Animal 16 (2022) 100513

Contents lists available at ScienceDirect

Animal
The international journal of animal biosciences

Breeding objectives for dairy cattle under low, medium and high production systems in the tropics

P.K. Wahinya [a,b,*], M.G. Jeyaruban [a], A.A. Swan [a], J.H.J. van der Werf [c]

[a] Animal Genetics & Breeding Unit, University of New England, Armidale, NSW 2351, Australia
[b] Department of Agricultural Sciences, Karatina University, PO Box 1957-10101, Karatina, Kenya
[c] School of Environmental and Rural Science, University of New England, Armidale, NSW 2351, Australia

ARTICLE INFO

Article history:
Received 5 September 2021
Revised 10 March 2022
Accepted 11 March 2022
Available online 15 April 2022

Keywords:
Bio-economic model
Economic weights
Profitability
Selection index
Trait emphasis

ABSTRACT

A deterministic bio-economic model was developed to estimate economic weights for genetic improvement of lactation milk yield, fat yield, age at first calving, calving interval, mature weight and survival under low, medium and high production systems in the Tropics. Input parameters were obtained from dairy production systems in Kenya which has a tropical environment. The highest proportion of revenue is from the sale of milk followed by sale of heifers, cull cows and sale of male calves under all production systems. On the other hand, feed cost is the most important production cost followed by labour, marketing, reproduction and health costs, respectively. Economic values for the six traits were derived from a profit equation using revenue and production costs per cow per year. The economic values were then discounted using diffusion coefficients which account for differences between traits in the time when the improvement is expressed. Economic weights were robust to changes in input and output prices, changes in feeding strategies, and changes in milk and surplus heifer marketing strategies. Genetic standard deviations were multiplied by economic values to standardise the economic value of traits and to compare their potential for economic response. When expressed as proportion of their sum, these relative economic weights under the low, medium and high production systems for lactation milk yield were 51.36, 59.79 and 63.98%; for fat yield 4.50, 10.69 and 9.05%; for age at first calving 3.16, 2.66 and 0.55%; for calving interval 33.59, 19.88 and 20.05%; for mature weight 1.55, 1.34 and 1.19% and for survival rate 5.84, 5.64 and 5.18%, respectively. The predicted responses followed the same pattern as the relative economic weights. This shows that milk yield and calving interval were most important in all production systems but the value of response for traits differed between production systems with more emphasis on milk yield and less on calving interval in the high production systems. Moderate correlations were estimated between the breeding objective for the low, medium and high production systems. To maximise response in the overall breeding objective, different selection criteria are required for the three production systems.

Implications

Dairy cattle farms in the tropics differ in the level of inputs and outputs. Genotypes also re-rank moderately between production systems. Our modelling showed that these two phenomena cause breeding objectives to be different for these production systems with moderate correlations estimated between the breeding objective for the low, medium and high production systems in the tropics. Milk yield and calving interval were the most important traits in all production systems but the relative emphasis on milk yield was higher in the most intensive system. To maximise the effectiveness of genetic improvement, different selection criteria are required within each system.

Introduction

The dairy cattle industry in tropics supports livelihoods through food, employment, insurance, and income. The demand for dairy products in most developing countries within the tropics is increasing, leading to pressure on dairy farmers to increase milk production under increasingly challenging conditions driven by climate change and feed limitations. Dairy production has also been improving to meet the demand but largely as a result of the

* Corresponding author at: Animal Genetics & Breeding Unit, University of New England, Armidale, NSW 2351, Australia.
E-mail address: pwihany2@une.edu.au (P.K. Wahinya).

https://doi.org/10.1016/j.animal.2022.100513
1751-7311/

increased animal population (Wambugu et al., 2011) rather than via the considerable opportunity to improve productivity (Thornton, 2010; Rege et al., 2011). Genetic improvement is a sustainable option to improve productivity under current and future production constraints. The initial step in designing a breeding programme for genetic improvement is to define the target production systems and their breeding objectives.

Definition of breeding objectives involves the identification of traits that influence profit and then the estimation of their economic weights. Economic weights are used in a selection index, to define the aggregate genotype which is a linear function of traits to be improved, each multiplied by its economic weight (Bekman and van Arendonk, 1993). Breeding objectives may be sensitive to production circumstances and production levels which in turn depend on the level of inputs and outputs (Walmsley, 2021). Dairy farms in developing countries differ based on the level of inputs and outputs implying that the breeding objectives should be designed to support sustainable genetic improvement within a specific production system. Bio-economic models can be used to model differences in production and future market conditions (Groen et al., 1997).

A bio-economic model is a multi-equation simulation model that can be used to study the effects of genetic changes in a production system on the efficiency and profitability of the farming enterprise. The first step in the development of a bio-economic model is the description of conventional herd management under a production system. Low, medium and high dairy production systems in Kenya have been described based on the level of milk production (Wahinya et al., 2020a). An intensive production system is a high input–output production system predominantly keeping exotic pure breed animals while the extensive system is a low input–output production system mainly with crosses between *Bos taurus* and *Bos indicus* breeds. The semi-intensive system is intermediate between the low and high production systems. The second step involves modelling profit from a conventional herd within each system as a function of economically important biological traits. Bio-economic models can then be used to estimate economic values from the effect of profitability of changing the mean of breeding objective traits (Ladd and Gibson, 1978). Sensitivity analysis can be applied to look at the effect of assumed parameter values such as market prices and other parameters used in the model (Groen et al., 1997). The bio-economic model also allows to account for many complex inter-relationships that exist among model variables and genetic traits (Nielsen et al., 2006).

Bio-economic models have been used to estimate economic values in different production systems for beef cattle (Rewe et al., 2006; Moreira et al., 2019), pigs (Mbuthia et al., 2015), sheep (Gizaw et al., 2018) and poultry (Okeno et al., 2013) in the tropics. However, economic values have not been estimated for dairy cattle production considering differences in production systems. The level of input and output factors and differences in other production parameters like herd fertility, herd milk productivity and replacement rate are expected to have an influence on the economic values for different traits under different production systems (Okeno et al., 2013). Economic values should also be updated to reflect the current and future production circumstances. This study, therefore, aims to estimate economic values and predict genetic responses for the traits of economic importance under low, medium and high production systems in the tropics.

Material and methods

Model description

Bio-economic models were developed in this study to describe low, medium and high production systems in the tropics using R software (R Core Team, 2021). Low, medium and high production systems described in Wahinya et al. (2020a) based on herds' average milk production were used to represent the existing dairy production circumstances in Kenya as a case study. Profitability was defined as the difference between revenue and cost per cow per year determined by input and output parameters. The model objective function was to maximise profit, which is commonly the main objective of individual farms. The main inputs included feed, husbandry (disease control, treatment and labour), reproduction, and marketing costs which all vary across the three production systems. Revenue included the sale of milk, sale of culled cows and, heifers, male calves and breeding heifers. Management, nutritional and economic variables (Tables 1 and 2) were obtained from representative farms to represent the current production and market circumstances. Some variables were sourced from the literature for the dairy cattle population in Kenya (Bebe et al., 2002; Kahi and Nitter, 2004; Menjo et al., 2009; Wambugu et al., 2011; Onono et al., 2013). The economic variables obtained from the literature were adjusted using an inflation index of 5.65% to account for the price changes over time due to inflation (KNBS, 2019).

Traits influencing revenue and costs

Revenue from dairy cattle is mainly derived from milk and the sale of animals (Kahi and Nitter, 2004). Fat yield is important because it influences the energy requirements and, therefore, the amount of feed required. Fertility traits, including age at first calving and calving interval, have an influence on the days in milk and

Table 1
Production, management, nutritional and economic variables used in the model for the low, medium and high dairy cattle production systems.

