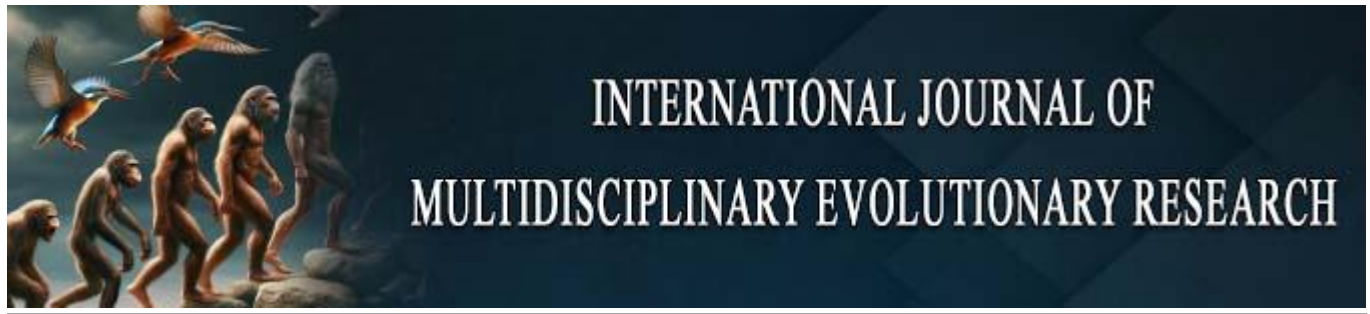




From Genetic Merit to System Fit: Rethinking Genetic Improvement under Livestock-System Uncertainty

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Abstract

Climate change creates complex challenges for smallholder livestock systems in which livestock simultaneously contribute to food production, income, savings, risk management and other household functions. Genetic improvement is increasingly recognised as a component of climate adaptation, with contemporary breeding approaches incorporating environmental heterogeneity, farmer preferences, resilience and changing production conditions. However, climate and socioeconomic change may alter not only the environments in which animals perform but also the configuration of livestock systems themselves through changes in species, breeds, herd or flock structure, enterprise combinations and management. This creates a conceptual problem for future-oriented genetic improvement when the future system for which animals are being improved is itself uncertain. This paper develops a conceptual framework for breeding-objective robustness under future livestock-system uncertainty, drawing together genotype $\times$ environment interaction, breeding-objective theory, climate-resilient breeding, community-based breeding, livestock diversification and decision-making under uncertainty. The framework positions future livestock-system configuration and function as an intermediate domain between climate adaptation and genetic-improvement planning. It proposes that where multiple future system configurations are plausible, breeding objectives should be evaluated for robustness across alternative trajectories rather than solely optimised for a single anticipated future. Where uncertainty is deep and alternative objectives diverge substantially, maintaining genetic diversity and the capacity to revise objectives may provide greater strategic flexibility than early narrow commitment. The conceptual contribution is to make uncertainty about future livestock-system configuration an explicit consideration in genetic-improvement planning and to connect this uncertainty with breeding-objective robustness and strategic genetic flexibility.

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Keywords: breeding objectives, genetic improvement, livestock systems, climate adaptation, genetic diversity, genotype $\times$ environment interaction, decision-making under uncertainty

1. Introduction

Genetic improvement is inherently oriented towards the future. Breeding programmes select animals today because their descendants are expected to perform under production conditions that will exist years or, in some cases, decades later. Consequently, breeding objectives necessarily incorporate expectations concerning future production environments, market conditions, management practices, farmer priorities and the functions that livestock will perform within production systems.

Contemporary livestock breeding increasingly recognises this forward-looking character through the incorporation of functional traits, resilience, farmer preferences, environmental heterogeneity and production-system considerations (Cassandro, 2020; Mrode *et al.*, 2026) ^[1, 5].

