Vulnerability assessment of the multi-sector North American bison \textit{Bison bison} management system to climate change

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Abstract

1. Bison \textit{Bison bison} are a keystone of a conservation system, but that system is vulnerable to the effects of a changing climate projected to alter land use through the 21st century.
2. The current bison population of North America is approximately 400,000 animals and is maintained by a self-assembled bison management system (BMS) of various stakeholders focused on bison conservation and production. The BMS is comprised of public, for-profit private, Tribal and not-for-profit non-governmental organization (NGO) sectors, with complementary values, attitudes and practices that contribute to a robust conservation footprint for the species.
3. Currently, the majority of grasslands (90%) and bison (85%) are privately owned which justifies the need for robust private land conservation strategies to maintain this iconic species and its grassland habitats.
4. We assessed vulnerability of the BMS to 21st century consequences of climate change with a vulnerability scoping diagram that emphasizes exposure, sensitivity and adaptive capacity, as well as environmental values, attitudes and practices. We surveyed 132 bison managers within both the private and public/NGO sectors. Respondents were predominantly educated white males located in the northern and central mixed grass prairies who manage bison herds of, on average, 51–100 animals.
5. Overall, the BMS is moderately vulnerable to climate change. While the public/NGO and private sectors differ in adaptive capacity, specifically in measures of information exchange, external revenue, use of management plans and access to grazing leases, the sectors act as partners for exchanging bison and rely on sustained interchange of bison; dimensions of exposure and sensitivity appear similar between public/NGO and private sectors.
6. The complementary, shared environmental values and attitudes of the private and public/NGO sectors shape the foundation for enhanced collaboration among the multi-sector BMS. But it is the sharing of diverse practices and respective consequences that will lead the BMS to discover credible, scalable adaptive solutions to climate change. This may lead to the bison community to decide whether to form a 'bison coalition' to seek solutions to adapt to climate change.
Grasslands and bison *Bison bison* are co-evolutionarily dependent, each facing challenges from climate change and land use in the 21st century. Yet each may facilitate the conservation success of the other. Grasslands of the Great Plains once encompassed 2.8 million km$^2$ at the time of European settlement representing 14% of the landmass of the United States and Canada combined (Johnsgard, 2003; Licht, 1997). Since then, Great Plains grasslands have undergone agricultural intensification, especially in the eastern portion of the region (i.e. tallgrass and mixed grass prairies) and today are 90% privately owned (Holechek et al., 2011). Historic populations of bison numbered between 30 and 60 million prior to 1868 (Flores, 1991; Hornaday, 1889) and predominately inhabited the Great Plains (Figure 1). North American bison conservation has overcome an incredible hurdle of restoring populations to nearly 400,000 from fewer than 1,000 individuals in 1884 (Stoneberg Holt, 2018). However, the International Union for Conservation of Nature, Red List assessment, considers bison ‘near threatened’, because their assessment relies solely on publicly owned (i.e. Federal and State) ‘conservation’ bison herds (Aune et al., 2017). Publicly owned bison populations have remained static around 30,000 bison since the 1930s because the extent of public lands has not expanded, especially not in the Great Plains (Gates et al., 2010). In addition, the few existing public herds are positioned at the margins of the historical bison range (i.e. in and near the Rocky Mountains) and each have populations that are considered too small (i.e. fewer than 1,000 individuals) for long-term conservation success (Sanderson et al., 2008). Meanwhile, the bison meta-population approaches 400,000, of which nearly 85% of those are privately owned and considered ‘production’ herds (Gates et al., 2010; United States Department of Agriculture, 2016), yet many of these ‘production’ herds satisfy ‘conservation’ guidelines established in the ‘Vermejo Statement’ about bison conservation (Sanderson et al., 2008). This suggests that private bison stewardship and private land conservation (Drescher & Brenner, 2018; Kamal et al., 2015; Lueck, 2002) is essential to maintain this iconic species and its grassland habitats.