Variables		Production system		
		Low	Medium	High
Milk yield per cow (kg)[1]	1st lactation	2 604	3 982	5 520
	2nd lactation	2 808	3 966	6 058
	3rd lactation	2 921	4 199	6 327
	4th lactation	2 845	4 244	6 293
	5th lactation	2 819	4 158	6 098
Lactation length (days)[1]	1st lactation	336	325	337
	2nd lactation	333	321	333
	3rd lactation	334	319	331
	4th lactation	323	317	329
	5th lactation	320	315	329
Fat yield in (kg)[1]	1st lactation	110	215	171
	2nd lactation	125	212	197
	3rd lactation	133	224	218
	4th lactation	123	231	230
	5th lactation	127	228	218
Calving interval (days)[1]	1st parity	495	455	417
	2nd parity	493	453	415
	3rd parity	500	454	413
	4th parity	494	456	415
Age at first calving (days)[1]		1 123	1 008	892
Heifer calf birth weight (kg)[2]		30	38	41
Weight at weaning (kg)[2]		70	92	100
Mature live weight (kg)[1,3,4,5]		300	400	450
Preweaning survival rate (%)[1]		90	93	94
Survival rate to age at first calving (%)[1]		81	86	88
Cow survival per lactations (%)[1]		90	93	94
Calving rate (%)[2]		67	74	77
Age at weaning (days)[2]		120	120	120
Age at culling (days)[1]		3 424	3 140	2 880

[1] Data from dairy farms' performance recording with the Dairy Recording Services of Kenya.
[2] Kahi and Nitter (2004).
[3] Lukuyu et al. (2012).
[4] Lukuyu et al. (2016).
[5] Lanyasunya et al. (2006).

Table 2
Economic variables (in Kenya shillings) used in the model for the low, medium and high dairy cattle production systems.

Variables	Production system		
	Low	Medium	High
Price of male calf[1]	5 000	5 000	5 000
Price per kg of live weight[1]	110	110	110
Heifer price[1]	80 000	100 000	120 000
Price of milk per kg[1]	40	40	40
Price butterfat per kg[2]	86.77	86.77	86.77
Cost of concentrates per Kg of DM[3]	–	20.55	20.55
Cost of calves concentrates per Kg of DM[1]	–	47.19	47.19
Cost of pasture/kg DM[2]	0.53	0.53	0.53
Cost of silage/kg DM[4]	12	12.00	12.00
Health cost for a heifer per day[1]	1.37	7.67	7.67
Health cost for a cow per day[1]	2.74	8.22	8.22
Reproductive cost for a heifer[1,5]	1 500.00	1 500.00	1 500.00
Reproductive cost for a cow[1,5]	3 000.00	3 000.00	3 000.00
Cost of labour per heifer per day[1]	10.96	13.70	15.66
Cost of labour per cow per day[1]	19.18	23.29	27.40
Fixed costs per day [2]	1.05	1.05	1.05

1 US dollar = 103.58 Kenya shillings (Central Bank of Kenya, 2020).
[1] Data from dairy farms' performance recording with the Dairy Recording Services of Kenya.
[2] Kahi and Nitter (2004).
[3] Lukuyu et al. (2012).
[4] SNV (2019).
[5] Reproductive cost includes the cost of artificial insemination including semen and labour.

the number of calves for replacement or sale in the productive lifetime of a cow. Cow survival is of economic importance in the tropics where diseases and mortality rate are constraints (Bebe et al., 2003). The live weight of animals has a significant effect on feed requirements. Currently, cows under the Dairy Recording Services of Kenya are performance recorded largely for milk yield, fat yield, age at first calving and calving interval traits.

Herd management

Trait means in the three production systems were obtained from historic data provided by the Dairy recording Service of Kenya courtesy of Kenya Livestock Recording Centre. It was assumed that cows in all three production systems are mated using artificial insemination. Male calves are assumed to be sold at a fixed price within 2 weeks of birth while female calves are retained, reared and used as replacement stock for the cows culled for age after the fifth lactation. Surplus heifers are sold after the first insemination as replacement stock. Cows in the three production systems are grazed on roughage in the form of pastures and silage. Throughout a year, metabolisable energy derived from roughage consumption was assumed to be made up of 80, 75 and 67% pasture, with the remaining part being silage, across the low, medium and high production systems, respectively, and concentrates for the medium and high production systems. It was assumed that calves are fed on milk equivalent to 15% of their birth weight for 7 weeks, 10% for the next 4 weeks and then 1 litre twice a day until weaning at 120 days (Lukuyu et al., 2012; Rosenberger et al., 2017). In the three production systems, calves are introduced to good quality forage after 2 weeks and to concentrate feed in the medium and high production systems. Feed consumption for heifer calves and cows was determined by their energy requirements for maintenance, growth, lactation and reproduction under all production systems. Calves are fed concentrates adding up to a total of 98 and 123 kg DM up to weaning under the medium and high production systems, respectively (Lukuyu et al., 2012; NAFIS, 2020). After weaning, heifers and cows are offered 0.89 and 1.34 kg of concentrate DM up to the age at first calving per day and during the dry periods when the cows are not lactating under the medium and high production systems, respectively. During the lactation period, an extra 0.89 kg of concentrate DM is offered for every 3 kg of milk produced under the medium and high production systems, respectively (Kitalyi et al., 2020). Standard management practices including parasite and disease control were assumed to be carried out and did not differ between systems. Fixed herd size is assumed in all the three production systems; therefore, cull for age cows are replaced by heifers reared within the herd while the surplus heifers are sold.

Fig. 1 shows the herd structure, dynamics and replacement policy under the low production system. A similar herd structure was adapted for the medium and high production systems with the same herd size but with different survival rates (Table 1) leading to different herd composition presented later in the results.

Tables 1 and 2 show the production, management, nutritional and economic variables assumed in this study for the three production systems. In most developing countries in the tropics, there are no dairy production quotas. Milk payment is based on volume. However, there are standards for raw milk quality and some efforts have been made to introduce a quality-based milk payment system to control and improve the quality and safety of milk, (Harcourt-Brown et al., 2018; Ndambi et al., 2018). In this study, the effect of payment of milk based on volume and fat content on the economic weights is investigated in the base situation. Surplus heifers were assumed to be sold as replacement stock at a fixed price while cull cows were sold for slaughter based on their live weight at the time of culling. An additional 5% marketing cost was applied to the prices of male calves and heifers, cull cows' live weight and milk sold to account for the marketing levies and transportation cost (Kahi and Nitter, 2004). Some variables were assumed to be the same across the production systems for ease of calculations or because they are not certainly different, including milk and live weight prices, the cost of concentrates and reproduction and fixed costs. Milk yield, lactation length, fat yield, calving interval and age at first calving parameters presented in Table 1 were obtained from performance records taken from dairy farms across Kenya by the Dairy Recording Service of Kenya.

Estimation of revenues, cost, and profit

Profit in this study was derived as the difference between revenue and cost per cow per year. The total revenue (**Rev**) was calculated as:

$$\mathrm{Rev} = \mathrm{Rev}_{\mathrm{milk}} + \mathrm{Rev}_{\mathrm{mcalves}} + \mathrm{Rev}_{\mathrm{sheifers}} + \mathrm{Rev}_{\mathrm{ccows}}$$

while the total cost was derived as:

$$\mathrm{Cost} = \mathrm{Cost}_{\mathrm{feed}} + \mathrm{Cost}_{\mathrm{Labor}} + \mathrm{Cost}_{\mathrm{Health}} + \mathrm{Cost}_{\mathrm{Reproduction}} + \mathrm{Cost}_{\mathrm{Marketing}}$$

where $\mathrm{Rev}_{\mathrm{milk}}, \mathrm{Rev}_{\mathrm{mcalves}}, \mathrm{Rev}_{\mathrm{sheifers}}$ and $\mathrm{Rev}_{\mathrm{ccows}}$ are the revenues from the sale of milk, male calves, surplus breeding heifers and cull cows, respectively, and $\mathrm{Cost}_{\mathrm{feed}}$, $\mathrm{Cost}_{\mathrm{Labor}}$, $\mathrm{Cost}_{\mathrm{Health}}$, $\mathrm{Cost}_{\mathrm{Reproduction}}$ and $\mathrm{Cost}_{\mathrm{Marketing}}$ are the costs incurred to feed the different classes of animals, cost of labour, health, reproduction, and marketing, respectively.

