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Comprehensive farm-level analysis of environmental and management descriptors for developing an efficient genetic evaluation of pasture-raised beef cattle

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Abstract

The main objective of this study was to investigate environmental factors affecting yearling weight (YW) in pasture-raised Nellore cattle. The dataset encompassed records from 143,332 animals across 60 farms, integrating animal-level information (i.e., phenotype and pedigree relationships) with farm-level data on environmental conditions (climate, soil classifications, and elevation) and management practices at the rearing sites, hereafter referred to as descriptors. Farm-level descriptors were carefully selected based on three steps: (i) evaluation of each descriptor's contribution to explaining the variance of YW across farms, (ii) assessment of collinearity among farm management descriptors, and (iii) comparison of models using a stepwise selection procedure. The selected descriptors were subsequently included as fixed effects in the genetic evaluation of YW. The analysis began with a traditional animal model ($\mathbf{M}_1$, benchmark model). It was extended to three alternative models that incorporated environmental descriptors ($\mathbf{M}_2$), farm management descriptors ($\mathbf{M}_3$), or both ($\mathbf{M}_4$). Model comparisons were based on the Akaike Information Criterion (AIC) and the proportion of the farm variance in YW explained by the fixed effects. The results indicate that climate and soil classifications, elevation, guidance from animal breeding technicians, period of the breeding season, age and weight of heifers at first breeding, no-till farming, reproductive technique (categorized as natural service, fixed-time artificial insemination—FTAI, synchronization protocols and/or herd bulls), years enrolled in the breeding program and livestock land area (categorized as small: ≤100 ha; medium: 101–999 ha; or large: ≥1000 ha) are key factors describing the macro-environmental effects contributing to variation of YW across farms. Among them, guidance from animal breeding technicians, age and weight of heifers at first breeding, and no-till farming were directly or indirectly associated ($P < 0.05$) with several descriptors of soil, supplemental feeding, and reproductive management. Indeed, when these environmental and farm management descriptors were simultaneously included in the genetic evaluation model ($\mathbf{M}_4$), they explained 65.7% of the YW variance across farms, while maintaining the model's goodness-of-fit. This finding explains substantial sources of environmental variation commonly accounted for by contemporary groups (CG) in genetic evaluations. This suitable characterization of environmental factors might be essential for future genetic evaluation in the context of genotype-by-environment interaction (GxE), as well as for forecasting cattle performance under different environmental conditions.

Lay Summary

This study aimed to explore how environmental factors and farm management practices are associated with yearling weight of Nellore cattle raised on pasture. We analyzed a wide range of data, including information on cattle performance and pedigree relationships, climate, soil, and elevation, as well as farm management descriptors at the animal-rearing locations to identify the key factors contributing to the differences in yearling weight across farms. The analysis revealed that climate, soil type, elevation, guidance from animal breeding technicians, years enrolled in the breeding program, livestock land area, and specific practices such as no-till farming, the period of the breeding season, and reproductive techniques are significantly associated with cattle growth. These findings could be used to assist farmers and breeders in optimizing management strategies to enhance cattle selection and performance, thereby promoting more sustainable beef cattle production.

Key words: climate, farm management practices, GxE interaction, Nellore, survey research, yearling weight.

Abbreviations: AIC, Akaike Information Criterion; BLUP, Best Linear Unbiased Prediction; CG, contemporary group; CNPGC, National Center of Research on Beef Cattle; EMBRAPA, Brazilian Agricultural Research Corporation; FAO, Food and Agriculture Organization; GxE, genotype by environmental interaction; EBV, estimated breeding value; FTAI, fixed-time artificial insemination; IBGE, Brazilian Institute of Geography and Statistics; IVF, in vitro fertilization; ISRIC, International Soil Reference and Information Centre; IUSS, International Union of Soil Sciences; ML, Maximum Likelihood; REML, Restricted Maximum Likelihood; RSG, Reference Soil Group; UNESCO, The United Nations Educational, Scientific and Cultural Organization; WRB, World Reference Base for Soil Resources; YW, yearling weight

Introduction

Pasture-raised beef cattle experience substantial environmental variability, which in turn affects their growth, health, and productivity (Aiken et al. 2020; Amaral et al. 2024; Greenwood 2021). Such variability arises from factors including climate, soil quality, forage availability, and water resources, all of which can vary widely across regions and seasons. Therefore, adaptive management practices are necessary to maintain cattle

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performance and ensure sustainable beef production under these changing conditions. In this context, successful beef production depends on a comprehensive understanding of the interactions among cattle genetics, environmental conditions, and management strategies.

The phenotypic expression of a quantitative trait in an animal is determined by the combined effects of genetics and environmental factors, including their interaction. A central component of livestock breeding programs is the estimation of breeding values, which represent the sum of additive genetic effects across all loci influencing the trait (Falconer and Mackay 1996). The breeding values can be computed from pedigree-based additive relationships among animals, molecular marker genotype information, or a combination of the two as in a single-step genetic evaluation (Legarra et al. 2009; Meuwissen et al. 2001). At the same time, environmental effects in beef cattle breeding programs are commonly adjusted by considering the combined effects of herd, year, and season, referred to as contemporary groups (CG). However, these macro-environmental effects (i.e., environmental factors shared by groups of animals) are known and can be directly accounted for in genetic evaluation models (Madsen et al. 2021; Mulder et al. 2013). Such macro-environmental factors encompass broader conditions, including climate, soil moisture, temperature, precipitation, farm management practices, and facilities.

A better understanding of the environmental factors associated with animal performance is essential for predicting outcomes and improving production systems (Aiken et al. 2020; Amaral et al. 2024). In addition, a suitable characterization of environmental factors is essential for genetic evaluation in the presence of genotype-by-environmental interaction (GxE). In this context, the phenotypic expression of genotypes changes differentially across environments, potentially leading to re-ranking of animals based on estimated breeding values (EBV) and to environment-specific heritability estimates. Consequently, inadequate modeling of environmental variability may reduce the accuracy of EBV, biased heritability estimates, and result in suboptimal selection decisions. Currently, the estimated average performance of animals within CGs is generally used as a proxy for the environmental gradient in reaction norm models to address GxE in beef cattle (Cardoso and Tempelman 2012; Chiaia et al. 2015; Mota et al. 2020; Nascimento et al. 2022; Oliveira et al. 2018). However, alternative environmental descriptors have been proposed in genetic evaluations for dairy cattle (Erbe et al. 2021; Fikse et al. 2003), swine (Fragomeni et al. 2016; Freitas et al. 2021, 2023; Tiezzi et al. 2020), and are extensively applied plant breeding (Costa-Neto et al. 2021; Crossa et al. 2017; Jarquín et al. 2014; Resende et al. 2021, 2024). Nonetheless, many of these studies do not include farm-specific management practices, such as grazing strategies, feed supplementation protocols, herd health management, and breeding techniques, that may be associated with production outcomes and contribute to explaining environmental variation across CGs. In this regard, the main objective of this study was to identify environmental and farm management factors associated with yearling weight (YW) in pasture-raised Nellore cattle, thereby providing insights that may support better management practices as well as future implementation of alternative environmental descriptors in GxE modeling.

Materials and methods

Animal Care and Use Committee approval was not required for this study, as the data analyzed were obtained from an existing database of the Geneplus beef cattle breeding program in Brazil, developed by Geneplus Consultoria Agropecuária Ltda in collaboration with the Brazilian Agricultural Research Corporation (EMBRAPA).

Data collection

The dataset comprised two main sources of information: (i) animal-level records, including phenotypes and pedigree relationships; and (ii) farm-level data on environmental conditions (i.e., climate, soil classifications, and elevation) and management practices at the rearing sites, hereafter referred to as descriptors. More details on these data sources are provided in the following sections, and a comprehensive description is presented in Table 1.

Animal data

Phenotypes of YW and pedigree information from Nellore cattle reared on pastures across Brazil, Bolivia, and Paraguay were provided by the Embrapa-Geneplus beef cattle breeding program (Campo Grande, MS, Brazil). The choice of YW as the target variable stemmed from its relatively larger dataset compared to other traits, the fact that it is not sex-limited, not strongly influenced by maternal effects, and, more importantly, that it is a key selection criterion in beef cattle breeding. The

Table 1. Summary of data from the Nellore cattle population used in the present study.

