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A Synthesis of Ranch-Level Sustainability Indicators for Land Managers and to Communicate Across the US Beef Supply Chain

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ABSTRACT

While increasing numbers of ranchers are striving to demonstrate sustainable ranching operations geared toward a healthy landscape, companies are seeking to advance sustainability along beef supply chains and consumers are making more environmentally oriented purchasing choices. Yet there is a need for greater clarity on which indicators are most effective for assessing and monitoring sustainable management and continuous improvement of ranching operations. Our objective was to synthesize existing guidance on monitoring and assessing ranch-scale sustainability in the United States and to identify core ecological, social, and economic indicators that could identify well-managed ranching, support adaptive management, and demonstrate producers' sustainability and continuous improvement to retailers and consumers. We evaluated 21 range and pastureland assessments from nongovernmental organizations, agencies, and academics that totaled 180 indicators. From this, we selected 20 commonly used "core" indicators (12 ecological and 8 socioeconomic). We identified indicators that are designed to detect change over time for management practices, common among many approaches, and/or critical indicators for outcomes of common interest to producers, companies, and consumers. The synthesis of indicators across many guidance documents offers insight into what a diverse set of range professionals and institutions see as critical to demonstrate and track ranch-level sustainability, and producers, consumers, and companies may find a subset of these indicators to be relevant for their operation and region, values, and/or company sustainability goals. The synthesis also highlights the need for more integration and agreement on socioeconomic indicators of ranch sustainability. We acknowledge that socioeconomic indicators are context dependent and discuss the pitfalls of not integrating them into ranch assessments. Finally, we identified four issues to consider in operationalizing widespread use of common indicators: 1) who bears the cost, 2) agreement on simple and robust standardized protocols, 3) developing region-specific thresholds, and 4) issues of data privacy and sharing agreements for data use.

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Introduction

Rangelands in the United States provide both livestock production and ecosystem services. Rangelands cover approximately 770 million acres in the United States, and about 404 million of those acres are privately owned (USDA 2020a). Livestock grazing is the dominant land use for rangelands (National Research Council 1994), supporting livelihoods and providing nourishment for millions of people. In 2018 alone, the US beef industry produced over 26 billion lb of beef and supported 2.1 million jobs (NASS 2019). Intact, well-managed rangelands also maintain large soil carbon stocks (e.g., Spawn et al. 2019), support a wide range of biodiversity (e.g., Pogue et al. 2018), and reduce erosion and nutrient runoff (e.g., Flynn et al. 2017). Socioeconomic benefits include preserving open space (Kline 2006), cultivating a sense of place (Ellingston et al. 2011), and keeping money in small rural economies. Proper grazing and land management is critical to ensure these benefits continue and to avoid or reverse rangeland degradation resulting in sustainable operations. We use the term "sustainable" to include ecological, social, and economic (socioeconomic) components (Young 1997; Elkington 1998). Regenerative ranching, which seeks to enhance and restore functional and resilient ecosystem processes, has emerged as an alternative framing for understanding sustainability (Gosnell et al. 2019), but for consistency, we use the term *sustainability* throughout.

The United States has a rich history of rangeland management research and monitoring, technical support through agencies, extension offices, producer-led organizations, professional societies, and peer-to-peer learning among rangeland managers. Monitoring is needed to inform land managers on how best to implement and adaptively manage practices aimed at improving ecological function of rangelands and socioeconomic factors for ranch operations and communities. The Natural Resource Inventory led by the Natural Resource Conservation Service (NRCS) began in the 1930s with surveys on soil erosion and progressed to extensive assessment of nonfederal rangeland conditions by the mid-1980s (Schnepf and Flanagan 2016). In the mid-1990s, rangeland and soil health reports from the National Research Council (National Research Council 1993, 1994) and efforts to unify rangeland assessment concepts from the Society for Range Management (Task Group on Unity in Concepts and Terminology Committee Members 1995) stimulated efforts to coordinate research, data collection, and interpretation of rangeland condition principles. These coordinated efforts have led to standardized protocols for assessing ecological condition of rangelands (e.g., Herrick et al. 2017) used by a number of government agencies (e.g., Bureau of Land Management [BLM], National Park Service [NPS]) that roll up to evaluate rangeland condition at a large scale (e.g., Toledo et al. 2014). These data are also now being integrated with other datasets, such as land cover and remote sensing products, and being used with new technology and machine learning techniques to track trends in rangeland resources (e.g., the Rangelands Assessment Platform https://rangelands.app/, the Rangeland Production Monitoring Service https://www.fuelcast.net, RangeSat https://www.rangesat.org/). These efforts have created general agreement on the ecological components important to rangeland health and some methods for assessing those. In addition, numerous approaches (e.g., certification standards, sustainability guidelines) have been developed to translate these rangeland health principles into an adaptive management framework to support sustainable ranching practices for individual operations and for informing outcomes for the supply chain. Today, efforts continue to further develop and communicate sustainable grazing land management, with heightened interest from constituents throughout the beef supply chain.

The US beef supply chain is one of the most complex food systems in the world, currently with little traceability, making translating on-ranch sustainability outcomes into economic incentives for ranchers challenging. Yet there is motivation and, increasingly, commitments by companies to advance sustainability across their supply chains (Rotz et al. 2019). For example, in 2016 Walmart committed to source beef more sustainably by 2025 (https://corporate.walmart.com/newsroom/2020/08/07/grazing-toward-a-sustainable-beef-supply-chain), and Cargill has committed to a 30% greenhouse gas (GHG) reduction in its North American beef supply chain by 2030 (https://www.cargill.com/story/cargill-aims-to-beefup-sustainability). The dominant conventional production system (accounting for ≈95% of beef produced in the United States) supply chain starts on the ranch or farm where cows graze while calves nurse, followed by a backgrounding period when weaned calves may continue to graze or start to be fed silage and grain. When they reach specified weight, cattle are transported to a feedlot and fed rations consisting primarily of grain and agricultural byproducts until they reach a final weight. Processing then occurs at meatpacking facilities, after which beef is distributed to retailers to be sold to consumers at the supermarket. The environmental impacts of beef production across the supply chain have been well documented (Lupo et al. 2013; Poore and Nemecek 2018; Rotz et al. 2019), and it is not our intention to revisit that here. Instead, we propose that a better understanding of sustainability at the ranch scale would be of value across the entire supply chain, as such understanding would better equip ranchers with the information necessary to communicate what "sustainability" means and how it is being achieved. Organizations such as the US Roundtable for Sustainable Beef (www.usrsb.org) are working across the supply chain to improve sustainability but currently lack uniform on-the-ground ranch-level measurements that can inform decision makers (i.e., ranchers, retailers, consumers). Simultaneously, the multitude of approaches to monitoring and the variability in the indicators included within those approaches complicates the ability to monitor and communicate in a unified manner.

