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Carbon footprint based on lifetime productivity for future cows selected for resilience to climate-related disturbances

S. Zira,[1*] A. Bouquet,[2] L. Rydhmer,[3] M. Kargo,[2] and L. Puillet[4]
[1]Department of Energy and Technology, Swedish University of Agricultural Sciences, 75007 Uppsala, Sweden
[2]Centre for Quantitative Genetics and Genomics, Aarhus University, 8000 Aarhus C, Denmark
[3]Department of Animal Breeding and Genetics, Swedish University of Agricultural Sciences, 75007 Uppsala, Sweden
[4]Université Paris-Saclay, INRAE, AgroParisTech, UMR Modélisation Systémique Appliquée aux Ruminants, 91123 Palaiseau, France

ABSTRACT

Droughts, which can affect feed production, are projected to become more common under future climate conditions. In light of this, breeding cattle resilient to changes in feeding regimens is increasingly becoming an important topic. Body reserves can play a crucial role when feed resources are limited. We simulated populations of dairy cows selected with 2 different breeding goals: one reflecting the current breeding goal and the other placing weight on minimum level of body reserves in early lactation and change in body reserves during lactation. We considered this latter as a breeding goal for resilience. We used the 2 dynamic simulation programs ADAM and AQAL to predict performance of the cows after selection. In AQAL, we modeled moderate and severe drought by decreasing feed quality and quantity offered to cows during one year. We compared cows selected with the 2 breeding goals under 3 environments: without disturbances related to climate and with moderate and severe drought. In the environments without disturbances and the moderate drought, the cows selected with the current breeding goal had higher lifetime lactation efficiency (energy invested in milk/energy acquired from feed) and lower carbon footprint per kilogram of protein in milk and meat than cows selected for resilience. However, with severe drought, cows selected for resilience had higher lifetime lactation efficiency and lower carbon footprint per kilogram of protein in milk and meat than those selected with the current breeding goal. This suggests that cows selected for high productive performance do not perform well under very limiting conditions, leading to increased climate impact. The importance of inclusion of body reserves as a resilience trait in dairy cattle breeding depends on the future environment in which the cows will be used.

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*Corresponding author: stanley.zira@slu.se

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INTRODUCTION

Grassland-based dairy farming is important in Europe as it delivers meat and milk and benefits to biodiversity and animal welfare without heavy dependence on fossil fuels and chemical inputs such as herbicides and pesticides (Delaby et al., 2020). Recent studies about global warming and its implications indicate that Europe, especially the southern parts, is already affected by drought, heat waves, and other extreme weather events that are anticipated to increase in frequency, duration, and intensity (Ouzeau et al., 2016; Fodor et al., 2018; Pfeifer et al., 2020). Long dry spells can lead to poor pastures, low forage quality, and low crop yields (Beillouin et al., 2020), which decrease farm output and increase environmental impacts per unit of product. Bearing in mind that environmental impacts of milk and meat production (Arvidsson-Segerkvist et al., 2020) are already a subject of concern, drought can further exacerbate the situation.

Resilient animals are a key component of the overall farming system resilience (Dumont et al., 2014). Friggens et al. (2022) reviewed the literature and found that researchers in general agree that "resilience is the capacity of an animal to respond to environmental disturbances." A resilient cow has the capacity to survive despite the presence of disturbances and possibly produce reasonable amounts of milk, thus ensuring that the carbon footprint does not increase drastically. Drought is a climate-induced disturbance affecting feed production. Cows differ in their genetic ability to cope with changes in feed quality and quantity. Breeding for resilient dairy cows has been suggested as a way to cope with disturbances associated with climate change (Burns et al., 2022). Therefore, it is essential to gain an in-depth understanding of the biological mechanisms underlying resilience and the benefits of improved resilience in dairy cows.

Resilience is an outcome of the cow's ability to balance energy expenditures between production and reproduction. Since this balance is dependent on energy intake, a cow's response to challenges such as reduced energy intake can be explained by its resource acquisition and allocation strategies (Puillet et al., 2021). There has been research on farming systems' environmental impacts in grass-based dairy production in Europe (Yan et al., 2013; O'Brien et al., 2014; Salou et al., 2017; Zira et al., 2023), but none has focused specifically on how dairy cows selected for increased resilience perform in terms of carbon footprint. The increasing prominence of resilience traits for dairy cattle (Poppe et al., 2020; Friggens, 2022), supports the idea of including resilience in the breeding goal. Increased selection pressure on resilience can, however, decrease the genetic progress in growth rate and milk yield per lactation (Bengtsson et al., 2022), which in turn influences the carbon footprint of milk and meat production. Furthermore, it is unclear to what extent selecting cows for resilience would affect the carbon footprint when cows are faced with feed shortage due to drought. To better understand the impacts of breeding for resilience, it is important to estimate the genetic change in traits included in the selection goal and in acquisition and allocation of resources, and compare cows selected for resilience to cows selected with the current breeding goal, under different environmental conditions.

The aim of this study was to estimate the performance of future dairy cows (year 2050) selected for resilience with cows selected using the current breeding goal and compare the carbon footprint of these 2 breeding goals under normal feeding conditions and under a moderate and a severe drought restricting cows' energy intake for a year. The results will be useful for the development of future resilient and sustainable grass-based production of milk and meat from dairy cows.

MATERIALS AND METHODS

We used 2 simulation programs called ADAM (Pedersen et al., 2009) and AQAL (Puillet et al., 2016) to predict performance of future cows selected with different breeding goals. The outcome of the different breeding goals was studied by comparing simulated genetic progress in production, reproduction, and resilience traits. Thereafter the cows resulting from these selection strategies were used as candidates to assess the effects of different feeding conditions in a simulated grassland-based farming system. Finally, the carbon footprint of these dairy cows selected for resilience or not was compared under normal feeding conditions, and under moderate and severe drought. The drought occurred during the third lactation.

No human or animal subjects were used, so this analysis did not require approval by an Institutional Animal Care and Use Committee or Institutional Review Board.

Type of Cow and Farming System

The modeling was calibrated to simulate selection and feeding of dairy cows in a farming system with grass-based diets and seasonal calving. Simulated phenotypes resulted from acquisition and allocation trajectories reflecting the innate characteristics of individual cows. The expression of these trajectories was modulated by available feed resources and management rules for reproduction and culling, as explained by Puillet et al. (2021). Three environments were simulated: normal (unlimited) feeding conditions, and feeding conditions disturbed during one year due to moderate and severe drought.

The simulated farms in our study were located in a region characterized by extensive grasslands that are highly suitable for cattle grazing. These grasslands had the capacity to support grazing activities for a duration of 8 mo annually, spanning from March to October. Our chosen theoretical setting closely mirrored the grass-based cattle production system that Ireland is renowned for within Europe. Ireland's production system is distinguished by its vast green pastures, recognized for their suitability for cattle rearing (O'Brien et al., 2018). Energy content of grass varied seasonally with 12.2 MJ/kg DM in March and 11.7 MJ/kg DM in November (GrassCheckGB, 2020). Silage was used when the cows were indoors (November to February). The energy content in silage was constant (11.8 MJ/kg DM; AFBI, 2015). Calving season ranged from mid-January to the end of March and drying-off occurred 70 d before calving. The 10-wk mating season started on April 10 every year. Heifers got their first calf just after 2 yr of age. The timing of reproductive events throughout the lifespan of individual cows was simulated based on conception probability influenced by energy balance and body reserves. Cows that were not pregnant at the end of a mating season were culled at next drying-off and nonpregnant heifers were culled at the end of the mating season. Cows dropped out of simulations when they were culled due to reproduction failure or died due to complete depletion of body reserves. Thus, longevity of each cow was an output of its simulated acquisition and allocation of energy.

Breeding

To assess the genetic performance of future dairy cows (year 2050), we modeled a breeding scheme and selected cows according to different breeding goals.

