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Gatekeepers of transformation: private landowners evaluate invasives based on impacts to ecosystem services

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Abstract. Biological invasions are not new, yet the anthropogenic drivers of global change have produced unprecedented ecological novelty through the expansion of invasive species. Private landowners play an important role in determining the trajectory of ecological transformations driven by invasives. Using the northern Great Plains of the USA as a case study, we examined private landowners' role as gatekeepers for an invasive species. We employed a factorial vignette survey experiment to understand how the impacts of an unnamed invasive grass modeled on Kentucky bluegrass (*Poa pratensis* L.) were related to landowners' acceptance of the species. We also explored the relationship between landowners' acceptance of the invasive grass and their management intention to reduce/control the species. Each landowner evaluated multiple vignettes that randomly varied based on how a novel grass species expanding in rangelands would affect provisioning services (season of forage availability, forage quality, forage quantity), regulating services (floral resources for pollinators, water infiltration and availability), and supporting services (grassland bird diversity, grass diversity). Acceptability was strongly associated with landowners' management intentions, and the status of all seven services was related to acceptability. Reductions to any ecosystem service reduced the acceptability of the invasive grass species; however, only increases in forage quality, forage quantity, and water regulation were related to increased acceptability of the invasive. Scenario modeling shows that landowners displayed greater sensitivity to losses in a suite of ecosystem services than to equivalent gains. Scenarios specific to ecosystem service trade-offs and Kentucky bluegrass invasion indicate that ecological losses may need to be severe before individual landowners change their management practices to reduce/control the species. Given the high thresholds for individual behavioral change, engaging private landowners in collaborative management efforts, whether to control an invasive grass or guide management toward co-existence, may be helpful to conserve desired biodiversity and the flow of ecosystem services from northern Great Plains grasslands.

Key words: ecosystem services; factorial survey experiment; grasslands; invasive species; *Poa pratensis*; private lands; prospect theory; rangelands.

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Introduction

As key drivers of ecosystem transformation, invasive species are typically considered a detriment to human and environmental well-being. Invasives can significantly impact ecosystem structure and function in ways that reduce biodiversity, alter long-term processes such as nutrient cycling and disturbance regimes, and diminish overall ecological productivity (Mooney 2005, Richardson and Gaertner 2013, Shackleton et al. 2019*b*). However, invasive species also give rise to ecological novelty that may have both cultural and ecological value (Kull et al. 2012). There is an increasing emphasis on the functional roles of species rather than their origins, prompting calls to more objectively and inclusively investigate how invasive species influence ecosystem functions and services (Bonanno 2016, Head 2017). Understanding how people perceive species invasions, and how these perceptions relate to management behavior, is a priority for invasion science and associated environmental management and conservation (Shackleton et al. 2019*a*).

When uncertainty exists around the impacts of an invasive, individuals may respond to it based on their perceptions of how the species affects the ecosystem goods and services they value. Alteration of ecosystem services resulting from the expansion of an invasive species may be perceived as positive or negative depending on both individual and culturally held values toward biodiversity and conservation, as well as people's view on the appropriate relationship between humans and nature (Bennett et al. 2017, Klain et al. 2017, Backstrom et al. 2018). Instrumental and utilitarian values are also important, particularly for resource users and local communities, as invasive species can have significant positive and negative impacts on local livelihoods and influence overall well-being (Shackleton et al. 2019*b*, *c*). Debates over invasive species exemplify wicked problems as the social and ecological costs and benefits of an invasive species and its potential eradication can be culturally and politically complex and highly contested (Game et al. 2014, Santo et al. 2015, Woodford et al. 2016). Consideration of the perceptions, preferences, and social–ecological outcomes experienced by stakeholders is imperative to the legitimacy, acceptability, and overall effectiveness of invasive species management (Santo et al. 2015, Bennett 2016, Bonanno 2016, Shackleton et al. 2019*a*, *b*).

Grasslands are globally important for human livelihoods and well-being, yet little is known about the human dimensions of invasive grasses (Asner et al. 2004, Shackleton et al. 2019*c*). Natural grasslands, often managed as native rangeland to support livestock grazing, are undergoing dramatic compositional shifts as native species increase in abundance or expand beyond their historic range, and as non-native species are introduced and achieve dominance (Archer et al. 2017, Bengtsson et al. 2019). Grasslands account for nearly one-third of the earth's terrestrial surface and are often biodiversity hotspots where human well-being has been closely coupled with biophysical conditions for millennia through livestock grazing and pastoral livelihoods (Safriel and Adeel 2005, Egoh et al. 2016, Bengtsson et al. 2019). While commonly associated with provisioning services such as the production of plant biomass for use as animal fodder, grasslands provide a wide range of additional services (Havstad et al. 2007). For example, grasslands regulate and purify water resources, contribute to climate regulation, prevent erosion, produce wild foods and medicinal resources, provide habitat for pollinator species, control biological pests, and produce an array of cultural services from recreational and aesthetic values to foundational aspects of people's livelihoods and identities (Safriel and Adeel 2005, Egoh et al. 2016, Bengtsson et al. 2019).

Using a case study of grasslands in the northern Great Plains of the USA, we investigated conditions under which private landowners facilitate or impede the spread of an invasive grass. Agriculture plays a large role in the history, culture, economy, and landscape of the northern Great Plains (Conant et al. 2018). Despite substantial conversion to cropland and areas of planted pasture, this region contains North America's largest remaining tracts of native rangeland (Conant et al. 2018, Hendrickson et al. 2019). Surrounded by a backdrop of land conversion and intensive management, invasive plants such as Kentucky bluegrass (*Poa pratensis* L.) are expanding on native rangelands and driving shifts in native plant communities with the potential to alter ecosystem structure, function, and the provision of services (DeKeyser et al. 2009, Toledo et al. 2014, Hendrickson et al. 2019). In rangelands, agricultural producers who operate farms and ranches are uniquely poised to both create and consume ecosystem services at multiple spatial scales (Swinton et al. 2007, Huntsinger and Oviedo 2014, Kragt and Robertson 2014, York et al. 2019). Previous research on agricultural producers highlights the importance of provisioning ecosystem services directly related to an operation's profitability (Swinton et al. 2007, 2015, Robertson et al. 2014). For example, ranchers tend to prioritize provisioning services related to forage production for livestock in their conservation and management efforts; however, this agricultural focus does not necessarily preclude managing for other ecosystem services (Roche et al. 2015, Aoyama and Huntsinger 2019, York et al. 2019). The human dimensions associated with invasive grasses remain far less understood than the ecological impacts of the invader, and ecosystem services are a useful entry point for such inquiry. Additionally, although there have been increasing efforts to identify the ecosystem services important to landowners, there remains a need to better understand how perceptions about ecosystem services relate to land management decisions (York et al. 2019).

