Swette Center for Sustainable Food Systems
Arizona State University

Unveiling the Hidden Capitals of Cow-Calf Operations in Rangelands of the West

A TCA TEEBAgriFood Application

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Global Alliance for the Future of Food
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The Global Alliance for the Future of Food (GAFF) is a coalition of twenty-nine different foundations from around the world. By working together, these foundations seek to amplify their individual efforts in creating positive transformations in our food systems. Since its formation in 2012, GAFF has employed a systems-level approach to look at the different intersections of food, the environment, government, and how to build and maintain resilient livelihoods and societies. In 2015, GAFF partnered with the United Nations Environment Programme to develop The Economics of Ecosystems and Biodiversity for Agriculture and Food initiative, which was then followed by the TEEBAgriFood Evaluation Framework. GAFF provided funding for this study. Lauren Baker, Ruth Richardson, and Amanda Jenkins were especially supportive in the course of our research. Furthermore, the TCA Community of Practice, organized and supported by GAFF and which Swette Center staff participate in, contributed knowledge important to this study.

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A Note on COVID

This project was impacted by the ongoing COVID-19 pandemic, causing it to take longer than initially planned. The research team lost an entire year when field research was not permitted, followed by delays due to stringent COVID protocols. Lab results were extremely delayed, in some cases by over six months, due to supply chain disruptions. More than the challenges presented to the research team, we want to acknowledge up-front the difficulties posed by COVID challenges—coupled with drought and Western wildfires—that were confronted by ranchers and the rural communities in which they reside. Their willingness to share information, meet with us over Zoom, and in-person during such stressful times for their businesses and families is a tribute to their dedication to their craft.

Rancher Confidentiality

To protect the ranchers, their families, and businesses, and to encourage an environment of open and honest discussions, we have maintained anonymity of all subjects involved in our ranch case studies. All respondents were informed of the scope of this study and its approval through the formal IRB process.

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Executive Summary

Beef livestock ranching is an important agricultural activity rooted in the history of the American West. There is a logic to beef ranching in this region, as pastures are tremendous in size and the soil, terrain, and arid climate are not favorable to other types of agricultural production.

Despite the long history and culture surrounding cattle and ranching in the West, recent times have left many cattle ranchers feeling under attack as media attention has highlighted potential environmental impacts of cows and health concerns around red meat. As these generalizations influence consumer perceptions around beef consumption, there is a need to employ a more robust understanding of beef livestock production as a complex socio-ecological system. While mainstream conversations around beef bring to light important concerns, they also leave much unexamined.

To address this, ASU and CSU collaborated on a pilot study conducted with twelve ranch partners, six in Arizona and six in Colorado. Using the True Cost Accounting (TCA) approach we implement a more holistic assessment that avoids broad generalizations of ranching as either good or bad. We focus our work at the intersection of human, cattle, and rangeland; namely, the cow-calf supply chain, which is the primary stage of beef livestock production that relies on western rangeland. It is here where cattle are bred and raised on pasture until they are weaned and transferred to feedlots, stocker programs, or kept on pasture and marketed directly by the ranch. In the American West, maintaining the cow-calf system is the primary driver of ranching.

We employ mixed qualitative and quantitative methods. These included case studies with ranchers, involving a survey as well as in-depth discussions with them; two regression models based on secondary county-level data, soil testing, a Life Cycle Assessment (LCA), and a geospatial assessment of biomass productivity and its variation. The different qualitative and quantitative methodologies employed built on and complemented each other providing a more complete and robust perspective on the cow-calf production systems.

Placing value on human, social, produced, and natural capitals we refine TCA for beef livestock. We contextualize beef livestock in the Western Mountain[1] region, finding evidence of the non-market stocks of wealth involved in cattle production—including key human and social elements. This report's ranch-level case studies further explain dependencies and outcomes that go beyond economic or environmental concerns,

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[1] In our literature review, we review the capitals in the context of the West, but our statistical models analyze the Western Mountain region in which Arizona and Colorado sit.

finding that the ranches we study play important roles in the culture of the West through social networks of rural communities, and the preservation of open space. We find negative externalities of greenhouse gas (GHG) emissions and water to be -$57.77 /kg Carcass Weight (CW)[2] with positive ecosystem externalities valued between $6.88 /kg CW to $52.23 /kg CW, depending on the carbon sequestered. Our findings suggest that livestock grazing on most rangelands is secondary to climate (temperature and precipitation) in influencing range productivity and health.

Together, we find the true cost of ranching to be between -$2.29 /kg CW to -$47.64 /kg CW depending on the rate of soil carbon sequestration.[3] It is important to note these numbers are estimates, representing key benefits and costs in cattle production. There is debate as to whether negative externalities can be subtracted from positive externalities to reach a net benefit or cost. Some feel that externalities are often not substitutive i.e., benefits of ecosystem services cannot substitute, or offset carbon emissions. We feel it is important to combine positive and negative externalities into a single output as a technique for visibility and applicability, especially if TCA aims to replace Cost-Benefit Analysis. For this report, we have combined our findings, but highlight the need for further discussion. Further, the true cost indicated by this analysis does not extend to the final finishing, slaughter, processing, and rendering of beef. This is an extension of this project we hope to pursue.

Additionally, the findings in this report have allowed us insight into how different government policies support western ranching and rangeland conservation. First among these insights is the realization that a wide range of research—including this report—depends on quality data from resources provided through different branches of the USDA. Secondly, we have observed the importance of generational knowledge on ranches and the increasing challenges ranchers encounter in transitioning ownership and knowledge from one generation to the next. These challenges require additional investment in the local and regional economies around rangeland, which can aid in building the next generation of ranchers and increasing the diversity of ownership. Lastly, we observed the need for greater collaboration among different stakeholders to work towards conservation of these lands and the different ecosystems they support. Part of this need for collaboration is to holistically understand how ranching on the rangelands can embrace climate smart practices to manage methane emissions, but to

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[2] Carcass Weight (CW) is the dressed weight of cattle measured per pound or kilogram.

[3] Conversion to /lb CW: Negative externalities valued at -$127.36/lb CW, positive externalities valued between $15.17-115.14 /lb CW, total cost range of -$5.06 /lb CW to -$105.03 /lb CW. The value of the positive externalities exhibited great variation because we use a range for the rate of soil carbon sequestration associated with grazing of between 0.05 and 3.0 Metric ton/ha/year (Sanderson et al., 2020).

also understand how to preserve these ecosystems in the face of increasing drought and wildfire pressure.

The results of these qualitative and quantitative analyses highlight how there are multiple factors impacting the cattle industry–many of which are not constrained to economic boundaries. We show that further research is required to understand ecological, societal, and economic benefits and costs of cattle. Further we signify the need to explore at a larger scale how ranchers employ adaptive management strategies in the face of climate change. By partnering with ranchers to better understand their experiences, we believe that we will be positioned to have the transparent, transdisciplinary assessments needed to develop successful strategies that support sustainable livestock production. With a larger project in mind for future research, we present this study as the beginning of an exciting pursuit to unveil the hidden capitals of beef livestock production.

Introduction

Livestock is the primary agricultural activity in rangeland ecosystems, areas that are not readily suitable for other types of agricultural production. Cattle production can offer a market-based ecosystem service derived from rangelands and of benefit to humans. While many people and organizations push for the world to consume more plant-based and vegetarian diets, including our own universities and students, it is important to recognize that cattle production often utilizes land unsustainable for crop production and is a historical and global land-use practice.

To conceptualize the importance of both rangeland and cattle, consider that rangeland covers 403.9 million acres in the US, accounting for 21% of the US surface area (USDA NRCS, 2020). These expansive rangelands allow the US to produce an enormous number of cattle and secure beef's place as an important component of US food systems, a key source of protein and other nutrients, as well as a food with important cultural meaning and social status. In simple monetary terms, in 2020 the beef cattle industry produced the retail equivalent of $123.3 billion in beef in the US (USDA ERS, 2022a). But beyond these numbers, we can illustrate the unique popularity of beef in the US when we see that the US has the second highest annual consumption per capita of beef in the world, 26.32 kg in 2020 and only surpassed by Argentina (OECD, 2022). Cattle production and consumption of beef are likely to remain prominent in US food systems for the foreseeable future.

While cattle production in the Western US has a long history since its introduction in the Southwest by the Spaniards in the 16th century, it is also crucial to look at how Indigenous people originally used these rangelands (Sluyter, 2016). It is estimated that tribes currently manage 46 million acres of rangeland in the United States, primarily in Western states and Alaska (BLM, 2016; Rangelands Gateway, 2022). Early historical texts written for white audiences often described the land of the American continent as "untouched" and "pristine," erasing the existence of Indigenous people and their relationship working together with the land (Black Elk, 2016; Diekmann et al., 2007). More recent publications, by both Indigenous and non-Indigenous scholars, have looked to correct our understanding of this relationship. For example, pre-colonial burn paths were often ascribed to lightning strikes, as colonists did not think Indigenous people utilized controlled burns on their rangelands. Williams (2003), writing for the USDA Forest Service, noted that colonists did not recognize the unusual nature and shape of these burn paths, as colonists burned wide swaths of land to create "uniformity in ecosystems," while Indigenous people "lived to create a diversity of habitats." To this end, Indigenous people purposefully burned very specific sections of rangeland to achieve different ends. These include creating fresh grazing areas for larger mammals, harvesting underground crops and grass seeds, and to aid in collecting insects, such as

the Paiute people's collection of *piuga*, the Pandora moth (Blake & Wagner, 1987; Williams, 2003).

While part of this belief that Indigenous people minimally utilize the rangeland comes from attempts at cultural minimization and erasure, it also comes from a disconnect between Indigenous and settler views on land management (Sabzalian, 2019). Black Elk (2016) describes how traditional ecological knowledge—what they call "Native science"—looks at ecological interrelatedness as a key for rangeland health. They note that Native science strives for holism in all things and acknowledges that humans are active participants in the natural world (Black Elk, 2016). This led to the development of agricultural processes that were unrecognizable to settlers. An example of these processes that seen in multiple tribes is preparing plants for basket weaving. Left to their own growth pattern, wild plants can grow bent, forked, and crooked, which can lead to difficulty in weaving. To maintain a reliable supply of weaving materials, Indigenous people developed the practice of transplanting, trimming, and coppicing grasses and reeds to encourage long, straight growth for weaving (Diekmann et al., 2007). Maintaining the health of these weaving plants also promoted overall rangeland health and ecosystem biodiversity. Anderson (2013) notes that one can see this "calculated, tempered use of nature," even in the agricultural tools developed by indigenous people (p. 2). In examining different tribes in California, they note that tools are not developed for increasing the speed or quantity of a harvest, but instead to prevent and minimize damage to the plant and avoid disturbing the larger ecosystem (Anderson, 2013). While settlers saw an untouched land or wilderness, Diekmann et al. (2007) suggests that it is "more useful to think of them as *cultural landscapes*, and perhaps working landscapes, in which human use also has the potential to enhance ecosystem productivity and diversity" (p. 48).

Along with cultivating different plant fibers for weaving, some tribes, such as the Hopi and Akimel O'odham also cultivated cotton for fiber as well as the edible seeds (Langmaid, 2017). Cotton production did slow after the introduction of *churra* sheep at the end of the 16th century by the Spanish, when tribes such as the Diné and Hopi began raising sheep on rangeland for their wool, milk, and meat (National Park Service, 2021). While some tribes shifted to raising sheep on their own accord, others—such as the Akimel O'odham—found that the water they relied upon for irrigation of their fields had been diverted away from the reservation by state and federal governments, forcing them to abandon cotton cultivation (Langmaid, 2017). Today grazing remains an important aspect of Indigenous people's use of the rangeland, although the specific regulations around livestock grazing will vary depending on tribal codes and the unique lifeways each tribe wishes to support (Grim, 1997; Rangelands Gateway, 2022).

Currently livestock production constitutes the largest land use in the US Western Mountain region, which includes Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming. In those states, grazing areas (rangeland, irrigated pastures, and grazed forests) occupied almost 400 million acres, accounting for 73% of all Western land uses (USDA ERS, 2017)[4]. According to the 2017 Census of Agriculture, there were 69,736 operations with cattle with an inventory of 12.7 million head (USDA NASS, 2017a) and cattle sales of $10.3 billion (USDA NASS, 2017b). In Arizona, grazing areas occupied around 77% of the land use in the state (USDA ERS, 2017), while according to the last Census of Agriculture there were 891,436 head of cattle and sales of almost $404 million (USDA NASS, 2017a, b). In Colorado grazing lands occupied 63% of the land use in the state (USDA ERS, 2017) and included 2.812 million head and sales of more than $3.3 billion (USDA NASS, 2017a, b).

In designing this report, we specifically looked at the cow-calf side of beef livestock production. For those unfamiliar with modern beef production, it is important to understand that the US beef supply chain is a complex series of systems that meet and branch off at different stages. In the simplest version of this supply chain, a rancher sells a cow to a consumer, which is then transported to a slaughterhouse for processing and packaging before being picked up by the consumer. Most cattle do not experience such a straightforward process; for most, life begins on a cow-calf operation where cattle are born, weaned, and then raised on pasture until reaching an ideal weight. From there, they are transferred to a feedlot, where they eat grain until reaching their final market weight. As the feedlot is a place for cows to quickly put on weight, feedlots are often located adjacent to or in close proximity to a slaughterhouse. From there, the cattle are processed into different cuts of beef and the offal and hides are send to rendering (NARA, 2022).

This study looks specifically at the cow-calf part of this value chain, as cow-calf operation are the primary function of ranching in the American West. While there are some feedlots throughout the west, they are primarily located in the Great Plains, particularly the Texas and Oklahoma panhandles, Nebraska, and Kansas (Drouillard, 2018; USDA ERS, 2022b). As this report performed case studies in Arizona and Colorado, it made sense to begin our TCA analysis with cow-calf. Not only is cow-calf the beginning of the beef value chain, but it is also the focus of ranching in both the case study states and the west at large. We hope to expand our scope to feedlots,

[4] Specifically, this data was taken from Summary Table 4 in the ERS Major Land Uses Report, available at https://www.ers.usda.gov/webdocs/DataFiles/52096/Summary_Table_4_total_grazing_land_by_region_and_state_2012.xls?v=6116.8

slaughterhouses, and processing, as well as the rendering stage of beef production in future reports.

Given the importance of cattle production in the US—particularly in the West—it is essential to have an integrated assessment of this industry, not only for its market value and impacts on land use, but also for the positive and negative externalities it produces. True Cost Accounting (TCA) is a tool that can be used to accomplish this. TCA is a holistic economic assessment that looks beyond conventional financial metrics and seeks to understand the broader human, social, and ecological impacts of food systems activities by "measuring what matters" (Baker et al., 2020). TCA recognizes that just looking at yields, profits, calories, and/or proteins to judge the success and appropriateness of our food systems is misleading and generates widespread unintended consequences and costs to the environment, human health, and society.

To address these unintended consequences and consider the hidden costs and benefits of different components of our food systems, TCA recognizes that the dependencies and impacts of food systems on four types of capital—natural, produced, social and human—must be made visible, measured, and (if possible) monetized. This is essential if we want to improve upon how we produce food. The most prominent framework for applying TCA across these different capitals is The Economics of Ecosystems and Biodiversity for Agriculture and Food (TEEBAgriFood) Evaluation Framework (Baker et al., 2020; TEEB, 2018) which has instructed our analysis. The goal of TCA is to provide decision makers, both in the public and private sector, full information to empower them to make better decisions about the food that we produce, market, and consume, and to improve the policies that undergird our food systems.

This report presents the results of the study "*Unveiling the Hidden Capitals of Cow-Calf Operations in Rangelands of the West: A TCA TEEBAgriFood Application*." The goal of this study is to contribute to methodological refinements of TCA and gain a more nuanced understanding of the complex systems underlining beef production. A combination of multiple qualitative and quantitative methodologies that complemented each other was used in this study.

Bringing together this variety of methodologies, the study offers a more complete story of beef on the range, contributes to the TCA Community of Practice methodological efforts, and elevates potential policy issues in cow-calf production systems in the West.

Today’s Context

There are increasing concerns about the externalities generated by beef production on rangelands. In recent times, many consumers, often driven by environmental or health concerns, are favoring alternatives to beef such as vegetarian, or vegan options. While consumers following vegan diets are still a small portion of the US overall (5.9%), the number of consumers identifying as vegan has risen quickly, increasing 500% from 2014 to 2019 (Alcorta et al., 2021). This interest in alternatives to meat goes beyond those adhering to vegetarian and vegan diets as seen in the rising success of plant-based foods. Plant-based foods sold as animal-sourced-alternatives have increased 54% at the retail level over the past three years (2018-2021), reaching $7.4 billion in retail sales (Ignaszewski, 2022). Further while plant-based meat accounts for only $1.4 billion of that total, as a stand-alone category it has risen 74% in dollar growth over the same period (Ibid). This rise in self-identified vegetarians, vegans, and overall plant-based meat sales is thought to go hand-in-hand with the modern zeitgeist around reducing meat consumption, no matter if the reason is environmental, personal health, or related to animal welfare. From celebrity-endorsed vegan diets to NYC public schools implementing a citywide Meatless Monday initiative, it is hard to find public conversations about meat consumption that do not bring up some negative opinions (Curry, 2019).

Compounding negative media attention surrounding beef production, COVID-19 has exposed longstanding problems with concentration in meat processing with the big four meat packers (Cargill, JBS USA, Tyson Foods and National Beef Packing) and the resulting economic struggles ranchers face in a consolidated market. While ranchers experienced meager returns on their cattle, this has not been the reality seen by consumers at the grocery store. Consumers, used to inexpensive and readily available beef, faced multiple unexpected meat price shocks during and after the COVID pandemic. These rising prices and the resulting consumer outcry led the Biden Administration to begin looking into consolidation among meatpacking plants. Throughout 2021, White House economic advisors released memos of their findings, including that livestock ranchers were paid lower prices while consumers continued to see rising prices and the dominant meat processors were reporting 300% gains in their net margins (Deese et al., 2021).

In January of 2022, the White House announced that USDA would invest $1 billion through the American Rescue Plan to support independent slaughterhouses and meatpackers to increase competition in the industry (The White House, 2022). In April, both the House and Senate Agriculture Committees held hearings with cattle ranchers and USDA employees to review transparency in beef pricing and increase oversight in packinghouses. Two bills addressed at these hearings, the Meat and Poultry Special

Investigator Act of 2022 and the Cattle Price Discovery and Transparency Act of 2022, are poised to also help tip the balance of power back towards small, independent ranchers (Hagstrom, 2022a). At the time of this report, these bills have passed out of their Senate committees and are waiting to be brought to a full Senate vote. Additionally, the President has voiced his support of a related bill that was just passed in the House, which will create an "Office of the Special Investigator for Competition Matters" in the Agricultural Department (Hagstrom, 2022b). While these bills currently have broad support in Congress, they have not become law. Between consumer confusion, climate change, and concentration, at the time this study has taken place beef is of great interest. It will be important to continue to monitor beef interventions and impacts along various parts of the supply chain.

Scope of Study

The scope of this study is the cow-calf supply chain, which takes place on ranches where there is a direct link between range ecosystems, range management, climate, and ranchers' decisions and welfare. Our study finishes with the sale of the calves to backgrounding or feedlot operations (though in some cases ranchers do the backgrounding themselves or keep possession of the animal until slaughter). Following the TEEBAgriFood Evaluation Framework, we focus our analysis on four capitals: natural, social, human, and production.

Natural capital refers to "the limited stocks of physical and biological resources found on earth, and of the limited capacity of ecosystems to provide ecosystem services" (TEEB, 2018). In other words, it is looking at the available resources in an ecosystem and that ecosystem's capacity to create benefits for individuals, organizations, and the environment itself (True Cost Initiative, 2022).

Social capital encompasses networks, institutions, shared norms, values and understanding that facilitates cooperation (TEEB, 2018). Social capital looks at the benefits derived from organizations and individuals developing a set of common values that aid in collaborating or offering assistance between these groups (True Cost Initiative, 2022).

Human capital refers to the proficiency and talents that individuals develop to improve their own welfare in terms of personal health, emotional well-being, and positive social interactions (True Cost Initiative, 2022).

Production capital refers to all manufactured capital, such as buildings, machinery, physical infrastructure, as well as financial capital and intellectual capitals (TEEB, 2018). It is the easiest capital to measure in monetary terms and the one best understood in society.

This study used both qualitative and quantitative methods, as well as different scales of inquiry, to collect data on the dependencies and outcomes of the cow-calf system on natural, social, human, and produced capitals. Using a mixed-methods approach allowed us to better contextualize the system at a regional level, to use robust quantitative data where available, to integrate qualitative data for indicators not available quantitatively, and to enrich and explain quantitative findings with local knowledge derived qualitatively. Consistent with the guidance on the implementation of the TEEBAgriFood Evaluation Framework (Eigenraam et al., 2020) this study project established an Advisory Committee with relevant stakeholders who provided input in our

study design. This study has several components, each with a particular methodological approach, results, indicators, and scale of inquiry (Figure 1). The components are:

(1) Model 1: Statistical model for quantifying the dependencies of the market value of cattle production on the four capitals identified by the TCA assessment. This analysis has been done at the county level for all states in the Western Mountain region of the US.
(2) Model 2: Statistical model using publicly available county-level data for the Western US and measures of the capitals to understand the relationship between community wealth and gross income from ranching, rotational grazing decisions, participation in the Environmental Quality Incentives Program (EQIP) as a proxy for engagement in government programs, profitability, and multigenerational ranch transfer.
(3) 11 case studies with ranchers (six in Arizona and five in Colorado). Each case study consisted of: (i) interviews with the rancher (in person or Zoom); and (ii) responses to a questionnaire.
(4) Soil sampling in two sites of each case study ranch and their respective soil analyses in a lab.
(5) For 10 ranches in the case-studies, temporal analysis (from 1986-2020) with comparisons between a ranch and an adjacent buffer zone to assess impacts on biomass production and biodiversity.
(6) A Life Cycle-Assessment (LCA) of the case-study ranches in terms of greenhouse gas (GHG) emissions, energy, and water impacts.

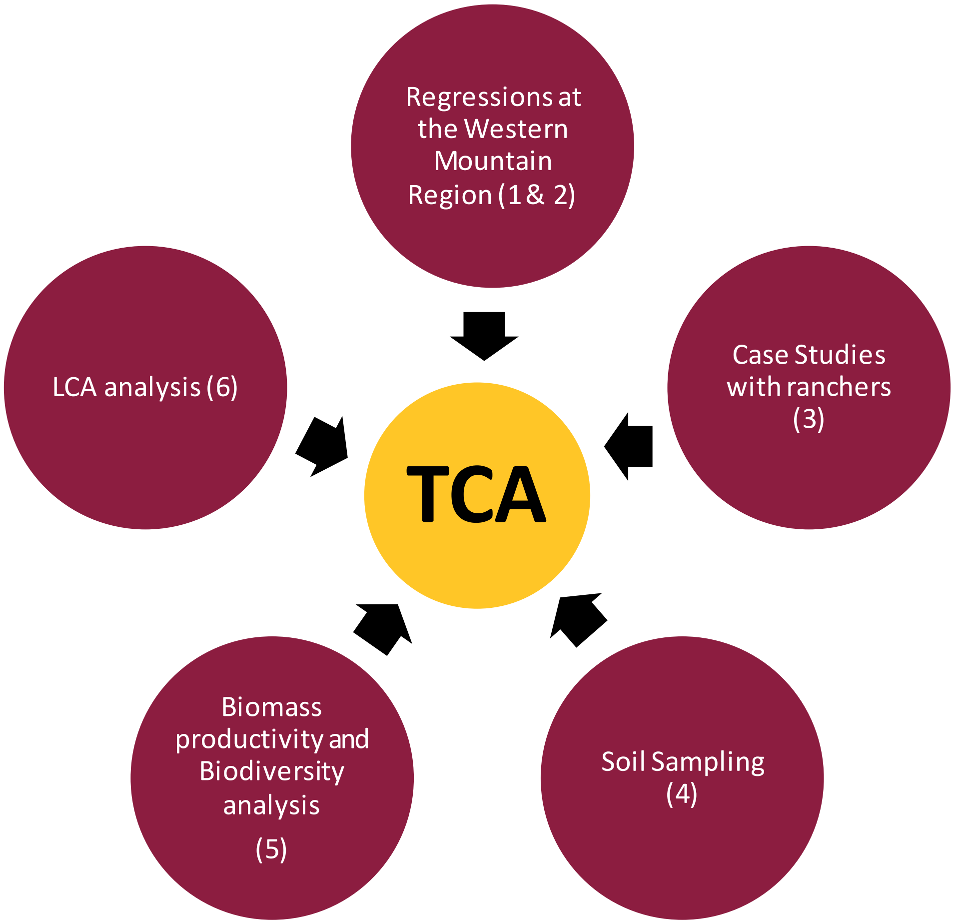

Figure 1. How project components relate to TCA.

We report each component providing information on the specific methodology used to obtain the data that underpins it, and the results. We begin contextualizing dependencies at the Western Mountain region, and follow with a more focused, detailed examination of dependencies and outcomes at the ranch-level to inform the TCA community of practice and build upon methodologies for future work. At the end of the document, we provide a synthesis that explores key take-aways, lessons learned, and our plans for future work. Tables 1 and 2 present the different aspects that constituted the capital base for production associated with the dependencies and resulting the outcomes, respectively, analyzed in the project by the four capitals. We present the indicators used for each aspect, the scale of measurement, the source of the data used, and the type of analysis used to indicate how they relate to the components in Figure 1 (number in parenthesis). Figure 2 presents a chart of the natural, human, social, and produced capital stocks, flows, and outcomes assessed reflecting the variables described in Tables 1 and 2. This figure is based on the model presented in Eigenraam et al. (2020; see also Figure 3 below).

Table 1. Dependencies.

Capital	Aspect	Indicator	Scale	Data	Source	Analysis
Natural	Land	Area in acres	ranch	survey	Ranchers' surveys	descriptive (3)
		Percent total acres in conservation-related programs and woodlands	county	secondary	USDA FSA (2017)	Regression analysis (2)
		Percent of total acres in conservation-related programs and woodlands	county	secondary	USDA FSA (2017)	Regression analysis (2)
		Percent of farmland acres designated as prime farmland	county	secondary	USDA NRCS (2012)	Regression analysis (2)
		Natural amenities scale	county	secondary	McGranahan (1999)	Regression analysis (2)
	Biomass	Annual & perennial forbs and grasses biomass production in pounds per acre	county	secondary	Rangeland Analysis Platform (2022)	Regression analysis (1)
	Water	Water consumption per animal	ranch	survey	Ranchers' surveys	descriptive (3)
	Energy	Fuel and electricity consumption by ranch	ranch	survey	Ranchers' surveys	descriptive (3)
Social	Diversity in size of cattle operations	Diversity of operations by herd size per county	county	secondary	USDA NASS (2017a)	Regression analysis
	Social capital (positive)	County social capital index	county	secondary	Rupasingha et al. (2006)	Regression analysis (1& 2)

	Social capital (negative)	County based on crime statistics	county	secondary	USDJ FBI (2014); CDC, (2014)	Regression analysis (2)
	Cultural capital	Arts and cultural institutions-libraries & museums	county	secondary	USDA ERS (2014), US Census Bureau (2010a, 2014), Kushner & Cohen (2018)	Regression analysis (2)
		Creative capital-creative industry businesses	county	secondary	Kushner & Cohen (2018)	Regression analysis (2)
Human	Experience	Years of experience	ranch	survey	Ranchers' surveys	descriptive
		Age diversity	county	secondary	USDA NASS (2017c)	Regression analysis (1)
	Labor	Amount of paid labor	county	secondary	USDA NASS (2017d)	Regression analysis (1)
		Amount of unpaid labor	county	secondary	USDA NASS (2017d)	Regression analysis (1)
	Health related aspects	Health factors and outcomes, formal education	county	secondary	RWJF (2010), US Census (2010b)	Regression analysis (2)
	Health security	food secure population, population with health insurance, access primary care	county	secondary	Feeding America	Regression analysis (2)

					(2010), RWJF (2010)	
Produced	Infra-structure	Fences, water points, pipelines,	ranch	survey	Ranchers' surveys	descriptive (3)
	Assets	Asset value of buildings, land, machinery,	county	secondary	USDA NASS (2017e, f)	Regression analysis (1)
	Built capital	Number of food, beverage, and other establishments	county	secondary	US Census Bureau (2014)	Regression analysis (2)
		Highway and broadband infrastructure	county	secondary	Derived from NTIA State Broadband Initiative (2011) data	Regression analysis (2)
	Financial capital	Financial capital solvency	county	secondary	US Census Bureau (2007), FDIC (2016)	Regression analysis (2)

Table 2. Outcomes.

Capital	Aspect	Indicator	Scale	Data	Source	Analysis
Natural	Biomass	Changes in annual & perennial forbs and grasses biomass production in pounds per acre 1986-2019	ranch	secondary	Rangeland Analysis Platform (2022)	Comparisons of ranches vs buffer (5) & regression analysis (1)
	Soil	Various soil characteristics	ranch	soil samples	Soil sampling in ranches Arizona & Colorado	Soil analysis (4)
	Water	Quantity and monetary value of water consumption per animal	ranch	survey, secondary	Ranchers' surveys, other sources	LCA (6)
	Energy	Quantity of energy consumption by ranch	ranch	survey, secondary	Ranchers' surveys, other sources	LCA (6)
	CHG	Quantity and monetary value of Carbon emissions and sequestration (including methane)	ranch	survey, secondary	Ranchers' surveys, other sources	LCA (6)
	Biodiversity	Changes in environmental heterogeneity as indicator of biodiversity 1986-2019	ranch	secondary	Rangeland Analysis Platform (2022)	Comparisons of ranches vs buffer (5)
	Wildlife	Wildlife presence in ranch (species observed)	ranch	survey	Ranchers' surveys, other sources	descriptive (3)

	Conservation	Adoption of rotational grazing	county	secondary	USDA NASS (2017g)	Regression analysis (2)
		Participation in Environmental Quality Incentives Program (EQIP)	county	secondary	USDA NRCS (2012) https://hensen.shinyapps.io/eqip/	Regression analysis (2)
Social	Diversity in size of cattle operations	Marginal monetary value of diversity of operations by herd size per county	county	secondary	Regression estimate	Regression analysis (1)
	Social capital (positive)	Marginal monetary value of county social capital index	county	secondary	Regression estimate	Regression analysis (1 & 2)
Human	Quality of life	Availability & costs health care	ranch	survey	Ranchers' surveys, other sources	descriptive (3)
		Subjective assessment of Quality of life	ranch	survey	Ranchers' surveys, other sources	descriptive (3)
	Succession plan	Presence of succession plan	ranch	survey	Ranchers' surveys, other sources	descriptive (3)
		Fraction of multigenerational grazing operations	county	secondary	USDA NASS (2017h)	Regression analysis (2)
	Labor	Marginal monetary value of paid labor	county	secondary	Regression estimate	Regression analysis (1)
		Marginal monetary value of unpaid labor	county	secondary	Regression estimate	Regression analysis (1)
		Marginal monetary value of age diversity	county	secondary	Regression estimate	Regression analysis (1)

Produced	Assets	Inventory and sales of cattle	ranch	survey	Ranchers' surveys, other sources	descriptive (3)
	Profitability	Operational costs	ranch	survey	Ranchers' surveys, other sources	descriptive (3)
		Revenues	ranch	survey	Ranchers' surveys, other sources	descriptive (3)
		Gross income from sales of cattle including calves	county	secondary	USDA NASS (2017i)	Regression analysis (1)
		Share of livestock operations that are profitable	county	secondary	USDA NASS (2017h)	Regression analysis (2)
		Gross income from ranching as percent of total agricultural sales	county	secondary	USDA NASS (2017h)	Regression analysis (2)

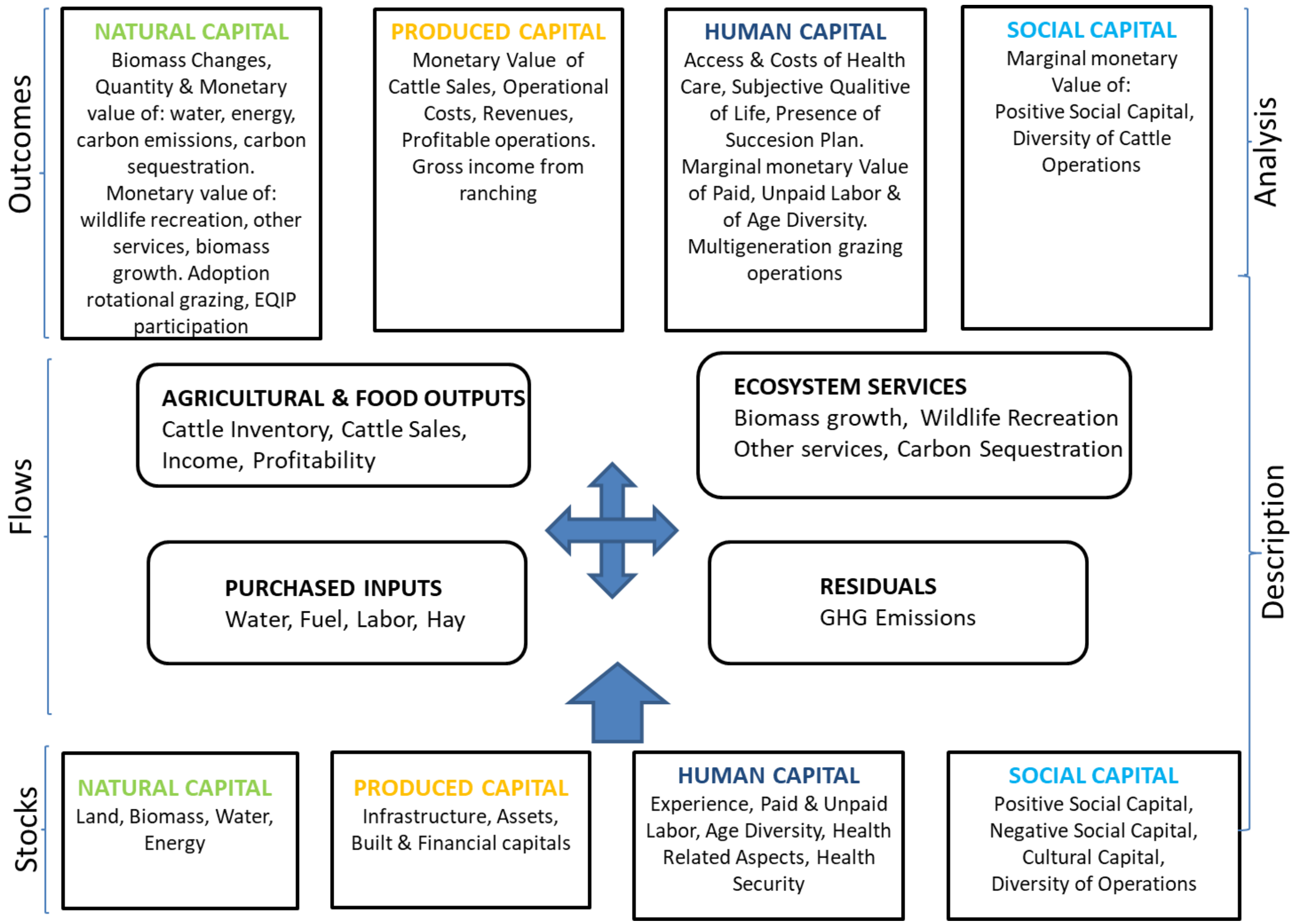

Figure 2. Chart of the natural, human, social, and produced capital stocks, flows, and outcomes analyzed.