Table 1. Mean values at the start of selection for acquisition and allocation traits and simulated selection traits

Trait	Abbreviation	Selection trait	Unit	Mean
Maximal feed intake of a nonreproducing cow (basal acquisition)	BasAcq	No, but same as BWcalv1	kg DM/d	7.0
Average daily increase in intake during lactation (lactation acquisition)	LactAcq	No	kg DM/d	10.3
Rate of transfer of energy from growth to survival (body reserve allocation)	ResAll	No	—	0.0035
Allocation of energy to lactation (lactation allocation)	LactAll	No	—	0.56
BW at first calving	BWcalv1	Yes	kg	500
Average daily milk production (ECM) during third lactation	MP3	Yes	kg/d	19
Average daily DMI during third lactation	DMI3	Yes	kg DM/d	14.0
Interval between first mating (after third calving) and conception	IFC3	Yes	d	43.0
Relative minimum level of body reserves[1] early in third lactation (labile mass/empty BW)	BRmin3	In some scenarios	%	25.0
Change in body reserves during third lactation[2] (body reserves at end of lactation − body reserve at calving)	ΔBR3	In some scenarios	Percentage units	4.2

[1]Example: If the cow's empty BW is 500 kg and the body reserve is 125 kg at that time (around d 80 after calving), then BRmin3 = 25%.

[2]Example: If the cow's relative body reserve at calving is 25% and its relative body reserve at the end of lactation is 22%, then ΔBR3 = −3 percentage units.

Selection Traits and Genetic Parameters. A panel of 6 selection traits were analyzed in this study to simulate the breeding goals. The body weight at first calving (**BWcalv1**) was considered as a measure of growth rate for meat production. For the other traits, we chose to study third-parity cows to reflect an average cow in a normal herd structure where cows have up to 6 parities or more. Thus, milk production (**MP3**) and dry matter intake (**DMI3**) were computed for third-parity cows. The interval between first mating and conception after third calving (**IFC3**) was considered a measure of reproduction. Finally, 2 indicators of resilience were computed for third-parity cows: the minimum level of body reserves in early lactation (**BRmin3**; the first 80 d), measured as the ratio of labile mass to empty BW, and the overall change in body reserves (measured as the ratio of labile mass to empty BW) during lactation (**ΔBR3**). The ΔBR3 trait reflects an optimal use of body reserves where the goal is a cow that uses body reserves when needed during early lactation but restores them in late lactation, so that the change in relative body reserves between end and start of lactation is not negative. BRmin3 reflects the ability to handle a disturbance during peak lactation (around d 80), which is a critical period in the cow's life. ΔBR3 reflects the cow's ability to return to a good body condition in time for the next calving.

Four acquisition and allocation parameters from AQAL (see section "Phenotypic Performance") were included as traits in the ADAM simulation together with the selection traits. The acquisition and allocation traits were assumed to be uncorrelated and have a heritability of 0.35 and a phenotypic coefficient of variation of 10%. Those parameters enabled simulating selection traits with realistic means based on additive genetic determinism among the 4 acquisition and allocation traits that are the main drivers underlying production and reproduction traits, as assumed by Puillet et al. (2021). The analyzed traits are presented in Table 1.

Genetic parameters were estimated with a linear animal mixed model using REML. The genetic correlation between BasAcq and BWcalv1 was close to 1, making the genetic covariance matrix nonpositive definite. Hence, we considered these traits as one single trait in the simulation and thus included 9 traits in a multitrait analysis. The estimated genetic parameters are presented in Table 2.

Breeding Scenarios. Initially, 4 different breeding goals were defined to create 4 different scenarios. Two of them were used later on, to study the carbon footprint. The breeding goal in the baseline scenario included BWcalv1, MP3, DMI3, and IFC3 and was supposed to reflect a current standard selection goal for dairy cows (which is a simplification since, for example, health traits are missing). The baseline breeding goal aimed for increased BWcalv1 and MP3, and decreased DMI3 and IFC3. BWcalv1 reflects the beef traits included in current breeding programs for dairy cows. Economic weights were adjusted to have a correlation of 0.70 between MP3 and an index including all the 4 selection traits in the baseline scenario. The 3 alternative breeding goals aimed for improved resilience were inspired by Bengtsson et al. (2022). These breeding goals were a new breeding goal with cows selected for high minimum body reserves between calving and end of lactation, including BRmin3 (**BRmin**), a new breeding goal with cows selected for low change in body reserves between calving and end of lactation, including

Table 2. Genetic parameters for acquisition, allocation, and simulated selection traits (heritability on the diagonal, genetic correlations above and residual correlations below the diagonal)[1]

Item	BasAcq/ BWcalv1	LactAcq	ResAll	LactAll	MP3	DMI3	IFC3	BRmin3	ΔBR3
BasAcq[2]	0.35	0	0	0	0.43	0.65	−0.09	0.25	−0.39
LactAcq	0	0.35	0	0	0.47	0.67	−0.11	0.17	0.37
ResAll	0	0	0.35	0	0.05	−0.06	−0.48	0.64	0.02
LactAll	0	0	0	0.35	0.65	0.01	0.57	−0.51	−0.65
MP3	0.48	0.51	0.06	0.76	0.33	0.63	0.38	−0.11	−0.48
DMI3	0.70	0.70	−0.03	0.05	0.69	0.34	−0.11	0.25	−0.04
IFC3	−0.01	−0.02	−0.10	0.10	0.12	−0.06	0.01	−0.65	−0.50
BRmin3	0.23	0.17	0.70	−0.54	−0.17	0.31	−0.16	0.26	0.37
ΔBR3	−0.46	0.39	0.06	−0.76	−0.54	−0.03	−0.05	0.50	0.30

[1]BasAcq = maximal feed intake of a nonreproducing cow (basal acquisition); LactAcq = average daily increase in intake during lactation (lactation acquisition); ResAll = rate of transfer of energy from growth to survival (body reserve allocation); LactAll = allocation of energy to lactation (lactation allocation); MP3 = average daily milk production (ECM) during third lactation; DMI3 = average daily DMI during third lactation; IFC3 = interval between first mating (after third calving) and conception; BRmin3 = relative minimum level of body reserves early in third lactation (labile mass/empty BW); ΔBR3 = change in body reserves during third lactation (body reserves at end of lactation − body reserve at calving).

[2]BasAcq and BW at first calving (BWcalv1) are analyzed as if they were the same trait.

ΔBR3 (**ΔBR**), and a new breeding goal with cows selected for minimum body reserves and change in body reserves (i.e., including both resilience traits with equal weights [**BR5050**]).

Weightings attributed to the different traits were adjusted to match the baseline scenario and the BCS scenario analyzed in Bengtsson et al. (2022). The relative weights used for the different breeding goals are presented in Table 3. Since the current ΔBR3 average was close to zero and its correlation to milk yield was negative (thereby having a risk of becoming negative), we gave ΔBR3 a positive weight in the breeding goal. Decreased DMI is not an evident goal because high resilience may be associated with high appetite in spite of disturbances. Our assumption for decreasing DMI3 was that a large part of the climate impacts from animal production are caused by feed production and that feed costs are crucial for the farmer's profit.

Simulation of a Dairy Cattle Breeding Scheme. A large-scale breeding nucleus was simulated over a 30-yr period with ADAM (Pedersen et al., 2009). ADAM simulates selective breeding schemes using stochastic processes. Our simulation consisted of 20,000 females equally distributed in 200 herds and mated with 100 sires each year (see Figure 1). True breeding values and phenotypes were sampled based on the genetic parameters in Table 2. BWcalv1, MP3, and IFC3 were recorded on all cows in all herds. DMI3 was only recorded on cows in a reference population. The resilience indicators BRmin3 and ΔBR3 were assumed to be recorded on all cows. These traits were calculated from BW and body reserves trajectories. Body weight can easily be recorded with a scale, but it is not possible to weigh the body reserve of live animals. We assume that weight of body reserve can be estimated with ultrasonic measurement or image processing technique (which could also be used to estimate BW). Many farmers already register BCS that is a proxy for body reserves.