We use an ecosystem service lens to investigate how large-acreage, agricultural landowners perceive and respond to invasive grasses. While most efforts to quantify trade-offs between ecosystem services consist of biophysical (Kragt and Robertson 2014, Eastburn et al. 2017) or economic approaches (Swinton et al. 2007, Lester et al. 2013), our social–psychological approach provides insight into the judgment processes that connect beliefs about ecosystem services to management actions via a landowner's judgment of acceptability (Fishbein and Ajzen 2010). Specifically, we examine the relationship between a landowner's acceptance of an invasive grass and how the grass affects ecosystem services. We then relate judgments of acceptability to landowner management intentions to either control, promote, or not actively manage the species. Based on these results, we model landowners' expected responses to an invasive grass under multiple scenarios of ecosystem service outcomes and trade-offs.

The impetus for this research is the expansion of Kentucky bluegrass (*Poa pratensis* L.) throughout the northern Great Plains of the USA. Scientific knowledge is increasing but the extent of ecological impacts on grasslands in this region remains uncertain and the nature of social impacts and perceptions are unknown (Toledo et al. 2014, Gasch et al. 2020). We used Kentucky bluegrass as a model to develop vignettes about a novel grass expanding in native rangelands. Through a factorial survey experiment, we asked landowners how they would respond to the grass based on its impact to ecosystem services. The experimental design of this vignette approach enables insight into perceptions about Kentucky bluegrass and the underlying processes that drive landowners' judgments and decisions about invasive grasses in general (Wallander 2009, Auspurg and Hinz 2015).

Materials and Methods

Study area

A microcosm of the northern Great Plains, North Dakota contains a wealth of agricultural and natural resources. Significant Euro-American colonization and settlement began in the later 19th century, spurred by the 1862 Homestead Act and western expansion of railroads (Remele 2020). Currently, agricultural production of crops and livestock is the state's largest industry and approximately 90% of North Dakota is privately owned as farms and ranches (USFWS 2019, NDDA *n.d.*). North Dakota is also renowned for waterfowl and wildlife and provides essential breeding habitat and key migratory areas for many wetland-dependent migratory bird species (USFWS 2019). Our study was based in nine counties that create an east–west transect spanning the state's four primary ecoregions to capture major variations in precipitation, regional geography, and primary land use (Fig. 1). In the four arid, westernmost counties (Golden Valley, Billings, Stark, and Morton County), predominant land uses are livestock grazing on the native shortgrass rangelands as well as some production of spring wheat and alfalfa (Bryce et al. 1996, USDA-NASS 2019). The central counties (Burleigh, Kidder, Stutsman, and Barnes County) contain a high density of permanent and seasonal wetlands and land use transitions from livestock production to intensive dryland farming as precipitation increases to the east (Bryce et al. 1996). The easternmost portion

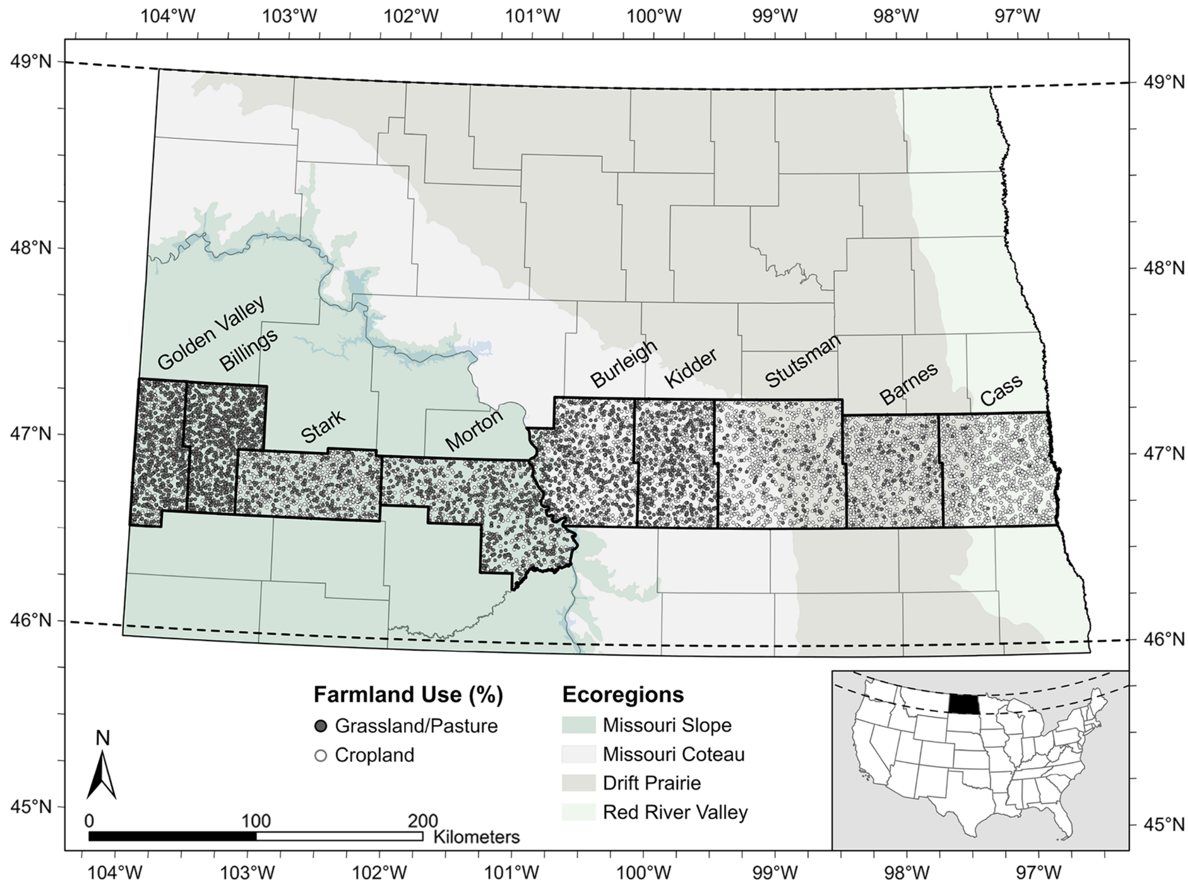

Fig. 1. The nine-county study area in North Dakota. The proportion of farmland, per county, that was used as grassland/pasture or cropland according to the 2017 Census of Agriculture (USDA-NASS 2019) is illustrated by a dot density plot (1 dot = 0.1%). Level III ecoregion boundaries, as defined by the U.S. Environmental Protection Agency (Bryce et al. 1996), are color coded and listed by common name (NDGF 2019).

of the study area, Cass County, is characterized by very flat, fertile, highly productive farmland (Bryce et al. 1996).