Item	N
Animals	
Animals with records	143,332
Animals in the pedigree file	253,027
Sires with progeny	22,584
Dams with progeny	111,053
Contemporary group (CG)	163
Animals per CG, min	44
Animals per CG, average	879
Animals per CG, max	4091
Farms in the survey with recorded animals	60
Koppen-Geiger Climate Classification	
Tropical zone, monsoon (Am)	9237
Tropical zone, savannah (Aw)	68,875
Temperate zone, without dry season, hot summer (Cfa)	44,509
Temperate zone, dry winter, hot summer (Cwa)	20,711
Soil Classification based on World Reference Base for Soil Resources	
Orthic Acrisols (Ao)	8799
Ferric Acrisols (Ap)	1099
Acric Ferralsols (Fa)	16,299
Orthic Ferralsols (Fo)	39,262
Rhodic Ferralsols (Fr)	22,233
Xanthic Ferralsols (Fx)	1312
Luvic Phaeozems (Hl)	851
Lithosols (I)	4611
Ferric Luvisols (Lf)	17,820
Ferralic Arenosols (Qf)	22,463
Dystric Planosols (Wd)	1403
Eutric Planosols (We)	7180

YW mean ± standard deviation (SD) was 305.10 ± 67.26 kg, with animals being measured at approximately 485.6 ± 43.9 d of age from 1999 to 2021.

CGs were defined by combining the month and year of measurement, with farm and sex included as additional factors. Records of animals in CGs with fewer than 40 observations were excluded from the analysis to ensure statistical robustness. After data editing, 143,332 animals with records from 60 farms were available for analysis, distributed across 180 animals from Bolivia, 1,403 from Paraguay, and 141,749 from Brazil, including the following states (with counts shown in parentheses): Acre (550), Bahia (4202), Goiás (2740), Maranhão (1175), Minas Gerais (2316), Mato Grosso do Sul (56,301), Mato Grosso (28,202), Pará (7788), Paraná (10,039), Rio de Janeiro (2478), Rondônia (3782), São Paulo (15,299), and Tocantins (6877). Pedigree information comprising three generations resulted in a total of 253,027 animals in the additive relationship matrix. A joint analysis of animals from Brazil, Bolivia, and Paraguay was performed due to their genetic connectivity and environmental similarity at animal-rearing sites. In our dataset, Bolivian animals share the tropical savannah climate and orthic Acrisols soils with Brazilian animals, while Paraguayan animals share the temperate climate without a dry season and hot summers. Despite differing soils (Dystric Planosols), Paraguayan animals were sufficiently represented for inclusion. Across countries, the animals studied were managed under pasture-based systems with similar grazing, supplementation, and reproductive practices.

Survey data

The survey targeted 118 Nellore cattle producers enrolled in the Embrapa-Geneplus beef cattle breeding program. The objective was to collect detailed information regarding soil, feeding, and reproductive management protocols implemented on their respective farms. Additionally, the survey included questions concerning reproductive efficiency measures.

Those who consented to engage in the survey received preliminary instructions via phone communication. Subsequently, a web-based survey, designed using Google Forms, was emailed to them. The form included sixty questions, including short-answer, multiple-choice, and checkbox responses, which were categorized into five sections:

- General information: Farm ID, animal breeding technician, number of years enrolled in the Embrapa-Geneplus beef cattle breeding program, geographic coordinates, total land area, land area allocated to livestock, and type of production system.
- Soil management: Questions covering the utilization of native grasslands, tillage, no-till farming, contour farming, crop rotation, or other practices.
- Supplementation feeding strategy by animal category: Including mineral mix, a combination of mineral mix and urea, protein, or protein and energy sources in the supplements for calves, heifers, cows, and sires.
- Reproductive management: Adoption of breeding seasons and their period and length, number of females exposed to breeding, bull-to-cow ratio, use of synchronization protocols or other reproductive techniques, age and weight of heifers at first breeding, and cows.
- Reproductive outcomes: Encompassing conception rate for heifers, primiparous, and multiparous cows in the breeding season.

Environmental data

Using the geographic locations of each farm (based on the World Geodetic System 1984—WGS84), we retrieved environmental data, including the Köppen-Geiger climate classification, soil classification, and elevation at the animal-rearing locations. These variables were defined as environmental descriptors.

The Köppen-Geiger climate classification is one of the world's most widely used systems (Köppen 1936), and has recently been updated (Peel et al. 2007). This classification categorizes global climate zones based on temperature, precipitation, and vegetation patterns. It employs a combination of letters to denote different climate types, with the main categories being A (tropical or equatorial), B (arid or dry), C (warm/mild temperate), D (continental), and E (polar). Each central zone is further subdivided based on temperature or dryness characteristics. In Brazil, twelve climate classifications have been documented (Alvares et al. 2013), four of which were identified at the farms included in this study (Fig. 1a), with counts shown in parentheses: tropical monsoon (5), tropical savannah (28), temperate without dry season and hot summer (18), and temperate with dry winter and hot summer (9).

The soil class at each rearing location was extracted from the World Reference Base for Soil Resources (WRB), an international soil classification system established by the International Union of Soil Sciences—IUSS (2015). Shaped by the legends of the Food and Agriculture Organization (FAO), the United Nations Educational, Scientific and Cultural Organization (UNESCO), and the International Soil Reference and Information Centre (ISRIC), the Soil Map of the World system operates on two levels (FAO 1988). The first level comprises 32 Reference Soil Groups (RSG), while the second level combines the RSG with specific qualifiers. This approach provides a comprehensive framework for classifying and characterizing soils, encompassing key features such as soil horizons, properties, and environmental contexts. For a detailed description, please visit https://soilgrids.org/. Among the 57 soil classifications recognized across South America, 12 were identified at the farms included in this study (Fig. 1b), with counts shown in parentheses: Orthic Acrisols (9), Ferric Acrisols (1), Acric Ferralsols (7), Orthic Ferralsols (10), Rhodic Ferralsols (8), Xanthic Ferralsols (2), Luvic Phaeozems (2), Lithosols (1), Ferric Luvisols (5), Ferralic Arenosols (10), Dystric Planosols (1), and Eutric Planosols (4). The elevation (289.80 ± 127.37 m), defined as vertical distance above sea level, was collected using the R package "elevatr" (Hollister et al. 2023).

Farm management data

Table 2 describes the variables concerning farm management protocols derived from survey data. Continuous variables, such as years enrolled in the Embrapa-Geneplus, livestock land area, period of use of established pasture, length of breeding season, age, and weight of heifer at first breeding, were converted into categorical variables. Nominal variables were appropriately labeled as categorical or binary (e.g., yes/no responses for soil management practices). Supplemental feeding strategies were evaluated separately for each animal category. Questions with fewer than three positive responses in any category were excluded. Also, to preserve anonymity, animal breeding technicians were labeled with letters A through K. After data cleaning, 25 questions remained for farm management characterization. The farm management descriptors included

