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Can heritage Criollo cattle promote sustainability in a changing world?

ABSTRACT

Viewpoints about the suitability of ruminant livestock in drylands vary, but most agree that strategies that maximize both land health and pastoral welfare are needed, especially as climate change intensifies. This special issue focuses on the use of heritage Criollo cattle as one such strategy for ranching in arid lands of the Americas. Authors report on fifteen years of research about Criollo cattle landscape distribution, heat tolerance, and diet selection. Many connect those behaviors and traits to the potential for ranching adaptive capacity, resilience, and sustainability. In this introduction to the special issue, we describe how we use an indicator system to systematically document that potential. Based on existing research and anecdotal evidence, we hypothesize that the use of Criollo cattle is associated with desirable outcomes for nine indicators, ordered from strong to weak certainty: biotic integrity, total factor productivity, water use efficiency, soil health, commodity quality, greenhouse gas mitigation, stability of profits, rancher self-determination, and rancher communion. Ongoing and new indicator measurements will be conducted at ranches in arid lands across the Americas. We aim to improve understanding of the benefits and inadvertent drawbacks of adopting Criollo cattle, to inform decisions that promote sustainable agriculture in a changing world.

1. Heritage cattle as a sustainability strategy

Attitudes vary about the production of ruminant livestock in arid lands. Some see ruminant livestock as crucial to human inhabitants because livestock industries employ at least 1.3 billion people and provide an essential livelihood for 600–900 million poor smallholder farmers (Upton, 2004; Thornton et al., 2006; Alary et al., 2011). Others maintain that livestock production is fundamental to the cultural identity of dryland societies, and therefore imperative for self-determination and social justice (Clutton Brock, 2014). Environmental effects are intensely disputed, especially in affluent western societies. While some argue that low intensity, extensive livestock production can conserve biota, water, and energy – especially compared with cropland agriculture – others cannot overlook ruminant methane emissions or the risk of land degradation when grazing is not adaptively managed (Herrero et al., 2009; Garnett et al., 2017; Lark et al., 2020).

Although dryland stakeholders do not always see eye to eye, most agree that innovative management approaches that maximize both the health of arid lands and the welfare of pastoral peoples are needed. Climate change is complicating these prospects. Forage productivity is forecasted to decline regionally in warmer and more variable future climates, which can accelerate land degradation and contribute to human suffering (Herrero and Thornton, 2013). Successful approaches would help pastoral enterprises and communities adapt while also ensuring sustainable production (i.e., ample food and fiber, ecological health, and economic welfare for current and future generations) (United Nations, 2015). Promising strategies range from improved grazing systems, to new technologies, to novel governance systems tailored to regional contexts (Bestelmeyer et al., 2021; Gregorini et al., 2022).

This special issue focuses on heritage cattle as one such promising strategy. "Heritage" breeds have received little artificial selection and have a long history in a specific locale (McIntosh et al., 2023 this issue). Researchers worldwide are exploring whether heritage livestock support adaptive capacity and sustainability of pastoral systems in their regions (McIntosh et al., 2023 this issue). In this special issue, we explore "Criollo" cattle, a heritage type in the Americas. Criollo cattle genetics originated in the Iberian Peninsula and were brought to the New World in the 15th Century. Since then, they have adapted to a wide variety of environments in the Americas, with many isolated from the genetic influence of European commercial breeds introduced much later (Anderson et al., 2015; Armstrong et al., 2022 this issue). Several articles focus on "Rarámuri Criollo", a biotype that adapted to the rugged Copper Canyon of northern Mexico over the course of 500 years, then was imported to the southwestern United States for rangeland research in the early 21st century (Anderson et al., 2015; Estell 2021 this issue). Other articles focus on Criollo in Uruguay, Argentina, and Mexico with geographically-specific histories of migration and adaptation (Herrera Conegliano et al., 2022 this issue; Roacho Estrada et al., 2023 this issue; Armstrong et al., 2022 this issue).