Multiple audiences along the supply chain are looking for easy-to-use indicators of the sustainability of a ranching operation: producers who want to continuously improve the impact of their management on the land and their business, companies who want to quantify the environmental impacts of their supply chain, consumers who want some confidence that the products they buy are sustainable, and public interest environmental organizations who seek to incentivize sustainable ranching and educate their members in how to distinguish well-managed operations. Rangelands are complex socioecological systems, with significant variation in climate, soils, dominant vegetation, land use and evolutionary histories, cultures, availability of technical and financial support, operation structure, and rancher values (Roche et al. 2015), and accurate, easy-to-use indicators of ranching sustainability are not immediately obvious. Furthermore, ownership of US rangelands is diverse (federal, tribal, state, nongovernmental organization [NGO], and private landowners), and with the diversity in ownership comes a combination of management approaches. This is further complicated when different rules or permit terms exist on leased public grazing lands that may also be grazed by multiple parties, compared with private lands, and ranchers must employ different grazing management strategies to meet sustainability targets or are limited in doing so. As governments, organizations, corporations, and individuals increasingly recognize the importance of tracking and communicating sustainability outcomes, the need for greater clarity on which indicators would be most important to use to assess sustainability and to monitor and track improvement over time is warranted. In connecting on-the-ground management to supply chains, we need indicators that are actionable at the ranch level, measure progress toward sustainability goals of interest to companies and consumers, and therefore, facilitate increased compensation for ranchers on the basis of these sustainable outcomes.

To understand which measurements are commonly used to indicate rangeland condition and sustainability, we synthesized existing guidance on indicators for ranch-level sustainability and explored how those indicators relate to common company, consumer, and public sustainability interests. Our focus was on summarizing commonly used ecological, social, and economic indicators, as recommended in various rangeland management resources that could inform adaptive management toward enhanced sustainability. We focused on the grazing lands aspect of the supply chain (with an emphasis on rangelands) and not the supplemental feed or feed lot components. We recognize this emphasis leaves out aspects of the beef production system that consumers also care about, but we focused on grazing lands because this is the base of the supply chain and offers significant conservation opportunity given the spatial extent of grazing lands in the United States. Our goal was to identify which indicators were not only commonly recommended but also useful to inform on-ranch adaptive management, as well as communicate sustainability outcomes for conservation practitioners and other interested audiences. As the stewards of such a vast area of land, cattle ranchers need to be equipped with the tools necessary to measure, manage, and communicate the sustainability of their ranch, especially given the intensifying environmental, economic, and social consequences of climate disruption and increasing societal attention to the provenance of food. In the synthesis, we examined both certification programs and rangeland health assessments with and without protocols. Great time and effort went into developing existing approaches, and our intention was not to create new certification schemes or replace existing protocols but simply to evaluate commonality. This also was not an exercise in identifying the best universal indicators of ranch sustainability, as that would depend on the values and specific contexts for individual producers and communities, companies, and customers. Instead, our goal was to understand which on-ranch sustainability indicators were identified most and potential gaps in indicators across the many technical assistance documents to inform sustainability efforts.

Synthesis Approach

Many different approaches exist for monitoring and evaluating sustainability of grazing lands, and we consulted as many of these documents as were publicly available. We sought to understand which indicators had broad support and where there might be gaps. Because many rangeland assessment documents are outside of the peer-reviewed literature, we did not use a traditional literature review approach. Instead, we started with a few of the widely used or known assessments and reached out to experts working in this arena to augment the list. We limited our synthesis to assessments that were free and publicly available, which meant exclusion of guidance from companies focused on ranch profitability (e.g., ranching for profit), which could have affected the indicators captured. We focused primarily on livestock production systems on unimproved grasslands, rangelands, and pasture in the United States and assessments that were broad in geographic scope and not limited to local- or state-focused assessments. Ultimately, we evaluated 21 different sets of indicators used for assessment and monitoring by a wide range of organizations, including federal agencies, ranching organizations, and conservation organizations (Table 1).

These documents ranged from on-the-ground monitoring protocols to detailed certification programs, and, therefore, the indicators emphasized or the way in which they were measured varied widely. Furthermore, the process used to identify indicators, including who was included and how, was likely different in each case. In a couple of instances, the indicators were preliminary. The Long-Term Agroecosystem Research (LTAR) network is still refining their indicators for evaluating sustainable intensification via a nationwide "Common Experiment" in rangelands, croplands, and integrated crop-livestock systems across the United States (Spiegal et al., in review). The inclusion of Field to Market's indicators (Field to Market 2018, 2019) within this assessment are limited to evaluating synergies between indicators for grazing lands and improving feed production sustainability related to the backgrounding and finishing phases of beef production.

In other instances, we combined indicator sets to facilitate comparison. For example, because the BLM Assessment Inventory and Monitoring (AIM; Herrick et al. 2017) and Natural Resource Inventory protocols (USDA 2020b) overlap almost completely, we combined the two approaches in the output (see Table 1). Finally, for two of the terrestrial approaches we evaluated, we were aware of complementary freshwater approaches (i.e., BLM AIM terrestrial [Herrick et al. 2017] and lotic [BLM 2017] protocols; Interpreting Indicators of Rangeland Health [Pellant et al. 2020] and Proper Functioning Condition [Dickard et al. 2015]). Although these terrestrial and aquatic protocols are not always used together, we combined them in the output for this synthesis (see Table 1).

For clarity, we follow the Conservation Measures Partnership definition of "indicator" (Conservation Measures Partnership 2020). Indicators should be a measurable quality related to a specific information need. Indicators can be quantitative or qualitative and, importantly, could be measured using different methods or metrics. Metrics are specific measurable attributes. For example, water quality could be an important indicator for ranchers and companies, and metrics such as abundance of macroinvertebrates or nitrate values in the water could both be used to report on the water quality indicator.

We reviewed each document and identified 180 indicators and metrics tracked by at least one approach (Table S1 available online at [insert URL here]). Although we define metrics as a subset of indicators, we treated them equally in our list because these terms were sometimes used differently and some approaches may have focused on one or the other. Some approaches used mainly indicators, some focused more on specific metrics, and some included both. The certification standards added the most indicators and metrics to the list as they more often included indicators for animal and worker well-being (Western Sustainability Exchange 2016; Audubon 2018; Savory Institute 2018; Field to Market 2018, 2019; Grasslands Alliance 2019).

Many approaches tracked the same or similar indicators or metrics, and after compiling the complete list, we reviewed each indicator and metric on the list, combined similar metrics into indicators (e.g., litter depth and % bare ground were grouped into the indicator ground cover). For ecological indicators we included indicators that were included in at least five of the approaches reviewed. For the socioeconomic indicators, there was less overlap among the approaches in indicators used, yet operational energy use, forage utilization, and capacity to experiment had some agreement among approaches. A core team created five categories of indicators that reflected the common groupings or themes of indicators included across the approaches: livestock-related income, non−livestock-related income, rancher satisfaction with livelihood, rancher connection to community, and community health. These categories and all indicators were reviewed by the full team.

Overall, we focused on indicators that evaluated outcomes of grazing management that would change over time in response to management. We did not attempt to address sustainability benchmarks for each indicator, as desired values for each indicator would be regionally and context specific. We excluded ranch attributes critical for planning, such as stocking rates, grazing rotations, acreage of ranch or native range, and status of infrastruc-

Table 1

Twenty-one[1] range and pastureland assessments reviewed for ecological and socioeconomic indicators to assess grazing land condition (gray boxes indicate related but separate approaches). Indicators are ticked ("X") to identify inclusion in the applicable assessment(s).

