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ORIGINAL PAPER

Linking calving intervals to milk production and household nutrition in Kenya

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Abstract

Maternal and child under-nutrition resulting in childhood stunting remains prevalent in east Africa, leading to increased disease risk, limiting cognitive development, and impeding human capital accumulation that constrains individuals, communities, and nations from reaching their full potential. In a western Kenyan population with a high prevalence of childhood stunting, frequency of milk consumption has been shown to increase monthly height gain in children, indicating the potential to improve health through livestock productivity. However, calving rates remain low, constraining the availability of milk to the household. Here we model average herd-level calving intervals and its relation to milk yield and nutrition in the context of an agricultural household production model, applying a dynamic panel econometric approach to household level data. We provide evidence that targeted on-farm specialization leads to significantly higher calving rates and shorter calving intervals, which in turn predictably increase milk production. Importantly, we show that the positive link between calving and household milk nutrition is present across households that primarily consume milk produced on-farm ("producer-consumers") and those that predominantly purchase milk ("milk buyers"), indicating that efforts to improve herd fertility in western Kenya could improve food security on a community scale.

Keywords Calving intervals · Calving rates · Milk yield · Agricultural household production model

JEL codes Q10

1 Introduction

Under-nutrition afflicts nearly one third of children in Kenya, increasing disease risk, limiting cognitive development, and impeding human capital accumulation (KNBS 2015; Mosites et al. 2015; Jin and Iannotti 2014; Neumann et al. 2002). Cattle milk produced on-farm is an important source of nutrition and income for smallholder farm households across low- and middle-income countries (Muehlhoff et al. 2013; Staal et al. 2008; Nicholson et al. 2003). The livestock-nutrition nexus is particularly important for children. Smallholder households engaged in dairy production enjoy higher nutritional statuses, benefiting women and school aged children (Hoorweg et al. 2000; Walton et al. 2012). Livestock ownership by women is positively associated with children's weight-for-age Z scores (Jin and Iannotti 2014).

The rate at which mated cows in a herd produce calves, referred to as the calving rate, and the amount of time that passes between calf births, known as the calving interval,

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indicate the reproductive efficiency of a herd. Herd fertility affects milk yields at the household level (quantity of milk produced per household). Calving rates and intervals in eastern Africa are persistently inefficient compared to those achieved in the U.S., Europe, and other countries with well-developed dairy industries. Average calving rates range from 25 to 60% while average calving intervals can be as long as 4 years (Odima et al. 1994; Zalla 1974; Dahl and Hjort 1976; Staal et al. 1997). Calving rates in Kenya are lower relative to more developed African countries—61% in South Africa—but are comparable to other developing countries—40 to 50% in Tanzania (Scholtz and Bester 2010; Tanzania Ministry of Livestock and Fisheries Development 2015). However, there is significant intra-country variation in cattle fertility. Estimates of Kenya's average calving rate are more in line with those of South Africa's emerging and communal cattle sectors (48% and 27%, respectively) (Scholtz and Bester 2010). In the broader picture, the impact of low calving rates and long calving intervals on milk production can have downstream effects on both income generation and nutritional security, and ultimately constrain countries from meeting sustainable development goals (UN General Assembly 2015).

While the challenges and consequences of low cattle productivity in Kenya are well known, the decision-making behavior and subsequent efficient application of resources to improve cattle productivity and reduce calving interval length is less well understood. Moreover, the downstream effects of improved cattle reproduction on human nutrition in the household remain unclear. The purpose of this study is then twofold. One, we explore how calving rates and intervals respond to pre-determined farm interventions, management, and market conditions. Second, we examine how calving rates and other factors affect milk production and ultimately household nutrition. We model the link between cattle productivity and household nutrition through an agricultural household production model, which accounts for both production and consumption of agricultural staples, and discuss the results in the context of improved resource utilization to improve household economic and food security.

We find that households that better optimize their cattle herd composition, invest in herd health interventions, and provide sufficient grazing enjoy higher average calving rates which leads to improved milk consumption on-farm. Cattle herd investments have both a direct effect (through animal health and milk productivity) and an indirect effect (through herd fertility) on the supply of milk available to the household. Improved herd fertility is linked to a higher intake of animal source carbohydrates and fats but is not necessarily linked to total household nutrition. Rather, calving raises the proportion of household calories, protein, carbohydrates, and fat derived from milk—suggesting some substitution between cow milk produced on-farm and other sources of nutrition. Changing the mix of household nutrition in favor of on-farm milk can help alleviate insufficient micronutrient intake among children. Conclusions drawn from our results focus on three sources of improvement: calving rates, market access, and cattle health investments.

2 Descriptive data

2.1 Ethics statement

Ethical clearance was obtained from the Kenya Medical Research Institute Ethical Review Committee and Animal Care and Use Committee (reference number SSC Protocol no. 2250). Participants over 18 years of age provided a written consent to participate in these studies, and parental consent was provided for children involved in the study.

2.2 Data source

Data for this study are derived from the ongoing Population-based Animal Syndromic Surveillance (PBASS) conducted since 2013 in 10 villages in the Asembo area of Kenya's Siaya County (Thumbi et al. 2015). At the time of this analysis, the survey contains approximately 2000 households observed between February of 2013 and July 2016. We restrict our analysis to cow owning households, producing a panel dataset of 1317 households observed yearly for a total of 3682 observations. See Table 1 for variable descriptions and summary statistics. See section S3 of the supplementary materials for a detailed overview of the dataset and variable construction.

2.3 Household characteristics

Households in the study region are generally representative of subsistence farmers in east Africa. Just over half of household heads are primarily employed on their own farm and the proportion of households with some secondary education is 43%. The majority of household heads are male (58%). Over 7% of female household heads are single vs. 3% of male household heads. Female household heads are more likely to be employed on-farm (73%) than are male household heads (61%). Women's empowerment in farming operations has been shown to improve maize productivity in Western Kenya (Dirro et al. 2018), though the researchers' analysis did not reveal strong gender-livestock productivity relationships.

The average household in the sample has 3.5 members over the age of 10 and 1.2 children under the age of 10. Nutrition at the household level averages 6433 cal, 233 g of protein, 934 g of carbohydrates, and 173 g of fat per day. On average, households generate 2692 Kenyan Shillings (KSh) per month in off-farm net income though nearly half of all households earn no income off-farm during the year, depending entirely on farm

