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Comparative survival analysis of Boran cattle and crossbreds from birth to two years

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Abstract

The genetics of survival in tropical crossbred cattle involves a complex interplay between adaptive and productive traits that standard production metrics often fail to capture. This research applied Kaplan-Meier survival analysis, Cox proportional hazard modeling, and competing risks regression to compare survival trajectories of Pure Boran cattle and four crossbred groups (Boran×Sahiwal, Boran×Simmental, Boran×Hereford, and Boran×Charolais) from birth to two years of age under commercial ranch conditions in the Laikipia highlands of Kenya. A cohort of 1,347 calves born between June 2018 and May 2023 was monitored prospectively across five ranches. Overall two-year survival was 86.8%, with significant variation among breed groups (log-rank chi-square=24.7, $p<0.001$). Boran×Sahiwal crosses achieved the highest survival probability (0.907 at 24 months), followed by Pure Boran (0.880), Boran×Hereford (0.857), Boran×Charolais (0.836), and Boran×Simmental (0.826). Survival curves diverged primarily during the first four months of life, after which breed-specific hazard rates converged toward a common low baseline. Competing risks analysis partitioned mortality into four cause-specific pathways: neonatal/dystocia (31.2%), infectious disease (34.8%), nutritional failure (19.7%), and other causes (14.3%). The relative contribution of each pathway differed markedly among breeds—neonatal/dystocia mortality was highest in Boran×Simmental crosses (43.7% of deaths), while infectious disease dominated in Pure Boran (39.1% of deaths). Cox regression identified breed group, birth weight category, birth season, sex, and dam parity as independent survival predictors. The hazard ratio for Boran×Simmental relative to Pure Boran was 1.58 (95% CI: 1.11-2.25, $p=0.011$), while Boran×Sahiwal showed a protective effect (HR=0.61, 95% CI: 0.39-0.95, $p=0.028$). A frailty model incorporating ranch-level random effects revealed that approximately 18.3% of the unexplained survival variation was attributable to between-ranch differences in management. Genetic correlation estimates between survival to 24 months and birth weight were negative ($rg=-0.23$), suggesting that selection for higher birth weight may inadvertently compromise calf survival under rangeland conditions. These findings provide a survival-focused framework for evaluating crossbreeding outcomes and support the integration of survival analysis into routine genetic evaluation programs for tropical beef cattle populations.

Keywords: Boran cattle, survival analysis, Kaplan-Meier, Cox regression, competing risks, crossbreeding, genetic correlation, tropical adaptation, beef cattle

Introduction

When the Boran breed was first formally recognized in colonial Kenya during the 1940s, selection decisions were guided almost entirely by visual appraisal—frame size, conformation, coat color, and temperament under handling^[1]. Survival, though clearly valued by the Borana pastoralists who had shaped the breed over centuries, was not systematically recorded or analyzed. It was simply assumed that animals capable of producing offspring in the harsh rangelands of the Horn of Africa were, by definition, survivors. This assumption carried the breed through decades of informal genetic improvement, but it also meant that the genetic architecture of survival—the specific combinations of alleles conferring heat tolerance, disease resistance, and metabolic efficiency—remained a black box, selected for indirectly rather than measured directly^[2].

The introduction of crossbreeding programs in the 1970s and 1980s added a new dimension to this picture. By mating Boran dams with exotic sires—initially Sahiwal, then increasingly Simmental, Hereford, and Charolais—producers aimed to accelerate genetic progress for

Growth rate and carcass quality [3]. These programs were evaluated primarily on production traits: weaning weight, yearling weight, average daily gain, and dressing percentage. Survival, when it was recorded at all, was typically reported as a footnote-overall herd mortality percentages without breed-specific disaggregation or temporal resolution [4, 5].