The number of cows (**Cows**) in different lactations was simulated using the total cow survival rate of mature cows (S_c) as:

$$\mathrm{Cows}_1 = \begin{cases} N \sum_{a=1}^{4} S_c^a & \text{for the first lactation} \\ \mathrm{Cows}_{i-1} \times S_c & \text{for subsequent lactations} \end{cases}$$

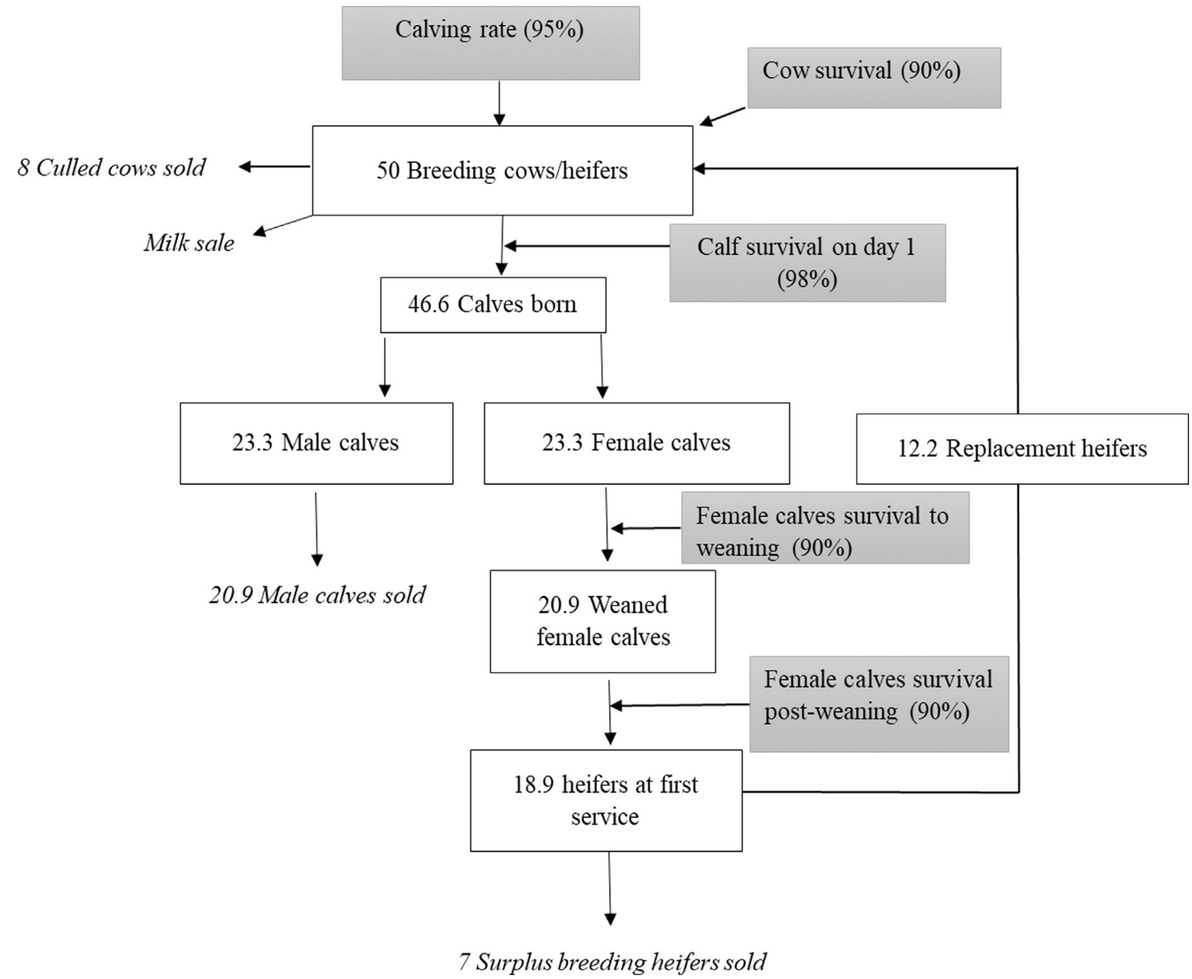

Fig. 1. Herd structure and dynamics in the low dairy cattle production systems.

where **N** is the total number of cows in the herd which is fixed and **i** is the lactation number. The number of calves was calculated as:

$$\text{Calves} = \sum_{i=1}^{5} \text{Cows}_i \times \text{CR} \times \text{S}_{D1}$$

where Cows_i is the number of cows in lactation i, **CR** the calving rate and S_{D1} is the survival rate within the first 24 hours after calving. Assuming a sex ratio of 1:1, the number of male calves ($\mathbf{NC_{male}}$) is:

$$\text{NC}_{male} = \frac{\text{Calves}}{2}$$

and the revenue from the sale of male calves ($\mathbf{Rev_{cmale}}$) was determined as:

$$\text{Rev}_{cmale} = \text{NC}_{male} \times \text{P}_c$$

where $\mathbf{P_c}$ is the price of a male calf. Revenue from milk ($\mathbf{Rev_{milk}}$) was derived based on the volume and fat yield content as:

$$\text{Rev}_{milk} = (\text{MY} \times \text{Price}_{milk}) + [(\text{MY} \times \text{FY\%}) - (\text{MY} \times 0.035)) \times \text{Price}_{fat}]$$

where **MY** is milk yield in kilograms; $\mathbf{Price_{milk}}$ is the price of milk per kilogram of standard milk with a 3.5% of fat yield; **FY** is fat yield in kilograms; FY% is the fat percentage in milk (derived using the lactation milk yield and fat yield in Table 1); $\mathbf{Price_{fat}}$ is the price per kilogram of fat yield above the standard 3.5%.

Assuming that the preweaning survival rate ($\mathbf{S_{pw}}$) is applied at weaning and the survival rate from weaning to first calving ($\mathbf{S_{w-afc}}$) is applied at a fixed age at first calving, the number of female calves at weaning ($\mathbf{NC_{fwean}}$) and heifers at first calving ($\mathbf{NC_{hafc}}$) were obtained as:

$$\text{NC}_{fwean} = \frac{\text{Calves}}{2} \times \text{S}_{pw}$$

$$\text{NC}_{hafc} = \text{NC}_{fwean} \times \text{S}_{w-afc}$$

All the cows after the fifth lactation were culled for age and sold for slaughter and replaced with heifers while surplus heifers were sold at a fixed price as replacement stock. After applying survival rates at different stages up to the point of culling, the realised total survival rates under the low, medium and high production systems are 48, 60 and 65%, respectively. Revenue from surplus heifers ($\mathbf{Rev_{sheifer}}$) and cull cows ($\mathbf{Rev_{ccow}}$) for age was therefore calculated as:

$$\text{Rev}_{sheifer} = (\text{NH}_{afs} - (\text{Cows}_5 + \text{Cows}_c)) \times \text{Price}_{heifer}$$

$$\text{Rev}_{ccow} = \text{Cows}_5 \times \text{Wt}_{ccow} \times \text{Price}_{lwt}$$

where $\mathbf{NH_{afs}}$ is the number of heifers at first service, $\mathbf{Cows_5}$ the number of cows culled for age after the 5th lactation and $\mathbf{Cows_c}$ the number of cows that do not survive within different lactations, $\mathbf{Price_{heifer}}$ the fixed price of replacement heifers, $\mathbf{Wt_{ccow}}$ the live weight of the cows at culling and $\mathbf{Price_{lwt}}$ the price per unit kilogram of live weight. Live weight was predicted assuming that feed intake and environmental conditions were constant over time and sufficient for the animal. Live weight at a time t was predicted assuming that growth from birth to weaning is represented by a straight line and subsequently from weaning to culling by a Brody curve (Brody, 1945), as follows.

$$Wt_t = \begin{cases} \left[\frac{(ww-bw)}{age_w} \times t\right] + bw & \text{when } t \le age_w \\ mw - (mw - ww)\{exp[-k(t - age_w) & \text{when } t > age_w \end{cases}$$

where $\mathbf{Wt_t}$ is live weight predicted at an age t, **ww** is weaning weight, **bw** the birth weight, age_w age at weaning, **mw** mature weight and k a maturity index calculated as $\left[\left(\frac{ww-bw}{age_w}\right)\right] \div (mw - ww)$. The rate of growth before weaning and after weaning has an effect on the amount of energy requirements and hence the feed intake. Preweaning daily gain ($\mathbf{DG_{t_{PrW}}}$) and post-weaning daily gain ($\mathbf{DG_{t_{PsW}}}$) were estimated as:

$$DG_t = \begin{cases} \frac{(ww-bw)}{age_w} & \text{when } t \le age_w \\ k(Wt_t - Wt_{t-1}) & \text{when } t > age_w \end{cases}$$

During the gestation period, the mass of the conceptus ($\mathbf{C_m}$) was added to the dam's weight and was predicted as (Agricultural Research Council, 1980):

$$C_m = 0.025bw \times 10^{2.932-3.347\times exp(-0.00406\times t_g)}$$

where 0.025 is used to scale the prediction to actual birth weight relative to a standard birth weight of 40 kilograms and $\mathbf{t_g}$ is the number of days from conception.