This future orientation becomes increasingly challenging under climate and socioeconomic change. Environmental conditions affecting livestock production may become more variable, while feed and water availability, disease pressures, markets, institutions and access to productive resources may also change. Genotype $\times$ environment interaction (G $\times$ E) research demonstrates that genetic performance and ranking can differ across environmental gradients, reinforcing the importance of considering the environments in which genetic improvement is expected to operate (Rovelli *et al.*, 2020; Silva Neto *et al.*, 2024) ^[7, 9]. Climate-oriented breeding therefore increasingly seeks animals capable of maintaining desirable performance under heterogeneous and changing conditions.

Yet environmental change does not necessarily leave the livestock production system itself unchanged. Households may respond to climatic and socioeconomic pressures through changes in livestock species, breeds, herd or flock structure, enterprise combinations, management arrangements and the relative importance assigned to different livestock functions. Recent evidence from smallholder systems illustrates how livestock portfolios can change in response to climatic conditions and interacting household considerations (Manyike *et al.*, 2026) ^[4]. Broader research on animal genetic resources has similarly recognised that livestock production systems are dynamic and that uncertainty about future system requirements has implications for the genetic resources that should be maintained (Seré *et al.*, 2008) ^[8].

This distinction introduces a problem that is related to, but analytically different from, uncertainty about the environment in which animals will perform. A breeding programme may be designed for a projected future climate, yet the livestock system through which households respond to that climate may also change. If species composition, enterprise structure, management arrangements or livestock functions change, the relative value assigned to particular genetic attributes may change with them. The issue is therefore not simply whether animals are genetically suited to a changing environment, but whether the breeding objective itself remains appropriate for the livestock system that emerges.

This issue is particularly revealing in smallholder systems where livestock commonly serve multiple functions simultaneously. Livestock may contribute to food, income, savings, manure, draught power, social obligations, risk management and asset accumulation. The relative importance of these functions can change as household resources, markets, climate risks and institutional conditions change. Community-based breeding programmes have demonstrated the importance of incorporating farmer-defined objectives and production-system realities into genetic improvement, particularly in low-input systems (Haile *et al.*, 2023) ^[3]. However, incorporating current farmer priorities does not by itself resolve the problem of uncertainty about how those priorities and the systems through which they are pursued may evolve.

The problem should not be interpreted as evidence that existing breeding science ignores production systems. Breeding-objective theory is explicitly future-oriented, and research has long recognised uncertainty surrounding future economic objectives and the value of maintaining alternative breeding stocks (Smith, 1985) ^[11]. Similarly, livestock genetic-resource research has recognised changing production systems, uncertainty over future requirements and the importance of maintaining genetic options (Seré *et al.*, 2008) ^[8]. The conceptual issue addressed here is narrower: how should breeding objectives be evaluated when the future livestock-system configuration for which genetic improvement is intended is itself uncertain?

The framework does not replace G $\times$ E analysis; rather, it places G $\times$ E within a broader decision context in which the future livestock system may itself be incompletely specified. G $\times$ E addresses differences in genetic performance across specified or characterised environments, whereas the present framework additionally considers uncertainty about the livestock system that future genetic improvement is intended to serve.

The conceptual contribution lies not in introducing climate-resilient breeding, breeding-objective theory, genotype $\times$ environment interaction, livestock diversification, community-based breeding or robust decision-making as new ideas. Previous research has recognised that breeding objectives are future-oriented, that alternative genetic strategies can preserve future options, and that livestock systems and their functions may change under environmental and socioeconomic pressures. The contribution developed here is to connect these established domains through an explicit analytical pathway in which uncertainty about future livestock-system configuration and function becomes an intermediate consideration in breeding-objective planning. This shifts attention from asking only which genotypes are expected to perform best under anticipated environments to asking whether the objectives used to define genetic improvement remain appropriate across alternative plausible future livestock-system configurations. The framework consequently provides a basis for distinguishing situations in which breeding objectives can be optimised from those in which robustness should be assessed or strategic genetic flexibility retained.

2. Genetic Improvement for Future Environments

The future orientation of genetic improvement is fundamental to breeding-objective formulation. A breeding objective defines the characteristics that genetic improvement seeks to change because they are expected to contribute to the desired future performance of the production system. Consequently, breeding objectives cannot be separated completely from assumptions about future production conditions, economic values, management practices and farmer priorities.