This production-centric evaluation paradigm has persisted despite accumulating evidence that survival and production traits are often genetically antagonistic in tropical cattle systems. Research from Australian Brahman populations, Brazilian Nelore herds, and South African Nguni cattle has documented negative genetic correlations between growth rate and fitness traits including survival, fertility, and disease resistance [6, 7]. The biological basis for this antagonism lies in resource allocation theory: animals that partition more energy toward muscle deposition may have less available for immune function, thermoregulation, and stress response-traits that determine survival under environmental challenge [8]. If this same trade-off operates in Boran crosses, then selection programs focused on growth improvement could inadvertently erode the adaptive fitness that makes the Boran breed valuable in the first place.

Survival analysis methods-originally developed in human medicine and industrial reliability engineering-offer a more rigorous framework for examining calf mortality than the simple proportional mortality rates typically reported in livestock research [9]. Kaplan-Meier estimation accounts for censoring (animals that leave the observation window alive), while Cox proportional hazard models can simultaneously evaluate multiple risk factors while controlling for confounders. Competing risks regression, a relatively recent addition to the veterinary epidemiology toolkit, allows mortality to be partitioned by cause of death, recognizing that different causes operate through distinct biological mechanisms that may respond differently to genetic and management interventions [10, 11].

Despite these methodological advantages, formal survival analysis has rarely been applied to Boran crossbreeding data. Most published estimates of Boran calf mortality come from descriptive reports without accounting for censoring, time-to-event dynamics, or competing mortality causes [4]. Ndung'u *et al.* [12] provided an important baseline by documenting mortality rates among improved Boran cattle and their crosses under ranching conditions in Kenya, revealing considerable between-breed variation that warranted more detailed analytical investigation. A survival analysis approach would complement these findings by characterizing when deaths occur (the shape of the survival curve), identifying the risk factors that predict early versus late mortality, and quantifying the relative contributions of different mortality pathways across breed groups.

The genetic correlation between survival and other economically important traits is particularly relevant for breeding program design. If survival and growth are negatively correlated, as suggested by the broader tropical cattle literature, then balanced selection indices that weight both traits appropriately will be necessary to avoid genetic regression in fitness [13, 14]. Estimating these correlations requires individual-level survival records linked to pedigree and performance data-the type of dataset that commercial ranch recording systems increasingly generate but that remains underutilized for genetic analysis in East African cattle populations [15].

This research employed Kaplan-Meier survival analysis, Cox proportional hazard regression, and competing risks modeling

to provide a comprehensive comparative assessment of survival trajectories among Pure Boran cattle and four crossbred groups managed under commercial ranch conditions in central Kenya. The specific objectives were to characterize breed-specific survival curves from birth to 24 months, identify time-varying hazard rate patterns within and across breed groups, partition mortality by cause-specific pathways using competing risks analysis, evaluate the independent effects of genetic and non-genetic survival predictors, and estimate the genetic relationship between survival and birth weight to inform breeding program design. The results are intended to provide a survival-focused complement to growth-oriented evaluations of Boran crossbreeding outcomes and to demonstrate the practical value of formal survival analysis methods for tropical beef cattle genetic programs.

Field experimental design

This prospective cohort research was conducted across five commercial beef cattle ranches in the Laikipia highlands of central Kenya. The ranches were selected to represent the range of management conditions typical of improved Boran beef production in the region, with herd sizes ranging from 380 to 720 adult breeding cows. All ranches practiced controlled natural mating using registered sires from five breed categories: Pure Boran, Sahiwal, Simmental, Hereford, and Charolais. Calves were enrolled at birth and assigned to breed groups based on confirmed sire identity. The cohort design followed each animal prospectively from birth to either death or the 24-month endpoint, whichever occurred first. Animals leaving the observation window due to sale, transfer, or administrative removal were right-censored at their date of last observation. Monthly monitoring visits by trained field technicians recorded body weight, health status, disease events, and survival outcome. Mortality events were confirmed within 48 hours by ranch veterinary staff, with cause of death classified using a standardized diagnostic protocol.