Across the study region and the broader northern Great Plains, concern is growing among rangelands managers and scientists about the potentially negative ecological consequences of Kentucky bluegrass (DeKeyser et al. 2009, Toledo et al. 2014, Hendrickson et al. 2019, Gasch et al. 2020). Bluegrass is a perennial, cool-season (C_3) grass that emerges from dormancy earlier in the spring than many of its native cool-season counterparts and most warm-season (C_4) grasses (Toledo et al. 2014, Hendrickson et al. 2019). Potential negative impacts include its characteristic formation of a dense thatch layer of living and dead plant material that alters microclimate at the soil surface and may affect hydrologic functions such as water infiltration and overland flow (Toledo et al. 2014, Gasch et al. 2020). As Kentucky bluegrass invasion progresses, it can suppress the growth of native grasses and forbs leading to a monoculture. Diminished floral diversity as a result of Kentucky bluegrass invasion can negatively impact native pollinators (Bendel et al. 2019) and grassland obligate butterflies (Kral-O'Brien et al. 2019). Grassland obligate birds are also sensitive to diminished plant diversity and the homogenization and simplification of rangelands that may result from Kentucky bluegrass expansion (Toledo et al. 2014, Hovick et al. 2015). Bluegrass expansion can shorten the potential grazing season for livestock as it displaces warm-season grasses, such as blue grama

(*Bouteloua gracilis*), that would become more prominent and available as forage once Kentucky bluegrass and other cool-season species become dormant (Gasch et al. 2020).

Despite growing concern among rangeland scientists, Kentucky bluegrass has a number of characteristics that may be considered beneficial to different rangeland users and has not been considered a management priority to most agricultural producers (Gasch et al. 2020). Kentucky bluegrass is tolerant of grazing disturbance, can provide high-quality forage in the spring, and has been used to stabilize soil against erosion (Huff and Bara 1993, Toledo et al. 2014, Olson et al. 2016). The severity of potential ecological impacts has considerable implications for the ecological and agricultural sustainability of northern Great Plains rangelands and underscores the need to better understand how people perceive invasive grasses.

Sampling and survey administration

We focused on large-acreage landowners as key actors whose management decisions can have substantial landscape-scale consequences. Although the distinction of what constitutes large acreage may vary greatly depending on location, the USDA's Census of Agriculture categorizes farm holdings of 1000 acres or more as their largest category (USDA-NASS 2019). Recognizing that any landholding size cutoff is somewhat arbitrary, we used this threshold to define large-acreage landowners in our research. This enabled us to approximate the total population of large-acreage landowners within our nine-county study area using Census of Agriculture data and design a sampling scheme to achieve a ±5% margin of error for true population values assuming maximum heterogeneity in responses (Dillman et al. 2014). Based on expected response rates, we randomly selected 142 landowners from each county for a target sample of 1278 landowners. This ensured geographic distribution across the study region to account for the transition of land use from primarily rangeland and livestock in the west to predominately crop production in the east (USDA-NASS 2014, 2019). To create the sampling frame for landowner selection, we obtained the 2019 public property records from each study area county and screened records to include only private landowners with at least 1000 acres of land. Two counties had fewer than 142 eligible landowners reducing our sample size to 1243. After USPS address validation, our sample size was 1219 landowners, still within our goal to achieve a ±5% margin of error.

We followed a modified tailored design approach using a 5-wave mail survey over seven weeks in November and December of 2019 (Dillman et al. 2014). Survey mailings consisted of an introductory letter (day 1), survey packet (day 7), thank you/reminder postcard (day 14), replacement survey packet to non-respondents who had not opted out (day 36), and a final reminder letter to remaining non-respondents (day 50). This research was approved by the Virginia Tech Institutional Review Board (19-312) and the U.S. Office of Management and Budget (# 0518-0048).

Survey design

We employed a factorial vignette survey experiment embedded in a self-administered mail survey about landowners' management practices and rangeland preferences. Factorial vignette experiments ask respondents to evaluate a series of scenarios describing variation across a particular phenomenon (Jasso 2006). Our phenomenon of interest was a new grass species expanding onto native rangeland and our vignettes focused on the impacts of the novel species across seven ecosystem services. Vignette survey experiments combine the robustness and internal validity of an experiment with the ability to attain a large sample and capture geographic and socioeconomic variability through survey research (Kinsbergen and Tolsma 2013). This approach reduces social desirability bias because it identifies determinants of decision-drivers that respondents may not be fully aware of, and allows researchers to quantify and isolate the influence of different factors and their trade-offs (Wallander 2009, Andorfer and Otte 2013, Auspurg and Hinz 2015).

The vignettes varied based on how a new grass species would affect seven ecosystem service attributes: season of forage availability, forage quality, forage quantity, floral resources available for pollinators, water infiltration and availability, diversity of grassland birds, and diversity of other grasses (Table 1). The evaluation of seven attributes follows best practices for vignette experiments to ensure consistency and reliability

Table 1. The ecosystem service attributes and levels in the vignette survey experiment.

Ecosystem service	Levels	Vignette text
Provisioning services		
Season of forage availability	(1) Early season	Provides palatable forage for livestock only early in the grazing season (April and May)
	(2) Summer season†	Provides palatable forage for livestock only during the summer grazing season (June, July, August)
	(3) Late season	Provides palatable forage for livestock only late in the grazing season (September, October, November)
Forage quality	(1) Decrease	Provides lower than average (25% less crude protein) quality forage for livestock during the primary growing period of this species
	(2) No change†	Provides average (in terms of crude protein) quality forage for livestock during the primary growing period of this species
	(3) Increase	Provides higher than average (25% more crude protein) quality forage for livestock during the primary growing period of this species
Forage quantity	(1) Decrease	Produces a lower than average (25% less) yield in terms of lbs/acre
	(2) No change†	Produces an average yield in terms of lbs/acre
	(3) Increase	Produces a higher than average (25% more) yield in terms of lbs/acre
Regulating services		
Floral resources	(1) Decrease	Leads to a considerable decrease (loss of 15%) in the amount of floral resources that provide pollen and nectar for pollinator species
	(2) No change†	Does not change the amount of floral resources that provide pollen and nectar for pollinator species
	(3) Increase	Leads to a considerable increase (gain of 15%) in the amount of floral resources that provide pollen and nectar for pollinator species
Water infiltration and availability	(1) Decrease	Considerably decreases (loss of 20%) water infiltration into the soil and the amount of water available to other plants
	(2) No change†	Does not change water infiltration into the soil and the amount of water available to other plants
	(3) Increase	Considerably increases (gain of 20%) water infiltration into the soil and the amount of water available to other plants
Supporting services		
Grassland bird diversity	(1) Decrease	Leads to a considerable decrease (loss of 3–5 species) in the variety of grassland birds
	(2) No change†	Does not change the variety of grassland birds
	(3) Increase	Leads to a considerable increase (gain of 3–5 species) in the variety of grassland birds
Grass diversity	(1) Large decrease	Greatly decreases (loss of 50% or more) the diversity of other grasses
	(2) Moderate decrease	Moderately decreases (loss of 20%) the diversity of other grasses
	(3) No change†	Has no effect on the diversity of other grasses

† The status quo level for each ecosystem service.

in judgment measurement (Auspurg and Hinz 2015). Each attribute had three different levels creating a balanced design. This minimizes potential response bias related to differences in the complexity of attributes and permits the exploration of nonlinear relationships between each attribute and the dependent variable (Auspurg and Hinz 2015). We employed an incomplete block experimental design using 28 vignettes randomly selected out of the 2187 (or 3^7) possible combinations. To reduce the cognitive burden on respondents, the 28 vignettes were blocked into seven survey versions so that each landowner only evaluated a subset of four randomly selected scenarios (Auspurg and Hinz 2015).