Recent work on African breeding programmes emphasises that breeding goals should be aligned with production systems, farmer participation and changing socioeconomic and environmental conditions (Mrode *et al.*, 2026) ^[5]. Community-based breeding programmes similarly demonstrate that genetic improvement can be designed around locally defined production objectives and the constraints of low-input systems (Haile *et al.*, 2023) ^[3]. Such

approaches represent an important movement away from narrow emphasis on single production traits towards broader definitions of livestock value.

Climate change adds another dimension because future production environments may differ substantially from those under which current genetic evaluations are conducted. Phenotypic plasticity and G×E provide important biological and statistical foundations for understanding how genetic performance responds to environmental heterogeneity (Rovelli *et al.*, 2020; Silva Neto *et al.*, 2024)^[7,9]. In livestock populations, differences in temperature, nutrition, disease exposure, management and production conditions can modify genetic expression and ranking.

These developments support breeding strategies that consider resilience and adaptation rather than maximising performance under a single favourable environment. However, the environmental perspective generally begins with an anticipated production objective and then asks which genetic attributes will allow animals to perform under the relevant environmental conditions.

The conceptual problem considered here arises when the production objective itself is uncertain. For example, an animal selected primarily for high milk production may be appropriate where a future household continues to operate a specialised dairy enterprise with adequate feed and market access. The same household, however, might respond to increasing feed costs, water scarcity, labour constraints or market instability by changing herd composition, reducing specialisation or placing greater value on multifunctionality. Under such circumstances, the genetic attributes considered valuable may extend beyond maximum milk yield to include fertility, survival, feed efficiency, disease tolerance, body condition maintenance or other functional characteristics.

The example does not imply that a particular climate trajectory necessarily produces a predetermined livestock transition. Rather, it illustrates that the relationship between environmental change and genetic value is mediated by the production system. This suggests that climate-resilient breeding should consider not only the expected environmental conditions but also uncertainty about the future production system through which livestock will be used.

3. Climate Adaptation as Livestock-System Reconfiguration

Climate adaptation in livestock systems is frequently discussed in terms of changes in management, feeding, housing, breeding or resource use. These remain important dimensions of adaptation. However, adaptation may also involve changes in the composition and organisation of the livestock enterprise itself.

Livestock-system reconfiguration refers to changes in the composition, organisation or functional role of livestock within a production system, including changes in species or breed composition, herd or flock structure, enterprise combinations, management arrangements and the relative importance of livestock functions. It does not imply a predetermined climate-driven transition.

Household responses are conditioned by resource availability, markets, institutions, gender relations, knowledge systems, cultural priorities and other socioeconomic circumstances. System reconfiguration need

not reflect deliberate optimisation by households; it may emerge incrementally through constrained adaptation, experimentation, shocks, institutional change and changing resource or market conditions.

Evidence from smallholder systems demonstrates that livestock species choices can respond to climatic and socioeconomic pressures and that species may function as part of an interdependent livestock portfolio rather than as isolated enterprises (Manyike *et al.*, 2026)^[4]. This reinforces the importance of analysing livestock systems as dynamic combinations rather than assuming that individual species or breeds operate within permanently fixed production arrangements.

Research on animal genetic resources reached a related conclusion from a different direction. Seré *et al.* (2008)^[8] highlighted the dynamics of livestock production systems and the uncertainty surrounding future requirements for animal genetic resources. Their argument reinforces the importance of maintaining genetic options when future production systems cannot be known with certainty.

If livestock-system configuration changes, the functions expected from livestock may also change. A change in enterprise structure may increase the value of reproductive efficiency, survival or multifunctionality relative to maximum output of a single commodity. Conversely, improved market access or increased production opportunities may increase the value of specialised productivity.

System reconfiguration does not mechanically determine genetic requirements. Rather, changes in system configuration may alter the relative importance of livestock functions, which in turn can change the attributes considered valuable within a breeding objective.

4. From Future System Functions to Genetic Requirements

Livestock contribute to household livelihoods through multiple functions, and these functions need not remain constant over time. The genetic attributes valued within a breeding programme are consequently related not only to biological performance but also to the functions animals are expected to perform.