A common pathway for agricultural research designed for sustainable development progresses from mechanistic research on how an innovation works to multidisciplinary research on how that innovation affects ecological and socioeconomic outcomes (Thornton et al., 2017). Our research group is at the turning point: Over a decade of research on traits and behaviors has provided the basis for hypotheses about the ecological and social outcomes of ranching with Criollo cattle. We will use a sustainability indicator system developed for the USDA Long-Term Agroecosystem Research network to systematically test those hypotheses. The indicator system comprises attributes of a sustainable ranch, indicators of the status or condition of the attributes, and site appropriate metrics to calculate the indicators (Fig. 1) (Spiegal et al., 2022;

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Gomez et al., 1997). The system is designed so that users can set benchmarks of desired condition for each indicator and measure departure from the benchmarks, which is why the hypotheses in Fig. 1 are written "directionally" toward desired outcomes. We will monitor outcomes of ranching with Criollo cattle at ranches and research units in the United States, Argentina, Uruguay, and Mexico in terms of nine indicators: biotic integrity, soil health, greenhouse gas mitigation, total factor productivity, commodity quality, water use efficiency, stability of profits, self-determination, and communion (Fig. 1) (Cibils et al., 2023 this issue; Spiegal et al., 2020). The initiative is noteworthy for the sustainable development canon, because it aims to systematically document a wealth of enthusiastic anecdotal evidence from devoted practitioners (Anderson et al., 2015; Estell, 2021 this issue).

In this introduction to the special issue, we summarize research on the traits and behaviors of heritage Criollo cattle, explain how that research translates into hypotheses about the sustainability of ranching with Criollo cattle, and outline how we are systematically testing the hypotheses with our indicator system. Potential tradeoffs between indicators are highlighted to inform decision-making.

2. Traits and behaviors of heritage Criollo cattle: research for arid rangelands

2.1. Landscape distribution

Landscape distribution of livestock is a fundamental management concern for producers in arid lands worldwide. Dryland forage resources fluctuate across space and time, driven by patchy, unpredictable rainfall interacting with inherent heterogeneity of landforms and soils. Ranchers use fencing and water to encourage animal distribution, but even with great monetary investment, high-value plant patches near watering points can become overgrazed, leading to permanent loss of topsoil, diversity, and productive capacity.

McIntosh et al. (2023 this issue) analyzed studies that compared the grazing behavior of heritage and hybrid cattle types in global grazinglands during the past 60 years. Most studies reviewed found that hybrid (*B. taurus* × *B. indicus*) and heritage cattle types displayed more desirable grazing distribution than conventional types. Cibils et al. (2023, this issue) analyzed eight studies that compared the foraging behavior of Rarámuri Criollo or Argentine Criollo cattle with conventional beef cattle at five locations in North and South America, including several studies published in this special issue (Duni et al., 2023 this issue; Roacho Estrada et al., 2023 this issue; Herrera Conegliano et al., 2022 this issue; Nyamuryekung'e et al., 2022 this issue; McIntosh et al., 2021; Spiegal et al., 2019). At the four settings with Rarámuri Criollo, when vegetation was greener and more abundant, the Criollo and their conventional counterparts both exhibited restricted spatial distribution and landscape use. Conversely, when forage was scarce, the Criollo cattle traversed longer distances and ranged farther from water to access forage. Much more than conventional breeds, both the Rarámuri and Argentine Criollo changed their behavior with season. The behavior is attributed to their lower intake and multigenerational adaptation to undeveloped, arid landscapes of the Americas (Anderson et al., 2015; Cibils et al., 2023 this issue).

2.2. Heat tolerance

As they manage for livestock landscape distribution, dryland pastoralists and their herds are experiencing more extreme hot and cold periods with longer and more frequent droughts. These climate change