Literature Review

True Cost Accounting

The Economics of Ecosystems and Biodiversity for Agriculture and Food (TEEBAgriFood) Evaluation Framework (TEEB, 2018) is the foundational basis for applying TCA to evaluate food products, agricultural systems, diets, national accounts, and policy options in agriculture and food systems (Sandhu et al., 2021). It emphasizes the need to fix the food metrics using a systems' approach that evaluates the impacts and dependencies between natural, human, agriculture, and food systems (Figure 3). The framework applies a multi-capital-based approach and supports the use of monetary and non-monetary approaches to impact assessment.

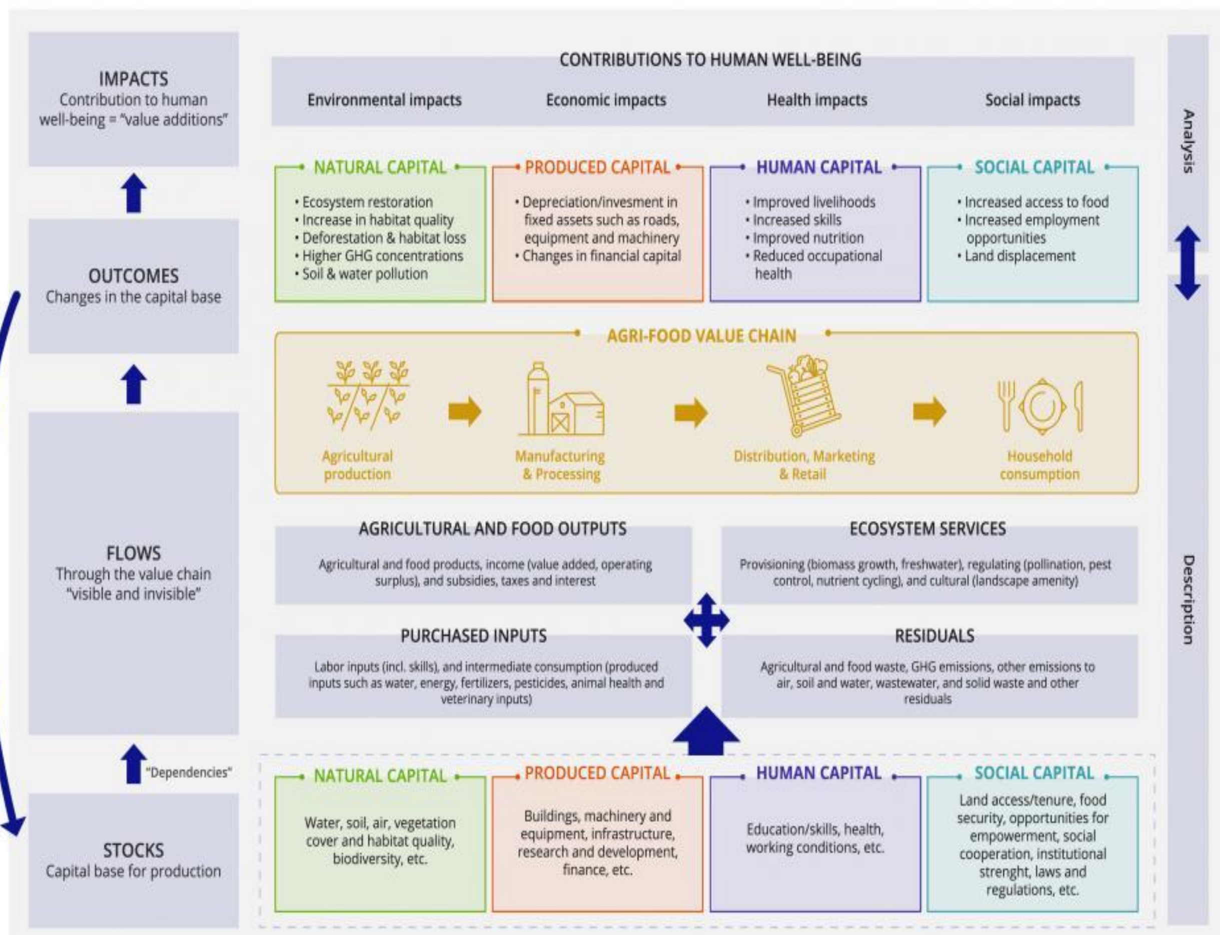

Figure 3. Graphic representation of the elements of the TEEB Evaluation Framework. Source: TEEB, 2018.

Food systems are complex and involve a myriad of products, processes, actors, institutions, networks, and environments, as well as interactions across scales from the consumer, the farm to international trade across the planet. TEEBAgriFood is a flexible evaluation framework that can be applied to different components of food systems and at different scales. The framework is applied by different stakeholders, such as governments, businesses, communities, and farmers (Sandhu et al., 2021) focusing on supply chains of specific commodities or products, productions systems, sectors, industries, and countries. The Global Alliance for the Future of Food (GAFF) has sponsored the development of an inventory of methodologies, case studies, databases, and other resources on TCA (Soil & More Impacts and TMG Thinktank for Sustainability, 2020).

Guidelines have been developed for the application of TCA (Eigenraam et al., 2020; Natural Capital Coalition, 2016; True Cost Initiative, 2022). These guidelines consist of several steps divided into four phases or stages: (1) Frame the issue of interest and purpose of the assessment; (2) Scope the focus of the assessment; (3) Measure impacts and dependencies and value—and if possible, monetize, them; and (4) Apply the results of the assessment and take action. Applying TCA requires defining boundaries and scope of application as well as combining the use of multiple methodologies and data types and sources and this in practice can be challenging (Sandhu et al., 2021). For example, data may not be available or accessible, methods involve assumptions that may not be valid in particular contexts, and there can be multiple sources of uncertainty that impact the TCA results. However, TCA is systematic, transparent, and flexible, and as Baker et al. (2020, p. 767) have stated, it should not be seen as an algorithm that generates specific solutions, but as a tool meant to support decision-makers—farmers, entrepreneurs, and policy makers.

An important but controversial issue is that of monetizing externalities. By definition, there are no market prices associated with externalities, both positive and negative. The point of monetization in TCA is not to commoditize or privatize nature or other nonmarket aspects of food systems, but to make the system more transparent and arrive at better decisions. Numerous valuation methods can be used to monetize externalities in food systems (TEEB, 2018, Chapter 7 for a description). However, as stated by Lord (2020, p. 3), "[M]onetary estimates are contentious." In particular, one has to be careful about adding up social and private benefits and subtracting natural and social capital costs to determine "total" or "true" value, since "…an amount in an economic valuation cannot necessarily be substituted with an amount of financial value. Monetization of costs and benefits does not necessarily imply substitution of costs for benefits." (Ibid, p. 10).

Despite imperfections in monetization and challenges of substitution, the tactic of monetizing and comparing costs and benefits for decision-making has long been used by governments as Cost Benefit Analysis (CBA). It has been argued that TCA is not a new concept, but can be seen as an evolved, modern variant of CBA (Merrigan, 2021). TCA extends beyond the scope of CBA by aiming to evaluate a wide range of positive and negative externalities. CBA proves challenging and controversial as well, yet it has been applied to numerous issues, highlighting the value of subtracting costs from benefits to arrive at a net benefit/cost monetary amount for decision-making (Ibid). Therefore, reaching a final cost, while disputed, is an important part of the practicality of TCA.

There are an increasing number of studies that are applying TCA to different aspects of food systems around the world (Soil & More Impacts and TMG Thinktank for Sustainability, 2020; University of Cambridge Institute for Sustainability Leadership, 2020). The Rockefeller Foundation (2021) study on the true cost of food of the US food system provides an estimated monetary value for the externalities generated at the country level. There are also TCA studies at different scales and in different countries. For example, related to livestock, Baltussen et al. (2016) analyzed the poultry, beef and dairy production systems on human systems and ecosystems in Tanzania. The Scientific Group for the UN Food Systems Summit commissioned a discussion paper for the 2021 Summit elevating TCA and estimating the externalities of global food production to be $19.8 trillion- nearly double the value of the current total global food consumption ($9 trillion; Hendriks et al., 2021). Significantly, the final paper put forth by the UN Scientific Committee recommends TCA to help manage externalities (von Braun et al., 2021).

The Negative Externalities of Beef

Externalities are a concept that connects economic production and consumption to indirect effects on both the environment, human health, and society, which may be either negative or positive effects (Helbling, 2020). Godfray et al. (2018) looked at some of the negative externalities created by meat production (not limited to only beef) and found a diet with high consumption of red meat led to increased risk of several diseases, including colorectal cancer and cardiovascular diseases. Their study also addressed the larger issue of meat production's role in climate change, especially in creating greenhouse gas (GHG) emissions and using freshwater resources. Godfray et al. positioned meat production and consumption as an ethical decision, particularly where wealthier countries can afford the monetary price of meat-heavy diets but globally all countries are faced with the burdens stemming from the increased effects of climate change. Therefore, a key concern when studying externalities is who benefits and who (or what) bears the cost.

While the Godfray et al. study focused on meat in general, including pork and poultry, studies focusing on beef livestock production trace several environmental externalities to cattle. For example, a 2019 Life Cycle Assessment publication found multiple negative environmental impacts stemming from beef livestock operations, including GHG and carbon emissions, fossil fuel consumption, blue water use, and nitrogen and phosphorus runoff into the water supply (Rotz et al., 2019). One downstream issue from this spread of nitrogen into nearby water sources is the eutrophication of lakes and rivers, which can lead to fish deaths and a loss of aquatic biodiversity (EPA, n.d.). A report in *Nature's* Knowledge Project listed eutrophication as a leading cause of water pollution in ecosystems located around both freshwater and coastal environments (Chislock et al., 2013). Additionally, though some consumers believe "grass-fed" beef to be more environmentally-friendly, there is controversial evidence that cattle finished on grass are responsible for more GHG emissions than cattle raised on a feedlot (Gerssen-Gondelch et al., 2017; Pelletier et al., 2010; Souza et al., 2022). These studies looked at feedlot cattle reaching market weight sooner than grass-fed, as well as the high fiber diet of grazing cattle which produced more GHG emissions with an overall lower CW.

One caveat surrounding such controversial findings is that improved grazing management can offset grass-fed emissions by utilizing the rangelands' ability to sequester carbon in soil (Stanley et al., 2018). For instance, adaptive multi-paddock grazing management has been shown to improve soil health across multiple criteria, including carbon sequestration but also by increased water retention, efficient nutrient cycling, and supporting biodiversity both above and below ground (Teague & Barnes, 2017). Further complicating matters in comparing grass-fed cattle to feed lots is that the grain rations used in a feedlot often require synthetic fertilizer, pesticides, and

transportation as opposed to the low/no-input native grasses and plants growing on rangeland (Capper, 2012). Lastly, to return to above point about diet, specific pasture management of grass-fed operations can also change the quality and fiber ratios in the feed, mitigating noted differences in GHG emissions (Ouatahar et al., 2021). Kumar et al. (2014) detailed a number of experimental methane mitigation strategies, including selecting plants that produce methane-reducing secondary compounds, offering cattle lipid supplements and organic acids, and utilizing phages (a virus that destroys bacteria) to target methane-producing bacteria inside of cattle rumen. So, depending on the scope of these studies and the variables considered, the same method of beef production can reflect either positive or negative externalities, depending on the framing (Capper, 2012). Klopatek et al. (2022) demonstrated this in their report that looked at four different cattle systems: conventionally-raised steers finished on grain for 128 days, grass-fed for 20 months, grass-fed for 20 months and grain finished for 45 days, and lastly grass-fed for 25 months. The report found both positive and negative externalities in each system, such as the lower GHG emissions of conventional systems coming at the highest energy cost, while the 20-month grass-fed system had the highest emissions with the lowest water use (Klopatek et al., 2022). Looking at the complete beef production system in this way is the best way to understand the complexities of differing systems. True Cost Accounting, like the LCA used by the Klopatek et al. study, allows us to understand the intricacies behind these different agricultural models.

Overgrazing, defined as grazing to such an excessive extent that vegetation is destroyed beyond the point of regeneration, leaves patches of bare earth behind which creates a risk of generating more negative externalities (Teague et al., 2011). Occurring most often in ecosystems lacking an evolutionary history of grazing by large herbivores (Milchunas, 1988) or around key resources such as water, overgrazing leads to negative externalities such as soil erosion and a decrease in water infiltration of the soil. This erosion occurs from cattle consuming rangeland plants faster than the plants can regenerate, which creates a feedback loop of cattle grazing becoming more concentrated on the remaining grasses (Bestelmeyer et al., 2018). Arid and semi-arid rangelands are also at additional risk of a specific type of land shift called desertification, where the ecosystem moves towards desert conditions and away from a rangeland system (Angerer et al., 2016). Livestock overgrazing also suppresses the growth of new grass, allowing woody shrubs to encroach on these rangelands and compete for dominance in the environment (Anderies et al., 2002). When these woody shrubs replace the rangeland there are a range of ripple effects, from biodiversity shifts in the rangeland, to the shrubs allowing more wind and rill erosion, and the loss of rangeland reduces the forage available to livestock (Angerer et al., 2016). While these shifts in land use are often perceived as a negative outcome for ranchers, who are the main beneficiaries of a productive rangeland, a patchwork ecosystem of rangelands and

shrublands has been found to support diverse groups of plants and animals, even if they are not endemic ecological groups (Bestelmeyer et al., 2018).

A secondary effect of desertification and spread of woody shrubs is an increase in the risk of forest fires. Shrubs have the dual characteristics of burning at hotter temperatures than grass and burning slower, extending the amount of time they stay ignited (Ozeran, 2019). Coupled with extended droughts in the Western US, this change in rangeland ecosystems increases the risk of widespread fires. The increase in forest fires can be in part, attributed to the practice of overgrazing. Managed grazing that does not lead to desertification has been found to have a positive effect on suppressing forest fires (Anderies et al., 2002). A second caveat is that grazing is not the only activity that can lead to desertification; changes in climate that favor drought and increased average temperature naturally select for more resilient shrubs that can access groundwater reserves unobtainable by grasses (Bestelmeyer et al., 2018).

Some controversial research finds that livestock grazing is always detrimental to wildlife and biodiversity. Such articles attribute this to a number of factors. Livestock can negatively impact rangeland both by overgrazing for food and by the trampling effect of their hooves, which disturb bird, rodent, and reptile habitats (Jones et al., 2003; Lindenmayer et al., 2018). Livestock grazing has the greatest negative impact on organisms that are primarily dependent on plants for sustenance, with livestock outcompeting native herbivores and pollinators (Filazzola et al., 2020). There are also described problems of ranchers killing large predators to protect their livestock, which further destabilizes the ecosystem and has been shown to be ineffective at reducing livestock mortality rates from predation (Goldfarb, 2016). Additionally, cattle waste products have been shown to have a detrimental impact on freshwater sources, which can kill aquatic species (Bragaglio et al, 2020; Foley et al., 2012). A study by Buxton et al. (2020) also noted that cattle waste in water leads to a significant rise in mosquito populations, which can increase the chance for vector-borne diseases to spread. Other studies find that negative impact on wildlife and biodiversity from grazing is context dependent, and that differences in ranch management lead to variable outcomes (Öllerer et al., 2019; Schieltz & Rubenstein, 2016; Veblen et al., 2019).

In evaluating different negative externalities, one trend reoccurs: these negatives can be either exacerbated or nullified depending on the herd density and grazing practices employed by the operation. For example, better managed systems of grazing can help remove organic material and reduce the severity of forest fires. Alternatively, poor grazing practices increase this risk. In the example of GHG emissions, cattle left to overgraze an area will release carbon and increase erosion, while cattle in regular grazing rotation can help to build soil health and fertility. It is important to keep this

distinction in mind when framing the narrative around livestock ranching, as operational practices vary widely. To return to our grazing example, a report issued through ERS notes that only 40% of all types of cow-calf and cow-calf combination operations employ rotational grazing. Of this 40%, 16% employ intensive rotational grazing (averaging 14 days or less per paddock) and 24% perform basic rotational grazing (averaging more than 14 days per paddock), which makes for widely different range conditions between operations (Whitt & Wallander, 2022).

The Positive Externalities of Beef

Farmers and ranchers produce multiple goods for society, including food, fuel, fiber, and in our specific case, cattle. There are numerous economic benefits tied specifically to ranchers utilizing Western lands for grazing: the Bureau of Land Management (BLM) estimated that in 2020 grazing on federal lands added 36,000 jobs and contributed $2.4 billion to the US economy (BLM, 2021a). While the culture of Western beef production abounds with images of cowboys and dusty cattle drives, a more recent phenomenon has erroneously connected ranchers with holding negative beliefs around land conservation. The 1970's saw the rise of several "sagebrush revolutions," where Western farmers and ranchers rose up against what they saw as government overreach, particularly when it came to the BLM enacting size restrictions for herds grazing on federal lands (American Folklife Center, 2002). These arguments and protests were widely covered in the news, which led to a public perception that ranchers were anti-conservation (Thompson, 2016). What has actually been found is that while Western ranchers hold a range of opinions—both positive and negative—of the federal government, nearly all ranchers hold only positive opinions of conservation, land ethic, and wildlife management (Lien et al., 2017).

Along with nearly universal support for conservation among ranchers, there is also evidence of other positive externalities, including recreational value, water conservation, and maintaining open space. Possibly the greatest positive impact from ranching is keeping the land "open" and safe from development. Further amplifying this impact, ranchers view the passage of property ownership from generation to generation as its own kind of conservation, as this prevents the land from being fractured into smaller parcels and developed (Schilling et al., 2015; Wilmer & Fernández-Giménez, 2016; Wilmer et al., 2020).

Ranching's preservation of open space has numerous positive effects, from protecting freshwater resources, allowing free movement of animal migration, maintaining space for wildlife habitats, and allowing rangelands to act as a cover to prevent wind and rill erosion (NRCS, 2010). There have also been several studies that demonstrate how herbivory performs an ecosystem service by maintaining habitats for other species, especially birds (Allison & Bender, 2017; Boyce et al., 2021; Ogada et al., 2008). Multiple species of rangeland birds have seen dramatic population drops over the past five decades, but their species density and diversity have been shown to increase on grazed lands (Boyce et al., 2021). This occurs because cattle grazing at low herd densities create habitats that are favored by a range of threatened species, remove overgrown vegetation that can prevent species from nesting, and also deter predators from entering the rangeland due to the cattle's large size (Allison & Bender, 2017; Ogada et al, 2008). As was previously discussed in the Negative Externalities section,

many of these environmental impacts are context dependent, and different grazing management yields varied outcomes.

Filazzola et al., (2020) conducted a meta-analysis of the impacts of cattle grazing and while they concluded that excluding cattle from temperate environments (such as forests in the North Pacific) could benefit native biodiversity, they also noted four independent studies that showed cattle increase both plant and animal diversity on rangeland. This increase in biodiversity is attributed to the inherent open nature of rangeland and that indigenous rangeland species are already adapted to open spaces and do not require extensive ground cover (Schieltz & Rubenstein, 2016). Schieltz & Rubenstein (2016) noted the wide variability of different ecosystems, indigenous species breeds, and grazing management strategies employed in cattle operations made it difficult to broadly declare whether grazing has more positive or negative externalities on wildlife and biodiversity. Instead, they call for expanded research on the different variables of grazing, wildlife, and cattle to understand the contextual relationship and impacts among these variables (Schieltz & Rubenstein, 2016).

While these impacts on wildlife are crucial from an ecological standpoint, the general public may be more personally familiar with the benefits from recreation on federal lands. These BLM lands—the same used for cattle grazing—are also open to the public to use for fishing, hunting, boating, hiking, and biking (BLM, 2021a). While there have been some concerns about grazing animals polluting water sources at recreational areas, studies have shown that this is rarely the case with managed grazing and water quality will return to normal unless stagnant conditions are present (Roche et al., 2013). As we will see throughout this report, a key factor here is "managed grazing," as overgrazing with either too many cattle or for too long of a sustained period will lead to land and water degradation (Brock & Green, 2003). With that distinction in mind, it has been shown that grazing and recreation are compatible functions of federal land (Wolf et al., 2017).

While land preservation might be seen as a passive activity, ranchers also engage in the active creation of positive externalities. An example of this would be building stock tanks that allow wildlife and migratory birds access to drinking water, something increasingly important as drought conditions continue across the Western United States (Rosenstock et al., 1999). Upkeep of the land is a positive externality that stems from some ranchers' desire to maintain the rangeland in a way that it is still accessible to the public at large.

Many ranchers are motivated to keep the land accessible as a public place of enjoyment and recreation (McSweeney & Raish, 2012). A 2021 case study by Reiter et

al. found that a majority of the ranchers polled felt that the public should be made more aware of the great lengths that ranchers go to protect these open spaces. One respondent in Reiter et al.'s (2021) study noted that if species conservation was part of the "greater good," then the public should support ranchers who help to preserve the rangeland for native species (p. 2386). In multiple publications, ranchers described themselves as stewards of the land who protect their ecosystems from negative impacts such as overdevelopment, excessive removal of resources, as well as maintaining the integrity of the ecosystem to continue to provide a habitat for livestock, wildlife, and a wealth of plant biodiversity (Lien et al., 2017; Raish & McSweeney, 2001). Wilmer and Sturrock (2020) looked to explore the mental state of a rancher to aid in modeling how decisions are made on a ranch. The rancher in their case study explained how as time went on, they realized they had less direct control over the land and environment, which shifted their decision-making to be more adaptative to the environmental conditions of any given year. This deference to the land and the corresponding importance on conservation and environmental protection is theme that repeats across multiple publications (Lien et al., 2017; Schilling et al., 2015; Wilmer & Sturrock, 2020; Wilmer et al., 2020).

Ranching generates important social and human value. Ranchers often note being drawn to their line of work because of the personal satisfaction they enjoy from an occupation in nature and agriculture (Lien et al., 2017). They often see one another as an interconnected community, even when competing for the same market share (Cronk et al., 2021). The concept of trust is succinctly framed in Falk and Kilpatrick's (2000) description as, "the critical component of any social cohesion" (p. 90). In ranching specifically, social capital is often referenced in publications as the "trust" ranchers have between themselves and members of the community that allows them to cooperate in times of need or when unexpected events disrupt normal ranching functions (Buckley Biggs, 2022). Ranchers can pull from this bank of social capital during times of economic and environmental hardship, such as an extended drought, which allows ranchers to build their adaptive capacity to unforeseen events (Bailey et al., 2019; Wilmer et al., 2020). What is especially interesting considering the individualism that traditionally defined Western ranchers is a trend to not expect to be repaid for providing mutual aid to other ranchers in times of need (Cronk et al., 2021). Ranchers view the larger sense of community (including high levels of rancher participation in cattle auctions, religious organizations, livestock business associations, 4H groups, and bull sales) as crucial for sharing information, sourcing outside expertise, and/or facilitating mutual aid when a member of the community experiences hardship (Cronk et al., 2021; McSweeney & Raish, 2012; Njuki et al., 2008).

Alongside the exchange of support, ranching builds identity and fosters diverse skills and the capacity of adaptive management in rural communities that can be sustained from one generation to the next. For the ranching families involved—as well as the broader community—this not only provides economic stability, but also works to support continued agricultural production on the rangeland (Raish & McSweeny, 2001). A 1999 conservation study by Pima County, AZ, highlighted the importance of this generational transfer of knowledge, stating:

> "For ranching and farming families, there is a knowledge and intimacy with the land that grows out of first-hand experiences. Moreover, they have the benefit of a wealth of wisdom passed on from previous generations who lived on the same land and know how to conduct the business of cattle growing and caring for the land. This fund of knowledge simply cannot be learned and understood as well as someone raised in that culture and on the land." (Mayro & McGibbon, 1999, p. 21)

Especially notable is that ranchers who identify as multigenerational ranchers have better resources and knowledge to pull from in instances of drought or other disasters, compared to first generation ranchers (Wilmer & Sturrock, 2020).

Many of the positive externalities generated from cow-calf and cow-calf combination operations blend across the four types of capital. A rancher can create human capital by employing members of the local community. These employees extend the rancher's social capital, while their increased labor on ranchlands improves the potential for greater production capital and natural capital (Ait Sidhoum, 2018). Grazing on rangeland prevents the range from being fragmented into smaller lots (natural capital) and keeps this land open to be used for produced capital with renewable sources of energy, such as wind and solar (Anderies et al., 2002). A connection has also been found with social capital creating a sense of peer-pressure, where ranchers do not want to be seen in their community as degrading the natural resources of the region. This social connection is so strong that it was found that ranchers with better standing in the community could encourage neighboring ranchers to take up innovative conservation practices, even without monetary compensation (Kreuter et al., 2006). These examples are a testament to the complexity inherent in beef livestock production and why the benefits of ranching are much greater than how many head of cattle a rancher produces.

The Cow-Calf System

Today's beef livestock operations are complex, multifaceted systems with operations including heterogenous practices and goals. While pastoral imagery exists around calves being born on-farm and living out their lives on adjacent pasture, there are several distinct phases of livestock production that have developed to meet consumer needs, market pressures, and best utilize economies of scale. The cow-calf supply chain is the dominant beef production system in the US, particularly in Arizona and Colorado. It consists of three stages (based on McBride & Matthews, 2011):

(1) Cow-calf: The cow herd is maintained for breeding, gestation, and calving until calves are weaned between 6 and 9 months of age, where they will weigh between 400-700 pounds.
(2) Backgrounding or Stocker: Weaned calves are raised mostly on forages, such as pasture and hay, sometimes in combination with grains, in order to increase their maturity and weight (by 200-400 pounds) before placing them in a feedlot.
(3) Feedlot: Calves are finished with a combination of forage and grain to reach a slaughter weight of 1,000-1,500 pounds. Lastly, they are sold to a slaughterhouse for processing and packing. In some cases, the producers retain the ownership of the calves throughout the different stages and until they are finished in the commercial feedlot.

> A cow-calf program's biggest benefit also comes from their biggest hurdle: access to land.

American beef production has consistently trended towards specialization and consolidation. Cow-calf operations are the first step in beef livestock production, where mature cows are bred and new calves are born. A cow-calf program's biggest benefit also comes from its biggest hurdle: access to land. The majority of a cow-calf programs' feed comes from foraging on pasture rather than from more expensive supplemental feed. If a farmer does not have access to productive pastures, however, they may find their land does not support a cow-calf operation (Fairbairn et al., 2020).

The grass-fed beef supply chain is a growing alternative to the conventional cow-calf supply chain. It still is small, however, accounting for less than 5% of the beef produced in the US (Bauman, 2021). It is defined as one in which the beef cattle are raised on grazed or stored forage for their entire lives, including through finishing. Most commonly, grass-fed cattle spend their entire lives on a single ranch or farm, differing distinctly from the grain-fed system. As grass-fed production grows, grass-based backgrounding and feedlot operations may emerge, but to date this has not occurred.

Grazing Fees

In the West, land is comprised of a patchwork of private and public lands. Due to the large amount of forage needed in cow-calf and cow-calf combination operations, ranchers often depend on public grazing permits to remain economically viable (Arnett, 2019). With Western expansion, best quality rangeland was often settled, but ranchers continued to graze on unsettled public rangelands to supplement limited private forage for their cattle. In response to decreased range health from overgrazing, the Forest Service (FS) established a federal grazing fee and leasing policy for rangelands in 1906 (Vincent, 2019). Non-FS federal lands did not fall under regulation or have designated grazing allotments until the Taylor Grazing Act (TGA) of 1934. Requested by Western ranchers for increased grazing access, TGA established a Grazing Service Agency to administer grazing fees and permits (Merrill, 2002).

In 1946 the Grazing Service Agency and General Land Office were merged to create BLM. Combined, the FS and BLM manage more than 98% of Federal grazing land today, with the remaining 2% managed by eight other agencies for land management purposes such as the US Fish and Wildlife Service that uses grazing to reduce less favorable grasses to promote prioritized bird species, or the US Department of Defense using livestock to maintain a favored grass height (GAO, 2005). Most of the land managed by the FS and the BLM is Western land, with a significant amount in rangeland. BLM manages 245.7 million acres with 154.1 million acres available to graze, and a total grazed acreage of 138.7 million in FY2017. The FS manages 192.9 million acres with 93 million acres available to graze, and a total grazed acreage of 74 million in FY2017 (Vincent, 2019).

BLM and FS grazing fees are both based on a formula from The Public Range Improvement Act (PRIA) of 1978 (OFR, 2016). PRIA established a fee formula to determine grazing fees on Western lands and was later permanently extended through President Reagan's Executive Order 12548 in 1986 (OFR, 2016). The PRIA formula:

> "Equals the $1.23 base established by the 1966 Western Livestock Grazing Survey multiplied by the result of the Forage Value Index (computed annually from data supplied by the Statistical Reporting Service) added to the Combined Index (Beef Cattle Price Index minus the Prices Paid Index) and divided by 100; provided, that the annual increase or decrease in such fee for any given year shall be limited to not more than plus or minus 25 percent of the previous year's fee, and provided further, that the fee shall not be less than $1.35 per animal unit month." (Executive Order 12548)

Using the 1966 base of $1.23, grazing fees under the PRIA formula are adjusted according to three variables: current private grazing land lease rates, beef cattle prices and the cost of livestock production (BLM, 2021b). While both the FS and BLM use the PRIA formula, FS uses head-month units (HD-MO), and BLM uses animal unit month (AUM). The units are fairly equitable, and result in a uniform grazing fee for FS and BLM land (they have charged the same rate since 1981). Federal grazing fees cannot be 25% higher or lower than the previous years and even with allowable changes they have remained relatively stagnant over time (Vincent, 2019).

The low and stagnant fees charged for public grazing in the West have been subject to public debate, with some pushing for an end to federal grazing and others calling for an increase in grazing fees, which they feel subsidizes ranching on public lands (Cody & Baldwin, 1998; Maxwell, 2019). Such debate is often connected to negative perceptions of grazing's impact on wildlife as discussed earlier, a lack of cost recovery for program administration, or arguments that pricing is not equitable to non-federal grazing leases, which are priced much higher due to bidding systems or formulas used in pricing (GAO, 2005). Ranchers advocate that the current fee system is fair; BLM and FS land is often lower quality than private or state land in the West, with less services and amenities provided along with many non-fee costs including maintenance costs, the cost of public use on the rangeland, and a higher price paid for the ranch due to its position regarding federal land (Burns & Schick, 2016; Glaser et al., 2015; Pianin, 2014). In short, grazing fees are a contentious element of ranching in the West, and multiple-use functions of public lands must be considered when analyzing cow-calf and cow-calf combination systems.

Dependencies and Stocks of Capital at the Regional Level

Model 1: Quantifying Dependencies of the Market Value of Cattle Production

To quantify the dependencies of the market value of cattle production, the most important "private" provisioning service from rangelands, on the four capitals, we developed a statistical model of the gross value of the sales of cattle and calves reported in the last Census of Agriculture (USDA NASS, 2017i) as a function of variables representing each of the capitals obtained mostly from the Census (USDA NASS, 2019). We use data from most counties[5] in the eight states of the West Mountain region of the US.

For natural capital, we use the score of the first principal component derived from a Principal Component Analysis (PCA) on the average annual biomass production of Annual and Perennial Forbs and Grasses in pounds per acre (AFG and PFG respectively) and their coefficients of variation calculated over a 31-year period (1986-2017). The data was obtained from the Rangeland Production Dataset (Rangeland Analysis Platform, 2022.)

For social capital, we use two variables. The first is a county-level index of social capital developed by Rupasingha et al. (2006) calculated for 2014 downloaded from https://aese.psu.edu/nercrd/community/social-capital-resources/social-capital-variables-for-2014/social-capital-variables-spreadsheet-for-2014. This index is the score of the first principal component derived from a PCA of the number of different types of organizations per capita, the percentage of voters who voted in presidential elections, the county-level response rate to the Census Bureau's decennial census, and the number of tax-exempt non-profit organizations per capita, by county. While the original index was calculated for all counties in the US, here we re-calculated the score only for counties in the Western states to reduce extraneous variation. The second variable is the Simpson diversity index of cattle operations of different scale[6] present in a county.

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[5]For some counties there was no data reported due to confidentiality and for a few others, no cattle were produced there.

[6] The Simpson diversity index was calculated based on the proportion of operations (ranches) grouped into seven categories based on the number of head of cattle held: (1-9), (10-19), (20-49), (50-99), (100-199), (200-499) and (500 or more) as reported in the Census of Agriculture 2017 (USDA NASS, 2017a).