This relationship can be represented conceptually as: future system configuration → future system functions → functional requirements → genetic requirements. The sequence is analytical rather than deterministic.

Consider a household that uses cattle simultaneously for milk, savings, reproduction and risk management. If the production system becomes increasingly specialised, milk yield may acquire greater relative importance. If market access deteriorates and feed costs increase, survival, reproductive efficiency and resource-use efficiency may become relatively more important. If the household increasingly relies on livestock as a financial buffer, attributes associated with longevity, reproductive stability or asset value may receive greater weight.

The same genetic population can therefore be evaluated differently depending on the system functions it is expected to fulfil. This does not imply that farmer preferences alone determine genetic value. Breeding objectives may incorporate biological, economic, environmental and societal considerations. Nor does it imply that indigenous breeds are

inherently superior or that specialised breeds are inappropriate. The relevant question is the relationship between genetic attributes and the functions required by the future production system.

Community-based breeding provides an important empirical foundation for this reasoning because farmers and other local actors participate in identifying relevant breeding priorities within their production systems (Haile *et al.*, 2023) ^[3]. African breeding-goal research similarly emphasises production-system relevance and the need for continuous evaluation as production conditions and societal demands change (Mrode *et al.*, 2026) ^[5].

The additional question is what happens when the future production system cannot be represented adequately by one anticipated trajectory.

5. Breeding-Objective Robustness under Future Livestock-System Uncertainty

The conventional formulation of a breeding objective requires assumptions about the future conditions under which improved animals will be used. Under relatively stable conditions, these assumptions may be sufficiently reliable to support optimisation.

Where the future production system is sufficiently specified, breeding objectives can be designed to maximise expected performance against the anticipated trajectory. This remains an entirely appropriate strategy. The framework does not argue that robustness should replace optimisation.

Where several plausible future livestock-system configurations exist, a breeding objective designed for only one trajectory may be vulnerable if the system develops differently. In this situation, breeding objectives can instead be assessed according to their performance across alternative plausible configurations. The objective is not necessarily to identify the single best outcome in every scenario, but to avoid excessive dependence on an uncertain assumption about the future system.

Robustness is treated here as an established decision logic rather than as a new theoretical construct. Its specific application is to the evaluation of breeding objectives across alternative plausible future livestock-system configurations. Where uncertainty is sufficiently deep that credible future configurations imply substantially different breeding objectives, selecting narrowly for one trajectory may reduce future options. Strategic flexibility refers to the capacity to retain genetic alternatives and revise breeding objectives as information about future system conditions changes.

Maintaining genetic diversity can therefore function as an option value under uncertainty. Alternative genetic resources,

populations, lines or breeding pathways may preserve the ability to redirect breeding programmes as information improves. This does not imply that maintaining all genetic alternatives is costless or universally optimal. Genetic conservation, population maintenance and broader breeding portfolios require resources. Strategic flexibility becomes particularly relevant where uncertainty is deep, and the costs of premature commitment are potentially high.

The resulting decision rule is: optimisation under specification, robustness under plurality and flexibility under deep uncertainty.

6. Integrated Conceptual Framework

The framework integrates the preceding arguments into a single analytical pathway. Climate and socioeconomic uncertainty may contribute to livestock-system reconfiguration, altering the relative importance of livestock functions and, consequently, the genetic attributes prioritised within breeding objectives.

The framework can be represented as: Climate + socioeconomic change → resource and livelihood uncertainty → livestock-system reconfiguration → future livestock-system functions → functional requirements → genetic requirements → breeding-objective design → optimisation / robustness / flexibility → genetic strategy → future livestock-system performance → household and system outcomes.

The feedback component is important because breeding objectives are not permanently fixed. Monitoring changes in system conditions, farmer priorities, markets and environmental pressures can provide information for revising breeding objectives.

Gender relations, Indigenous and local knowledge, markets, institutions and resource access operate across this pathway. They influence which adaptation options are feasible, which livestock functions are prioritised and which genetic strategies can be implemented. They are therefore conditioning dimensions rather than additional sequential stages.