We selected ecosystem service attributes and levels that were agriculturally and ecologically salient in the region, within the domain of realistic outcomes for an invasive grass such as Kentucky bluegrass, and characteristics that commonly vary among grass species. We began vignette development with a scientific literature review (e.g., Toledo et al. 2014) and preliminary interviews with landowners and rangeland experts (n = 20) to identify the ecosystem services that Kentucky bluegrass may alter in grasslands. We then iteratively pretested vignettes and consulted with landowners and experts (n = 23) to ensure that the attributes and levels were salient, provided detail and variation sufficient for respondents to consider trade-offs, resulted in realistic potential outcomes of an invasive grass, and spanned multiple ecosystem service categories (MEA 2005, Wallander 2009, Auspurg and Hinz 2015). Cultural ecosystem services are an important aspect of grasslands and rangelands, particularly for those with agricultural livelihoods (Bengtsson et al. 2019). However, preliminary interviews and pretesting indicated that landowners viewed cultural services, such as sense of place, as an outcome of other services. This is consistent with the conceptualization of an ecosystem service cascade that culminates in cultural services, as well as the consideration of cultural ecosystem services as emergent and relational, rather than purely intrinsic or extrinsic (Chan et al. 2016, Fish et al. 2016). This perceived hierarchy and interdependence led to attribute combinations that landowners considered confusing or impossible to answer. To maintain the psychological realism recommended for vignette experiments (Auspurg and Hinz 2015), we did not include any cultural ecosystem service attributes and instead focused on provisioning, regulating, and supporting services.

Each attribute contained three levels, one of which was a status quo condition. For most services, the remaining two levels represented a decrease or increase in the service. However, levels for season of forage availability were spring, summer (status quo), or fall grazing season and levels for grass diversity were greatly decreased, moderately decreased, or no change (Table 1). Each attribute level was characterized with both a descriptive (e.g., greatly decreases) and a quantitative identifier (e.g., loss of 50% or more) to calibrate the respondent's mental models of what, for example, constitutes a considerable change or what is meant by the early grazing season. This precision improves clarity and consistency in interpretations of each attribute level, thus helping standardize responses (Auspurg and Hinz 2015). The numeric quantities in each level consist of estimates derived from the literature and expert opinion of rangeland specialists in the area.

Each vignette began with a static introductory statement that employed neutral phrasing to introduce the respondent to a new grass species expanding onto native rangeland that, once established, would have particular outcomes on their land (Box 1). This characterizes common definitions of invasive species related to both impacts (IUCN 2000) and spread (Richardson et al. 2000) without introducing the potential bias that may be associated with the value-laden label of invasive species or ecosystem services (Larson 2005). We presented the outcomes in a bulleted list format to mitigate the potential primacy and recency effects of a fixed attribute order in running text (i.e., paragraph format; Auspurg and Hinz 2015). Additionally, the bulleted list is similar to the format of common plant identification descriptions that agricultural landowners are likely familiar with, which may reduce cognitive burden on respondents (Auspurg and Hinz 2015). We used bold text to support information intake by indicating where variation in each attribute occurred (Shamon et al. 2019).

Box 1.

Example of a vignette used in the survey. Each landowner evaluated four unique vignettes.

Description of grass 1

A new grass species is expanding onto your native rangelands. Based on current scientific research and the best available information from other landowners, you know that once established this grass:

1. Leads to a considerable decrease (loss of 3–5 species) in the variety of grassland birds.
2. Doesn't change the amount of floral resources that provide pollen and nectar for pollinator species.
3. Doesn't change water infiltration into the soil and the amount of water available to other plants.
4. Provides higher than average (25% more crude protein) quality forage for livestock during the primary growing period of this species.
5. Provides palatable forage for livestock only late in the grazing season (September, October, November).
6. Greatly decreases (loss of 50% or more) the diversity of other grasses.
7. Produces a lower than average (25% less) yield in terms of lbs/acre.

For each vignette, landowners rated the acceptability of the new species on their rangeland and indicated their intention to manage the species by focusing on decreasing or controlling it, actively maintaining or increasing it, or not changing their current management. Landowners rated acceptability on a 7-point Likert-type scale where 1 = extremely unacceptable, 4 = neither acceptable or unacceptable, and 7 = extremely acceptable. Management intention for the grass species was rated on a 7-point Likert-type scale where 1 = definitely reduce/control, 4 = would not change current management, and 7 = definitely promote/maintain. Because we were interested in understanding the intention to reduce or control the species, we reverse coded the management intention scores to aid in interpretation.

Data analysis

Survey respondents were classified in three ways: (1) respondents who skipped the vignette experiment entirely, (2) respondents who participated in the vignette experiment but did not express variation in their responses, and (3) respondents who participated in the vignette experiment and provided variation in their responses (Appendix S1: Fig. S1). Landowners in these groups may systematically differ in ways which could affect the generalizability of results from the vignette experiment. We investigated the potential for systematic differences between landowners who skipped the vignette experiment and those who participated in the vignette experiment using *t* tests and chi-square tests to explore differences between land ownership and land use characteristics of the two groups.

Similarly, we were concerned that respondents who participated in the vignette experiment but provided the same response to each vignette may systematically differ from respondents who expressed variation in their responses. We considered respondents who evaluated at least two vignettes and expressed variation in their responses to be conditional responders. We considered respondents to be unconditional responders if their ratings of acceptability or management intentions did not vary across the vignettes they evaluated. Although unvarying answer patterns across vignettes are sometimes treated as protest responses (Champ et al. 2003) and can be related to cognitive satisficing (Shamon et al. 2019), we recognize that unconditional responses can also reflect valid opinions. For instance, a landowner who values native rangelands with historical fidelity to pre-European conditions may reject all new species. Similarly, landowners who are not heavily dependent on their rangelands may espouse a consistently neutral stance on new grass species. We used *t* tests and chi-square tests to explore differences in land ownership and land use characteristics between conditional and unconditional responders.

To model responses to vignettes, we used multi-level mixed models with a random effect to control for error associated with repeated measurements of individuals (Degenholtz et al. 1999, Auspurg and Hinz 2015). This model allows individual thresholds to vary randomly for respondents via random intercepts, but assumes that the effect of each independent variable is the same across individuals (i.e., fixed slopes). This reflects judgment processes shared by respondents, while accounting for individual differences in judgment thresholds through the random intercept (Wallander 2009, Andorfer and Otte 2013, Auspurg and Hinz 2015).