Bison conservation on private lands is unique because this native wildlife species can be managed as livestock in some respects (Aune & Plumb, 2019; Ranglack & du Toit, 2015; Redford et al., 2016). For example, they can be bought and sold, and vaccinated as are livestock, but genetic manipulation and use of artificial insemination is allowed only for research purposes (National Bison Association, 2013). The duality of this conservation and production system exists at the intersection of the conventional North American Model for wildlife management with their respective mandates (Clark & Milloy, 2014; Geist et al., 2001; Peterson & Nelson, 2017) and conventional large livestock production (Byrd et al., 2017). Bison and their management transcend multiple sectors of ownership including public, private, tribal and non-governmental organizations (NGOs). We refer to this
multi-sector combination of land and bison ownership as the bison management system (BMS).

Private land conservation has proven challenging because of the tension that resides between societal benefits realized from non-provisioning ecosystem services (e.g. supporting, regulating and cultural) and private market-based provisioning services optimized on private property. Procedures to balance private ownership with the costs of conservation have remained elusive (Drescher & Brenner, 2018; Kamal et al., 2015). Consequently, the potential for private bison ownership to contribute to future bison conservation in the absence of collaboration with other sectors is unknown. Effective collaboration among sectors may prove necessary for the BMS to adapt to climate change and increasing climate variability (Klemm et al., 2020a).

Accelerating climate change throughout the Great Plains in the 21st century (Wuebbles et al., 2017) may represent the next major challenge to bison survival. Climate change directly affects bison by increasing thermal stress (Martin & Barboza, 2020b) and decreasing forage and water availability. Indirect consequences of climate change include increasing distribution and intensity of parasites (Kutz et al., 2005; Morgan & Wall, 2009; Patz et al., 2000) and several diseases (Janardhan et al., 2010) that are known to reduce reproductive success (Fuller et al., 2007). These stresses have been estimated to collectively reduce bison body size by 50% if global temperature warms by 4°C near the end of the 21st century (Martin & Barboza, 2020a; Martin et al., 2018). Furthermore, climate change, particularly warming and drought, may have cofounding impacts on sustainability of the remaining grasslands of the Great Plains by altering intensification rates of agriculture, land use and woody plant encroachment (Allred et al., 2013; Bowler et al., 2020; Klemm et al., 2020b; Knapp et al., 1999).

A vulnerability assessment of the BMS to increasing climate variability and change throughout the 21st century was conducted to further clarify the challenges that bison conservation may face in future climates. Data referencing the exposure, sensitivity and adaptive capacity of both private and public bison managers were collected via an email survey. Data describing these three components were analysed with a vulnerability scoping diagram (VSD; Supporting Information Figure S1) and framework as described by Adger (2006) and Polsky et al. (2007). Exposure characterizes the stressors or hazards that may threaten a system, especially coupled human and natural systems. Sensitivity characterizes the rate and magnitude of ecological or economic impact on these systems. Adaptive capacity characterizes the societal responses that mitigate system sensitivity to stressors and hazards. The VSD provides a holistic approach to incorporate elements of social connections, biological responses, climatological drivers and decision making for assessing first-, second- and third-order effects of climate change (Supporting Information Figure S1).

2 | METHODS

Participation in the survey was restricted to managers of bison herds who were 18 years or older, spoke English, resided in North America and provided informed consent. The survey was delivered online and remained open for 1 month (from 11 February 2019 to 14 March 2019). Participants were recruited through listserv emails and social media posts of the National Bison Association and herd managers. The study was approved by the Institutional Review Board at Texas A&M University (TAMU IRB: 2018–1654).

2.1 | Survey instrument

Our VSD relied on participant responses to a survey questionnaire we developed which contained 68 total questions—divided into 18 measures, two measures for each of the nine components that represent three dimensions of vulnerability—exposure, sensitivity and adaptive capacity (Table 1). We also queried stakeholders about their environmental values, attitudes and management practices. Total vulnerability scores are derived from the 11 questions measuring exposure, 23 questions measuring sensitivity and 15 questions measuring adaptive capacity (Table 1; Supporting Information Table S2). To test whether survey participants could understand the scale items (i.e. face validity), a pretest was conducted with a 10-person focus group comprised of private and public bison herd management officials (Martin, 2020). Although the dimensions of the VSD are consistent with Polsky et al. (2007), the components, measures and survey questions are tailored to the bison management system (BMS). Additionally, to determine underlying drivers of differences in adaptive capacity, we measure environmental values, attitudes and management practices of participant perceptions.