		Certification-type programs					Approaches with protocols									Approaches w/o protocols				
Category	Indicator	Audubon –Bird Friendly Land	Field to Market[2]	Grasslands Alliance	Savory Ecological Outcome Verification & Holistic Mgmt. Plan	Western Sustain-ability Exchange	BLM AIM/NRI & AIM Lotic[3]	Interpreting Indicators of Rangeland Health & Proper Function and Condition[3]	Soil Health Insti-tute[4]	First Nations Develop-ment Institute	Long-term Agroe-cosystem Research	Noble Research Institute, LLC [5]	Point Blue	Resource Manage-ment Services, LLC	Sustainable Rangelands Roundtable –Criteria & Indicators	Sustainable Rangelands Roundtable –Guidebook	FAO – Bio-diversity & Livestock Sector	Sustainable Intensifica-tion	US Roundtable for Sustainable Beef – Cow-Calf Sector[6]	Total
Ecological indicators	Abundance and/or diversity of invasive plants	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	17
	Abundance and/or diversity of native plants	X	X	X	X	X	X	X		X	X	X	X	X	X		X	X	X	16
	Ground cover (e.g., bare ground)	X	X	X	X		X	X		X	X	X	X	X	X	X	X	X	X	16
	Soil stability			X	X	X	X	X	X		X	X		X	X	X		X	X	13
	Soil carbon	X	X	X	X				X		X	X	X		X		X	X	X	12
	Plant productivity	X	X	X	X		X[7]	X		X	X	X			X			X	X	12
	Animal species of interest (e.g., concern, pollinators, game species)		X	X	X	X				X	X			X	X	X	X	X	X	12
	Water retention (e.g., infiltration)	X		X	X		X	X				X	X		X			X	X	10
	Extent & condition of riparian systems		X	X	X	X	X	X							X	X			X	9
	Water quality (e.g., nutrient loading)		X	X		X	X			X					X		X	X	X	9
	Soil compaction (e.g., bulk density)	X		X	X			X	X			X	X					X		8
	Bird diversity	X	X	X							X		X							5
Ecological indicators	Forage utilization	X		X	X	X					X	X				X			X	8
	Livestock related income	X			X						X				X	X		X	X	7
Socioeconomic indicators	Operational energy use		X	X	X						X							X		5
	Non−livestock-related income				X										X	X		X	X	5
	Rancher connection to community			X	X						X							X		4
	Community health				X						X				X			X		4
	Capacity to experiment				X						X							X		3
	Rancher satisfaction with livelihood				X						X							X		3

[1] References for all 21 approaches are included in Supplemental Information.
[2] Harmonizing Sustainable Grazing Indicators with Field to Market's Sustainable Feed Indicators.
[3] Terrestrial and aquatic protocols included in these columns even though they are separate documents and not always used together.
[4] Soil Health Institute are all lab analyses.
[5] Land Stewardship Pilot Project.
[6] USRSB does not require these indicators, but they are recommended as part of a grazing management plan.
[7] Only NRI uses productivity as part of their core methods.

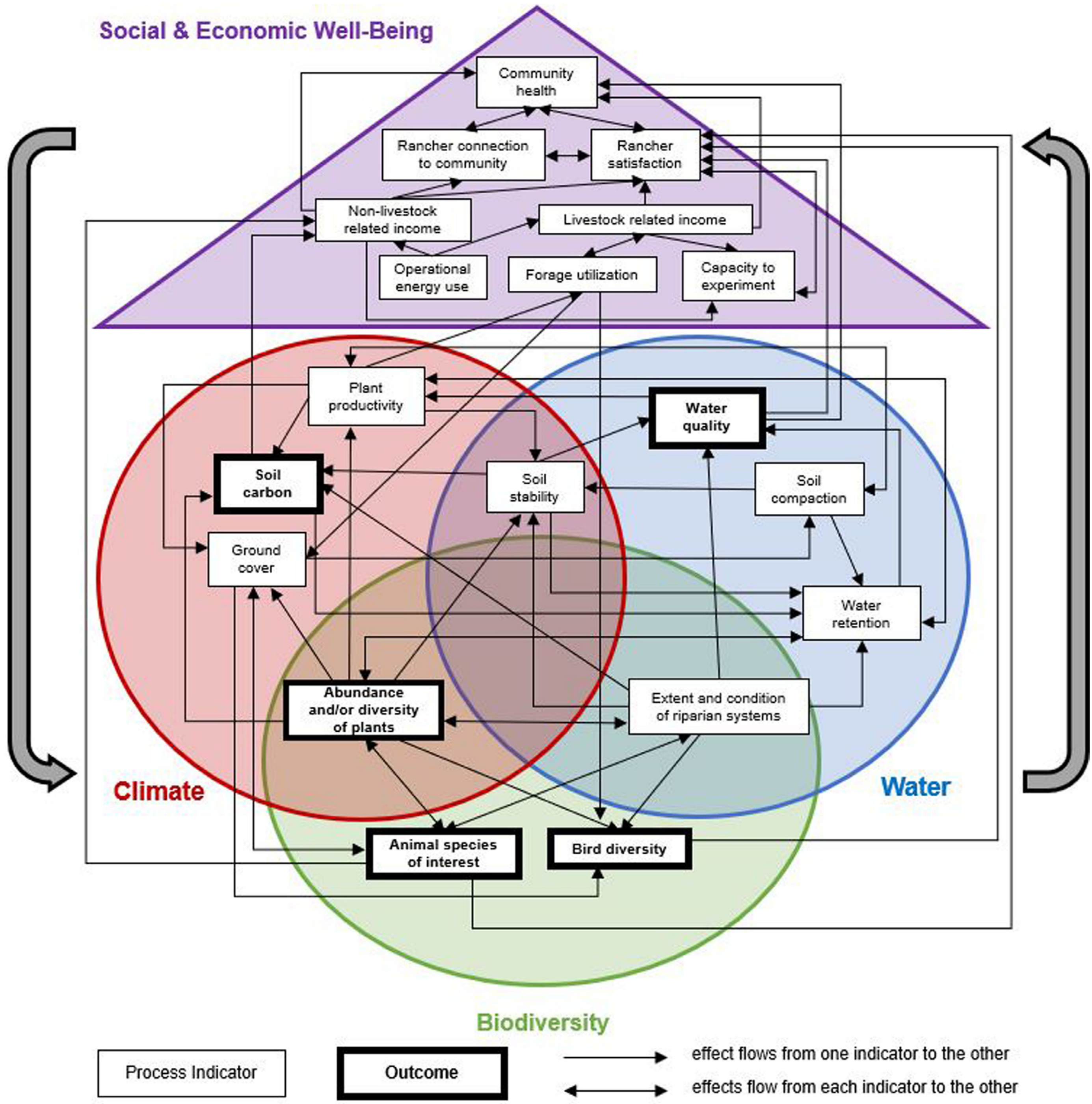

Figure 1. This conceptual diagram shows the direct relationships between core indicators identified through the synthesis (individual boxes) and how they relate to ranch and company sustainability goals (colored bubbles). Because these indicators are intricately connected, we only visualized direct connections between indicators. The native and invasive plant indicators were combined for this diagram. Each arrow between indicators represents a recognized, direct effect. Some effects are one-directional, whereas others are two-directional (i.e., each indicator influences the other). Some indicators are not directly linked by arrows but aso connected through other indicators (e.g., soil compaction affects soil carbon through its effects on plant productivity and soil stability). The *large gray arrows* surrounding the figure indicate the overall linkage between ecological indicators and socioeconomic indicators. Indicators are organized by the sustainability goals they most closely relate to (red for climate; green for biodiversity; blue for water; and purple for social & economic well-being). Indicators in boxes with a bolded border and text are also in and of themselves sustainability outcomes (e.g., bird diversity).

ture or water sources, but we acknowledge tracking these types of ranch attributes is essential for understanding the context of the outcomes measured by the identified indicators. Furthermore, some of these attributes might also be indirect socioeconomic indicators as well. We then illustrated the relationships among these indicators to visualize which indicators were directly linked to each other (Fig. 1).