Table 1 Variable descriptions and summary statistics

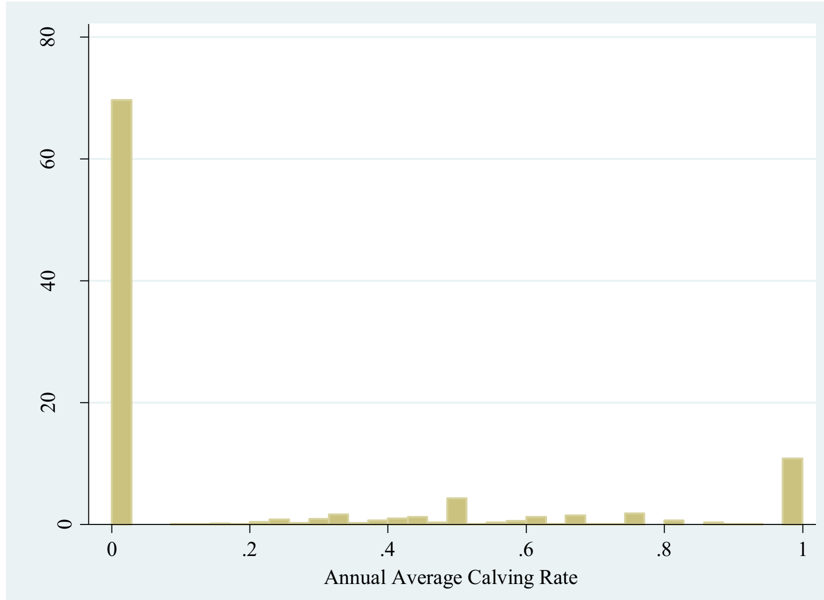
Variable	Description	Obs.	Mean	Std. Dev.	Min	Max
Annual Calving Rate	Average calves born per cow per year.	3682	0.21	0.35	0.00	1.00
Expected Calving Interval (Days)	Average number of days between calving for the average cow in the herd.	1117	669.71	381.22	365.00	4015.00
Household Members	Number of family members 10 years of age and older reported as living in the household.	3680	3.50	1.59	1.00	11.00
Secondary Ed	Dummy equal to 1 if highest education earner has at least some secondary education.	3682	0.43	0.50	0.00	1.00
On-Farm Occupation	Dummy equal to 1 if household head is employed primarily on-farm.	3682	0.52	0.50	0.00	1.00
Off-Farm Income	Average monthly net income generated off-farm by the household (100 s KSh/month).	3679	26.92	75.86	0.00	2860.00
Cows Owned	Average number of cows (2+ years old) owned by the household during the year.	3682	1.89	1.46	0.25	22.00
Bulls Owned	Average number of bulls (2+ years old) owned by the household during the year.	3676	1.23	1.96	0.00	20.75
Exotic/Cross Breed	Dummy variable equal to 1 if household reports owning at least one exotic or exotic cross-breed during the year.	3670	0.02	0.13	0.00	1.00
Milk Yield	Average number of liters produced per cow per day during the year.	3668	0.38	1.27	0.00	50.00
Milk Consumed	Average number of liters consumed per day by the household	3680	0.38	0.51	0.00	24.08
Beef Price	Average price of beef consumed in a village during the year (100 s KShs/Kg).	3682	2.82	0.62	0.94	3.90
Milk Price	Average price of milk consumed in a village during the year (100 s KShs/Liter).	3682	0.73	0.11	0.44	1.01
Maize Price	Average price of maize consumed in a village during the year (100 s KShs/Kg).	3682	0.50	0.24	0.23	2.61
Cattle Supplements Used	Dummy variable equal to 1 if household reports using cattle supplements (e.g. salts or minerals) at any time during the year.	3682	0.06	0.23	0.00	1.00
Cattle Labor Employed	Dummy equal to 1 if household employs labor specifically to work with their cattle herd.	3682	0.16	0.36	0.00	1.00
Cattle Feed Bought	Dummy equal to 1 if household reports expenditure on cattle feed at any point during the year.	3682	0.02	0.14	0.00	1.00
Acaricide Spray	Dummy equal to 1 if household uses acaricide spay to control ticks during the year.	3682	0.80	0.40	0.00	1.00
Deworming	Dummy equal to 1 if cattle deworming measures are taken by the household during the year.	3682	0.21	0.41	0.00	1.00
Antibiotics Used	Dummy equal to 1 if the household rented land for crop production during the year.	3682	0.21	0.41	0.00	1.00
Grazing Acres Owned	Average number of acres owned by the household.	3681	0.34	0.42	0.00	5.00
Communal Grazing	Dummy equal to 1 if household has access to common grazing land during at least one quarter of the year.	3682	0.78	0.41	0.00	1.00
Own Vehicle	Dummy equal to 1 if household owns a vehicle.	3682	0.02	0.12	0.00	1.00
Own Plough	Dummy equal to 1 if household owns a plough.	3682	1.00	0.07	0.00	1.00
Own Mobile Phone	Dummy equal to 1 if household owns a mobile phone.	3682	0.90	0.30	0.00	1.00

output. Households report owning 1.9 cows and 1.2 bulls on average during a given year. Households own less than half an acre of grazing land on average while 78% of respondents have access to some form of communal grazing. Though only 2% of households own a vehicle, almost all households use farm implements (ox or cow-drawn ploughs) and own mobile phones.

2.4 Calving rate

Cattle owned by sampled households are predominantly Zebu (98%) while only 2% are non-native exotic or zebu/exotic cross-breeds. The average household in our dataset generates a calving rate (number of calves born per cow per year) of 0.21, translating to a sample average calving interval of

Fig. 1 Distribution of average herd calving rates

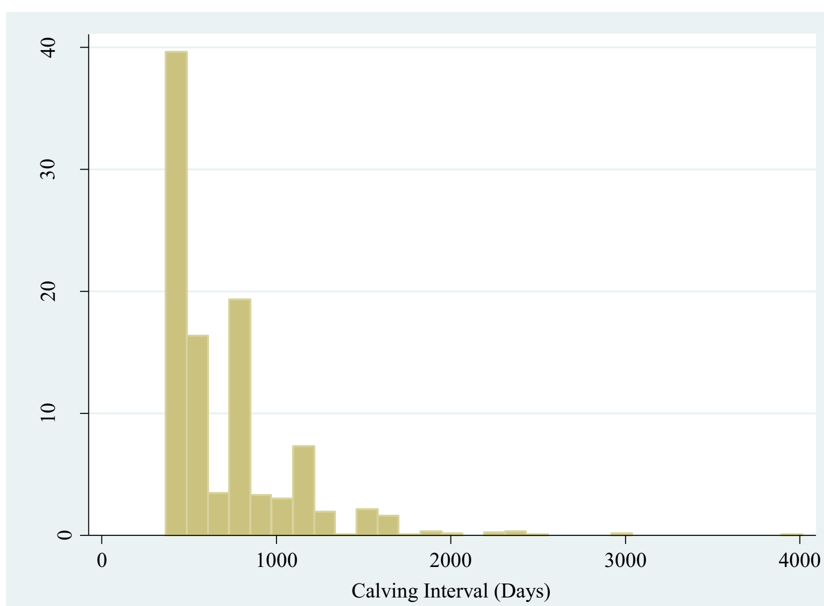


670 days. Age-at-first-calving (AFC) is an important predictor of cattle productivity and fertility (Eastham et al. 2018; Watanabe et al. 2017; Muhuyi and Carles 2004). Though we do not observe AFC among survey respondents, previous literature estimates an AFC of around 40 months for similar indigenous herds (Muhuyi and Carles 2004). Both calving rates and calving intervals exhibit high variance. Figures 1 and 2 show the sample distributions of annual calving rates and calving intervals, respectively. Calving rates are concentrated at either end of the distribution with 70% of observations having calving rates of zero and 11% with calving rates equal to one. For those with positive (non-zero) calving rates, the conditional mean is 0.68 calves per cow per year. Calving intervals are skewed strongly to the right due to the fact that calving intervals can only be calculated from non-zero calving rates. Our sample average calving interval is consistent with estimates for Kenya found elsewhere in the literature (Odima et al. 1994; Staal et al. 1997).

2.5 Milk yield

The average daily milk yield is 0.38 l per cow, lower than other estimates for Kenya (Staal et al. 1997; Muraguri et al. 2004; Marsh et al. 2016; Muriuki 2011). Much of the discrepancy can be explained by herd characteristics. The above referenced studies focus on or included smallholder dairy

Fig. 2 Distribution of estimated calving interval (days)



operations that maintain exotic or exotic cross-breed cattle, intentionally bred for increased milk production. Only 2% of observations in our sample report owning exotic or exotic cross-breed cows, indicating an absence of dairy specialization and reliance on indigenous breeds. Cow owning household consume 0.38 l of milk per day on average. Most of the daily consumption, 66%, is produced on-farm, suggesting a high degree of self-sufficiency among households in the study region. Cow milk makes up 30% of households' daily intake of animal source calories but only 3.5% of total household calories. This is due to the reliance of smallholder households on plant source food, maize in particular.

2.6 Disease prevention

Spraying livestock with acaricide is a common method of preventing tick-borne disease. Eighty percent of survey respondents spray their livestock with acaricide at least once during the year and of these households, the majority spray routinely, suggesting this practice is believed to be an effective tick control measure and worth the cost. This estimate is consistent with Staal et al. (1997) who show a 71% take-up of acaricide treatment in Kiambu District. Cattle deworming practices and antibiotics are both used by 21% of households at least once per year.

3 Estimation results

We begin with our empirical strategy then report our regression results. The determinants of calving rates and intervals are reported first, followed by the impact of calving on milk productivity, household milk nutrition, and off-farm sales. Regression output can be found in Tables 2, 3, 4, 5, 6 and 7. See sections S4 and S5 in the supplementary materials for an expanded explanation of the empirical approach, model specifications, and estimation.

3.1 Empirical model specifications

We estimate the following statistical regression equations using a combination of Tobit and Ordinary Least Squares (OLS) models:

$$CR_{ijt} = CR\Big(H_{ijt-1}, P_{jt-1}, N_{ijt-1}, A_{ijt-1}, M_{ijt}, \alpha_i, \mu_j, \tau_t\Big) + e_{ijt} \quad (1)$$

$$MY_{ijt} = MY\Big(CR_{ijt}, H_{ijt}, P_{jt}, N_{ijt}, A_{ijt}, \alpha_i, \mu_j, \tau_t\Big) + v_{ijt} \quad (2)$$

$$C_{ijt} = C\Big(CR_{ijt}, H_{ijt}, P_{jt}, N_{ijt}, A_{ijt}, M_{ijt}, I_{ijt}, \alpha_i, \mu_j, \tau_t\Big) + u_{ijt} \quad (3)$$

where the random error terms are represented by e_{ijt}, v_{ijt},and u_{ijt}. The dependent variable in Eq. (1) is CR_{ijt}, the average herd calving rate for household i, located in village j, during year t. Because of the dynamic, biological nature of calving, calf output in the current year is a function of exogenous variables and decisions made during the previous year, with only the random shock e_{ijt} entering the equation contemporaneously. This strategy also controls for any contemporaneous endogeneity between calving and household decision making as all behavior is pre-determined. From Eq. (1), we can indirectly estimate the impact of management practices on herd average calving intervals based on the relationship between calving rates and intervals.