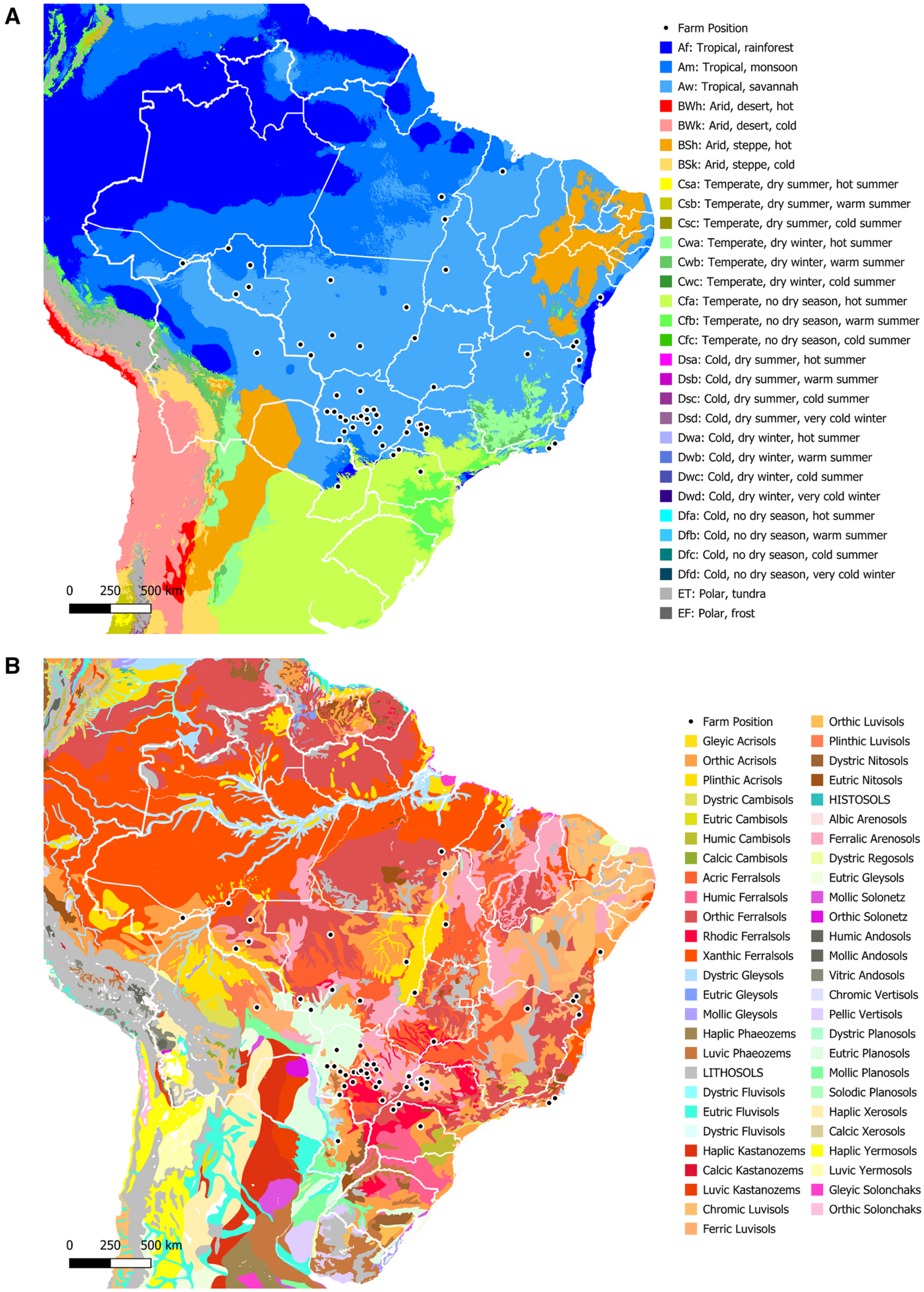

Fig. 1. Maps of South america illustrating a) the Köppen-Geiger climate classification and b) soil classification with locations of farms (black-filled circles) included in this study. The maps were plotted using public domain data from Beck et al. (2023) and the ISRIC world soil information, respectively, and visualized using the QGIS geographic information system.

in this study, along with their respective levels and corresponding animal counts, after data cleaning, were as follow: animal breeding technician (11 levels; A: 14,466, B: 18,324, C: 2883, D: 42,270, E: 20,689, F: 17,459, G: 3195, H: 676, I: 2478, J: 3933, and K: 16,959), years enrolled in the Embrapa-Geneplus (5 levels; between 1996 and 2000: 52,708, between 2001 to 2005: 13,064, between 2006 and 2010: 28,915, between 2011 and 2015: 31,795, and between 2016 and 2020: 16,850), livestock land area (3 levels; large: 112,016, medium: 29,666, and small: 1650), production system (2 levels; crop-livestock: 22,369, grazing: 120,963). Concerning soil management practices: length of pasture establishment (4 levels; up to 5 yr:

Table 2. Description of explanatory variables assessed by the survey conducted with 80 farmers enrolled in the Embrapa-Geneplus nellore cattle breeding program from october to december 2021.

Explanatory variables	Description	Number of levels
General information		
Animal breeding technician	The technician affiliated with Embrapa-Geneplus who provides animal breeding guidance to the farm	11
Years enrolled in the Embrapa-Geneplus	The time categorized in 5-year increments, ranging from less than 5 to 25 years	5
Livestock land area	The land area allocated for livestock categorized into classes: small (≤100 ha) medium (101–999 ha) large (≥ 1000 ha)	3
Production system	Adopting grazing or crop-livestock as a production system	2
Soil management		
Length of pasture establishment	The time categorized in 5-year increments, ranging from less than 5 to 20 years	4
Native grasslands	Choosing exclusively native grasslands for pasture use (yes/no)	2
Tillage	Adopting tillage as a soil management method (yes/no)	2
No-till farming	Adopting no-till farming as a soil management method (yes/no)	2
Contour farming	Adopting contour farming as a soil management method (yes/no)	2
Crop rotation	Adopting crop rotation as a soil management method (yes/no)	2
Pasture recovery and renewal	Adopting methods for recovery and renewal of degraded pastures (yes/no)	2
Fertilization	Adopting fertilization (yes/no)	2
Irrigation	Adopting irrigation (yes/no)	2
Natural resource conservation	Adopting buffer strips, riparian forest buffers, or stabilization of gullies and slopes for natural resources conservation (yes/no)	2
Supplemental feeding[a]		
Mineral	Inclusion of mineral mix in the supplement (yes/no)	2
Mineral and urea	Inclusion of mineral mix and urea in the supplement (yes/no)	2
Protein	Inclusion of any protein source in the supplement (yes/no)	2
Protein-energy	Inclusion of both protein and energy sources in the supplement (yes/no)	2
Reproductive management		
Period of the breeding season	The time is categorized into various monthly increments (e.g., October to February)	14
Length of the breeding season	The number of months is categorized as short-term (up to 4) and long-term (from 5 to 7)	2
Reproductive technique	The use of reproductive techniques is categorized into classes: Natural service (exclusively) Fixed-time artificial insemination and herd bulls Fixed-time artificial insemination, synchronization protocols, and herd bulls	3
In vitro fertilization	Use of in vitro fertilization as a reproductive technique (yes/no)	2
Age of the heifer	The age of the heifer at first breeding is categorized into classes: 12–14 mo 16–18 mo 20–22 mo 24–26 mo	4
Weight of the heifer	The weight of the heifer at first breeding is categorized into classes: ≤ 270 kg 271–300 kg 301–329 kg 330–359 kg 360–389 kg ≥390 kg	6

[a] Supplemental feeding was assessed for each animal category. As a previous step of farm management descriptor selection, the questions were merged and reclassified based on the animal category, resulting in four new descriptors: Supplemental feeding for calves (5 levels), heifers (5 levels), cows (6 levels), and sires (7 levels).

34,337, from 6 to 10 yr: 70,126, from 11 to 15 yr: 19,679, from 16 to 20 yr: 19,190), native grasslands (yes: 10,7710 or no: 35,622), tillage (yes: 79,818 or no: 63,514), no-till farming (yes: 44,437 or no: 98,895), contour farming (yes: 89,874 or no: 53,458), crop rotation (yes: 94,475 or no: 48,857), pasture recovery and renewal (yes: 92,372 or no: 50,960), fertilization (yes: 97,510 or no: 45,822), irrigation (yes: 27,359 or no: 115,973), and natural resource conservation (yes: 99,538 or no: 43,794). The supplemental feeding strategy per animal category: calf (5 levels; mineral: 77,375, protein: 27,697, mineral and protein-energy: 9873, mineral and protein: 10,258, and mineral, protein and protein-energy: 18,129), heifer (5 levels; mineral: 63,863, mineral and urea: 29,457, mineral and protein: 16,431, mineral and protein-energy: 4649 and mineral, urea, protein and protein-energy: 28,932), cow (6 levels; mineral: 28,157, mineral and urea: 40,681, mineral and protein: 12,031, mineral and protein-energy: 20,699, mineral, urea and protein: 15,008, and mineral, urea, protein and protein-energy: 26,756), and bull (7 levels; mineral: 41,774, mineral and urea: 16,644, mineral and protein: 10,774, mineral and protein-energy: 34,966, mineral, urea and protein: 16,734, mineral, urea and protein-energy: 2714, and mineral, urea, protein and protein-energy: 19,726). Lasty, descriptors related to reproductive management: period of the breeding season (14 levels; categorized in various monthly increments, e.g.: October to February: 36,137), length of the breeding season (2 levels; short-term: 79,986 or long-term: 63,346), reproductive technique (3 levels; natural service: 876, fixed-time artificial insemination—FTAI and herd bulls: 10,248, and FTAI, synchronization protocols, and herd bulls: 132,208), in vitro fertilization—IVF (2 levels; yes: 72,343 or no: 70,989), age (4 levels: between 12 and 14 mo: 59,504, between 16 and 18 mo: 13,163, between 20 and 22 mo: 12,705 and between 24 and 26 mo: 57,960) and weight of heifer at first breeding (6 levels; ≤270 kg: 5535, between 271 and 300 kg: 44,573, between 301 and 329 kg: 45,938, between 330 and 359 kg: 22,437, between 360 and 389 kg: 6238, and ≥390 kg: 18,611).