Sustainability domain	Attribute of a sustainable ranch	Indicator of attribute's status	Hypothesis about the outcomes of Criollo production	Type of Criollo research informing the hypothesis	Metrics to calculate the indicator
Environmental	Land & Water Health	Biotic Integrity	Grass cover is maintained; bare ground and invasive species establishment are limited.		Ground and satellite monitoring of plant species composition, cover, production. Wildlife sign.
		Soil Health	Capacity of the soil to function as a living ecosystem that sustains plants, animals, and people is maintained.		Ground and satellite monitoring of bare ground, soil aggregate stability, and biocrusts. Modeled erosion risk.
	Atmospheric Health	Greenhouse Gas Mitigation	Soil carbon is maintained and feed inputs are reduced over the long term. Methanogenesis differs vs. other breeds.		Carbon retained in ecosystem versus methane emitted by cattle. Modeled ranch-level greenhouse gas emissions.
Economic	Production Abundance & Quality	Total Factor Productivity	The ratio of inputs to outputs is acceptably low due to reduced inputs.		Inputs (land, feed, labor, fertilizer, machinery) ÷ outputs (livestock or beef).
		Commodity Quality	Live cattle and beef meet market standards.		Body condition score. Weaned calf weight as % of dam weight. Beef qualities.
		Water Use Efficiency	The ratio of cattle productivity to freshwater inputs is acceptably high due to cattle drinking patterns.		Weight of weaned calf ÷ m^3 of water intake from troughs.
	Financial Stability	Stability of Profits	Net returns are steady despite variation in forage and cattle prices due to adaptive capacity of cattle.		Annual operating costs, overhead costs and cattle sales. Consumer willingness to pay for heritage Criollo beef.
Social	Individual Well-Being	Self-Determination	Ranchers have flexibility in plans and work schedules due to adaptive capacity of cattle.		Degree to which rancher schedules or investments are opportunistically modified.
	Community Well-Being	Communion	Community recognizes ranchers for sustainability impacts, animal heat tolerance, and social learning.		Rancher community participation and co-production with neighbors.

Fig. 1. Indicator system to measure the effects of an agricultural innovation on ranch sustainability. The system's architecture comprises three sustainability domains, six attributes of a sustainable ranch, nine indicators of the status of the attributes, and metrics that we will use to calculate indicators for the innovation of Criollo cattle. It is designed so that users can set benchmarks of desired condition for each indicator and measure departure from the benchmarks (not shown). Hypotheses were derived from the Criollo cattle research showcased in this special issue, spanning themes of landscape distribution (map), heat and disease tolerance (Criollo cow with sun), and diet selection (Criollo cow with grass).

impacts affect animals through disease, pests, heat and cold stress, and mortality (Nyamuryekung'e et al., 2021 this issue; McIntosh et al., 2023 this issue). In the Americas, such animal responses can impart economic risks through production losses and diminished consumer support (Alonso et al., 2020), and even social risks due to disapproval by fellow producers who tend to prioritize an ethic of care (Spooner et al., 2012).

Comparing Criollo cattle with other breeds, ranchers and researchers have observed fewer instances of eye cancer, foot root, and keratoconjunctivitis (Armstrong et al., 2022 this issue). Resistance to internal parasites observed may stem from consuming a broader array of plants with higher concentrations of plant secondary metabolites (Anderson et al., 2015; Provenza et al., 2003). Observers have also noted greater heat tolerance thought to be a function of foraging plasticity, coat color, or partitioning of body fat. Comparing the body temperature of Rarámuri Criollo vs. commercial beef cows, Nyamuryekung'e et al. (2021 this issue) found that during the summer in the Chihuahuan Desert, the heritage cows had lower body temperatures during the hottest hours of the day. And, during those hot hours, the Criollo traveled farther and faster, spending more time grazing and traveling, and less time resting.

2.3. Diet selection

Warming and drying trends in arid rangelands signal reduced forage production (McIntosh et al., 2019) and compromised ruminant diet quality (Gherardi and Sala, 2015; Estell et al., 2012). The need to import harvested forages can exacerbate environmental and economic costs on ranches and in the regional and national agri-food systems in which ranches are nested (Shrum et al., 2018; Havstad et al., 2018; Herrero et al., 2013).

The Jornada Experimental Range and partners undertook research on Rarámuri Criollo partially in response to enthusiastic anecdotal accounts of Criollo having a wide diet breadth, seeking options for ranchers coping with a world with more shrubs and less grass (Estell et al., 2012). Early-adopter producers reported on a capacity to consume shrubs and other non-grass plants while maintaining acceptable productivity and body condition (Estell 2021 this issue; Anderson et al., 2015). In the case of Rarámuri Criollo, this diet breadth probably stems from 500 years of foraging in the woody plant-dominated ecosystems of the Copper Canyon in Mexico (Anderson et al., 2015). Interestingly, heritage types adapted to arid systems in other parts of the world are also observed to have more diverse diets than their conventional counterparts (e.g., Shabtay, 2015; McIntosh et al., 2023 this issue).

Estell et al. (2022 this issue) compared the diet selection of Rarámuri Criollo and conventional cows using DNA metabarcoding of fecal samples. Dominant plant species were similar in samples from both breeds, but a few key differences were detected. The Criollo fecal samples contained a higher proportion of mesquite (Prosopis) and Yucca spp.: shrubs/succulents that are generally less preferred forages than grasses. Samples from the conventional breed contained about twice as much black grama, a highly preferred and often overgrazed grass. Notably, the finding of less black grama grass in diets of Criollo cows corroborates findings of feeding site selection in landscape distribution studies described above.