Equation (2) models milk yield, MY_{ijt}, defined as the average daily milk produced per cow. Eq. (3) estimates daily household milk consumption, C_{ijt}, (in calories per day) separately by source (purchased off-farm, produced on-farm, and total). As an extension of (2), we also estimate off-farm milk sales in liters sold per day which derive from household milk yields. In (3), we include productive factors in addition to the traditional consumption determinants of price and income to incorporate the household as both producer and consumer (see section S1 for the theoretical motivation). Milk yields, milk consumption, and all continuous explanatory variables in Eqs. (2) and (3) are logged ("log-log" specification) allowing for interpretation of marginal effects in percentage terms (elasticities) following Marsh et al. 2016.

The calving rate enters Eqs. (2) and (3) as a biologically necessary determinant of herd lactation which impacts consumption. Herd characteristics and genetics are important for fertility and milk productivity. The vector $\boldsymbol{H}_{ijt}$ includes herd features such as the number of adult cows and bulls owned and whether the herd contains exotic or exotic cross-breed cattle. Relevant agricultural staple prices make up the vector $\boldsymbol{P}_{jt}$ which are observed at the village level. Price relationships are ambiguous in our theoretical framework due to the nature of households as both producers and consumers of agricultural goods (see section S2). Herd health inputs are included in vector $\boldsymbol{N}_{ijt}$. Herd interventions that improve cow health should increase the probability of calving and reduce disease incidence, such as East Coast Fever, that depress milk production. Asset endowments that contribute to farm and herd productivity are represented by the vector $\boldsymbol{A}_{ijt}$. We control for household characteristics that change over time such as household size and education with the vector $\boldsymbol{M}_{ijt}$. Household income earned off-farm is measured by the variable I_{ijt}.

To capture unobservable factors that may be correlated with our explanatory variables, we use various combinations of household, village, and year fixed effects represented by α_i, μ_j, and τ_t, respectively. Household fixed effects control for all unobserved household characteristics that do not vary over time while village level fixed effects control for all regional characteristics that may affect the dependent variables. Year fixed effects capture any unobserved temporal factors that impact all

Table 2 Calving rate regression results

Variables	Dependent Variable: Annual Average Calving Rate					
	Tobit Regression Marginal Effects[a]				OLS Fixed Effects[b]	
	(1)	(2)	(3)	(4)	(5)	(6)
Household Members	−0.00	0.00	0.00	0.00	0.01	0.01
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)
Secondary Ed	0.01	0.01	0.00	−0.00	0.03	0.00
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)
On-farm Occupation	0.06***	0.05***	0.05***	0.05***	0.06***	0.04**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)
Lag Cows	0.03***	0.03***	0.03***	0.03***	0.01	0.03***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)
Lag Bulls	−0.02***	−0.02***	−0.02***	−0.02***	−0.02**	−0.01
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)
Lag Beef Price (100 s of KSh/Kg.)	−0.04***	−0.06***	0.01	0.01	−0.06***	0.04***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
Lag Milk Price (100 s of KSh/Liter)	−0.21***	−0.37***	0.12*	0.14*	−0.30***	0.17**
	(0.05)	(0.07)	(0.06)	(0.08)	(0.07)	(0.07)
Lag Maize Price (100 s of KSh/Kg.)	0.78***	1.00***	0.32***	0.15	0.82***	−0.12
	(0.09)	(0.13)	(0.10)	(0.15)	(0.15)	(0.15)
Lag Supplements	0.04*	0.04*	0.04*	0.03	0.03	0.01
	(0.02)	(0.02)	(0.02)	(0.02)	(0.04)	(0.04)
Lag Cattle Labor	−0.01	−0.01	−0.00	−0.00	−0.01	0.01
	(0.02)	(0.02)	(0.02)	(0.02)	(0.04)	(0.04)
Lag Cattle Feed	−0.04	−0.03	−0.03	−0.03	−0.07	−0.05
	(0.04)	(0.04)	(0.04)	(0.04)	(0.06)	(0.05)
Lag Acaricide Spray	0.08***	0.07***	0.08***	0.08***	−0.02	−0.02
	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)
Lag Deworming	−0.00	0.00	0.00	0.00	−0.00	−0.00
	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)	(0.02)
Lag Antibiotics	0.04***	0.04**	0.02	0.02	0.04**	0.01
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)
Lag Grazing Acres Owned	0.04***	0.03*	0.00	−0.00	0.01	−0.03
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)
Lag Communal Grazing Access	0.05**	0.05**	0.03	0.03*	0.02	0.01
	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)
Lag Vehicle	−0.03	−0.03	−0.03	−0.03	0.08	0.09
	(0.05)	(0.05)	(0.05)	(0.05)	(0.10)	(0.10)
Lag Implements	0.18	0.18	0.19	0.17	0.17	0.26*
	(0.12)	(0.12)	(0.12)	(0.12)	(0.11)	(0.15)
Lag Mobile Phone	−0.01	−0.00	0.01	0.01	0.00	0.02
	(0.02)	(0.02)	(0.02)	(0.02)	(0.05)	(0.05)
Village Fixed Effects	No	Yes	No	Yes	NA	NA
Household Fixed Effects	No	No	No	No	Yes	Yes
Year Fixed Effects	No	No	Yes	Yes	No	Yes
Observations	2623	2623	2623	2623	2623	2623
Households	1140	1140	1140	1140	1140	1140

Robust standard errors in parentheses. All explanatory variables with the exception of household characteristics are lagged one year. [a] Tobit regression marginal effects are computed at the sample mean for all variables. [b] The coefficients reported by OLS are marginal effects

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

households during the same time period, e.g. government policy enacted at the national level, climate shocks, or large-scale disease outbreaks.

Due to the large number of observations with outcome variables equal to zero, we employ a Tobit model approach using Maximum Likelihood Estimation (MLE). The Tobit estimation technique contends with large probability densities centered on a specific value, in our case zero. Ignoring the influence of censoring may produce biased and inconsistent estimates.

For comparison purposes, we estimate the above relationships within households, that is, controlling for unobservable and time-invariant characteristics, using OLS fixed effects specifications alongside our Tobit models. Estimated marginal effects are reported in Tables 2, 3, 4, 6 and 7 for different combinations of regional, temporal, and household fixed

Table 3 Milk yield and calving rates

Variables	Dependent Variable: Milk Yield					
	Tobit Regression Marginal Effects				OLS Fixed Effects	
	(1)	(2)	(3)	(4)	(5)	(6)
Log Calving Rate[a]	0.03*	0.03*	0.01	0.01	0.09***	0.07**
	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)
Any Calving[b]	0.17***	0.17***	0.17***	0.17***	0.12***	0.12***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.03)	(0.02)
Exotic Breed[b]	0.07***	0.06***	0.07***	0.06***	0.07*	0.06
	(0.02)	(0.02)	(0.02)	(0.02)	(0.04)	(0.04)
Log Milk Price[a]	0.04	0.02	0.10***	0.10***	0.02	0.09***
	(0.02)	(0.03)	(0.02)	(0.03)	(0.03)	(0.03)
Acaricide Spray[b]	0.11***	0.11***	0.10***	0.10***	0.06***	0.05***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Deworming[b]	0.00	0.00	0.00	0.01	0.00	0.00
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Antibiotics[b]	0.02***	0.02***	0.02*	0.02*	0.04***	0.02*
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Grazing Acres Owned[c]	0.06***	0.06***	0.04***	0.04***	0.06***	0.03**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Communal Grazing Access[b]	0.08***	0.08***	0.07***	0.07***	0.04***	0.03**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Village Fixed Effects	No	Yes	No	Yes	NA	NA
Household Fixed Effects	No	No	No	No	Yes	Yes
Year Fixed Effects	No	No	Yes	Yes	No	Yes
Observations	3490	3490	3490	3490	3490	3490
Households	1298	1298	1298	1298	1298	1298

Robust standard errors shown in parentheses. Tobit regression marginal effects are calculated at the sample mean for each variable. Daily milk yield is measured in liters per cow per day and logged. [a] Marginal effects of logged variables are interpreted as estimated elasticities. [b] Binary variable marginal effects are the expected percent change in milk yields. [c] Marginal effects are the percent change in milk yield resulting from a one unit increase in the variable

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

effects. See section S5 for a detailed explanation of marginal effect calculations.