Genomic selection was simulated using the pseudogenomic selection approach. The accuracy of genomic breeding values (**GEBV**) was estimated using selection index theory to combine information from bull and cow reference populations (Buch et al., 2012). We assumed the same genomic reference population size as Bengtsson et al. (2022) with 180,000 animals for MP3, 85,000 animals for BWcalv1 and IFC3, and 10,000 animals for DMI3. For BRmin3 and ΔBR3, we assumed the refer-

Table 3. Relative weights attributed to the simulated traits in a goal scenario without resilience (baseline) and 3 breeding goal scenarios including resilience (BRmin, ΔBR, and BR5050)[1]

Selection trait[2]	Baseline	BRmin	ΔBR	BR5050
BWcalv1	0.09	0.08	0.08	0.08
MP3	0.45	0.41	0.41	0.41
DMI3	0.14	0.12	0.12	0.12
IFC3	0.32	0.29	0.29	0.29
BRmin3	0.00	0.10	0.00	0.05
ΔBR3	0.00	0.00	0.10	0.05

[1]BRmin = a new breeding goal with cows selected for high minimum body reserves between calving and end of lactation (i.e., including BRmin3); ΔBR = a new breeding goal with cows selected for low change in body reserves between calving and end of lactation (i.e., including ΔBR3); B5050 = a new breeding goal with cows selected for minimum body reserves and change in body reserves (i.e., including both resilience traits with equal weights). BWcalv1 = body weight at first calving; MP3 = average daily milk production (ECM) during third lactation; DMI3 = average daily DMI during third lactation; IFC3 = interval between first mating (after third calving) and conception; BRmin3 = relative minimum level of body reserves early in third lactation (labile mass/empty BW); ΔBR3 = change in body reserves during third lactation (body reserves at end of lactation − body reserve at calving).

[2]DMI and interval between first mating (IFC) have negative weights in all breeding goals.

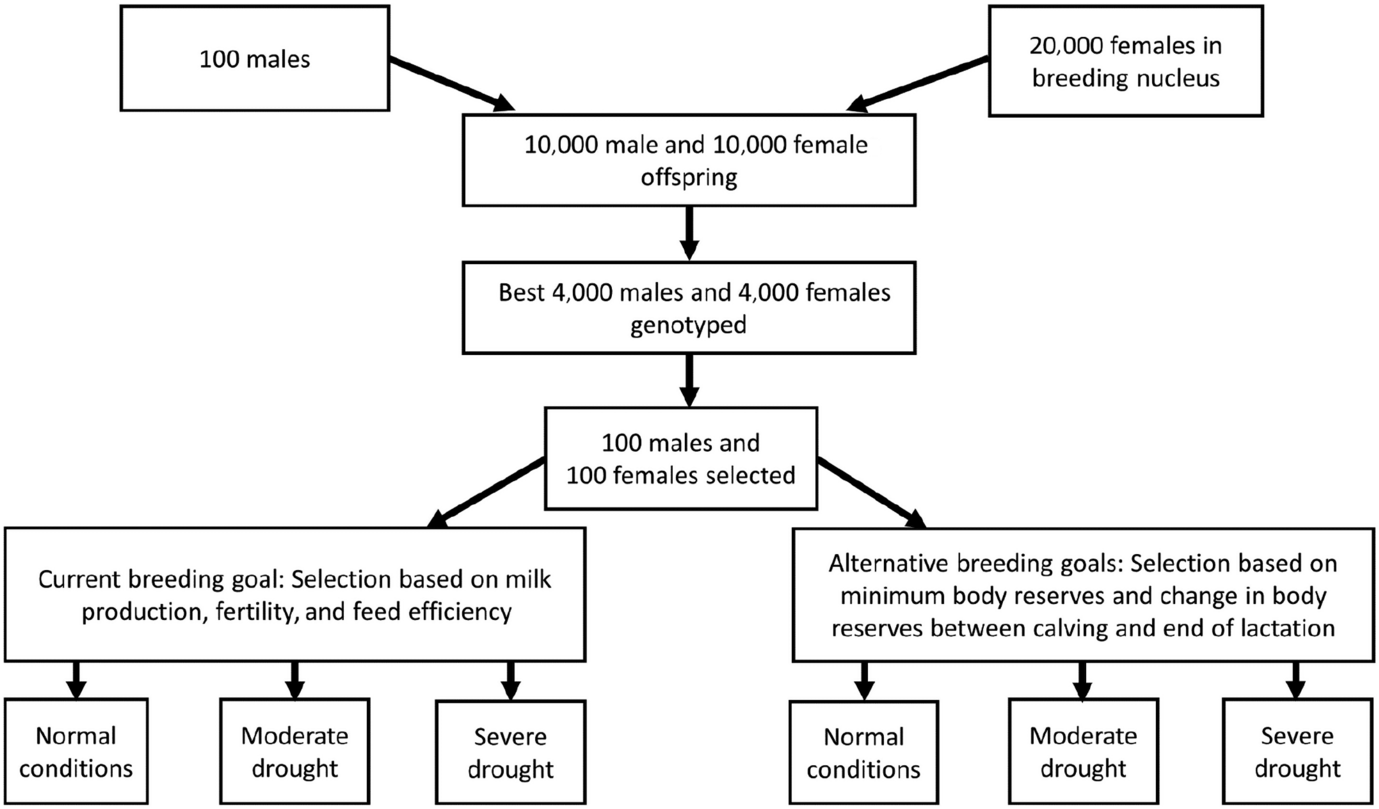

Figure 1. Breeding scheme for the different scenarios with breeding goals without (current) or with (alternative) resilience traits. The outcome of selection is studied under normal feeding conditions and under drought conditions restricting cows' energy intake.

ence population included 25,000 animals. The GEBV accuracy of candidates without performance was 0.54 for BWcalv1 and MP3, 0.47 for DMI3, 0.48 for IFC3, and 0.50 for BRmin3 and ΔBR3. Using simulated phenotypes, pseudogenomic phenotypes, and pedigree, GEBV were predicted using DMU software (Madsen and Jensen, 2013). Each year, the best 4,000 male and 4,000 female calves were genotyped based on parental breeding values. After genotyping, the best 100 1-yr-old males were selected to be used as sires for one year. Within each herd, the best 100 females aged from 1 to 5 yr were selected using estimated breeding values.

The first 20 yr of the ADAM simulation were considered as burn-in period and were discarded. Annual genetic gain was predicted for each trait by regressing mean true breeding values of selection candidates on their birth year over the last 10 yr of simulation. The correlated genetic gain was estimated for lactation efficiency for the third lactation (**LactEff3**) as a percentage of energy invested in milk over energy acquired from feed throughout third lactation. At the start of selection, the average LactEff3 was 55.6% (phenotypic standard deviation 6.52%). The ADAM simulation included 30 replicates.

Phenotypic Performance

To assess the phenotypic performance of future dairy cows (year 2050), we incorporated the energy acquisition and allocation of the animals selected with the different breeding goals under different climatic conditions in AQAL, a bioenergetic model (Puillet et al., 2016). A dynamic mechanistic model, AQAL is based on resource acquisition (energy intake) and resource allocation (proportion of energy allocated to biological functions), and it describes cows' responses to nutritional challenges.

Cows' trajectories of milk production and energy utilization over lifetime were simulated with the AQAL model depending on the amount of energy available (Puillet et al., 2016, 2021). Variability in the response observed at the population level is induced by assuming genetic and phenotypic variance for 4 input parameters describing acquisition and allocation. The 2 acquisition parameters correspond to the maximal intake of a nonreproducing cow, basal acquisition (**BasAcq**), and the cow's average increase in intake during lactation, lactation acquisition (**LactAcq**). Thus, BasAcq reflects the intake throughout life as if the cow never had a calf and

LactAcq the additional acquisition related to lactation needs. The unit of BasAcq and LactAcq is kilograms of DM per day. Under normal (unlimited) conditions, the simulated individual feeding regimen for nonlactating animals is equal to BasAcq and during lactation it is equal to the sum of BasAcq and LactAcq.

The body reserve allocation (**ResAll**) parameter is a dimensionless parameter, controlling the rate of transfer from allocation to growth function toward allocation to survival (maintenance and body reserves). The transfer of allocation from growth to survival reflects the general aging process of the animal; in early life, a cow invests in growth to build structural mass. As time passes, the investment in growth decreases, in favor of survival. The parameter ResAll controls the speed of this process and defines the trade-off between structural mass and body reserves. A cow with a high value of ResAll rapidly down-prioritizes energy allocation to growth in early life and switches energy investment toward survival, and therefore body reserves. The lactation allocation (**LactAll**) parameter describes the allocation of energy to lactation, defining the energy investment in milk production during lactation. A high value of LactAll means that the cow has a high priority for lactation and has more energy allocated to the production of milk.