The relationships developed above are integrated in a conceptual framework that links climate and socioeconomic uncertainty to livestock-system reconfiguration, changing system functions, genetic requirements and breeding-objective design. The framework further distinguishes between optimisation where the future system is sufficiently specified, robustness assessment where multiple plausible configurations exist, and strategic flexibility where uncertainty is deep and alternative breeding objectives diverge substantially (Fig. 1).

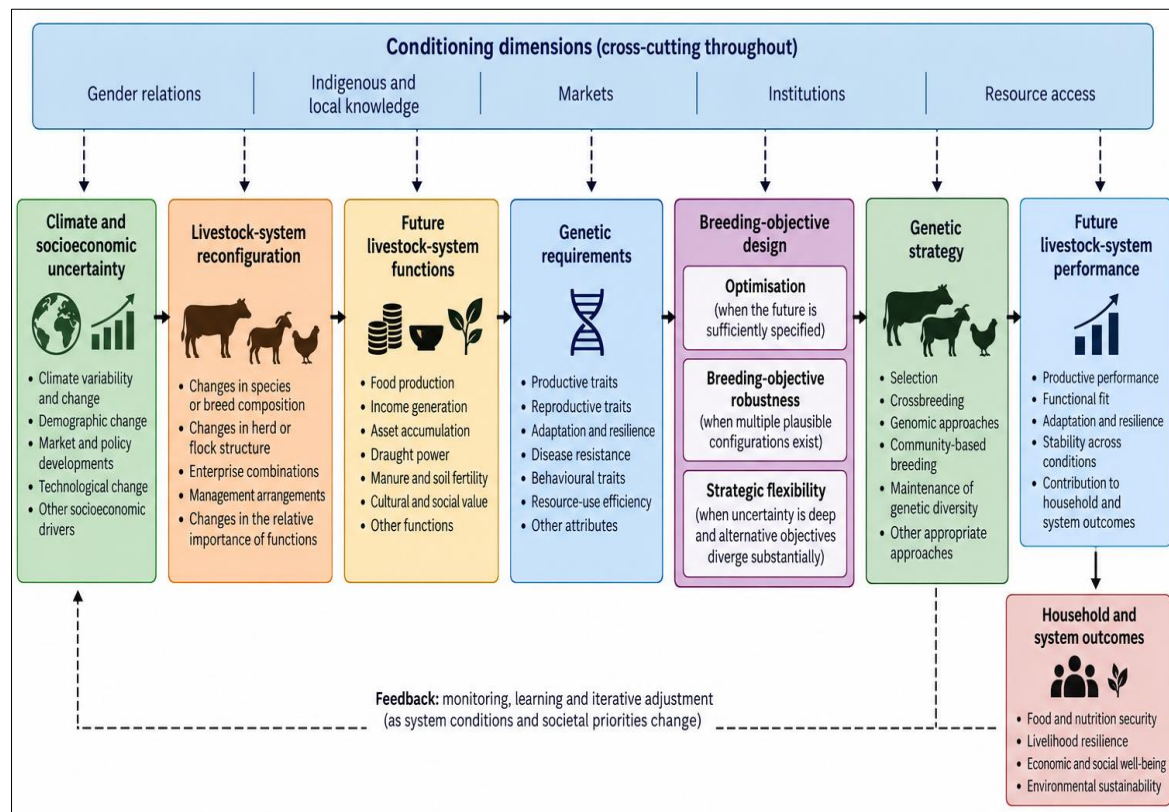


Fig 1: A conceptual framework for breeding-objective robustness under future livestock-system uncertainty. Climate and socioeconomic uncertainty may contribute to livestock-system reconfiguration, altering the relative importance of livestock functions and, consequently, the genetic attributes prioritised within breeding objectives. Where future system configurations are sufficiently specified, objectives may be optimised; where multiple plausible configurations exist, objectives can be assessed for robustness; and where uncertainty is deep and alternative objectives diverge substantially, maintaining genetic diversity and the capacity to revise objectives may provide strategic flexibility. Gender relations, Indigenous and local knowledge, markets, institutions and resource access condition these processes rather than constituting separate sequential stages. Feedback represents monitoring, learning and iterative adjustment as system conditions and societal priorities change.