Selection of environment and farm management descriptors

The process of identifying optimal farm-level environmental and management descriptors for the genetic evaluation of YW was conducted through three sequential steps:

1. Each descriptor was fit one at a time as a fixed effect in the general statistical model. The decision to retain a descriptor was based on its capacity to explain at least 4% of the YW variance attributed to the farm effect. The general statistical model employed for this assessment can be written as: $\boldsymbol{y}^* = \boldsymbol{X\beta} + \boldsymbol{Wf} + \boldsymbol{e}$, where $\boldsymbol{y}^*$ is the vector of the phenotypes adjusted for random additive genetic effects; β is a vector with fixed effects of sex, CG, age (linear covariate) at measurement, and the evaluated descriptor; *f* is a vector of random farm effects, assumed to follow $N\left(\mathbf{0}, \boldsymbol{I}\sigma_f^2\right)$, where σ_f^2 is the farm variance; and e is the residual vector, assumed $N\left(0, \boldsymbol{I}\sigma_e^2\right)$. The $\boldsymbol{X}$ and $\boldsymbol{W}$ are known incidence matrices related to fixed and farm effects, respectively. The estimation of fixed effects and variance components was performed utilizing the Maximum Likelihood (ML) method through the application of the *lmer* function, available in the R package "lme4" (Bates et al. 2015). The adjusted phenotypic vector was computed as $\boldsymbol{y}^* = \boldsymbol{y} - \hat{\boldsymbol{a}}$, where $\hat{\boldsymbol{a}}$ is the vector of EBVs,obtained using a traditional animal model,including the effects from the general statistical model described above,along with additive genetic effects $\boldsymbol{a}$ (ie,true breeding values),assumed to follow $N\left(\mathbf{0}, \boldsymbol{A}\sigma_a^2\right)$,where σ_a^2 is the additive genetic variance and $\boldsymbol{A}$ is the numerator relationship matrix. This analysis was implemented on the BLUPF90+ software (Misztal et al. 2014).
2. Considering that farm management descriptors can be associated with each other, we used the Chi-Squared test (at a 5% significance level) to identify and prune highly associated variables, thereby reducing collinearity and redundant information (McHugh 2013). Whenever a marginal association was statistically significant, it was classified as a direct association. On the other hand, when two variables did not present a significant marginal association, but both were significantly associated with a third variable, this was referred to as an indirect association between them.
3. Model comparison and variable selection were performed separately for environmental descriptors and for farm management descriptors retained in step two, using a stepwise procedure based on the general statistical model defined in step one. For each group, the best model was identified based on the Akaike Information Criterion (**AIC**; Akaike 1973) and the proportion of the YW variance explained by the farm effect. In cases where the best model in AIC differed from the model explaining the largest farm variance, both criteria were jointly considered to select the most suitable model. Finally, the selected variables from both groups were then combined, and a final stepwise selection was conducted to obtain the best complete model.

Final statistical analysis

The genetic evaluation analysis of YW began with a traditional animal model ($\mathbf{M}_1$, benchmark model) and was extended to three alternative models, including the previously selected key environmental ($\mathbf{M}_2$), farm management ($\mathbf{M}_3$), or combined descriptors ($\mathbf{M}_3$). Further details about these descriptors are provided in subsequent sections. The general form of $\mathbf{M}_1$ can be described as follows:

$$Y = X\beta + Za + Wf + e$$

where $\boldsymbol{y}$ is the vector of the YW observations; β is a vector with fixed effects of sex, CG, age (days, as a linear covariate) at measurement, and the descriptors previously identified in the selection procedure; $\boldsymbol{a}$ is a vector of random additive genetic effects, assumed to follow $N\left(0, \boldsymbol{A}\sigma_a^2\right)$, where σ_a^2 is the additive genetic variance and $\boldsymbol{A}$ is the numerator relationship matrix; $\boldsymbol{f}$ is a vector of random farm effects, assumed to follow $N\left(0, \boldsymbol{I}\sigma_f^2\right)$, where σ_f^2 is the farm variance and $\boldsymbol{I}$ stands for an identity matrix; and $\boldsymbol{e}$ is the residual vector, assumed $N\left(0, \boldsymbol{I}\sigma_e^2\right)$. The $\boldsymbol{X}$, $\boldsymbol{Z}$ and $\boldsymbol{W}$ are known incidence matrices related to fixed, additive genetic, and farm effects, respectively.

The variance components and breeding values were estimated using the Restricted Maximum Likelihood/Best Linear Unbiased Prediction (REML/BLUP) method, implemented in the BLUPF90+ software (Misztal et al. 2014). Estimates of the within-farm heritability (h_w^2) were calculated according to Visscher and Goddard (1993) as follows: $h_w^2 = \frac{\hat{\sigma}_a^2}{\hat{\sigma}_a^2 + \hat{\sigma}_e^2}$, where $\hat{\sigma}_a^2$ and $\hat{\sigma}_e^2$ are the estimates of the additive genetic and residual variances, respectively. The model comparisons were performed based on the AIC and the proportion of the YW variance across farms explained by the key descriptors included as fixed effects in the genetic evaluation. This proportion was calculated by comparing the farm variance component (σ_f^2) from $\mathbf{M}_1$ (including only basic fixed effects) to those from $\mathbf{M}_2$, $\mathbf{M}_3$ or $\mathbf{M}_4$, which included additional descriptors. The proportion of explained variance was given by $PVE = 100 \times \left(\sigma_{f_{M_1}}^2 - \sigma_{f_{M_\bullet}}^2\right) / \sigma_{f_{M_1}}^2$

Results

Description of survey data outcomes

Sixty-eight percent of the targeted beef cattle breeders (80 farms) completed the survey during the period spanning from October to December 2021. These farms have been enrolled in the Embrapa-Geneplus beef cattle breeding program since the following periods: 1996–2000 (15%), 2001–2005 (10%), 2006–2010 (21.7%), 2011–2015 (21.7%), and 2016–2020 (31.7%). Eleven technicians with expertise in animal breeding support these farms, with one technician assisting 23% of all farms.

The majority of the sampled farms were located in the state of Mato Grosso do Sul, accounting for 23 farms (38%), followed by the states of Mato Grosso and São Paulo with 7 farms (11.7%) each, Bahia and Rondônia with 4 farms (6.7%) each, Paraná with 3 farms (5%), and Goiás, Pará, and Rio de Janeiro with 2 farms (3.3%) each. Furthermore, single-farm representation was observed in the states of Acre, Maranhão, Minas Gerais, and Tocantins, as well as in Bolivia and Paraguay (1.7% each). Regarding land use, 6.7%, 36.7%, and 56.7% of producers reported allocating small, medium, and large areas, respectively, to livestock production. Among these areas, 85% of the animals are managed in pasture-based systems, while the remaining 15% are part of crop-livestock integrated systems. Notably, the pasture is the primary feed source used in the diets of the farms that answered the survey. In this context, producers have adopted several soil management practices aimed at enhancing forage quality, increasing production, and promoting soil conservation, such as pasture recovery and renewal (73%), fertilization (65%), tillage (63%), natural resources conservation (50%), contour farming (48%), crop rotation (47%), no-till farming (32%), native grasslands (20%), and irrigation (5%).

Supplemental feeding strategy was reported for all animal categories described in the survey. Breeders provided at least a mineral source for calves (46.7%), heifers (48.3%), cows (36.7%), and sires (40%). Additionally, other supplements included urea for heifers (15%), cows (25%), and sires (11.7%); protein for calves (13.3%), heifers (18.3%), cows (15%), and sires (15%); and protein-energy for calves (6.7%), heifers (8.3%), cows (8.3%), and sires (16.7%). Some supplemental strategies involved combining multiple sources, such as mineral, protein, and protein-energy for calves (13.3%) and sires (5%); mineral, mineral and urea, and protein for cows (5%), and sires (5%); and mineral, mineral and urea, protein and protein-energy for heifers (10%), cows (10%), and sires (6.7%). In the case of calves, 20% of the animals were supplemented exclusively with protein sources.

All respondents confirmed the adoption of a defined breeding season on their farms, either in the short (51.7%) or long term (48.3%), as part of their reproductive management strategy. The most frequent breeding season periods were from October-January (21.7%), October-February (20%), and November-February (13.3%). Additionally, September-December and November-March were reported by 6.7% of respondents, while December-March, October-March, September-January, and September-March were each cited by 5%. Less common periods included October-December and September-February (3.3% each), as well as January-March, August-January, and October-April (1.7% each). The most widely adopted reproductive technique was the combined use of FTAI, synchronization protocols, and herd bulls (86.7%), followed by FTAI and herd bulls (11.7%). Only one farm indicated the exclusive use of natural service. Also, 51.7% of respondents reported employing in vitro fertilization (**IVF**) as part of their reproductive management.

On average, 887 heifers and cows were exposed to the breeding season during the period covered by the survey, with the number of females ranging from a minimum of 50 to a maximum of 3,500. Cows entered the breeding season at an average weight of 497.2 ± 49.9 kg, while heifers at their first breeding had an average age of 18.8 ± 4.79 mo (Minimum = 11 mo; Maximum = 28 mo) and an average weight of 325.4 ± 41.86 kg (Minimum = 250 kg; Maximum = 430 kg). When herd bulls were used during the breeding season, the average bull-to-cow ratio was 1:31 ± 1:12 (Minimum: 1:15; Maximum: 1:80).

Concerning reproduction outcomes, the average conception rate achieved through FTAI was 55% ± 15.4% for heifers, 52.6% ± 14.1% for primiparous cows, and 61.3% ± 12.9% for multiparous cows. By the end of the breeding season, the average conception rate increased to 81.3% ± 10.6% for heifers, 75.4% ± 9.6% for primiparous cows, and 84.5% ± 6.1% for multiparous cows. After data cleaning at the animal level and subsequent merging with farm records, information from 60 farms was retained to evaluate farm management descriptors.