Each individual approach used their own criteria for determining which indicators to include in their assessment or monitoring protocol, and many, though not all, of the approaches we re-

Table 2
Corporate sustainability goals and the ecological indicators (see Table 1) in each category. Some individual ecological indicators could be used to inform multiple sustainability goals (e.g., soil stability relates to potential for long-term carbon storage, as well as water quality impacts from erosion). In addition, while some indicators are in and of themselves outcomes (plain text below), others track key processes that inform outcomes (*italics* below).

Climate	Water	Biodiversity
Abundance and/or diversity of native plants	*Extent & condition of riparian systems*	Abundance and/or diversity of native plants
Ground cover (e.g., bare ground, litter)	*Soil compaction*	Animal species of interest (e.g., concern, game species, pollinators)
Plant productivity	*Soil stability*	
Soil carbon	Water quality (e.g., nutrient loading)	Bird diversity
Soil stability	*Water retention (e.g., infiltration)*	*Extent & condition of riparian systems*

viewed made those criteria explicit in their documents. The most widely used criterion for selection was that the indicators have documented relationships with the ecosystem functions or social system the assessment or monitoring protocol was designed to address. Beyond the clear link to environmental or social factors of interest, five other commonly used criteria were sensitivity to change, repeatability among observers, standardized protocols already exist and are widely used, cost, and ease of interpretation. We discuss the resulting indicator list in the context of these common indicator selection criteria where relevant. Instead of developing our own list of criteria, our approach here was to synthesize; we attempted to draw out the commonalities.

Notably, all of the approaches included ecological indicators, but not all approaches included economic and social indicators. Our synthesis therefore reflects this emphasis, although we do still include the economic and social indicators that were common to several of the approaches and explore why they were less represented.

Core Indicators

Our synthesis resulted in a list of 20 indicators (12 ecological and 8 socioeconomic; see Table 1). Some indicators are themselves outcomes, whereas other indicators track important processes and can inform adaptive management toward desired outcomes. Relatedly, some indicators take time to demonstrate change (e.g., 3−5 yr), whereas others are more sensitive and demonstrate change quickly (e.g., within a growing season). Not all approaches included all 20 indicators, and all approaches included indicators not included in the final list of 20. Yet it was clear that all approaches were focused on measuring outcomes toward similar sustainability goals based on the consistency of certain indicators and the stated goals of the programs and approaches assessed. While this list may not include all the indicators that would be important for every producer, operation, company, NGO, or consumer, it captures a common set of indicators that would be useful for aiding ranchers in measuring their own sustainability on the ranch, guiding adaptive management plans to meet their needs, and communicating core tenants to other parts of the supply chain (Table 2).

Ecological indicators

All approaches (or combinations of approaches) reviewed included at least three of the ecological indicators (range = 3−12; see Table 1). Within the ecological indicators, soil, water, vegetation, and biodiversity indicators were common categories included. Soil indicators such as soil carbon, ground cover, plant productivity, or soil stability were important in all approaches. Within ground cover, we included various measures of residual vegetation (e.g., litter depth and residual cover), and not surprisingly this was one of the most common indicators for assessing ranch management outcomes. Estimates of residual dry matter or litter depth have been important ways of evaluating pasture utilization for many years (Tsalyuk et al. 2015), and this indicator would score well for all five common indicator selection criteria. Many different indicators for water quantity and quality were covered among the various methods (e.g., aquatic invertebrate community indicators, measures of water contamination, volume of water available on the ranch). We included two common indicators, water quality and water retention, where we thought annual variability would provide regular feedback to ranchers for adaptive management decisions. Water quality indicators can be assessed with many different metrics (Saether 1979; Khalil et al. 2010; Roche et al. 2013; BLM 2017), and which of these metrics is most appropriate will likely depend on the geographic and ecological context of the ranch. For example, ranches that primarily use surface versus groundwater sources will likely need to assess water differently.

Nearly all (94%) the guidance documents included indicators related to invasive plants. The other most common (89%) indicators were the cover and/or abundance of native plant species and ground cover. Given that vegetation as forage production for livestock operations is foundational (Holechek et al. 2010), this is not surprising and why plant productivity was also a common (67%) indicator. Understanding how ranch productivity responds to changes in management is one of the most basic adaptive management feedbacks a rancher can use for decision making (Teague et al. 2011; Derner and Augustine 2016). Although indicators of the plant community are common, complete, species-specific assessments of the plant community will require botanical expertise that will increase the cost for these indicators. We considered riparian habitats separately because these plant communities tend to be vulnerable to overuse (Kauffman and Krueger 1984; Trimble and Mendel 1995; Sarr 2002; Lucas et al. 2004). Moreover, because of the water resources and generally higher levels of forage productivity provided by riparian habitats, they are of great importance within ranching operations.

The plant community is also a frequent indicator because it is generally assumed that if you create the appropriate habitat, animal species will thrive (James and Shugart 1970). This is a reasonable assumption but does not always hold true due to loss of connectivity or other external factors like disease (Antolin et al. 2002; Knowles et al. 2002), conspecific attraction (Ahlering and Faaborg 2006), or in some cases targeted mortality (Freilich et al. 2003). Monitoring animal populations themselves is often necessary to understand impacts. Many of the approaches we evaluated included indicators for some type or taxa of animals (67%), specifically grassland bird diversity and abundance (28%). The species of birds present on a ranch can be good indicators of vegetation structure because many species have specific habitat structure requirements (Cody 1981; Knopf and Samson 1997). Monitoring for any of these indicators can be done outside the scope of a given approach, but this may be especially true for animal population monitoring due to the oftentimes more intense effort, and thus greater cost, required for accurate data collection.

In addition to informing ranch management, ecological indicators can be readily related to corporate sustainability goals, which we have simplified into three general categories following common priorities: climate, water, and biodiversity (TNC 2020). We classified each of the ecological indicators into at least one of these categories, combining the abundance and/or diversity of native and invasive plants into one indicator (see Table 2). A few of these indicators could be used to track progress toward more than one corporate sustainability category. For example, soil stability is an important indicator for understanding both carbon storage and water infiltration (Six et al. 1998; Printz et al. 2014; Schilling and Drobney 2014; see Fig. 1), and the extent and condition of riparian areas could be used to track goals related to both water and biodiversity. In addition, although not a direct indicator for climate, restoration and management of riparian areas can have many benefits for climate mitigation (Dybala et al. 2019; Matzek et al. 2020).