3.2 Determinants of calving rates and calving intervals

We examine the specific household practices and characteristics that influence herd level calving rates in Table 2 from which we estimate associated effects on calving intervals. Due to the biological nature of cattle reproduction, we explain calving productivity in the current period with lagged variables. Four categories of variables emerge as important to calving success. First, the number of cows and bulls and their ratio within the herd significantly affects calving rates. An additional cow (female over 2 years old) raises the herd average calving rate by three percentage points, a 14% improvement for the average household. All else being equal, adding a cow to the herd can shorten the average herd calving interval by 257 days. In contrast, an additional bull (male over 2 years old) depresses calving rates by two percentage points and extends herd average calving intervals by 171 days. Second, commodity prices in the previous year are positively associated with calving in the current year, after controlling for unobserved temporal factors. Increases in the prices of beef, cow milk, and maize are significantly associated with improved herd calving, suggesting a supply response that outweighs any losses in purchasing power. Certain health interventions, specifically spraying cattle with acaricides, which would protect against multiple tick-borne diseases as well as from tick burden itself, are positively associated with calving rates. The associated improvements in calving however, may be driven by productivity factors unique to households that regularly invest in cattle health interventions. Lastly, we find that households with access to communal grazing lands produce herd

Table 4 Milk yield and calving rates marginal effects by household type

Variables	Dependent Variable: Milk Yield*	
	Milk Buyers[a]	Milk Producer-Consumers[b]
	Tobit Regression Marginal Effects	
Log Calving Rate[c]	−0.02	0.05**
	(0.02)	(0.03)
Any Calving[d]	0.14***	0.13***
	(0.02)	(0.02)
Exotic Breed[d]	0.01	0.08**
	(0.03)	(0.03)
Log Milk Price[c]	0.04	0.15***
	(0.03)	(0.04)
Acaricide Spray[d]	0.04***	0.12***
	(0.01)	(0.02)
Deworming[d]	0.00	0.02
	(0.01)	(0.01)
Antibiotics[d]	0.01	0.02
	(0.01)	(0.01)
Grazing Acres Owned[e]	0.01	0.06***
	(0.01)	(0.01)
Communal Grazing Access[d]	0.04***	0.06***
	(0.01)	(0.02)
Village Fixed Effects	Yes	Yes
Household Fixed Effects	No	No
Year Fixed Effects	Yes	Yes
Observations	1531	1935
Households	652	632

Robust standard errors shown in parentheses. Tobit regression marginal effects are calculated at the sample mean for each variable. Daily milk yield measured in liters per cow per day and logged. [a] Milk buyers are households that purchase the majority of their milk consumption. [b] Milk producer-consumers derive the majority of their milk consumption from on-farm production. [c] Marginal effects of logged variables are interpreted as estimated elasticities. [d] Binary variable marginal effects are the expected percent change in milk yields. [e] Marginal effects are the percent change in milk yield resulting from a one unit increase in the variable

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

calving intervals that are as much as 428 days shorter than those without access.

3.3 Calving and Milk production

We attempt to explain variations in milk yields, the average number of liters produced per day per cow, using contemporaneous calving rates, herd characteristics, health inputs, assets, and milk price (see Table 3 for the full regression output). As calving is a necessary precondition for milk production, the estimated relationship between calving rates and milk yield is predictably strong and positive. The discrete event of producing at least one calf from the herd is associated with a 12 to 17% rise in household milk yields. Marginal increases in calving rates are shown to modestly improve milk production. We suspect the minor marginal effect of calving rate on milk production is an artifact of herd size and it is a characteristic of this smallholder population. Though somewhat self-evident, these results reflect internal consistency of households' responses in a livestock production context. Households that own exotic or exotic cross-breed cattle have milk yields that are 6–7% higher than households that own only indigenous cattle.

Herd health practices are positively related to milk productivity. Spraying cattle with acaricide at least once during the year raises herd average milk yields by between 5 and 11% while using antibiotics increases daily yields by about 2%. Both the number of grazing acres owned and access to communal grazing are associated with higher milk productivity, consistent with reliable forage as an important contributor to reproductive efficiency and milk production. Lastly, the outcomes for the price of milk are found to be mixed with respect to statistical significance and weakly related to average milk yields. Our results show that, when appropriate controls are employed, a 1% increase in the market price of milk is associated with an increase in daily milk yields of about 0.1%.

Milk yield impacts differ across types of milk consumers (see Table 4 for regression results and Table 5 for a descriptive comparison of milk consumer types). Households that produce most of their milk consumption on-farm, or "producer-consumers," show far greater returns to exotic breed ownership, herd health investment, and grazing access relative to households that predominantly, but not exclusively, purchase their milk off-farm, or "milk buyers." For example, the use of acaricide lifts milk yields by 12% for producer-consumers but only 4% for milk-buyers. The impact of milk prices on yields is exclusive to producer-consumers who increase yields by 0.15% in response to a 1% increase in price. Calving rates and milk yields are positively related for both milk buyers and milk producer-consumers.

3.4 Calving and household consumption, sales, and nutrition

While a link between herd fertility and milk yields should be expected, the channels through which improved yields benefit household food security are less clear. To better understand these relationships, we estimate the effects of calving, milk price, and herd inputs on milk nutrition and sales by household type (see Table 6 for regression output). We find that producing any calves is positively associated with milk consumed from on-farm production, as would be expected, but is unrelated to nutrition derived from milk purchases. The effect of calving is comparable for both producer-consumer households and milk buying

Table 5 Comparison of livestock productivity by household type

Variables	Milk Buyers[a] ($N = 1562$)	Milk Producer-Consumers[b] ($N = 2079$)
Avg. Milk Yield (liters/cow/day)	0.17	0.47
Avg. Calving Rate (calves born per cow per year)	0.12	0.27
On-Farm Occupation	0.50	0.54
Avg. Number of Cows Owned	1.38	2.27
Avg. Number of Cows Producing Milk	0.16	0.56
Avg. Number of Bulls Owned	0.96	1.44
Exotic Breed (one if any exotics are owned, zero otherwise)	0.01	0.02
Acaricide Spray (one if used, zero otherwise)	0.72	0.86
Deworming (one if used, zero otherwise)	0.19	0.23
Antibiotics (one if used, zero otherwise)	0.18	0.24
Avg. Number of Grazing Acres Owned	0.29	0.37
Communal Grazing Access	0.71	0.84
Avg. Off-farm Net Income (KSh/month/hh)	3100.23	2392.75
Avg. Off-farm Hours Worked (hours/month/hh)	43.16	35.59
Off-farm Wage Rate (KSh/h)	40.48	35.42

[a] Milk buyers are households that purchase the majority of their milk consumption. [b] Milk producer-consumers derive the majority of their milk consumption from on-farm production. Averages of off-farm income and off-farm hours include a significant number of zeros. Some observations report positive income but zero hours worked. These are likely business owners or salaried workers. Off-farm wages can only be computed when positive off-farm income and hours are observed. A single outlier observation for wages of producer-consumers was excluded in the summary statistics

households. Having a positive calving rate is associated with a 11 to 12% increase in the household's caloric intake from milk. Though calving has a small positive effect on off-farm milk sales for those classified as producer-consumers, calving is not found to meaningfully influence the amount of milk purchased by either household type.

For producer-consumers, exotic breed ownership is positively related to the calories consumed from on-farm production and the quantity of milk sold off-farm, but is unrelated to milk purchases. Owning exotic cattle is positively associated with calories from purchased milk for milk buyers. The use of acaricide to prevent ticks has a generally positive effect on milk nutrition derived from on-farm production, an increase of 2 to 3%. Producer-consumers that use acaricide sell 4% more milk off-farm than those that do not. Deworming can raise total household milk calories by 1 to 3%. Administering antibiotics raises the amount of milk produced for home consumption by 2% for households identified as producer-consumers. In general, households with large grazing land holdings and access to communal grazing enjoy higher amounts of milk consumption. The relationship between grazing and milk consumption is strongest among producer-consumers.

We find that off-farm income matters most for households that purchase their milk supply off-farm. For producer-consumer households, we only detect a small income effect for those in the upper end of the income distribution. However, for households that are predominately milk buyers, we find statistically significant positive effects across the income distribution with larger impacts at higher income levels.

Milk prices are positively related to milk nutrition and sales for producer-consumers, though effect sizes are small in both cases. We find that a 1% increase in the price of milk raises total daily milk consumption by a mere 0.07% and the quantity sold off-farm by 0.06% for producer-consumer households. A doubling of the market price of milk would only boost nutrition by about 7100 cal and the amount of milk sold off-farm by about four liters for the entire year.