Feed intake was predicted based on the energy requirements of animals at different stages. The energy intake per day was estimated as the sum of maintenance, growth, pregnancy and lactation requirements. It was assumed that the total metabolic energy (**ME**) requirements were met throughout the year. Maintenance ME requirements ($\mathbf{M_e}$) in megajoules per day were predicted according to Agricultural Research Council, 1980:

$$M_e = \left[\frac{\left[K \times S \times M \times 0.28W_t^{0.75} \times exp(-0.03A_Y)\right]}{k_m} + 0.1(M_g + M_l)\right] \times G$$

where K is breed difference correction factor for *Bos taurus* or intermediates which is 1.4 and 1.2 for *Bos indicus,* S is the sex correction factor which is 1 for females and castrates or 1.15 for males, M the correction factor for suckled calves which is 1 + (0.23 × propotion of digestible energy from milk), A_Y is the age in years with a maximum of 6, k_m the net efficiency of use of metabolisable energy for maintenance calculated as 0.35q + 0.503, where q is the metabolisability of the diet assumed to be 0.62, 0.70 and 0.72 for the low, medium and high production systems, respectively, M_g, M_l and G are the ME requirements for growth, lactation and correction factors (1.3) to account for the extra ME for pasture grazing under the low, medium and high production systems, respectively. The ME requirement for growth ($\mathbf{M_g}$) in mega joules (**MJ**)/day was predicted as (Agricultural Research Council, 1980):

$$M_g = \left[\frac{4.1 + 0.0332W_t - 0.000009W_t^2}{1 - 0.1475DG_t}\right] \times \left(\frac{DG_t}{0.78q + 0.006}\right)$$

where W_t and DG_t are live weight and daily gain at time t, respectively, the constants (0.78q + 0.006) represent the efficiency of utilisation of dietary ME for growth. The ME for lactation ($\mathbf{M_l}$) in megajoules per day was predicted as (Agricultural Research Council, 1980):

$$M_l = \frac{MY \times (1.509 + 0.00406FY)}{0.35q + 0.42}$$

where MY is the milk yield in kilograms per day and FY the fat yield in the milk in grams per kilograms of milk, while $0.35q + 0.42$ represents the efficiency of utilisation of ME for milk production. Daily milk yields $\mathbf{Y_t}$ ( ) along the lactation were simulated using the Wood function (Wood, 1967):

$$Y_t = at^b e^{-ct}$$

where t is the day in milk while a, b and c are Woods function parameters (Supplementary Table S1) estimated using the Gauss-Newton algorithm in nls statistical software package in R (R Core Team, 2021) and test-day milk yield records for dairy cattle under low, medium and high production systems in Kenya (Wahinya et al., 2020b). The metabolisable energy for gestation ($\mathbf{M_p}$) in megajoules per day was calculated as (Agricultural Research Council, 1980):

$$M_p = 0.025bw \times \frac{\left[(0.0201 \times exp(-0.0000576t_g) \times 10^{151.665\times exp(-0.0000576t_g)}\right]}{0.113}$$

where the term 0.025 is a correction factor for calves with birth weight (bw) greater than 40 kg, t_g is days from conception, while 0.113 is the utilisation of ME by the conceptus for growth.

Calves were assumed to depend on milk to meet their ME requirements during the first 2 weeks of life. Thereafter, they are fed on milk and introduced to dietary feed. The calves' ME intake from the dietary feed ($\mathbf{M_{cfeed}}$) was estimated as the difference between the total ME requirement for growth and maintenance less the ME supplied from milk as follows:

$$M_{cfeed} = (M_e + M_g) - M_{milk}$$

where $\mathbf{M_{milk}}$ is the ME from cow's milk calculated as:

$$M_{milk} = 0.94MY \times EV_m$$

assuming that the metabolisability of milk is 0.94 and EV_m is the energy value of milk assumed to be 3.45 MJ/kg (Barłowska et al., 2011). The total energy requirement supplied by feed was determined as the sum of M_e, M_g, M_p, and M_{cfeed}. The total amount of feed was then determined by converting the total energy requirements into proportions of pasture, silage and concentrate. The energy supplied from a fixed amount of concentrate feed under the medium and high production systems was determined and subtracted from the total energy requirement first to determine the energy supplied by pasture and silage. The energy provided by concentrate feed ($\mathbf{E_{conc}}$) was determined as $E_{conc} = Conc \times 11.8$ where Conc is the total amount of concentrate feed consumed and 11.8 the energy content in concentrates (MJ of net energy per kilogram of DM) (SNV, 2020). The remaining energy was supplied as pasture and silage ($\boldsymbol{E_{pas-sil}}$). Under the low production system, roughage consumption was assumed to be 80% pasture and 20% silage, 75% pasture and 25% silage for the medium production system and 67% pasture and 33% silage for the high production system. The amount of pasture ($\mathbf{Feed_{pas}}$) and silage ($\mathbf{Feed_{sil}}$) DM intake was determined as $Feed_{pas} = \frac{(E_{pas-sil} \times P_{pas})}{7.5}$ and $Feed_{sil} = \frac{(E_{pas-sil} \times P_{sil})}{7.5}$, where7.5 and 10.9 (SNV, 2020) are the energy content in pasture and silage, respectively, while P_{pas} and P_{sil} are the assumed proportions of pastures and silage under the different production systems. The amount of concentrates, pastures and silage in kilograms of DM were then multiplied by the price of each (Table 2) to obtain the cost of feed. Revenue and costs were estimated per year by regressing the revenue and costs on actual production period under the low (3 424 days), medium (3 140) and high (2 880 days) production systems then predicting to a year.

Derivation of economic weights

Economic values in this study are defined as the unit change in profit due to a unit improvement of a trait while keeping all the other traits constant. A discounting factor was then applied to the economic values using diffusion coefficients to get economic weights adjusted for future profit and the frequency of expression. Since the traits were measured in different units, to allow direct comparison between the traits' value of genetic improvement, economic weights were standardised as follows:

$$SEW_j = EW_j \times \sigma_{aj}$$

where SEW, EW and σ_a are the standardised economic weights, economic weights and genetic standard deviation for trait j, respectively.

The discounting procedure of McArthur and del Bosque Gonzalez, 1990 was used to account for differences between traits in the delays observed between selection and when improvements are expressed in the herd. This method is different from the gene flow method (McClintock and Cunningham, 1974) which accounts for both the delays between the time an animal is selected and the time its descendants are born, and the time when the improvement is expressed. Diffusion coefficients account for the delay between selection and when the descendants are born (McArthur and del Bosque Gonzalez, 1990). This method is applied in the BREED-OBJECT programme for beef cattle (Brash et al., 1990). The diffusion coefficients were calculated using a 5% discounting rate.

The genetic standard deviations and correlations (used later in the prediction of selection responses) between traits (Table 3) were based on genetic parameters estimated in low, medium and high production systems in Kenya by Wahinya et al., 2020a. Genetic standard deviations for mature weight and survival rate were obtained from other published studies (Kahi and Nitter, 2004; Ilatsia et al., 2011; Musingi et al., 2018). Using the SEW, relative economic weights (REW_j) were then calculated as follows:

$$REW_j = \frac{|SEW_j|}{\sum_{j=1}^{6}|SEW_j|} \times 100$$

where $|SEW_j|$ is the absolute value of the standardised economic weight for trait *j*.

Correlation between breeding objectives

The correlation ($\boldsymbol{r_{x,y}}$) between the low, medium and high production system's breeding objectives was calculated as.

$$r_{x,y} = \frac{a_x' G_{x,y} a_y}{\sqrt{a_x' G_x a_x \times a_y' G_y a_y}}$$

where a_x and a_y are vectors with trait economic values in x and y production systems, $G_{x,y}$ the genetic variance–covariance matrix between any two production systems and G_x and G_y are genetic variance–covariance matrices for the breeding objective traits in x and y production systems.

Production and marketing scenarios

Economic weights were also derived under three alternative feeding scenarios. The first scenario was applied as an alternative under the low production system, where cows are fed supplementary concentrates. In the second scenario, it was assumed that con-

Table 3
Phenotypic SD (σ_P) and genetic parameters (heritabilities (diagonal) genetic (above diagonal) and phenotypic (below diagonal) correlations) for traits under the low, medium and high dairy cattle production systems.