Survey responses were recorded on a Likert scale from 0 to 5—equating to no response, strongly disagree, somewhat disagree, neutral, somewhat agree, strongly agree—or on a scale of agreement with three points (agree–neutral–disagree) or two points (positive or negative perceptions). Focal topics included elements of management philosophy, diversity of income, land and animal health monitoring, management practices, perceived value of economic and ecological factors, quality of life and career experiences and personal characteristics. Attitudes towards various ecological and management practices, such as using prescribed burning or diversifying livestock species were also surveyed. Respondents were also questioned about their perceptions and/or observations of climate over the last 10 years, such as warming mean summer temperature or shifting calf survival rates on their operations.

Responses from the VSD indicating more vulnerability were valued higher (e.g. ‘Do you provide water to your animals?’—Yes or no; where yes is scored as 0 and no as 1). An alternative procedure was developed to interpret and visualize the results of the VSD. All non-personal trait questions were standardized to a 10-point scale for subsequent analyses with high scores to each question indicating higher vulnerability. We collated the respective questions within each measure of the VSD to record the median score. Building up to the scores of each dimension, we collated the respective measures within each dimension of the VSD to record the median score. High scores (> 6) indicate increasingly lower vulnerability, at the
individual, sector and system level, and are depicted on the outer edge of a 10-point radar plot (Adger, 2000, 2006). The overall vulnerability score is calculated as the mean of the three median dimension scores of exposure, sensitivity and adaptive capacity.

2.2 | Respondents

We collected 156 responses from an estimated pool of 1,049 bison managers (National Agricultural Statistics Service, 2019) for a response rate of 15%. We removed 24 incomplete or unqualified responses for an analytical set of 132 responses. The median time spent by each respondent on the survey was 10.4 min. We classified respondents by sector, region, ecosystem, operation size and education level. Respondents were asked if they represent private, public or non-governmental organization bison herds. Demographic attributes of respondents are presented in Table 2.

An independent two-sample t test using groups was conducted to determine the difference among various attitudes and practices of public and NGO sectors. There were no significant differences between public and NGO sectors in their environmental values, attitudes and practices (albeit, each group has low n; Supporting Information Table S1). As an example, their attitudes towards economic diversification are not significantly different ($\mu = 3.6$ and $3.8$; $\sigma = 1.7$ and 0.8; $p = 0.82$). We present additional Supporting Information in the Supplemental Information about ecosystem and regional variance using Pearson’s correlation coefficients, of which do not significantly vary, yet indicate that sector variance is similar for the public and NGO sectors (Supporting Information Figures S2–S4). As such, the public and NGO sectors were combined into one group because of overlap in common values, attitudes and practices that was compared to the private sector in subsequent analyses. Most responses were from the private sector (121% or 92%) with 5 (4%) responses from NGO, and 6 (5%) from managers of public herds—for a combined public/NGO sector of 11 (9%) responses. This sample reflects the proportional ownership of bison in North America: 81% private, 5% NGO, 8% public and 5% tribal. Bison herd sizes ranged between $<$15 head and $>$5,000 head with a mean size of 145 animals (United States Department of Agriculture, 2016). Respondents were predominantly male (85%) in both the public/NGO (91%) and private sectors (82%), have attained higher educations (67%), and 62% have over a decade of experience with bison.

Regions of North America were separated into northern, central, southern and eastern sections (Figure 1; Supporting Information Table S3). Ecosystems were parsed using categories of tallgrass, mixed grass, shortgrass grasslands—and an ‘other’ category (Omernik & Griffith, 2014; U.S. Environmental Protection Agency, 2014). The ‘other’ category refers to ecosystems that are not grasslands; most often in regions other than the Great Plains such as the forests of the Appalachians. When the regions and ecosystems of the Great Plains are overlaid, nine distinct sections become apparent—northern