For human capital we use three variables reported in the Census of Agriculture: diversity of ages of principal producers (USDA NASS, 2017c), paid labor, and unpaid labor (USDA NASS, 2017d). Labor is probably one of the best indicators of human capital available for a production process, as it reflects the skills and motivations of those involved. The amount of paid labor reflects the stock of workers with the necessary skills to be hired. The amount of unpaid labor is most likely related to the principal operators (ranchers) and their families since they are the most likely workers not to be paid. There is a strong correlation between the number of unpaid workers and persons in the household of principal producers (0.96). Because the number of paid and unpaid workers reported in the Census is for all farming activities and not specific for ranching, we use the average number of workers in the county for both categories to reduce potential biases.[7] Diversity of ages shows a mixture of experience (older ranchers) and innovation and risk taking (younger ranchers) that should positively influence the creation of benefits and the management of costs from cattle production.

For produced capital, we use two variables. The first is the asset value of buildings and land plus the asset value of machinery measured in $ weighted by the ratio of the number of operations with cattle including calves to the total number of operations with asset value (USDA NASS, 2017e, f).[8] The second is a county-level Gini coefficient calculated on the distribution of the number of head of cattle by the size of operations (calculated with data from USDA NASS, 2017a). For example, according to the last Census of Agriculture, across all Western states less than 7% of operations, those with 500 head or more, accounted for almost 70% of all head of cattle, while operations with less than 10 head accounted for 34% of operations but less than 1% of all head of cattle. For the Western states this translates into an overall Gini coefficient of 0.8. A high Gini coefficient indicates that a small proportion of operations concentrate most of the cattle, thus achieving high economies of scale. It has been documented that economies of scale in cattle production are associated with operations with higher profitability and adoption of new technologies (McBride & Mathews, 2011). So, this index can be interpreted as reflecting the profitability of cattle operations at the county level.

We also included the number of operations in a county to correct for the fact that counties with more operations may have larger inventories and higher sales. Since our

[7] In the case of unpaid labor, there was a very high correlation between the number of unpaid workers and the number of operations, so to avoid multicollinearity we use the average number instead. We checked for multicollinearity using the average number of unpaid workers and there was no problem.

[8] This variable had to be weighted because as reported in the Census of Agriculture it refers to all farming operations, not just operations with cattle and calves. The weight is the ratio of the variable "AG LAND, PASTURELAND, (EXCL CROPLAND & WOODLAND) - NUMBER OF OPERATIONS" to the variable "AG LAND, INCL BUILDINGS- OPERATIONS WITH ASSET VALUE" per county.

focus is on cow-calf and cow-calf combination operations in rangelands, but the gross value of the sales of cattle and calves includes animals in dairy operations and cattle on feed, we included two covariates to account for their impact on the dependent variable: the share of operations with milk cows and the share of operations with cattle on feed relative to the total number of operations with cattle.

Finally, we included a series of indicator variables for each state to take into account unobserved factors in each state that could influence the regression outcome, such as differences in history, policies, or infrastructure.

We use Ordinary Least Squares to estimate the model. Regression results (Table 3) show that all indicators of the different capitals were statistically significant indicating that they contributed to the gross value of sales of cows and calves in 2017. For ease of interpretation, we report only the sign of the relationships and the levels of significance for the effects (quantitative coefficients are presented in Appendix F, Table F1). The total value of the sales of cattle for the 236 counties included in the regression was $9,003,368,000, while the average value of the sales of cattle per county was $38,149,864 (USDA NASS, 2017i).

For natural capital, the score of the indicator variable was positive. Given that this score has a strong and positive correlation with average biomass production of perennial forbs and grasses (PFG) (0.70), and strong and negative correlations with the coefficients of variation of both variables (AFG=-0.73, PFG=-0.65), this indicates that counties with higher average annual biomass productivity of PFG and lower variability in both AFG and PFG generate higher gross value.

For social capital, the county-level index of social capital was positive. This index is highly and positively correlated with the number of different tax-exempt non-profit organizations and the number of types of organizations per capita in a county (0.91 and 0.85 respectively), indicating that the social capital of the county contributes positively to gross value.

The Simpson diversity index of cattle operations of different scales has the largest statistical significance of all variables. This is a novel result, suggesting that having more diversity of operations of different sizes contributes to creating multiple business opportunities for supporting goods and services, job opportunities, as well as smaller operations benefiting from the services that the presence of larger operations enable. This is a relationship that merits further research to confirm that in fact this diversity creates a richer social environment that is conducive to more profitable ranching operations as a group, not just individually.

For human capital, paid labor is associated with the gross value of cattle sales. The positive association of diversity of ages suggests that having a mixture of ranchers with different levels of experience and capacities is positive for generating value in cattle production. The negative association of unpaid labor indicates that counties with a higher average number of unpaid workers generate lower gross value of cattle sales. Since ranchers and their families are the most likely to be unpaid workers, it may reflect ranchers' willingness to accept lower returns on investment and be involved in ranching for motivations that go beyond profit-making, probably due to non-market interests such as lifestyle or identity (e.g., Gentner & Tanaka, 2002; McSweeney & Raish, 2012; Torell et al., 2001).

Table 3. Regression results. Dependent variable: Natural log of the gross value of the sales of cattle and calves 2017 ($).

Explanatory variable	**Natural log of the gross value of the sales of cattle and calves (USD)**
Intercept	
Natural Capital	
Principal Component 1	(+)***
Social Capital	
Social capital index	(+)*
Diversity of scale	(+)****
Human Capital	
Average number of paid workers/operations	(+)**
Average number of unpaid workers/operations	(-)**
Diversity of ages of principal operator	(+)****
Produced Capital	
Value of assets building, land, machinery ($)	(+)****
Gini coefficient	(+)****
Covariates	
Number of operations with cattle	(+)**
Share of cattle on feed	(+)****
Share of milk cows	
Arizona	
Colorado	
Idaho	(-)*
New Mexico	
Nevada	
Utah	(-)*
Wyoming	

Significance at the .10, .05, .01, .001 level indicated by *, **, ***, **** for a two-tail t-test.

Produced capital and the value of assets is highly associated with the gross value of cattle production. The Gini coefficient also has a positive and highly significant association with the gross value, indicating that counties with a few larger ranches generate higher gross value which is consistent with the idea that they reflect high economies of scale and thus profitability.

In terms of the covariates, the number of operations with cattle as well as the share of operations with cattle on feed have positive associations with gross value. However, share of operations with milk cows has a negative association. The share of operations of cattle on feed indicates that more intensive production led to higher gross value, while the share of operations with milk cows may indicate the lower value of milk cows when sold. Table 4 presents the elasticities of the gross value of the sale of cows and calves ($) with respect to each of the indicator variables for the four capitals, as well as the monetized value of their marginal contribution based on those elasticities. An elasticity represents the percentage change in the dependent variable for 1% change in an independent variable. An advantage of reporting elasticities is that they are unitless, so they are comparable. This is particularly useful for variables that are either scores derived from a PCA or from an index of diversity. The diversity of ages of principal operators has the highest elasticity, followed by the diversity of operations, both of which are very large. So, a 1% change in diversity of ages increases the value of the gross sales of cattle by 6.2% and a similar increase for diversity of operations increases the gross sales by 5.2%. These increases are very large, larger than the increases associated with an increase in the Gini coefficient of 1.91% which is associated with increased profitability. The importance of these variables is clear by the large, monetized value of their marginal contributions.

Table 4. Elasticities of indicator variables for the four capitals and the monetized value of their marginal contributions.

Natural Capital	**Elasticity (Δ%Y/1% Δx)**	**Marginal value of contribution ($, 2020)[a]**
Principal Component 1	1.051	373,067
Social Capital		
Social capital index	0.200	70,952
Diversity of scale	5.243	1,861,209
Human Capital		
Average number of paid workers/operations	0.194	68,920
Average number of unpaid workers/operations	-0.624	(221,404)
Diversity of ages of principal operator	6.270	2,225,791
Produced Capital		
Value of assets building, land, machinery (USD)	0.762	270,588
Gini coefficient	1.913	676,054

[a] Original values in $ of 2017 updated in the table to $ of 2020 using PPI Commodity from farm products-livestock[9] to make them comparable with the True Cost estimates presented later.

Elasticities were derived from the coefficients in Table 3 (see Appendix F, Table F1) which are semi-elasticities, evaluated at the mean value of each independent variable. Marginal value of contribution was evaluated at the mean value of the dependent variable per county across the eight states of the Mountain Western region.

These results suggest that there are emergent properties that have to do with interactions among ranching operations at the county-level and that go beyond their individual characteristics, and after correcting for more conventional factors such as paid labor, value of assets, biomass productivity, and number of operations. Furthermore, these results show the important dependencies of the key market value generated by cattle production on non-market aspects of both social and human capitals. Unfortunately, we do not understand the mechanisms that mediate these interactions and that underpin these emergent properties.

[9] PPI Commodity from farm products-livestock (https://beta.bls.gov/dataViewer/view/84ec40f9349b4005b4f9278986c1cdf4).

Model 2: Quantifying Dependencies and Desirable Ranch Outcomes

Model 2 is a statistical analysis using secondary data to understand the relationship between the capitals and gross income from ranching, rotational grazing decisions, participation in the Environmental Quality Incentives Program (EQIP) as a proxy for engagement in government programs, profitability, and multigenerational ranch transfer.

This analysis addresses the question: what is the effect of the stocks of wealth on different livestock outcomes? We believe that this approach is useful to begin to quantify the relationships between different types of capital and livestock outcomes.

Methods

Following Schmit et al. (2021) and Jablonski et al. (forthcoming), we use a multivariable indexing approach relying on principal components analysis (PCA) to define our stocks of community wealth.[10] A PCA is the same instrument used earlier in this report, Dependencies and Stocks of Capital at the Regional Level. Schmit et al. (2021) conducted a comprehensive literature review that identified multiple variables associated with measures of community capital stocks. The result is a set of indicators for each of the capital assets from secondary data at the county level for the Western US.

To account for private built capital, the variables include the number of food and beverage manufacturing establishments and other manufacturing establishments per 10,000 people (Table 5). Public infrastructure variables include access to fixed advanced telecommunications (i.e., high-speed internet access) and proximity to interstate highways.

Variables associated with tangible cultural capital include the number of public libraries, museums, creative industry businesses per 100,000 people, and the percentage of workers employed in the arts. For intangible cultural capital, they include a racial/ethnic diversity index based on six ethnic categories tracked by the US Census: White not Latino, African American, Native American, Asian American, Latino, and Other.

Financial capital is defined over stocks of both private and public wealth. For private wealth, they include the number of owner-occupied units without a mortgage per capita and the level of deposits to FDIC-insured institutions per capita. For public wealth, they use county government cash and security holdings net of government debt per capita.

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[10] For more information on PCA please see Appendix D.

They include the percentage of the adult population with a bachelors, graduate, or professional degree as a measure of educational and skills components of human capital. They include Z-scores that represent physical and mental health with respect to today's health (health outcomes z-score) and tomorrow's health (health factors z-score). They also include the percentage of the population defined as food secure, having health insurance, and the number of primary care physicians per 10,000 people.

To capture renewable and nonrenewable aspects of natural capital, variables include the Natural Amenities Scale (NAS) designations, the percentage of acres defined as prime farmland, and the percentage of acres covered by conservation easement. Additionally, they include the collective percentage of acres enrolled in the Conservation Stewardship Program, Conservation Reserve Program, Environmental Quality Incentives Program, Grassland Reserve Program, Wetland Reserve Program, Wildlife Habitat Incentive Program, emergency watershed/floodplain designations, trees for timber, wildlife food plots, and woodland/native understory, much of which includes farmland conversion for environmental purposes. They include the percentage of acres owned and managed by the US Forest Service (USFS, 2017). In addition to the natural capital indicators used by Schmit et al. (2021), we add in some natural capital indicators for annual and perennial biomass to better reflect rangelands and thus natural capital in the Western US. These indicators include the average annual biomass production of Annual forbs and grasses (Afg_ppa) and of Perennial forbs and grasses (Pfg_ppa) in pounds per acre (PPA), as well as the coefficients of variation (Afg_ppa_cv, Pfg_ppa_cv) for both types of biomass production for all counties in the Western Mountain region, calculated for the period 1986-2017. The data was obtained from the Rangeland Production Dataset (Rangeland Analysis Platform, 2022).

Schmit et al.'s (2021) measure of social (including political) capital follows Rupashinga et al., (2006, with updates) based on the number of social business establishments per 1,000 people, percent voter turnout, Census response rate (respn10), and the number of nonprofit organizations excluding those with an international focus per 1,000 people. We also include negative social capital indicators. Social capital has been critiqued for making it appear that everyone has access to resources in a classless social order (DeClercq et al., 2012). In this vein, social capital can be viewed as wealth used to create more wealth only for those with access (Durrenberger, 2002). Similarly, Putnam (2001) considers organizations such as the Rotarians, Oddfellows, Knights of Columbus, and other types of fraternal organizations that may actually undermine equality. To incorporate aspects that undermine social capital and can be understood as indicators of negative social capital, we looked to data available at the county level on crime and drug use. To address this important dimension, we added in five variables to capture negative aspects of social capital, including: drug poisoning by county,

robberies by county, aggravated assault by county, burglaries by county, and driving under the influence by county.

Once the indicators were compiled, following Schmit et al. (2021) and Jablonski et al. (forthcoming), we used PCA to reduce the dimensionality of the data, facilitating a focus on the indicators within each capital type that account for the most variation. We followed Kaiser's rule (e.g., Nunnally & Bernstein, 1994) and retained only factors with eigenvalues exceeding 1.0 and rotated the factor loadings matrix to obtain the highest possible correlations on the fewest possible factors.

The PCA retained 14 components reflecting the different types of community wealth, including: two reflecting built capital, one that loaded heavily on establishments – food/beverage and other, the other on highway and broadband infrastructure; two reflecting types of cultural capital, one of which we refer to as "arts and cultural institutions" and one labeled "creative capital"; for financial capital we retained one component reflecting financial solvency; two components reflecting aspects of human capital, including health-related aspects, and health security; three components related to natural capital, including national forests and variation in perennial biomass, variation in annual biomass, and prime farmland and annual biomass; and four reflecting social capital components including negative social capital, death rate and census response rate, aggregate of social capital, and number of nonprofits. We provide descriptive statistics for each of the indicators, by type of capital, and the retained principal components in Table 5.

Table 5. Capital asset descriptive statistics.

Variable Description	Data Source	Mean	Std. Dev
PC1 - Built capital – establishments (food, beverage and other)	Author-derived	0.00	1.41
PC2 - Built capital – highway and broadband infrastructure	Author-derived	0.00	1.14
Percent of pop with access to fixed terrestrial broadband at ≥25 mbps download/3 mbps upload, June 2011	Derived from NTIA State Broadband Initiative (2011) data	11.84	27.19
Inverse of population-weighted mean distance in km to the nearest interstate highway on-ramp or intersection, 2007	Dicken et al. (2011)	0.09	0.12
Food and beverage manufacturing establishments per 10,000 people, 2015	US Census Bureau (2014)	2.64	9.49

Other manufacturing establishments per 10,000 people, 2015	US Census Bureau (2014)	14.29	68.90
Cultural Capital			
PC1 - Cultural capital - arts and cultural institutions	Author-derived	0.00	1.35
PC2 - Cultural capital - creative capital	Author-derived	0.00	1.21
Percent of workforce employed in the arts (creative class), 2007-2011	USDA ERS (2014), US Census Bureau (2014)	15.37	6.11
Public libraries per 100,000 population, 2012	Kushner and Cohen (2018)	27.69	35.94
Creative industry businesses per 100,000 population, 2009	Kushner and Cohen (2018)	248.62	198.26
Author constructed racial diversity index from 0 (no diversity) to 10 (complete diversity), 2010	US Census Bureau (2010a)	3.64	2.03
Museums per 100,000 population, 2015	Kushner and Cohen (2018)	39.13	39.96
Financial capital			
PC1 - Financial capital - financial solvency	Author-derived	0.00	1.16
Per capita cash and security holdings less government debt, 2007	US Census Bureau (2007)	0.76	1.75
Per capita bank deposits, FDIC-insured institutions, 2016	FDIC (2016)	22.94	41.08
Per capita number of owner-occupied units without a mortgage, 2010	US Census Bureau (2010b)	6,245.59	18,438.84
Human Capital			
PC1 - Human capital – health-related aspects	Author-derived	0.00	1.59
PC2 - Human capital –health security	Author-derived	0.00	1.15
Percent of adult pop with at least a Bachelor's degree, 2010	US Census Bureau (2010b)	27.14	13.66
Health Factors Z-Score, 2013	RWJF (2013)	0.00	0.47
Health Outcome Z-Score, 2013	RWJF (2013)	0.00	0.68
Percent of population food secure, 2010	Feeding America (2010)	84.56	2.99

Percent of population with health insurance, 2010	RWJF (2010)	77.	5.88
Number of primary care physicians per 10,000 population, 2010	RWJF (2010)	5.51	3.34
Natural Capital			
PC1 - Natural capital – FSA and variation perennial biomass	Author-derived	0.00	1.49
PC2 - Natural capital – variation annual biomass	Author-derived	0.00	1.25
PC3 - Natural capital – prime farmland and annual biomass	Author-derived	0.00	1.25
Natural Amenities Scale, 1999	McGranahan (1999)	3.04	2.10
Percent of farmland acres designated as prime farmland, 2012	USDA NRCS (2012)	0.01	0.02
Percent of total acres with conservation easement, 2016	National Conservation Easement Database (2016)	1.62	2.79
Percent of total acres in conservation-related programs and woodlands, 2017	USDA FSA (2017)	1.31	2.78
Percent of total acres in National Forests, 2017	USFS (2017)	19.93	22.35
Afg_ppa	Rangeland Analysis Platform (2022)	65.44	87.01
Afg_ppa_cv	Rangeland Analysis Platform (2022)	0.72	0.26
Pfg_ppa	Rangeland Analysis Platform (2022)	523.34	292.45
PFG_ppa_cv	Rangeland Analysis Platform (2022)	0.18	0.10
Social Capital			
PC1 – Social Capital - negative	Author-derived	1.02	1.41
PC2 – Social Capital – death rate and census response rate	Author-derived	0.00	1.26
PC3 – Social Capital – aggregate of social capital variables	Author-derived	0.00	1.20
PC4 – Social Capital – number of nonprofit orgs	Author-derived	0.00	1.15
Number of social establishments per 1,000 population, 2009	Rupasingha, et al. (2006)	1.16	0.79

Percent of eligible voters that voted, 2008	Rupasingha, et al. (2006)	61.48	10.89
US Population Census response rate, percent, 2010	Rupasingha, et al. (2006)	61.41	14.11
Number of nonprofit organizations per 1,000 population, 2009	Rupasingha, et al. (2006)	10.92	21.75
Drug poisoning by county (Model based death rate)	CDC (2014)	17.83	5.48
Robberies by county, 2014	USDJ FBI (2014)	0.00	0.00
Aggravated assault by county, 2014	USDJ FBI (2014)	0.00	0.00
Burglaries by county, 2014	USDJ FBI (2014)	0.00	0.00
Driving under the influence, by county, 2014	USDJ FBI (2014)	0.00	0.00
Dependent Variables			
Gross income from ranching as a percent of total agricultural sales in 2017, per county in 2017	USDA NASS (2017i)	0.48	0.27
Share of operations that participate in rotational grazing in 2017, per county	USDA NASS (2017g)	0.38	0.16
EQIP participation in 2014, per county	USDA NRCS (2012)	53.02	52.38
Share of multigenerational livestock operations in 2017, per county	USDA NASS (2017h)	0.12	0.06
Share of livestock operations that are profitable in 2017, per county	USDA NASS (2017h)	0.42	0.16
Control Variables			
Percent of the population below the poverty line in 2014	US Census Bureau (2014)	27.73	7.36
Rural-urban continuum code (RUCC) 1 (large metro) 2013	USDA ERS (2016)	0.05	0.22
RUCC 2 (medium metro) 2013	USDA ERS (2016)	0.08	0.28
RUCC 3 (small metro) 2013	USDA ERS (2016)	0.10	0.30
RUCC 4 (nonmetro, adjacent to metro with large town) 2013	USDA ERS (2016)	0.06	0.24
RUCC 5 (nonmetro, not adjacent to metro with large town) 2013	USDA ERS (2016)	0.06	0.23
RUCC 6 (nonmetro, adjacent to metro with small town) 2013	USDA ERS (2016)	0.12	0.33
RUCC 7 (nonmetro, not adjacent to metro with small town) 2013	USDA ERS (2016)	0.25	0.44

RUCC 8 (nonmetro, adjacent to metro, completely rural) 2013	USDA ERS (2016)	0.06	0.25
RUCC 9 (nonmetro, not adjacent to metro, completely rural) 2013	USDA ERS (2016)	0.21	0.41
Arizona		0.05	0.23
Colorado		0.22	0.42
Idaho		0.16	0.36
Montana		0.20	0.40
Nevada		0.06	0.24
New Mexico		0.12	0.32
Utah		0.10	0.31
Wyoming		0.08	0.28

Note: Indicators to measure the stocks of wealth are taken directly from Jablonski et al. (forthcoming), which follows Schmit et al. (2021), except for their additional indicators for built capital that use food and beverage manufacturing establishments and other manufacturing establishments. We exclude these two variables, given that they are captured in our dependent variables.

We use publicly available Census of Agriculture data (2017) to get county level data on total sales from livestock operations and all of agriculture to calculate livestock sales as a percent of total agricultural sales for each county[11]. We use restricted access Census of Agriculture microdata (2017)[12] to calculate the share of multigeneration livestock farms, share of profitable livestock farms, and share of livestock farms participating in value-added activities in each county. Additionally, we use data from the National Resource Conservation Service (USDA NRCS 2012; https://hensen.shinyapps.io/eqip/) on producer participation in Environmental Quality Incentive Programs (EQIP), to calculate EQIP participation, used as a proxy for engagement in government programs.

Econometric specification

We estimate separate models to understand the relationships between community wealth and five dependent variables including: livestock sales as a percent of all agricultural sales, rotational grazing, EQIP participation, share of multigenerational livestock operations, and share of livestock operations that were profitable in 2017. We include percent of the population below the poverty line, location along the rural-urban continuum (proxy for rurality), and state as control variables. We run a Global Moran I's Test and a Lagrange multiplier test to determine if there is spatial dependence

[11] 45 counties did not report sale amounts due to confidentiality. These counties are considered missing data.

[12] We are missing data from two counties in Colorado, one county in New Mexico, and one county in Nevada.

(autocorrelation). In other words, it evaluates if patterns are clustered, dispersed, or random.

Spatial regression methods allow us to account for dependence between observations, which often arise when observations are collected from points or regions located in space. In other words, data collected in space are often not independent, but rather spatially dependent, meaning that observations from one location tend to exhibit values similar to those from nearby locations.

We find evidence of spatial autocorrelation in all models with the exception of EQIP participation. Accordingly, to determine the best spatial model to use, we conduct a Lagrange multiplier test for spatial dependence and based on these tests, we estimate a Spatial Durbin Error Model (SDEM) to account for both spatial autocorrelation and spatial spillover effects.

We regress the county-level outcome variables on the 14 asset indices defined above (K_{ij}, j = 1 to 14). As controls, we include Rural Urban Continuum Codes ($RUCC_{ir}$, r = 1 to 8)[13] to account for the effects of population size and urbanicity of communities, state-level fixed effects (S_n, n=7)[14] to capture unobservable differences in factors associated with each state that may affect our dependent variables, and proportion of the population below the poverty line (Pi) to capture effects of poverty on our dependent variables (equation 1).

$$(1) \quad Dependent\ variable_i = \alpha + \sum_{j=1}^{14} \beta_j K_{ij} + \sum_{r=1}^{8} \delta_r RUCC_{ir} + \sum_{n=1}^{7} \theta_n S_n + \lambda_i P_i + e_i$$

Results

Here we report the results from the Spatial Durbin Linear Model for the capital stock variables in the own county (local) and in neighboring counties due to spatial spillovers (global) (Table 6). For ease of interpretation, we report the sign of the relationships and the levels of significance for direct and indirect effects. Regression results exclude RUCC, population, and state fixed effects coefficients (quantitative coefficients are presented in Appendix F, Table F2).

[13] There are nine RUCC categories, we left out the most rural classification (RUCC 9: completely rural or less than 2,500 urban population, not adjacent to a metro area) due to linear dependence among these variables.

[14] We leave out Wyoming due to linear dependence among these variables.

Own[15] county statistically significant positive associations between the capital stock variables and at least one outcome variable are evident for built capital - establishments (percent profitable), built capital – highway and broadband infrastructure (percent multi-generational), cultural capital – creative capital (rotational grazing, percent profitable, percent multi-generational), human capital – health related aspects (rotational grazing, EQIP participation, percent multi-generational, percent profitable), human capital – health security (percent livestock sales, EQIP participation, percent profitable), natural capital – FSA and variation perennial biomass (percent profitable), natural capital – variation annual biomass (percent multi-generational, percent profitable), social capital – negative (percent livestock sales, rotational grazing, percent multi-generational), social capital – death rate and census response rate (rotational grazing, percent multi-generational), social capital – aggregate of social capital variables (percent multi-generational, EQIP participation), and social capital – number of nonprofit orgs (percent livestock sales, EQIP participation). Collectively, these results suggest that the capital stocks have the most county-based effect on percent profitable, and percent multi-generational followed by rotational grazing. EQIP participation and percent livestock sales appear to be less impacted by the stocks of local assets.

Some of the coefficients of the spatial lagged capital stock variables are statistically significant in the Spatial Durbin Linear Model, including built capital – establishments (percent livestock sales, rotational grazing, and percent profitable), cultural capital – arts and cultural institutions (rotational grazing, percent profitable), human capital – health related aspects (percent profitable), human capital – health security (percent profitable), natural capital – FSA and variation perennial biomass (rotational grazing, percent profitable), natural capital – variation annual biomass (percent multi-generational), natural capital – prime farmland and annual biomass (percent livestock sales), social capital – negative (percent multi-generation), social capital – death rate and census response rate (rotational grazing, percent profitable), social capital – number of nonprofit orgs (EQIP participation, rotational grazing). These results suggest that some of the capital stocks have spillover effects on neighboring counties and vice versa, especially on percent profitable and rotational grazing. Interestingly, the only capital stock with statistically significant spillover effects on EQIP participation is social capital - number of nonprofit orgs.

[15] Own meaning the county where the data is from.

Table 6. Spatial Durbin Linear Model results, local and global.

Explanatory Variable		Percent livestock sales	Rotational grazing	EQIP participation	Percent multi-generational	Percent profitable
Built capital – establishments (food beverage and other)	Direct					(-)***
	Indirect		(-)*			(-)**
Built capital – highway and broadband infrastructure	Direct		(+)*		(-)***	
	Indirect	(+)*				
Cultural capital – arts and cultural institutions	Direct					
	Indirect	(+)*				(+)**
Cultural capital – creative capital	Direct		(+)***		(-)**	(-)***
	Indirect					
Financial capital – financial solvency	Direct					
	Indirect				(-)*	(-)*
Human capital – health-related aspects	Direct		(+)***	(-)**	(+)***	(+)***
	Indirect					(+)**
Human capital – health security	Direct	(+)***		(-)***		(-)**
	Indirect	(+)*				(-)**
Natural capital – FSA and variation perennial biomass	Direct					(+)***
	Indirect		(-)**			
Natural capital – variation annual biomass	Direct				(+)***	(+)***
	Indirect		(-)*		(-)*	
Natural capital – prime farmland and annual biomass	Direct					
	Indirect	(+)**				
Social Capital – negative	Direct	(-)**	(-)**		(+)*	
	Indirect	(+)		(-)**		
Social Capital – death rate and census response rate	Direct		(-)**		(-)**	
	Indirect					(+)**
Social Capital – aggregate of social capital variables	Direct			(-)**		
	Indirect		(+)**			

Social Capital – aggregate of social capital variables	Direct	(+)***		(+)*		
	Indirect					(-)**
Constant		(+)***	(+)***	(+)***	(+)***	(+)***
Observations		201	235	211	234	234
Lambda		(+)***				

Notes: *p**p***p<0.01, results are only shown for the principal components.

Considering the results in our model that are statically significant both at the local and global level suggests that built capital related to establishments, human capital-health related aspects, human capital-health security, natural capital – FSA and variation perennial biomass impact the percent of livestock operations that are profitable. Built capital – establishments and human capital – health security have negative associations with the percent of livestock operations that are profitable. Natural capital – FSA and variation perennial biomass have positive associations at the county level, and negative spillover effects on neighboring counties. Human capital – health related aspects is the only PC that has a positive association both at the county and neighboring-county level with percent of livestock operations that are profitable. Additionally, natural capital – variation annual biomass appears to promote the percent of operations that are multi-generational and the percent of livestock operations that are profitable.

Overall, results reveal important relationships between different stocks of assets and livestock-related outcomes at the county level. These relationships have financial value, as is evident with the many significant positive and negative associations we see with ranch profitability in particular. Additionally, we find evidence that the stocks of wealth in one county impact different ranching outcomes in neighboring counties; thus, there are spatial feedback loops whose financial value also needs to be considered. Therefore, the primary contribution of this research to the TCA framework is understanding the types of wealth that have positive or negative associations (and therefore financial value - both positive and negative) with several ranch outcomes in our specific context of the Western US. These results and this research can help policymakers, philanthropy, and other stakeholders to understand the types of wealth that may help to realize the specific range-system outcomes they want to incentivize.

A limitation of this research is that we were unable to fully value these relationships. Accordingly, a key next step to support the future of TCA is to quantify the marginal effects of the stocks of wealth that positively or negatively contribute to the ranch outcomes (profitability would be particularly straightforward as it has a clear financial value). Doing this would enable one to understand the value of additional stocks of wealth in financial terms. The challenge is that for this analysis we were unable to calculate marginal effects on principal components. And thus, this step of the work is left to future research.

Ranch-Level Analysis

Case Studies in Arizona and Colorado

Methods

Eleven ranchers[16] were selected, six in Arizona and five in Colorado, for in-depth case studies to better understand how to apply TCA methodologies to beef livestock production. The case studies are not a random sample, they are composed of ranchers and operations that already work closely with CSU or were connected to us through our Stakeholder Advisory Board, and who were willing to participate in the study[17]. Due to the network sampling process used, our sample is not a random sample, rather the case studies likely represent a "good" case scenario of ranchers who are well connected, were interested to take the time to participate in our study and—as will be shown in the results— look at ranching as a business and also take other considerations, (i.e., the environment, biodiversity, and social capital) into account in their decision-making.

Ranchers' interviews and discussion

There were several rounds of interviews and discussions with the ranchers. Due to COVID, the first round of discussions took place by Zoom. During this round, the research team introduced itself to each rancher, explained the objective and rationale of the study, and addressed any doubts or questions from the study participants. The research team then held a discussion with the ranchers on the general aspects of their operations to familiarize themselves with the different procedures and goals of the ranchers. This was followed by visits to each ranch in Arizona by a team of two researchers to apply a questionnaire, but also involved personal interactions and discussions with the ranchers on topics that emerged during the visit. These interactions were noted and recorded with the ranchers' authorization and then transcribed, coded, and organized by common topics. In Colorado, since the CSU team was already familiar with the ranchers, the questionnaires were sent to the ranchers who answered them independently and returned them to the CSU team. There were no face-to-face meetings at that stage, but subsequently, the ASU team conducted a series of Zoom interviews with those Colorado ranchers to provide a similar opportunity to elicit views

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[16] The original study design included 12 ranches, six in Arizona and Colorado each. Unfortunately, one of the ranches in Colorado did not provide a completed questionnaire, though it did provide some other information, leading to varied sample size depending on the method.

[17] Ranchers were compensated for participation in this study.

as in Arizona. The resulting qualitative data was recorded, coded, and organized by common themes as well.

Questionnaire

The questionnaire elicited general information about the ranch, as well as specific data on various aspects of social, natural, human, and produced capitals. Most of the questions provided pre-selected and coded answers, but open answers could be given and were recorded and coded. Additional comments and clarifications from the rancher were included in the answers to the coded questions as well.

Produced capital included information on the number of animals managed, marketing, profitability, income, ranching infrastructure, internet, and cell access. Natural capital aspects included the number of acres managed, land tenure, energy use, fertilizer applications, irrigation, water use, its conservation and pollution, and biodiversity (particularly wildlife). For social capital, aspects included questions on the rancher's participation in organizations that support ranching, a subjective rating of their value in terms of the contribution of different types of knowledge, information and support, and willingness to participate in collective action. For human capital, aspects included ranch management experience, creation of rural employment, succession planning, living conditions, access to healthcare, levels of revenue, income, and savings, as well as a subjective rating of their quality of life. Ranch management reflects experience, general knowledge and local knowledge, skills, planning and decision-making capabilities—all key indicators of human capital—and this information was reported in this section. It also included data on planning, decisions on stocking rate, breeds used and breeding and culling strategies.

The quantitative data elicited through the questionnaire consists mainly of the counts of the number of ranchers that provided a particular answer to the questions. These data points were used to develop a descriptive narrative characterizing the dependencies and impacts of the ranches in the four capitals. The quantitative results were complemented with qualitative information elicited during the application of the questionnaire and interviews.

Results of the case studies in Arizona and Colorado

Results are presented as a narrative combining quantitative data from the responses to the questionnaires and quotes from discussions during the interviews by type of capital. The number of responses behind each statement is presented either in parenthesis or in narrative form when there were few responses. The quotes were included to help illustrate ranchers' experiences across the capitals. We include a sampling of quotes from ranchers in both Arizona and Colorado. These quotes have been sourced evenly

from our recorded rancher interviews, with no ranch repeated per a category, and have been anonymized to ensure rancher confidentiality and to prevent associations between quotes across categories.