Within each corporate sustainability goal category, some indicators are also outcomes (e.g., soil carbon), whereas other indicators track critical processes related to outcomes (e.g., soil stability). Corporate sustainability goals around climate are generally related to reducing greenhouse gas (GHG) emissions along their supply chain, and therefore, we included all indicators relevant to quantifying or tracking carbon storage and maintenance in the climate category. We recognize that this list falls short of identifying all GHG sources (i.e., methane emissions), but that was beyond the intention of this synthesis. Sustainability goals for water may vary depending on whether a corporation wants to reduce or offset their water use or whether their activities are likely to have impacts on water quality. Therefore, we included indicators for water quality and water retention in the water category. Finally, biodiversity is a relatively new but burgeoning category of corporate sustainability (Bull and Strange 2018, e.g., https://op2b.org) and will likely vary among companies based on the products they source, such as crops that rely on pollinators or where rare species coexist in grazing lands. Biodiversity can be challenging to quantify, but tracking plant communities and certain taxa of interest are common biodiversity indicators.

Socioeconomic indicators

Though economic and social outcomes are as important for sustainable ranching as ecological outcomes (Pretty 2008; Maczko et al. 2012), the inclusion of metrics used to measure them varied substantially across approaches and generally were less common (see Table 1). Of the 21 approaches reviewed, all had ecological indicators but only 11 had economic indicators and 5 had social indicators. When socioeconomic indicators were included, they often were highly specific (e.g., number of visitor days by activity or public beliefs and attitudes about natural resources; Table S1, available online at …). We therefore combined and categorized some of the more common types of socioeconomic indicators included among the approaches evaluated, as we did with the ecological indicators, focusing mainly on indicators relevant at the individual ranch scale.

Economic indicators at the ranch level were the most common of the socioeconomic indicators included across approaches evaluated. We summarized economic indicators into two direct economic indicators, livestock-related income and non−livestock-related income, and three indirect economic indicators: capacity to experiment, operational energy use, and forage utilization. The non−livestock-related income indicator was chosen to represent the various indicators across approaches used to quantify the diversification of income streams for a ranching operation (e.g., annual removal of native hay, nonforage plant, woody product and other saleable material; see Table S1). All the economic indicators identified through this synthesis are ranch level and likely the most useful for supporting adaptive ranch management and continuous improvement. This ranch-level data could inform economic modeling for a typical ranch, which could in turn be aggregated into regional economic modeling to understand community-level economic sustainability. Other economic indicators, such as poverty rate, income inequality, and employment diversity (among others), have been suggested as useful at a community scale (McCollum et al. 2010) but were not included here because of the ranch-level focus. Although economic security is clearly critical to the success and sustainability of a ranch, these types of indicators are extremely sensitive and include private information, which suggests there would be limited interest in communicating these indicators to other parts of the supply chain.

All ranchers will have different personal objectives for their ranches and their lifestyles, and these differences are particularly relevant when it comes to social indicators. While there is growing agreement around social indicators of rangeland sustainability (McCollum et al. 2010), it may be challenging to standardize common indicators across the production system when personal objectives differ. Furthermore, many of these personal objectives and well-being indicators are also sensitive and include private information when reported at the ranch scale (e.g., years of education). Among the approaches reviewed, social indicators at both the ranch level and aggregated across larger spatial scales were prevalent (see Table S1). Given our focus on ranch-level sustainability, we included two categories of social indicators at the ranch level: rancher satisfaction with livelihood and rancher connection to community. Because social indicators measured at the ranch scale were less common than indicators measured at larger spatial scale, we did include one social indicator measured at a larger scale than the individual ranch, community health, which can also influence the ranch-level indicators identified. Community health can be measured using many different attributes (e.g., poverty rate, income inequality) but generally tries to understand the local economic and social structure, well-being, and capacity (McCollum et al. 2010). Although only one of the certification approaches included indicators related to rancher and community well-being as we grouped them here, the authors think it is critical for understanding overall sustainability. Larger-scale social indicators (e.g., community health) are important for consumers and corporations who are interested in supporting rancher well-being and rural communities but would be difficult to certify in connection to any specific ranch. This mismatch in scale between social well-being indicators that consumers care about and ranch-level indicators that can be tied to a specific producer is a challenge that requires additional attention. In particular, identifying which ranch-level social indicators could be aggregated to inform community-scale social well-being would be valuable to communicating across parties with different objectives and interests. Another option around this mismatch would be to certify ranches within a certain community or region so that certification schemes better match with the scale of socioeconomic systems.

Ranchers track socioeconomic indicators such as income and satisfaction regularly as part of their business management. However, socioeconomic outcomes are notably absent from corporate sustainability goals for beef sustainability. For example, across the 21 approaches evaluated, only three included indicator(s) related to equity, fair treatment, and employee rights for ranch workers (see Table S1): Grassland Alliance (Grasslands Alliance 2019), Sustainable Intensification (Musumba et al. 2017), and the US Roundtable for Sustainable Beef framework (USRSB 2019). The act of choosing indicators is embedded in relationships of power (Constance et al. 2018) and in turn is performative in the sense that it influences how people see reality and structure systems (Hale et al. 2019). It has been suggested that one way to get around these inherent power dynamics is to focus on deliberative rather than technocratic forms of governance, which better develop relationships and mutual understanding (Hatanaka 2020). It is important to ask why these indicators are not prioritized. It is possible that it is because socioeconomic indicators are less developed, more costly, and more challenging to standardize, or it could be perceptions of

Table 3
Number of direct connections leading to and from each indicator as depicted in Figure 1 and the originating and destination category of those arrows.

Indicator	No. of arrows TO indicator	Category of TO arrows	No. of arrows FROM Indicator	Category of FROM arrows
Rancher satisfaction with livelihood	8	5 SEW 2 BIO 1 W	3	3 SEW
Water retention (e.g., infiltration)	6	2 CLM 1 W 1 CLM/W 1 CLM/BIO 1 W/BIO	3	1 CLM 1 W 1 CLM/BIO
Community health	5	1 W 4 SEW	2	2 SEW
Plant productivity	4	3 W 1 CLM/BIO	5	2 W 1 CLM/W 2 CLM
Ground cover (e.g., bare ground)	4	1 SEW 1 CLM/BIO 1 BIO 1 CLM	3	1 W 2 BIO
Soil stability	4	1 CLM 1 W 1 W/BIO 1 CLM/BIO	3	2 W 1 CLM
Soil carbon	4	1 CLM 1 CLM/W 1 W/BIO 1 CLM/BIO	2	1 SEW 1 W
Bird diversity	4	1 SEW 1 W/BIO 1 CLM/BIO 1 CLM	1	1 SEW
Abundance and/or diversity of plants (native & invasive lumped)	3	1 W 1 W/BIO 1 BIO	8	3 CLM 1 W 1 W/CLM 1 W/BIO 2 BIO
Animal species of interest (e.g., concern, pollinators, game species)	3	1 CLM 1 CLM/BIO 1 W/BIO	5	1 CLM/BIO 1 W/BIO 2 SEW 1 CLM
Non−livestock-related income	3	1 BIO 1 CLM 1 SEW	4	4 SEW
Water quality (e.g., nutrient loading)	3	1 CLM/W 1 W/BIO 1 W	3	1 CLM 2 SEW
Rancher connection to community	3	3 SEW	2	2 SEW
Capacity to experiment	3	3 SEW	1	1 SEW
Extent & condition of riparian systems	2	1 BIO 1 CLM/BIO	7	1 CLM 2 W 2 BIO 1 CLM/BIO 1 CLM/W
Livestock-related income	2	2 SEW	4	4 SEW
Forage utilization	2	1 CLM 1 SEW	3	1 SEW 1 BIO 1 CLM
Soil compaction (e.g., bulk density)	2	2 CLM	3	1 CLM 1 W 1 CLM/W
Operational energy use	0	–	2	2 SEW

SEW indicates social & economic well-being; W, water; BIO, biodiversity; CLM, climate.

lack of customer demand or assumptions that socioeconomic well-being flows from other measures of sustainability. This review has highlighted a gap in the way that rangeland sustainability is conceptualized and measured.