### Table 1: Vulnerability dimensions, components and measures mapped to survey questions for the vulnerability scoping diagram created from survey responses. Supplemental Information presents the survey questionnaire. Abbreviations: C, cultural ecosystem services; P, provisioning ecosystem services; R, regulating ecosystem services; S, supporting ecosystem services

| Dimension   | Component               | Measure                      | Survey question number(s)* | Ecosystem services |
|-------------|-------------------------|------------------------------|----------------------------|--------------------|
| Exposure    | Exposed resource        | Number of bison              | 19                         | P, R, S            |
|             |                         | Bison harvest                | 20                         | P                  |
| Extreme     | Event frequency         |                             | 31, 34i                    | S                  |
|             | Climate velocity        |                             | 34e, 34f, 34g, 34h         | S                  |
| Exposed     | Number of workers       |                             | 17                         | C, P               |
| population  | Geographic extent       |                             | 16, 28d                    | S                  |
| Sensitivity | Rangeland response      | Environmental variation      | 34i, 34j, 34k              | R                  |
|             | Bison carrying capacity |                             | 27b, 29, 35a               | P, R, S            |
| Bison       | Bison health            |                             | 27c, 27d, 27f, 27e, 34c, 34d| C, P, R, S        |
| response    | Herd production         |                             | 27g, 34a, 34b              | C, P               |
| Demographics| Markets for bison       |                             | 9, 11a, 11b, 27a, 28a, 28c| P                  |
|             | Age and gender of managers|                            | 2, 7                       | C                  |
| Adaptive    | Access to information   | Information exchange         | 35b, 35c, 35d              | R                  |
| capacity    | Experience and education|                             | 5, 37                      | C                  |
| Management  | Management plans        |                             | 15, 39, 42                 | R, S               |
| structure   | External revenue        |                             | 10, 11c, 11d, 28b          | P                  |
| Access to   | Grazing leases          |                             | 38                         | P                  |
| land        | Water access            |                             | 40, 41                     | R                  |

*See Supporting Information Table S1, Bison Manager Survey Questionnaire.
Most public/NGO bison herds (55%) were located in northern and central regions (82%) on shortgrass and mixed grass prairies (64%). Most private bison herds (65%) were also located in northern and central regions (81%) on shortgrass and mixed grass prairies (79%; Supporting Information Table S3). Combined, most private and public/NGO bison herds (64%) were located in the northern and central shortgrass and mixed grass prairies (Supporting Information Table S3).

| Attributes                  | Bison system sectors (n = 132) | Private (n = 121) | Public/NGO (n = 11) |
|-----------------------------|---------------------------------|------------------|---------------------|
| Gender                      |                                 | Most are male (82%) | Most are male (91%) |
| Male                        | 99                              | 10                |                     |
| Female                      | 19                              | 1                 |                     |
| Preferred not to answer     | 3                               | –                 |                     |
| Region                      |                                 | Most are from northern and central regions (81%) | Most are from the central region (64%) |
| Northern                    | 56                              | 2                 |                     |
| Central                     | 42                              | 7                 |                     |
| Southern                    | 17                              | 2                 |                     |
| Eastern                     | 6                               | –                 |                     |
| Ecosystem                   |                                 | Most are in mixed grass prairies (62%) | Ecoregions are equally distributed among tallgrass, mixed grass and shortgrass prairies (~33%) |
| Shortgrass                  | 21                              | 3                 |                     |
| Mixed grass                 | 75                              | 4                 |                     |
| Tallgrass                   | 10                              | 4                 |                     |
| Other                       | 15                              | –                 |                     |
| Education level             |                                 | Most have at least some college experience (83%) | Most have at least some college experience (91%) |
| Without college experience  | 20                              | 1                 |                     |
| With college experience     | 68                              | 7                 |                     |
| Graduate degrees            | 33                              | 3                 |                     |
| Management experience with bison | Management experience is balanced with a slight skew towards more than 4 years of experience | Management experience is bi-modal, split between less than 4 years and more than 20 years of experience |
| <4 years                    | 16                              | 4                 |                     |
| 4–10 years                  | 34                              | –                 |                     |
| 11–20 years                 | 36                              | 2                 |                     |

(Continues)
2.3 | Statistical analyses

All data visualizations and computations were performed in Stata/IC (v16.0, 2019, StataCorp). Slideplots (Stata Statistical Software Components package slideplot), which are similar to Likert graphs without neutral illustrated, were used to show relative perceptions of respondents' values, attitudes, practices and observations of various economic and ecological issues and techniques by sector. Finite population correction is 0.95 because we sampled from an estimated 15% of the bison manger population without replacement (Valliant & Dever, 2018). We used t tests to compare means between private and public/NGO sectors with $\alpha$ at $p < 0.05$.