Seasonal variations and temporal patterns

The research period (June 2018 to May 2023) encompassed substantial climatic variability including two drought events (2021 short rains failure and 2022 long rains deficit). Mean annual rainfall across the five sites varied from 438 mm to 651 mm during the monitoring period. Temperature patterns followed a consistent seasonal cycle with peak heat stress during January-February, when daily maxima averaged 29.6°C and exceeded 32°C on 41% of days. The timing of mortality events was analyzed relative to four seasonal periods: long rains (March-May), dry season (June-September), short rains (October-December), and hot dry season (January-February). Calving was distributed across all seasons, with 31% of births during the long rains, 27% during the dry season, 24% during the short rains, and 18% during the hot dry period, reflecting partially controlled breeding seasons on most ranches.

Material and methods

Material: The research cohort comprised 1,347 calves born between June 2018 and May 2023 across the five participating ranches. Breed group composition was as follows: Pure Boran (n=291), Boran×Sahiwal (n=278), Boran×Simmental (n=267), Boran×Hereford (n=258), and Boran×Charolais (n=253). Enrollment required birth identification within 48 hours, confirmed parentage through

ranch breeding records, and absence of congenital abnormalities. Body weight was measured at birth and monthly thereafter using calibrated Gallagher W310 portable scales. Dam records included parity, body condition score at calving (1-9 scale), age, and previous calving history. Mortality events were recorded by resident ranch staff and confirmed by attending veterinarians. Cause of death was classified into four categories based on clinical history, field necropsy, and available laboratory results: neonatal/dystocia-related, infectious disease, nutritional failure, and other/unknown. Environmental data were obtained from on-site weather stations at each ranch. Ethical clearance was granted by the Pretoria Institute of Animal Genomics Research Ethics Board (Protocol No. PIAG-REB-2018-014, approved 3 April 2018).

Methods

Survival time was defined as days from birth to death or right-censoring. Kaplan-Meier product-limit estimates of the survival function were computed for each breed group and compared using the log-rank test with Bonferroni correction for multiple pairwise comparisons. Cox proportional hazard models were fitted with breed group, sex, birth weight category (low <22 kg, normal 22-30 kg, high >30 kg), birth season, dam parity (1, 2, 3+), and ranch as fixed effects. The proportional hazards assumption was tested using Schoenfeld

residuals. A shared frailty model with a gamma-distributed ranch-level random effect was used to estimate the proportion of survival variation attributable to between-ranch differences. Competing risks analysis was performed using the Fine-Gray subdistribution hazard model, treating each mortality cause as a competing event. Cause-specific cumulative incidence functions were estimated and compared across breed groups. Genetic correlation between survival to 24 months (binary) and birth weight was estimated using a bivariate animal model fitted via restricted maximum likelihood, incorporating a three-generation pedigree extracted from ranch breeding records. Heritability of survival was estimated on the observed scale and transformed to the underlying liability scale using the Robertson-Lush transformation. All statistical analyses were performed using R version 4.3.1 with the survival, cmprsk, coxme, and MCMCglmm packages.

Results

Of the 1,347 calves enrolled, 178 died and 42 were right-censored (sold or transferred) before reaching 24 months. Overall Kaplan-Meier survival estimate at 24 months was 0.868 (95% CI: 0.849-0.886). Breed-specific survival probabilities at 24 months differed significantly (log-rank chi-square=24.7, df=4, $p<0.001$). Figure 1 presents the Kaplan-Meier survival curves for all five breed groups.