While we find a positive correlation between calving and household milk nutrition, it is unclear how calving impacts household nutrition from all food sources. To test this relationship, we estimate the effect of calving on total daily intake of animal and plant source nutrition and report the results in Table 7. We find that having a non-zero calving rate lifts daily carbohydrate intake from animal source foods (ASF) by 36%. This is a direct result of increased on-farm milk production as cow milk contributes over 90% of the animal source carbohydrates households consume. We find a positive relationship between ASF fat and marginal changes in calving rates. A 1% increase in average calving rates raises the consumption of ASF fats by 0.26%. No association between calving and total ASF calories or protein is found and calving rates are not found to impact nutrition derived from plant source foods.

Herd fertility is, however, positively and significantly related to milk's share of total household nutrition. A positive calving rate raises the proportion of household calories and

Table 6 Daily milk consumption, calving rates and milk prices by household type

	Tobit Regression Marginal Effects							
	Milk Buyers[a]				Milk Producer-Consumers[b]			
	Milk Bought (kcal)	Milk Produced & Consumed (kcal)	Total Milk Consumed (kcal)	Milk Sold (liters)	Milk Bought (kcal)	Milk Produced & Consumed (kcal)	Total Milk Consumed (kcal)	Milk Sold (liters)
Log Calving Rate[c]	−0.03	0.03	−0.01	0.01	−0.01	−0.06*	−0.07**	0.00
	(0.04)	(0.06)	(0.06)	(0.01)	(0.01)	(0.03)	(0.03)	(0.03)
Any Calving[d]	−0.01	0.12***	0.11***	0.00	−0.01*	0.14***	0.12***	0.05***
	(0.03)	(0.04)	(0.03)	(0.00)	(0.01)	(0.02)	(0.02)	(0.02)
Exotic Breed[d]	0.06**	0.01	0.02	−0.00	−0.01	0.07***	0.07***	0.06***
	(0.02)	(0.03)	(0.03)	(0.01)	(0.01)	(0.03)	(0.02)	(0.02)
Log Milk Price[c]	−0.02	0.01	−0.02	0.01*	−0.03*	0.08***	0.07**	0.06**
	(0.02)	(0.02)	(0.03)	(0.01)	(0.01)	(0.03)	(0.03)	(0.03)
Acaricide Spray[d]	−0.01	0.02***	0.00	0.00*	−0.01	0.03**	0.01	0.04***
	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)
Deworming[d]	0.01	0.01	0.03***	−0.00	0.01**	0.00	0.01*	0.01
	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)
Antibiotics[d]	0.01	0.01	0.01	0.00	−0.00	0.02***	0.02***	0.00
	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)
Grazing Acres Owned[e]	−0.02**	−0.01	0.01	0.01***	−0.01	0.03***	0.04***	0.02**
	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)
Communal Grazing Access[d]	−0.01	0.02***	0.00	−0.00	0.00	0.03***	0.02**	−0.00
	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)
Household Members[e]	0.00	0.01***	0.01***		0.00**	0.01***	0.02***	
Off-Farm Income[f]								
1000–2000 KSh/month	0.02***	−0.00	0.03**		0.01	−0.01	−0.00	
	(0.01)	(0.01)	(0.01)		(0.01)	(0.01)	(0.01)	
2000–3000 KSh/month	0.02	0.03*	0.04***		0.01	0.00	0.01	
	(0.01)	(0.01)	(0.01)		(0.01)	(0.02)	(0.02)	
3000–4000 KSh/month	0.03***	0.00	0.03*		0.00	0.03*	0.03*	
	(0.01)	(0.01)	(0.02)		(0.01)	(0.02)	(0.02)	
4000–5000 KSh/month	0.04***	0.05***	0.09***		0.02	−0.02	0.02	
	(0.01)	(0.02)	(0.02)		(0.01)	(0.03)	(0.02)	
> = 5000 KSh/month	0.06***	0.01	0.09***		0.03***	0.01	0.04***	
	(0.01)	(0.01)	(0.01)		(0.01)	(0.01)	(0.01)	
Village Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1447	1545	1543	1568	2050	1863	1953	2080
Households	636	655	654	655	643	632	637	638

Robust standard errors shown in parentheses. All dependent variables are in natural logs. [a] Milk buyers are households that purchase the majority of their milk consumption. [b] Milk producer-consumers derive the majority of their milk consumption from on-farm production. [c] Marginal effects of logged variables are interpreted as estimated elasticities. [d] Binary variable marginal effects are the expected percent change in the dependent variable. [e] Marginal effects are the percent change resulting from a one unit increase in the variable. [f] Income dummy variables marginal effects are the percent difference between the income category and the base category (0–1000 KSh/month)

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 7 The relationship between calving and animal source and plant source food nutrition

Variables	Animal Source Food Nutrition (logged)				Plant Source Food Nutrition (logged)			
	Energy (kcal)	Protein (g)	Fat (g)	Carbs (g)	Energy (kcal)	Protein (g)	Fat (g)	Carbs (g)
Log Calving Rate[a]	0.18	0.06	0.26*	0.26	0.05	0.03	0.12	0.02
	(0.14)	(0.14)	(0.16)	(0.17)	(0.09)	(0.08)	(0.09)	(0.09)
Any Calving[b]	0.10	0.07	0.10	0.36***	−0.01	0.01	−0.05	0.01
	(0.08)	(0.08)	(0.08)	(0.09)	(0.05)	(0.04)	(0.05)	(0.05)
Exotic Breed[b]	0.32***	0.32***	0.32***	0.29**	−0.02	−0.04	0.06	−0.05
	(0.09)	(0.09)	(0.11)	(0.13)	(0.09)	(0.08)	(0.08)	(0.10)
Log Milk Price[a]	−0.04	−0.07	−0.03	0.15	−0.02	0.01	−0.10	0.04
	(0.10)	(0.10)	(0.11)	(0.14)	(0.05)	(0.04)	(0.06)	(0.05)
Household Members[c]	0.04**	0.05***	0.04*	0.08***	0.08***	0.08***	0.06***	0.09***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
Off-Farm Income[d]								
1000–2000 KSh/month	0.03	0.00	0.05	0.05	0.03	0.01	0.05	0.02
	(0.05)	(0.05)	(0.06)	(0.07)	(0.03)	(0.02)	(0.03)	(0.03)
2000–3000 KSh/month	0.07	0.05	0.09	0.01	0.06	0.03	0.03	0.06*
	(0.06)	(0.06)	(0.07)	(0.08)	(0.03)	(0.03)	(0.04)	(0.04)
3000–4000 KSh/month	0.01	−0.02	0.02	0.14	0.03	0.01	0.06	0.03
	(0.07)	(0.06)	(0.08)	(0.09)	(0.04)	(0.04)	(0.04)	(0.04)
4000–5000 KSh/month	0.12*	0.11	0.14*	0.09	0.10**	0.06	0.05	0.13***
	(0.07)	(0.07)	(0.07)	(0.11)	(0.04)	(0.04)	(0.03)	(0.05)
>= 5000 KSh/month	0.03	0.02	0.04	0.03	0.06**	0.06**	0.07**	0.06**
	(0.05)	(0.05)	(0.06)	(0.06)	(0.03)	(0.03)	(0.03)	(0.03)
Household Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3660	3660	3660	3494	3671	3671	3671	3671
Households	1310	1310	1310	1286	1314	1314	1314	1314
R-squared	0.06	0.05	0.06	0.08	0.04	0.04	0.03	0.05

Robust standard errors shown in parentheses. All dependent variables are in natural logs. [a] Marginal effects of logged variables are interpreted as estimated elasticities. [b] Binary variable marginal effects are the expected percent change in the dependent variable. [c] Marginal effects are the percent change resulting from a one unit increase in the variable. [d] Income dummy variables marginal effects are the percent difference between the income category and the base category (0–1000 KSh/month)

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

protein contributed by cow milk by one percentage point and milk's share of household fats and carbohydrates by about three percentage points (see section S7 and Table S5 of the supplemental materials for estimation results). Though small in absolute terms, these changes are more meaningful when interpreted proportionally as households derive most of their nutrition from plant source foods (see Table S2 in the supplemental materials).