3. Potential effects of the traits and behaviors on ranch sustainability: research for a changing world

3.1. Environmental indicators

Research in this special issue and beyond suggests that the landscape distribution and diet selection of heritage Criollo cattle likely impart a lighter footprint on arid rangelands compared with breeds typically used in American ranching, thereby positively influencing **biotic integrity** and **soil health** indicators (Fig. 1). For instance, Nyamuryekung'e et al. (2022 this issue) found that compared with a conventional breed, Rarámuri Criollo cows traversing larger home ranges spent less time grazing patches of black grama (*Bouteloua eriopoda*), a declining perennial grass of high conservation value in the Chihuahuan Desert. In arid southern California, a rancher observed more frequent grazing by Rarámuri Criollo cattle in shrub-dominated upland areas previously avoided by his commercial beef herd, with recovery of riparian lowlands since introducing Criollo cattle eight years before (Cibils et al., 2023 this issue). In an earlier study, Spiegal et al. (2019) found that during the weeks immediately preceding forage green up, a time of the year when herbaceous forages in the Chihuahuan Desert reach their lowest biomass, grazing of Rarámuri Criollo cows resulted in fewer hotspots of intense use (vegetation patches grazed multiple times for > 2h) relative to their commercial beef breed counterparts. As a potential tradeoff, increased use of formerly ungrazed patches may compromise habitats and forage resources used by wildlife, and generally diminish landscape heterogeneity (Fuhlendorf et al., 2017). Biotic integrity measurements accounting for both vegetation and wildlife are needed (e.g., Funk et al., 2022). Given the correlation between vegetation integrity and soil health in rangelands (Brown and Herrick 2016), we expect Criollo landscape distribution to have a favorable effect on soil health – to be assessed in future measurements.

At this time, less is known about the impacts of ranching with Criollo cattle on **greenhouse gas mitigation**, an issue of dire concern in arid and semi-arid rangelands – indeed, in all lands – worldwide (Brown and Herrick, 2016; United Nations, 2015; Herrero et al., 2013). Cattle-related strategies for greenhouse gas mitigation under exploration worldwide include: 1) favoring ruminant gain or growth such that animals are more productive but live for a shorter time (e.g., Basarab et al., 2013; White and Capper, 2013; Derner et al., 2017); 2) improving feed efficiency in some areas of the world (e.g., Herrero et al., 2013); and 3) selecting animals with favorable greenhouse gas emissions traits (e.g., Donoghue et al., 2016). We have begun our explorations with a focus on the third strategy, with the hypothesis that the larger home ranges, wider diet breadth, and possibly specific physiology of Criollo will impact soil Carbon and greenhouse gas exchanges in favorable ways compared with other breeds. We will measure gas production by Criollo and the ecosystems they graze and use life cycle analysis to model whether diverse Criollo landscape use and diets reduce the need for feed crop inputs, thereby improving supply chain-level greenhouse gas emissions (Spiegal et al., 2020; Rotz et al., 2019). A wealth of data will be needed for reliable budgets and models.

3.2. Economic indicators

Anecdotal evidence and a ranch budget by Torell et al. (2023 this issue) have shaped a working hypothesis that Criollo landscape use, heat tolerance, and diet selection result in greater unit of output per unit of input. Working in the Chihuahuan Desert, the researchers and producers who constructed the ranch budget compared annual operating costs, overhead costs, and revenues of producing a conventional cattle type whose calves were exported off-ranch for grain finishing versus on-ranch grass-finishing of Rarámuri Criollo cattle. On an annual basis, the latter required lower operating and overhead costs per unit of cattle produced – in part due to improved use of forage resources. In addition, we suspect that Criollo heat tolerance will reduce the need for heat buffers and additional watering points, infrastructure becoming economically and environmentally infeasible under a changing climate (Malloy, 2020). Heat tolerance may also result in less overall water intake per unit of beef produced (Heinke et al., 2020; Hoover et al., 2022), and ultimately help ranchers avoid costly destocking during severe drought (Shrum et al., 2018). We hypothesize that these mechanisms will have desirable effects for on-ranch **total factor productivity**,[1] and **water use efficiency** indicators (Fig. 1); indicator monitoring in a variety of conditions will be required to help us test these hypotheses.