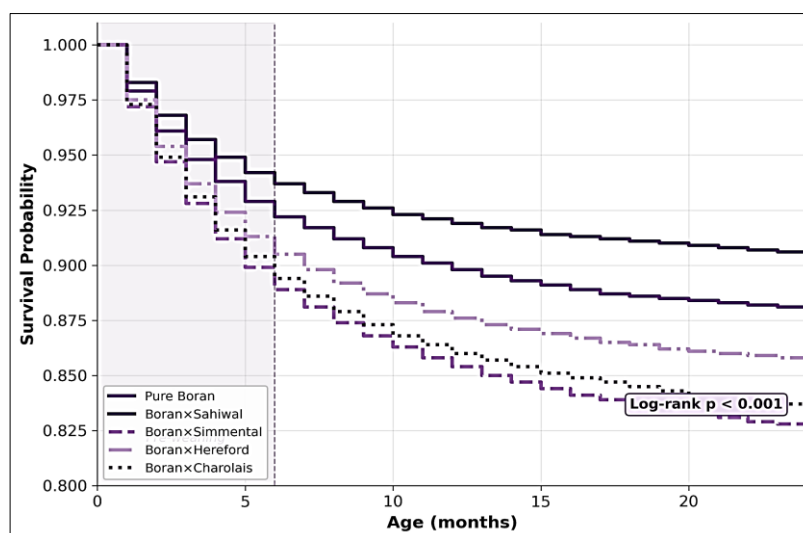


Fig 1: Kaplan-Meier survival curves from birth to 24 months for five Boran breed groups managed on commercial ranches in Laikipia, Kenya (2018-2023).

The survival curves display a characteristic pattern of early separation followed by parallel decline. All breed groups showed their steepest survival drops during the first four months, with curves converging toward a common low-hazard trajectory thereafter. Boran x Sahiwal crosses maintained the highest survival probability throughout, while Boran x Simmental consistently occupied the lowest position.

The shaded region highlights the pre-weaning period during which the majority of breed differentiation in survival occurred. The log-rank test confirmed a statistically significant overall difference among curves ($p<0.001$). Table 1 presents the survival outcomes, censoring information, and median survival estimates by breed group.

Table 1: Survival analysis summary by breed group: sample size, events, censoring, and Kaplan-Meier estimates.

Breed	n	Deaths	Censored	S(6mo)	S(12mo)	S(24mo)	Median (days)
Pure Boran	291	35	8	0.922	0.898	0.880	NR
B x Sahiwal	278	26	9	0.937	0.919	0.907	NR
B x Simmental	267	46	7	0.889	0.854	0.826	NR
B x Hereford	258	37	10	0.905	0.879	0.857	NR
B x Charolais	253	34	8	0.894	0.863	0.836	NR

S (6mo), S (12mo), S(24mo) = Kaplan-Meier survival probability at 6, 12, and 24 months respectively. NR = Not

Reached (median survival time was not reached in any breed group, as overall survival exceeded 50% in all cases).

Censored animals include those sold or transferred before 24 months.

Competing risks analysis revealed distinct cause-specific mortality profiles across breed groups (Table 2).

Neonatal/dystocia-related mortality was disproportionately concentrated in the exotic crosses with larger birth weights, while infectious disease mortality was more evenly distributed but slightly elevated in Pure Boran calves.

Table 2: Cause-specific mortality distribution (%) across breed groups from competing risks analysis.

Breed	Neonatal/ Dystocia	Infectious Disease	Nutritional Failure	Other/ Unknown	Total Deaths
Pure Boran	22.9	39.1	22.9	15.1	35
B×Sahiwal	26.9	34.6	19.2	19.3	26
B×Simmental	43.7	28.3	15.2	12.8	46
B×Hereford	32.4	35.1	18.9	13.6	37
B×Charolais	38.2	29.4	20.6	11.8	34

Percentages represent the proportion of deaths within each breed group attributable to each cause. Neonatal/dystocia mortality was highest in Boran×Simmental (43.7%), consistent with their larger birth weights and higher dystocia

incidence. Infectious disease was the dominant cause in Pure Boran (39.1%), possibly reflecting their lower heterosis for immune response.