Relationships among indicators

Overall, the indicators are intricately connected (see Fig. 1, Table 3). By visualizing the direct connections between indicators, we see the extent of these connections (i.e., the number of arrows in Fig. 1; Table 3) and also that some are especially informative for other indicators or outcomes of interest (i.e., boxes with many arrows extending outward in Fig. 1). For example, plant productivity influences forage utilization (which is the basis of the social and economic well-being indicators), water retention (which is important for water quality), soil stability (which has implications for water quality and carbon storage), soil carbon, and ground cover (which affects bird diversity). In contrast, soil compaction affects plant productivity, soil stability, and water retention. Although soil compaction is certainly important for those processes, between the two, plant productivity may be more impactful to measure. It is important to note that the total number of arrows in or out of a box does not necessarily make it the most important; this will depend on the goals and specific context of a rancher's operation.

While socioeconomic and ecological indicators have influences on each other (Fox et al. 2009), there is less research on whether and how socioeconomic indicators are linked to ecological sustainability (Brunson 2002; McCollum et al. 2010). While Figure 1 focuses on direct connections between the included indicators, there likely exist moderating variables that would indirectly connect them. For example, land use change could result from lowered income, which could in turn influence ecological indicators such as ground cover, water quality, soil compaction, and others. While focusing just on direct connections (see Fig. 1) suggests that social and economic well-being indicators are mostly supported by ecological indicators, and not the other way around, a more comprehensive view that incorporates indirect influences and moderating forces (not depicted in Fig. 1) would likely highlight many more feedbacks from social and economic indicators to sustainability outcomes. Related, it is important to note that socioeconomic indicators often fail to match with the temporal and spatial scales of ecological data (Fraser et al. 2006) and, as a result, feedback between socioeconomic and ecological indicators could occur across longer timescales and broader spatial scales than individual indicators.

Using Core Indicators to Link Across the Supply Chain

We conducted this synthesis to understand the leading guidance for assessing and monitoring sustainability outcomes on US ranches. In doing so, our goal was to not only understand existing recommendations but also identify whether common indicators create the opportunity to support ranch-scale adaptive management and communicate sustainability gains through supply chains to companies and consumers. One finding is that there are fewer common socioeconomic than ecological indicators across assessments, highlighting a gap in current sustainability assessments and associated need for more attention to the reasons why, how to better include them, and how assessment goals influence indicators. Here, we discuss how these common indicators could be useful to producers, corporations, and consumers with an emphasis on ecological indicators because the synthesis revealed that they are more widely used and agreed on.

Producers

Livestock production is the dominant land use for grassland pasture and rangelands across the United States (NASS 2019); therefore, it is imperative that conservation and sustainability begins at the ranch level. Producers are faced with the difficult task of maintaining the ecological condition of the ranch while supporting enough grass production that they can economically sustain their livelihood, all while meeting consumer demand. The focus needs to be on data and science that is directly applicable to land management decisions and can be incorporated into an adaptive management framework. The set of indicators identified here would enable producers to close the adaptive management loop between cattle grazing and ecological condition, while tying this to the socioeconomic impact of ranch management decisions.

Achieving a desired ecological condition outcome for a specific ranch context requires a careful evaluation of the ecological processes that are occurring at the ranch scale. With this information, producers can adjust their management to make improvement toward sustainability goals. For example, if the ultimate goal of the rancher is to produce more grass forage, there is an intricate link between ecological indicators on this list such as vegetation composition, plant productivity, water retention, and soil carbon content (Teague et al. 2011; Wang et al. 2016; Porzig et al. 2018). While soil carbon may be slow to register change in response to changes in grazing management, water retention is sometimes one of the most immediate changes and is relatively easy to observe through changes in water flow patterns (Pellant et al. 2020). Soil carbon can also be measured, though the level of replication and cost per measurement typically make it cost prohibitive (see replication requirements in Herrick et al. 2009 Volume II appendices). Furthermore, information about the ecological condition of the ranch can be used to increase resiliency of an operation when incorporated into a long-term ranch management plan and adaptive management framework (Derner and Augustine 2016). For example, precipitation is becoming less predictable than in the past, with some regions experiencing increased drought while others are experiencing more moisture, and extreme weather events are becoming common. By regularly and proactively monitoring the ecological condition of the ranch and making management adjustments as needed, one can better prepare for and cope with drought or other weather events (Roche 2016).

Understanding the connections between indicators (see Fig. 1) could help identify a subset of indicators to measure based on goals and other common selection criteria used by individual approaches, such as cost. Some of these indicators are easy and low cost to measure (e.g., plant productivity, water retention) while some are more time and resource intensive (e.g., soil carbon, bird diversity, and abundance). Routinely measuring indicators with a lot of "out" arrows may be especially helpful to inform management decisions, given that those indicators will affect multiple processes. In contrast, indicators with more "in" arrows could be especially important for demonstrating outcomes. Information from the ecological indicators can ultimately be correlated with livestock productivity metrics (calving success, daily cattle weight gain, etc.), thereby improving the socioeconomic indicators, such as livestock related income and forage utilization, as well. For producers interested in certification schemes, most of the indicators identified here were also used by organizations that certify sustainably produced beef, though it should be noted the intent of this synthesis is not to identify certification criteria. Following a certification standard would allow producers access to a small but growing array of premium markets among other numerous benefits of increased ranch sustainability.

Corporations

In addition to use for adaptive management, ranch-scale indicators would also be useful to report sustainability outcomes to companies that purchase and sell beef products. These companies are increasingly under pressure to demonstrate and document sustainability in their supply chains. An example of corporate climate action is the Science Based Targets initiative (https://sciencebasedtargets.org/), which is focused on standardizing the level of ambition and the process by which companies set greenhouse gas reduction goals for their operations and their supply chains. Nearly 1 000 companies have made commitments to reduce their environmental footprint as part of this initiative. Though examples of this are less well developed in the land use sector, companies are taking it upon themselves to make actionable change. There is a growing movement of companies teaming up with NGOs to ensure they are using the best available science and are being held accountable to their commitments (e.g., Ecosystem Services Market Consortium, https://ecosystemservicesmarket.org). The United States does not currently have a robust tracking system that can be used to trace individual cattle from a ranch through a company's supply chain. Therefore, outside of specific certification programs, companies often do not know where the beef they are selling was born, how it was raised, or its associated environmental or sustainability impact. In lieu of this, if the common set of indicators proposed here were to be widely adopted and measured on numerous ranch operations within a region, the aggregated data could inform the general range condition from the region where companies are sourcing. This information could then be used to support company commitments to sustainability. For example, the same indicators ranchers use for tracking their desired ecological condition, plant productivity, water retention, and soil carbon could be aggregated and translated to impact metrics such as greenhouse gas emissions across a supply shed to communicate to companies about improvements in climate and water sustainability goals over time.

