our model captures the trade-offs among performance indicators under different policy options and the institutional arrangement of dairy market hub. Further policy analysis would identify the extent to which additional household profit would be spent on foods other than milk, and whether the purchased food offered the same nutritional value as milk, especially to household members with pronounced protein needs. In a similar vein, further research should target finding an optimal proportion of contracted milk sales to avoid the decline in productivity of dairy cows, and investment in agricultural inputs such as supplementary feed to further extend the production capacity.

Despite concerns over the viability of dairy processing due to limited capacity utilization, the dairy market hub is shown in this analysis to be a viable option (for dairy farmers) even in the presence of milk supply that maintains the highly seasonal patterns observed in extensive arid production systems. However, further research is needed to evaluate costs of establishing and operating a market hub, and in identifying the costs and benefits of investing in feeding and forage systems that reduce fluctuations. Furthermore, using AI and developing a dairy market hub to trade milk to local consumers and milk processing plants in peri-urban and urban markets could potentially create more value for transporters and intermediate traders involved in the hub to supply milk to milk processing plants and/or urban traders.

The principal policy finding of this study is that there are potential benefits to upgrade the dairy value chain in Kilosa district in Tanzania by way of technology interventions (using AI) in combination with market re-organization (implementing the market hub). Such value chain upgrading however requires a significant initial investment from producers. Given producers' low incomes, it is unlikely that producers are willing or able to invest. This concern is magnified, indeed justified, by our model findings that it takes 6 to 7 years from the time producers begin investing in AI until they receive sufficient benefits to recoup these costs. The inherent lags in the biology of dairy breeding and production are the main reasons for this lengthy payback period. This calls for government agencies and NGOs to develop practical mechanisms to tackle the issues of initial investments on one hand and the lagged nature of benefits on the other.

A low cost option of establishment with initial focus on promoting business linkages around existing milk traders as entry points for crystallizing formation of farmer groups could be explored by investors as a basis for growing commercial dairy market hubs in predominantly pre-commercial areas like Kilosa district. That is, a trader would lead the hub (stock named *dairy market hub center* in Fig. 1) which purchases milk from producers to trade it to processors in Morogoro region. In different words, this would be a private sector incentive (a trader) that interlocks the output transaction from producers to markets that otherwise inaccessible to individual producers. Our study shows the likely volume of milk that could be traded through this market hub under different scenarios (see Tables 2 and 3) and the expected seasonality of milk trading (see Fig. 3) which could provide an initial assessment for an investment case. A pilot program would ideally demonstrate roles for smallholder producers and other actors in the dairy value chain such as processors.

The model presented here can be improved in terms of specification of costs and returns associated with dairy market hub establishment and operation, given that these are not included in the current analysis. In particular, price and cost advantages associated with hub-enabling structures such as co-operatives, and processing of milk surpluses into shelf stable products such as yogurt, butter, and cheese offer productive scenarios for analysis. As was the case in the development of the model presented here, such future scenarios will be best specified in consultation with stakeholders that know and understand the constraining

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factors such as a lack of training, marketing skills, appropriate volumes of milk, and infrastructure issues. Where a whole-chain analysis can extend to social costs and benefits and the transfer of benefits, costs and risks amongst actors, roles of government and support agencies can be specified and examined in ex ante scenarios that extend our model.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0022029919000840

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