System	Trait	σ_P	Low						Medium						High					
			LMY	FY	AFC	CI	MWT	SR	LMY	FY	AFC	CI	MWT	SR	LMY	FY	AFC	CI	MWT	SR
Low	LMY	626.10	0.21	0.65	−0.38	−0.11	0.23	0.24	0.42	0.56	−0.14	−0.46	0.23	0.27	0.64	0.62	−0.05	0.00	0.21	0.26
	FY	29.70	0.83	0.11	−0.22	0.02	0.11	0.20	0.56	0.33	−0.12	−0.01	0.10	0.19	0.66	0.84	−0.12	0.15	0.11	0.21
	AFC	156.48	0.02	−0.09	0.25	0.03	−0.09	−0.01	−0.22	−0.09	−0.06	0.29	−0.09	−0.01	−0.25	−0.12	−0.64	−0.50	−0.11	0.02
	CI	130.85	−0.01	0.08	0.00	0.06	−0.41	−0.22	−0.53	0.03	0.24	0.05	−0.40	−0.25	−0.07	0.06	0.51	0.08	−0.45	−0.24
	MWT	31.97	0.31	0.00	−0.11	0.03	0.21	0.01	0.16	0.10	−0.15	−0.40	0.06	0.01	0.12	0.11	−0.13	−0.35	0.51	0.03
	SR	11.77	0.16	0.16	−0.04	0.00	0.00	0.02	0.26	0.20	−0.01	−0.03	−0.26	0.50	0.22	0.21	−0.04	0.03	0.01	0.50
Medium	LMY	923.12	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.54	−0.05	0.34	0.16	0.26	0.75	0.61	−0.47	0.51	0.17	0.22
	FY	60.47	0.00	0.00	0.00	0.00	0.00	0.00	0.84	0.20	0.34	−0.04	0.10	0.19	0.65	0.58	−0.15	0.15	0.11	0.20
	AFC	129.67	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.15	0.26	−0.12	−0.15	0.01	−0.21	−0.10	0.32	0.06	−0.16	0.00
	CI	97.56	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.08	0.03	0.03	−0.40	−0.23	0.14	0.03	−0.44	0.62	−0.42	−0.25
	MWT	54.14	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.00	−0.11	0.03	0.30	0.01	0.12	0.11	−0.13	−0.34	0.51	0.03
	SR	11.77	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.16	−0.04	0.00	0.00	0.02	0.26	0.21	0.00	−0.01	0.00	0.50
High	LMY	1 226.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.73	−0.28	0.43	0.16	0.22
	FY	56.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.81	0.25	−0.14	0.14	0.12	0.22
	AFC	60.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−0.01	0.01	0.05	0.09	−0.13	−0.01
	CI	68.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.08	0.03	0.04	−0.39	−0.19
	MWT	54.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.00	−0.11	0.03	0.30	0.01
	SR	11.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.16	−0.04	0.00	0.00	0.02

Abbreviations: MY = lactation milk yield (kgs); FY = butterfat yield (kgs); AFC = age at first calving (days); CI = calving interval (days); MWT = mature weight (kgs); SR = cow survival (%).
Source for genetic parameters: Haile-Mariam et al., 2003; Kahi et al., 2004; Ilatsia et al., 2011; Heise et al., 2018; Wahinya et al., 2020a.
The genetic correlation matrices were bent to make them positive definite using Higham, 1988 algorithm in R software (R Core Team, 2021).

centrate feeds are not available in the medium and high production systems and therefore metabolisable energy requirements were met by additional pasture and silage, fed in the same ratios as in the base situation (75 and 67% pasture in the medium and high production systems, respectively). In the third scenario, economic weights were additionally estimated similar to the base but with 50% of the metabolisable energy met by roughage coming from pasture and the remainder from silage in all production systems. These alternative feeding strategies were selected because concentrate feeds are expensive and their use is variable with a likelihood of farmers decreasing the proportion of concentrates. Due to the decreasing farm sizes, confinement of cows is a common way to intensify dairy production which involves conservation of feeds which in turn leads to animals being fed on a higher proportion of silage.

Two additional marketing scenarios were simulated, firstly with milk marketed based on volume (40 Kenya shillings per kg of milk) only (compared to payment based on volume and fat in the base scenario), and secondly with surplus heifers were sold based on their live weight (Kenya shillings 110 per kg of live weight) for slaughter (compared to sale at a fixed price in the base scenario).

Sensitivity analysis

A sensitivity analysis was carried out to assess the effect of changing input parameters on economic weights. Sensitivity analysis was done by increasing and decreasing prices of milk, fat, live weight, concentrates and roughages by 10% while holding all the other parameters constant. This was simulated to assess the sensitivity of the economic weights to future changes in the main input and output prices.

Response to selection

Multiple trait selection indexes were used to predict the expected individual trait response per year using the MTINDEX spreadsheet model (Van Der Werf, 2020). Response to selection per year ($\mathbf{R_{yr_j}}$) for trait j was predicted as:

$$R_{yr_j} = \frac{ib'G_j\sigma_I^{-1}}{L}$$

where i is the selection intensity, b is the vector of index weights, G the jth column of genetic variance–covariance matrix for trait j, σ_I the standard deviation of the index, L the generation interval, respectively. Selection intensities were derived assuming 80% of females are selected with generation intervals of 5 years. A more comprehensive analysis with selection in males and females is shown in a separate study (Wahinya, 2020). Information was assumed to be from own performance, dam and female half-sibs. The predicted responses to selection for the traits in the breeding objective were multiplied by their respective economic weights to get economic response per trait in Kenya shillings and as a percentage of the overall economic response within the production systems. Overall economic responses were then derived by summing up the economic response for all the traits within the production systems.

Results

Herd structure, costs and revenue

The herd structure in the base situation under the low, medium and high production systems are shown in Table 4. The herd composition was different between the production systems. Table 5 shows the simulated cost and revenue per cow per years in the base situation. Feed cost accounted for 51, 65 and 68% of the total production costs under the low, medium and high production systems, respectively. The feed cost was calculated from the simulated DM intake which was within 2–4% of the BW at respective stages of growth as in National Research Council, 2001. Labour cost was the second most important cost (12–23%) followed by marketing costs (12–16%). Under the low production system, reproductive costs were higher than health costs while under the medium and high production systems, the reverse was observed. Revenue from milk sales was 84–88% of the total revenue with the remainder obtained from the sale of surplus heifers, cull cows and male calves in diminishing order. Revenue, cost and profit were highest under the high production systems and lowest under the low production system.

Table 4
Herd structure under the low, medium and high production systems (rounded to the nearest whole numbers – 50 cows).

Variable	Production system		
	Low	Medium	High
Herd structure			
Male calves sold	23.3	23.3	23.3
Female calves at weaning	20.9	21.6	21.9
Heifers at first service	18.9	20.1	20.6
Cows in 1st lactation	12.2	11.5	11.3
2nd lactation	11.0	10.7	10.6
3rd lactation	9.9	9.9	10.0
4th lactation	8.9	9.3	9.3
5th lactation	8.0	8.6	8.8

Economic weights

Table 6 shows the economic weights, standard and relative economic weights for lactation milk yield, fat yield, age at first calving, calving interval, mature weight and survival rate under the low, medium and high production systems. The economic weights in the base situation for lactation milk yield (Kenya shillings (**Kes**) 21.45–22.63), fat yield (Kes 51.30–61.54) and survival rate (Kes 399.26–604.27) were positive under all the production systems. Age at first calving (Kes −4.61 to −7.89), calving interval (Kes −114.69 to −296.71) and mature weight (Kes −5.95 to −7.80) had negative economic weights. The standard and relative economic weights of the different traits varied among the three production systems. Lactation milk yield (53.92–66.16%) had the highest relative economic weights under all the production sys-

Table 5
Cost, revenue and profit (in Kenya shillings) in the base situation per cow per year under the low, medium and high production systems.

Variable	Production system		
	Low	Medium	High
Costs			
Feed	19 533	49 470	68 405
Reproduction	2 422	2 599	2 791
Health	1 210	4 217	4 233
Labour	8 678	10 675	12 517
Marketing	6 254	9 222	13 369
Fixed cost	544	550	552
Total cost	38 640	76 732	101 867
Revenue			
Milk	88 840	144 801	220 062
Male calves	2 328	2 328	2 328
Surplus heifers	10 629	17 258	22 300
Cull cows	3 515	4 788	6 258
Total revenue	105 312	169 175	252 144
Profit (Revenue – Total cost)	66 672	92 444	149 633

Table 6
Economic weights, standard and relative economic weights for the base situation under the low, medium and high dairy cattle production systems.