Each animal was simulated with a set of the 4 acquisition and allocation parameters driving the priorities between animal's biological functions during its whole life. Mean values of these acquisition and allocation parameters were determined by a calibration procedure using real data of dairy cows in a grass-based system, as described by Puillet et al. (2021). The nutritional environment, described by energy content in feed (MJ/kg DM) and maximum DM offer (kg of DM/animal and day), was an input to the model. Variation in the nutritional environment was modeled by changing the amount of available energy (MJ/day) for the animal. During normal conditions, the maximum DM offer did not limit the feed intake of the cows.

To predict genetic change, it was assumed that selection on production and reproduction traits changes the mean genetic level of the acquisition and allocation parameters. Thus, updating initial acquisition and allocation parameters considering this correlated response is a way to simulate new performance data sets mimicking the effects of selection with AQAL. The method consists of 3 steps. First, data sets with a pedigree structure were simulated with AQAL considering the same acquisition and allocation parameters as Puillet et al. (2021) and a nonlimiting nutritional environment typical of breeding herds. This environment corresponded to the "high and stable scenario" in Puillet et al. (2021). Simulated data from AQAL were used to estimate heritabilities for simulated goal traits and acquisition and allocation input parameters, as well as genetic correlations between them. Second, the ADAM breeding scheme simulation tool (Pedersen et al., 2009) was used to estimate the correlated selection response expected on acquisition and allocation traits for a given breeding goal and a typical dairy cattle breeding scheme structure. Finally, new phenotypic levels of goal traits were simulated by updating the acquisition and allocation input parameters in AQAL with the correlated selection response to estimate the change in goal traits due to selection.

Changed Feeding Conditions Related to Climate Change

We modeled 3 different feeding conditions: normal feeding conditions, energy intake restricted by moderate drought conditions and energy intake restricted by severe drought conditions. These feeding conditions were modeled in the AQAL bioenergetic model by reducing the energy in feed during one year by 17% for the moderate drought and 34% for the severe drought when compared with the normal conditions. In practice, the consequences of drought can vary between farms and these levels were chosen to mirror potential outcomes of extreme yet plausible weather disturbances (R. Spörndly, Swedish University of Agricultural Sciences, Uppsala, Sweden, personal communication).

The effects of selection after 30 yr were evaluated with AQAL as the change simulated for each trait between the initial values of acquisition and allocation parameters and the updated values of acquisition and allocation parameters and considering the nonlimiting nutritional environment, reflecting the environment for nucleus herds. This system was similar to the "high and stable scenario" modeled by Puillet et al. (2021). The simulation of the nucleus included 2,000 cows. Thereafter, the genetic gain cumulated in the breeding nucleus was transferred to a production herd and the outcome was estimated in AQAL in the same way as for the nucleus herd. As previously described, the production system was based on pasture and roughage, and calving was seasonal. The production herd was simulated under 2 different environmental conditions named "normal" and "drought." Quantity and quality of available feed, and thereby energy intake, differed between these feeding conditions. During normal conditions the cows had unlimited access to grass when they were on pasture and to roughage when they were indoors. Feed and energy intake under normal conditions is a consequence of energy acquisition and allocation partly driven by the

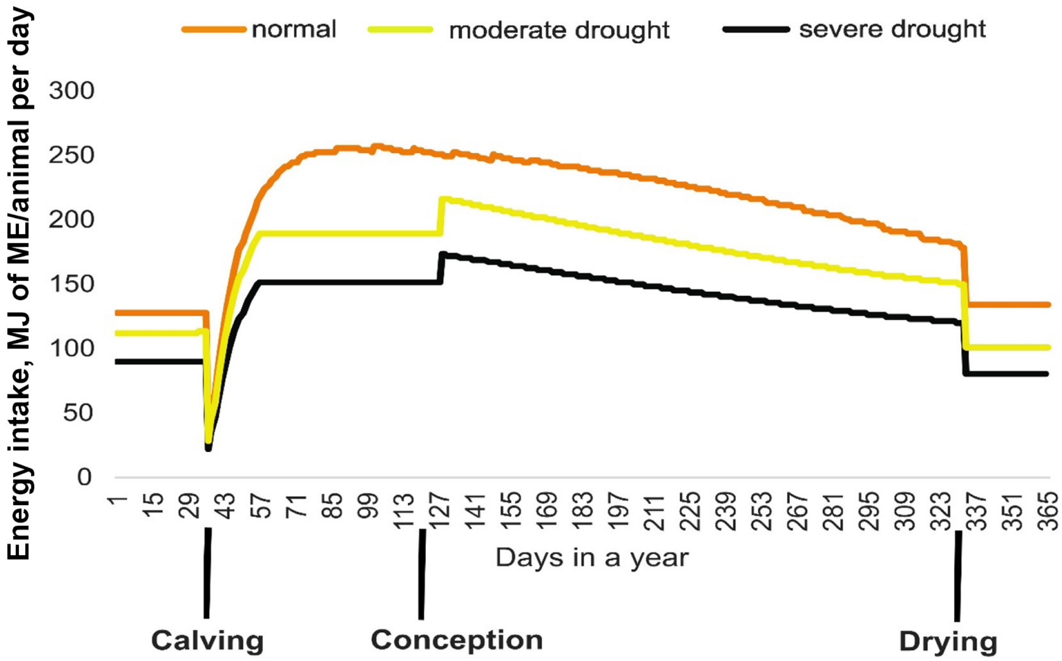

Figure 2. The energy intake (MJ of ME/animal per day) during a year with normal feeding conditions, and moderate and severe drought conditions for a third-lactation cow selected with the baseline breeding goal. Day 1 is January 1.

genetics of the cow. In the simulation of drought conditions, a severe drought reduced both feed quantity (and thus feed intake) and feed quality (energy content) for one year. This disturbance occurred during the fifth year (i.e., during cows' third lactation). Each simulation included 2,000 cows. All simulated cows were born on the same day and were simulated during their whole lifetime until culling. The outcome of selection under normal conditions was studied for all 4 breeding goals (i.e., baseline, BRmin, ΔBR, and BR5050) and the outcome of selection under drought was studied for baseline and BR5050.

In AQAL, the feeding environment is described by daily energy content in feed (MJ/kg of DM) and maximum DM offer (kg DM/animal and day). These input variables are the same for all cows within a scenario. The energy intake of cows in the nucleus and in the production herd under normal conditions and moderate and severe drought conditions are shown in Figure 2. Under normal conditions, the feed energy content was around 12 MJ/kg of DM. Under drought conditions, we assumed that the feed energy content was 8 MJ/kg of DM for severe drought and 10 MJ/kg of DM for moderate drought (R. Spörndly, Swedish University of Agricultural Sciences, Uppsala, Sweden, personal communication). For both moderate and severe drought, DM offer was restricted to 21.5 kg per day for a period of 365 d and the drought occurred during the year when the cows were in third lactation.

Estimation of Climate Impact for Different Breeding Scenarios

Based on the AQAL output, we studied the climate impact of groups of 2,000 simulated cows selected according to the baseline or the BR5050 breeding goal. Feed intake, milk yield, and age at culling were outputs from AQAL (Table 8). Meat yield was based on BW at culling, with an assumed carcass weight of 50% of live BW and a meat content in carcass of 60%.