Because management response is a behavioral intention and acceptability is an evaluation that informs intention (Fishbein and Ajzen 2010), we considered acceptability to represent an attitude and first regressed management response on acceptability. Our second model regressed acceptability on ecosystem services. We modeled forage quality, forage quantity, and water infiltration as linear continuous variables. We treated forage availability and grass diversity as ordinal categorical variables and, based on data exploration, we modeled floral resources and bird diversity as nonlinear continuous variables. We examined the possible effects of survey version and vignette order on responses and found no statistical significance (Auspurg and Hinz 2015). We present our models without these control variables.

Using the acceptability model, we then estimated expected acceptability ratings of a new grass species under key ecosystem service scenarios representing maximum potential gain, maximum potential loss, and trade-offs between provisioning, regulating, and supporting services. We also considered three scenarios specific to Kentucky bluegrass at early, moderate, and advanced stages of invasion. Finally, we related these expected values for the acceptability of each scenario back to the management intention model.

In our analysis, we were cognizant that simply removing unconditional responders may eliminate valid responses. Instead, we created acceptability and management intention models for two samples, a conditional responder-only sample and a pooled sample including both conditional and unconditional responders. Our results focus on the sample of conditional responders because our goal is to understand and explain variation in acceptability and management intentions. The analysis of the pooled sample including unconditional responders is provided in Appendix S1 as a sensitivity analysis to understand the effect of unconditional responders on the models.

Results

Descriptive results

Of the 1219 landowners invited to participate in this study, 55 were ineligible (e.g., undeliverable address, deceased, had sold land, etc.) adjusting our initial sample size to 1164 people. We received contact from 509 landowners, and 373 of them completed the survey. Although the selection criteria for our random sampling scheme were based on public property records for landowners who owned at least 1000 acres, 25 landowners who completed the survey indicated they owned less than 1000 acres. We implemented an additional inclusion criterion based on total acres operated and included 17 of the 25 landowners who had total operations between 598 and 4640 acres (see Appendix S1: Fig. S2 for additional detail). Accounting for this, we received a survey response rate of 32% (n = 365) based on a final adjusted sample size of 1156 landowners.

Approximately 75% of survey respondents provided useable responses to the vignette study (n = 269). Vignette respondents indicated that they primarily used their land for livestock production (40%), followed by crop production (27%), and mixed crop and livestock production (21%). On average, these landowners earned the majority of their income (69%) from activities on their land. Most resided full time on their land (73%) and had inherited or acquired their land from their family (68%). Compared with these landowners, those who opted out of the vignette experiment placed a lower emphasis on rangelands and livestock production, and were less likely to consider themselves to be a rancher (see Appendix S1: Tables S1, S2). They operated a greater proportion of cropland and placed a higher emphasis on crop production than vignette responders. Vignette non-respondents were less engaged with their land in terms of decision-making and involvement in land management. They also leased out a greater proportion of their land, consisted of a greater number of retirees no longer working, and were more likely to report net annual incomes over $100,000.

For landowners who completed the vignette experiment, about 75% were conditional responders who expressed variation in either their acceptability rating (n = 206) or management intention (n = 193) across at least two vignettes (Fig. 2). The remaining 25% of vignette respondents were unconditional responders who did not express any variation in their responses. Most unconditional responders consistently responded that the new grass was neither acceptable nor unacceptable (59%) and that they would not change their current management (71%; see Appendix S1: Fig. S3). A smaller proportion of unconditional responders consistently rated the new grass as unacceptable, to some degree (27%), and consistently indicated management intentions to reduce/control it (20%). Unconditional responders included more landowners who used their land primarily for crop production and expressed less dependence on rangelands for livestock than conditional responders (Appendix S1: Tables S3, S4). While these differences limit the generalization of results, it suggests that the salience of invasive grasses in rangelands may vary among agricultural landowners in this sample area.

Modeling management intentions and acceptability

Although we focus on the sample of conditional responders, the results from the pooled sample of both conditional and unconditional responders display similar but slightly dampened estimates for both the acceptability and management intention models (Appendix S1: Tables S6, S7). These estimates are likely muted by reduced variation in responses from the majority of unconditional responders who considered the new grass neither acceptable nor

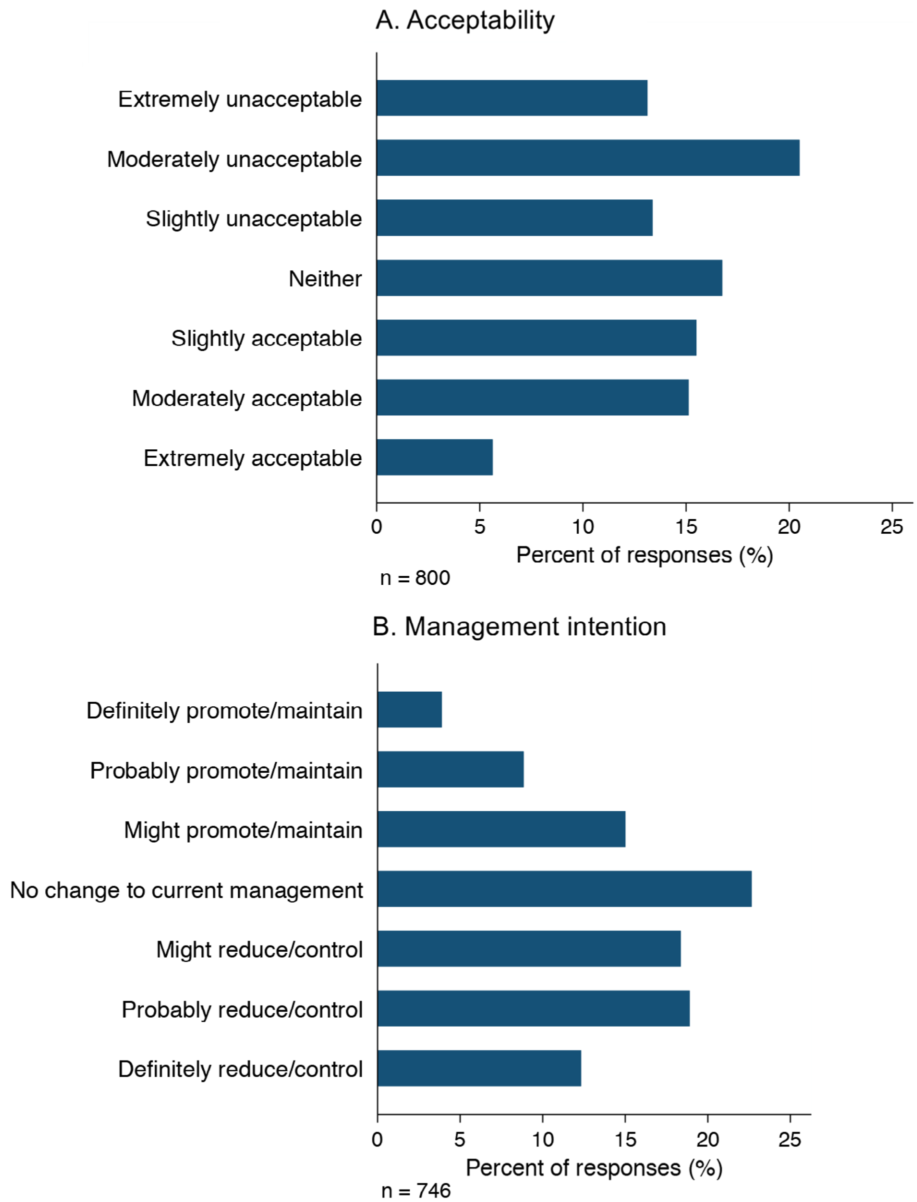

Fig. 2. The distribution of acceptability ratings (A) and management intentions (B) across all vignettes for conditional responders.

unacceptable and indicated that they would not change their current management. Results from the pooled sample provide a conservative estimate of the relationship between changes to ecosystem services and acceptability, and acceptability and management intentions.