Our group evaluates **commodity quality** based on body condition score, weaned calf weight, and meat qualities (Fig. 1). Previous studies found favorable Criollo meat quality and average daily gains despite their grazing in hot and cold seasons in the U.S. and Uruguay (McIntosh et al., 2021; Armstrong et al., 2021). Anecdotally, ranchers and customers of direct marketing of Criollo beef enjoy its flavor, tenderness, juiciness, and knowledge of its provenance. However, little is known about commodity quality from *extreme* heat or cold, or combining Criollo genetics with conventional genetics. To learn more, our group will sample in a variety of ranching conditions, and has expanded to include meat scientists for laboratory testing and consumer taste panels (Miller 2020).

Ranch **stability of profits** has a complicated relationship with input costs and cattle pricing. Criollo cattle have different size and body conformation than the breeds most often used in ranching in the Americas. This difference can result in price docking at auctions and feedlots (Spiegal et al., 2020). On the other hand, niche marketing can capitalize on consumer support for meat from heat tolerant, heritage animals (Alonso et al., 2020). We are tracking cattle sales and surveying consumers to learn more about their willingness to pay for Criollo beef, including grass-finished and grain-finished options (Palma et al., 2019).

3.3. Social indicators

Through our work with ranchers, we hypothesize that the rustic traits and behaviors of Criollo allow more flexibility in daily ranching schedules due to reduced time on spent vet care and relocating the animals from sensitive areas. We posit that these dynamics will positively influence the **self-determination** indicator (Fig. 1; Ryan and Deci, 2000). Further, we speculate that the heat tolerance and landscape use by the heritage animals in the harsh conditions of American deserts may garner respect from fellow ranchers (Spooner et al., 2012), and improve **communion** in the places where Criollo ranchers reside. Previous research is several degrees removed from these hypotheses. We will work with social scientists in the USDA Long-Term Agroecosystem Research network (Meredith et al., 2022) to develop systematic surveys of Criollo ranchers to understand linkages between Criollo cattle use and well-being (Bentley-Brymer et al., 2020). Motivations of adopting new cattle genetics in arid lands ranching systems will need to be understood in order to design effective producer surveys (Gifford et al., 2023).

4. Into the future

As we continue to build the bridge between mechanistic cattle research and multidisciplinary sustainability research, we will refine our indicator system on ranches with Criollo cattle across the Americas. We recognize that we cannot measure everything that is relevant, and that we cannot study production systems in all relevant geographies and scales. Nonetheless, we will continue our multidisciplinary approach with the intention of helping producers and managers avoid the pitfalls of narrow perspectives and overreliance on anecdotes that bedevil scientific support for sustainability solutions.

Ranchers may wonder where they can purchase Criollo cattle featured in this special issue. Our international research network is acting as a genetic repository of Criollo, managing biotypes in New Mexico, Mexico, Uruguay, and Argentina, with constant improvement that contributes to the genetic and phenotypic diversity of the global cattle herd. The availability of Criollo stock is now limited in many regions, but the favorable results from studies to date are contributing to increased interest. We aim to increase accessibility, so that pastoralists will have the option to use Criollo cattle in the future, alongside comprehensive, science-based information on which to base that decision. We encourage interested parties to reach out to authors in their regions to learn more.

[1] Total factor productivity, or TFP, is the ratio of agricultural outputs (gross crop and/or livestock output) to inputs (e.g., land, feed, labor, fertilizer, machinery, livestock). It increases when outputs rise yet inputs remain unchanged (USDA National Institute of Food and Agriculture, 2018).

5. Dedication

This work is dedicated to the memory of Alfredo L. Gonzalez and the memory of L. Allen Torell. We are grateful for their unique brands of visionary leadership, which continue to inspire us to solve sustainability challenges in arid rangelands worldwide.

CRediT authorship contribution statement

Sheri Spiegal: Conceptualization, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Rick E. Estell:** Conceptualization, Validation, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Andres F. Cibils:** Conceptualization, Validation, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Eileen Armstrong:** Validation, Investigation, Writing – review & editing. **Lisandro J. Blanco:** Validation, Investigation, Writing – review & editing. **Brandon T. Bestelmeyer:** Conceptualization, Validation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Data availability

Data will be made available on request.

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