Silage was produced and used during the 4 mo of the year when the animals were indoors due to cold weather. The effect of silage production was based on a yield of 13,500 kg of DM/ha and dinitrogen oxide emissions of 0.278 g/DM grass silage from Ecoinvent Data version 3.9.1 (Ecoinvent, 2022). We assumed a 30% drop in grass silage yield during the severe drought year based on an example from United Kingdom reported by PDA (2011) and 15% drop for the moderate drought. A slurry manure handling system was used for manure indoors. The enteric methane emissions were calculated based on the Tier II method (IPCC, 2019, Eq. [10.21]) with gross energy intake of the animals from the cattle systems, methane conversion factor as a percentage of gross energy in feed (i.e., 6.3% for the normal scenario and 7.0% for the drought scenario; IPCC, 2019, Table 10.12). Manure methane emissions were calculated based on volatile solids, a gross energy intake of 18.45 MJ/kg of DM, feed digestibility of 67% for the normal scenario and 62% for the drought scenario, and urinary energy of 4% and ash of 13% (IPCC, 2019 Eq. [10.24]). We assumed that N excretion was 75% (Powell et al., 2010). The direct nitrous oxide emissions from pastures were determined using the default emission factors specified in the Intergovernmental Panel on Climate Change (**IPCC**) 2019 guidelines, employing the Tier I method. Specifically, for urine on pasture, the emission factor used was 0.0077 kg/kg N excreted, whereas for dung on pasture, the emission factor was 0.0013 kg/kg N excreted (IPCC, 2019, Table 4A). The direct nitrous oxide emissions resulting from slurry manure were estimated based on the default emission factor for the Tier I method, which was 0.005 kg/kg N excreted (IPCC, 2019, Table 10.21). Additionally, the calculation of indirect nitrous oxide emissions relied on the default emission factors provided in the IPCC (2019) guidelines for the Tier I method. These factors were 0.01 kg/kg volatized N and 0.24 kg/kg leached N (IPCC, 2019, Table 11.3). Electricity was used for milking and lighting for animal housing and we assumed that 195 kg watt hour per cow were used per year. This was based on electricity consumption in Irish grass-based dairy farms (Shine et al., 2019). The climate impact was calculated as global warming potential for 100 years per kilogram of milk, meat, and protein and allocation of milk and meat were based on a meat to milk ratio calculated from the live weight of all slaughter animals (IDF, 2015). We assumed the pastures were fertilized with 100 kg of nitrogen, 30 kg of phosphorus, and 155 kg of potassium per hectare (Teagasc, 2020). We used impact factors from the IPCC's Sixth Assessment Report (IPCC, 2021; i.e., 1 for carbon dioxide, 27.2 for biogenic methane, and 273 for dinitrogen oxide).

RESULTS

Selection resulted in correlated genetic changes (presented in genetic standard deviation units in Table 4) in acquisition and allocation parameters reflecting changes in acquisition and allocation strategies, and lactation efficiency during third lactation (LactEff3). All presented results were averaged based on 30 replicates. The correlated genetic change in LactEff3 was favorable. The trends in acquisition and allocation traits showed that the gain in MP3 in the baseline scenario (see the result after 30 yr of selection in Table 5) depended more on genetic gain in acquisition than in allocation parameters. The genetic gain in feed efficiency (LactEff3) was lowered by half or more when resilience was included in the breeding goal). The breeding goal without and the breeding goals with resilience traits had high genetic gain in acquisition (BasAcq and LactAcq), which increases energy amounts available for production. Compared with the baseline scenario, a shift in genetic gain was observed from LactAll to ResAll, meaning that cows selected for resilience will invest less energy for milk production and growth, and thereby build larger body reserves. The 3 scenarios with resilience in the breeding goal led to similar trends in terms of acquisition and allocation of energy.

Table 4. Annual genetic change (expressed in genetic SD units) estimated with dynamic simulation program ADAM (Pedersen et al., 2009) for the acquisition and allocation traits and lactation efficiency, for breeding goals without (baseline) or with resilience traits (BRmin, ΔBR, and BR5050)[1]

	Breeding goal			
Trait	Baseline[2]	BRmin[3]	ΔBR[3]	BR5050[4]
BasAcq	0.306	0.287	0.257	0.279
LactAcq	0.171	0.169	0.212	0.190
ResAll	0.112	0.158	0.134	0.148
LactAll	0.154	0.076	0.050	0.065

[1]BasAcq = maximal feed intake of a nonreproducing cow (basal acquisition); LactAcq = average daily increase in intake during lactation (lactation acquisition); ResAll = rate of transfer of energy from growth to survival (body reserve allocation); LactAll = allocation of energy to lactation (lactation allocation).

[2]SEM of 30 replicates was 0.002 to 0.003.

[3]SEM was 0.02. BRmin = a new breeding goal with cows selected for high minimum body reserves between calving and end of lactation (i.e., including BRmin3); ΔBR = a new breeding goal with cows selected for low change in body reserves between calving and end of lactation (i.e., including ΔBR3).

[4]SEM was 0.001 to 0.003. BR5050 = a new breeding goal with cows selected for minimum body reserves and change in body reserves (i.e., including both resilience traits with equal weights).

The results showed that when energy intake was reduced by drought, the milk production decreased and the calving interval increased (Table 5). The severe drought also had a large unfavorable effect on body reserves. Lactation efficiency decreased, which is explained by the fact that more cows were lost due to negative energy balance during the severe drought conditions (319 versus 1,031 remaining cows, see Table 5) and the surviving cows had lower milk production (i.e., gave lower priority to milk production compared with those that left the herd).

Including resilience in the breeding goal reduced growth, milk production, and lactation efficiency but had a favorable effect on calving interval and body reserves (Table 6). We hereafter focused on baseline and BR5050 because we wanted to simplify the communication of the carbon footprint results by using 2 instead of 4 breeding goals. The drought occurred during the year when cows were in third lactation and therefore BWcalv1 was not affected. The changed feeding due to severe drought had an unfavorable effect on cows in both scenarios (compared with normal conditions), but the effect was larger for the baseline scenario in all

Table 5. Phenotypic mean values before and after 30 yr of selection for BW at first calving, milk production, DMI, and mating-conception interval (baseline), expressed during different feeding conditions[1]

			After selection		
Trait	Unit	Before selection	Normal conditions (n = 1,031 cows)	Moderate drought conditions (n = 831 cows)	Severe drought conditions (n = 319 cows)
BWcalv1	kg	500	748	748	748
MP3	kg/d	18.3	31.5	26.5	22.5
DMI3	kg/d	14.0	19.9	18.5	17.3
IFC3	Days	43.2	46.3	55.4	71.7
BRmin3	%	25	26.5	16.2	8.11
ΔBR3	Percentage units	4.2	−1.7	2.0	7.7
LactEff3	%	55.6	66.7	67.3	64.3

[1]BWcalv1 = body weight at first calving; MP3 = average daily milk production (ECM) during third lactation; DMI3 = average daily DMI during third lactation; IFC3 = interval between first mating (after third calving) and conception; BRmin3 = relative minimum level of body reserves early in third lactation (labile mass/empty BW); ΔBR3 = change in body reserves during third lactation (body reserves at end of lactation − body reserve at calving); LactEff3 = lactation efficiency for the third lactation.

traits except ΔBR3 (Table 7). For the remaining cows, lactation efficiency increased with moderate drought in the baseline scenario but decreased in BR5050 scenario because priority was given to milk production in the baseline scenario, whereas in the BR5050 scenario priority was on body resources (compare Table 6 and Table 7).

Cows selected with the current breeding goal (baseline scenario) had a 25% decrease in milk production and those selected for resilience had a 14% decrease in lifetime milk production during severe drought conditions (i.e., one year of drought during third lactation), as compared with normal conditions. Under moderate drought conditions, the cows selected with the current breeding goal had an 8% decrease and those selected for resilience had a 5% decrease in lifetime milk production as compared with normal conditions. During drought conditions, cows selected for resilience had higher longevity than cows selected with the current breeding goal (baseline scenario). During severe drought conditions, cows selected for resilience had slightly higher lifetime lactation efficiency than cows selected with the current breeding goal (baseline scenario). During severe drought conditions, more cows were culled due to failure to keep body reserves, especially those selected with the current breeding goal. The distribution of culling age for heifers and cows selected without (baseline scenario) or with (BR5050) resilience traits in the breeding goal during different conditions is shown in Figures 3, 4, and 5. The first calf was born by heifers during yr 3. In the fifth year (third lactation), the occurrence of a drought led to a significant increase in the number of culled cows, particularly in the baseline scenario (Figure 5).