Management intention mixed model.—There was a strong, inverse relationship between a landowner's evaluation of the acceptability of a new grass species and their management intention to reduce or control the species on their rangelands (Wald $\chi^2_{(1)}$ = 2166.32, P <0.001, R^2 = 0.753, ICC = 0.170). Acceptability explained 75% of the variation in management intentions. Each one-level decrease in acceptability, such as moving from slightly unacceptable to moderately unacceptable, relates to a 13% increase in the intention to reduce or control the species (b = −0.77, standard error = 0.02, $P < 0.001$). Given the strong relationship between acceptability and management intentions, we focus on explaining acceptability.

Acceptability mixed model.—All ecosystem service attributes significantly contributed to the acceptability model indicating that each of these services plays a role in landowners' judgments about a new grass species (Wald $\chi^2_{(11)} = 349$, $P < 0.001$, $R^2 = 0.246$, ICC = 0.286). The seven ecosystem services accounted for 25% of variation in landowners' acceptability ratings. To understand the individual effect of each service, we used the model to estimate the acceptability of a new grass that has no effect on the ecosystem services (i.e., all services are at status quo levels). We considered this scenario as a baseline. Baseline acceptability is 4.7, between 4 = neutral and 5 = slightly acceptable on a 7-point Likert-type scale (Fig. 3A–G, gray lines).

1. *Provisioning services.*—Provisioning services included season of forage availability, forage quality, and forage quantity. Compared with the status quo of summer forage availability, landowners found grasses that are only available in the spring less acceptable ($b = -0.30$, $z = -2.51$, $P = 0.01$) but did not differ in preference for fall availability compared with summer ($b = -0.03$, $z = -0.26$, $P = 0.79$; Fig. 3A). Landowners preferred increases in both forage quality ($b = 0.45$, $z = 7.63$, $P < 0.01$; Fig. 3B) and quantity ($b = 0.38$, $z = 6.52$, $P < 0.01$; Fig. 3C).

2. *Regulating services.*—Changes to floral resources for pollinators were nonlinear ($b = 1.84$, $z = 4.40$, $P < 0.01$; $b^2 = -0.35$, $z = -3.38$, $P < 0.01$; Fig. 3D), meaning that responses to increases and decreases were asymmetrical. Controlling for changes in other attributes, a 15% increase in floral resources relates to an expected increase in acceptability of 0.09 from the baseline, remaining near slightly acceptable (4.8). However, if floral resources decrease by 15%, the expected acceptability decreases by 0.79 dropping below neutral. Thus, the effect of diminished pollination services is potentially eight times greater than the effect of an increase. Water infiltration and availability, however, was symmetrical and landowners preferred increases ($b = 0.55$, $z = 9.40$, $P < 0.01$; Fig. 3E).

3. *Supporting services.*—A nonlinear relationship between acceptability and grassland bird diversity ($b = 1.48$, $z = 3.50$, $P < 0.01$; $b^2 = -0.31$, $z = -2.98$, $P < 0.01$) indicates that landowners were largely indifferent to an increase in 3–5 species (expected change in acceptability = −0.07), but found a decrease in 3–5 bird species unacceptable (expected change in acceptability = −0.55; Fig. 3F). Compared with the status quo of no change, landowners found decreases in the diversity of grass species to be unacceptable at both moderate ($b = -0.61$, $z = 5.10$, $P < 0.01$) and high levels ($b = -0.95$, $z = -8.07$, $P < 0.01$; Fig. 3G).

4. *Acceptability of ecosystem service trade-offs.*—The scenario analysis examines the expected acceptability of a novel grass expanding in rangelands with different configurations of ecosystem service outcomes (Fig. 4). Recall that the baseline acceptability of a new grass species is 4.7, near slightly acceptable (gray line in Fig. 4). For a scenario representing maximum potential gain in ecosystem services (scenario 1 in Fig. 4), we examined the expected acceptability if forage quality, forage quantity, floral resources, water availability, and bird diversity all increase and forage availability and grass diversity are set at their preferred levels (summer and no change, respectively). Under conditions of the maximum gain scenario, the acceptability of the species is expected to increase to moderately acceptable (6.1).

Given the importance of provisioning services to agricultural landowners, we examined the change in expected acceptability if forage quality and quantity increase, and forage is available in summer (the status quo level, which was preferred by landowners) with no change to regulating and provisioning services (scenario 2 in Fig. 4). The expected acceptability increases to 5.5, between slightly and moderately acceptable. This increase above the baseline scenario is undermined if either regulating or supporting services decrease. For example, if provisioning services are enhanced but regulating services are decreased (scenario 3 in Fig. 4), acceptability is reduced to a neutral level (4.2). If provisioning services are reduced but regulating and supporting services are increased (scenario 4 in Fig. 4), expected acceptability remains at a similar level (4.1). A new grass expanding in rangelands may be considered moderately unacceptable (2.2) if provisioning services do not change but both