Produced capital

Cattle are the main product, or output, of the operations we study, specifically, animals that are marketed through various channels up the supply chain. The number of heads of cattle managed at the eleven ranches in Arizona and Colorado varied greatly, ranging from 65 to 3,000 head (though most ranches managed ≤ 350). In drier counties, lower numbers reflect the difficulties of the previous two years of drought (beginning in 2020) that impacted some operations and created lower than typical herd sizes, since ranchers indicated that they had to reduce their herds to adapt to the lower availability of forage biomass, livestock drinking water, and to minimize the expense of buying supplemental feed.

All ranches in this study are cow-calf and cow-calf combination operations, but some ranchers also market cattle through additional channels with direct marketing (grass finishing on ranch) and the production and sale of seedstock, or are a combination of cow-calf, stocker/backgrounder, and custom grazing operations.

Most ranchers sell their animals at auction (9 case ranches), retain ownership (6) or use a private treaty (a closed-sale negotiated personally with the buyer) (5). Only a minority use other marketing means such as a forward contract (1), direct to consumer sale (1) or a contractor (1). These are not mutually exclusive categories, so a rancher may sell some of the calves at auction, some through private treaty, or retain ownership for others. Most of the sales take place with multiple people and in different places (7) with the remaining sales having one very reliable and important buyer (4). In most cases, the relationship between the rancher and important buyers is reliable and consistent (8), only in two cases, the relationship is unreliable, and for another, unimportant. Some of the ranchers complemented this information by describing some of the strategies they use to sell their cattle. For example, one rancher indicated that he invested time into relationship building with the buyer interested in premium US beef, which allows him to sell with only seven days' notice. Another said that the ranch has name recognition at auction, which leads to higher prices. Another utilizes markets in the City of Phoenix and has a large local following for direct-to-consumer sales. It is noteworthy that this respondent indicated that COVID wreaked havoc on their direct sales. Some of the ranchers complemented this information by describing some of the strategies they use to sell their cattle. For example, one rancher said that, in general, they marketed cattle to established clientele in different locations. Regarding the impact of COVID on their operations, some of the ranchers said that in early 2020 sales went "through the roof," but by the end of year that upsurge in demand had completely disappeared.

Over half (8) of our producers have operational costs above $70,000. The majority of the ranchers in Arizona derived more than 50% of their net income from their cattle operations (4)[18], but in Colorado there was greater variability ranging from 30-100% of net income derived from cattle operations. Other sources of income included pension, social security, agritourism (dinners, weddings), or businesses not associated with the ranch. In the last five years some ranchers reported revenue exceeding costs most (4) of the time, while for others revenue exceeded costs only some of the time (4). In the case of the remaining three farms' revenue rarely or never exceeds costs. While only two Arizona ranchers have savings[19], all the Colorado ranches have accrued savings. A rancher said that the goal is to break even and another that, "in ranching there is no such thing as profit." Many producers in interviews spoke of market failures and economic barriers they face in selling their cattle -- the story was one of struggle in an unfair market where low-prices and a lack of market infrastructure hurts even the best of ranchers.

> *"On my marketing side, economies of scale hinder me, because if we fatten cattle out through the feed yard I am a one hit wonder. JBS* [a global beef buyer] *doesn't care. I am a place filler. Okay, we will provide them with really good cattle, but I have no stick, basically."*[20]

> *"But hey, I mean we would love to be profitable, don't get me wrong, the reality is breaking even is success."*

> *"If you have any money left at the end of the year it typically goes right back in."*

> *"Found out that the feedlots were going to pay a premium for dehorned steers, like OK we'll start dehorning steers and then we got a premium. Well, the year after if you had a horn steer, they cut you right. And so, our premium turned into normal market price. So then, what's the next step? What do we have to do next to get the next price low? Then you have to give an extra shot, or you have to hold your cattle for 45 days after you wean them and so this premium becomes a discount if you don't do it. The premium only lasts a year or two. Every time we come up with a better*

[18] One did not provide information.

[19] Two did not provide information.

[20] Ranch names are not attributed to quotes to protect anonymity of participants and prevent association between quotes that may reveal ranch identity. Quotes throughout this section have been evenly pulled from nine ranch interviews which were recorded and transcribed with two ranchers forgoing a formal interview.

thing to do to make ourselves more valuable there's always something else. And I bet you a dollar that every rancher you talk to will say that in some capacity. It's just how it is. So now our calves are dehorned and keeping calves for 45 days after you wean them off their mom, you know you have to give them shots on top of that. You have the costs of the shots, you have the costs of the feed, you have the costs of the sickness, cost of the tractor and the fuel and the labor in there."

"We saw the retail price go up by sometimes 200 to 250%. All while our wholesale price was falling by that same amount. You tell me on an economic side of things-there's absolutely no sense to that whatsoever. Right? The demand is at an all-time high, probably the highest in my lifetime, and yet we're getting 50% of value on our animals."

"My parents, tend to be almost apologetic. In the sense of you know, we almost hate to leave you this, you know this liability because it's seen on any given day, more as a liability than as an asset. It's complicated."

"Every rancher I know, including my parents more or less, is the victim of whatever the weekly aggregated price ends up being. If you could go in there with a floor and say, well, I'm not going to sell this animal for anything less than X, that would be the better way to do it. What ended up happening is you take your cattle, and you drop them off and you hope for a check the next week. And you just take whatever they give you."

Infrastructure is important in ranching; most ranchers in these case studies have sophisticated equipment to vaccinate and manage their cattle, as well as vehicles and other equipment for day-to-day cattle management. Most of the ranchers (10) use the internet to obtain information on latest best practices and solve problems, however for some the internet quality and speed are unreliable (4). Just over half of the ranchers have access to broadband (6), mostly by cable. Most ranchers (9) do have adequate cell phone service coverage.

"My parents, tend to be almost apologetic. In the sense of you know, we almost hate to leave you this, you know this liability **because it's seen on any given day, more as a liability than as an asset.** It's complicated."

Water points and pipelines were the most widely owned pasture infrastructure (9), followed by fixed fences (7). Most ranchers (10) received USDA cost sharing support for installation of infrastructure, particularly for animal watering systems (6), fences (4), and

irrigation infrastructure (2). Major constraints to expand the pastures include water and land availability, the high cost of water, and lack of time and labor. As might be expected, in Arizona the most important infrastructure relates to moving water in the range. It includes pipelines, water tanks, dirt tanks, solar pumps, and drinkers.

Natural capital

In terms of energy use, half (6) of the ranchers indicated that they use a variety of fuel in their operations, including both fossil fuels and renewable energy sources (primarily solar). While most did not provide specific information, those who did showed that consumption can vary substantially. The respondents who provided their usage showed diesel consumption varied between 800 and 8,000 gallons per year, gas between 1,000 and 3,000 gallons per year, and for propane (mostly for home consumption) 4,000 to 5,000 gallons per year.

All ranchers use feed supplements, either protein (5) or minerals (4). No ranchers use antibiotics, growth hormones or energy supplements. There is very low premature mortality, mostly associated with snakebites, mountain lions, or cattle eating noxious weeds. The most common culling reason is animal poor performance (4) followed by open cows/heifer post-breeding (2), age (1), and overall lower quality animals (1). While all ranchers use feed supplements, the primary feed of these operations are natural vegetation from the rangeland, and ranchers depend on the natural capital of Western land to raise their herds. The size of these ranches varied between 2,100 and 88,000 acres. The number of acres per animal varied between 6 to 169[21] suggesting that there is a low environmental footprint of these animals on the rangelands. In total, the ranchers we interviewed accounted for 5,920 animals in an area of 272,090 acres. The cattle are the product that utilizes vegetation on the rangeland, transforming it into a marketable agricultural commodity.

> *"I think the primary purpose of the cow is to be able to harvest solar energy that is not palatable, not edible by humans so that we can utilize these rangelands"*

> *"Most of our grasses are not tall structure grasses, they're short grassland, prairie things. And so, wind out here will fracture off the grass. So, if all you're doing is storing it, eventually mother nature just fractures it off and takes it someplace else. And so, we try to utilize dormant season grazing as best we can"*

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[21] These numbers refer to generic animals without distinction among cows, calves, bulls, and are not in Animal Equivalent Units (AEU).

"We use very little supplemental feed, we're able to sustain the livestock primarily on grass alone."

> "I think the primary purpose of the cow is to be able to harvest solar energy that is not palatable, not edible by humans so that we can utilize these rangelands"

Land is a crucial input to these operations, and ranches are high-cost land and water areas, so operations are often dependent on a mix of ownership and rental arrangements with a combination of private, state, federal, and county owned land. In Arizona, all operations had a minimal amount of private ownership, with most of the land leased from the state and federal government. Colorado ranches also leased public land, but more of them (3) owned between 50-100% of their land. Ranchers discussed different experiences with public land management, often preferring to work with the state over the federal government for grazing leases. Half of the ranchers indicated that land tenure limited their ability to invest in or implement new livestock practices, indicating the complexities of land tenure relations and perceptions in the West.

"In the state, there really aren't any constraints other than you have to get all your improvements approved. I've never heard of an improvement getting turned down."

"The state will reimburse you for the improvements you've made."

"There is probably somewhat less of a motivation to invest substantial life savings into a project on Federal land, particularly on Forest Service land because you have as the lessee, no actual rights to that. If you put in $10,000 worth of water or fence development those improvements do not go to you in any form or fashion. It's effectively a donation to the Federal government. So there is a disinclination to do that. The State is different. The State actually considers those improvements as improvements which accrue to the person doing the improving. So, if we were to sell the ranch, for instance, those improvements would be calculated into the price and you would, at least get your money back. And then of course with private land, then you have the standard private motivation for investing in real property."

Most (8) ranches indicated that they are trying to reduce their energy consumption by having well-maintained machinery, use of efficient lightweight vehicles, reducing trips to town, utilizing the eco-mode in vehicles, and two indicated that they switched from a

high voltage/high pressure pump to using lower electric solar pumps in their wells and water points. Over half of the ranches (7) in this study use renewable energy—which is predominantly solar energy—and have the necessary infrastructure installed on their ranch.

In terms of water use, all ranchers have pumps and watering points (discussed further in the Produced Capital section) for their animals. Water consumption by animals varies according to the season in both states. The ranchers provided different estimates varying between 15 to 50 gallons per animal per day, depending on the season. Just over half (7) of the ranchers said that they apply water conservation practices, including water harvesting installations, dirt tanks[22] and small dams. The ranchers also try to prevent the water streams on their land from being polluted by keeping animals away from waterways (5), erosion control measures (4), and one rancher monitors the nutrient levels to prevent eutrophication (1). Irrigation varied across ranches, but rainfall was the primary source of water used for vegetative growth on the rangeland (especially in Arizona). The majority of ranches irrigated not at all (6) or under 10 acres worth (3). Overall fertilizer use was minimal, about half (7) of the ranches applied mineral fertilizers at a low rate (0.1 pound/100 ft^2), while the rest did not apply any (5).

All but one ranch indicated that they have observed negative changes in their land.[23] Observations included changes in drought (4), changes in gully formation and soil erosion (by water or wind) (5), fire frequency and intensity (3), and soil water retention capacity (5). Two ranches also noticed other natural capital outcomes, with one being the species diversity of native plants, ground cover, and resilience to drought (1), while another noticing the amount of water available in streams (1). Even when applying adaptive and innovative measures these ranchers have felt the difficulty of climate change over the past couple of years. Megafires and extended droughts directly impact the natural capital that they depend upon for their livelihood.

> *“We're very lean at the moment thanks to no rainfall.”*
>
> *“Drought would be the key factor for us. And we've gotten through a tough summer and still grass-finished cattle, but we had a couple thunderstorms on one portion of the ranch, so overall it was a bad year precip’-wise but had enough rain in certain spots to go ahead and finish the cattle.”*

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[22]Also called stock tanks, these are man-made water reservoirs to hold drinking water for livestock.
[23] Survey instrument did not specify over what period of time observations took place.

"We normally get around 12 inches of rain in the summer months in season. We got six. So, the northern third of our ranch looks dead when we left it in our rotations last year. It's about drought."

"It's sad because now everything is just catastrophic and we've gone, I don't know if we've had a summer where we haven't had a fire in the last 10 years. Some are worse than others, but still."

"This is the first year in my lifetime that I can remember we had absolute death of plants; I mean dead. So existing plants that a normal year would have, the second you get a drop of rain on them, they start to grow the head, put seed, they get after it, so to speak. And this year nothing, I mean nothing."

"One guy sent me a text message yesterday, he keeps 400 cows, and he said, the message is that the well at the headquarters went dry yesterday morning, and he's got 400 calves in that pasture."

"Without hesitation, I think it's easy to say that it's been the driest in my lifetime."

"In the 16 years that I've been here I think I've been through four major droughts. And so, I don't know that our cow herd isn't just built for the drought situation because we've had so many, or if that's just my new normal."

All ranchers indicated that there is a presence of wildlife on their ranches. Wildlife mentioned by the ranchers included black hawks, bears, javelinas, Gila monsters, pumas, deer, wild turkey, antelopes, doves, quail, and many bird species. One rancher said that the wildlife follows the cattle and that they complement each other. Another rancher noted that their ranch is a predator-friendly environment. A majority of ranches (8) have water points that benefit wildlife, and pastures resting from grazing (10). Both states had some ranchers indicate they created habitats for biodiversity (3), rehabilitated natural areas in their ranches (5), or installed biodiversity-friendly infrastructure (habitat preservation) (5). Two of the ranches reported utilizing hedgerows and buffer zones for wildlife, while three ranches indicated they have areas on their ranch that serve as migratory corridors. One of the ranchers has a conservation easement on their land which is home to many endemic species. No ranchers indicated that they see a trade-off between ranching and wildlife conservation. All of the ranchers in these case studies shared a great awareness of the wildlife around their lands and

were proud of their actions to conserve, promote and allow for increased diversification of wildlife.

> *"You know, over 70 years I've kind of kept a record of the animal, the change in wildlife and what I grew up with that aren't there anymore, and what is coming in, which is really fascinating."*
>
> *"I actually did a presentation to the range science group, and when we first moved on to the ranch in 2008 in the salt meadow riparian area, we were able to identify five climax grass species. In 2017 we were able to identify 17 out of 17 climax grass species for that area. So, we've seen a huge increase in biodiversity, not only plants and but in animals, wildlife, as well."*
>
> *"We've seen everything from elk, a lot of your different mammal species, we've got, had over almost 283 different bird species identified here on the ranch. We recently, about two years ago, reintroduced beavers to our riparian areas and we've got two colonies of beavers on the ranch. So, yeah, we've seen a lot of diversity in the plants and animals."*
>
> *"Lots of wildlife. There's no elk, at least at this point, there's a lot of mule deer, there's white tail, we have Blackhawks which are rare, but we have them. And everything from javelina, mountain lions, bear, Gila monsters, and rattlesnakes…"*

Human capital

The ranchers we interviewed all had more than 10 years of ranching experience. They were evenly distributed among generations of ranchers: first (4), second (4), and third (3). Discussions with the ranchers indicated that most have a high level of formal education and work experience in other areas besides ranching, which gives them skills to deal successfully with markets, other businesses, and the government. They also have substantial experience in ranching and have high technical knowledge of range management, cattle genetics, and the business and managerial components of ranching. They understand the markets where they sell their calves and employ sophisticated marketing strategies. Lastly, they often have other businesses and sources of income that allow them to better manage cattle production and business risks. Given described barriers to profitability, off farm-income was often noted as crucial to ranch survivability.

The majority (9) have a succession plan in place to ensure the ranch will continue for future generations (whether in the family or through a new apprentice). Most of the

operations hire workers (9), with around half (5) hiring workers from the local community. Many ranchers employ day laborers, but a few have dedicated full time employees, providing important training opportunities with one producer even offering an apprentice program to pave pathways for the next generation into agriculture -- at the time of our interview he employed two budding agricultural apprentices. The knowledge passed down in multi-generational ranches was rich, and the intention ranchers placed on passing their own knowledge to others is notable as they described the legacy of family ranches and the many skills that ranching requires.

> *"That operation right now- that's where I was born and raised, and I learned everything from my dad, and he learned everything from his dad and his uncle who learned everything from their father. My great grandfather started that ranch in 1885 and so we have a long history there."*
>
> *"My folks have been ranching this for 45 years."*
>
> *"I got the ranching bug very early—both my parents were raised on farms and ranches."*
>
> *"You know a good cowboy, you know, who's been doing it all his life is worth his weight in gold. You know, they're just real quick and fast. That's what they have done all their life."*
>
> *"I fell in love with what I do now, because of very good people that I worked with. When I was down at [place] I worked with a very large ranch, we ran about 3000 cows. And that's where I fell in love with being a cowboy."*
>
> *"We don't want what we've spent our adult life building to just go away. Right? And so, our goal is that we find the right young people to come on board, and we help them out, no differently than what my wife's parents did for us, and kind of follow that same model."*
>
> *"It's not only about the transition into the next generation, but into the one after as well."*

In terms of health care, none indicated any constraints to access to medical treatment. For most, treatment costs cause no difficulty (7) and for a few even if costs can be difficult to bear, they do not prevent them or household members from obtaining medical care (4).

In general, most ranchers rated their subjective quality of life as good (8), two as neither good nor bad, and only one as bad. Ranchers had various motivations for ranching that extended far beyond profit -- in fact many joked that if they wanted to make money this is not what they would be doing in life. The culture and lifestyle of ranching brought value and meaning to their lives. Ranching is an important piece of their well-being and happiness in a way that compensates for less profit.

> *"I liked the outdoors and buying this place was a way to put my money in a place where I could enjoy it, rather than having to just think of it as another set of digits on a computer screen [...] Had I kept it [my money] in [Visionary] medical systems, I don't know it would be a lot of money by now, but I feel happy."*

> *"We're not doing this as a charity, but [profits] are not the primary thing. There are many other things we could do with our time and our skills that would generate more income."*

> *"[Ranching] is just something I've always been interested in, involved in. That actually skipped a generation in my family. But I originally got started with 4H, and then I had some good mentors in high school and in college. It's just, I enjoy the natural world and the ecosystems and the livestock"*

> *"I think the expectation amongst the whole family is that the land will be conserved. [...] The idea is to maintain the open space and the open character."*

Even with the benefits of the ranching lifestyle, two ranchers explicitly stated that the COVID-19 pandemic took a heavy toll on their health. One rancher noted that the pandemic had "decreased overall quality of life," and their "psyche has changed." Another noted that their operation found people coming up from the city during the pandemic to escape the monotony of lockdowns and that these visitors would interfere with operations and were not responsible with the land. In some cases, the ranchers found that people had trespassed on their land and left open gates, allowing cattle to roam free. In the most extreme case, a rancher reported cattle had been hit with a vehicle, killing the cow.

"I think the expectation amongst the whole family is that the land will be conserved. [...] The idea is to maintain the open space and the open character."

The adaptive management of the herd by ranchers is a key indicator of human capital since it reflects experience, general and local knowledge, skills, planning and decision-making capabilities. All ranchers have a grazing plan (11), most carry out forage

analysis (8), have a breeding plan and a drought preparation plan (8), while a few carry out mesquite removal (2), erosion and wildlife planning (1) and prescribed burning (1). For example, the drought preparation plan includes a systematic plan to reduce the herd size according to the incidence of drought, while forage analyses are based on monitoring transects.

All this information is used by all ranchers interviewed to make decisions on grazing, stocking rates, timing of grazing season, and the necessity of additional forage requirements. Most ranchers also use this information for controlling soil erosion (8). Ranchers did not use mineral fertilizers, or plant introduced-forage species and nitrogen-fixing plants. Rather, to improve soil fertility, all ranchers use animal rotations and most leave the manure in the field. Ranchers described planning and adapting in a fluid system centered on systematic sustainability.

> *"I've always got a short and a long term [plan], but in general operations you always have a plan A, B and C, and hopefully if you're on C you're not doing real well. Those are just different decisions based upon a general management plan and that is just following, watching your cattle and figuring it out."*

> *"The reason we made it to [September] when the rain showed up is because we manage the ranch with the idea of a savings account so to speak, you've got an extra year of savings in grass. So when the cattle leave a pasture after grazing, there's at least another whole season of grazing left in that pasture the day they leave, assuming it doesn't burn up."*

> *"We focus on the land and then also, different pastures. So, we have different pastures that we look at, and that if we need to change our rotation, OK. So, you focus on the land, because it does change what you do and how many [heads] you keep where."*

> *"In my opinion, especially in [the Southwest], you have to be adaptive, as you have to be changing as you go. You have to because you cannot manage this land by a textbook. It gives you good guidance for sure, but you have to be able to change as you go."*

> *"We'll use decision-making processes and try to identify the weak links as we're making decisions and evaluate from the social, economic standpoints and make our decisions. We use grazing planning for managed grazing processes."*

Relating to the natural capital of the rangeland, stocking rate is a crucial decision for any rancher and while plans are important, most ranchers indicated that weather, and particularly drought, is the most important factor for this decision. To determine the stocking rate, ranchers evaluate plant recovery and forage availability three to four times a year, assume no additional precipitation will come to encourage plant growth, and adjust stocking rates accordingly. Some ranchers even do forage estimates and rain analysis each month. The ranchers in this study self-identified as particularly conservative in their stocking rates and took exceptional care to monitor and plan with rangeland sustainability in mind. Sustainability and environmental services were a large focal point in decision making of the ranch.

> "In my opinion, especially in [the Southwest], you have to be adaptive, as you have to be changing as you go. You have to because you cannot manage this land by a textbook. It gives you good guidance for sure, but you have to be able to change as you go."

> *"We will go in and with NRCS and Game and Fish, decide if we need to add to and plant for wildlife coverage, just for how they live. And vegetation yeah to just coverage for the cows as well, but more to lessen the erosion. And the natural grasses, from what we can see, things are growing we've never seen before."*

> *"We get 33% of our rain here in July. Right? And I got zero, and I'm watching the grass go down and I go 'This is not going to go well,' OK sold some to a couple ranchers, 'cause you'd have to keep them for a whole 'nother year to breed. So, I sold some good heifers, and that went to my rainy-day fund -- this is why lots of other ranchers are dumping cows too. So that was a tough time."*

> *"At the moment we're in major drought restocking. We're just getting now summer rains so I've got to go back here in the next couple of weeks to help get the herd back onto the operation. It's rated quote, unquote at about a 200 head operation, we have about 65 head. But we've destocked immensely in order to deal with the drought conditions."*

> *"We've reduced our cow numbers a little bit based on changing environment, less rain in June, which is what we rely on for the pastures where the cows are. I have neighbors to the west of me that have sold out because there's no grass."*

> *"[Sustainability] really is divided up into environmental and which subset is you know, making sure you're not overgrazing or taking care of the land and making it better doing those kinds of things, and assessment of how*

much you're using the land, how many cows that you have, and what's sustainable on [the land]. And then the other side. That is, balancing with when you have some sustainability up here and then under subset, it's the environmental piece and all the little environmental pieces under that. Then you have the financial side. How do you balance that out and make the environmental piece sustainable and so that's where you know, watching the markets and watching your operations and funding your operations. [...] You want to pencil things out. So, it is a system, it's all interacting and you can't really isolate one piece from the other."

"Our grazing system, whenever you start looking at what happens after a rainstorm during the summer, we leave enough biomass on the ground that when you look at it, it doesn't rill out and create erosion issues, it creates little micro dams."

"It's a dry climate. The preparation plan, such as it is, is just having the infrastructure in place and the sort of transportation plans in place to be able to destock relatively quickly and get the animals off when you have to."

Due to the continued drought in 2020, many ranchers indicated that they had to reduce their herds substantially (especially in Arizona). For example, one rancher said that he had to sell more than 500 pregnant cows because of drought. Another rancher reported that they could only carry 250 head, while the ranch fully stocked under good conditions can carry between 800-1,000 head, adding that in general their stocking rates are very conservative, e.g., 550 cows/80,000 acres with a 10-20% utilization. It is important to note that selling cattle is a large loss to these producers as herd genetics are built slowly and intentionally over the years. When these ranchers sell off cattle, they are losing not just part of their herd but part of their genetic diversity. So, while reducing the herd size can help alleviate environmental pressures and prevents negative impacts of overgrazing, it does negatively impact the ranch in the long run by hampering the development of a genetically robust herd. The number of grazing groups varies from one to six groups and is carefully decided by the season, the composition of the herd and the type and stage of cattle production. In one

> "We get 33% of our rain here in July. Right? And I got zero, and I'm watching the grass go down and I go 'This is not going to go well,' OK sold some to a couple ranchers, 'cause you'd have to keep them for a whole 'nother year to breed. So, I sold some good heifers, and that went to my rainy-day fund -- this is why lots of other ranchers are dumping cows too. So that was a tough time."

case, the rancher allows the cows to self-divide, forming small groups of three or four animals spread through the range.

As mentioned, in regard to stocking decisions, ranchers invest great time and planning into herd genetics and breed. In terms of breed selection, Black Angus is the dominant breed of choice, driven by market preferences. All of the ranchers mentioned the importance of building up favorable herd genetics, often through cross breeding. Some use Angus and Brahman crosses (Brangus), while others cross the Brahman for heat tolerance with Hereford cattle for increased marbling. Corriente was crossbred as its smaller frame helps the cattle grow better in arid environments with less forage and water needed. Simmental, and recent introductions of Wagyu and Belted Galloway also were noted by some for advantages such as flavor. One rancher purposely has a mixture of breeds, which he believes is better in terms of adaptation to the local environment. Ranchers stressed the importance of balancing sustainability and market demand. While Black Angus is in high demand due to the marketing of Certified Angus Beef (carrying premiums) other breeds prove more efficient in Western rangeland conditions.

Many ranchers had highly specialized knowledge and diagnostic tools. For example, the use of Expected Progeny Differences[24] (EPDs) and genomic analyses were common.

> *"We artificially inseminate all of our cows and heifers, and we pick the bulls on their EPDs, which I think you've all heard about, and what we focus on is marbling, calving because they calve on their own in the mountains, so calving and docility. So those are the top three things, mostly marbling."*
>
> *"Feed efficiency is something they just started testing for and have an EPD. If that cow can eat less and still produce a good calf, they have cows now because they've been interbreeding this for the efficiency that is almost as good as a chicken."*
>
> *"We had the Hereford cattle because that's just what you did in the West, and so I decided that in order to keep the red color we started, initially with Black Angus and then switched to red cause the colors were both recessive. And I also liked the philosophy behind the Red Angus Association in that they require performance testing of the animals and I had learned so much about that at Wyoming. And so that was a big part of it, and, you know, the stupid old Hereford cows they'd have a calf and say,*

[24] Expected Progeny Differences is a model that helps ranchers to predict the genetic traits that would most likely be expressed among different breeding partners.

“now, what do I do?” And the Red Angus cows are so much more interested in being moms.”

“The Corrientes and Longhorns are not really considered beef cattle, they have small frames, not a lot of muscle. But they do really well in a tough environment, they’re very good at getting pregnant over-year, raising a calf over-year, the longevity of the herd can be double that of beef cattle. So, they have some advantages.”

“We're looking for efficient cows and that's where we really like the Corriente, Corriente-cross cows. They’re weighing, you know 700 to 800 pounds and they're weaning 500-pound calves. Whereas I’ve also run for some clients, the big, highly genetic Angus cows weighing 13, 1400 pounds and they're only weaning 575- or 600-pound calves and we're able to do it with a lot less feed and everything and so we're able to maintain our profitability, by not worrying about genetics per se. And even if the calves are little lighter weight, we can run two of our Corriente cows for every one of those big cows and so we're actually producing more beef per acre then these people that have these high genetics and cows weighing 1400 pounds and that sort of thing.”

Body conditions scores[25] were used for weaning and culling decisions. Ranches indicated a focus on superior genetics is part of their marketing strategy of trying to sell superior cattle. While a few ranchers use artificial insemination, almost all conduct breeding soundness exams and track the age of pregnancy at the time of pregnancy checks (8). All ranches vaccinate their animals, relying on veterinarians and serving as their own veterinarians under many circumstances due to the remote nature of ranching. Ranchers ensure the well-being of their cattle and most (8) of the operations provide outdoor access with adequate space and shelter preventing unnecessary stress in the cattle and serving as stewards to both land and animal.

Social capital

Most ranchers indicated that they belong to agriculturally focused organizations that support ranching or rural development (10), including both paid and free membership organizations. Almost all the ranchers involved in these organizations felt that they received as much personal benefit as they invested themselves in these organizations (10). These organizations provide knowledge and information on production and marketing issues, business operation, crisis management, conservation, as well as

[25] This is a scoring of how much fat cover is visible on a cow. This allows the rancher to make informed judgements about the type of feed a cattle should be receiving and if the cow is at an ideal weight for weaning and breeding.

general educational and training opportunities, support in legal fights, and political support. Many ranchers noted that information flow is important, especially keeping up with politics. Others mentioned learning new skills and technology like drones, pinkeye management, weaning methods, best protein supplements, or branding alternatives such as the electronic ID reader system[26]. One rancher traded labor with his network of fellow ranchers in what he called "trade works". One of the ranchers interviewed actually held regular seminars to network and suggest improvements to other ranchers, but this stopped with COVID-19. All ranchers indicated that they had personally adopted strategies and technologies based on interactions with their friends and associates. In return, they all also shared suggested improvements with peers that were implemented. This supports the common response that the ranchers "get back what they put into the club". Interviews illustrated that information flow from both formal and informal networks make significant contributions to these ranchers' operations, and that these ranchers in turn invest their time, energy and resources into cattle organizations and networks in a mutually beneficial way.

> *"All the ranchers, we know each other, and we know what our strengths and weaknesses are, and we talk about issues. I pick up the phone and say I haven't seen this before or I have you know that kind of thing. And a lot of us just inter- trade between ourselves. Let's say I need a bull, call, I have you know how much. Well, OK, there you go. You know we trust each other. We're not going to take advantage of each other whereas in the markets you can get taken advantage of."*

> *"It [social networks] absolutely has value, there's—to back up a little bit, when I became interested in Allan Savory's management ideas and began implementing them and going, as you said, became engaged with the research community, there's kind of a subculture of ranchers that have engaged holistic management in one form or other, and within that subculture the communication at those meetings, it's really valuable. Just interacting with people who are struggling to solve the same problems you are has huge value, and they've tried things that didn't work, or it can be really interesting, you both tried the same thing, and it works for one person and not the other, which isn't unusual in the face of complex systems. So, trying to sort out all the minutiae of what works and what are the key details that make it work, that subculture is really critical."*

> *"We're all having lunch and meeting with another rancher about something that they did, so it's not just the [Beef Association] meeting, it's meeting*

[26] Small button-like tags fixed to an animal's ear with a unique identification code that can be read with an electronic scanner.

with the other people that are going through similar things, or they're trying something new."

"I think we all kind of look around to see what's going on and you just do best management practices right. Why wouldn't you? If you have a neighbor that's doing something that works that you didn't think of, wow well yeah where do I do that? I mean, I think you would kind of be foolish not to learn from each other, right? And it goes, it's back and forth, but some things may work at our ranch that's in the mountains that may not work on your ranch in the desert, or vice versa. So, you know, OK, that may not work, but that might, or a piece of it or something."

Almost all ranches indicated that they would consider partnering with other ranchers to develop action plans to build more resilient beef supply systems (10), and some of them were already in active partnerships (2). One rancher noted that partnering with others is difficult in practice because ranchers are "an independent lot."

> "You know we trust each other. We're not going to take advantage of each other whereas in the markets you can get taken advantage of."

Many ranchers indicated that there is a strong sense of community in their surrounding areas (7). The community bond in more rural areas, especially the network of ranchers in the region, provided emotional support to the ranchers. Ranchers described how when a fire destroys forage on an operation, ranchers from areas unaffected pooled together hay to provide feed to the farm in need. Other ranchers impacted by drought sent entire grazing groups to areas where forage was still available on other ranchers' lands. When slaughterhouses closed during COVID-19, one rancher banded together with a group of local ranchers and a butcher to open a local slaughter and packing cooperative. Community and shared values in the ranching lifestyle helped various ranch operations survive a pandemic, intense droughts, and destructive fires of the Southwest.

"Our network is our fabric, it's strong and resilient. People get along and help each other out."

> "Our network is our fabric it's strong and resilient. People get along and help each other out."

"This community came together, the million acres of ranches. The other notion was they'd like to protect their lifestyle, the culture that they knew. Right in the middle of it were emerging subdivisions, you know, right on the edge of rodeo there was a couple hundred or a couple sections, couple of square miles of property. They've been sold by

someone who couldn't make it anymore, and they started putting in houses [...]. But the [ranch] group got put together because of interest in open spaces, the ranching lifestyle, and managing the environment as a landscape, rather than as a single ranch with a fence on the corner. And that's really how the group came together."

"We had just purchased, and the fire was eight months later. It's just hard on your watch to have that happen, and so after moving the cattle to different ranches because of our connections through these networks they would allow us to graze their land for free so we would have 40 cows at one ranch, 40 at another. Once we came home and there were 19 bales, of the huge bales, 1000 pounds of hay and I had never met [the rancher who donated]. But it's because the association - they knew [about the fire]. Hopefully we'll do that for the next person. Really community affairs."

"There's a lot of industries where if something happens, you know you're just out of luck. Your problem. That's competition, yeah. But I think we all try to help each other and there's room for all of us, and all of us play a part."

Summary

Qualitative results from surveys and interviews highlight key relationships and flows of capital on the ranch operations. The local context and place-based knowledge illustrates the nuances of the four different capitals and how they often blur and overlap as ranchers work to meet their goals. Along with contextualizing the capitals on the ranch, our findings are consistent with our statistical and econometric models, helping to explain some of our quantitative findings. Ultimately, these results showcase the resilience of the ranchers interviewed, who simultaneously juggle livestock management, financial considerations, both state and federal regulations, environmental conservation, and the increasingly unpredictable weather effects of climate change on their operations. Of specific interest, we identify harder to quantify indicators relating to the social and human aspects of ranching including adaptive management, multi-generational knowledge, quality of life, and the social fabric of ranching communities.