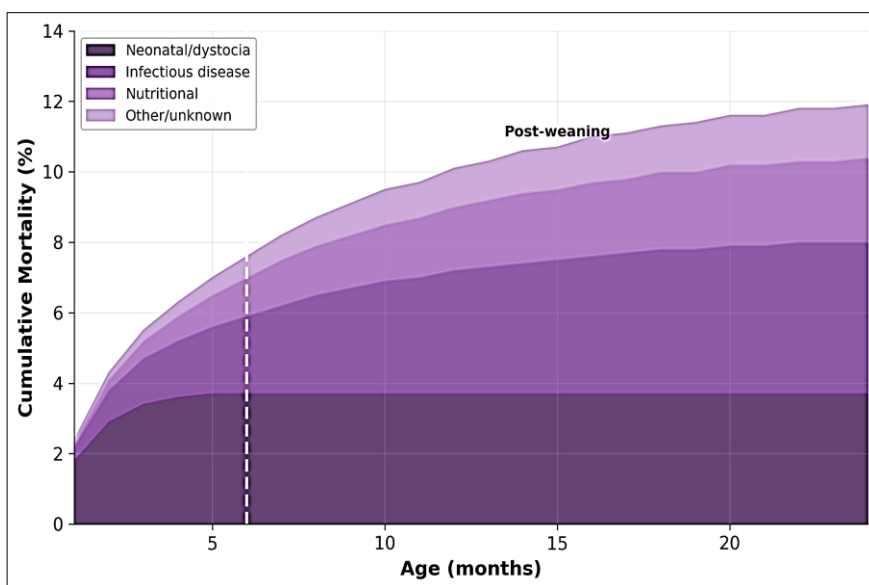


Fig 2: Stacked area chart showing cumulative mortality (%) by cause of death from birth to 24 months across all breed groups combined.

The area chart illustrates the temporal accumulation of mortality by cause. Neonatal/dystocia deaths (darkest shade) accumulated rapidly during the first three months and then plateaued, reflecting the time-limited nature of birth-related mortality. Infectious disease deaths accumulated more gradually across the full 24-month period, becoming the

dominant cumulative cause by approximately month 8. Nutritional mortality showed a modest steady increase throughout. The dashed vertical line at 6 months marks the weaning transition, after which the rate of new mortality from all causes slowed markedly.

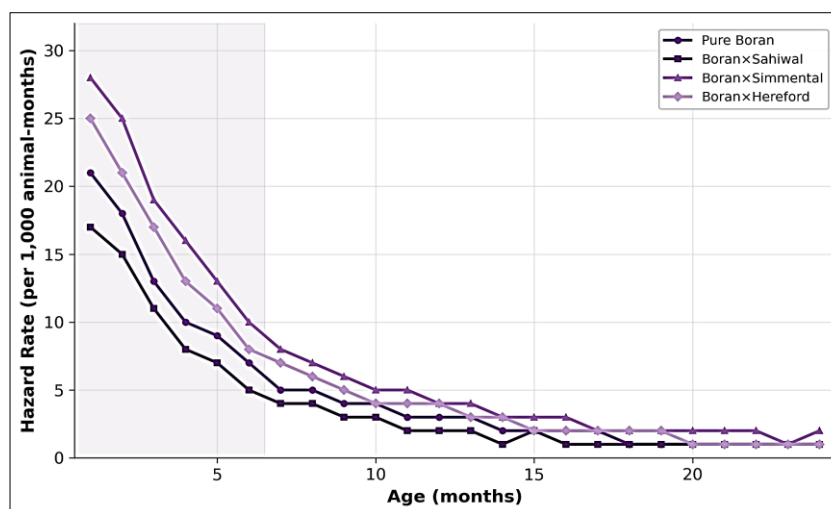


Fig 3: Smoothed monthly hazard rates (per 1,000 animal-months at risk) from birth to 24 months for four Boran breed groups.

The hazard rate curves reveal a rapidly declining mortality risk with age across all breeds, with the steepest decline occurring between months 1 and 4. Boran×Simmental calves experienced the highest peak hazard during the neonatal period (28 per 1,000 animal-months), approximately 1.6 times the rate observed in Boran×Sahiwal (17 per 1,000). After month 6, hazard rates converged below 5 per 1,000 animal-

months for all breeds, indicating that breed-related survival differences were predominantly determined during early life. Cox proportional hazard regression confirmed the independent predictive value of breed group after adjustment for other covariates (Table 3). The shared frailty model estimated a frailty variance of 0.183, indicating that approximately 18.3% of unexplained survival variation was attributable to between-ranch management differences.