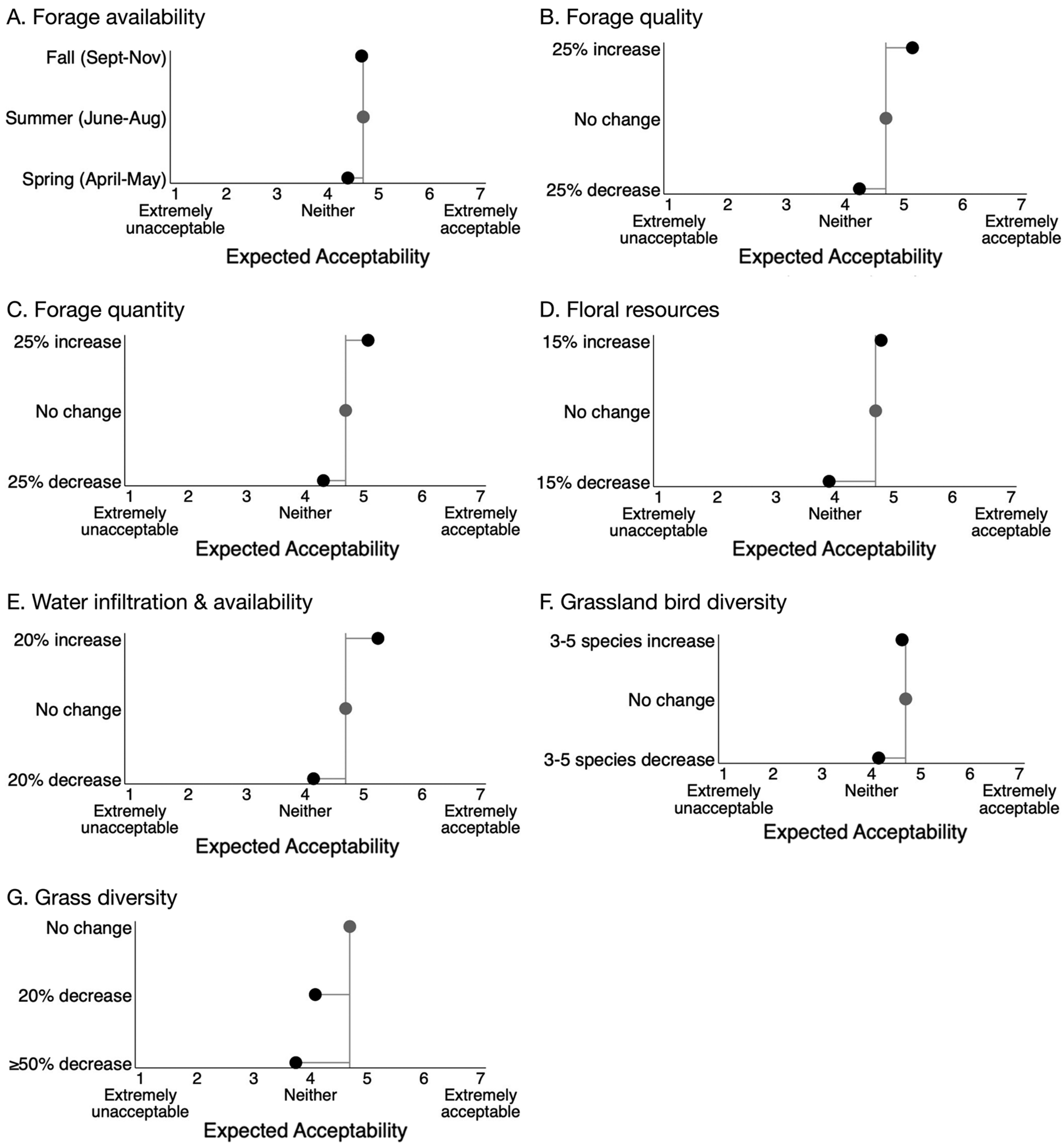

Fig. 3. The expected acceptability of a grass for each ecosystem service attribute (A–G) when isolating the effects of each level (black points), while holding the other services constant at their status quo. The gray line indicates the baseline acceptability when all ecosystem services are set at the status quo level.

regulating and supporting services decrease (scenario 5 in Fig. 4). Finally, when all ecosystem services decrease or are set at the least preferred outcome, the expected acceptability is below its theoretical bounds of extremely unacceptable (0.7; scenario 6 in Fig. 4). This is an artifact of the regression model, and we interpret it as being extremely unacceptable.

The scenarios also demonstrate an asymmetry in how changes to ecosystem services relate to

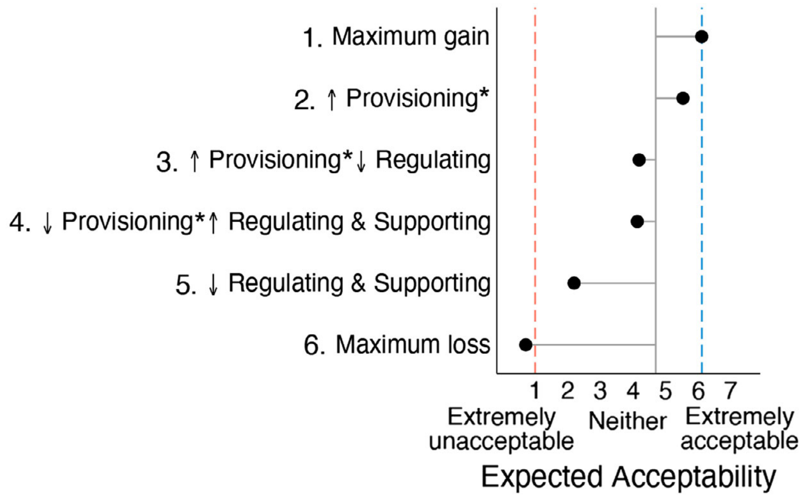

Fig. 4. The expected acceptability of a grass under ecosystem service conditions modeled by six different scenarios. The gray line indicates the baseline acceptability when all ecosystem services are set at the status quo level. Attributes were held at no change unless specified. *An increase in provisioning services includes summer forage availability while a decrease includes spring availability.

acceptability. This is highlighted by the changes in acceptability for the maximum gain and maximum loss scenarios (Fig. 4). In the maximum gain scenario, acceptability only increases by an expected 27% over the baseline scenario and does not reach the level of extremely acceptable. The maximum loss scenario, however, represents an 85% decrease in acceptability, and the new grass is expected to be considered extremely unacceptable. This asymmetry reflects a greater concern with losses in ecosystem services over the potential benefits of enhanced services brought by the new grass species.

5. *Invasion scenarios specific to Kentucky bluegrass*.—The expected acceptability of Kentucky bluegrass at early, moderate, and advanced stages of invasion ranges from slightly acceptable to slightly unacceptable (Fig. 5). At early stages, Kentucky bluegrass may be considered beneficial because it can provide increased quality and quantity forage for livestock in the spring grazing season before most native grass species become palatable. Controlling other ecosystem services at the status quo, the expected acceptability of Kentucky bluegrass at early stages of invasion is just greater than slightly acceptable (5.2). As the invasion progresses to moderate levels, Kentucky bluegrass can begin to outcompete other grasses. Combined with the aforementioned enhanced forage quality, quantity, and spring availability, a moderate loss in the diversity of other grasses reverses the influence of any forage gains and expected acceptability drops back to near the initial baseline (4.6). At advanced stages of invasion, Kentucky bluegrass can create a monoculture resulting in large decreases in the diversity of other grasses to the detriment of grassland birds and floral resources. Even with the forage benefits provided early in the grazing season, our model suggests that landowners would consider Kentucky bluegrass as slightly unacceptable (2.9) under the conditions of advanced invasion.