4 Discussion

Generally, we find that calving rates and intervals respond favorably to on-farm investment in the form of herd composition, health interventions, and available grazing. We show that higher cow numbers realize higher calving rates and shorter calving intervals. Given the small herd sizes (1.9 cows on average) of this sample, having more than one cow is crucial to herd fertility, acting as a form of insurance. If the herd is made up of only one cow, a single occurrence of disease or predation can end the possibility of calving. Adding a cow to the herd decreases the average calving interval by about 260 days. Conversely, adding bulls to the herd tends to depress calving rates and extend calving intervals. On average, households in our sample report owning 0.63 bulls for every one cow. Our statistical analysis suggests that any positive impact of grazing additional bulls with the cow herd to increase the probability of successful impregnation is likely negated by the diversion of input resources such as forage, acaricides, antibiotics, and labor. While we recognize that some households may keep bulls for other purposes such as traction, gifts, or dowry, substantially decreasing the bull:cow ratio at the individual household level either through sharing a bull among households (a single bull can service 20 to 30 cows) or increasing uptake of artificial insemination would better connect household resource allocation to improved nutrition. As households that own exotic breed cattle have milk yields that are 6–7% higher than those that own exclusively indigenous livestock, this supports investment in improved genetics. However, milk quality is not significantly different across breeds or by degree of cross-breeding (Cheruiyot et al. 2018). In light of recent regulations requiring quality-based milk pricing in Kenya, breed selection may only impact profitability on the extensive margin (quantity) rather than the intensive margin (quality) (Foreman and De Leeuw 2016). The higher cost of purchasing a single bull of superior breeding stock may be prohibitive for a single household, leading to an over-accumulation of generic bulls (Ouma and Abdulai 2009), but feasible when shared among households. Similarly, the costs of artificial insemination, a common strategy to improve production traits, require investment at the community rather than the single household level.

Certain herd health inputs such as spraying cattle with acaricide and providing dietary supplements, are positively related to calving rates. Using acaricide, for example, is associated with an improvement in calving rates of 8%. Controlling for household features shows that these correlations are likely driven by household characteristics that are generally related to productive cattle operations. The number of grazing acres owned by the household and access to communal grazing lands are positively related to calving rates but again, these associations are sensitive to time-invariant household characteristics. We are unable to definitively say that encouraging the use of these health interventions or expanding forage opportunities will cause calving intervals to fall. Rather, we identify households that consistently employ these practices and who also enjoy shorter calving intervals as being specialized in cattle management. Specialized households offer a model for subsistence farmers wishing to improve calving productivity.

Importantly, we find that high prices for beef and milk can motivate better cow productivity in the form of higher calving rates and shorter calving intervals. Because prices are determined on the market and are unlikely to be influenced by any one household, we can say confidently that prices are exogenous to producer behavior and safely interpret price effects as causal responses to higher livestock profitability. This result is an extension of the profit effect often found in the agricultural household production literature where high prices for beef and milk increase the future profitability of cattle, which incentivizes investment in cattle productivity. Losses in potential purchasing power resulting from high commodity prices are outweighed by this profit effect.

Maize prices are also positively related to calving. We might expect that as maize becomes more profitable to sell off-farm, households will shift investment away from livestock production to crop production and calving rates/intervals would suffer. Moreover, the loss in household purchasing power resulting from higher maize prices can hurt the farm's ability to invest in their livestock herd. It may be the case that households respond to high maize prices by maintaining their existing crop acreage and directing profits from crop sales into livestock. The profit margins on beef and milk may be relatively high enough to draw investment away from maize. Alternatively, high maize prices may encourage maize planting, providing post-harvest forage that benefits herd health.

Viewing the downstream effects through a calving interval lens has important implications. Improved calving rates emerge in the form of higher milk productivity, which boosts on-farm consumption of milk, the nutritional benefits derived therefrom, and increases off-farm sales. A positive household calving rate naturally lifts daily herd milk yields by as much as 17%. This is critical in households with such low herd sizes. By investing in the resources that improve calving, detailed above, the household can indirectly increase its milk supply. The household may directly and contemporaneously raise milk yields by changing their herd characteristics, investing in animal health, and providing grazing access. Several household inputs, such as acaricide spraying and forage availability, influence milk production both directly (contemporaneously) and indirectly (with a time lag) through their effect on calving rates. Spraying cattle with acaricide at least once during the year increases milk yields by as much as 11% on average. The tick-borne disease East Coast Fever, highly prevalent within the study region, increases livestock mortality and reduces milk yields in infected cattle (Mukhebi et al. 1992). We find evidence, even after controlling for household characteristics, that the use of acaricide spray as a tick control measure meaningfully improves average milk productivity. Administering antibiotics, owning additional grazing acres, and access to communal grazing all lead to higher daily milk yields. Taken together, our results show that specialization in management practices and investing in cattle health improves milk production consistent with other studies (Marsh et al. 2016).

The returns to these practices, however, are enjoyed directly by households that produce their own milk supply, what we call "producer-consumers." Direct effects are small or nonexistent for households that purchase the majority of their milk off-farm, or "milk buyers," who may realize indirect benefits. Producer-consumers specialize in on-farm production and possess capital endowments that allow them to receive the full potential of their investment on the farm. Milk buyers, by contrast, have higher off-farm marginal productivity and are more likely to sell their labor in the market place (see Table 5 for a comparison of household types). The upshot is that we find that the effect of non-zero calving rates on nutrition is enjoyed by all households, regardless of productive endowments. This suggests that policies directed at improving calving rates and reducing calving intervals in western Kenya can generate benefits on a large scale.

Improved calving rates lead to greater milk consumption and nutrition by increasing on-farm supply. Positive herd fertility raises household milk nutrition by between 11 and 12%. The resulting increase in on-farm milk consumption raises the level of animal source carbohydrate and fat intake but does not necessarily lead to an increase in total (plant and animal source) nutrition at the household level. However, looking at changes in the proportion of household calories, protein, carbohydrates, and fat contributed by cow milk reveals that the nutritional makeup of the household is altered by herd productivity. A non-zero calving rate leads to a 2.6 percentage point increase in milk's share of total household fat consumption, a 35% increase in milk's share of fat consumption for the typical household in our sample. For carbohydrate consumption the proportional impact is even larger. Producing at least one calf raises the share of household carbohydrates consumed from milk by nearly three-fold. This suggests that improvements in herd health—leading to higher on-farm milk supply—raises the nutritional contribution of cow milk but may displace other sources of nutrition. Murphy and Allen (2003) point out that animal source foods can meet the micronutrient needs of rural Kenyan children at lower quantities of consumption than plant-based foods. Raising the share of calories from milk then, even if total calories consumed remains constant, can help alleviate micronutrient deficiencies among smallholder children—particularly those stemming from calcium and vitamin B-12 shortfalls.

Other farm management practices such as owning exotic cattle, spraying acaricide, administering antibiotics, and providing access to grazing are associated with higher milk nutrition for producer-consumer households. Again, the food security benefits of investing in farm inputs and capital accrue to those households with the productive capacity to apply the investments most effectively.

Off-farm income is the most important determinant of milk consumption for milk buyers. Milk buying households that earn at least 5000 KSh per month consume 9% more milk than households with monthly incomes below 1000 KSh per month. Differential impacts of off-farm income are found throughout the income distribution for milk buyers. Milk buyers are more likely to sell their labor in the market based on comparatively high off-farm productivity. Their milk demand is a sequential function of labor supply decisions and income earned therefrom. Off-farm income is not meaningful for milk consumption and nutrition among producer-consumers. Rather, these households match consumption with on-farm supply as determined by productive inputs. The separability assumption typical of economic agricultural household production models is more likely to hold for milk buying households than milk producer-consumers (see section S2 of the supplemental materials for an in-depth discussion of separability). Transfer payments may have a larger direct impact on nutrition for milk buying households than producer-consumers.

We observe some small supply responses to price and farm inputs for milk producer-consumers, but we do not find evidence that the additional income generated by the incremental sales has a detectable effect on the amount of milk purchased off-farm. It is important to note that while relatively specialized in dairy production, producer-consumers in this sample sell little of their milk off-farm. High transactions costs limiting the ability of these households to access formal markets may explain their tendency toward self-sufficiency and relative lack of market participation. Modernizing the dairy sector and improving access to formal markets in Kenya may strengthen the responsiveness of smallholder farms to changes in market prices and inputs. Efforts directed at reducing transactions costs associated with market access may generate larger returns in western Kenya than are suggested by this study.

The price effects on production and supply should be interpreted in context. Recall that high milk prices raise the probability of producing calves in the future which in turn, generates higher milk yields, on-farm consumption, and sales. The full dynamic impact of changes in milk prices are likely larger than the static period effects imply.

Understanding the setting of the study may provide insights for applying results to other contexts. Siaya County (formerly a district of Nyanza Province) in western Kenya is defined by high-humidity and rainfall with bi-modal precipitation occurring in the spring and fall (Wetende et al. 2018). Agriculture is made up of small-scale intensive farming (the average farm is less than one hectare) producing staple crops, raising livestock, and fishing. Livestock intensity and dairy production in the region lags the rest of Kenya. There are 118 cattle per km^2 in Siaya County compared to 249 cattle per km^2 nationally. Former Nyanza Province accounts for 6% of all dairy cows in Kenya and dairy cows make up only 10% of all cattle in the region. Milk productivity averages 16.2 l per capita, 75% below the national average, mostly due to underrepresentation of specialized breeds (Muriuki 2011). The region is also poorer and less food secure. Forty-two percent of people report lacking food or the financial means to acquire food vs. 31% of the overall Kenyan population (KNBS 2015). Locations that share similar challenges (poverty, a small and underproductive dairy sector, food insecurity) and agro-climatic conditions (high rainfall and humidity) and may benefit most from practices suggested here to improve milk production and consumption.