Trait	Economic weights			Standard economic weights			Relative economic weights		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
LMY	22.63	21.45	22.28	6 470.06	10 023.54	13 656.79	53.92	63.46	66.16
FY	51.30	56.91	61.54	509.91	1 534.70	1 763.83	4.25	9.72	8.54
AFC	−4.61	−5.74	−7.89	−358.26	−382.31	−107.44	2.99	2.42	0.52
CI	−114.69	−180.42	−296.71	−3 819.60	−2 852.18	−3 876.78	31.83	18.06	18.78
MWT	−5.95	−6.48	−7.80	−176.43	−192.03	−231.39	1.47	1.22	1.12
SR	399.26	486.40	604.27	664.51	809.52	1 005.71	5.54	5.13	4.87

Abbreviations: LMY = lactation milk yield (kgs); FY = butterfat yield (kgs); AFC = age at first calving (days); CI = calving interval (days); MWT = mature weight (kgs); SR = cow survival (%).

Table 7
Cost, revenue and profit per cow per year (in Kenya shillings) in the alternative feeding and marketing scenarios per cow per year under the low, medium and high production systems.

Variable	Scenario 1[1]	Scenario 2[2]		Scenario 3[3]			Milk volume[4]			Cull heifer[5]		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
Costs												
Total feeding	34 440	26 592	35 043	31 918	57 760	74 091	19 533	49 470	68 405	19 533	49 470	68 405
Total reproduction	2 422	2 599	2 791	2 422	2 599	2 791	2 422	2 599	2 791	2 422	2 599	2 791
Total health	1 210	4 217	4 233	1 210	4 217	4 233	1 210	4 217	4 233	1 210	4 217	4 233
Total labour	8 678	10 675	12 517	8 678	10 675	12 517	8 678	10 675	12 517	8 678	10 675	12 517
Milk marketing cost	6 254	9 222	13 369	6 254	9 222	13 369	6 254	9 222	13 369	6 254	9 222	13 369
Fixed cost	544	550	552	544	550	552	544	550	552	544	550	552
Total cost	53 547	53 854	68 505	51 025	85 022	107 553	38 640	76 732	101 867	38 640	76 732	101 867
Revenue												
Sale of milk	88 840	144 801	220 062	88 840	144 801	220 062	87 128	139 075	220 557	88 840	144 801	220 062
Sale of male calves	2 328	2 328	2 328	2 328	2 328	2 328	2 328	2 328	2 328	2 328	2 328	2 328
Sale of cull heifers	10 629	17 258	22 300	10 629	17 258	22 300	10 629	17 258	22 300	3 653	5 635	6 682
Sale of cull cows	3 515	4 788	6 258	3 515	4 788	6 258	3 515	4 788	6 258	3 515	4 788	6 258
Total revenue	105 312	169 175	250 948	105 312	169 175	250 948	103 599	163 449	251 442	98 336	157 552	235 329
Profit	51 765	115 321	182 442	54 287	84 153	143 395	64 959	86 717	149 576	59 697	80 820	133 463

[1] Scenario 1 = concentrate feed is offered under the low production system.
[2] Scenario 2 = no concentrates are offered under the medium and high production systems.
[3] Scenario 3 = 50% of the metabolisable energy met by roughage is offered from pasture and the remainder from silage in all production systems under all production systems.
[4] Milk volume = an alternative scenario where milk is marketed based on volume.
[5] Cull heifer = an alternative scenario where surplus heifers are sold for slaughter based on their live weight.

tems followed by calving interval (18.06–31.83%). Under the low production systems, survival rate (5.54%) was more important than fat yield (4.25%), age at first calving (2.99%) and mature weight (1.47%). The relative economic weights were 9.72, 5.13, 2.42 and 1.22% for fat yield, survival rate, age at first calving and mature weight under the medium production system, respectively. Under the high production system, the order was fat yield (8.54%), survival rate (4.87%), mature weight (1.12%) and age at first calving (0.52%).

Cost, revenue and profit in the three alternative feed scenarios are shown in Table 7. Also presented in the table are the cost, revenue and profit under a scenario with milk marketing based on volume only and a scenario where surplus heifers are sold for slaughter based on their live weight. The profit under the low production system decreased when concentrates were offered to meet the simulated nutritional requirements of the cows (Scenario 1) while profit increased when concentrate feeds were not offered under the medium and high production systems (Scenario 2). Scenario 3 had a lower profit due to higher usage of silage which is more costly than pasture. Marketing milk by volume only (Milk volume) and marketing of surplus heifers for slaughter based on their live weight (Cull heifers) resulted in a reduction in profit under all production systems compared to the base scenario. Under these alternative scenarios, feed cost accounted for the highest production cost and the other cost were in the same order as described earlier for the base scenario.

Table 8 shows the economic weights for the three alternative scenarios modified as; (a) concentrate feed is offered under the low production system (Scenario 1), (b) no concentrates are offered under the medium and high production systems (Scenario 2) and (c) 50% of the metabolisable energy met by roughage is offered from pasture and the remainder from silage under all production systems (Scenario 3). The low production system was the most sensitive to change in the ratio of pasture and silage. The economic value for lactation milk yield decreased under the low production systems (reduction of 2.5%) unlike in the medium and high production systems where it increased (increase of 0.3% in both). The economic weights for age at first calving (reduction of 34–93%) and mature weight (reduction of 101–273%) were the most sensitive under all production systems. Economic values for lactation milk yield and survival rate decreased, while economic values for age at first calving and calving interval increased when concentrate feeds were assumed to be available under the low production system. Under the medium and high production systems, when concentrate feeds were assumed to be unavailable, the economic weights for lactation milk yield and survival rate increased but decreased for age at first calving and calving interval.

Table 9 shows the economic weights for scenarios when milk is marketed based on volume and the base situation when surplus heifers are sold for slaughter based on their live weight. Marketing of milk based on volume leads to a decrease in the economic weights for lactation milk yield and calving interval, fat yield and

Table 8
Economic weights for scenarios with different feeding strategies based on the ratio of pasture and silage and concentrate availability under the low, medium and high dairy cattle production systems.

Trait	Scenario 1[1]	Scenario 2[2]		Scenario 3[3]		
	Low	Medium	High	Low	Medium	High
LMY	18.60	25.81	26.81	22.06	21.52	22.35
FY	51.30	56.91	61.54	49.94	55.65	60.59
AFC	−4.13	−6.93	−10.20	−8.88	−9.32	−10.55
CI	−98.96	−205.48	−337.02	−111.17	−178.95	−295.46
MWT	−5.95	−6.48	−7.80	−22.17	−19.08	−15.65
SR	381.39	509.51	635.96	399.27	489.04	606.30

Abbreviations: LMY = lactation milk yield (kgs); FY = butterfat yield (kgs); AFC = age at first calving (days); CI = calving interval (days); MWT = mature weight (kgs); SR = cow survival (%).
[1] Scenario 1 = concentrate feed is offered under the low production system.
[2] Scenario 2 = no concentrates are offered under the medium and high production systems.
[3] Scenario 3 = 50% of the metabolisable energy met by roughage is offered from pasture and the remainder from silage in all production systems under all production systems.

Table 9
Economic weights for scenarios when milk marketing is based on volume and surplus heifers are sold for slaughter based on their live weight.

Trait	Milk Volume[1]			Cull heifer[2]		
	Low	Medium	High	Low	Medium	High
LMY	22.15	20.34	22.35	22.63	21.45	22.28
FY	−1.22	−1.61	−2.22	51.30	56.91	61.54
AFC	−4.61	−5.74	−7.89	−3.43	−3.29	−3.68
CI	−112.42	−172.09	−297.49	−114.69	−180.42	−296.71
MWT	−5.95	−6.48	−7.80	2.49	3.93	2.36
SR	395.50	478.17	594.41	212.79	254.49	317.02

Abbreviations: LMY = lactation milk yield (kgs); FY = butterfat yield (kgs); AFC = age at first calving (days); CI = calving interval (days); MWT = mature weight (kgs); SR = cow survival (%).
[1] Milk volume = alternative scenario where milk is marketed based on volume.
[2] Cull heifer = alternative scenario where surplus heifers are sold for slaughter based on their live weight.

survival rate under all production systems except under the high production system where the economic value for lactation milk yield was slightly higher. Marketing of surplus heifers did not have an influence on the economic value for lactation milk yield, fat yield and calving interval but it leads to an increase in the economic value for age at first calving and mature weight and a decline for survival rate.