Consumers

The final step in the supply chain where the use of ranch-scale indicators could be informative is with the consumer. Consumer demand for sustainably produced beef, including grass fed and organic, continues to increase, as illustrated by an expected annual growth rate of 20% from 2009 to 2013 (Matthews and Johnson 2013; Sitienei et al. 2020) and a doubling of grass-fed beef sales every year between 2012 and 2016 (Cheung et al. 2017). While the intention of this assessment is not to be a certification scheme, this trend points to consumer demand for more sustainable beef products. This demand is influencing companies' desires to achieve sustainability goals in their supply chains. However, demonstrating an ongoing commitment to land stewardship and continuous improvements to sustainability outcomes on rangelands directly to consumers would be beneficial in building trust and sustaining a stable consumer base. If more producers are equipped to monitor range condition in a unified way and use that information to demonstrate continuous improvements to their operation, consumers could be assured that beef production is being done in a sustainable manner that promotes greenhouse gas mitigation, improves water quality, and supports biodiversity. It is also possible that consumers care about and would like to support thriving rural economies (particularly given growing awareness of popularity in Fair Trade certified products; https://www.fairtradecertified.org/why-fair-trade/our-impact), which more developed socioeconomic indicators could help inform. Furthermore, research has shown that consumers are willing to pay more for products they know are produced sustainably (Stampa et al. 2020), and because the shelf price of a product ultimately dictates the profits that are made, starting with a common set of indicators at the ranch level would be beneficial to all parties along the supply chain. What is currently a niche market could gain further recognition and increased uptake if such measures were more widely adopted. While generally a good thing for sustainability, if premiums start to disappear as practices are mainstreamed, how rewards and costs are distributed across the supply chain needs to be considered.

Further Incorporation and Agreement on Socioeconomic Indicators Needed

To achieve ranch sustainability, progress is needed on at least two legs of the sustainability stool (Young 1997; Elkington 1998): economic and social. Although balance among multiple uses, agriculture, and/or local communities alongside natural resources is needed, the focus is primarily on ecological indicators (Popovic et al. 2018). This highlights the gap between what is known about the importance of socioeconomic well-being for sustainability (Brunson 2002; McCollum et al. 2010) and management guidance on what to measure over time to support decision making (explored further later).

While rare, there are prior assessments of social sustainability measures within supply chains (Hutchins and Sutherland 2008), agricultural commodity production (Rasmussen et al. 2017), and for rangeland systems specifically (McCollum et al. 2010). Furthermore, there is a robust and growing field of socioeconomic and well-being–related research in rangelands systems (Brunson 2002; McCullum et al. 2010). Why, then, do we see a disconnect between academic scientific understanding and management guidance on how to best demonstrate and track ranch-level sustainability (Wilmer et al. 2018), as further evidenced by this synthesis? Potential contributors include different organizations' limitations due to data privacy and context-dependencies of socioeconomic indicators.

Different organizations and institutions are bound by different policies and laws dictating the types of data and information they are permitted to collect. For example, for sustainability certification of ranch operations, ranch-level economic and social indicators are important to the certification process. However, US government agencies may have laws preventing them from collecting socioeconomic information unless it is guided by a structured framework, such as a National Environmental Policy Act (NEPA) analysis for environmental impacts. When socioeconomic indicators are used at the ranch level, these data privacy issues are heightened, compared with more community-scale measures of well-being. This could partially explain the smaller number of socioeconomic indicators identified here applicable to ranch-scale sustainability, given that the focus of this synthesis was on ranch-scale sustainability.

The literature on social sustainability indicators calls for indicators that are tailored to local contexts (Fraser et al. 2006; Magee et al. 2012). Prior work on social-economic indicators has suggested that focusing on the local scale may be most appropriate, as there is large variation between contexts (McCollum et al. 2010). Even within a state, the cultural, historic, and economic contexts can vary dramatically, resulting in a need for localized, context-dependent socioeconomic indicators. In some cases, county-level data and indices that might be able to bridge local context with national comparison (e.g., the Centers for Disease Control's social vulnerability index; Flanagan et al. 2011) exist. Furthermore, producers' values and ranch objectives differ widely (Roche et al. 2015), highlighting the importance of flexibility in indicators. Although the context-dependent nature of social-economic indicators lends itself well to ranch-level management guidance, it highlights how difficult it may be to identify universally important socioecological indicators (akin to plant productivity). This also leads to scalar differences between social and ecological systems (Fraser et al. 2006), with socioeconomic systems often more expansive than local ecosystems, leading to suggestions for a multiscale perspective (e.g., McCollum et al. 2010). Indeed, the scale at which the socioeconomic indicators were measured varied from ranch level to larger spatial scales such as communities or counties.

Although the selection of specific socioeconomic indicators may need to vary given context (McCollum et al. 2010), without some agreed-on categories (even if broad, like "community health"), it is unlikely that socioeconomic indicators will be incorporated in ranch management guidance developed for regional or national scales. The Sustainable Rangelands Roundtable and the LTAR network have made great strides in thinking about how to quantify socioeconomic indicators (Mitchell 2010; Hamilton et al. 2011; Spiegal et al. In review), and wider adoption and agreement on methods and approaches is warranted.

Inadequate inclusion of socioeconomic indicators may have unintended repercussions. For example, failure to include them could mask potential tradeoffs or unintended consequences of management decisions, leading to ecologically beneficial outcomes, but outcomes that weaken rural economies and social structure (Rasmussen et al. 2017). If sustainability assessments lack socioeconomic indicators, they limit the sphere of their assessment and may fail to support producers in meeting their goals or capture consumer values such as livable working conditions, thriving rural communities, and family-owned operations.

Failure to identify socioecological indicators with local communities may also alienate producers and fail to capture important local dynamics (Chambers 1997; Fraser et al. 2006). Identification of social indicators of sustainability with producers across different regions and ecosystems may be an effective and worthwhile future research direction. For example, a recent study on the Northern Great Plains found that lifecycle stages of producers influenced the importance of different social sustainability indicators (Haggerty et al. 2018). Recent explorations that combine top-down efforts at standardization with bottom-up awareness of local sustainability issues may strike the balance between utility at a local level and standardization across locations (Fraser et al. 2006; Magee et al. 2012).

Implications—Moving from Indicators to Impact

To move from a set of common indicators to on-the-ground impact—both in supporting adaptive management and improved outcomes on the ranch and in demonstrating and rolling up sustainability outcomes—there are important implementation questions to consider. In particular, who collects the indicator data, how will they do so, and how will those data be used or shared? How will demonstrations of sustainable grazing management benefit ranchers who are part of the conventional supply chain, whose beef cattle are typically fed, slaughtered, and sold by geographically distant corporations? While answers to these questions were beyond the scope of this synthesis, we recommend further consideration of these important aspects of measuring and tracking sustainability indicators. Here we focus our discussion on the ecological indicators, where there was more agreement among approaches.

Who executes and finances the data collection, and who accrues the reward?

While some producers may already track some of these indicators on their operations, we would not expect a rancher to measure and track all these indicators. Similarly, although ranch technical advisors currently support monitoring of some of these indicators, they may not be trained or familiar with all indicators. For example, the animal species of interest indicator may require surveyors with a particular skill set. In addition to questions around expertise and who is best positioned to assess and track indicators, it is important to consider the time and resources required to assess these various aspects of sustainability for an entire ranch operation. Depending on both time and costs (both of tracking indicators and further training to support doing so), there are important questions around practicality/feasibility and whose responsibility it is to provide support. For example, if a company is committed to demonstrating retention of soil carbon in operations it sources from, should the company cover the costs of sampling and assessing soil carbon? Or, if an indicator is most useful to informing on-ranch management and less useful for directly tracking sustainability outcomes of interest to companies or consumers (e.g., forage production), would a sourcing company not cover costs related to assessing plant productivity?