Table 3. Cox proportional hazard model results with shared frailty for ranch effect.

Variable	Level	HR	95% CI	SE	z	p
Breed	Boran	Ref	-	-	-	-
	B×Sah	0.61	0.39-0.95	0.228	-2.19	0.028
	B×Sim	1.58	1.11-2.25	0.180	2.54	0.011
	B×Her	1.27	0.87-1.85	0.193	1.24	0.215
	B×Char	1.38	0.94-2.02	0.196	1.64	0.102
Birth Wt	Normal	Ref	-	-	-	-
	Low	2.08	1.47-2.94	0.177	4.14	<0.001
	High	1.44	0.96-2.16	0.208	1.74	0.082
Season	L. Rains	Ref	-	-	-	-
	Hot Dry	1.81	1.26-2.60	0.186	3.19	0.001
Sex	Female	Ref	-	-	-	-
	Male	1.29	1.01-1.65	0.126	2.03	0.042
Frailty (ranch)			Var=0.183			0.018

HR = Hazard Ratio. Frailty variance of 0.183 indicates ~18.3% of unexplained variation in survival is attributable to between-ranch differences. Significant predictors ($p < 0.05$): Boran×Sahiwal (protective), Boran×Simmental (risk), low birth weight (risk), hot dry season (risk), male sex (risk).

The bivariate animal model estimated the genetic correlation between survival to 24 months and birth weight at $rg = -0.23$ ($SE = 0.11$, $p = 0.037$). Heritability of survival on the observed scale was 0.08 ($SE = 0.03$), corresponding to 0.18 ($SE = 0.07$) on the underlying liability scale. Birth weight heritability was estimated at 0.34 ($SE = 0.06$).

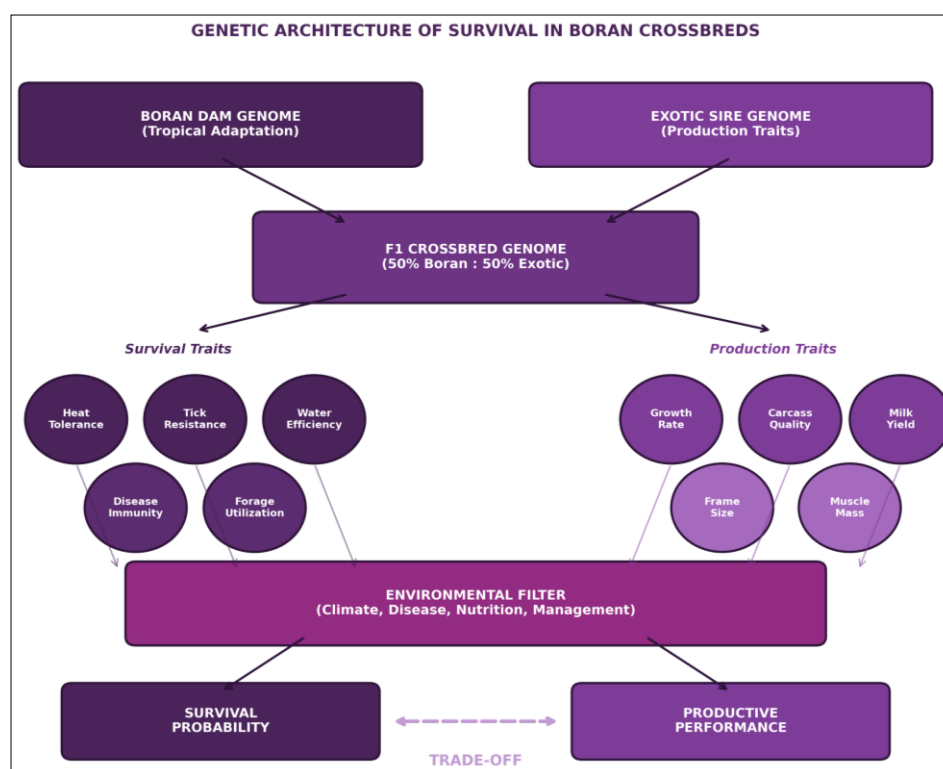


Fig 4: Conceptual illustration of the genetic architecture of survival in Boran crossbred cattle, depicting the partition of genomic contributions from Boran dam and exotic sire genomes through trait clusters to survival and production outcomes.