Selection of environment and farm management descriptors

The main findings from the descriptor selection procedures are summarized in Tables 3, 4, and 5. Table 3 presents the variance component estimates and AIC values for each environmental and farm management descriptor, alongside the general statistical model effects. The inclusion of individual descriptors explained between 0.2% and 37.9% of the YW variance attributed to farms, while the residual variance remained unchanged (Table 3). The largest contributors to YW variance across farms were the guidance from animal breeding technicians (37.9%), period of the breeding season (31.9%), soil classification (21.1%), elevation (18.2%), and age of the heifer at first breeding (16.6%). Next in importance were descriptors of weight of the heifer at first breeding, period of use of established pasture, no-till farming, calf and bull supplemental feeding, and irrigation, each accounting for 10.3–14.1% of the YW variance attributed to the farm effect. Additional descriptors, including fertilization, contour farming, cow and heifer supplemental feeding, reproductive technique, years enrolled in Embrapa-Geneplus, crop rotation, production system, livestock land area, and IVF, each explained between 4.2% and 8.7% of the farm-attributed YW variance.

Although some of these descriptors did not improve model goodness-of-fit, they still contributed meaningfully to explaining the YW variance attributed to the farm (Table 3). For example, the period of the breeding season and soil classification showed poorer model fit yet ranked among the most influential variables. To provide a more comprehensive understanding, descriptors with an AIC higher than the general statistical model but explaining at least 4% of the YW variance (e.g., soil classification, elevation, breeding season period, weight of heifer at first breeding, supplemental feeding practices, reproductive technique, years in Embrapa-Geneplus, and livestock land area) were retained for further consideration.

The associations among farm management descriptors, identified in step one, were investigated using the Chi-squared test (Table 4). The animal breeding technician exhibited direct associations with the period of use of established pasture, calf supplemental feeding, irrigation, and contour farming. The age of the heifer at first breeding also showed a direct association with

Table 3. Maximum likelihood estimates of farm variance (σ_f^2), residual variance (σ_e^2) and Akaike Information Criterion (AIC) from the general statistical model analyzing each environmental and farm management descriptor. The entries are ordered based on the proportion of farm variance explained (PVE, %) by the included fixed effect on yearling weight (kg) evaluated in Nellore cattle.

Model	σ_f^2	σ_e^2	AIC	PVE
General Statistical Model	1249.97	923.33	1,386,267	–
Environmental descriptors				
Soil classification (SOIL)	986.2	923.33	1,386,275	21.1
Elevation (ELE)	1023.03	923.33	1,386,257	18.16
Climate classification (CLI)	1163.37	923.33	1,386,268	6.93
Farm management descriptors				
Animal breeding technicians (TEC)	776.76	923.33	1,386,258	37.86
Period of the breeding season (PBS)	851.49	923.33	1,386,270	31.88
Age of heifer (AHF)	1042.72	923.33	1,386,262	16.58
Weight of heifer (WHF)	1073.96	923.33	1,386,268	14.08
Length of pasture establishment (LPE)	1091.45	923.33	1,386,265	12.68
No-till farming (NTI)	1100.22	923.33	1,386,261	11.98
Calf supplemental feeding (CFSF)	1105.18	923.33	1,386,267	11.58
Bull supplemental feeding (BSF)	1118.81	923.33	1,386,272	10.49
Irrigation (IRR)	1121.37	923.33	1,386,262	10.29
Fertilization (FER)	1140.60	923.33	1,386,263	8.75
Contour farming (CON)	1142.87	923.33	1,386,263	8.57
Cow supplemental feeding (CWSF)	1157.01	923.33	1,386,272	7.44
Reproductive technique (RTC)	1186.68	923.33	1,386,268	5.06
Years enrolled in the Embrapa-Geneplus (YEN)	1191.08	923.33	1,386,272	4.71
Crop rotation (CRO)	1192.46	923.33	1,386,266	4.60
Heifer supplemental feeding (HSF)	1193.46	923.33	1,386,272	4.52
Production system (PRS)	1193.79	923.33	1,386,266	4.49
Livestock land area (LLA)	1197.25	923.33	1,386,268	4.22
In vitro fertilization (IVF)	1197.51	923.33	1,386,266	4.20
Tillage (TIL)	1223.40	923.33	1,386,267	2.13
Native grasslands (NGR)	1230.86	923.33	1,386,268	1.53
Natural resources conservation (NRC)	1237.78	923.33	1,386,268	0.98
Length of the breeding season (LBS)	1240.78	923.33	1,386,268	0.73
Pasture recovery and renewal (PRR)	1247.63	923.33	1,386,269	0.19

contour farming, while the weight of the heifer at first breeding was directly associated with fertilization and crop rotation. Additionally, no-till farming was directly associated with crop rotation, fertilization, and production system.

Indirect associations were also observed (Table 4). The guidance from animal breeding technicians was indirectly associated with fertilization (via period of use of established pasture), with heifer, cow, and bull supplemental feeding strategies (via calf supplemental feeding), and with crop rotation and IVF (via contour farming). Similarly, the age of the heifer at first breeding was indirectly associated with crop rotation and IVF (via contour farming). The weight of the heifer at first breeding was indirectly associated with contour farming, crop rotation, production system, and IVF (via fertilization). Lastly, no-till farming was indirectly associated with contour farming and IVF (via fertilization).

No significant associations were detected for the period of the breeding season, years enrolled in the breeding program, reproductive technique, and livestock land area (Table 4). In summary, the farm management descriptors retained in step two of the selection procedure were: guidance from animal breeding technicians, period of the breeding season, age and weight of the heifer at first breeding, no-till farming, reproductive technique, years enrolled in the breeding program, and livestock land area.

In the final step of selection procedure, a stepwise procedure was applied separately to environmental descriptors and farm management descriptors retained in step two. The selected variables from both groups were then combined for a final selection to obtain the best full model, with the main findings summarized in Table 5, and detailed in Supplementary Table S1. The inclusion of selected descriptors in the general statistical model proved effective in explaining the YW variance attributed to the farm effect. Environmental descriptors explained from 19.1% to 36.9% of the YW variance attributed to the farm effect, farm management descriptors retained in step two from 7.1% to 77.4%, and the combination of both descriptor types from 60.6% to 97.8% (Table 5). Residual variance estimates remained unchanged across models.

The best environmental model included all descriptors (ie, climate, soil classifications, and elevation), in addition to the general model effects (Table 5). Although this model resulted in a marginal increase in the AIC, it explained nearly twice the proportion of YW variance attributed to farm effect compared to the best-fitting model. The best-fitting model for farm management descriptors retained in step two was achieved by including guidance from animal breeding technicians, age of heifer at first calving, no-till farming, and livestock land area, which accounted for 56.5% of the YW variance attributed to the farm effect (Table 5). On the other hand, the model

Table 4. Chi-squared test of independence with p-values (upper diagonal) and chi-squared value (lower diagonal) for the pre-selected farm management descriptors.

	TEC	PBS	AHF	WHF	LPE	NTI	CFSF	BSF	IRR	FER	CON	CWSF	RTC	YEN	CRO	HSF	PRS	LLA	IVF
TEC		0.23	0.1	0.61	0.02*	0.55	0.01*	0.43	0*	0.2	0.03*	0.21	0.82	0.56	0.17	0.3	0.41	0.08	0.45
PBS	141.61		0.33	0.62	0.4	0.24	0.14	0.96	0.76	0.1	0.29	0.36	0.99	0.33	0.72	0.06	0.17	0.43	0.29
AHF	40.3	42.21		0.18	0.67	0.12	0.34	0.14	0.59	0.08	0.03*	0.07	0.6	0.87	0.64	0.58	0.37	0.17	0.21
WHF	36.84	48.29	16.2		0.65	0.18	0.62	0.52	0.78	0.02*	0.12	0.16	0.97	0.39	0.04*	0.16	0.21	0.52	0.09
LPE	47.69	40.53	6.67	9.62		0.54	0.64	0.33	0*	0.04*	0.09	0.78	0.21	0.47	0.16	0.52	0.21	0.86	0.07
NTI	8.85	16.2	5.81	6.3	2.16		0.51	0.73	0.48	0.02*	0.2	0.54	0.77	0.67	0.04*	0.43	0*	0.46	0.86
CFSF	64.43	63.22	13.39	13.72	9.67	3.28		0*	0.46	0.56	0.64	0*	0.98	0.6	0.33	0*	0.84	0.35	0.19
BSF	61.4	57.11	24.62	22.98	19.99	3.6	53.07		0.41	0.09	0*	0*	0.92	0.48	0.22	0*	0.04*	0.26	0.34
IRR	26.42	9.12	1.9	1.75	20.53	0.49	3.61	6.14		0.49	0.21	0.36	0.78	0.75	0.91	0.5	0.93	0.3	0.95
FER	13.53	20	6.62	11.32	8.22	5.83	2.99	11.07	0.47		0*	0.97	0.34	0.49	0.02*	0.67	0.04*	0.78	0.01*
CON	19.5	15.36	8.71	7.4	6.6	1.66	2.51	18.71	1.55	17.17		0.17	0.33	0.7	0*	0.46	0.12	0.34	0*
CWSF	57.74	68.51	23.47	26.32	10.54	4.05	58.49	133.36	5.52	0.89	7.76		0.87	0.21	0.76	0*	0.96	0.07	0.07
RTC	14.27	11.9	4.58	2.37	8.41	0.52	2.08	5.9	0.49	2.17	2.22	5.26		0.18	0.55	0.81	0.91	0.18	0.33
YEN	38.05	55.83	6.84	17.01	11.65	2.34	14.03	23.72	1.91	3.44	2.18	24.78	11.31		0.09	0.18	0.08	0.74	0.31
CRO	14.01	9.69	1.7	10.21	5.18	4.09	4.59	8.27	0.01	5.44	13.01	2.61	1.19	8.15		0.92	0*	0.98	0.62
HSF	44.09	68.93	10.37	21.64	11.11	3.8	44.3	78.38	3.38	2.38	3.64	116.1	4.51	20.92	0.9		0.4	0.53	0.06
PRS	10.37	17.79	3.15	5.9	4.49	13.06	1.41	13.16	0.01	4.04	2.42	1.07	0.19	8.19	9.71	4.03		0.58	0.91
LLA	29.24	26.69	9.11	7.13	2.58	1.57	8.87	14.59	2.41	0.49	2.13	17.41	6.27	5.12	0.03	7.07	1.1		0.06
IVF	9.85	15.36	4.58	8.15	7.04	0.03	6.06	6.76	0	6.34	8.04	10.1	2.22	4.8	0.25	9.02	0.01	5.73	