Finally, who along the supply chain accrues the benefits from implementation of sustainability indicators is an important consideration. From a producer standpoint, economic increases can come through a variety of means including, but not limited to, reduced input costs, increased production, or a premium for a product. However, premiums for sustainably raised livestock are most common through third-party certification programs that ensure a safe, ethical, sustainable product (Hatanaka et al. 2006; e.g., Audubon's conservation ranching initiative, https://www.audubon.org/conservation/ranching). Other types of performance-based sustainability measures may not come with a guaranteed market premium (Konefal et al. [in press]), but indicators useful to a rancher's adaptive management could help reduce input costs or increase production with improved ecological condition. Given the push for sustainability indicators from consumers and retailers, it is important to consider how the benefits and rewards of this approach will be distributed across the supply chain to ensure those benefits will reach producers.

How should the data be collected?

Not all indicators will be relevant for all ranches, and the common criteria used by individual approaches to select indicators could also inform a rancher's decision for which indicators to use. Two of the more common criteria, cost and sensitivity to detect change, would be important to consider. For example, soil carbon can be expensive to quantify and slow to change in response to management while ground cover and abundance or diversity of native plants can be readily assessed in the field and are likely to respond more rapidly to changing conditions (Herrick et al. 2017). Finally, as remote sensing technologies improve, prioritizing indicators that are either closely related to or could transition to remotely sensed indicators could significantly reduce the cost and improve repeatability and standardization of information. For example, the spatial and temporal resolution of Normalized Difference Vegetation Index data is increasingly used to accurately assess plant productivity in grasslands (e.g., Reeves and Baggett 2014; Tsalyuk et al. 2015), and advances in remote sensing products are better able to predict fractional cover of relevant plant groups, estimating vegetation composition (Allred et al. 2020).

For monitoring selected indicators, we recommend using established protocols and national standardization where possible. Indeed, many of the approaches reviewed have established protocols for the ecological indicators on this list, and a few of these approaches even use the same field protocols. For example, BLM, NRCS, and LTAR sites focused on evaluating performance of rangeland production systems, and Point Blue use the line-point intercept method to assess the native and invasive vegetation indicators (Herrick et al. 2017; Porzig et al. 2018), which also cooperate with emerging smartphone apps for assessing rangelands such as LandPKS (https://landpotential.org). Selecting indicators that have standardized, well-tested protocols, and can be accepted by third-party certification schemes if desired, will also increase the chance that the chosen indicators will be cost effective, sensitive to change, repeatable, and easy to interpret and communicate across the supply chain, further improving the adoption of sustainable practices (Hatanaka et al. 2006). However, how the data should be collected is also tied to the question of who executes the data collection and their level of expertise. For example, many existing protocols may require knowledge in plant or animal identification that will limit who can collect the data. Although well-tested protocols may be cost effective for the type of data they collect, the cost of implementation of species-specific protocols may be prohibitive for individual ranching operations. Finally, using standardized protocols to establish a baseline for a ranch will be important, but establishing region or even more locally specific benchmarks or thresholds for indicators using established protocols would be useful for producers and companies to track progress toward specific ecological outcomes. NRCS's ecological site descriptions will be a good starting place for developing these benchmarks (https://edit.jornada.nmsu.edu/catalogs/esd).

Who has access to the data and how will it be used?

Questions of data privacy and which information is necessary for ranchers to adaptively manage their operations versus which information is necessary for retailers or customers to assess an operation's sustainability, given company and consumer sustainability objectives (e.g., biodiversity or climate), also needs to be considered. Even for globally remotely sensed data, it is important to address the issue of who gets to use data that can be analyzed for private lands. Furthermore, as technology advances and data become even easier to access, there is the potential for actors to leverage data in unintended ways. For example, big data platforms have been used by corporations to vertically and horizontally integrate across supply chains, leading to mergers that can monopolize sectors of the agrifood industry (iPES-Food 2017; Prause et al. 2020). However, potential risks could be ameliorated by careful considerations up front, such as anonymized data aggregation, and when used as intended the rewards outweigh the risk. Whatever the mechanism, producers and producer-led groups absolutely must be part of the decision process for design and development of data platforms, as the data ultimately belongs to them and doing so will ensure resulting tools and platforms are useful for their management. In certification programs, the independent, third-party verifier translates on-ranch outcomes into sustainability outcomes communicated via the certification process. Outside of certification programs, we recommend drawing on existing models for data sharing and navigating data privacy issues (e.g., Findable, Accessible, Interoperable, Reuseable data use principles; Wilkinson et al. 2016). Similarly, although some indicators may not be immediately clear in their utility for retailers or customers to assess climate, water, or biodiversity outcomes, there are likely ways in which they further enable (or inhibit) conservation outcomes (e.g., social and economic vibrancy of communities could have long-term consequences for land management and conservation). We suggest further consideration and streamlining of which information is necessary to inform on-ranch adaptive management versus demonstrating sustainability.

Conclusion

We identified 12 common ecological and 8 socioeconomic ranch-level indicators from 21 different assessments and demonstrated that many of the same ecological indicators are used across nearly all of the approaches reviewed for assessing ranch sustainability. These indicators are relevant for rangelands across the United States. However, they may be measured differently in different parts of the country, and there are various metrics that could be used to represent each indicator depending on ranch context. Which indicators, and which metrics for those indicators, are used for assessment and/or monitoring should be related to outcome goals, as producers have unique goals for their operations and companies have unique goals for driving sustainability in their supply chains. Future work related to indicators should use participatory frameworks to ensure producers' interests and concerns are front and center and that they have decision-making power. These indicators have the potential to link on-ranch outcomes with corporate sustainability goals for climate, water, and biodiversity. The synthesis also demonstrated that while there is a growing body of knowledge on socioeconomic indicators in the literature, integration of these indicators into sustainability evaluation guidance documents is still somewhat limited. Only 5 of the 21 assessments reviewed included socioeconomic indicators.

While common ecological indicators and even some protocols clearly exist, there is still a need to achieve more widespread use and agreement on metrics of socioeconomic indicators to inform adaptive management for producers and to link continuous ranch and rangeland improvement outcomes to supply chain sustainability outcomes for companies and consumers. Currently, incentives for a "value-added" product that includes rangeland monitoring are limited for ranchers outside of certification programs, in part due to the disconnect between ranchers and retailers along the conventional beef supply chain (Spiegal et al. 2020). To achieve more widespread adoption of rangeland monitoring by these ranchers, we identify four issues that need to be addressed by the ranching industry as a whole: 1) who bears the costs (e.g., time and money) for assessing or monitoring these indicators in the field and who benefits; 2) agreement on simple, robust, and standardized protocols; 3) region-specific thresholds for those indicators; and 4) issues of data privacy and sharing agreements and principles. Ultimately, if these issues were adequately addressed, a select suite of clear, simple, and easy-to-measure indicators of ranch sustainability could help producers advance biodiversity, water, climate, and social well-being outcomes in their operations and not only communicate the benefits clearly to beef retailers and consumers but also provide valuable ecosystem services that benefit nature and people at large.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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