Measuring Ecosystem Health

Soil Sampling

Soil samples and field observations on soil characteristics were collected at each of the 12 ranches, with the location of the two sample sites of interest being decided under the ranchers' guidance. Four soil samples were collected from a 2x2 meter square box divided into four quadrants. In each quadrant, one soil sample was collected and then the four samples (one by quadrant) were mixed and bagged for lab analysis, with identifying information (NRCS, 1999). The samples were kept cold and sent to Ward Laboratories, a commercial soil analysis lab. Lab results of the soil samples from the ranches in the study for Arizona and Colorado (Table 7) show the ranges of Total Carbon, Organic Matter and Bulk Density.

Table 7. Key soil characteristics from sampled ranches in Arizona and Colorado.[27]

Soil characteristic	**Units**	**Arizona**		**Colorado**	
		Range	Difference (max-min)	Colorado	Difference (max-min)
Total Carbon	%	0.41-4	3.59	0.68-2.83	2.15
Organic Matter	%	.9-8	7.1	1.5-4	2.5
Water Holding Capacity	inches/sample	0.14-0.74	0.6	0.24-0.46	45.76
Bulk Density	g/cm3	0.79-1.93	1.14	0.79-1.48	0.69
Haney test					
Soil respiration	ppm of CO2-C	6.4-238	231.6	31-57	26
C:N ratio	ratio	6.6-19.4	12.8	6.5-18	11.5
Soil Health Score	score	1.85-24.6	22.75	6.09-10.2	4.11
PLFA test					
Total Living Microbial Biomass	index	103-2100	1997	127-1279	1152
Functional Group Diversity Index	index	0-1.38	1.38	1.302-1.47	0.168
Fungal to Bacterial ratios	ratio	0-0.07	0.07	high	nd

In Arizona, the observed C:N ratio among ranches shows substantial variation ranging up to three times from the lowest to the highest values recorded. The Soil Health Score is calculated based on soil respiration and water extractable carbon and nitrogen, and

[27] Results of soil samples and geospatial results were shared with all ranch partners and a debrief of findings was offered upon request.

observed values showed differences of more than 13 times between the lowest and the highest values. However, although the score can range anywhere from 0 to 50, most soils nationally do not score higher than 30, therefore the observed values do not seem out of range. The Phospholipid Test (PLFA) is a biological analysis that provides information on microbial biomass and functional groups that are important in biological processes. Total Living Microbial Biomass shows a very large variation with differences 20 times from the lowest to the highest value recorded. The values for Functional Group Diversity Index of ranches can be considered above average. The values for Fungal to Bacterial ratios can be considered low. Biologically, the soils from ranches in Arizona are on the low end of microbial biomass with low diversity and many unidentified undifferentiated species.

In Colorado, the observed C:N ratio among ranches shows substantial variation ranging up to two and a half times from the lowest to the highest values recorded. The Soil Health Score did not show high variation (less than 70% difference between the highest and the lowest scores), with values well below 30. Given that a score of 7 and above is more desirable, ranches in Colorado in general seem to have good soil health conditions. In terms of the PLFA test, the Total Living Microbial Biomass shows a large variation with differences 10 times from the lowest to the highest value recorded. The values can be considered very poor to slightly below average. The values for Functional Group Diversity Index of ranches can be considered above average. The values for Fungal to Bacterial ratios can be considered high, which is indicative of late successional rangelands. Soils are on the low end of microbial biomass, but with good diversity and above average Fungal to Bacterial ratios.

Although results from ranches in Arizona and Colorado are not comparable due to the different biophysical conditions, they show that in both states our case studies exhibit large variation in soil characteristics. Soil sampling provided indicators for specific sites selected, but due to high variation in soils and the large size of ranches these results were unable to provide broader overall ecosystem health information.

Impacts on Natural Capital: Comparisons between Ranches and a Buffer Zone

The production of herbaceous above-ground biomass in rangelands is a fundamental ecosystem service upon which livestock, wildlife, and humans depend, but it is also influenced by human use and management (Jones et al., 2021). Biomass production is a crucial indicator of natural capital for rangelands as it relates to both cattle production and sustaining wildlife. To measure how this fundamental aspect of natural capital may be impacted by the ranches in our case studies, we acquired data on annual biomass production of Annual Forbs and Grasses (AFG) and of Perennial Forbs and Grasses (PFG) in Pounds Per Acre (PPA) for the time period 1986 to 2021 from the Rangeland Production Dataset (Rangeland Analysis Platform, 2022)[28] for each ranch and a surrounding buffer zone.[29] The buffer zone represents an area not under the rancher's management, but in close proximity[30]. We used these data sets to test for changes in biomass production over time and for differences between the ranch and its buffer zone to try to detect the impact of the rancher's management on biomass production over time and space. For this analysis, we use the following terminology: (a) each specific combination of a ranch and its buffer zone is referred to as a location; (b) within a location, the ranch and the buffer zone are referred to as land-uses. Unfortunately, we could only get data for 10 locations (4 in Arizona and 6 in Colorado). Therefore, there are 10 locations, each involving two land-uses.

To carry out these comparisons we use a time-series regression using Generalized Least Squares implemented in R (Fox & Weisberg, 2018) using a covariance matrix that corrects for autocorrelation of the time series data.[31] Since precipitation and temperature are known to affect biomass production, we estimated a full model that included these two variables, year, land-use, and all possible interactions. In addition to the full model, we estimated nested models of all combinations of these variables and

[28] These data have been estimated through a process-based model that uses three primary inputs to estimate plant productivity: (a) continuous vegetation cover, (b) absorbed solar radiation, (c) meteorology (see https://support.rangelands.app/article/49-rangeland-production for further details). The estimates refer to new accumulated growth over a 16-day period that then is summed to an annual total (idem), and thus indicates biomass productivity of an acre over a year.

[29] To do this, we obtained and/or created shapefiles, georeferencing with ranch maps for each of the ranch boundaries and drew a buffer zone surrounding them. Only ten ranches provided us with the needed information for geospatial analysis.

[30] An important caveat for these comparisons is that buffer zones may or may not be similar in environmental terms, land history, topography or even climate to the nearby ranches. However, since the comparison is based on data for more than 30 years it provides a simple benchmark to compare the ranchers' management to an area not under their control.

[31] In this context, autocorrelation means that the value of a variable in a year is correlated with its values in previous years. Ignoring these correlations will lead to incorrect statistical inferences.

interactions. Nested models include a subset of the variables in the full model. We compared these models using Akaike's Information Criteria (AIC) which helps determine the best model to use to fit the data and which models are the simplest (Akaike, 1973). When models had similar AIC scores, we chose the simpler model (see Appendix 4 for details). Using this model selection procedure, a model was chosen for annual biomass, and another for perennial biomass. Parameter estimates, estimate uncertainty, significance, and contrasts were assessed using the *emmeans* package (Searle et al., 1980), assuming significance of effects when p-values were less than 0.05. Given the importance of precipitation and temperature for biomass production, we first report on the dynamics of these variables during the time period of this analysis.

Weather

Over the 35 years and 10 locations, annual precipitation varied from 5.7 to 38.5 inches, with a mean of 16.8 inches. Mean air temperatures ranged from 38 to 69 degrees Fahrenheit (deg F), with a mean of 55 deg F. Overall, cumulative annual precipitation significantly decreased over the time period ($p=0.03$) by an estimated 0.06 inches per year, while the mean annual air temperature significantly increased ($p<0.001$) by an estimated 0.05 deg F per year. The magnitude of changes varied by location (Figure 4). However, it is important to bear in mind that variability in year-to-year precipitation may be more important than total precipitation. Even with this caveat, it is clear that the ranches in our case studies are experiencing substantial and detrimental changes in precipitation and temperature, particularly in Arizona. The overall effects of these changes on biomass production are context specific. For example, in locations with high precipitation but low average temperatures, an increase in temperature may result in higher biomass production. However, in areas with low precipitation, an increase in temperature can result in lower biomass production. Additionally, the response of vegetation to these changes will depend on the types of vegetation present. Therefore, while these changes are significant, their interpretation requires context-specific considerations.

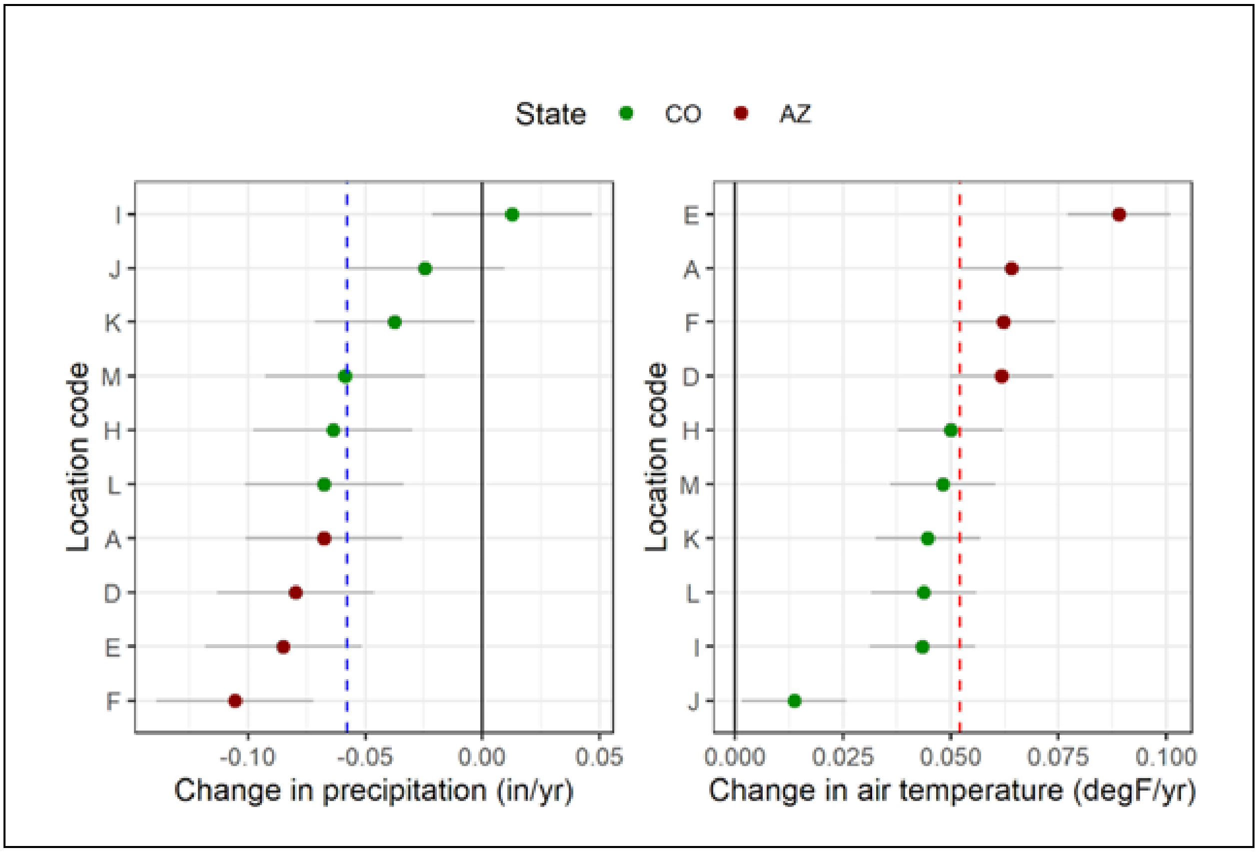

Figure 4. Estimated changes in weather from 1986-2021 with standard errors of estimates. (Left) Long term decreases in precipitation by location with dashed line representing the mean decrease (right) long term increases in temperature by location with dashed line representing the mean increase. Each capital letter represents a location.

Biomass

Annual herbaceous biomass production ranged from 0.02-613 lbs./ac, and perennial from 87-1843 lbs./ac (Appendix B, Figure B1). The best-fitting model for annual biomass included terms for precipitation and temperature, while the best-fitting model for perennial biomass included terms for precipitation, temperature, and their interaction. All results therefore account for the changes in precipitation and temperature observed over the time period studied (see Figure 4).

The three-way interaction between year, land-use (buffer, ranch), and location was not significant for either biomass type (annual, perennial), meaning ranching did not significantly affect the biomass production trajectory at any location.

For both annual and perennial biomass, the effect of year depended on the location (p=0.02 and p<0.01 for annual and perennial biomass, respectively, Appendix B, Tables B3, B4). This means that while biomass trajectories did not depend on land-use type, they varied by location. After correcting for changes in weather, no location saw a significant decline in annual or perennial biomass production over time (Figure 5).

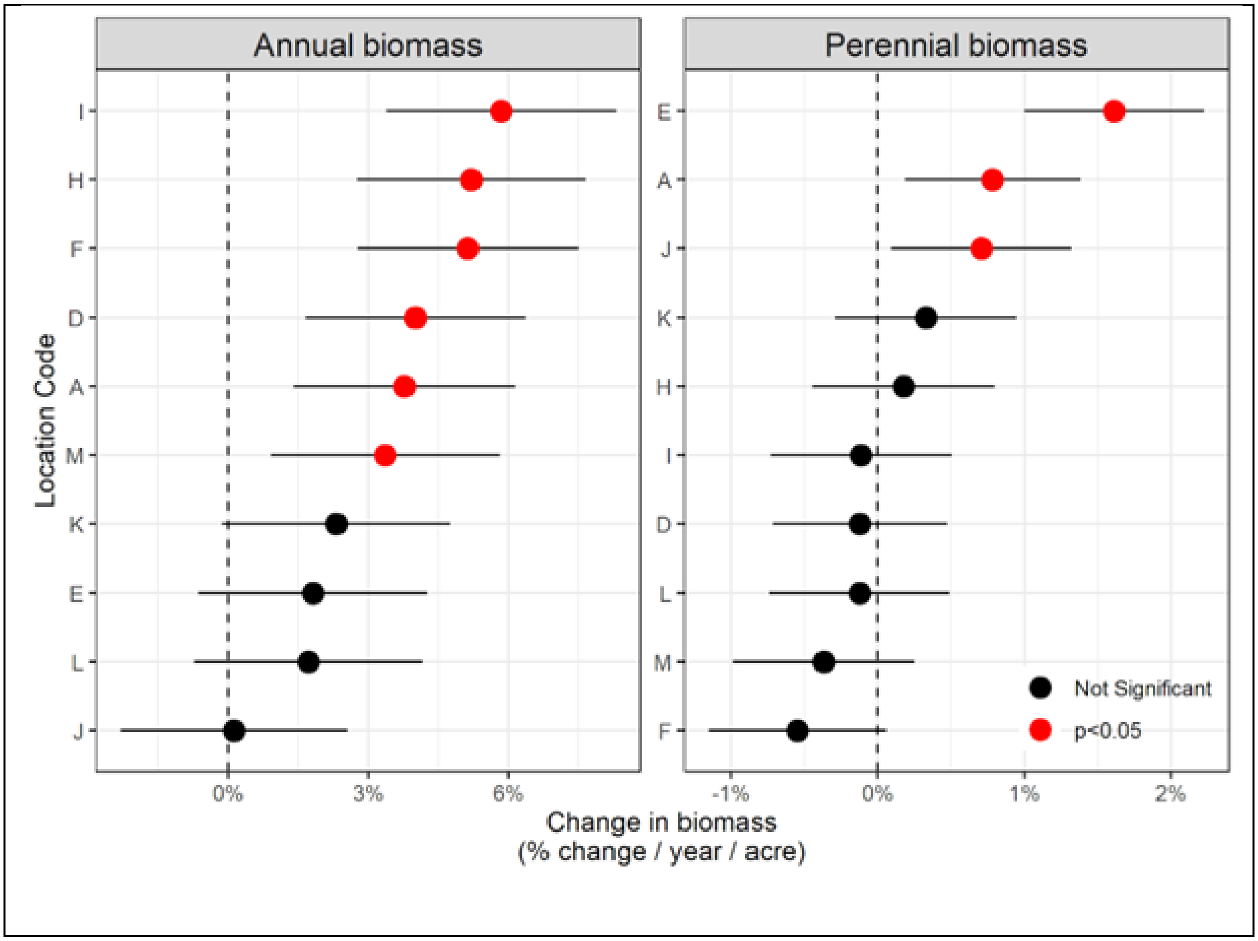

Figure 5. Estimated change in biomass from 1986-2021 at 10 locations with 95% confidence intervals. Each capital letter represents a location.

Annual biomass significantly increased over the study period in six of the ten locations, with increases ranging from 3-5% annually. In three locations, perennial biomass significantly increased over the study period, ranging from 1-2% annually. At a given location, increases in annual biomass were generally associated with decreases in perennial biomass (Appendix B, Figure B2), although one location (Arizona, Location A) exhibited a significant increase in both annual and perennial biomass.

While the change in biomass production over time did not differ by land-use, at two locations the ranches had 1.4-1.5 times more perennial biomass than the buffers (Figure 6). However, in the majority of locations, the mean biomass production did not differ between the ranch and buffer areas.

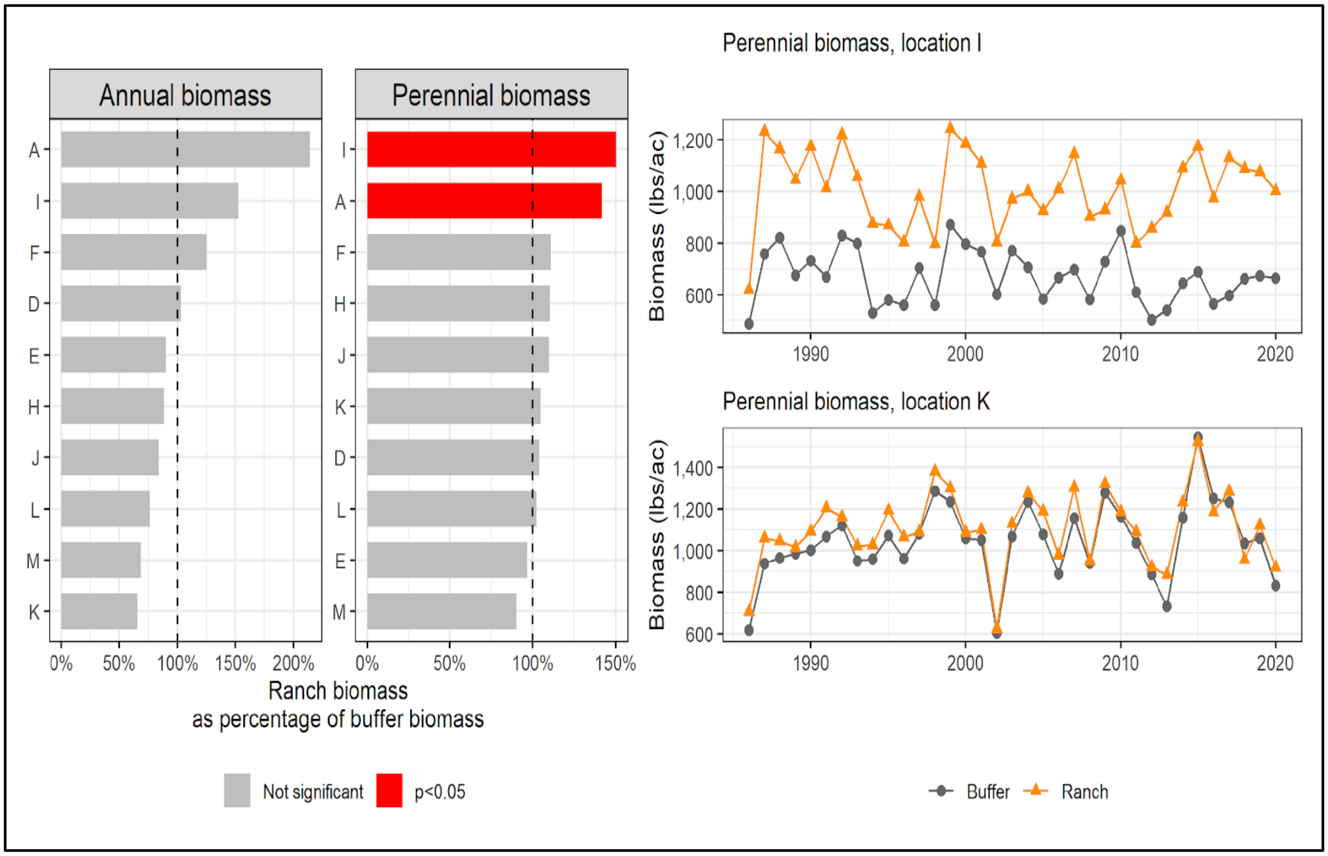

Figure 6. Differences in biomass production in ranch and buffer areas. (Left) Ranch biomass as a percentage of buffer biomass. (Right top) Location I, where ranch perennial biomass was 1.5 times higher than the buffer. (Right bottom) Location K, where there was no difference in perennial biomass production between the ranch and buffer. Each capital letter represents a location.

In summary, for the ranches in our case studies results show that there is no evidence of biomass decline over time. While we do not know the exact nature of the buffer zone, in general there does not seem to be any measurable differential effects of ranch management compared to the buffer zone. Even when trends are present, ranching was associated with higher biomass production. Furthermore, in spite of important changes in precipitation and temperature (Figure 4), there is no evidence of these changes negatively affecting annual and perennial biomass production, and even in some locations there have been statistically significant increases in both types of biomasses.

However, it should be stressed that these results apply only to the ranching activities at these sites. It is certainly possible to undertake ranching activities that have detrimental effects on the environment. While we can conclude that that ranching per se is not detrimental to the production of AFG and PFG—and have shown evidence from a subset of ranches validating this—it is important to not infer that "all" ranching is associated with higher biomass production.

Biodiversity (Land Cover)

In general, in a landscape, biodiversity is favored by environmental heterogeneity. Some of the reasons for this are because environmental heterogeneity promotes species diversity by creating increases in the niches, or types of habitats, allowing more species to coexist; environmentally heterogenous areas provide shelter and refuge from adverse environmental conditions and periods of climate change; and heterogeneity increases the probability of speciation due to isolation or adaptation to diverse environmental conditions (Stein et al., 2014). Although direct measurement of biodiversity in rangelands is a complex endeavor, measuring heterogeneity in vegetation cover is a straightforward process and the data is available at the scale of the ranches in our case studies. This data is available from the same database used for aboveground biomass production and for the same period (Rangeland Analysis Platform, 2022). We used this data to test for changes in diversity of vegetative cover over time and for differences between the ranch and its buffer zone to try to detect the impact of the rancher's management on vegetative cover (and thus environmental heterogeneity) and by inference on biodiversity over time and space.

Employing the same approach as used to obtain the data from ranches and their respective buffer zones, we extracted the data on vegetation cover. This data consists of the percentage cover in six categories: (i) Perennial Forb and Grass (PFG), (ii) Annual Forb and Grass (AFG), (iii) Litter, (iv) Shrub, (v) Tree, and (vi) Bare Ground per Year. With this data we constructed a Simpson Diversity Index[32] that provides a synthetic measure of the number of different categories and the evenness by which they are represented. The index varies between 0 and 1. A high index indicates high diversity/heterogeneity. Its theoretical maximum of 1 corresponds to the percentages of all six categories being the same, while a value of zero represents that only one category accounts for 100% of the cover.

We use the same independent variables and estimation approach as for biomass production, fitting first a full model and then simpler models (i.e., nested models) by

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[32] The Simpson diversity index of vegetation cover diversity is calculated as follows:

$$D_{it} = 1 - \sum v_{ijt}^2$$

where: v_{ijt} = percentage of vegetation cover category i, for location j, at time t

eliminating independent variables. By employing the model selection procedure as described above, models were fitted to each cover category separately to provide insight into the drivers of differences in Simpson's Diversity Index. We also included precipitation and temperature as covariates in the models.

Over the 30 years and 10 locations, Simpson's Diversity Index ranged from 0.43-0.83, with higher values indicating a more diverse land cover. The best-fitting model describing Simpson's Index included precipitation only (Appendix B, Table B5). The three-way interaction between land-use, location, and year was not significant, meaning ranching in these sites does not significantly change land cover diversity over time compared to the buffer zone. However, the change over time significantly depended on the location ($p<0.001$, Figure 7).

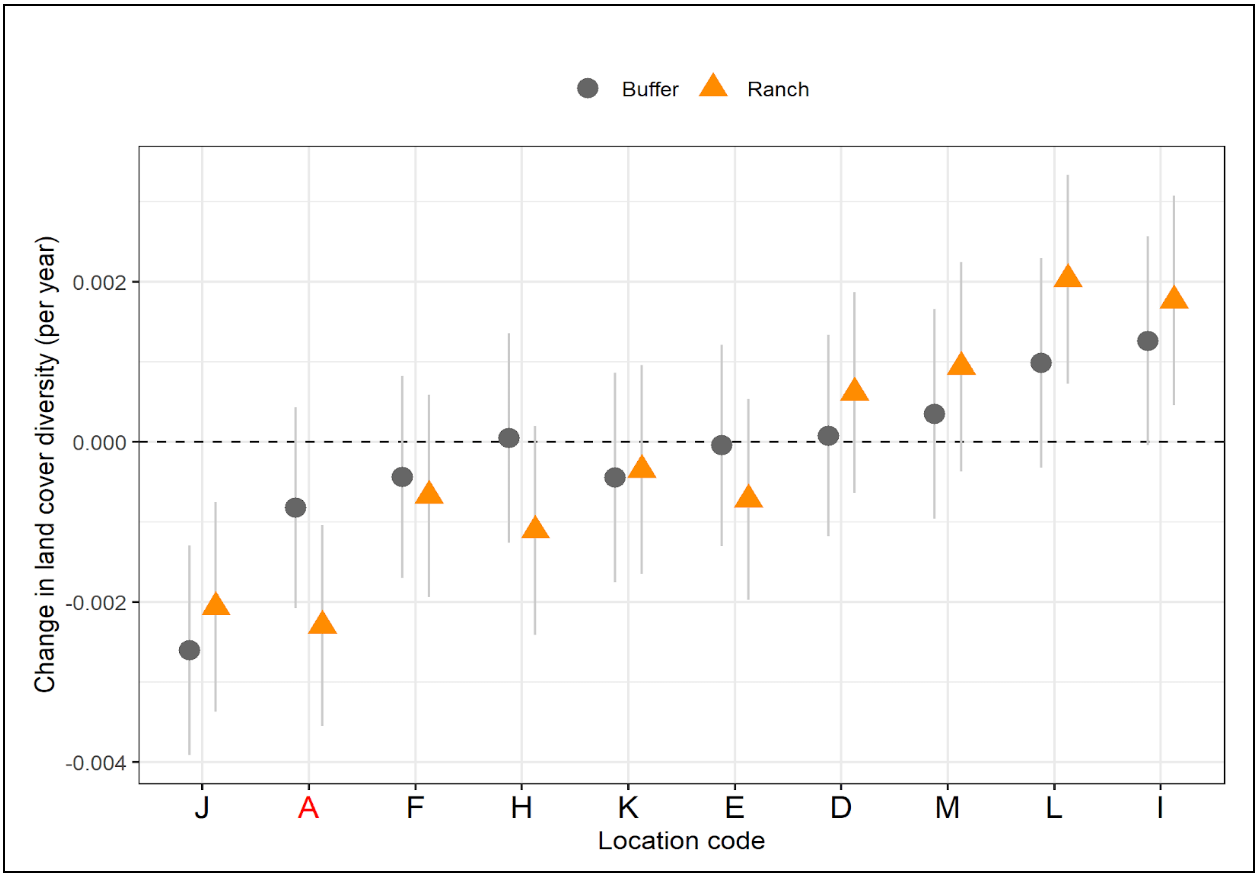

Figure 7. Change in Simpson's Diversity Index over time for buffer areas (gray circles) and ranch areas (orange triangle) with 95% confidence intervals. Ranching and buffer areas differed in only one location (Arizona, Location A, red) where the ranch land cover diversity was decreasing at a faster rate compared to the buffer area. Each capital letter represents a location.

The effect of land-use on the overall land cover diversity also significantly depended on the location ($p<0.001$). In four of the ten locations, the ranch had less land cover diversity than the buffer area (Figure 8).

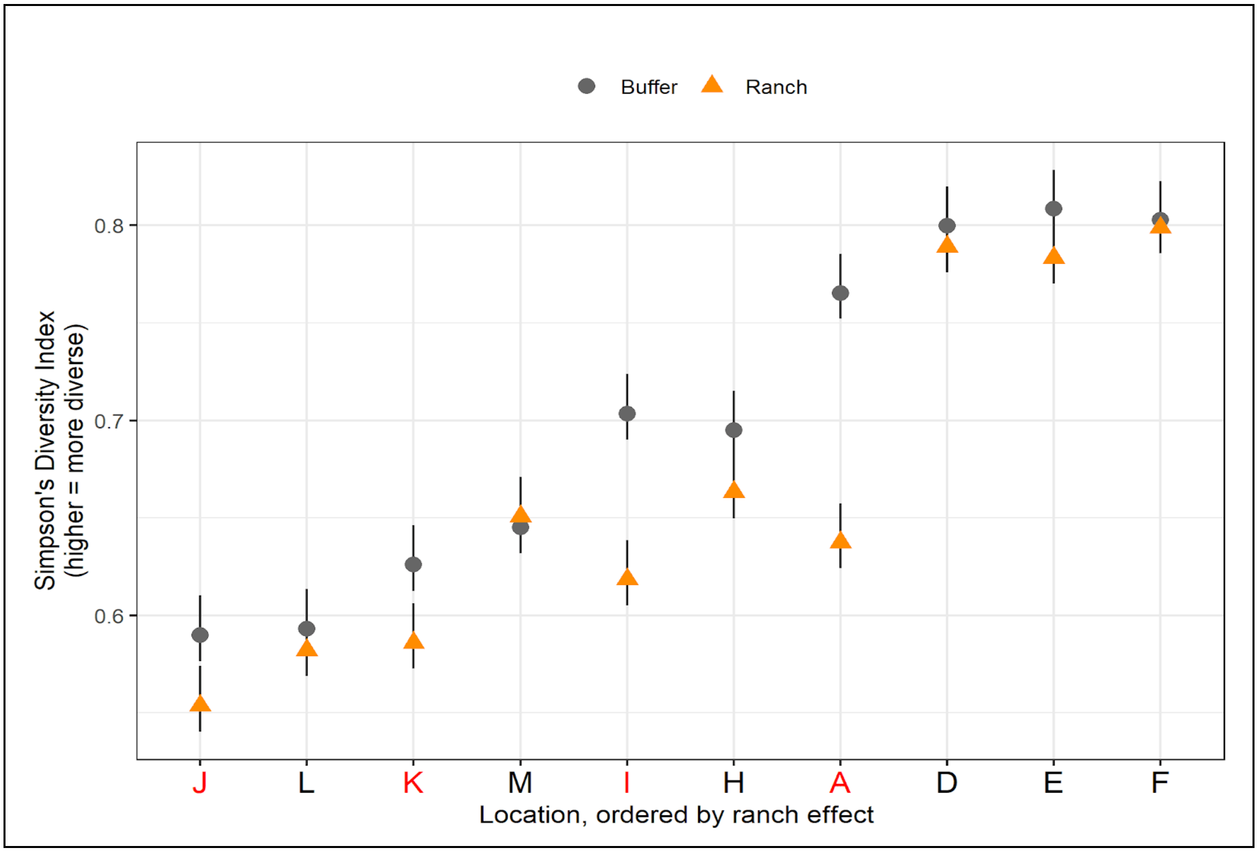

Figure 8. At four locations (red) ranch areas (orange triangles) had significantly lower land cover diversity compared to the buffer area (gray circles). Line ranges represent 95% confidence intervals. Each capital letter represents a location.

These differences in land cover diversity in the ranch versus buffer areas were not consistent across location, and included differences in annual biomass, perennial biomass, trees, shrubs, and bare ground.

Bare ground is of particular interest, so it was investigated explicitly. While bare ground is part of any semi or arid system, when it exceeds system norms, it increases susceptibility to erosion and decreases the capacity of a system to capture the little rainfall that does occur. This can lead to a vicious cycle of biotic feedbacks. Ranchers are also interested in reducing bare ground out of the perception that it increases forage production, which may or may not be true (Moechnig, 2010). The best-fitting model describing bare ground included temperature, precipitation, and their interaction.

Individual years and locations ranged from a low of 0.5% bare ground to a high of 48%. The modeled mean for the data was 16% bare ground. There was a significant interaction between the effect of land-use and location ($p<0.001$), meaning the impact of ranching on bare ground compared to the buffer varied by location (Figure 9).