3 | RESULTS

Total vulnerability, on a scale of 0 to 10—10 being the most vulnerable, codifies the average vulnerability score for the three dimensions of exposure, sensitivity and adaptive capacity that bison managers face regarding climate change. The average total vulnerability of the 132 respondents from the BMS was 4.1 (=moderately vulnerable) overall. However, individuals scored across the entire spectrum of vulnerability, ranging from 0.5 (=low to not at all vulnerable) to 9.5 (=highly vulnerable). The public/NGO and private sectors had similar total vulnerability values; 4.2 and 4.0 respectively (Figure 2). The utility of overlaying a radar plot on the vulnerability scoping diagram is to visualize differences among groups in each of the three dimensions of vulnerability. For each measure, the distance from the centre to the outer circle represents increasing vulnerability (e.g. from 0 to 10). Additionally, measures of significant difference between groups are indicated with double asterisks and double daggers.

Scores greater than five (=5.0) for these measures indicate that vulnerability of any coupled human–natural system to climatic change would be considered 'high', but the BMS scores as only 'moderately' vulnerable (4.1) to climate change. For each measure, there were high vulnerability scores in the public/NGO sector associated with one primary measure of exposure (bison herd size), three primary measures of sensitivity (herd production, other markets, age and gender) and two primary measures of adaptive capacity (external revenue, grazing leases). Similarly, there were high vulnerability scores in the private sector associated with two primary measures of exposure (bison population, and harvest), three primary measures of sensitivity (environmental variation, herd production, age and gender) and one primary measure of adaptive capacity (grazing leases; Figure 2).

3.1 | Exposure, sensitivity and adaptive capacity

Adaptive capacity was the only dimension of vulnerability that varied significantly between the two sectors (Figure 3). Public/NGO respondents had less adaptive capacity (median $= 6.0 \pm 1.8$;
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2.5–9.3; ≈highly vulnerable) than private sector respondents (median = 4.0 ± 2.1; 0–8.6; ≈moderately vulnerable; Table 3). Public/NGO respondents perceived slightly less exposure (median = 3.8 ± 1.4; 1.3–5.3) than private sector respondents (median = 4.2 ± 1.2; 1.3–7.3; Table 3). Public/NGO and private sector respondents had similar perceptions of sensitivity with 3.4 ± 1.9 (ranging 0–7.3) and 3.9 ± 1.5 (ranging 0–9.8) respectively (Table 3). Overall, exposure (4.2 ± 1.2) was perceived slightly less than sensitivity (3.8 ± 1.6). Means of exposure, sensitivity and adaptive capacity did not differ significantly across regions and ecosystem types (Supporting Information Figure S4).

Between public/NGO and private sectors, the largest differences in adaptive capacity were based on four measures: information exchange, external revenue, access to leased grazing lands and management plans (Figure 3). Information exchange—monitoring vegetation and wildlife diversity—was more prevalent in public/NGO (p ≤ 0.001). Management plans, specifically having or creating drought contingency plans, were more prevalent in the private than the public/NGO sector (p ≤ 0.04). Seventy-five percent (75%) of public/NGO managers had existing plans in place and an additional 9% in development, whereas only 45% of public/NGO managers had existing plans and an additional 18% in development. Managers in both sectors attempted to provide drinking water and to expand their access to grazing leases. However, the NGO sector accessed additional grazing leases for bison to a much greater extent than the public sector. A comprehensive description of the responses from bison managers that provided measures of vulnerability is presented in Supporting Information Table S4.

### 3.1.1 Educational level

An increase in formal education of managers corresponded to a lower vulnerability score. Estimated scores were 4.7 for those without

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**TABLE 3** Overall vulnerability scores and composition of dimension vulnerability scores by sector

| Sector       | Vulnerability score | N  | Median | SD  | Min | Max |
|--------------|---------------------|----|--------|-----|-----|-----|
| Private      | Overall vulnerability| 119| 4.0    | 1.3 | 0.5 | 9.5 |
|              | Exposure            | 115| 4.2    | 1.2 | 1.3 | 7.3 |
|              | Sensitivity         | 119| 3.9    | 1.5 | 0.0 | 9.8 |
|              | Adaptive capacity   | 119| 4.0    | 2.1 | 0.0 | 8.6 |
| Public/NGO   | Overall vulnerability| 11 | 4.2    | 1.9 | 1.3 | 8.6 |
|              | Exposure            | 10 | 3.8    | 1.4 | 1.3 | 5.3 |
|              | Sensitivity         | 11 | 3.4    | 1.9 | 0.0 | 7.3 |
|              | Adaptive capacity   | 11 | 6.0    | 1.8 | 2.5 | 9.3 |