TEC, animal breeding technicians; PBS, period of the breeding season; AHF, age of heifer at first breeding; WHF, weight of heifer at first breeding; LPE, length of pasture establishment; NTI, no-till farming; CFSF, calf supplemental feeding; BSF, bull supplemental feeding; IRR, irrigation; FER, fertilization; CON, contour farming; WSF, cow supplemental feeding; RTC, reproductive technique; YEN, years enrolled in the Embrapa-Geneplus breeding program; CRO, crop rotation; HSF, heifer supplemental feeding; PRS, production system; LLA, livestock land area and IVF, in vitro fertilization. *
P-value < 0.05.

Table 5. Maximum likelihood estimates of farm variance (σ_f^2), residual variance (σ_e^2) and the Akaike Information Criterion (AIC) from the general statistical model analyzing combinations of environmental and key farm management descriptors. The entries are ordered based on the proportion of farm variance explained (PVE, %) by the included fixed effects on yearling weight (kg) evaluated in Nellore cattle.

Model	σ_f^2	σ_e^2	AIC	PVE
General Statistical Model	1249.97	923.33	1,386,267	-
Environmental descriptors				
CLI, SOIL, ELE	788.19	923.33	1,386,269	36.94
SOIL, ELE	806.54	923.33	1,386,265	35.48
CLI, SOIL	973.68	923.33	1,386,280	22.10
CLI, ELE	1011.89	923.33	1,386,262	19.05
Farm management descriptors				
TEC, PBS, AHF, WHF, NTI, YEN, RTC, LLA	281.91	923.33	1,386,258	77.45
TEC, PBS, AHF, WHF, NTI, YEN, RTC	305.24	923.33	1,386,258	75.58
TEC, PBS, AHF, WHF, NTI, YEN, LLA	311.66	923.33	1,386,260	75.07
TEC, PBS, AHF, WHF, YEN, RTC, LLA	325.26	923.33	1,386,264	73.98
TEC, PBS, AHF, NTI, YEN, RTC, LLA	329.67	923.33	1,386,257	73.63
TEC, PBS, AHF, NTI, YEN, RTC	335.58	923.33	1,386,254	73.15
TEC, PBS, WHF, NTI, YEN, RTC, LLA	337.12	923.33	1,386,262	73.03
TEC, PBS, AHF, WHF, NTI, YEN	338.16	923.33	1,386,261	72.95
TEC, PBS, AHF, WHF, YEN, LLA	345.48	923.33	1,386,264	72.36
TEC, PBS, WHF, NTI, YEN, RTC	347.36	923.33	1,386,260	72.21
TEC, AHF, WHF, NTI, YEN, RTC, LLA	405.94	923.33	1,386,253	67.52
TEC, AHF, WHF, NTI, RTC, LLA	449.42	923.33	1,386,252	64.05
TEC, AHF, WHF, NTI, LLA	476.54	923.33	1,386,251	61.88
TEC, AHF, WHF, NTI, RTC	494.44	923.33	1,386,253	60.44
TEC, AHF, NTI, YEN, LLA	512.01	923.33	1,386,253	59.04
TEC, AHF, NTI, RTC, LLA	521.24	923.33	1,386,250	58.30
TEC, AHF, NTI, LLA	543.27	923.33	1,386,249	56.54
TEC, AHF, NTI, RTC	556.37	923.33	1,386,250	55.49
TEC, AHF, NTI	585.05	923.33	1,386,249	53.20
TEC, AHF, LLA	586.50	923.33	1,386,251	53.08
Environmental and farm management descriptors				
TEC, PBS, AHF, WHF, NTI, YEN, RTC, LLA, CLI, SOIL, ELE	27.88	923.35	1,386,152	97.77
TEC, PBS, AHF, WHF, NTI, YEN, RTC, LLA, CLI, ELE	234.96	923.33	1,386,255	81.20
TEC, AHF, NTI, LLA, CLI, SOIL, ELE	313.41	923.33	1,386,246	74.93
TEC, AHF, NTI, LLA, CLI, ELE	492.96	923.33	1,386,251	60.56

CLI, Köppen-Geiger climate classification; SOIL, Soil classification based on World Reference Base for Soil Resources, ELE, elevation; TEC, animal breeding technicians; PBS, period of the breeding season; AHF, age of heifer; WHF, weight of heifer; NTI, no-till farming; RTC, reproductive technique; YEN, years enrolled in the Embrapa-Geneplus and LLA, livestock land area. Main findings are presented here; for full details, please see Supplementary Table S1.

Table 6. Random and fixed effects used in the genetic evaluation model of yearling weight (kg) in nellore cattle.

Model	Fixed effects	Random effects
Benchmark (M_1)	AGE, S, CG	a, f
Environmental (M_2)	AGE, S, CG, CLI, SOIL, ELE	a, f
Farm Management (M_3)	AGE, S, CG, TEC, PBS, AHF, WHF, NTI, RTC, YEN, LLA	a, f
Environmental and Farm Management (M_4)	AGE, S, CG, CLI, SOIL, ELE, TEC, PBS, AHF, WHF, NTI, RTC, YEN, LLA	a, f

AGE, age at measurement (days, as a linear covariate); S, sex; CG, contemporary group; CLI, Köppen-Geiger climate classification; SOIL, soil classification based on World Reference Base for Soil Resources; ELE, Elevation (meters, as a linear covariate); TEC, animal breeding technicians; PBS, period of the breeding season; AHF, age of heifer at first breeding; WHF, weight of heifer at first breeding; NTI, no-till farming; RTC, reproductive technique; YEN, years enrolled in the Embrapa-Geneplus breeding program and LLA, livestock land area; *a*, additive genetic effect and *f*, farm effect.

including all farm management descriptors retained in step two (i.e., guidance from animal breeding technician, period of the breeding season, age and weight of heifer at first caving, no-till farming, reproductive technique, years enrolled in the breeding program, and livestock land area) explained the largest proportion of YW variance attributed to farm effect (77.4%), and had a superior goodness-of-fit compared to the general statistical model. When combining environmental and farm management descriptors, the optimal model included climate and soil classifications, elevation, guidance from animal breeding technicians, breeding season period, age and weight of heifer at first calving, no-till farming, reproductive technique, years in the breeding program, livestock land area, along with the general model effects (Table 5). This model achieved the best fit and accounted for the largest proportion of YW variance attributed to farm effect among all evaluated models. Using the farm-level descriptors identified in the selection procedure, we compared three genetic evaluation models: environmental (**M**$_2$), farm management (**M**$_3$), and a combined model (**M**$_4$), as shown in Table 6.

Additionally, because the guidance from animal breeding technician effect is confounded with many other factors (Table 4), we conducted supplementary analyses by omitting this descriptor to investigate the potential effect of different factors. The results of these analyses are also presented in Table S1. In summary, when the guidance from animal breeding technicians was omitted from the model, the main descriptors explaining to the YW variance across farms were period of use of established pasture, period of the breeding season, age and weight of heifer at first caving, calf supplemental feeding, no-till farming, reproductive technique, years enrolled in the breeding program, and livestock land area.

Model comparison

The estimates of variance components and within-farm heritabilities from genetic evaluation models are presented in Table 7. In line with the selection procedure results, both environmental and farm management descriptors consistently helped explain the YW variance attributed to farm effect across all models. Among them, $\mathbf{M}_4$ explained the largest proportion (65.7%), followed by $\mathbf{M}_3$ (29.7%), and $\mathbf{M}_2$ (22.1%). The inclusion of these descriptors progressively improved model fit in the same order. Importantly, their inclusion did not affect the estimates of additive genetic or residual variance components, which were 678.3 ± 15.28 and 1,254 ± 10.98 (kg^2), respectively, yielding stable within-farm heritability estimates of 0.35 ± 0.01 across models (Table 7).