Six Propositions

P1. System reconfiguration: Climate and socioeconomic change can alter livestock-system configuration rather than merely changing environmental conditions under which existing populations perform.

P2. Functional mediation: Changes in livestock-system configuration can alter the relative importance of livestock functions within household livelihoods.

P3. Genetic translation: Changes in the relative importance of livestock functions can alter the relative importance of genetic attributes and influence breeding-objective priorities.

P4. Objective robustness: Where multiple future configurations are plausible, breeding objectives should be evaluated for robustness across those configurations rather than solely against a single anticipated production trajectory.

P5. Temporal alignment: Where livestock-system reconfiguration occurs more rapidly than genetic change, temporal mismatch may increase the risk of misalignment between breeding objectives and emerging system functions.

P6. Strategic flexibility: Where uncertainty is deep and alternative breeding objectives diverge substantially, maintaining genetic diversity and the capacity to revise breeding objectives may provide greater strategic flexibility than early narrow commitment.

7. Implications for Genetic Improvement

The framework has several implications for breeding programme design. First, where future system uncertainty is

substantial, breeding objectives could be evaluated against more than one plausible livestock-system trajectory. Scenario analysis could vary species composition, enterprise specialisation, feed-resource availability, market orientation, household labour, disease pressure, environmental stress and the relative importance of livestock functions. The objective would not be to predict the future precisely, but to examine whether breeding priorities remain desirable across plausible alternatives.

Second, genetic evaluation and breeding-objective formulation should remain conceptually distinct. Genetic evaluation estimates genetic merit using available data and specified models. Breeding-objective formulation determines which attributes should contribute to the desired direction of genetic change. A future-system uncertainty framework therefore does not necessarily require a new genetic evaluation method. Instead, it may change the decision environment in which genetic evaluations are interpreted and used. G×E remains essential where environmental heterogeneity affects genetic expression and ranking.

Third, community-based breeding programmes provide an established pathway through which farmer priorities and production-system conditions can inform breeding objectives. The framework extends the temporal question by asking whether those objectives remain appropriate as the production system itself changes (Haile *et al.*, 2023) [3].

Fourth, genetic diversity can be understood as a resource for maintaining future breeding choices. The value of retaining

alternatives may increase when future system uncertainty is high, alternative breeding objectives differ substantially, genetic change is difficult to reverse, future information is expected to improve and premature selection could narrow future options (Smith, 1985; Seré *et al.*, 2008)^[11, 8].

Smallholder livestock systems in sub-Saharan Africa provide a revealing context for examining these relationships because livestock commonly perform multiple functions while production is influenced by interacting climatic, resource, market, institutional and household conditions. The conceptual problem is not unique to the region; rather, these systems make particularly visible the possibility that changes in system configuration and function can alter the assumptions underlying genetic-improvement decisions.

8. Empirical Research Agenda

The framework is intended to generate empirical hypotheses rather than provide an empirically validated robustness metric. Longitudinal research could examine whether changes in climate, markets, resources and institutions are associated with measurable changes in livestock-system configuration.

Studies could examine whether changes in livestock-system configuration correspond with changes in the relative importance households assign to production, reproduction, survival, income, savings, risk management and other livestock functions.

Researchers could assess whether changes in livestock functions are reflected in changes in farmer-defined or economically derived breeding objectives.

Alternative livestock-system scenarios could be developed and used to compare breeding objectives across plausible futures. This would allow researchers to ask whether an objective that is optimal under one trajectory remains satisfactory across others.

Longitudinal data could examine whether livestock-system reconfiguration occurs more rapidly than measurable genetic change and whether such divergence creates observable misalignment between breeding objectives and system functions.

Finally, the economic and biological value of maintaining alternative genetic resources could be examined under different levels of uncertainty and different degrees of divergence between future breeding objectives. These empirical applications would transform the framework from conceptual propositions into testable decision-support approaches.