Table 6. Phenotypic mean values after 30 yr of selection for BW at first calving, milk production, DMI, and mating-conception interval, without (baseline) or with resilience traits (BRmin, ΔBR, and BR5050) in the breeding goal, expressed during normal (unlimited) feeding conditions[1]

Trait	Unit	Baseline (n = 1,031 cows)	BRmin (n = 1,338 cows)	ΔBR (n = 1,335 cows)	BR5050 (n = 1,293 cows)
BWcalv1	kg	748	723	705	724
MP3	kg/d	31.5	28.6	27.7	28.6
DMI3	kg/d	19.9	19.5	19.7	19.7
IFC3	d	46.3	42.2	40.3	41.7
BRmin3	%	26.5	36.3	37.1	36.2
ΔBR3	Percentage units	−1.7	0.1	1.1	−0.7
LactEff3	%	66.7	61.7	59.2	61.1

[1]BRmin = a new breeding goal with cows selected for high minimum body reserves between calving and end of lactation (i.e., including BRmin3); ΔBR = a new breeding goal with cows selected for low change in body reserves between calving and end of lactation (i.e., including ΔBR3); B5050 = a new breeding goal with cows selected for minimum body reserves and change in body reserves (i.e., including both resilience traits with equal weights). BWcalv1 = body weight at first calving; MP3 = average daily milk production (ECM) during third lactation; DMI3 = average daily DMI during third lactation; IFC3 = interval between first mating (after third calving) and conception; BRmin3 = relative minimum level of body reserves early in third lactation (labile mass/empty BW); ΔBR3 = change in body reserves during third lactation (body reserves at end of lactation − body reserve at calving); LactEff3 = lactation efficiency for the third lactation.

Table 7. Phenotypic mean values after 30 yr of selection for BW at first calving, milk production, DMI, mating-conception interval, without (baseline) or with resilience traits (BR5050) in the breeding goal, expressed during moderate and severe drought conditions[1]

		Moderate drought conditions		Severe drought conditions	
Trait	Unit	Baseline (n = 831 cows)	BR5050 (n = 1,227 cows)	Baseline (n = 319 cows)	BR5050 (n = 977 cows)
BWcalv1	kg	748	724	748	724
MP3	kg/d	26.5	23.8	22.5	22.3
DMI3	kg/d	18.5	18.5	17.3	18.3
IFC3	d	55.4	44.5	71.7	52.6
BRmin3	%	16.2	26.8	8.1	14.4
ΔBR3	Percentage units	2.0	4.0	7.7	7.8
LactEff3	%	67.3	59.6	64.3	58.6

[1]BWcalv1 = body weight at first calving; MP3 = average daily milk production (ECM) during third lactation; DMI3 = average daily DMI during third lactation; IFC3 = interval between first mating (after third calving) and conception; BRmin3 = relative minimum level of body reserves early in third lactation (labile mass/empty BW); ΔBR3 = change in body reserves during third lactation (body reserves at end of lactation − body reserve at calving); LactEff3 = lactation efficiency for the third lactation.

Cows selected for resilience (BR5050) had higher total feed intake and lived longer (see Table 8). A greater total feed intake and longevity were observed in the cows selected for resilience (BR5050), resulting in an increased demand for feed resources compared with the current breeding goal (baseline scenario). The decline in lifetime milk production during severe drought conditions can be attributed to both reduced daily milk production during the third lactation and elevated mortality rates. The input variables used in the calculation of the lifetime carbon footprint for groups comprising 2,000 animals is presented in Table 9. The substantial culling that occurred as a consequence of the severe drought is also illustrated in Table 9 by the number of remaining cows in year 6 (fourth lactation).

Severe drought conditions increased greenhouse gas emissions per kilogram of product. Enteric emissions were the main contributor to the impact with 62% of the impact. Cows selected with the current breeding goal (baseline scenario) had lower climate impact than those selected for resilience (BR5050) under normal conditions and moderate drought conditions (Table 10). For BR5050 cows, one year of moderate drought increased total lifetime greenhouse gas emissions per kilogram of protein (milk and meat) with 10% of the value under normal conditions and for baseline cows the corresponding increase was 12%. In contrast, cows selected for resilience had lower climate impact than those selected with the current breeding goal under severe drought conditions. For BR5050 cows, one year

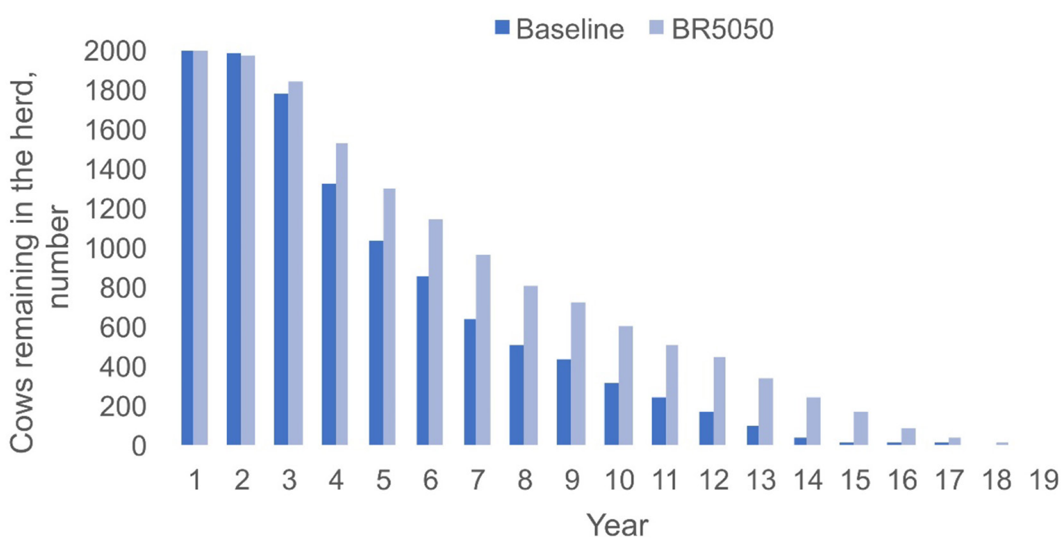

Figure 3. The number of remaining animals by lactation under normal feeding conditions for a group of 2,000 animals selected without (baseline) or with resilience traits (breeding goal including both resilience traits with equal weights, BR5050) in the breeding goal.

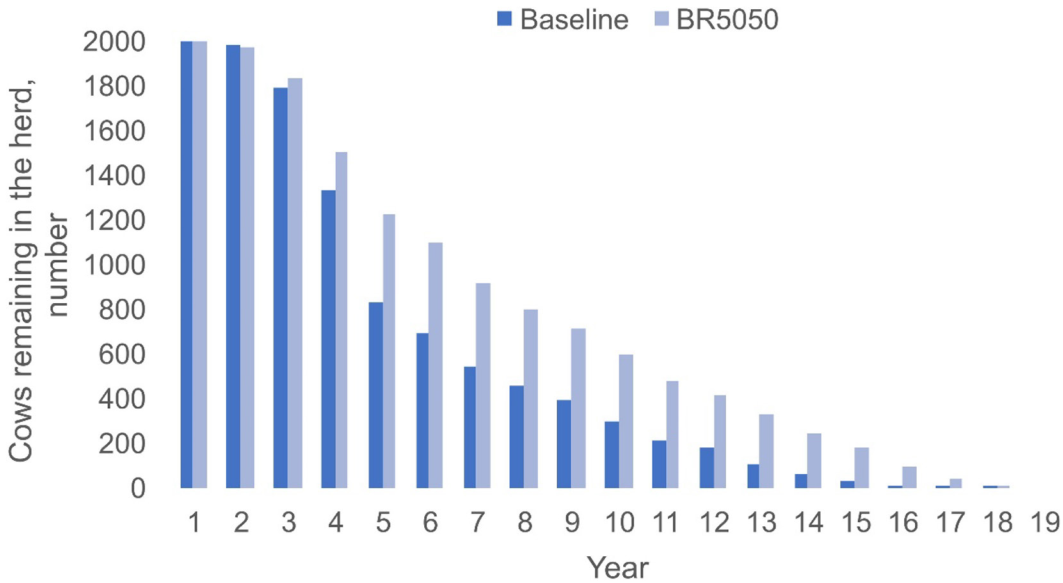

Figure 4. The number of remaining animals by lactation under moderate drought conditions for a group of 2,000 animals selected without (baseline) or with resilience traits (breeding goal including both resilience traits with equal weights, BR5050) in the breeding goal.

of severe drought increased total lifetime greenhouse gas emissions per kilogram of protein (milk and meat) by 16% of the value under normal conditions and for baseline cows the corresponding increase was 27%.