Table 10 shows the sensitivity of economic weights as percentage change to changes in the price of milk, fat, live weight and feed cost (pasture, silage and concentrates). The actual feed intake under the three production systems for the base and alternative feeding strategies on age at first calving is shown in Supplementary Table S2. Economic weights for most traits were sensitive to the changes in input and output prices, feeding strategies, milk and heifer marketing scenarios. An increase in the price of milk caused a rise in the economic weight for lactation milk yield and survival rate but leads to a drop in the economic weight for calving interval under all the production systems. A 10% marginal increase in the price of fat led to an increase in the economic weight for fat yield (10.24–10.36%) and survival rate (0.09–0.18%) under all production systems. Under the low and medium production systems, a 10% marginal increase in fat price led to an increase in the economic weights for lactation milk yield and a decrease in calving interval. However, under the high production system, a marginal increase in the fat price decreased the economic weight for lactation milk yield and calving interval. A higher price per kg of live weight increased the economic value for mature weight and decreased the economic weights for age at first calving, calving interval and survival rate. All the traits were sensitive to an increase in feed prices. A 10% reduction in the prices of milk, fat, live weight and feed cost (pasture, silage and concentrates) (Table 10) resulted in similar changes to a 10% increase in the input and output prices but had an opposite effect on the economic weights.

Response to selection

Positive responses were predicted for lactation milk yield (13.35–23.13 kg/year), fat yield (0.14–0.89 kg/year), mature weight (0.08–0.26 kg/year) and survival rate (0.01–0.02%/year) while negative responses were predicted for age at first calving (-0.17 to −2.51 days/year) (Table 11). Negative response (−0.26 days/year) was predicted for calving interval under the low production systems while positive response was predicted under the medium (0.35 day/year) and high (0.17 day/year) production systems. Predicted response for lactation milk yield, mature weight and survival rate increased from the low to the high production system. Higher responses were predicted for fat yield under the medium and high production systems than under the low production system. The low production system however had the highest predicted response for the fertility traits. The economic response (Table 11) followed the same trend as the relative economic weights (Table 6). Based on the relative response to selection, milk yield had the highest response to selection for all the production systems. Under the low production system, calving interval was second then age at first calving, fat yield, survival rate and mature weight, respectively. Under the medium and high production systems, fat yield had the second highest relative response after milk yield, followed by calving interval, mature weight, survival rate and last age at first calving, respectively. The overall economic response was highest under the high production system (525.47) compared to low (356.10) and medium (429.18) production systems.

Correlations between breeding objectives

Moderate correlations were estimated between low and medium (0.79), low and high (0.66) and medium and high (0.77) pro-

Table 10
Sensitivity of economic weights as percentage change to changes in milk, fat, live weight and feed prices under the low, medium and high dairy cattle production systems.

Variable	System	Change	Traits					
			LMY	FY	AFC	CI	MWT	SR
Milk price	Low	10	10.01	0.00	0.00	−10.06	0.00	3.00
		−10	−10.01	0.00	0.00	10.06	0.00	−3.00
	Medium	10	11.84	0.00	−0.01	−11.21	0.00	3.46
		−10	−11.84	0.00	0.01	11.21	0.00	−3.46
	High	10	12.47	0.00	0.01	−11.72	0.00	3.84
		−10	−12.47	0.00	−0.01	11.72	0.00	−3.84
Fat price	Low	10	0.21	10.24	0.00	−0.20	0.00	0.09
		−10	−0.21	−10.24	0.00	0.20	0.00	−0.09
	Medium	10	0.52	10.28	0.00	−0.46	0.00	0.17
		−10	−0.52	−10.28	0.00	0.46	0.00	−0.17
	High	10	−0.03	10.36	0.00	0.03	0.00	0.16
		−10	0.03	−10.36	0.00	−0.03	0.00	−0.16
Live weight price	Low	10	0.00	0.00	−1.70	−0.26	14.41	−0.01
		−10	0.00	0.00	1.70	0.26	−14.41	0.01
	Medium	10	0.00	0.00	−2.08	−0.25	14.80	−0.01
		−10	0.00	0.00	2.08	0.25	−14.80	0.01
	High	10	0.00	0.00	−2.15	−0.22	13.53	−0.02
		−10	0.00	0.00	2.15	0.22	−13.53	0.02
Feeds price	Low	10	−0.22	−0.24	−8.30	0.27	−24.41	0.00
		−10	0.22	0.24	8.30	−0.27	24.41	0.00
	Medium	10	−2.35	−0.28	−7.95	1.74	−24.80	−0.49
		−10	2.35	0.28	7.95	−1.74	24.80	0.49
	High	10	−2.44	−0.36	−7.86	1.78	−23.53	−0.57
		−10	2.44	0.36	7.86	−1.78	23.53	0.57

Abbreviations: LMY = lactation milk yield (kgs); FY = fat yield (kgs); AFC = age at first calving (days); CI = calving interval (days); MWT = mature weight (kgs); SR = cow survival (%).

Table 11
Predicted response per year per trait, economic response of trait change and relative response to selection under the low, medium and high production systems under the low, medium and high dairy cattle production systems.

Trait	Response to selection			Economic response			Relative economic response		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
LMY	13.35	21.64	23.13	302.19	464.16	515.39	84.64	83.66	81.36
FY	0.14	0.29	0.89	7.07	16.65	54.67	1.98	3.00	8.63
AFC	−2.51	−0.42	−0.17	11.58	2.42	1.32	3.24	0.44	0.21
CI	−0.26	0.35	0.17	29.52	−62.50	−51.95	8.27	11.26	8.20
MWT	0.08	0.05	0.26	−0.47	−0.31	−2.06	0.13	0.06	0.32
SR	0.02	0.02	0.01	6.21	8.76	8.1	1.74	1.58	1.28
Total				356.10	429.18	525.47	100	100	100

Abbreviations: LMY = lactation milk yield (kgs); FY = butterfat yield (kgs); AFC = age at first calving (days); CI = calving interval (days); MWT = mature weight (kgs); SR = cow survival (%).

duction systems. The breeding objective for the low production system was more strongly correlated with the breeding objective for medium production systems than the high production systems.

Discussion

In this study, a bio-economic model was developed to represent low, medium and high production systems for tropical dairy production systems of Kenya. Economic and biological input and output parameters used in this study (Tables 1 and 2) are the most common and were assumed to represent the average performances under the three production systems. There could be deviations around these parameters within the production systems. Due to the limitation of obtaining these parameters and for simplicity, some parameters were assumed to be the same across the production systems. Labour cost was assumed per cow and heifer per day in this study which might not be necessarily linear. Economic weights were then derived from the models with profit estimated per cow per year. Replacement heifers for cows culled for age were assumed to be raised within the herds and that all cows were mated by artificial insemination. Revenue was derived from the sale of milk, male calves, surplus heifers, and cull for age cows. Costs included feeding, reproduction, health, labour, marketing and fixed cost. Cows were simulated throughout their lifetime and culled for age after five lactations. The three production systems were described using different production and economic parameters (Tables 1 and 2).

In all production systems, feed costs were the highest cost followed by labour and marketing costs, while a significantly large amount of revenue was derived from the sale of milk. Similar results have been reported for dairy cattle in Kenya (Lukuyu et al., 2011; Wahinya, 2014; Walmsley and Barwick, 2018). Cost, revenue and profit increased with the intensity of production. The higher cost of production under the high production system was as a result of higher inputs to support a higher level of production compared to the lower inputs under the low production system (Wahinya et al., 2020a). The revenue was higher in the high production system because of a higher productivity. The revenue and costs estimated in this study were higher than estimated by Kahi and Nitter, 2004, mainly due to the changes in the input and output prices.

Positive economic weights were derived for lactation milk yield, implying that genetic improvement of lactation milk yield would result to an increase in the profitability of dairy cattle production under all production systems. Positive economic weights for lactation milk yield have also been reported in the literature (Kahi and Nitter, 2004; Wahinya et al., 2015; Gebretnsae et al., 2018). Some studies have also reported negative economic weights (Bekman and van Arendonk, 1993; Pryce et al., 2009; Banga et al., 2014). In these studies, negative economic weights were reported for scenarios where milk prices are based on fat and protein.