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**FIGURE 3** Correlation between adaptive capacity and overall vulnerability scores for private (n = 119) and public/NGO (n = 11) sectors with kernel density plots illustrating overlapping distribution. Adaptive capacity scores differ significantly (p ≤ 0.005) between sectors, with private and public/NGO sector scores of 4.0 (moderately vulnerable) and 6.0 (highly vulnerable) respectively (Table 3).
college experience, 4.0 for those with college experience (some college experience or have attained a 2-year or 4-year degree), and 3.8 for those with a graduate degree. Vulnerability scores were linearly related to gender and management experience and education level \((n = 129, R^2 = 0.08, p \leq 0.001)\). A summary cross-tabulation of bison manager education level attainment and education discipline is provided in Supporting Information Table S5.

### 3.2 | Values, attitudes and practices

Adaptive capacity is the primary vulnerability dimension that differed between private and public/NGO sectors. This may primarily be a consequence of the administrative mandates that limit management activities of the public/NGO sector compared to the private sector. Overall, private and public/NGO bison managers share similar values and attitudes towards ecological integrity values (Figure 4) and economic diversification (Figure 5). Ecological integrity values was endorsed by 90% of public/NGO and 86% of private managers (Figure 4). Only 60% of public/NGO managers valued economic diversification, which was endorsed by 81% of private managers (Figure 5). However, when presented with various attitudes and practices for ecological and economic management techniques, consensus of affirmation declined within and between the sectors as described below.

Ecological attitudes were consistently affirmative in both sectors for hunting (70% positive), prescribed burning (72% positive), faecal...
analyses for diet and disease (84% positive), vaccinations (81% positive) and necropsies (83% positive; Figure 4). Treatment for intestinal parasites was more acceptable in the private sector (89% positive) than the public/NGO sector (66% positive). Both sectors were ambivalent about the use of genotypic and pedigree tools for breeding (53% positive). Private sector managers were more likely than public/NGO managers to treat parasites (91% vs. 36% affirmative), treat diseases (89% vs. 45% affirmative) and monitor spring green-up (93% vs. 64% affirmative).

Economic attitudes were less consistent than ecological attitudes in both sectors (Figure 5). Public/NGO sector managers viewed agricultural subsidies (such as tax credits) negatively (33% positive) but were open to cost sharing programs (78% positive), diverse livestock (78% positive) and diverse land use (100% positive). Private sector managers were divided on attitudes towards cost sharing (51% positive), agricultural subsidies (61% positive) and diverse livestock use (58% positive), but largely agreed with diverse land use (90% positive) and hunting on property (71% positive). Over 75% of private managers pumped drinking water and prepared drought management plans while also monitoring grasslands, bison pregnancy and survival of bison calves whereas only 50% of public/NGO managers implemented these practices.

4 | DISCUSSION

Grasslands and bison are co-evolutionarily dependent, and both will face further challenges from the effects of climate change and land use in the 21st century. Alternative strategies are required to enhance conservation of both grasslands and bison, and they may synergistically reinforce conservation efforts when integrated within the BMS. Private land ownership throughout the Great Plains represents a fundamental consideration that justifies exploration of a private land conservation framework to facilitate the simultaneous conservation of both grasslands and bison.

Survey responses indicated that private bison managers were ‘moderately vulnerable’ and exhibit ‘moderate adaptive capacity’ to climate change (Table 3), whereas previous studies have described cattlemen as ‘highly vulnerable’ (Joyce et al., 2013; Williamson et al., 2012; Wilmer et al., 2018). However, sole reliance on private bison managers is insufficient for a comprehensive bison and grassland conservation strategy. We found the public/NGO sector to be ‘moderately vulnerable’ to climate change, which was greater than the private sector (Table 3). The private and public/NGO sectors share common values and attitudes for bison conservation even though management practices vary (Figures 4 and 5).