DISCUSSION

In the present study, we conducted a comparative analysis of the carbon footprint associated with 2 breeding goals: one involving cows selected for resilience and the other with cows selected with the current breeding goal. The assessment was performed under varying environmental conditions, including normal feeding conditions, as well as during moderate and severe drought conditions. Our findings show that the cows selected for resilience had a notably lower carbon footprint under severe drought conditions in comparison to cows selected using the current breeding goal. This outcome highlights the potential benefits of incorporating resilience traits into the breeding goal, particularly in the face of climate change with severe droughts. The aforementioned difference in carbon footprint between the 2 breeding goals was not evident under moderate drought conditions. This observation suggests that the resilience traits may predominantly manifest their positive impact under more extreme and challenging environmental circumstances. Under moderate drought conditions, other factors and adaptations might play a more significant role in determining the carbon footprint of the selected cows. The disparity in carbon footprint observed between severe and moderate drought conditions underscores the importance of accurately characterizing and differentiating the predicted frequency and intensity of droughts when evaluating selection for resilience to disturbances caused by climate change. Furthermore, it emphasizes the need for a comprehensive understanding of the interactions between genetic capacity for different traits, environmental factors, and their implications for sustainability and carbon emissions within livestock production systems. In principle, under very limiting conditions, a resilient cow has the ability to cope with lower acquisition by allocating less energy to lactation and growth in favor of fitness-related traits (Puillet et al., 2021).

In the genetic simulations in ADAM, the selection traits were recorded only once for each cow. This kind of simplification, assuming high genetic correlations between traits recorded in different lactations, is common in simulation studies (Bengtsson et al., 2022), although genetic evaluations in practice are often based on repeated records from several lactations. The selection in ADAM was based on data from third lactation (except BW at first calving) to reflect the average cow in a normal herd structure. When the outcome of different breeding goals was compared in AQAL, the entire lifespan of each cow was simulated, from birth to culling. Thus we estimated the climate impact of dairy cattle covering the entire lifespan of the cattle, in contrast to studies that focus on the annual productivity of cattle. Few studies have investigated the lifetime productivity of cows for dairy cattle (Mc Geough et al., 2012; Garg et al., 2016) and beef cattle (Beauchemin et al.,

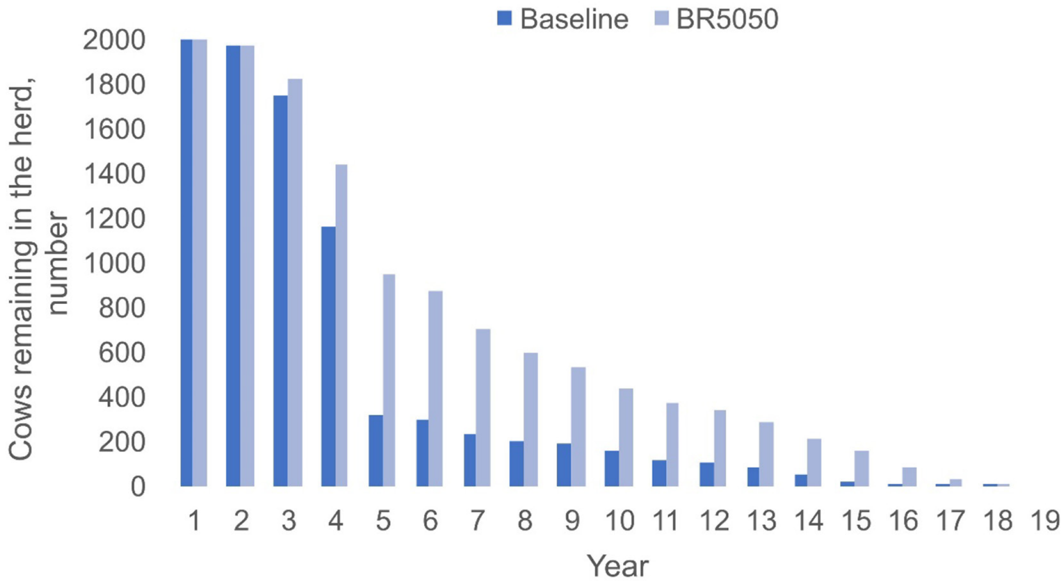

Figure 5. The number of remaining animals by lactation under severe drought conditions for a group of 2,000 animals selected without (baseline) or with resilience traits (breeding goal including both resilience traits with equal weights, BR5050) in the breeding goal.

2011; Hietala et al., 2021). All cows were assessed as a single cohort, rather than being continuously replaced over time. While we acknowledge that this modeling approach deviates from the practical reality of a farm setting, it has previously been employed in footprint assessments, as demonstrated by Beauchemin et al. (2011).

Despite its deviation from the conventional farm practice, the modeling of all cows as one cohort offered a perspective for studying the lifetime carbon footprint of dairy cows by assessment of the cumulative effects of various stages, from birth to culling, providing insights into the overall sustainability and efficiency of dairy cattle production systems. Our results for the carbon footprint for the current breeding goal under normal feeding conditions (1.00 kg CO_2 equivalent per ECM) were in the same range as results from Mc Geough et al. (2012). The longevity results from our simulation are in line with studies indicating that cows with high longevity have better reproductive performance, shorter calving interval, and require lower number of inseminations to become pregnant (Dallago et al., 2021). Extreme weather disturbances are rare and we assumed that the drought happened once in a cow's lifetime, during third lactation. In a future study, it could be interesting to simulate the whole production system with a typical herd structure of a dairy farm, showing the effect of feed restriction on cows in different lactations and during different phases of lactation.

Both genetic and environmental changes were considered in our scenarios, not just the effects of genetic changes in the same environment as done in previous studies on livestock (e.g., dairy cattle [van Middelaar et al., 2014] and pigs [Ottosen et al., 2020]). This is a first step to integrate systemic modeling, genetic modeling, and life cycle assessment and explore the potential of

Table 8. Phenotypic mean values of total milk production and DMI from birth to culling, lifetime lactation efficiency, average lactation number at culling and culling reason, after 30 yr of selection without (baseline) or with resilience traits (BR5050) in the breeding goal, expressed during normal feeding conditions and moderate and severe drought conditions[1]

		Normal conditions		Moderate drought		Severe drought	
Trait	Unit	Baseline	BR5050	Baseline	BR5050	Baseline	BR5050
MP	kg/d	14.0	13.8	12.9	13.1	10.5	11.8
DMI	kg/d	19.0	22.2	18.7	21.3	16.7	20.3
LactEff	%	43.6	41.9	42.3	41.1	38.2	39.3
Lactation at culling	number	4.7	6.4	4.4	6.2	3.3	5.4
Culled, body reserves	cows	120	150	253	153	1,030	410
Culled, reproduction	cows	1,880	1,850	1,747	1,847	970	1,590

[1]Drought occurred when cows were in third lactation, restricting energy intake for one year. LactEff = lifetime lactation efficiency.

Table 9. Input variables for carbon footprint assessment of groups of 2,000 cows selected without (baseline) or with resilience traits (BR5050) in the breeding goal, expressed during different feeding conditions

		Normal conditions		Moderate drought		Severe drought	
Trait	Unit	Baseline	BR5050	Baseline	BR5050	Baseline	BR5050
No. at start	Heifers	2,000	2,000	2,000	2,000	2,000	2,000
No. fourth lactation year 6	Cows	854	1,144	689	1,096	291	871
Cumulative cow feed intake	tonne of feed	66,124	84,820	61,597	82,289	45,549	72,072
Cumulative milk production	tonne of ECM	73,234	89,915	64,922	84,493	42,184	69,964
Cow meat production	tonne of meat, retail weight	422	402	392	401	265	370

different breeding goals to mitigate climate impacts accounting for environmental and physiological constraints. But more work is needed to enrich the mechanistic model and refine the description of production systems (changed diets, herd renewal, and so on) to provide a scientific base for decisions on breeding goals. Efforts to collect more data on feed intake using sensors or 3-dimensional cameras (Antanaitis et al., 2021) may help by providing relevant data to mechanistic models.