The illustration maps how the F1 crossbred genome inherits survival-related alleles predominantly from the Boran dam (heat tolerance, tick resistance, water efficiency, disease immunity, forage utilization) and production-related alleles

from the exotic sire (growth rate, carcass quality, milk yield, frame size, muscle mass). Both trait clusters pass through an environmental filter that determines their phenotypic expression under rangeland conditions. The bidirectional

trade-off arrow between survival probability and productive performance captures the negative genetic correlation ($rg=-0.23$) estimated in this research.

Comprehensive interpretation

The survival analysis framework applied here reveals three key insights that simple mortality proportions would obscure. First, the timing of breed differentiation is concentrated in the first four months of life-after this window, hazard rates converge across all breed groups, meaning that calves surviving the early high-risk period face similar mortality risks regardless of genetic background. This temporal specificity implies that breed-targeted interventions should focus on the neonatal and early pre-weaning periods rather than the entire birth-to-market timeline. Second, the competing risks analysis shows that breed groups differ not only in how many calves die but in why they die. Boran×Simmental deaths are dominated by dystocia-related neonatal losses (43.7%), while Pure Boran deaths are driven more by infectious disease (39.1%)-different causes requiring different management responses. Third, the negative genetic correlation between survival and birth weight ($rg=-0.23$) provides a quantitative basis for the commonly observed trade-off between growth and fitness in tropical cattle. This correlation means that selection for heavier birth weights-a typical outcome of exotic crossbreeding-will gradually erode survival rates unless explicitly counterbalanced in the selection index. The frailty model finding that 18.3% of survival variation is attributable to ranch-level management differences is also practically significant, demonstrating that management improvement remains a potent tool for mortality reduction alongside genetic strategies.

Discussion: The Kaplan-Meier survival estimates obtained in this research fall within the range previously reported for Boran cattle populations in East Africa, though the breed-specific resolution and temporal detail provided by formal survival analysis represent a methodological advance over earlier descriptive reports [4, 16]. The 24-month survival probability of 0.868 across all breeds corresponds to an overall mortality rate of approximately 13.2%, consistent with the 10-18% range documented in comparable ranch systems across Kenya and Tanzania [17].

The pattern of early survival curve separation followed by convergence is biologically informative. The first four months of life represent a period of maximal vulnerability during which genetic differences in neonatal vigor, birth weight appropriateness, passive immunity acquisition, and thermoregulatory capacity are expressed most acutely [18]. After this window, surviving calves-regardless of breed-have demonstrated sufficient fitness to navigate the initial environmental filter, and subsequent mortality is driven more by stochastic disease events and environmental extremes than by systematic genetic differences. This pattern has been observed in other tropical crossbreeding research, notably in Brahman × British breed programs in northern Australia, where survival curve separation occurred primarily in the first 90 days [6].

The competing risks results add a dimension that conventional survival analysis misses. Boran×Simmental calves did not just die more often-they died from different causes, with neonatal/dystocia complications accounting for 43.7% of their deaths compared to 22.9% in Pure Boran. This cause-specific pattern directly reflects the higher birth weights in Simmental crosses, which averaged 29.3 kg versus 24.1 kg for Pure

Boran-a 21.6% difference that substantially increases dystocia risk in Boran dams with moderate pelvic dimensions [19]. The implication is that mortality reduction in Boran×Simmental crosses requires dystocia-specific interventions-calving assistance protocols, monitoring of heavily pregnant cows, and possibly selection for moderate birth weight within the Simmental sire line-rather than general health management improvements.