Genetic improvement of fat yield would result in an improvement in profitability of dairy production in all three production systems. Selection for a higher fat yield increased the cost of feed due to a higher energy requirement but this was offset by the economic return from the sale of milk at a higher premium due to a higher fat content. Positive economic weights for fat yield are mainly reported in scenarios where milk is sold based on fat and protein (Kahi and Nitter, 2004; Pryce et al., 2009; Banga et al., 2014). Negative economic weights have been reported when milk is solely marketed on volume (Banga et al., 2014), which was also observed in this study. The economic value for protein yield is often estimated together with milk yield and fat yield (González-Recio et al., 2004; Pryce et al., 2009; Cardoso et al., 2014); however, in this study, protein yield was not included because it is not considered in milk marketing.

Increasing the age at first calving by one day reduced profitability by Kes 4.62, Kes 5.73 and Kes 7.88 under the low, medium and high production systems, respectively. Negative values are reported in the literature for the Kenyan (−0.17 and −2.72) (Kahi and Nitter, 2004; Wahinya et al., 2015) and Spanish dairy cattle (González-Recio et al., 2004). Increasing the age at first calving led to a higher heifer rearing cost which leads to a reduction in profit. Breeding for a shorter age at first calving, therefore, would reduce the unproductive life of a cow and shorten the generation interval. Reducing the age at first calving also has an influence on the replacement policy which can be used to improve the product output levels of a herd (Kahi and Nitter, 2004). Since profit was predicted per cow per year, an increase in the calving interval was associated with a reduction in the revenue from the sale of milk, cull animals and male calves per year, which lead to a negative economic value. Negative economic weights are favourable for calving interval.

Mature weight of cows had negative economic weights, the marginal revenue from sale of heavier cull cows could not compensate for the marginal increase in feed cost. Larger cows require more energy for maintenance which cannot be used for production, therefore, increasing the total feed cost. This implies that in all the three production systems, increasing the mature weight would reduce profitability. Negative economic weights are mainly reported for mature weight (Koenen et al., 2000; Hietala et al., 2014; Wahinya et al., 2015).

The economic value for survival in all the three production systems was positive and desirable. A higher survival rate leads to a higher revenue from milk and cull cows for age as well as a reduction in other rearing costs. Increasing the survival rate led to an increase in the milk revenue per cow from a higher proportion of mature cows and higher revenue from sale of surplus heifers as reported in studies by other authors (Veerkamp et al., 2002; Kahi and Nitter, 2004). Cow survival has an impact on the productive lifetime of a cow and therefore the lifetime profitability. Although the economic weight for survival rate was high under the three production systems, the standardised and relative economic weights were not high due to the low genetic standard deviation of the trait.

The ranking of traits based on the standard and relative economic weights differed among the production systems (Table 6). This gives an indication of the differences in the importance of the traits among the three production systems. Milk yield and calving interval ranked first in descending order under all production systems. Fat yield, age at first calving, mature weight and survival rate on the other hand ranked differently among the production systems. The ranking of these traits in descending order was survival rate, fat yield, age at first calving and mature weight under the low production system; fat yield, survival rate, age at first calving and mature weight under medium production system and fat yield, survival rate, mature weight and age at first calving under the high production system.

Economic weights were sensitive to changes in input and output prices, changes in feeding strategies, and milk and surplus heifer marketing scenarios. The changes had different effects on different traits depending on the level of production and interactions between traits and biological inputs within the bioeconomic model. Confinement of cattle or what is regularly referred to as "stall feeding/Zero grazing" is a common way to intensify dairy production in Kenya, especially with the smallholder farmers. Overall, the economic values under Scenario 1 decreased due to a decrease in profit (Table 8) when concentrates are offered under the low production system. Under scenario 2, a higher profit led to higher economic values. Under the low production system, scenario 3 led to a lower economic value for lactation milk yield compared to the base due to a higher feed cost (from higher silage proportion offered). Under medium and high production systems, the economic value for lactation milk yield was slightly higher than in the base scenario. Increasing milk yield by one unit led to a higher level of concentrate supplementation which reduced the metabolisable energy supplied from roughage. The reduction of roughage (pasture and silage) was marginally higher under scenario 3 compared to the base leading to lower cost of feed. The economic values for lactation fat yield and mature weight did not change under scenarios 1 and 2. This is because a unit increase in both traits did not change the amount of concentrate and, therefore, the extra metabolisable energy requirements due to a unit increase in traits were supplied by pasture and silage which were not significantly different. These results show that these management strategies have an influence on the economic weights of traits. It is also important to account for genotype-by-environment interaction to achieve sustainable genetic progress by ensuring that sire genotypes are matched to the production environment. The genetic and economic efficiency of these strategies, however, needs to be assessed.

The economic value for lactation milk yield under the low and medium production systems was higher in the base situation (marketed based on both volume and fat) compared to the alternative scenario with milk marketing based on volume only. Under the high production system, the economic weight for lactation milk yield was higher when milk was marketed based on volume. Lower fat percentage in the first two lactations under the high production system (3.1 and 3.2%) leads to a penalty on milk yield with fat percentage below the payable percentage (>3.5%). Higher economic values have been estimated for lactation milk yield in Kenya for a scenario based on volume marketing compared to marketing based on volume and fat (Kahi and Nitter, 2004). This difference can be explained by the fact that in this study, fat percentage was kept constant allowing a proportional increase in the fat yield with a unit increase in milk yield. This was done to account for the part correlation between milk yield, fat yield and fat percentage. The economic value for fat yield was negative when milk is marketed based on volume only, similar to what is reported in other studies in Kenya (Kahi and Nitter, 2004; Wahinya et al., 2015). The economic value for survival when marketing milk by volume was lower due to the lower value of extra milk from a higher proportion of cows with a unit increase in survival compared to marketing milk by both volume and fat. Marketing of heifers for slaughter based on their live weight increased the economic values for age at first calving and mature weight. This is due to the heavier weight from selling heifers a day older and with a unit increase in live weight, respectively.

An increase in the price of product outputs resulted in a corresponding increase in profit of the related traits while an increase in price of inputs resulted in a reduction of profit. Economic weights should, therefore, be updated periodically to match the changing production and marketing conditions. Feed is the largest input and, therefore, has a significant influence on profit. In future, the cost of feed is likely to raise due to the diminishing farm sizes and increasing competition for feed resources (Bebe et al., 2002).

Desirable responses to selection were predicted for lactation milk yield, fat yield, age at first calving, and survival rate under all the production systems. Calving interval under the low production system also had a favourable response to selection per year. Due to the moderate and positive genetic correlation between milk yield and calving interval under the medium and high production systems, an economically unfavourable positive response was estimated for this trait in the two production systems. A similar trend was observed for mature weight under all the production systems.

Moderate correlations exist between the breeding objectives for the low, medium and high production systems. These correlations are partly due to genotype-by-environment interaction and partly due to differences in trait emphasis across the systems. For instance, the emphasis on milk yield was higher in the high production system while reproduction and survival traits had higher emphasis in the low production system. It is important that the genetic evaluation system accounts for genotype-by-environment interaction especially when correlations between breeding objective traits are low. Selection of animals across systems will be difficult when the correlation between the breeding objectives is low, such as between the low and high production systems. However, moderate correlations between the breeding objectives for the low and medium and the medium and high production systems indicate that it is possible to achieve genetic improvement through selection across these systems.

Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.animal.2022.100513.

Ethics approval

Not applicable.

Data and model availability statement

None of the data and model were deposited in an official repository. The data that support the study findings are confidential.

Author ORCIDs

P.K. Wahinya: https://orcid.org/0000-0003-4268-6744
J.G. Jeyaruban: https://orcid.org/0000-0002-0231-0120
A.A. Swan: https://orcid.org/0000-0001-8048-3169
J.H.J. van der Werf: https://orcid.org/0000-0003-2512-1696

Author contributions

P.K. Wahinya: Conceptualization, Modelling, Original draft preparation.
J.G. Jeyaruban: Supervision, Reviewing and Editing.
A.A. Swan: Supervision, Reviewing and Editing.
J.H.J. van der Werf: Reviewing and editing.

Declaration of interest

None.

Acknowledgements

The authors thank the Dairy Recording Services of Kenya (Nakuru) in Kenya for providing data and Peter Amer for reviewing the paper. This work was conducted as part of a PhD thesis titled: "Wahinya, P.K. (2020). *Strategies for genetic improvement of dairy cattle under low, medium and high production systems in Kenya.*" (PhD thesis), University of New England, Armidale, Australia.

Financial support statement

PKW acknowledges the financial support from the University of New England (Armidale, Australia) International Postgraduate Research Awards (IPRA) to pursue PhD studies at the Animal Genetics and Breeding Unit.

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