5 Conclusions

Kenyan smallholder farms depend on livestock for sustenance and income, but livestock calving intervals remain persistently long. Shortening the amount of time that passes between calving raises the value of cattle, which increases income and provides insurance against income shocks. Calving may also affect household nutrition through milk production. Milk is a key source of nutrients, particularly for children and mothers (Walton et al. 2012). We find a direct link from improved calving rates (or shorter calving intervals) to higher milk productivity and greater milk consumption which raises the amount of nutrition the household derives from milk. We do not find evidence that herd fertility lifts the total level of household nutrition. Rather, positive calving rates raise the share of household nutrition contributed by cow milk—particularly for fats and carbohydrates. The on-farm investments necessary to boost herd fertility may displace other on-farm food sources, e.g. maize production. The degree to which on-farm milk productivity displaces other staple foods is a potential area of future work.

Altering the household's mix of nutrition in favor of milk can help close shortfalls in micronutrient consumption, especially in children. Murphy et al. (1995) find that 91% of Kenyan school-age children do not get an adequate amount of calcium while 87% do not get enough vitamin B-12—cow milk is high in both. Neumann et al. (2007) find that relative to a snack of only githeri (a mix of maize, beans, and greens) Kenyan school children given a calorie equivalent snack of githeri plus milk showed greater vitamin B-12 intake and improved growth rates among stunted children.

Our results are consistent with previous work on food insecurity among smallholder cattle-owning households in identifying three areas for targeted investments: improved calving rates, greater market access, and cattle health interventions.

We show that the simple act of producing a calf from the herd can pay large dividends in terms of milk production and household nutrition. Importantly, we find that the benefits of higher calving rates and shorter calving intervals are enjoyed by all household types regardless of their productive disposition. However, breeding productivity is constrained by both cultural and structural challenges. Odima et al. (1994) point out that early oestrus detection can reduce calving intervals in smallholder Kenyan farms, but preferences for long milking periods between calves limits this practice. Mbugua et al. (1998) find stall-fed cows come into heat sooner after calving than grazed cows, resulting in shorter calving intervals, higher milk yields, and fewer resource inputs per conception. The importance of tracking calving intervals, infertility, and early term abortions could be emphasized as few smallholders in the region maintain farm records (Omore et al. 1998). Education and extension services can address these knowledge gaps in herd fertility-improving practices. Genetic optimization also plays an important role in improved calving and milk productivity—particularly through the use of artificial insemination (AI) services. Mutavi et al. (2016) find that smallholders that use AI technology enjoy significantly higher milk yields than those relying solely on bulls. Though our results point to inefficiencies associated with excess bull ownership, the cost of AI services is prohibitively high for many smallholder farms (East Africa Dairy Development Project 2013).

We find that downstream nutritional benefits of greater cattle productivity are primarily enjoyed by self-sufficient milk producer-consumer households. Yet researchers demonstrate positive economic returns to dairying in rural Kenya (Staal et al. 2003; Kibiego et al. 2015). Improving market access would open additional channels through which milk productivity can affect household nutrition, e.g. via the profit effect. However, smallholder dairy enterprises face multiple constraints in bringing surplus milk to market. Since de-regulation of the dairy sector in the 1990s, most milk is sold in informal markets where demand, prices, quality, and safety are variable (Odero-Waitituh 2017). Poor infrastructure and distance from market centers—particularly during rainy seasons—raise transportation costs associated with marketing milk and sourcing inputs (Muia et al. 2011). Simple upgrades to rural road networks could reduce transportation costs and incent market participation (Staal et al. 2003). International trade can also play an important role in sustaining livestock prices. It is estimated that domestic prices in the Horn of Africa fell 30% after Saudi Arabia banned livestock exports from that region due to an outbreak of Rift Valley Fever in 1998 and 1999 (EMPRES 2001). However, the cost of complying with international food safety regulations may be prohibitive for developing countries (Finger and Schuler 2000). WTO obligations that affect market access—particularly those regarding sanitary and phytosanitary (SPS) standards—could be reevaluated with this in mind.

Market access may have a reinforcement effect. Commercial networks improve on-farm cattle productivity which leads to more market participation (Muia et al. 2011). Bebe et al. (2003) find that smallholder farms that maintain exotic breeds are more likely to sell surplus milk off-farm than households dependent on local Zebu cattle but Kenduiwa et al. (2016) show that credit access influences cattle breed specialization. Access to formal credit markets or microloans may boost commercialization, leading to better market access.

Health interventions that deter tick borne diseases like East Coast Fever (ECF) are especially important for communal grazing livestock—a practice of nearly 80% of the participants in this study (Omunyin et al. 2014). Our results point to both the direct and indirect impacts of tick treatments on household food security. However, this study does not fully consider the nexus between land use, feeding practices, and grazing for herd health in the East African context. For example, stall-fed cattle are less susceptible to tick borne diseases but unreliable feed sources can lead to poor animal nutrition—both of which depress fertility and milk production (Omore et al. 1998).

Institutional efforts have been made to address the areas of improvement identified in this paper including the East Africa Dairy Development Project (EADD), the Kenya Market-led Dairy Program (KMDP), and the Kenya Smallholder Dairy Project (KSDP). The EADD, now in its second phase, establishes dairy hubs similar to farmer co-operatives. These hubs provide services such as AI, market information, and interventions to reduce calving intervals for its farmer members (East Africa Dairy Development Project 2013).

As a final note, we recognize several limitations of our study. First, calving and milk production data are observed at the herd level based on survey responses as opposed to tracking individual cows over time. This "aerial" view of cattle productivity provides for broad impressions of livestock outcomes but is less precise than other studies. Second, endogeneity among on-farm decisions often persists despite our best efforts to correct for it. We cannot attribute all estimated relationships to causality, though correlations among key variables may still be informative for policymaking. Lastly, there are several factors we do not observe or observe imperfectly which may be a direction for future work. We do not observe relevant transactions costs, such as distance to market centers, where livestock goods are sold. A clearer understanding of the barriers to market participation may explain why some households purchase farm products while others resort to self-sufficiency.

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Compliance with Ethical Standards

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

References

Bebe, B. O., Udo, H. M. J., Rowlands, G. J., & Thorpe, W. (2003). Smallholder dairy Systems in the Kenya Highlands: Breed preferences and breeding practices. *Livestock Production Science, 82*, 211–221.

Cheruiyot, E. K., Bett, R. C., Amimo, J. O., & Mujibi, F. (2018). Milk composition for admixed dairy cattle in Tanzania. *Frontiers in Genetics, 9*, 142.

Dahl, G., & Hjort, A. (1976). *Having herds: Pastoral herd growth and household economy*. Stockholm: Department of Social Anthropology, Stockholm Studies in Social Anthropology.

Dirro, G. M., Seymour, G., Kassie, M., Muricho, G., & Muriithi, B. W. (2018). Women's empowerment in agriculture and agricultural productivity: Evidence from rural maize farmer households in Western Kenya. *PLoS One, 13*(5), e0197995.

East Africa Dairy Development Project. 2013. *Final Report for the East Africa Dairy Development Project Evaluation*. Retrieved Aug 2019 from https://cgspace.cgiar.org/bitstream/handle/10568/79437/EADD%20FINAL%20REPORT.pdf

Eastham, N. T., Coates, A., Cripps, P., Richardson, H., Smith, R., & Oikonomou, G. (2018). Associations between age at first calving and subsequent lactation performance in UK Holstein and Holstein-Friesian dairy cows. *PLoS One, 13*(6), e0197764.

EMPRES. 2001. Transboundary Animal Diseases Bulletin 16: 15–21. FAO Corporate Document Repository. Retrieved Nov. 2019 from http://www.fao.org/3/y0482E/y0482e00.htm

Finger, J. M., & Schuler, P. (2000). Implementation of Uruguay round commitments: The development challenge. *The World Economy, 23*(4), 511–525.

Foreman I. and De Leeuw, B. (2016). Quality Based Milk Payment Study: Kenya Dairy Sector for SNV KDMP Project. *Mission Rep.* 1 1–79.

UN General Assembly resolution 70/1, Transforming Our World: The 2030 Agenda for Sustainable Development, A/RES/70/1 (25 September 2015), available from undocs.org/en/A/RES/70/1.

Hoorweg, J., Leegwater, P., & Veerman, W. (2000). Nutrition in agricultural development: Intensive dairy farming by rural households. *Ecology of Food and Nutrition, 39*, 396–416.