9. Limitations and Boundary Conditions

Several limitations define the boundaries of the framework. First, future livestock-system configurations cannot be predicted with certainty. The framework therefore does not assume that scenario analysis will identify the actual future system. Its purpose is to make uncertainty explicit in breeding-objective planning.

Second, system reconfiguration is not deterministic. Similar environmental pressures may produce different household responses depending on resources, institutions, markets, knowledge and social relations.

Third, livestock-system configuration does not mechanically determine genetic requirements. The proposed pathway is mediated through changing livestock functions and the values assigned to different genetic attributes.

Fourth, robustness is not universally preferable to

optimisation. Where future conditions are sufficiently specified, optimisation may remain the most appropriate strategy. Robustness becomes more relevant when multiple plausible futures exist.

Fifth, strategic flexibility has costs. Maintaining alternative genetic resources and preserving the capacity to revise breeding objectives require investment. The framework therefore does not imply that maximum genetic diversity is always economically optimal.

Sixth, the framework does not provide a quantitative measure of robustness. Empirical work is required to develop operational metrics capable of comparing breeding objectives across alternative livestock-system trajectories.

Finally, the framework is most relevant where future uncertainty is consequential enough to affect production-system configuration or the functions livestock perform. Its value may therefore be lower in relatively stable and highly specified production systems.

The framework should not be interpreted as implying that uncertainty necessarily favours broader or more conservative breeding objectives. Where future system conditions are sufficiently specified, optimisation may remain appropriate. The relevance of robustness and strategic flexibility increases with the number and divergence of plausible future system configurations and with the potential costs of premature genetic commitment.

10. Conclusions

Climate-resilient livestock genetic improvement is necessarily future-oriented, but the future for which breeding programmes are designed may be less certain than is often assumed. Existing approaches to genotype × environment interaction, breeding-objective formulation, climate-resilient breeding and community-based breeding provide strong foundations for incorporating environmental heterogeneity, farmer priorities and anticipated changes in production conditions. At the same time, research on climate adaptation demonstrates that households may respond to climatic and socioeconomic pressures by altering not only management practices but also the configuration of their livestock systems. The framework developed in this paper connects these domains by treating uncertainty about future livestock-system configuration as an explicit consideration in genetic-improvement planning. It positions future system configuration and function between climate adaptation and genetic requirements, thereby distinguishing uncertainty about the environment in which animals will perform from uncertainty about the livestock system that future animals will be expected to serve.

The framework does not claim that system reconfiguration automatically determines breeding traits, that future livestock systems can be predicted, or that robust objectives are always preferable to optimisation. Rather, it proposes a conditional decision logic. Where the future system is sufficiently specified, breeding objectives can be optimised for the anticipated trajectory. Where several plausible configurations exist, objectives can be evaluated for robustness across those trajectories. Where uncertainty is deep and alternative objectives diverge substantially, maintaining genetic diversity and the capacity to revise objectives may provide greater strategic flexibility than early narrow commitment.

The central conceptual shift is therefore from asking only which animals are likely to perform best under future environments to asking which breeding objectives remain

appropriate when climate and socioeconomic adaptation may change the livestock system itself. Optimise when the future is sufficiently specified, assess robustness when multiple futures are plausible, and preserve flexibility when uncertainty is deep.

Declarations

Author Contributions

Edmore Masama: Conceptualization, Literature search and screening, Methodology, Data curation, Formal analysis, Writing – original draft.

Enock Muteyo: Literature search and screening, Data curation, Evidence synthesis, Writing – review and editing.

Takudzwa Mafigu: Literature search and screening, Data extraction, Evidence synthesis, Visualization, Writing – review and editing.

Never Assan: Conceptualization, Methodology, Supervision, Critical synthesis, Writing – review and editing, Project administration.

All authors contributed to the interpretation and synthesis of the reviewed literature, critically reviewed and revised the manuscript, approved the final version, and agreed to be accountable for all aspects of the work.

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Competing Interests

The author declares no competing interests.

Ethics Approval

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Data Availability

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During the preparation of this work, the author used PAPERPAL to assist with conceptual development, manuscript organisation, language refinement and editorial revision. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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