We modeled genetic and phenotypic responses using 2 simulation tools, ADAM and AQAL, that complement one another. ADAM simulates the genetic gain on underlying components of lifetime lactation efficiency and AQAL dynamically simulates phenotypic performance (i.e., the partitioning of energy within the animal over its lifetime given feed availability). Thus both genetic changes and changes in the animals' environment caused by drought were considered in our scenarios. The simulated lifetime performance of cows enabled the calculation of the greenhouse gas emissions. Modeling is a way to study resilience without exposing cows to poor animal welfare conditions.

Our modeling study only took energy intake of the cows into account in AQAL, but not protein intake. The drought that we simulated would have influenced protein intake as well as energy intake, but taking both energy and protein into account in the model is complex. Our results are limited to energy, but they provide a guide for future research and discussions on breeding goals. Our study does not describe the reality at a farm because when cows are culled at a farm they are replaced, resulting in cows of different age in a herd. Replacing the cows in the cohort could have increased the climate impacts (because recruitment of heifers leads to greenhouse gas emissions long before any milk is produced). We chose to model the effect of breeding for resilience on a group of animals born on the same day in this study because AQAL is constructed to simulate such groups, and transforming the output from AQAL to realistic farm scenarios would just have added a lot of assumptions without adding any extra scientific results. The increase in BW at first calving from 500 to 748 kg over 30 yr may be too much. Considering that farmers do not want bigger cows due to costs implications on housing, this could be problematic.

We assumed a steady state for soil carbon (i.e., we did not include soil carbon loss or sequestration), and future studies may include this. We did not include greenhouse gas emissions from production of capital goods such as barns, machinery, and milking equipment because we assumed these to have a small effect due to utilization over time and similar needs of capital goods under all feeding conditions. In addition, the publicly available specification 2050 (BSI, 2011) states that emissions from capital goods should not be included in carbon footprints for food. We did not include land use change because we assumed that feed (pasture and silage) was produced on existing cropland in the studied grass-based system regardless of feeding conditions. In reality, farmers may import feed under drought

Table 10. Greenhouse gas emissions (GHG) in tonnes of carbon dioxide equivalents (eq) from production systems with cows selected without (baseline) or with resilience traits (BR5050) in the breeding goal, expressed during different feeding conditions

		Normal conditions		Moderate drought		Severe drought	
Source	Unit	Baseline	BR5050	Baseline	BR5050	Baseline	BR5050
GHG, enteric fermentation	tonne of CO_2 eq	50,089	64,251	51,844	69,259	38,337	60,660
GHG, feed production	tonne of CO_2 eq	2,441	3,131	2,275	3,039	1,683	2,663
GHG, manure	tonne of CO_2 eq	30,160	38,688	28,095	37,533	20,775	32,873
GHG, electricity	tonne of CO_2 eq	574	900	520	872	296	710
GHG per kg ECM	kg of CO_2 eq	1.01	1.08	1.12	1.18	1.26	1.24
GHG per kg meat	kg of CO_2 eq	22.9	24.0	25.7	26.4	29.2	27.9
GHG per kg protein (milk and meat)	kg of CO_2 eq	34.1	36.0	38.2	39.6	43.3	41.7

but importing roughage is complicated due to large volumes. Replacing roughage by imported cereals is a more plausible scenario, but with a severe drought as in this study cereal prices would become very high. Our simulation approach, combining ADAM and AQAL, can be used in future studies to investigate the climate impact of cereal import and other strategic choices during drought conditions.

Today, resilience of farm animals is a hot topic often discussed at animal science conferences and it is timely to suggest selection for increased resilience (Friggens et al., 2017; Berghof et al., 2019). For dairy cattle, resilience traits could be included in the total merit index, as proposed by, for example, Poppe et al. (2020) and Bengtsson et al. (2022). Selection for increased resilience has a cost when there is a goal conflict between resilience and efficiency. Our results illustrate this general goal conflict (with presumed consequences for economic result) under normal conditions, and most farm animals are selected for normal conditions. However, the goal conflict vanishes under a disturbance as extreme as the simulated severe drought in this study. The frequency of disturbances related to extreme weather varies between regions but being extreme they are obviously rare. In this study we assumed one year of severe or moderate drought under a cow's lifetime. Bio-economic models used for calculations of economic weights are usually based on average results of the current production and do not take environmental fluctuations and risk into account. Risk is a function of the probability that the disturbance will happen and the severity of its consequences. The probability of future extreme weather events is predicted in climate scenarios (Lee et al., 2021) but with a large uncertainty and a wide range between scenarios. The probability also differs between regions and many breeding companies act across regions. The severity of the consequences depends on environmental factors at farm and regional level (e.g., geography of the landscape, technical equipment, farm building design, self-sufficiency of feed, and farmers' economic status).

The willingness to put weight on resilience traits in a breeding goal depends on both the estimated risk of disturbances and the stakeholders' willingness to take risks. Including risk aversion in breeding goals affects the cost-benefit analysis that economic weights are based on (Kulak et al., 2003) and risk-rated economic weights can differ substantially from traditionally calculated economic weights (Okeno et al., 2012). We have not studied economic weights here, but the results imply that resilience traits should be included with some weight in the breeding goal when severe disturbances related to climate change are predicted. Since the economic weights of resilience traits partly depend on stakeholders' risk aversion, studies on economic weights incorporating risks are needed.

In this study, the disturbance was a drought event hindering appropriate feeding during one year. Disease outbreak is another example of disturbance. The probability of a new vector-borne disease appearing in a region increases due to climate changes that affect reproduction and survival of vectors (Caminade et al., 2019). Many risks can be reduced by investments. For example, a fence stopping wild animals from entering the region may reduce the probability of an infectious disease and performing systematic vaccinations can reduce the consequences of an infectious disease. The breeding program is, of course, also an investment. How valuable are actions like the ones described in the examples above in relation to investments in a changed breeding goal? Who pays for various investments and who takes the risks if preventive investments are not done?

No one can accurately foresee the future, but scientists together with stakeholders can use today's best knowledge to build scenarios of future production systems. Then the geneticists can use alternative breeding goals to simulate the phenotypic performance of future animals aimed for these future production systems. Thereafter the consequences of using these breeding goals can be evaluated with regard to genetic trends for goal traits and various sustainability aspects (as illustrated with emissions of greenhouse gases in this study) in environments with more or less disturbances. Economic weights used in breeding goals are not simply results of breeding organizations' calculations; they reflect these organizations' fundamental values. We propose that breeding organizations can make better informed decisions, based on economic calculations (as done today) and sustainability assessments of simulated scenarios. A sustainability assessment of the future production system, taking into account the future animals and their exposure to varying levels of disturbances, will provide insights into the consequences of selecting breeding goals that prioritize resilience traits to different degrees, or not at all. The results, combined with findings from a bio-economic model, can serve as a basis for discussions on breeding goals within the breeding organization and with its stakeholders.

CONCLUSIONS

We showed that cows selected for resilience traits have a lower carbon footprint per unit milk and meat product than those selected using the current breeding goal when feeding conditions are very limiting. The development of breeding goals that address resilience to disturbances caused by climate changes is important for sustainable dairy production and the appropriate economic weight for resilience traits needs to be further studied.

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ORCIDS

S. Zira https://orcid.org/0000-0002-7333-3610
A. Bouquet https://orcid.org/0000-0002-5567-7284
L. Rydhmer https://orcid.org/0000-0002-2167-5475
M. Kargo https://orcid.org/0000-0003-1981-2722
L. Puillet https://orcid.org/0000-0003-2358-7302