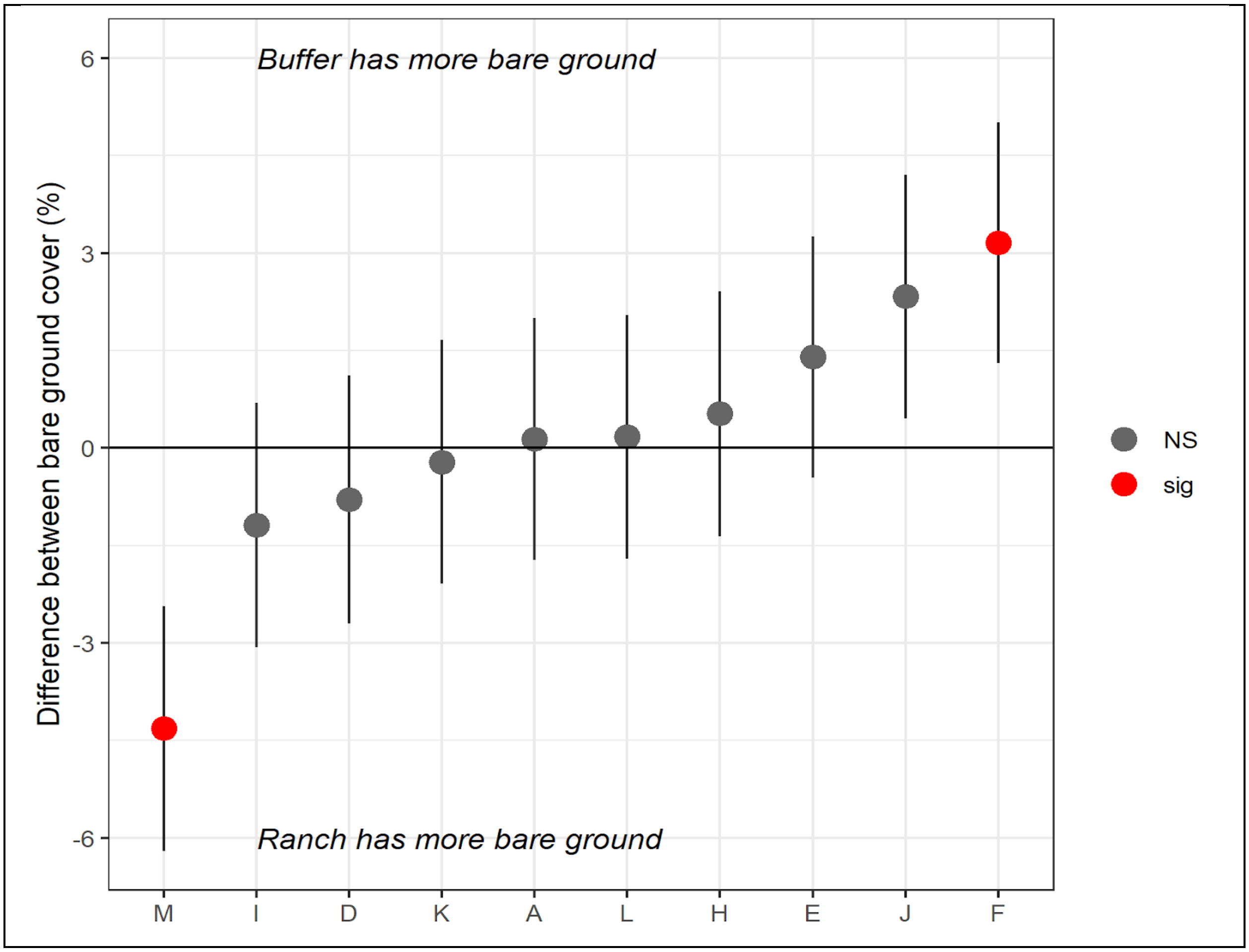

Figure 9. 95% confidence intervals of differences in bare ground between ranch and buffer. Each capital letter represents a location.

At one location (Colorado, location M) the ranch had 29% bare ground compared to the buffer area with 24% bare ground. Conversely, at another location (Arizona, location F) the buffer area had 17% bare ground compared to the ranch with 14% bare ground. Overall, there was no consistent change in bare ground, with the trend varying significantly by location ($p<0.001$). Six locations had significantly decreasing bare ground cover at rates of around 0.2% per year, while four had no change (Figure 10). In summary, ranching in these sites does not significantly change land cover diversity over time compared to the buffer zone, although results differed by location. This suggests that ranch management in general has no discernible effect on environmental

heterogeneity as measured by diversity of vegetative cover, and thus on biodiversity. While four ranches had lower diversity than in their associated buffer areas, these differences were present since the beginning of the measurement period. As stated in the section on biomass, we should be careful not to construe that these results indicate that ranching does not have an effect on vegetative cover, environmental heterogeneity, and biodiversity. There may be cases where it does, but we have shown evidence that well-managed ranches (as in our case studies) may not negatively impact the environment.

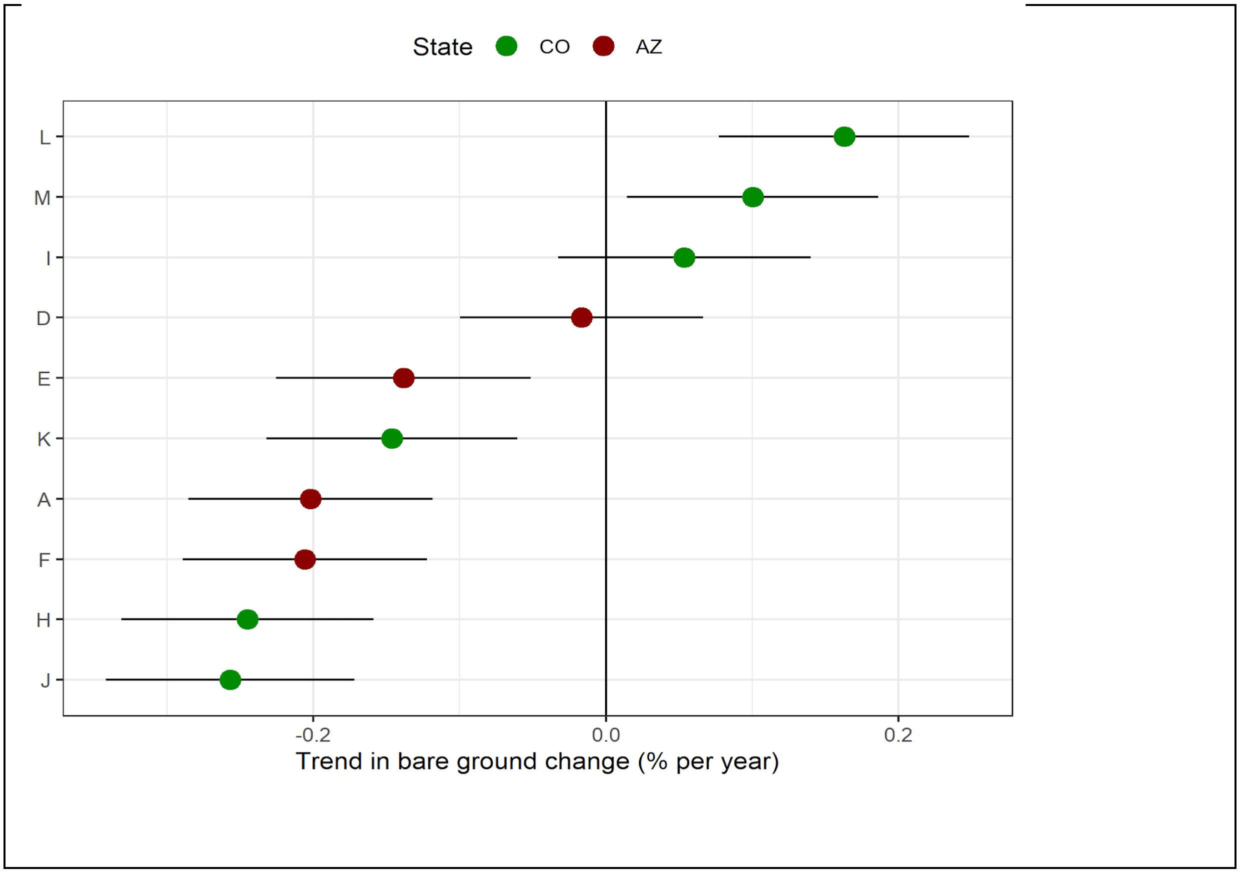

Figure 10. Trends in bare ground changes. Each capital letter represents a location.

Life Cycle Assessment

A Life Cycle Assessment (LCA) is a methodology used to assess the impact of material flows. LCA breaks down a supply chain system into subsystems that can be analyzed to calculate the environmental impact of a product. A simplified example would be breaking down each step in the creation of a product, with each step constituting a subsystem in the larger system of a product's lifecycle. Typically, all products require raw materials that must first be extracted from the ecosystem and then transported to a facility for some form of processing to convert these raw materials into a usable material. Once the usable material is obtained, it is sent to a manufacturing location where the product of interest is made and packaged, and from there the product is transported to a point of sale. Once sold, the product is used over a period of time, after which the product is disposed of into a recycling system or landfill. The LCA is especially useful because it has the capacity to evaluate the environmental impact across this entire supply chain.

When preparing to conduct a LCA it is important to both define the start and end points of the product's lifecycle and also decide how one plans to quantify the amount of product being measured. Setting the start and end points establishes the boundaries that will represent the scope of the LCA. By defining how one will quantify the amount of product that is produced through the supply chain one can determine how to measure the environmental impacts from the system of production. This measurement is presented as a Functional Unit (FU), as it is based on the function of the product (Weidema et al., 2004). For example, one could set the FU as measuring the tons of stone removed from a quarry or the number of eggs produced by a henhouse. It would make less sense in evaluating the supply chain to measure the number of stones removed from the quarry, as the rocks vary widely in size and weight. In this LCA we look at CW, which is the dressed weight of cattle measured per kilogram. This CW is assigned as the average weight of a dressed, slaughtered commercial beef cow as reported by the USDA NASS (2020). This average weight of 366.8 kg is assigned to cows and bulls, with calves being factored into methane emissions only at 26% of the average cow (based on Basarab et al., 2012) at each of the ranches in this case study.

Since the LCA is proficient at analyzing the environmental impacts from material flows, it is best suited to evaluate the impact created by the consumption of natural capital. There are multiple stages (or subsystems) in the production of beef, with the starting point being the birth and weaning of a calf on a cow-calf and cow-calf combinations operation, the growth stage to market weight of the cattle on the ranch or feedlot, and the transport to and the slaughter and processing of the cattle at a slaughterhouse or packing facility. All these stages require resources such as feed, water, and energy. The production of these materials and making these resources available to the operation

managing these cattle are individual subsystems and each creates their own impacts. In our study, we specifically evaluate the impacts associated with ranching operations in the cow-calf phase using the LCA to identify the natural capital costs across the ecosystem.

It is important to realize that the key resources considered here (feed, energy, and water) also vary greatly within each resource type. For feed there are different kinds of feed like hay, silage, corn, and soy. These feeds are produced as part of an agricultural system designed to supply livestock operations, which creates different levels of impact on GHG emissions, energy, and water use depending on the feed used. For energy, we consider renewable energy and fossil fuel energy and their different impacts on the environment. Last but not the least is water, which for the purpose of this study is calculated to be blue water, or water sourced from irrigation or groundwater supplies.

There are energy, water, and carbon impacts associated with the consumption of all these resources. We present the results in the form of carbon, energy, and water because those are the most common impact categories presented in an LCA and carbon costs are much more established than GHG emissions. These three impacts also allow us to measure the cost of these impacts, since there are monetary values associated with water and energy. There is also the carbon market that is in the process of finalizing the cost of carbon. Using these financial tools, these impacts can be monetized, which then allow us to quantify the embedded cost of beef production and explore the true cost of this system.

LCA results, specifically GHG emissions results, are presented excluding the full biogenic carbon cycle in cattle: from methane emitted to carbon sequestered (to be addressed in later section). In the academic world there is some understanding of the biogenic carbon cycle, but it has not translated to a standardized accounting mechanism yet as there is debate about the actual climate effects of methane belched from cattle (Werth, 2020). Similar concerns exist around nitrogen and its role in the biogenic carbon cycle. Nitrogen is also complicated, as the GHG emissions protocols around nitrogen emissions on ranch operations have not been standardized and accepted. For these reasons, the nitrogen included in this LCA is included only for the fertilizer needed in corn or soy feed, not hay. LCA standards assume a warming potential of methane of about 28 times that of carbon dioxide (Thompson & Rowntree, 2020). It is important to note that a large portion of the carbon dioxide emissions in the livestock system are from feed and fuel, while methane is largely from livestock themselves. We consider only the emission of methane since its removal is not a standardized process. One molecule of methane results only in one molecule of carbon dioxide after it's complete combustion (oxidation). But methane has the lifetime of a

decade before it undergoes complete combustion to become carbon dioxide, which can exist for more than 1000 years (NOAA, 2022).

Given the rates of land use change and deforestation over the past decade, it is not possible to guarantee that molecules of biogenic carbon dioxide are reabsorbed into the vegetation (Ritchie & Roser, 2021). If biogenic carbon dioxide is absorbed by feedstock, it is critical that the time of storage aligns with the removal and storage timeframes being discussed in the GHG emissions protocol. The extent of removals is severely dependent on land use and land use change (EPA, 2011). Given the amount of uncertainty regarding methane recyclability in the biogenic carbon cycle, the metrics used in this LCA are not agreed upon. Methane is a short-lived pollutant, leading some to believe the impact is often over-estimated (Allen et al., 2018; Pierrehumbert, 2014; Thompson & Rountree, 2020). The short lifespan of methane also raises questions towards the use of Global Warming Potential (GWP), with exploration into better suited metrics such as Global Temperature Potential (GWP*), which uses a decadal time scale argued as more appropriate for short-lived pollutants, but is not yet widely accepted (Allen et al., 2018; Shine et al., 2005; Thompson & Rountree, 2020).

While there was LCA data for carbon dioxide emissions for feed, fuel, and other cow-calf and cow-calf combinations operations, the methane emissions were estimated from Rotz et. al. (2019). It was assumed that the methane emissions estimated are largely from livestock in the American Southwest. To address the controversy regarding methane calculations in LCA, we incorporate an estimated range for carbon sequestered specific to Western Rangelands from Sanderson et al. (2020) to pair with LCA findings.

OpenLCA is a publicly available LCA software that has a collection of datasets that allow us to identify these carbon, energy, and water impact factors. In an LCA, the results need to be assigned to impact categories that are both relevant to the supply chain being analyzed and independent enough to not overlap or allow for double-counting. All three impacts are calculated using the Environmental Footprint (EF) 2.0 method, which was developed by the European Union to standardize the process by which organizations measure the environmental impacts of their products (European Union, 2013). Due to limitations on the impact categories available in OpenLCA, these impact categories are chosen. While OpenLCA uses older categories, these categories still present the best available approach to measure carbon, energy, and water using publicly available data sources. When specific data on water use or energy use of feed was not available, data from Rotz et. al (2019) were used. This paper presents regional averages of energy use based on the source, water use, and feed.

Since much of the data used in this LCA are drawn from the responses of the ranches participating in this case study, the results are not a representation of all beef produced in Arizona and Colorado. We are using these samples to pilot this LCA methodology in estimating environmental impacts on natural capital. There was considerable variability in the ranch management strategies adopted across all the ranches. All ranches had their cattle on ranges with varying levels of control over the grazing area. While many of the ranches discussed being impacted by drought, each seemed to experience the effects and severity of the drought differently. This led to a wide variability in the amount of supplemental feed provided to cattle when there was no rangeland forage available. Breeds varied from Angus and Hereford to Corrriente and Brahman, with the latter two being preferred for their hardiness during a drought, but the former two breeds are preferred for their marketing value. Most likely these varying breed characteristics, coupled with each ranch's unique ecosystem, drove the difference in the amount of water consumed by these cattle. Some ranches used renewable energy for water supply while others used grid energy. Other ranches also had significant fuel consumption for their ranch operations. Given this expansive variability it is important to consider these various cases as individual cases.

The graphs below show the GHG emissions, energy, and water impact for all these ranches normalized by kg of CW. These graphs are presented as a box plot, which depicts the range of variation among the different impacts. The area within the box contains the results of the lower and upper quartile, with the median represented as the horizontal line within the graph, and the mean represented by the "x". By viewing these box plots, one can see that normalized Carbon and Water Cost (Figure 14), (Figure 15)[33] is variable among ranches. The water impacts were primarily driven by the water consumed by the cattle, although in some cases this was also impacted by irrigation. The energy impacts were driven by use of fuel on farms and the indirect energy from the production of fuel. The carbon impacts were driven primarily by animal derived methane followed by increasing fuel use on site.

[33] The LCA calculations for water are based on blue water consumption since there is insufficient data to estimate the water returned to the system. Water consumption used is a consumption metric, not a net balance metric. Blue water excludes the flow of water from the cattle to the system.

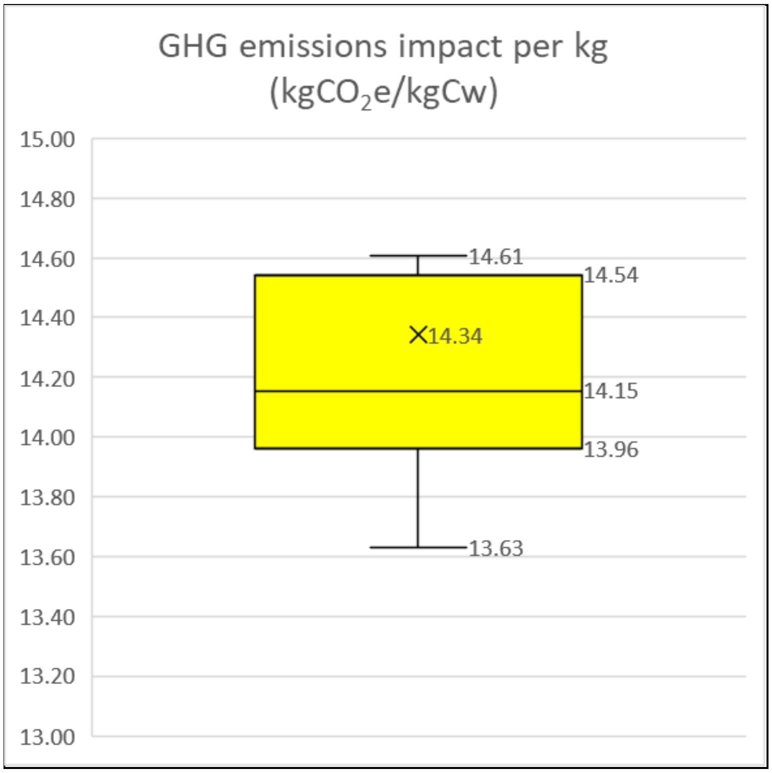

Figure 11. GHG emissions impact per kg CW.

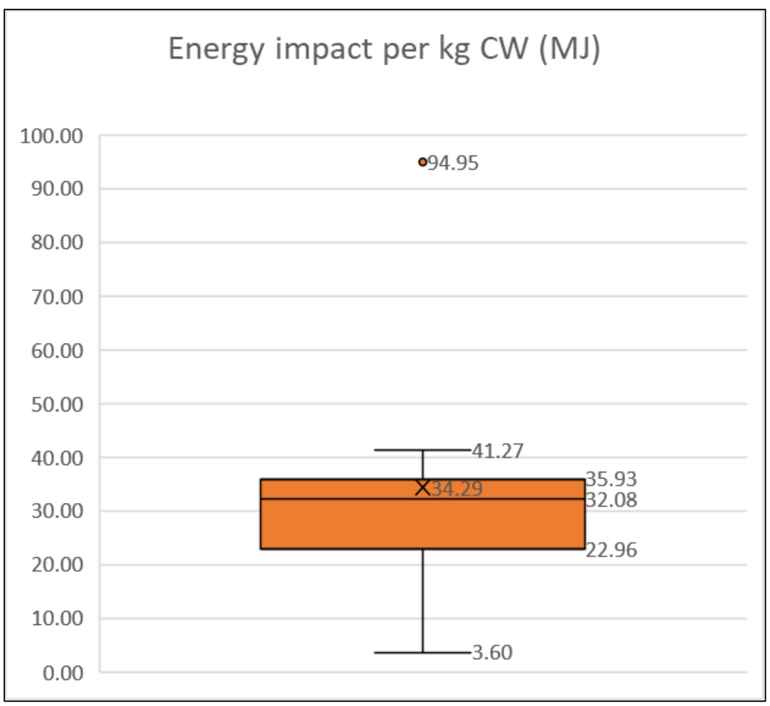

Figure 12. Energy impact per kg CW.

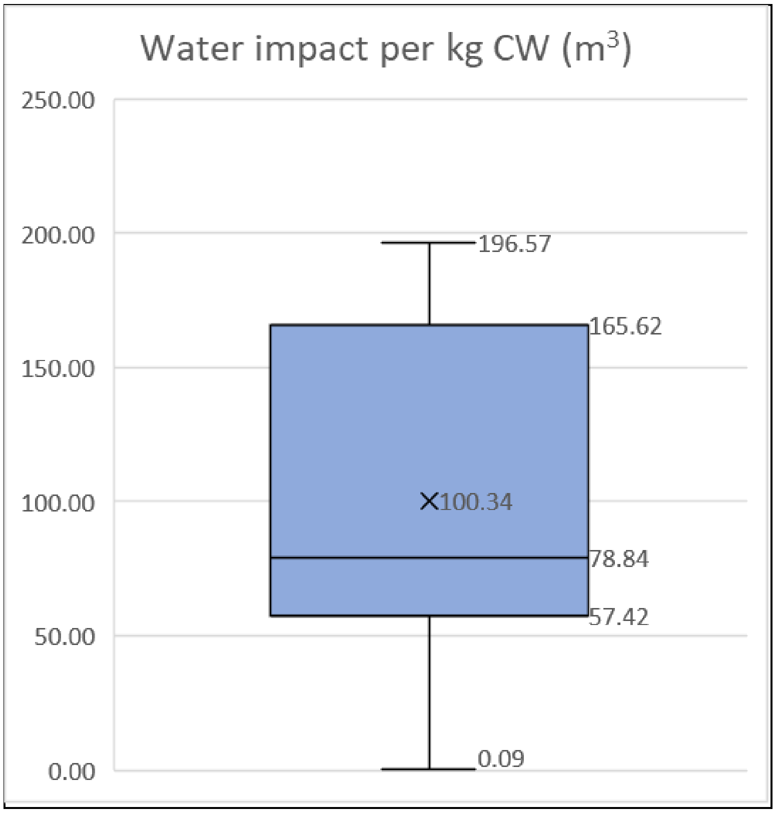

Figure 13. Water impact per kg CW.

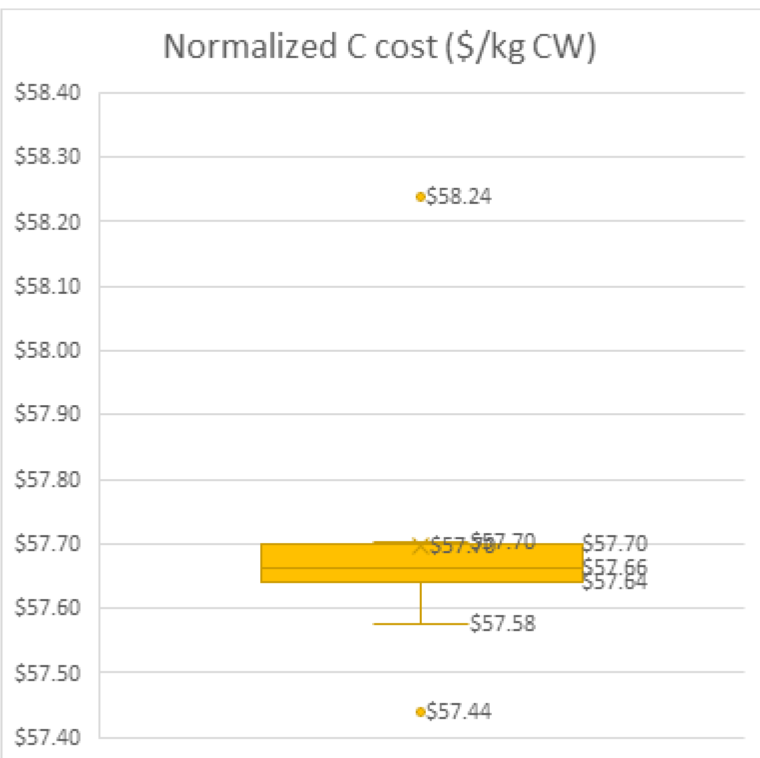

Figure 14. Carbon cost per kg CW.

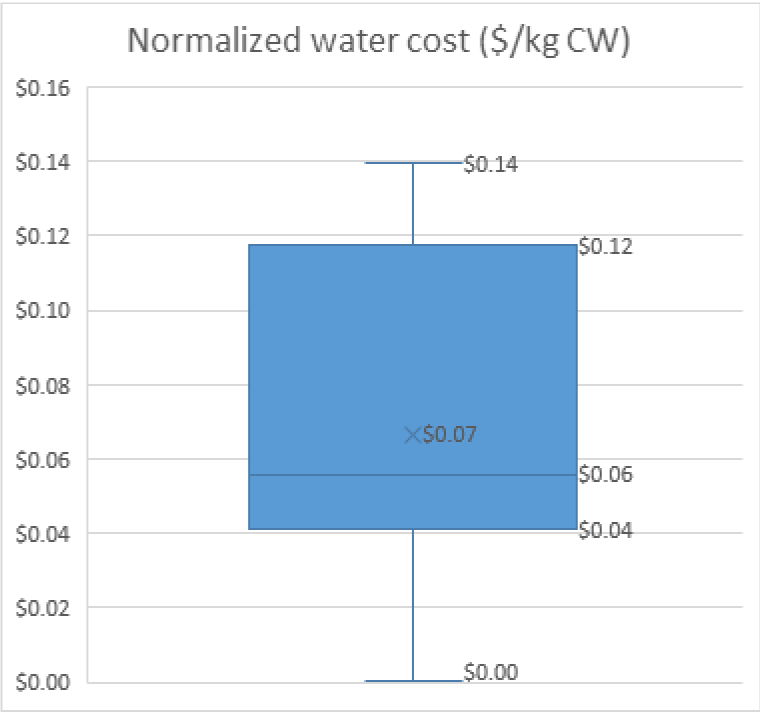

Figure 15. Water cost per kg CW.

It is crucial to understand that LCA presents results based on the data that is provided. Given that negative externalities are a crucial component to the concept of TCA, it becomes necessary for practitioners to access records to fuel use, electricity use, water use, and feed use at the farm level. Background data is the second side of the coin. There are many standardized datasets for a LCA, but many of them are getting old and may not be applicable. Access to latest data specific to a geography will be crucial for a more accurate interpretation. Each farm is unique, and the management practices vary. Farm level style data collection and data matching, while expensive to both the farmer and the examiners, is critical. This will account for variability as well as some uncertainty.

From a methodological perspective, uncertainty must be dealt with some kind of uncertainty assessment while carrying a TCA style accounting procedure. While this pilot project has analyzed a small sample of select farms in Arizona and Colorado, uncertainty assessments become very important as larger sample sizes are chosen. Even within the select farms, there was considerable variability in the kind of energy sources, feed sources, cattle breeds, management styles, as well as water consumed. When analysis is expanded to scale, it will be best to carry out a Monte-Carlo assessment to identify regional net balance using the TEEBAgriFood Evaluation Framework.

There are standards being developed to carry out accounting for biogenic methane. The key concept around biogenic methane is permanence. How long does the carbon get stored? Early insights into permanence indicate that it will be crucial to account for aboveground and belowground biomass in order to account for biogenic methane. A similar argument can be made for nitrogen. Nitrous oxides are GHG emissions but were not included in the current pilot. The assessment of nitrous oxides is especially critical for agriculture due to the extensive use of fertilizers in the feed system. The cattle system is highly dependent on the feed system, which makes it a key driver of nitrous oxide emission.

The final key takeaway is at a much larger level and deals with rural-urban boundaries, land use change, and material flows. While the beef product typically flows from the rural region to the urban region, the resources associated with the production of beef is in constant competition with resource intensive urban regions. In a planet with finite resources, it is critical to understand where the resources are needed, and a fair resource allocation needs to be carried out. For example, regions with extreme water stress may not be able to afford exporting embedded water through high water intense products. In other cases, water costs might need to be adjusted so that it accounts for some monetary value representative of the high-water stress in the region. The same economic principles can be applied for other resources and scarcity.

Assigning a True Cost

Our findings suggest that there may be no cost associated with grazing the rangeland on the ranches we study; we do not find evidence that cattle on the range significantly increase or decrease annual biomass production and biodiversity over time. Ranching seems to be only a secondary effect in this regard, as temperature and precipitation drive the productivity and biodiversity of the range. While the ranchers hoped certain practices would improve the range and may be disappointed to not have evidence of this, it is possible the methods used on these operations prevent the degradation associated with overgrazing, minimizing the negative associations per head of cattle (in CW) coming out of their operation. We also see qualitative evidence that in times of drought, these operations may support conservation through water development projects which help support various populations of wildlife.

Through our case studies, we find evidence of value generated by the ranches in the form of human and social capital. The ranches we study have highly experienced and educated operators. Specific place-based knowledge, animal stewardship skills, rangeland management experience, and more establish these ranches as successful businesses that help provide a significant protein source consumed daily in the US. Further, there is value generated generationally as training and mentorship transfer skills to the next generation of ranchers in the US, a crucial transfer that ensures farmland protection and food security: without farms there would be no food, and without farmers there can be no farms. Lastly, the ranchers we study contribute value to the social makeup of rural America, fostering a sense of trust and community that contributes to societal well-being. We see this value in many forms, from ranch specific technical assistance to network information exchanges, and crisis support. While we have not yet assigned a dollar amount to these qualitative elements of the ranches, it is important to note that value is generated, and so our "True-Cost" of cattle is coupled with harder to quantify benefits that one could view as the less tangible societal services these ranchers provide. We can, however, assess the monetary value of social and human capital to the cow-calf and cow-calf combinations operations, and interpret a socio-cultural value of ranching at the county level when evaluating unpaid labor motivations.

The LCA of the eleven ranches in our study quantified some important negative externalities such as GHG emissions, water use, and energy consumption. Based on the price of carbon from the US Interagency Working Group on Social Cost of Greenhouse Gases (2021) and of irrigation water (assuming average maximized value of water) from D'Odorico et al (2020), GHG emissions and water use, which can be considered negative externalities, were monetized. However, as the qualitative results show, ranches also produce positive externalities, such as wildlife conservation. To

quantify and monetize some of these positive externalities, we used the range of carbon sequestered specifically associated with grazing provided by Sanderson et al (2020) to calculate an estimated benefit using the same monetization factor as used in the LCA. They reported that where grazing has increased soil C ranges of between 0.05 and 3 ton/ha/yr. So, we calculated a monetary value for those rates of soil carbon sequestration (low and high) based on the same price of carbon as for carbon emissions (Table 8). In addition to carbon sequestered, we use the method developed by Maher et al. (2021) and the monetization factors provided by Maher et al. (2020) for Arizona and Colorado. Maher et al. (2021) identified three categories of ecosystem services that constitute positive externalities associated with cattle ranching in the US: (1) wildlife-related recreation; (2) forage production; and (3) other ecosystem services. They estimated a per hectare value for each of these ecosystem services. Values for wildlife recreation were estimated based on the number of recreation days per year and estimates of net economic values for wildlife-related recreation per day. The value of forage production was based on pasture rental rate data for private lands, and for leased public lands, the value was estimated through a complex process based on the NASS private lease rate for each US state. Therefore, these authors calculated different monetization factors for forage in leased federal lands and in private lands. The value of other ecosystem services was based on the CRP Grasslands annual rental payments for non-specified services (for details see Maher et al., 2021). [34]

Table 8. Value of positive externalities from recreation, forage, general ecosystem services, and carbon sequestered ($, 2020).

Positive externalities	**Arizona**	**Colorado**
Carbon sequestration		
Value of sequestered carbon low ($/ha)[a]	8.45	8.45
Value of sequestered carbon high ($/ha)[b]	507.00	507.00
Ecosystem services		
(a) Federal forage ($/ha)	2.98	3.73
(b) Private forage ($/ha)	6.01	14.62
(c) General ecosystem services ($/ha)	5.54	11.17
(d) Wildlife-related recreation value ($/ha)	47.15	47.18
Total value/ ha Federal land ($/ha) (a+c+d)	55.66	62.09
Total value/ ha Private land ($/ha) (b+c+d)	58.69	72.97

[a] Low rate of soil C increase: 0.05 ton C/ha/yr.
[b] High rate of soil C increase: 3 ton C/ha/yr.

[34] Value of positive externalities from recreation, forage, and ecosystem services from Maher et al., (2021) in $ of 2017 updated to $ of 2020 using the CPI. Data for the carbon price originally in $ of 2020 (U.S. Interagency Working Group on Social Cost of Greenhouse Gases, 2021).

Source: Maher et al., 2020. Value of Arizona Beef Cattle Ranching Ecosystem Services p. 16. Value of Colorado Beef Cattle Ranching Ecosystem Services p. 25. Values in $ of 2020 using the CPI. Data for carbon price originally in 2020.

Tables 9 shows the estimated monetary value calculated for the positive and negative externalities for each of the eleven ranches in our study, showing not only total values but also the value of the different components associated with both types of externalities (a detailed description of the methodology is presented in Appendix E). We assume that in Arizona, 10% of the land area is private and the remaining 90% is leased. We also assume that the value of forage is similar between federal and state lands since Maher et al. only provide estimates for federal land, but our study showed that ranchers leased both federal and state lands. In Colorado, we assume that 90% is private land and 10% is leased land. With those assumptions we calculated a monetary value for the positive externalities between $1.28 and $20.59 per kg of CW for the low rate of soil C sequestration and between $9.26 and $179.94 for the high rate of soil C sequestration.[35] These estimates show great variation across ranches, particularly since some of the ranches had lower than usual stocking rates due to drought. We also show overall estimates of the positive and negative externalities calculated by aggregating the data across ranches, thus smoothing the variation in the data to provide a better sense of the magnitudes of the different types of externalities. The positive externalities in the case of the low rate of soil carbon sequestration are dominated by wildlife value. However, in the case of the high rate of soil carbon sequestration, positive externalities are dominated by the value of carbon sequestration that are many orders of magnitude larger than any other externality.

As indicated earlier, the value of negative externalities was obtained from the LCA. The estimated monetary value for the negative externalities varied between $57.65 and $58.35 per kg of CW and these estimates were mostly due to the normalized Carbon cost with relatively low variability. The table also shows the average market value of CW based on the total number of animals sold and the total value of the sales, which is included as a positive economic contribution.

[35] As indicated in Table 9, the estimates of the magnitude of positive externalities may be overestimated in the case of a few ranches since they had lower than usual stocking rates due to drought.

Table 9. Summary of monetization of positive and negative externalities and average market price of CW in kg ($, 2020).