Variation in adaptive capacity among the private and public/NGO sectors (Figure 2) originated from differences in management practices specific to each sector (Figures 4 and 5), not from ecoregional variation (Supporting Information Figures S2–S4). This is to be anticipated given the economic concern of private managers and the agency and federal mandates prescribed for public/NGO sectors. However, tensions between production and conservation goals may be surmountable based on their shared environmental values and attitudes and high level of education. Higher levels of education of bison managers may be key to reducing vulnerability in two ways: (a) education increases the ability to seek, sort and apply new information from multiple sources (Supporting Information Table S4), and (b) education also increases the ability to generate external income that diversifies revenue streams (Supporting Information Figure S5). Education facilitates information exchange through social networks and associations beyond the bison system, which may be critical to recruitment of new private sector managers and the development of additional adaptive capacity (Table 1).

Here, we propose that the BMS should be further organized into a bison management coalition to collective mitigate and adapt to accelerating challenges throughout the region, especially climate change. Formal comprehensive integration of the robust, nascent multi-sector BMS into a bison management coalition could potentially resolve tensions between the conservation and production goals and collectively reduce system wide vulnerability. For example, enhanced collaboration may promote development of regional drought adaptation plans that seek to strategically destock and re-stock bison populations between and among sectors and regions. This strategy may minimize non-harvest, lethal culling practices and promote non-lethal, translocation culling practices that potentially enhance and share operational costs by increasing external revenue for the public/NGO sectors. Bison conservation goals may be enhanced by the transfer of animal genetics from public herds to non-public (i.e. private, NGO and Tribal) herds that may increase both meta-population size and bison production. This represents the implementation of conservation-oriented bison strategies that conserve unique genetic traits in public herds while sustaining the meta-population.

Examples currently exist for inter-sector and inter-agency management coordination (Table 4). These examples illustrate the extent and complexity of current interactions among sectors that may serve as the foundation for a more formal bison management coalition. Cross-sector coordination may greatly enhance bison population regulation by facilitating animal distribution and improve development and implementation of management plans and strategies. Bison exchange among sectors will inevitably increase the potential for disease and parasite transmission, but a system wide monitoring program could minimize regional exposures. Moreover, monitoring diseases and parasites across sectors would improve zoonotic exchange for other wildlife species, such as pronghorn antelope (Antilocapra americana) and elk (Cervus canadensis). Minimizing the extent, and therefore cost, of culling bison safely (i.e. free of diseases and parasites) will increase the overall conservation of the species in their native grassland habitats.

Gray et al. (2020) describes the surprisingly accurate solutions derived from utilizing the collective intelligence of stakeholders for solving environmental and conservation challenges. Sharing cross-sector experiences, potential problems and outcomes of various management strategies across the BMS would enhance cross-site analyses and assist in establishing adaptive management strategies.
for various environmental change scenarios. Those BMS stakeholder collective intelligence experiences may elucidate novel, scalable solutions for integrated conservation and production solutions that re-couple the ecologically and evolutionarily bison-dependent grasslands in the Great Plains—where these grasslands are 90% privately owned and bison are 85% privately owned. Coordination of these shared experiences, varied outcomes and collective intelligence would benefit from targeted, interdisciplinary research approaches. For decades past, bison research has been conducted independently with some level of redundancy in some disciplines, neglect in others and often lack cross-cutting interdisciplinary studies (Huntington et al., 2019). Concentrating the disparate research efforts will help to increase efficiency and enhance stakeholder participation and outreach of newly generated information. Concerted efforts to fully collaborate among stakeholders of the BMS and various research groups may assist to formalize the robust, nascent multi-sector BMS into a bison management coalition that functions at the intersection of the North American Model for wildlife management (i.e. conservation) and of conventional livestock agriculture (i.e. production). The complementary, shared environmental values and attitudes that currently exist among the private and public/NGO sectors help shape the foundation for enhanced organization and collaboration among the multi-sector BMS. This coalition may function as a ‘learning community’ in which sharing experiences and diversity of practices, goals and values may contribute to the discovery of credible, scalable adaptive solutions to climate change.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHORS’ CONTRIBUTIONS

J.M.M. and P.S.B. conceived the ideas and designed methodology; J.M.M. collected the data. All authors interpreted and analysed the data, and drafted, revised and approved the final manuscript for publication.

DATA AVAILABILITY STATEMENT

Data are available on figshare https://doi.org/10.6084/m9.figshare.12230381.v2 (Martin et al., 2021).

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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