Discussion

Description of survey data outcomes

The survey provided comprehensive insights into farm management practices and environmental conditions, which advanced the understanding of their effects on herd performance. Moreover, the findings highlighted opportunities to improve data recording procedures within the Embrapa-Geneplus breeding program. Survey responses showed that producers joined the Embrapa-Geneplus beef cattle breeding program at different times; however, a notable share (31.7%) enrolled more recently, between 2016 and 2020. This substantial increase in enrollment might be attributed to initiatives by Brazilian beef cattle producers to enhance productivity and sustainability in response to the robust growth observed in the meat market. In 2022, the Brazilian beef cattle agribusiness generated US$198.12 billion, of which US$920.8 million came from genetically improved animals (ABIEC 2024). For comparison, the cumulative revenue from genetically improved animals accumulated in Brazil between 2019 and 2021 amounted to US$938.6 million (ABIEC 2024).

By assessing the geographical distribution, production system, and herd size of the studied farms, we observed that most farms and recorded animals are in the Mato Grosso do Sul and Mato Grosso states under grazing systems, which is consistent with the distribution of livestock heads and pasture areas in Brazil. According to the Brazilian Institute of Geography and Statistics—IBGE (2022), the states Mato Grosso do Sul and Mato Grosso, in the Central-West region of Brazil, accounted for 52.68 million heads (22.5% of the Brazilian total) across ~35 million hectares of pasture (Lapig/UFG 2024). Furthermore, the Embrapa-Geneplus beef cattle breeding program and the National Center of Research on Beef Cattle (CNPGC), both overseen by EMBRAPA, are in the city of Campo Grande, the capital of Mato Grosso do Sul. This strategic location, with its established research infrastructure and robust networks, may have contributed to the higher concentration of farms enrolled in the breeding program in Mato Grosso do Sul state.

Regarding the size of the studied farms, according to Brazilian Law 8.629 (1993) for rural property areas, most farms in this study are classified as large (80%), followed by medium (18.3%), and a minor group categorized as small farms (1.7%). However, some large farms have allocated small to moderate areas for beef cattle, suggesting that livestock production might not be their main business focus or that the remaining areas are dedicated to native vegetation, permanent preservation, or legal reservation requirements.

The Brazilian beef cattle production system includes three main stages: cow-calf operations, growing, and finishing. The feedlot, when used, is typically employed in the finishing stage. In 2022, Brazil—the world's second-largest beef producer—achieved a production milestone of 10.8 million tons of carcass-weight equivalent. During this period, the national herd size increased by 3.3%, while the pasture area decreased by 5.7% (ABIEC 2024). Additionally, a significant proportion (82.8%) of the slaughtered animals were pasture-raised (ABIEC 2024), demonstrating the importance of grasslands for Brazilian livestock production. In this context, the producers included in our study indicated the use of several soil management practices, such as soil conservation (e.g. crop rotation and contour farming), low-carbon agriculture techniques (e.g., pasture recovery and renewal, no-till farming, and integrated crop-livestock systems), and management improvements (e.g. fertilization and irrigation). These practices aim to enhance forage biomass production while increasing soil organic carbon storage, which contributes to sustaining soil fertility, conserving water quality, and mitigating greenhouse gas emissions (Conant et al. 2001; Komatsuzaki and Ohta 2007; Ogle et al. 2004). Moreover, supplemental feeding strategies observed across the farms, primarily relying on mineral

Table 7. Restricted maximum likelihood estimates of additive genetic variance (σ_a^2), farm variance (σ_f^2), residual variance (σ_e^2), within-farm heritability (h_w^2), and their standard errors, and Akaike Information Criterion (AIC) analyzed from different models. The entries are ordered based on the proportion of farm variance explained (PVE, %) by the included fixed effects on the genetic evaluation of yearling weight (kg) in Nellore cattle.

Model	σ_a^2	SE	σ_f^2	SE	σ_e^2	SE	h_w^2	SE	AIC	PVE
Benchmark (M_1)	678.48	15.29	1263.80	233.89	1254.00	10.98	0.35	0.01	1,475,996	-
Environmental (M_2)	678.42	15.28	984.14	211.08	1254.00	10.98	0.35	0.01	1,475,861	22.13
Farm Management (M_3)	678.29	15.28	888.39	290.04	1254.10	10.98	0.35	0.01	1,475,617	29.70
Environmental and Farm Management (M_4)	678.25	15.28	433.60	310.04	1254.10	10.98	0.35	0.01	1,475,471	65.69

sources, highlight the critical need for the availability of high-quality forage for all animal categories. Recent trends reveal that agribusiness within the beef cattle industry has allocated more resources to fertilizers, plant protection products, and seeds compared to the expenses on nutritional supplements (ABIEC 2024). These investments reflect industry's efforts to enhance efficiency through adoption of technologies focused on tropical environments, while simultaneously supporting biodiversity and minimizing the use of natural resources.

In addition, reproductive management practices play a vital role in improving the efficiency of cow-calf and full-cycle beef cattle production systems, while also contributing to the genetic progress of the herd. Implementing a defined breeding season, adopting reproductive techniques, and focusing on reproductive and nutritional management practices for heifers and primiparous cows may reduce female reproductive failure (Diskin and Kenny 2014; Moorey and Biase 2020).

Regarding the timing of the breeding season, our data indicates that the breeders choose to schedule it during the rainy summer months (October-March) in the tropical climate zone of the Southern hemisphere. This timing corresponds to the period of abundant and high-quality pasture, which is desired for heifers and cows with increased energy requirements to support gestation (Schmidt et al. 2018). Consequently, the calving season occurs during the dry winter months, providing advantages for the calves by reducing the incidence of diseases (e.g. pneumonia), ticks, and endoparasites (Lorenz et al. 2011; Siqueira et al. 2021).

Many farms reported the adoption of FTAI and embryo transfer alongside the breeding season. In FTAI, ovulation and insemination are synchronized in females using hormonal treatments, allowing for controlled and simultaneous artificial mating (Pursley et al. 1995). This technology enhances reproductive efficiency while allowing breeders to select superior sires within and across different herds (Bó and Baruselli 2014). On the other hand, embryo transfer aims to accelerate genetic progress and optimize breeding outcomes through the collection and transfer of embryos from genetically superior donors to recipient females (Nicholas and Smith 1983).

The lifetime reproductive efficiency of females is closely associated with the reproductive success of heifers (Núñez-Dominguez et al. 1991; Wathes et al. 2014). In this study, the farms exposed their heifers to first breeding at an earlier age, on average, than Brazilian farms raising Nellore females within animal breeding programs (Costa et al. 2020; Mota et al. 2020; Schmidt et al. 2018), including those enrolled in the Embrapa-Geneplus (Ramos et al. 2021). Considering a gestation length of about 292 d (Paschal et al. 1991), the studied heifers are expected to have an age at first calving (AFC) of around 28 mo. This relatively low AFC suggests that the surveyed farms prioritize reproductive management practices aimed at identifying sexually precocious females.

The farms in this study achieved higher conception rates under artificial insemination and at the end of the breeding season compared to commercial farms across South America, as reported by Zoetis and Inttegra. According to the beef cattle FTAI report published by Zoetis (2025), which analyzed data from over 13 million Zebu heifers and cows, the average pregnancy rates for heifers, primiparous cows, and multiparous cows following FTAI are 46.5%, 49.2%, and 54.7%, respectively. Similarly, the benchmark published by Inttegra (2023), which includes data from over 2 million *B. indicus*, *B. taurus* purebreds, and *B. indicus* × *B. taurus* crossbred animals, reports average conception rates at the end of the breeding season of 77.6%, 73.3%, and 79.8% of exposed heifers, primiparous and multiparous cows, respectively. The superior reproductive performance observed in the studied farms might be attributed to effective management practices, including optimized nutrition, reproductive strategies, and health protocols, as well as favorable genetic factors.

Selection of environment and farm management descriptors

The ML method was used to fit and compare the different models. Although REML is commonly preferred for variance component estimation, it is less suitable for comparing models with different fixed effects (Harville 1977; Patterson and Thompson 1971). By using ML, we were able to directly compare the likelihoods of models when the structure of fixed effects is modified, thereby facilitating the evaluation of alternative model specifications. In evaluating goodness-of-fit, we used the change in the farm variance explained by the fixed effect as a complementary criterion to AIC. Information criteria, such as AIC, do not quantify the variance explained by the model (Orelien and Edwards 2008), and are not comparable across different datasets (Nakagawa and Cuthill 2007). Thus, the variance explained by fixed effects provides a direct measure of the model's explanatory power, in addition to the information derived from AIC.