State	Arizona						Colorado					Overall
Ranch	**A[d]**	**B**	**D[d]**	**E[d]**	**F**	**G[d]**	**H**	**I**	**J**	**K**	**L**	
Positive externalities (Low)[a]	**9.66**	**4.20**	**19.62**	**20.59**	**8.58**	**13.18**	**9.67**	**1.28**	**3.06**	**8.71**	**3.84**	**6.88**
Positive externalities (High)[b]	**84.42**	**36.75**	**171.48**	**179.94**	**75.02**	**115.16**	**69.66**	**9.26**	**22.04**	**62.76**	**27.65**	**52.23**
Forage	0.49	0.21	1.00	1.05	0.44	0.67	1.63	0.22	0.52	1.47	0.65	0.80
General services	0.83	0.36	1.69	1.77	0.74	1.13	1.34	0.18	0.43	1.21	0.53	1.02
Wildlife value	7.07	3.08	14.36	15.07	6.28	9.65	5.68	0.75	1.80	5.11	2.25	4.29
Carbon sequestration (Low)[a]	1.27	0.55	2.57	2.70	1.13	1.73	1.02	0.14	0.32	0.92	0.40	0.77
Carbon sequestration (High)[b]	76.03	33.09	154.43	162.05	67.56	103.71	61.01	8.11	19.30	54.96	24.21	46.12
Negative externalities	**-57.76**	**-57.48**	**-57.72**	**-57.84**	**-57.78**	**-58.35**	**-57.74**	**-57.65**	**-57.70**	**-57.70**	**-57.74**	57.77
Normalized C Cost	-57.70	-57.44	-57.70	-57.70	-57.66	-58.24	-57.70	-57.65	-57.64	-57.58	-57.66	57.70
Normalized Water Cost	-0.06	-0.04	-0.01	-0.14	-0.12	-0.11	-0.04	0.00	-0.06	-0.13	-0.08	0.07
Average market price[c]	**2.79**	**2.79**	**2.79**	**2.79**	**2.79**	**2.79**	**3.31**	**3.31**	**3.31**	**3.31**	**3.31**	**3.25**
Market price + net value externalities												
Rate of soil C increase (Low)[a]	**-45.31**	**-50.49**	**-35.30**	**-34.46**	**-46.40**	**-42.38**	**-44.76**	**-53.05**	**-51.33**	**-45.68**	**-50.59**	**-47.64**
Rate of soil C increase (High)[b]	**29.45**	**-17.94**	**116.56**	**124.89**	**20.04**	**59.60**	**15.23**	**-45.08**	**-32.34**	**8.37**	**-26.78**	**-2.29**

[a] Low rate of soil C increase: 0.05 ton C/ha/yr.
[b] High rate of soil C increase: 3 ton C/ha/yr.
[c] Sales prices from NASS (2017i) in $ of 2017 updated to $ of 2020 using the PPI Commodity index from farm products-livestock.
[d] Estimates from these ranches may overestimate positive externalities since their stocking rates were lower than usual due to drought as ranchers indicated during the interviews.

Results show that the monetary value of the examined positive and negative externalities are substantial compared to the market value of the animals sold by the eleven ranches in the study, and there is considerable variation across ranches for the positive externalities, but not for the negative externalities (Figure 16). The True Cost that includes the market price plus the positive externalities minus the negative externalities is always negative for the low rate of soil C sequestration and it is quite substantial. However, it can be positive for certain ranches for the high rate of soil C sequestration since the magnitude of C sequestration more than compensates the cost of C emissions of those ranches. Although, these externalities are only partial, they show the substantial values of cattle production are overlooked in the cow-calf supply chain.

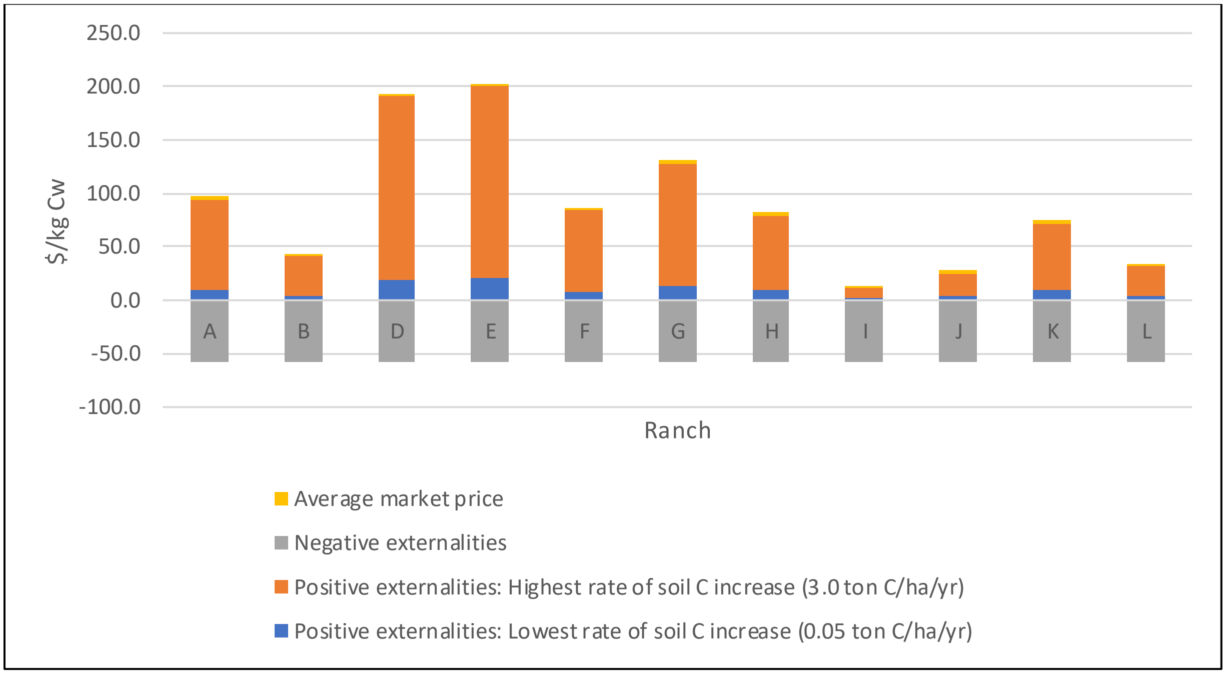

Figure 16. Monetized value of positive and negative externalities, and average market price per ranch ($, 2020).

It should be pointed out that the way positive externalities are calculated is associated with the area of a ranch, while calculations of the negative externalities are associated with the ranches' number of head of cattle. The way these two types of externalities interact can be illustrated by plotting the True Costs per ranch against the hectares per animal per ranch showing linear relationships with different slopes depending on low or high rate of soil C sequestration (Figure 17). Unlike a simple LCA that only captures negative environmental externalities, the TCA captures both positive and negative externalities generated through different mechanisms (e.g., land vs. number of animals). Since the most important component is the rate of soil C sequestration and this is based on area, the larger the area the larger the positive externality and since to convert to kg

CW depends on the number of animals, the smaller the number of animals relative to the land, the larger the benefit per kg CW.

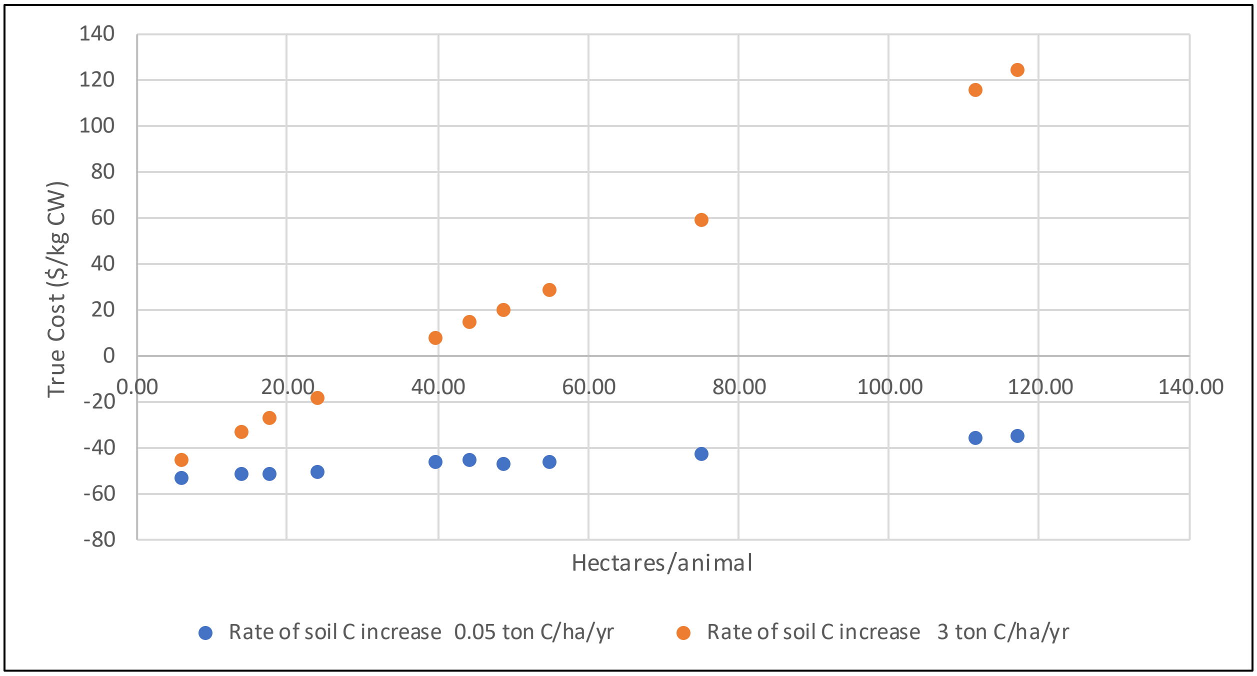

Figure 17. Relationship between the land per animal and the True Cost by ranch for the low and high rates of soil C sequestration ($, 2020).

Methodological Lessons Learned

Use of Mixed Methods and Mixed Scales

Our study utilizes varying methods and scales to understand the relationships between the four capitals as dependencies, outcomes, and impacts in cow-calf and cow-calf combination operations of Arizona and Colorado. We understand dependencies as stocks of wealth at the community level, and to accurately quantify and monetize such stocks of wealth requires a larger scale than that of the ranch, making available county-level data the optimal available scale to understand how capitals at the community level contribute to cow-calf market in the Western Mountain region. To understand outcomes and impacts across the capitals, however, we must use methodologies that can uncover more granular, ranch specific data, and the ranch becomes the unit of analysis. Our case studies provide important qualitative data to help explain quantitative findings (including dependencies, outcomes, and impacts) and most notably to develop a deeper understanding around human and social characteristics of the ranches we partner with.

Natural capital

Soil sampling helped us to test how useful soil samples may be to understand the value or cost of cow-calf and cow-calf combinations operations on the soil health of the rangeland. Throughout this process we learned that due to the vast size of cow-calf operations, and the great variability in soil (even within pastures), soil samples in the field that are from one period in time are limited in use. Results give only a characteristic for pastures studied at that time period, proving insufficient to characterize the impact of grazing on the rangeland. Increasing the number of soil samples to cover vast areas of the range over long periods of time is cost-prohibitive for practical use in TCA. We needed a temporal analysis at the ranch-level that spans decades to help us better quantify the health of the rangeland and impacts on rangeland health over time.

To address these shortcomings in our study, we developed a new methodology that assessed biomass and biodiversity of the ranch as a whole over time to assess whether biomass was significantly increasing or decreasing (when controlled for temperature and precipitation). Biomass production is assumed to be indicative of soil health as improved soil health will allow for more biomass production. This methodology offered great value in allowing us to look for significant changes from 1986-2019 with many data points, and we were able to determine that when controlled for temperature and precipitation there has not been significant decreases in our biomass and biodiversity indicators over time. This suggests that in these cases there is no cost associated with grazing the rangeland, but a more robust study is needed to further expand

comparisons (such as our buffer experiment) with a larger sample more representative of the population at large. Further, it would be beneficial to expand the type of data used for our biomass and biodiversity indicators and expand our use of satellite data to understand the quality and a more precise composition of biomass and biodiversity on the rangeland. In future study design, it may be beneficial to complement geospatial datasets with data collected by ranch partners over the years. Many ranchers collect on-site data on soil health and have on-going monitoring sites to inform decision making.

When sampling, it may be beneficial to inquire about available data and monitoring with ranch partners to evaluate if localized available data exists at the ranch level that could complement geospatial findings. Lastly, our LCA model allows us to account for linear relationships in natural capital. It complements our quantification of ranch biomass and biodiversity with more transactional components of natural capital, quantifying and monetizing GHG emissions, water, and energy impacts at the ranch-level. The LCA model proved to be very useful for assessing transactional relationships in natural capital but was unable to holistically account for more hard-to-capture elements which required us to turn to the literature and other methods to understand the system at large.

Human and social capital

A very interesting insight that arose from our case-studies was the flow of human and social capitals. Ranches use social and human capital as inputs into their ranch and contribute to stocks of wealth in human and social capital at the community level through their sharing of knowledge, community support offered, and participation in social groups. This informs that a methodology focused on quantifying human and social impact must unravel this feedback loop and find anchors to understand positive and negative impacts of cow-calf and cow-calf combination operations. While our study used the ranch as the unit of analysis in data collection on impact of human and social capital, we were unable to quantify these impacts due to the complexity of the system in which dependencies and outcomes are exchanged across scales. One of the big problems that emerges in this type of complex system is the relationship between variables under study. Dependencies have an impact on outcomes and outcomes feed back into dependencies. While we have quantified and monetized the dependencies of human and social capital at the county-level, the study and quantification of human and social capital as outcomes/impacts merits more research and deep thought.

Reflections of methodological learnings

In general, the results from different methods point to similar conclusions and reinforce each other. The case studies were the basis for our study and are recommended for applied TCA approaches as they provided important data and insights. However, the

quantitative data obtained from rancher surveys was limited due to concerns with confidentiality and the sample size. For example, the data on different capitals collected was simple consisting mainly of frequencies, and the monetary data elicited was limited, involving ranges of income or subjective evaluations of revenue. Future work should target larger sample sizes and refine surveys carefully to obtain easily quantifiable data that can ideally be monetized.

The use of secondary data complemented the data from the case studies. The LCA combined with survey data and data from the literature enabled an estimation of the True Cost of a kg of CW of beef bringing together the market price and the monetization of the associated positive and negative externalities. The temporal analysis of biomass and biodiversity over time with the buffer was consistent with the case study data that show a conservative management of the range and no negative impacts. This analysis also helped overcome limitations of soil sampling on expansive ranches and helped analyze the ranch as the unit of analysis. Statistical models, Model 1 and Model 2, do not contribute to the true cost, but they both evaluate dependencies, and make social, human and natural dependencies visible by evaluating their relationship to cow-calf outcomes.

Table 10. Methodologies across the study.

Methodology	Scale	Contributions	Shortcomings
Model 1	County	Quantifies and monetizes the social, human, produced and natural dependencies of the market value of cow-calf operations.	We assume causation even though it is based on correlations, this model is focused on TCA dependencies and cannot assess TCA outcomes or impacts.
Model 2	County	Replicable approach using peer-reviewed indicators of wealth available via secondary data for almost every county in the US that demonstrates the relationship between different development outcomes and comprehensive wealth.	Potential endogeneity of the capital stock variables (i.e., that they may be correlated with the error term resulting in biased estimates). Such a correlation could be present if the capital stocks are affected by the dependent variable (reverse causality), if capital stocks and the outcomes variables are

			responding to unmeasured factors that lead to correlations between the capital stocks and the outcomes (omitted variable bias), or due to measurement error in the capital stock variables.
Case studies with ranchers (questionnaires and interviews)	Ranch	Provides very detailed qualitative and quantitative data at the ranch-level. Helped us to understand the relationship between the capitals, human, social, produced, and natural and to qualitatively assess dependencies, outcomes, and impacts. Data was used in the LCA to help quantify impacts at the ranch-level.	This type of data and sample variation/size has a limited capacity for establishing clear associations or quantification and monetization of the capitals.
Soil Sampling	Pastures	Tests soil sample methodology on rangeland. Can provide quantifiable data on specific pastures.	Ranches cover vast areas, and soil changes occur slowly over decades, making it difficult to conclude a meaningful quantification or characterization with soil samples from fields in one period of time.
Temporal analysis of biomass and biodiversity over time with buffer	Ranch	Assesses the ranch biomass production and biodiversity over time allowing for a more reliable quantification of natural capital by ranch. An innovative method to	The buffers are theoretical and an uncertain comparison. We cannot monetize at the ranch-level (but are able to at the county scale), as we do not

		be expanded with remote sensing in future work. Allows us to see the impact of climate change with temperature and precipitation.	have more granular data on the composition and quality of biomass and vegetative cover.
A Life Cycle-Assessment (LCA) of the case-study ranches in terms of greenhouse gasses (GHG) emissions, energy, and water impacts	Ranch	Quantifies and monetizes aspects of natural capital on the ranches; GHG emissions, water, and energy.	Assesses only costs for a limited number of aspects related only to natural capital, the estimates are based on a very small number of observations that are not representative of the population. The monetization factors involve uncertainty. We use literature to calculate variables for positive externalities.

Policy Insights

Through a holistic TCA analysis, our research team drew policy insights that touch on a wide range of areas related to ranching. Firstly, our work would not have been possible without high quality publicly available data sources, emphasizing the need for continued investment in data collection efforts at USDA Economic Research Service (ERS), National Agricultural Statistics Service (NASS), and Natural Resources Conservation Services (NRCS).

With a focus on incorporating human and social aspects of TCA, our results highlight the importance of ranch survivability and the transition of operations, with a value ingrained in multi-generational ranch knowledge. While existing policies include incentives at state and federal levels to support land transfer and beginning farmers and ranchers such as the Conservation Reserve Program-Transitions Incentive Program (federal) or easements and tax credit structures (state), we need policies that combine economic incentives with the human-social aspects uncovered in this work. Multigenerational ranches are valuable because of the localized knowledge passed down. Policies that focus on transferring ownership of land should be combined with incentives to transfer the business skills, agricultural knowledge, and land stewardship to a new generation (both familial and outside of the family).

Further, social, and human stocks of wealth contribute to market outcomes of ranches and are important intervention points for a thriving cattle herd in the Western US. Supporting the rural safety net through investments in rural hospitals, broadband, telehealth, telelearning, and other important social investments can lead to beneficial outcomes at the ranch.

Another interesting finding, diversity in size of ranches was a valuable input to the cow-calf market. We must build policies that support this diversity. Strengthening local and regional markets is one means to fostering a more diverse marketplace with diverse actors. Investment and policies to strengthen more and better markets for ranchers should be prioritized. Consolidation and anti-competitiveness further up the supply chain hurts ranch survivability, especially for smaller players. The current legislation aimed at correcting anti-competitive behavior in the meatpacking industry and recent funding allocated to new and smaller meat-packing plants may result in a more robust meatpacker's market to support diverse ranch operations.

Through our interviews, ranchers discussed increased pressure as the public increased rangeland access and recreation during the pandemic. Fences were often left open and there were concerns of speeding on back roads and fire safety. As more of the public explore these multi-purpose spaces it is important to increase public education around

recreating responsibly. Another issue surrounding rancher relations with the public; environmentalists and ranchers have long been pitted against one-another in the West with great tension over public grazing fees. While environmental groups often push for higher grazing fees on public lands, if replicated in larger studies, our findings support the continuation of low grazing fees on public lands as we do not find evidence of degradation, and we find benefits associated with these ranches. Further, due to the patchwork of actors and land managers in the West, collaboration is key. We need more policies that break through silos and bring stakeholders together in the West to co-manage for shared values and common interests (most notably conservation of the land and resources).

Lastly, climate change brings great challenges to ranching as we know it in the West. Especially in arid regions, the forage cow-calf operations depend upon are threatened by drought and fire stress. Funding is needed to explore sustainable, affordable feed alternatives for dry years such as insect proteins, and to explore more climate resilient breeds that are drought tolerant and feed efficient. Further, when supporting climate resilient agriculture initiatives, there has been a great focus on carbon capture. Policies around land and soil health are often not applicable to arid and semi-arid rangeland health indicators. Our soil samples show the complexity of measuring soil benefits such as carbon sequestration in the ranching context. There are also many important benefits beyond carbon to consider in these agricultural ecosystems. Moving forward, it will be important to build climate policies that take a more tailored approach to assessing climate sustainability. Considering the global warming potential (GWP) of methane, and the lack of consensus surrounding recyclability of methane in the cow-calf system it is crucial to fund more research in this area. Such research could build consensus around the cost of methane for different systems and management practices and drive innovations to reduce negative impacts in the cattle industry through feed, breed, or even species of livestock on the range. Given the importance and the span of rangelands in the US, policies should consider rangelands in the methods developed for measuring outcomes and incentivizing climate-smart practices.

Study Limitations

Our study presents limitations in design and interpretation. Initially this study had planned to research the role of slaughterhouses and meatpacking facilities, and rendering plants, but we decided to narrow the scope of our analysis in the face of COVID and the complexity of our undertaking. We had also aimed to compare various typologies that included grass-fed and more conventional systems, but in the field, reality did not allow for such a comparison. The cow-calf part of the beef supply chain is basically the same for conventional and grass-fed beef, and ranchers often have both types of supply chains coexisting side by side. Therefore, basing a TCA analysis on comparisons of conventional and grass-fed beef supply chains was not feasible under the conditions of Arizona and Colorado. Typologies are valuable analytical devices that allow meaningful comparisons useful for quantifying impacts at the ranch level. However, we are unable to create any typologies with our sample as our sample size is too small and lacks variation to piece out similarities and differences needed for meaningful comparisons.

We acknowledge selection bias in the choice of participants in our study due to our sampling methodology which relied heavily on networks. This may have resulted in our sample representing a “best-case” scenario of cattle as a commodity. The results may have been entirely different had we sampled randomly and considered the cost of poor rangeland management and overgrazing. Such bias in our sample may restrict the applicability of our findings.

Because of our sample size, our geospatial analysis of biomass and biodiversity cannot provide substantive evidence that ranching does not influence vegetative cover, environmental heterogeneity, and biodiversity. There may be cases where it does, but we have shown evidence that well-managed ranches (as in our case studies) may not negatively impact the environment. Our results are only applicable to the sites of our case studies, and we cannot make broader generalizations about ranching at large. Other limitations in our geospatial analysis involve missing data for land-use history of our buffer zones which limit what we can infer from the buffer and ranch comparison. Essentially, our buffers are land not managed by the specific ranchers we study, but we do not know if other ranchers may be grazing parcels of the buffer zone, or how that land is used. It would be valuable for future work to piece out both land use and land use history to strengthen what our analysis can suggest. Our biodiversity metric is based on heterogeneity of vegetative cover, but not on any direct measurement of vegetative species diversity. To improve this metric, we hope to expand our biodiversity metric by exploring the use of more detailed remote sensing in the future.

Similarly, our LCA model is limited to a ranch-by-ranch case and cannot be applied to monetize the cost of feed, water, and GHG emissions in all cow-calf and cow-calf combinations operations. Even at the ranch level, our LCA derived costs are limited to feed, GHG emissions and water and are uncertain. They assume blue water is used for all water use, assume all cattle is the average CW (366.8 kg), and in cases where data was not available, we assume type and amount of feed based off national averages. Methane emissions vary by the quality of feed on the range and supplemental feed used. There is also great debate surrounding the recyclability of such emissions, which we could not discern and so we paired it with a range of assumed carbon sequestered based on the literature. Methane emissions prove a significant negative externality of cattle, leaving important work for future research. With these assumptions, we are unable to discern the impact of different breeds of cattle, which differ in frame size and weight, and our output may not be reflective of the ranch's more specific management techniques. Another major limitation was found in our soil sampling which is very limited in meaning and interpretation. Because ranches are vast and have variation even within pastures, and soil health changes occur very slowly over time, it is better to combine larger data sets (such as the Soil Survey Geographic Database [SSURGO] and geospatial data) with data the ranchers themselves have collected over time than to rely on single samples at one point in time from specific pastures.

Further, issues are often raised around beef livestock production that we did not see in our ranch-level analysis. For example, erosion is an issue that was brought up in our ranch interviews and is also a subject of discussion in academic journals and the popular press (Bland, 2012). Alternatively, Concentrated Animal Feeding Operations (CAFO's) have been cited as leading to respiratory issues and an increased occurrence of both asthma and allergies in neighboring residential neighborhoods (Schultz et al., 2019). These negative impacts on social and human capitals never arose in this study, likely due to the low-density stocking observed at the case study ranches, and the small sample size.

Lastly, our statistical analyses provide important context to the dependencies across capitals in the cow-calf system, but in Model 1 the marginal values of different indicators are challenging to interpret and in Model 2 we are unable to calculate marginal effects on principal components. Ideally a TCA approach would be able to monetize all dependencies in comparable functional units, leaving more work to be done in this space.

Many of these limitations illuminate the challenges in applying the TCA methodology in the real world at smaller scales, and at mixed scales. Addressing multiple scales creates difficulty for interpretation, as there is not an automatic relationship between

scales. Reports that reach more definitive "True Costs" than ours, such as the Rockefeller Report (Rockefeller Foundation, 2021) or the University of Cambridge's framework to support better stewardship of biodiversity in global supply chains (University of Cambridge Institute for Sustainability Leadership, 2020), rely on data at much larger, national scales. In our case, using county-level data allowed for the monetization of dependencies due to the improved quality of large data sets available, but there were large technical difficulties presented when trying to quantify and monetize all the capitals as impacts at the smaller-scale of the ranch, most specifically surrounding social and human outcomes. Even with these limitations in mind, our results still provide important and valuable insights that are relevant beyond the specific scope of the study and make novel contributions to understanding both the potential for sustainable ranching, and the challenges ranchers face.

Conclusion

Our study explores dependencies associated with ranch performance and the negative and positive externalities of ranches in Arizona and Colorado. We see a significant relationship between cattle sales and indicators of social, human, and natural capital at the county level. Model 1, based on counties in the Western Mountain region, quantifies the contributions of produced, natural, human, and social capitals to the gross value of the sales of cattle and calves, i.e., the key market value produced by the cow-calf supply chain. In other words, the most important market-based provisioning ecosystem service derived by humans from rangelands. Through our results, we estimate a monetary value for the contributions of social, human, and natural capitals based on their association with the gross value of cattle sales.

Of specific interest are aspects of the cow-calf system that are less examined in the literature: human and social capital. In the Western Mountain Region, the additional value generated from social capital amounted to an average of $70,952 per county for community-centered indicators[36] (Calculated using PCA, please see Appendix D for an expanded explanation), and $1,861,209 per county for our ranch-specific indicator (diversity in operations). Two of our indicators for human capital (diversity in age of ranchers and the number of paid workers) generate an additional value of $2,225,791 and $68,920 per county respectively. The high values associated with these social and human indicators show how the market performance of ranches in the Western Mountain region depends on non-market factors associated with these capitals. In our case studies, almost all ranchers described an equal exchange of giving and receiving from social organizations. Informal and formal social groups were viewed as extremely valuable, offering business advice, emotional support, political support, and aid in times of crisis. Community reciprocity helped ranching communities survive the difficult past few years of fire, drought and a pandemic serving as both an input and output of ranches.

With another indicator of human capital used (unpaid labor), our results show a negative association with the value of cattle sales. The amount of unpaid labor is most likely related to the principal operators (ranchers) and their families since they are the most likely workers not to be paid.[37] This negative relationship (consistent with the literature) may reflect ranchers' motivation to be involved in ranching even when profitability may

[36] In the regression we applied the county-level index of social capital developed by Rupasingha et al. (2006) to cattle production. While this index has been widely used in the literature, this report is the first to use it in this context, showing that there is a positive association of this index and the gross value of the sale of cattle and calves.

[37] Unpaid labor's relationship to principal operators' work is reflected in the strong correlation between the number of unpaid workers and persons in the household of principal producers (0.96).

be very low or nonexistent because of non-market interests of lifestyle, identity, and culture (e.g., Gentner & Tanaka, 2002; McSweeney & Raish, 2012; Torell et al., 2001). This is consistent with our case studies in which the majority of ranchers rated their subjective quality of life as good, but in interviews many ranchers described profits as either low or non-existent. They attributed their motivations for staying in the game (even with low-to-no profits) to the culture of ranching and the emotional well-being that comes along with such a lifestyle. With this in mind, unpaid labor serves as an indicator that reflects the motivations of ranchers beyond profit-making and the loss associated with unpaid labor can be interpreted as an implied subsidy ranches provide to society due to the cultural and personal benefits ranching generates. In other words, the socio-cultural impact of ranching can be valued at $221,404 per county (the decreased cow-calf market value associated with unpaid labor).

The variables with the greatest impact on the value of the gross sales (i.e., magnitude of the regression coefficient) and statistical significance (a low probability that the observed relationship was due to chance) are the diversity of the ages of the principal operator and diversity of the size of operations. These variables reflect human and social capital respectively. It is noteworthy that they have a larger impact on the value of sales than the asset value of buildings and land plus the asset value of machinery, indicators of produced capital. One of our most interesting qualitative results comes in understanding the social value of multigenerational ranches, and the importance of transferring the skills and knowledge from one generation of ranchers to the next. There is value at both the individual and community level as these relationships foster thriving rural communities and lifestyles in the West. Consistent with our qualitative findings, the positive monetization of a diversity in age of producers suggests the importance of fostering human capital and implies an important role for existing operations to play in training a next generation. This further highlights the importance of multi-generational ranches who can serve as hot-spots for building human capital over time and transferring knowledge to younger producers in a mixed-age system. The positive monetization of the diversity in scale of operations (size) and social capital indicators (such as number of social groups and voting participation) emphasizes that the social make-up is valuable in rural America and serves a vital role in Western ranching.

The significance of the diversity of the size of operations is a novel result, suggesting that having more diversity of operations of different sizes may contribute to creating multiple business opportunities for supporting goods and services, job opportunities, as well as smaller operations benefiting from the services that the presence of larger operations enable. This is a relationship that merits further research to confirm that in fact this diversity creates a richer social environment that is conducive to more profitable ranching operations as a group, not just individually. We also show the significance of

the Gini coefficient of the distribution of the number of head of cattle by the size of operations, indicating that counties with a few larger ranches generate higher gross value which is consistent with the idea that they reflect high economies of scale and thus profitability. These results taken together suggest a trade-off between concentration and diversity that merits further exploration. Overall, Model 1 results highlight how non-market human and social factors are significant to the sales of cattle and calves, estimating high levels of monetary value associated with social and human "public goods" that are not formalized parts of the marketplace.

Consistent with Model 1, Model 2 further explores dependencies, adding five outcome variables of interest. This model again shows how stocks of wealth at the community level have important relationships to ranch outcomes selected as dependent variables: livestock sales as a percent of agricultural sales, rotational grazing, EQIP participation, share of multigenerational livestock operations, and share of livestock operations profitable. Our qualitative results demonstrate the importance of valuing ranch survivability, managed grazing, and the survivability of multigenerational ranches. Recognizing how stocks of wealth are related to desirable (and undesirable) outcomes, our econometric model provides further evidence of the need to look beyond the ranch when formulating solutions for sustainable livestock production. Further, our results suggest some spill-over effects of stocks of wealth on neighboring counties, revealing the importance to look even beyond individual communities to the web of interconnections and relationships at large considering clusters of communities when quantifying dependencies and outcomes of a system.

Homing in on impacts cow-calf and cow-calf combinations operations have on natural capital, we turn to the ranch as the unit of analysis. Our study tells a more nuanced story compared to popular media surrounding ranching, which often focuses on cattle as major contributors to climate change and environmental degradation. Our temporal analysis of biomass production and biodiversity does not find evidence of environmental degradation from grazing and suggests climate as the main driver in changes to environmental health of the rangeland. We also find through surveys and interviews that the ranchers in our case studies often perceive themselves as stewards of the land and are driven by motivations to conserve open space and support wildlife. It can be argued that the semi-arid Western rangelands are a more sustainable landscape for cattle production and supporting cattle production in these environments is preferable to spaces where deforestation for the purpose of cattle production generates larger social and environmental costs. An example of these larger costs would be Brazil's continued clearing of the Amazon rainforest in order to keep up with demand for beef exports (Fearnside, 2017). Our calculations based on the literature and our specific case studies monetize a range of positive externalities of $6.88 /kg CW to $52.23 /kg CW. While

these quantitative and qualitative findings signify a generation of natural capital, preserving open space also contributes to community well-being (social capital) as ranchers support outdoor recreation such as hiking and hunting.

Although we find no evidence of grazing causing environmental degradation among our case studies, we do find that ranchers are already experiencing the effects of climate change, a hard reality reaffirmed by described experiences. Our results document the trends of increasing temperatures and decreasing rainfall for ranches in our case studies. The qualitative results show that such trends are impacting their operations and ranchers are already adapting to a new era of ranching. Our interviews with ranchers revealed the importance of both human and social capital for climate resilience in ranching. We see climate resilience exhibited in the human capital of the ranchers as they utilize adaptive management practices such as forage analyses, grazing plans, breeding decisions, and drought plans. They detail focusing on the land and adapting to conditions with a hybrid model of preparation and flexibility to meet the challenges of a changing climate. Further, social capital exists as a feedback loop in ranching communities, where ranchers give and take support in a mutually beneficial support system. This adaptive resilience through community helps ranchers navigate wildfires and droughts through the sharing of resources whether that be lending a pasture or dropping bales of hay at the ranch door. Such findings highlight the important role ranchers and rural communities play in climate solutions. They are already experiencing climate change, and already addressing it daily. We need a more robust understanding of how ranchers experience climate change and adapt to it, as well as how their adaptations compare to those proposed by government agencies or universities, in order to develop new strategies for climate change adaptation on the rangeland.

Where we do see more negative impacts from this phase of cattle production is in our LCA analysis, largely driven by animal derived methane emissions. Based on our specific case studies and LCA model, we monetize negative externalities to be -\$57.77 /kg CW and there was little variability across ranches. When combined with our positive externalities we reach a true cost of -\$2.29 /kg CW to -47.64 /kg CW depending on carbon sequestered. Given the weight methane holds in the true cost of ranching, it is important to dedicate attention to the cycle of biogenic emissions to understand recyclability, something we are unable to fully discern in this study. Further, we should explore the impact of cattle through the finishing stages as we hypothesize larger impacts may arise further down the supply chain, and these impacts may offer important intervention points for improving the sustainability of the cattle industry.