Jin, M., & Iannotti, L. L. (2014). Livestock production, animal source food intake, and young child growth: The role of gender for ensuring nutrition impacts. *Social Science & Medicine, 105*, 16–21.

Kenduiwa, A. A., Mwonya, R. A., & Kinuthia, L. N. (2016). Influence of smallholder dairy farmers' participation in microfinance on breed improvement in dairy farming in Longisa Sub-County, Bomet County, Kenya. *Journal of Agriculture and Veterinary Science, 9*(7), 66–75.

Kenya National Bureau of Statistics (KNBS). (2015). Kenya Demographic and Health Survey 2014. Retrieved Sep. 2018 from https://dhsprogram.com/pubs/pdf/fr308/fr308.pdf

Kibiego, M. B., Lagat, J. K., & Bebe, B. O. (2015). Competitiveness of smallholder Milk production Systems in Uasin Gishu County of Kenya. *Journal of Economics and Sustainable Development, 6*(10), 39–45.

Marsh, T. L., Yoder, J., Deboch, T., McElwain, T. F., & Palmer, G. H. (2016). Livestock vaccinations translate into increased human capital and school attendance by girls. *Science Advances, 2*(12), e1601410.

Mbugua, P. N., C. K. Gachuiri, R. G. Wahome, M. M. Wanyoike, and A. Abate. (1998). Performance of Dairy Cattle Under Two Feeding Systems, as Practiced in Kiambu and Nyandarua Districts of Central Kenya. Retrieved Aug 2019 from http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/30/042/30042868.pdf

Mosites, E. M., Rabinowitz, P. M., Thumbi, S. M., Montgomery, J. M., Palmer, G. H., May, S., Rowhani-Rahbar, A., Neuhouser, M. L., & Walson, J. L. (2015). The relationship between livestock ownership and child stunting in three countries in eastern Africa using National Survey Data. *PLoS One, 10*(9), e0136686.

Muehlhoff, E., Bennett, A., & McMahon, D. (2013). Milk and dairy products in human nutrition. In *Food and agriculture Organization of the United Nations (FAO)*. Rome: Italy.

Muhuyi, W. B., & Carles, A. B. (2004). Genetic and environmental influences on age at first calving of the Kenya Sahiwal cattle. *East African Agricultural and Forestry Journal, 70*(1), 7–10.

Muia, J., Kariuki, J. N., Mbugua, P., Gachuiri, C. K., Lukibisi, L. B., Ayako, W. O., & Ngunjiri, W. V. (2011). Smallholder dairy production in high altitude Nyandarua milk-shed in Kenya: Status, challenges and opportunities. *Livestock Research for Rural Development 23*(5).

Mukhebi, A. W., Perry, B. D., & Kruska, R. (1992). Estimated economics of Theileriosis Controlin Africa. *Preventive Veterinary Medicine, 12*(1,2), 73–85.

Muraguri, G. R., McLeod, A., & Taylor, N. (2004). Estimation of Milk production from smallholder dairy cattle in the coastal lowlands of Kenya. *Tropical Animal Health and Production, 36*, 673–684.

Muriuki, H. G. (2011). Dairy development in Kenya. In *Food and agricultural Organization of the United Nations (FAO)*. Rome: Italy.

Murphy, S. P., & Allen, L. H. (2003). Nutritional importance of animal source foods. *The Journal of Nutrition, 133*(11), 3932S–3935S.

Murphy, S. P., Calloway, D. H., & Beaton, G. H. (1995). Schoolchildren have similar predicted Prevalences of inadequate intakes as toddlers in village populations in Egypt, Kenya, and Mexico. *European Journal of Clinical Nutrition, 49*, 647–657.

Mutavi, S. K., Kanui, T. I., Njarui, D. M., Musimba, N. R., & Amwata, D. A. (2016). Innovativeness and adaptations: The way forward for small scale PeriUrban dairy farmers in semi-arid regions of south eastern Kenya. *International Journal of Scientific Research and Innovative Technology, 3*(5), 1–14.

Neumann, C. G., Harris, D. M., & Rogers, L. M. (2002). Contribution of animal source of foods in improving diet quality and function in children in the developing world. *Nutrition Research, 22*, 193–220.

Neumann, C. G., S. P. Murphy, C. Gewa, M. Grillenberger, and N. O, Bwibo. 2007. Meat supplementation improves growth, cognitive, and behavioral outcomes in Kenyan children. The Journal of Nutrition 137(4): 1119–1123.

Nicholson, C. F., Mwangi, L., Staal, S. J., and Thornton, P. K.. (2003). Dairy cow ownership and child nutritional status in Kenya. Paper presented at ASSA Annual Meeting, Montréal, Québec, Canada, July 27-30, 2003.

Odero-Waitituh JA (2017). Smallholder dairy production in Kenya: A review. *Livestock Research for Rural Development, 29*(7).

Odima, P. A., McDermott, J. J., & Mutiga, E. R. (1994). Reproductive performance of dairy cows on smallholder dairy farms in Kiambu District, Kenya: Design methodology and development considerations. *The Kenyan Veterinarian, 18*, 336–368.

Omore A. O., J. J. McDermott, H. M. Muriuki, and W. Thorpe. 1998. Smallholder dairy herd Management in Kenya. Small Dairy Holder Project. Pp: 1–6.

Omunyin, M. E., Ruto, J., Yegon, M. K. A., & Bii, F. (2014). Dairy production constraints in Kericho and Bomet counties of Kenya: Evidence from farmers fields. *International Journal of Science and Research, 3*(12), 1241–1246.

Ouma, E. A. and A. Abdulai. (2009). Contributions of social capital theory in predicting collective action behavior among livestock keeping communities in Kenya. Paper presented at the International Association of Agricultural Economists Conference, Beijing, China, August 16-22, 2009.

Scholtz, M. M., & Bester, J. (2010). Off-take and Production Statistics in the Different South African Cattle Sectors: Results of a Structured Survey. *Applied Animal Husbandry & Rural Develop, 3*(1), 19–23.

Staal, S. J., Chege, L., Kenyanjui, M., Kimari, A., Lukuyu, B., Njubi, D., Owango, M., Tanner, J., Thorpe, W., & Wambugu, M. (1997). *Characterization of Dairy Systems Supplying the Nairobi Milk Market* (41 pp). Nairobi, Kenya: KARI/ILRI/MALDM Collaborative Dairy Research Program, ILRI.

Staal S. J., Waithaka, M., Njoroge, L., Mwangi, D. M., Njubi, D., and Wokabi, A.. (2003). Costs of Milk production in Kenya estimates from Kiambu, Nakuru and Nyandarua districts. Smallholder dairy (R&D) project, Kenya Ministry of Livestock and Fisheries Development (MoLFD).

Staal, S. J., Pratt, N. A., and Jabbar, M.. (2008). Dairy development for the resource poor. Part 2: Kenya and Ethiopia. Dairy development case studies. FAO/PPLPI working paper, no. 44-2.

Tanzania Ministry of Livestock and Fisheries Development. (2015). Tanzania Livestock Modernization Initiative. Retrieved Aug 15, 2019 from https://livestocklivelihoodsandhealth.org/wp-content/uploads/2015/07/Tanzania_Livestock_Modernization_Initiative_July_2015.pdf

Thumbi, S. M., Njenga, M. K., Marsh, T. L., Noh, S., Otiang, E., Munyua, P., Ochieng, L., Ogola, E., Yoder, J., Audi, A., Montgomery, J. M., Bigogo, G., Breiman, R. F., Palmer, G. H., & McElwain, T. F. (2015). Linking human health and livestock health: A "one-health" platform for integrated analysis of human health, livestock health, and economic welfare in livestock dependent communities. *PLoS One, 10*(3), e0120761.

Walton, C., J. Taylor, J. Vanleeuwen, F. Yeudall, F., and S. Mbugua. 2012. Associations of diet quality with dairy group membership, membership duration and non-membership for Kenyan farm women and children: A comparative study. Public Health Nutrition 17(2): 1–10.

Watanabe, K., Lewis, B., Mlewah, T. B., & Tetsuka, M. (2017). Age at first calving and factors influencing it in dairy heifers kept by smallholder farmers in southern Malawi. *Japan Agricultural Research Quarterly, 51*(4), 357–362.

Wetende, E., Olago, D., & Ogara, W. (2018). Perceptions of climate change variability and adaptation strategies on smallholder dairy farming systems: Insights from Siaya Sub-County of Western Kenya. *Environmental Development, 27*(1), 14–25.

Zalla, T. M. (1974). Herd composition and farm management data on smallholder Milk producers in Kilimanjaro: Some preliminary results. Economic research bureau paper no. 74.8. University of Dar-es-Salaam.

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