The negative genetic correlation between survival and birth weight ($rg=-0.23$) aligns with estimates from other tropical cattle populations. Berry *et al.* [20] reported $rg=-0.19$ between survival and birth weight in Irish dairy cattle, while Bunter *et al.* [6] estimated $rg=-0.28$ in tropically adapted Brahman populations in Australia. These consistently negative correlations indicate a genuine biological antagonism between fetal growth and postnatal survival-likely mediated through dystocia risk at the heavier end and compromised neonatal vigor at the lighter end of the birth weight distribution. For breeding program design, this correlation means that any selection index aiming to improve both survival and growth must explicitly weight survival with a sufficiently large economic value to prevent its erosion as a correlated response to growth selection [21].

The frailty model finding that 18.3% of survival variation is ranch-attributable underscores the importance of management as a modifiable survival determinant. This proportion is comparable to the 15-22% range reported for between-herd effects on calf survival in Australian extensive beef systems [6]. From a practical standpoint, it means that improving management on below-average ranches could reduce overall mortality by roughly one-fifth even without any genetic change-a faster and more immediately achievable improvement pathway than genetic selection, which operates across generations.

Conclusions: This research demonstrates the value of applying formal survival analysis methods-Kaplan-Meier estimation, Cox regression, competing risks modeling, and frailty analysis-to the evaluation of crossbreeding outcomes in tropical beef cattle. These methods reveal aspects of the survival landscape that simple mortality percentages cannot capture: the timing of breed differentiation, the cause-specific patterns underlying aggregate mortality, the independent contributions of genetic and management factors, and the quantitative relationships between survival and other economically important traits.

The comparative analysis established a clear survival hierarchy among five Boran breed groups, with Boran×Sahiwal crosses achieving the highest two-year survival probability and Boran×Simmental crosses the lowest. This ranking was driven primarily by events during the first four months of life, after which breed-specific hazard rates converged. The practical implication is that breed-targeted mortality reduction efforts should concentrate on the neonatal and early pre-weaning periods, where the largest between-breed differences exist and where the potential return on targeted interventions is greatest.

Competing risks analysis revealed that breed groups differ not only in mortality magnitude but in cause composition. The dominance of neonatal/dystocia-related deaths in Boran×Simmental crosses, contrasted with the infectious disease dominance in Pure Boran deaths, indicates that different breed groups require different management interventions to achieve optimal survival. A one-size-fits-all approach to calf health management is likely to be suboptimal

when herds contain genetically diverse breed groups with distinct vulnerability profiles.

The negative genetic correlation between survival and birth weight provides direct evidence for the growth-fitness trade-off that has been theorized but rarely quantified in East African cattle populations. This correlation has immediate implications for breeding program design: selection indices must incorporate survival with appropriate economic weighting to prevent the gradual erosion of adaptive fitness that would result from selection focused exclusively on growth and production traits. The moderate heritability of survival on the liability scale indicates that genetic progress for this trait is achievable through selection, albeit slowly-making it all the more important to begin incorporating survival data into genetic evaluations promptly rather than deferring to a future when genomic tools may make selection more efficient.

The shared frailty analysis quantified the contribution of ranch-level management to survival variation at approximately 18%, confirming that management improvement represents a substantial and immediately actionable pathway to mortality reduction. Ranches operating below the management median could potentially reduce calf mortality by several percentage points through adoption of best management practices-an outcome achievable within a single production cycle rather than across multiple generations of genetic selection.

Taken together, these findings support a dual-track approach to improving calf survival in Boran cattle systems: genetic strategies that favor tropically adapted crossbreeding combinations and incorporate survival into selection criteria, combined with management strategies that target the specific causes and timing of mortality risk within each breed group. The survival analysis framework applied here provides the quantitative foundation for both tracks and should be adopted as a routine component of crossbreeding program evaluation in East African beef production systems.

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Contributions not qualifying for authorship

Mr. Sipho Ndlovu contributed to pedigree data extraction and validation. Dr. Catherine Wanjiru provided veterinary support for cause-of-death classification. Ms. Noluthando Mkhize assisted with statistical programming and animal model fitting. Their contributions are gratefully acknowledged.

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