Our findings show the importance of evaluating both the ranch as the unit of analysis and the communities (in our case counties) that compose the socio-ecological system at

large, especially when understanding complex human and social elements of a system. Ranch management, history, conditions, and profitability are important, as are factors at higher scales, e.g., communities, counties in the positive and negative externalities generated by cow-calf operations. Our results show that there are emergent properties from the interactions among ranchers and their communities that are important for beef cattle production, such as multigenerational ranches, social networks, and stocks of natural capital and social capital at the county level. These may be important intervention points to support sustainable ranching, and merit further attention and research in the cattle industry. However, we also heard from ranchers how profitability and ranch survivability is threatened by market consolidation in the meatpacking industry. These testimonies hold weight given recent policy actions taken to investigate market consolidation in the meatpacking industry and allocated funds to support smaller scale slaughter and packing facilities.

Continuing research on the value of ranch survivability across all capitals, especially social and human capital elements that are less visible in the market, will be important to better quantify the cost of a loss of ranches. Popular media often overlooks non-market aspects of the system focusing on the main hurdles to farmers as economic issues and policy decisions, such as bailout programs that primarily benefit the largest producers (Heeb, 2020). Ideally, a monetary value could be attributed to all outcomes as we have assigned them to the dependencies to better communicate the unaccounted aspects of cattle production with the public as well as policy makers. By bringing transparency on what food really costs in these areas, we also hope to understand the hurdles ranchers face to drive equitable solutions for a more sustainable food system.

In summary, the key messages are:

- Combining multiple scales of analysis is challenging but provides a better perspective of the system of interest since they complement each other.

- Analysis around rangeland health needs to be done over time and at the ranch-level (overcomes limits to soil sampling on large ranges).

- Future work should target the full supply chain to ideally monetize differences in supply chains.

- Incorporating positive externalities is very important to reach a true cost and is understudied in the TCA approach.

- Interviews were consistent with quantitative models and confirmed non-market motivations for ranching including identity, cultural, familial and conservation values.

- For dependencies, estimated monetary values were higher for social and human capital indicators than natural and produced capital indicators.

- Social and human capital are important dependencies, or non-market factors in cow-calf operations that require deeper policy consideration and research.

- The true cost of ranching on cow-calf operations is extremely sensitive to methane - it is a dominant force in the true cost.

- Conflicting approaches towards methane evaluation complicates TCA in this area.

- More consensus is needed for the monetization of methane, the biogenic carbon cycle.

Appendices

Appendix A. Arizona Ranch Selection Advisory Committee

Early on in this study's inception an Advisory Committee (AC) was assembled. To benefit from hearing from relevant stakeholders and incorporate their perspectives in the study. This study's AC included individuals representing a diverse group of stakeholders, particularly experts on ranching and the cattle industry in Arizona and Colorado. The AC reviewed and gave feedback on the original design of the study and on the preliminary draft of our ranch questionnaire.

Feedback from this committee shaped this final report in several ways. First, committee members almost universally suggested shortening the questionnaire and to avoid asking specific questions about a ranch's financial information, as those may be seen as intrusive and have a chilling effect on the rancher's desire to share additional information. Some feedback was much more specific, such as a caution that our original intent to compare conventional cattle operations with strictly grass-fed operations would be difficult to achieve, as there are few (if any) operations of significant size in Arizona that continuously raise cattle only on grass. Advisors also mentioned it would be hard to identify ranches that owned a majority of their grazing land, due to the widespread practice of leasing rangeland in the West.

Along with helping shape the final questionnaire, committee members also facilitated identifying potential ranches to use in the case studies. They directed us to certain ranches and also encouraged reaching out through the cooperative extension since the ranchers would already be familiar with the extension agents. They cautioned about introducing selection bias by relying solely on the cooperative extension. The committee pushed for this report to clearly explain the organization strategies that would be used to evaluate the four capitals and adhere to the TEEBAgriFood Evaluation Framework when analyzing the data from this report. By engaging this committee early on in the design of this report we were able to meet the TEEBAgriFood Evaluation Framework goal of engaging stakeholders and bringing both credibility and legitimacy to this study. We would like to give the Advisory Committee our sincere thanks for their time and efforts in producing this final report.

Appendix B. Supplemental Tables and Figures

Comparisons between ranches and a buffer zone.

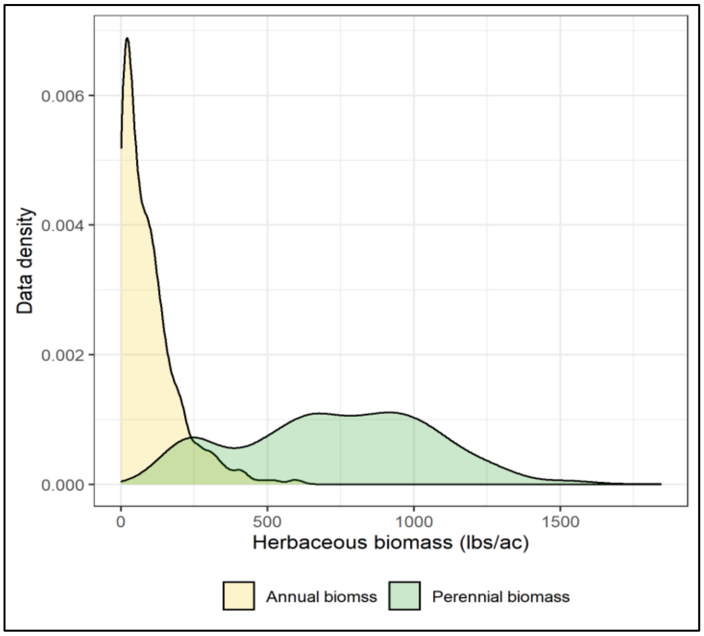

Figure B1. Distribution of annual and perennial biomass productions.

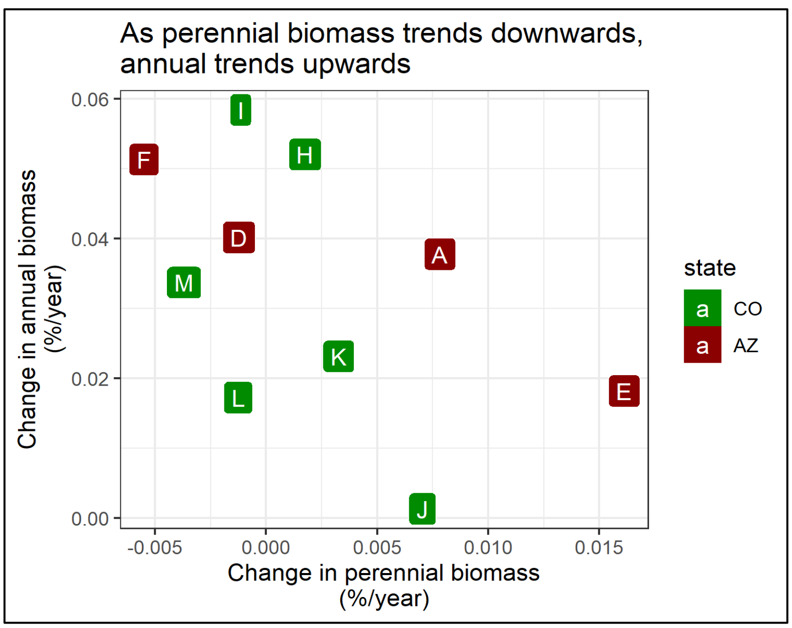

Figure B2. Annual trends of perennial versus annual biomass production. Each capital letter represents a location.

Table B1. ANOVA table for precipitation model.

Variable	df	Sum of squares	Mean sum of squares	statistic	p-value
Location	9	6244.53	693.84	54.35	0
Year	1	127.34	127.34	9.98	0.002
Location*year	9	190.14	21.13	1.65	0.099
Residuals	334	4263.93	12.77	NA	NA

Table B2. ANOVA table for temperature model.

Variable	df	Sum of squares	Mean sum of squares	statistic	p-value
Location	9	21224.63	2358.29	2624.79	0
Year	1	102.51	102.51	114.10	0
Location*year	9	25.60	2.84	3.17	<0.01
Residuals	334	300.09	0.90	NA	NA

Table B3. ANOVA table for annual biomass model.

Variable	DF	F-value	p-value
(Intercept)	1	9311.73	0
Annual precipitation	1	34.53	<0.001
Annual temperature	1	303.48	<0.001
Land-use	1	0.20	0.656
Year	1	51.48	<0.001
Location	9	57.30	<0.001
Land-use* year	1	1.49	0.223
Land-use*location	9	2.21	0.020
Year*location	9	2.20	0.021
Land-use*year*location	9	0.12	0.99

Table B4. ANOVA table for perennial biomass model.

Variable	DF	F-value	p-value
(Intercept)	1	386787.10	0
Annual precipitation	1	285.60	<0.001
Annual temperature	1	653.88	<0.001
Land-use	1	29.59	<0.001
Year	1	17.00	<0.001
Location	9	173.47	<0.001
Annual precipitation*annual temperature	1	13.57	<0.001
Land-use*year	1	0.25	0.620
Land-use*location	9	6.02	<0.001
Year*location	9	4.52	<0.001
Land-use*year*location	9	0.64	0.77

Table B5. ANOVA table for Simpson's Diversity Index model.

Variable	df	Sum of squares	Mean sum of squares	statistic	p-value
Annual precipitation	1	0.032	0.032	20.04	<0.00001
Land-use	1	0.25	0.25	154.83	0
Year	1	4.98E-05	4.98E-05	0.03	0.86
Location	9	4.86	0.54	341.92	0
Land-use* year	1	4.69E-05	4.69E-05	0.023	0.86
Land-use*location	9	0.28	0.0307	19.45	0
Year*location	9	0.098	0.0109	6.91	0
Land-use*year*location	9	0.012	0.0013	0.82	0.60
Residuals	667	1.054	0.0016	NA	NA

Appendix C. Geospatial Statistical Models

Short description of models used for comparing ranches with a buffer zone.

We first fitted a full model that included annual precipitation and temperature, plus an interaction between these two variables (precipitation * temperature). Since it is unlikely that the relationships between biomass and precipitation and temperature respectively are linear,[38] we also included the square of both variables. We included a variable for the year, and an indicator variable for land-use (whether the data was from the ranch (value=1) or from the buffer zone (value=0). Locations were taken into account by including an indicator variable for each location, except one that becomes the baseline of comparison. Since there may be several interactions among these factors we tested for interactions between year and location, year and land-use, location and land-use, and the three-way interaction among year, location, and land-use. Besides estimating the model with all these variables, we estimated nested[39] models including all combinations of covariates. We compared models using Akaike's Information Criteria (AIC) which helps determine the best model to use to fit the data and which models are the simplest (Akaike, 1973). When models had similar AIC scores, we chose the simpler model. The best models were used to derive the figures presented and their respective analyses in the text.

[38] Because as temperature or precipitation increase, their marginal effect on biomass may be decreasing.

[39] Models that included only part of the variables in the full model.

Appendix D. Principal Component Analysis

Principal Component Analysis (PCA) is a very common technique used in many fields. It is a mathematical method that summarizes the information contained in many variables into a new set of variables where a few of them capture most of this information. The method uses the correlation among the original variables and linear algebra to accomplish this. The new set of variables are the “principal components.” Each principal component is correlated with the original variables in different ways (highly or minimally correlated and with different signs). The first “principal component” contains the highest amount of information, capturing a large portion of the variation present in the original set of variables. The second “principal component” contains the second highest amount of information, capturing the second largest portion of variation present in the original set of variables, and so on. Usually, the first and second principal components capture most of the variation present in the original set of variables. An important advantage of the principal component variables is that they are not correlated among themselves. Each one captures a different aspect of the variation in the original set of variables. So, instead of using many correlated variables in an analysis, we can use the first principal component variable as a proxy for an issue of interest, e.g., social capital (sometimes we can also use additional principal component variables (second, third) if they capture a large portion of the variation present in the original data). Due to the correlation between the scores of the principal component variable and the values of the original variables we can also provide some meaning to the principal component.

For example, social capital is an issue that involves many variables (or dimensions) such as participation in different types of networks, social processes, trust, sharing of information, etc. Some of these variables are measurable and others are “latent, “i.e., we know they exist but cannot be observed directly. However, we know that they are correlated with variables that can be observed, e.g., participating in social organizations (observable) involves trust and sharing of values (latent). In this report, we rely in part on a study of social capital by Rupasingha et al. (2006) in which the first principal component variable (PC1) from a PCA as a county-level of social capital for all counties in the US was developed. The PCA was applied to four variables:

- The number of different types of organizations per capita per county (Religious, Civic, Business, Political, Professional, Labor, Bowling, Recreational, Golf, Sports)
- Percentage of voters who vote in presidential elections
- County-level response rate to the Census Bureau’s decennial census
- Number of tax-exempt non-profit organizations per capita

PC1 variable accounts for 49% of the variation, i.e., it captures 49% of the information contained in the four original variables. The score of the PC1 is positively and highly

correlated with the number of tax-exempt non-profit organizations per capita (correlation 0.91) and the number of different types of organizations per capita per county (correlation=0.85), suggesting that the PC1 reflects high participation in privately led organizations.

Although, Rupasingha et al. do not use the second principal component variable, this variable accounts for 28.6 % of variation and is highly correlated with the county-level response rate to the Census Bureau's decennial census (correlation 0.76) and the percentage of voters who vote in presidential elections (0.75), suggesting that the PC2 reflects participation in government organized processes. In our regression analysis, we use the county-level of social capital as one proxy for social capital (we calculated the PCA only for counties in the Western states instead of using the data for all the US).

Appendix E. Methods to Calculate Positive and Negative Externalities

Positive externalities

Monetization factors of wildlife-related recreation, forage production, and other ecosystem services

We use the data generated by Maher et al. (2020; 2021). They estimated a per hectare value for three categories of ecosystem services: (1) wildlife-related recreation; (2) forage production; and (3) other ecosystem services on a per hectare basis (2021, p.3). For forage production, values were calculated separately for private lands and for leased federal lands. Only lands managed by the BLM and USFS were analyzed (p.4). In Maher et al. (2020) they provide specific values for Arizona (Table 1, p. 16) and Colorado (Table 1, p. 25). The data is presented in Table E1 below. The total is the average of both states.

Table E1. Value of positive externalities from recreation, forage, and ecosystem services ($, 2017) (Maher et al., 2020).

	Arizona	**Colorado**	**Total**
Federal forage ($/acre) (a)	1.14	1.43	1.29
Private forage ($/acre) (b)	2.30	5.60	3.95
General services ($/acre) (c)	2.12	4.28	3.20
Wildlife value ($/acre) (d)	18.06	18.07	18.07
Total value/ acre Leased land ($/acre) (a+c+d)	21.31	23.78	22.55
Total value/ acre Private land ($/acre) (b+c+d)	22.47	27.95	25.21

Monetization factors of Carbon sequestration rates

To monetize the value of Carbon sequestration rates, we use the data from Sanderson et al. (2020). They reported that where grazing has increased soil C, observed rates of increased in soil C of between 0.05 to 0.50 Metric ton per hectare per year[40]. However, they also reported that for highly degraded lands in areas with higher annual precipitation observed rates of increase of up to 3 Metric ton per hectare per year (p. 6A). We chose the lowest and highest values reported for our estimates (0.05- and 3-

[40] "Where grazing has increased soil C, the rate of increase has typically been low (0.05 to 0.50 Mg C ha^{-1} y^{-1} [0.02 to 0.22 tn C ac^{-1} yr^{-1}] [Schuman et al. 2002; Henderson et al. 2015]), although higher sequestration rates have been reported on highly degraded lands in areas with higher annual precipitation (e.g., 3 Mg C ha^{-1} y^{-1} [1.3 tn C ac^{-1} yr^{-1}] [Teague et al. 2016])." Sanderson et al. (2020, p. 6A)

ton/ha/year). These numbers were multiplied by the social cost of CO_2, for 2025, 3% 95th Percentile (Table ES-1: Social Cost of CO_2, 2020-2050 (in $ of 2020 per metric ton of CO_2)) (U.S. Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 2021). The reported price was $169/ metric ton of CO_2. This number was multiplied by the low and high estimates of C sequestration rates converted to acres. Table 2 presents the results.

It should be pointed out that to make the monetary value of externalities compatible we adjusted the values of forage, general services and wildlife that were originally in 2017 into $ of 2020 ($, 2020) by using the Consumer Price Index (factor of 1.057).

Table E2. Monetization of C sequestration rates ($, 2020).

	Minimum	**Maximum**
C sequestration rates	0.05 ton/ha/year	3 ton/ha/year
Value of sequestered carbon ($/acre)	3.42	205.18

Herd composition

We collected information on the number of head of cattle per ranch, but we did not have specific information about the composition of the herd. Therefore, we approximate the composition as follows. Based on data from the Supplemental Material of Rotz et al. (2019) Tables S6 and S7 for the Southwest, we calculated the ratio of calves to beef cows (0.76775). We also use a ratio of cows per bull of 20 obtained from Asem-Hiablie et al. (2017, Table 2).

First, we calculated an approximate number of cows by dividing the number of head of cattle by 1.76775 (one plus the ratio of calves to beef cows). Then we divided that number by 20 to estimate the number of bulls needed. The resulting number of bulls was subtracted from the total number of head of cattle and the resulting number was divided by 1.76775 to have an adjusted number of cows. This adjusted number was multiplied by ratio of calves to cows to estimate the number of calves. Finally, the estimated number of bulls, cows, and calves were added together and compared to the total number of head of cattle to check that they were the same. The total number of bulls and cows were used in the LCA for the calculations of energy and water used, and non-biogenic carbon produced. We assumed that all calves have not weaned yet and therefore their consumption impacts are through the mother cows. The number of bulls, cows, and calves were used also to estimate the amount of methane emissions (explained below).

Monetary value of wildlife-related recreation, forage production, and other ecosystem services

To calculate the monetary value of the positive externalities associated with wildlife-related recreation, forage production, and other ecosystem services for the ranches in our study, we use the total number of acres of the ranches in Arizona and Colorado. Since Maher et al. (2020) data distinguishes between private and federal leased lands and we did not have specific values for the ranches, we assume that in Arizona 90% of the land was leased and 10% private. The converse was assumed for Colorado. These assumptions are based on qualitative data gathered during interviews. So, we estimated the number of acres of private and leased land for the ranches in our study. We multiplied the number of acres in leased land by the total value per acre in federal leased land and the number of acres in private land by the total value per acre in private land (bottom two values in Table E1 above). The numbers were then added together providing the total monetary value of the positive externalities associated with wildlife-related recreation, forage production, and other ecosystem services for the ranches in our study. To obtain this value in terms of CW, we divided the total value by the number of cows and bulls estimated above. This provided the monetary value of these externalities per animal, which in turn was divided by 808 lb, the average dressed weight of cattle obtained from USDA NASS (2020) to obtain the monetary value of these externalities per CW. We calculated the value also per kg of CW by multiplying the value per lb of CW by 2.205 lb/kg. Table E3 present the results of these calculations aggregated for ranches in Arizona and Colorado. In the report the data is presented by ranch.

Table E3. Monetary value of wildlife-related recreation, forage production, and other ecosystem services ($, 2020).

	Arizona	**Colorado**	**Overall**
Area (acres)	147,040	125,050	272,090
Private	14,704	112,545	127,249
Leased	132,336	12,505	144,841
Animals (number of cows+bulls, no calves)	818	2,485	3,303
lb per animal (CW)	808	808	808
Total value of externalities ($)	3,330,308	3,637,830	6,968,138
Value per beef cow	4,071.28	1,463.09	2,109.64
Value per lb ($/lb CW)	5.04	1.81	2.61
Value per kg ($/kg CW)	11.11	3.99	5.76

Monetary value of Carbon sequestration as a positive externality

To calculate the monetary value of Carbon sequestration, we multiply value of sequestered carbon (bottom of Table E1) by the total number of acres of all ranches in our study. This number was divided by the number of cows and bulls to obtain the value per animal and then divided by the average dressed weight of cattle obtained from

USDA NASS (2020) to obtain the monetary value of Carbon sequestration per CW. This procedure was done for the lowest and highest values of rates of C sequestration reported above.

Market price of cattle

From county data from the 2017 Agricultural Census (NASS, 2017a,i) we obtained the total number of head of cattle sold and the value of the sales in 2017. From these numbers we calculated the average sale price per head of cattle. We converted the price that was in $ of 2017 to $ of 2020 using the PPI Commodity from farm products-livestock (https://beta.bls.gov/dataViewer/view/84ec40f9349b4005b4f9278986c1cdf4). In turn, this number was divided by the average dressed weight of cattle to obtain the average sale price per CW in $/lb and $/kg. Table E4 shows the results for Arizona and Colorado.

Table E4. Market value of cattle ($, 2020)

Price per head of cattle (NASS 2017)	Arizona	Colorado	Overall
Number of counties	11	49	60
Total number of head	367,472	2,556,629	2,924,101
Total value of sales ($)	375,775,919	3,104,637,815	3,480,413,735
Average sale price of a head	1,022.60	1,214.35	1,190.25
Average sale price per CW ($/lb)	1.27	1.50	1.473083
Average sale price per CW ($/kg)	2.79	3.31	3.25

Negative externalities

Carbon emissions

Greenhouse gas (GHG) emissions were calculated through a LCA by multiplying the consumption of irrigation water, electricity from the grid, solar energy, gasoline, Diesel, natural gas, different types of hay and water consumed by the herd in each ranch by their respective GHG coefficients from. The quantity was in kgCO_2e (excludes biogenic methane).

Methane emissions were calculated by multiplying the CW of cattle (number of cows and bulls in herd multiplied by the average dressed weight of cattle). Calves have been found to have 74% lower emissions than cattle per kg CW (Basarab et al., 2012), therefore the number of calves was multiplied by 26% of the emissions of cattle and added to the emissions of cattle, providing total methane emissions from cow and calf in kg CH_4.

To obtain the normalized GHG emissions with methane the amount of methane calculated in (2) was multiplied by 28 since methane has a global warming potential (GWP) 28 time of CO2 (Thompson and Rowntree, 2020).

This number was then added to the GHG emissions calculated in (1) which is the GHG without methane. The resulting sum was divided by the total CW of all cattle (cows and bulls, excluding calves) in the ranches providing a normalized GHG emissions with methane (kgCO_2e).

To monetize the GHG emissions with methane, the amount of GHG emissions without methane (1) divided by CW was multiplied by the price of carbon ($169/metric ton) (U.S. Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 2021).

To the normalize amount of GHG emissions with methane calculated in (5) the normalized amount of GHG emissions without methane was subtracted (to avoid double counting) and then multiplied by the price of methane of $4,500/metric Ton of CH_4 obtained from Table ES-2; Social Cost of CH4, 2020-2050 in $ of 2020 per metric ton of CH_4) for the 3%, 95^{th} percentile. (U.S. Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 2021).

Then the cost of (6) and (7) were added together and divided by 1000 to obtain the normalized Carbon cost including methane ($/kg CW).

Water

Water consumption was calculated through a LCA by multiplying the consumption of irrigation water, electricity from the grid, solar energy, gasoline, Diesel, natural gas, different types of hay and water consumed by the herd in each ranch by their respective water coefficients from OpenLCA (https://www.openlca.org/). Total water consumption then was divided by total CW to obtain the normalized water consumption (m^3/CW). Normalized water consumption was multiplied by the average maximized value of water of $0.71/$m^3$ of irrigation water from D'Odorico et al. (2020) to obtain a normalized water cost ($/kg CW).

True Cost

Positive externalities were added to the market price of cattle and negative externalities were subtracted to obtain the True Cost of ranching in $/kg CW. Since there was a range of values for the positive externalities based on the rate of Carbon sequestration, we calculated two True Costs, one for each value in the range. Table E5 presents the results of these calculations aggregated for ranches in Arizona and Colorado. In the report the data is presented by ranch (Table 9).

Table E5. True Cost ($, 2020).

Value of externalities	Arizona	Colorado	Overall
Positive externalities ($/kg CW)	**12.79**	**4.46**	**6.88**
Positive externalities ($/kg CW)	**111.74**	**32.17**	**52.23**
Forage ($/kg CW)	0.65	0.75	0.80
General services ($/kg CW)	1.10	0.62	1.02
Wildlife value ($/kg CW)	9.36	2.62	4.29
Lowest rate of soil C increase ($/kg CW)	1.68	0.47	0.77
Highest rate of soil C increase ($/kg CW)	100.63	28.17	46.12
Negative externalities ($/kg CW)	**57.82**	**-57.71**	**57.77**
Normalized C Cost ($/kg CW)	57.74	-57.65	57.70
Normalized Water Cost ($/kg CW)	0.08	-0.06	0.07
Average market price of kg CW	**2.79**	**3.31**	**3.25**
True Cost (market price+ net value externalities)			
Lowest rate of soil C increase ($/kg CW)	**-42.24**	**-49.93**	**-47.64**
Highest rate of soil C increase ($/kg CW)	**56.71**	**-22.23**	**-2.29**

Appendix F. Regression Results-Detailed Estimates

Table F1. Regression results. Dependent variable: Natural log of the gross value of the sales of cattle and calves 2017 ($, 2017).

Variable	Coefficient	Std. Error	t value	Pr(>|t|)	
Intercept	1.4244	1.5356	0.9280	0.3547	
Natural Capital					
Principal Component 1	0.1456	0.0450	3.2390	0.0014	***
Social Capital					
Social capital index	0.0901	0.0509	1.7710	0.0779	*
Diversity of scale	6.7531	0.6102	11.0660	< 2e-16	****
Human Capital					
Average number of paid workers/operations	0.0498	0.0249	2.0030	0.0465	**
Average number of unpaid workers/operations	-0.2600	0.1314	-1.9790	0.0491	**
Diversity of ages of principal operator	8.0027	1.9259	4.1550	0.0000	****
Produced Capital					
Value of assets building, land, machinery ($)	0.0037	0.0004	8.5530	0.0000	****
Gini coefficient	2.7324	0.5166	5.2900	0.0000	****
Covariates					
Number of operations with cattle	0.0006	0.0003	2.2150	0.0278	**
Share of cattle on feed	11.4074	3.0234	3.7730	0.0002	****
Share of milk cows	-1.6095	1.1279	-1.4270	0.1550	
Arizona	-0.0541	0.2523	-0.2140	0.8306	
Colorado	-0.1998	0.1394	-1.4330	0.1532	
Idaho	-0.2764	0.1611	-1.7150	0.0877	*
New Mexico	0.0095	0.2437	0.0390	0.9690	
Nevada	0.2235	0.1900	1.1770	0.2406	
Utah	-0.3870	0.2142	-1.8060	0.0723	*
Wyoming	-0.0327	0.1628	-0.2010	0.8410	

Significance at the .10, .05, .01, .001 level indicated by *, **, ***, **** for a two-tail t-test.

Residual standard error: 0.6035 on 216 degrees of freedom (46 observations deleted due to missingness). Multiple R-squared: 0.7952, F-statistic: 51.48 on 18 and 216 DF, p-value: < 2.2e-16.

Table F2. Spatial Durbin Linear Model results, local and global.

Explanatory Variable	Percent livestock sales	Rotational grazing	EQIP participation	Percent multi-generational	Percent profitable
Local value of capital variables (direct)					
Built capital – establishments (food beverage and other)	0.010 (0.029)	-0.019 (0.013)	-2.744 (6.317)	-0.001 (0.007)	-0.031*** (0.012)
Built capital – highway and broadband infrastructure	-0.028 (0.020)	0.020* (0.010)	-2.389 (4.798)	-0.013*** (0.005)	-0.012 (0.009)
Cultural capital – arts and cultural institutions	0.020 (0.019)	-0.010 (0.009)	-3.809 (4.747)	0.003 (0.004)	0.0009 (0.008)
Cultural capital – creative capital	-0.0005 (0.020)	0.023*** (0.010)	5.391 (5.547)	-0.010** (0.005)	-0.026*** (0.009)
Financial capital – financial solvency	-0.014 (0.019)	0.011 (0.008)	-5.405 (4.170)	-0.001 (0.004)	-0.010 (0.007)
Human capital – health-related aspects	0.010 (0.015)	0.018*** (0.007)	-6.292** (3.525)	0.013*** (0.003)	0.017*** (0.006)
Human capital – health security	0.066*** (0.019)	0.002 (0.009)	-15.834*** (4.363)	0.002 (0.005)	-0.017** (0.008)
Natural capital – FSA and variation perennial biomass	-0.023 (0.019)	-0.005 (0.011)	3.713 (4.842)	-0.007 (0.005)	0.024*** (0.009)
Natural capital – variation annual biomass	0.018 (0.021)	0.001 (0.011)	2.684 (5.276)	0.014*** (0.005)	0.024*** (0.009)
Natural capital – prime farmland and annual biomass	0.029 (0.021)	-0.001 (0.011)	-2.687 (5.168)	-0.006 (0.006)	-0.012 (0.010)
Social Capital – negative	-0.045** (0.021)	-0.022** (0.009)	-0.091 (4.964)	0.009* (0.004)	0.002 (0.008)
Social Capital – death rate and census response rate	-0.026 (0.019)	-0.018** (0.008)	-1.445 (4.428)	-0.009** (0.004)	-0.011 (0.007)
Social Capital – aggregate of social capital variables	-0.016 (0.015)	0.009 (0.007)	-8.840** (3.667	0.001 (0.004)	-0.006 (0.006)

Social Capital – number of nonprofit orgs	0.063*** (0.019)	0.014 (0.010)	7.952* (4.745)	0.005 (0.005)	0.012 (0.008)
Spatial lag of capital variables (indirect)					
Built capital – establishments (food beverage and other)	0.039 (0.079)	-0.075* (0.039)	-0.459 (17.260)	0.023 (0.018)	-0.069** (0.032)
Built capital – highway and broadband infrastructure	0.075* (0.043	0.004 (0.021)	-12.996 (9.515	-0.002 (0.011	0.001 (0.019)
Cultural capital – arts and cultural institutions	0.069* (0.041)	0.032 (0.021)	0.598 (10.586)	0.005 (0.011)	0.047** (0.020)
Cultural capital – creative capital	0.046 (0.047)	0.002 (0.022)	1.208 (10.569)	-0.011 (0.011)	0.004 (0.020)
Financial capital – financial solvency	-0.080 (0.059)	-0.025 (0.018)	-11.113 (9.101)	-0.016* (0.010)	0.032* (0.017)
Human capital – health-related aspects	0.013 (0.032)	0.020 (0.015)	-4.061 (6.955)	0.010 (0.007)	0.027** (0.013)
Human capital – health security	0.074* (0.040)	-0.005 (0.021)	5.275 (9.685)	-0.008 (0.011)	-0.035** (0.019)
Natural capital – FSA and variation perennial biomass	-0.008 (0.031)	-0.041** (0.017)	-1.935 (7.981)	0.005 (0.008)	-0.017 (0.015)
Natural capital – variation annual biomass	-0.024 (0.039)	-0.037* (0.020)	2.414 (9.474)	-0.017* (0.010)	-0.019 (0.018)
Natural capital – prime farmland and annual biomass	0.094** (0.040)	0.019 (0.020)	-0.574 (8.399)	0.002 (0.010)	0.016 (0.018)
Social Capital – negative	0.004 (0.045)	0.018 (0.019)	-25.794** (10.363)	0.003 (0.010)	0.026 (0.018)
Social Capital – death rate and census response rate	-0.004 (0.043)	-0.021 (0.020)	7.976 (10.416)	-0.011 (0.010)	0.039** (0.018)
Social Capital – aggregate of social capital variables	0.014 (0.031)	0.034** (0.014)	-9.388 (7.311)	-0.002 (0.007)	-0.006 (0.013)
Social Capital – number of nonprofit orgs	0.030 (0.044)	0.017 (0.022)	-1.084 (10.219)	0.005 (0.011)	-0.043** (0.020)

Constant	0.702*** (0.175)	0.360*** (0.087)	73.936*** (38.573)	0.224*** (0.045)	0.452*** (0.082)
Observations	201	235	211	234	234
Lambda	0.293**	-0.154	-0.143	-0.0132	0.110
Log Likelihood	70.948	218.571	-1,091.458	381.051	250.377
$sigma^2$	0.028	0.009	1,813.431	0.002	0.007
Akaike Inf. Crit.	-15.896	-311.142	2,308.917	-636.102	-374.753
Wald Test (df = 1)	11.767***	2.475	2.077	0.019	1.430
LR Test (df = 1)	5.478**	1.784	1.295	0.013	0.878

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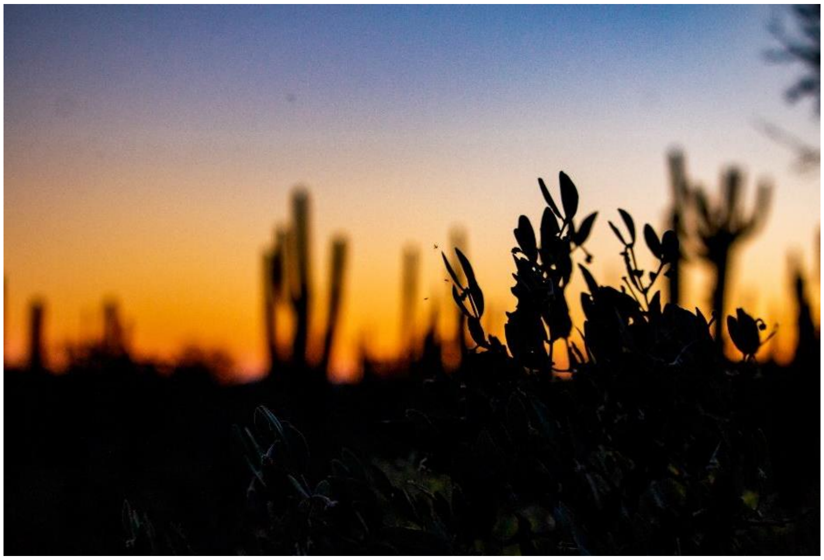

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