The initial step of selection procedure (Table 3) showed that all evaluated descriptors were associated with YW at the farm level, although some farm management descriptors accounted for small proportion of the YW variance across farms. Among these, heifer supplemental feeding and length of the breeding season, which are factors often related to female fertility (Butler 2014; Deutscher et al. 1991; Moorey and Biase 2020). Thus, while they did not have a relevant association with YW, these factors might still be important in the study of reproduction traits. Likewise, while the production system (grazing or crop-livestock) showed slight importance in the current analysis, several studies have reported the significant role of crop-livestock systems in maintaining productivity, recovering and renewing degraded pastures, and improving grazing animal performance (de Faccio Carvalho et al. 2010; Sekaran et al. 2021; Sulc and Tracy 2007). The integrated crop-livestock system involves complex interactions among soil, plants, animals, management practices, and climate. Future research should explore this system further by incorporating detailed information on factors such as grazing and planting schedules, stocking density (AU/ha), crops and forage types, and other factors.

Overall, most selected descriptors reflected both direct and indirect associations among farm management practices. Guidance from animal breeding technicians, for instance, captured information related not only to established pasture use and supplemental feeding, but also to irrigation, contour farming, fertilization, crop rotation, and IVF. Similarly, heifer age and weight at first breeding served as indicators for multiple management strategies, while adoption of no-till farming reflected broader practices such as crop rotation, fertilization, and production system. These interconnected associations were accounted for during the selection procedure, so that descriptors associated with others were retained as representatives of their groups and subsequently included in the genetic evaluation models for YW, ensuring that the effects of correlated management practices were captured without redundancy.

Regarding the environmental descriptors, the climate classification was weakly associated with YW when evaluated independently, likely due to the narrow distribution of farms across climates zones. The dataset encompassed four of the twelve climate zones observed in Brazil (Alvares et al. 2013), with the tropical savannah climate predominating in both number of farms and recorded animals. To enhance the broadness of these findings, future studies should include farms from a broader range of geographical regions and climate conditions.

Model comparison

The descriptors identified in the selection procedure remained highly relevant within the genetic evaluation framework, with farm management practices and environmental factors explaining a substantial proportion of YW variance across farms. These results highlight key sources of environmental variation commonly accounted for by CG. They provide a robust basis for modeling alternative environmental gradients in the context of GxE, rather than relying on CG-based average performance estimates that do not directly represent environmental information.

In agreement with the findings by Aiken et al. (2020) on forecasting beef production and quality, technical advisory support plays an important role in enhancing production outcomes through strategic decision-making. Specifically, the expert guidance provided by the animal breeding technician is closely associated with soil management practices, supplemental feeding, as well as herd reproductive management (Table 4). Collectively, these decisions can enhance productivity and optimize resource use. These findings suggest that the role of the technician within the Embrapa-Geneplus breeding program extends beyond genetic selection. Technicians might also act as pivotal agents in the dissemination of technologies and knowledge related to production management.

The number of years each farm has been enrolled in the animal breeding program also proved relevant to understanding the environmental variation accounting by the farm in YW. Farms with longer enrollment might be more effective in using genetic evaluation tools to select superior animals, while also leveraging expert guidance from the Embrapa-Geneplus team to support decision-making. In contrast, more recent enrolled farms might still need time to consolidate the use of these tools and realize selection gains, due to the generational interval in beef cattle.

Regarding soil management practices, no-till farming, crop rotation, and contour farming demonstrated varying levels of importance (Table 3). These practices are often implemented jointly with the aim of soil conservation and to sustain forage productive in areas grazed by cattle. No-till farming and contour farming improve soil structure and water-holding capacity, while the cover crops introduced through crop rotation increase soil carbon and nitrogen content, enhancing microbial activity supporting pasture regrowth (Giller et al. 2015). The length of pasture establishment also showed relevant importance in characterizing the farm environment. This variable likely reflects pasture degradation, which often results from prolonged and intensive use without adequate management (Teague et al. 2011). Indeed, the length of pasture establishment was directly associated with fertilization and irrigation, both of which mitigate nutrient leaching and soil degradation, thus contributing the long-term pasture productivity.

Reproductive management, including the age and weight of heifers at first breeding, as well as use of reproductive techniques were also important to explain the YW variation across farms. In practice, heifers are not naturally exposed to reproduction upon reaching reproductive maturity; instead, the timing of their first breeding is typically determined by age and body weight, which may be indicators of physiological maturity and the quality of farm management. Importantly, body weight at first breeding is influenced not only by age but also by farm management practices, including supplementation strategies, forage availability, as well as environmental factors such as climate and seasonal conditions (Day and Nogueira 2013).

Although less influential, livestock land area also helped to explain the environmental variation in YW across farms, potentially due to resource availability. Beef producers with larger grazing areas might have greater capacity to invest in supplemental feed, management practices, veterinary care, and other factors that contribute to higher YW.

Concerning environmental factors, we identified climate, soil classifications, and elevation emerged as relevant descriptors affecting YW. In line with our findings, Aiken et al. (2020) highlighted soil quality as a key predictor of the age at finishing in beef cattle. The quality and quantity of forage available, which are critical for cattle growth and development, are directly influenced by soil characteristics (e.g., levels of nutrients, water retention capacity, and pH level) and management conditions. The climate may affect pasture-based systems by shaping forage growth cycles, availability and nutritional quality (Rojas-Downing et al. 2017). Elevation also plays a significant role in environmental variation. Higher elevations typically result in cooler temperatures and varying precipitation patterns, both of which influence the types of grasses that can grow and their phenological responses (Munson and Long 2017). Cooler temperatures at higher elevations can slow down forage growth but can also reduce the stress on cattle, potentially enhancing growth rates (Godde et al. 2021). Understanding the impact of elevation might be important for optimizing grazing strategies and selecting animals best suited for specific altitudinal ranges. A better understanding of these environmental factors is essential for optimizing grazing management and refining genetic selection to improve cattle performance under diverse regional conditions.

Regarding variance components, the inclusion of the relevant farm-level descriptors did not affect the additive genetic and residual variances in the studied models ($\boldsymbol{M}_2$, $\boldsymbol{M}_3$ or $\boldsymbol{M}_4$). However, the within-farm heritability estimates for YW are slightly lower than the heritabilities reported by Boligon et al. (2010) and Marestone et al. (2022), who used the conventional CG to account for the environmental effects in a Nellore cattle population. Nonetheless, our heritability estimates fall within the range reported by Chiaia et al. (2015) and Oliveira et al. (2018) under the reaction-norm GxE approach.

A suitable characterization of environmental factors is especially important in the context of GxE, as well as for forecasting animal performance under different environmental conditions. Traditionally, these environmental gradients are represented by CG (Cardoso and Tempelman 2012; Chiaia et al. 2015; Mota et al. 2020; Nascimento et al. 2022; Oliveira et al. 2018). However, these studies often lack information on environmental factors and farm-specific management practices, which this study has shown to be a key source of macro-environmental variation. Environmental effects, as well as weather data, can be readily assessed using open-source tools based on remote sensing and geographical information systems, allowing their integration into genetic evaluations within the GxE framework (Costa-Neto et al. 2021; Resende et al. 2021, 2024). On the other hand, understanding farm-specific management practices requires a more targeted approach, such as survey (e.g. Amaral et al. 2024). Surveys conducted directly with beef producers can improve the characterization of farm environments, enabling the integration of this information into the breeding program focused on GxE and providing valuable insights into management practices of farms enrolled in the Embrapa-Geneplus breeding program. Such surveys, however, need periodic updates, as management practices adopted by breeders can change over time. Furthermore, analyzing data from detailed surveys presents challenges, especially when numerous nominal variables are involved. Despite these challenges, surveys could enhance the engagement of beef producers, encouraging their investment in animal breeding programs. Consequently, this increased collaboration might lead to better implementation of recommended practices and more widespread adoption of superior genotypes. Furthermore, leveraging farm-level surveys could help geneticists and breeders gain a better understanding of how environmental factors interact with economically important traits under diverse farming conditions over time. Nonetheless, it is important to note that the results of this study reflect associations between variables and should be interpreted with caution regarding potential causal effects, given the risk of confounding inherent in observational studies (Bello et al. 2018; Rosa and Valente 2013).

Conclusion

An extensive farm-level analysis identified climate and soil classifications, elevation, guidance from animal breeding technician, breeding season period, age and weight of heifers at first calving, no-till farming, reproductive technique, years enrolled in the breeding program, and livestock land area as important for better describing the macro-environmental effects contributing to variation in YW across farms. Among these, the animal breeding technician and no-till farming were significantly associated ($P < 0.05$), either directly or indirectly, with several descriptors related to soil, supplemental feeding, and reproductive management. These findings highlight key sources of environmental variation typically captured by CG in genetic evaluations. Accurate characterization of these environmental factors is particularly important for genetic evaluations involving GxE and for forecasting animal performance under varying environmental conditions.

Supplementary data

Supplementary data are available online at *Translational Animal Science*.

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Disclosures

The authors declare that they do not have any conflict of interest.

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