Estimating management intentions based on expected acceptability.—Given that a landowner's evaluation of acceptability was strongly related to their management intention, we mapped the expected acceptability of the scenarios modeled in Figs. 4, 5 onto the expected management intention model (Fig. 6). For the baseline scenario in which the establishment of a new grass species does not change the status quo of ecosystem services, landowners are not expected to change their current management. Of the ten scenarios we examined, three are associated with management intentions to promote or maintain the new species. The common thread among these

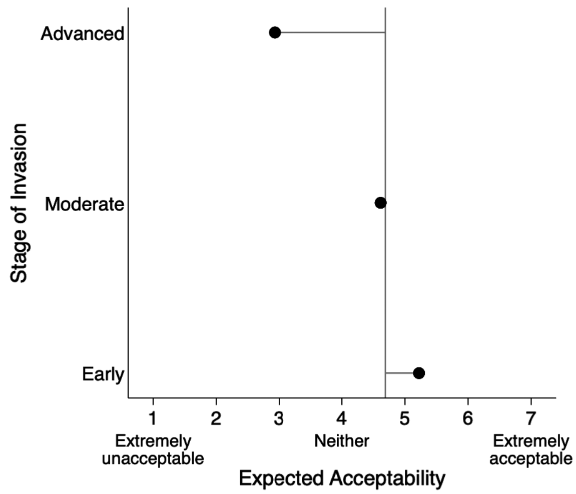

Fig. 5. The expected acceptability of a grass similar to Kentucky bluegrass at early, moderate, and advanced levels of invasion based on expected ecological impacts of bluegrass to ecosystem service attributes. The gray line indicates the baseline acceptability when all ecosystem services are set at the status quo level.

scenarios is that they involve enhanced provisioning services through increases in forage quality and quantity with minimal to no losses in other services. As with the baseline scenario, three other scenarios reflect maintenance of the intention to not change current management. These scenarios include trade-offs among ecosystem service categories in which favorable changes, regardless of ecosystem service type such as increased provisioning services or enhanced regulating and supporting services, were offset by losses to any other ecosystem service category. Finally, three scenarios are associated with management intentions to control or reduce the new grass. The loss of regulating and supporting services (with no change to provisioning services) results in a moderate intention to control the grass, and advanced-stage invasion of Kentucky bluegrass relates to a slight possibility of controlling the species. The only scenario demanding action is one in which all ecosystem services are reduced and desired outcomes are lost.

Discussion

Expansion of invasive species on grasslands is a global conservation concern and invasive grasses are a growing threat to both biodiversity and agriculture operations (Newbold et al. 2016, Schirmel et al. 2016, Godfree et al. 2017). This is especially true in managed grazing systems, which have the largest global extent of any land use (Asner et al. 2004). Our work investigated

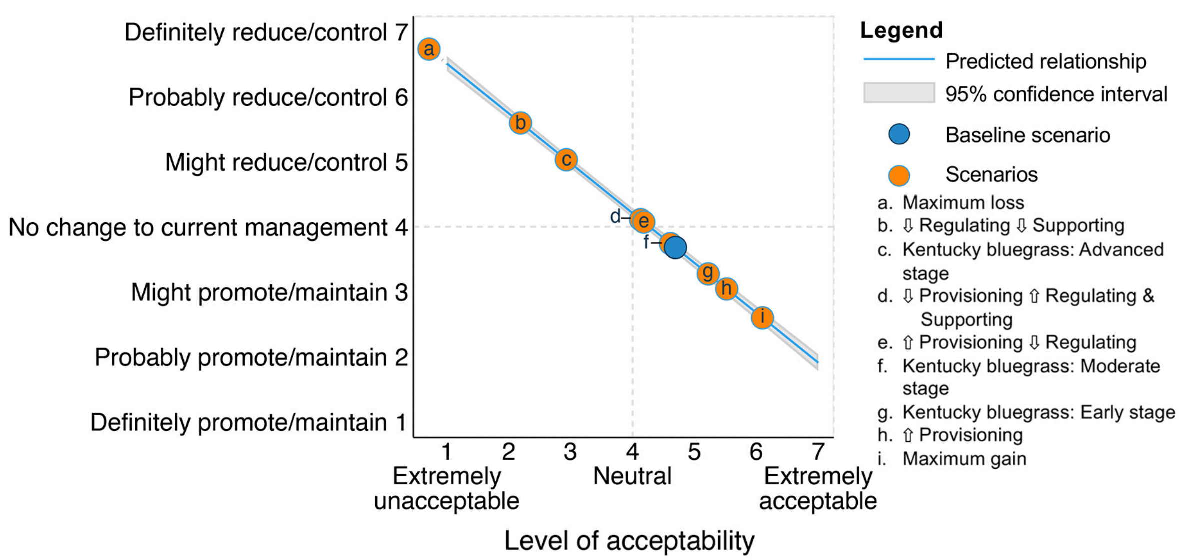

Fig. 6. The relationship between landowners' expected acceptability ratings of a new grass and their expected management intentions.

potential trajectories of ecological change in the northern Great Plains of the USA, a landscape characterized as both an economically valuable working landscape and a priority conservation area of ecological importance (Perkins et al. 2019). In multifunctional landscapes, private landowners play a vital role as gatekeepers influencing the spread of invasive species and the flow of ecosystem services.

Ecosystem service influences on landowners' acceptance and management of invasive grasses

Landowners may view the presence of a new grass species expanding in rangelands as inconsequential until placed in the context of affecting multiple ecosystem services. Considering the dynamics of non-response and the number of unconditional responses indicating a neutral perspective, novel grasses expanding in rangelands may be a low salience issue to many agricultural landowners who are primarily involved in crop production or otherwise less dependent on rangelands. Species origin and so-called nativeness are often used as proxies for potential harm and criteria for implementing control efforts (van Der Wal et al. 2015, Head 2017). However, landowners in this study were generally tolerant of, and would not change their current management for, a new grass species that did not affect the status quo of ecosystem services currently provided. Rather than an inherent bias against new species, there may be a lack of perceived vulnerability to such change. Our findings support previous research that the functions and impacts of novel species are stronger drivers of behavior than concerns about nativeness or invasiveness alone (Fischer et al. 2011, Marshall et al. 2011, van Der Wal et al. 2015, Bonanno 2016).

Landowners' acceptance of the invasive grass reflects a greater sensitivity to losing ecosystem services than to achieving gains. This is true for particular ecosystem services, including floral resources for pollinators and grassland bird diversity, and is highlighted by the contrast between the maximum gain and the maximum loss scenarios. This unequal weighting of losses and gains can be understood through the lens of prospect theory, which posits that in decision-making under conditions of risk and uncertainty, concern about potential losses carries greater weight than the potential to achieve equivalent gains (Kahneman and Tversky 1979, Tom et al. 2007). This loss aversion among landowners was evident not only in comparisons of losses to gains, but also in the scenarios where the novel grass improved some ecosystem services while undermining others (Tom et al. 2007, Holmes et al. 2011). Consistent with prospect theory, landowners were averse to losing any ecosystem service in the trade-off scenarios rather than consistently focusing on a particular category of ecosystem service over another, such as provisioning services over regulating services.

Based on our results, we propose that the unequal weighting of gains and losses is most applicable to landowners' evaluations of ecosystem services with indirect or less tangible benefits for which there may be a greater degree of uncertainty about consequences of change. This is reflected in our data through the nonlinear responses to forage availability, floral resources, avian diversity, and grass diversity as opposed to the linear responses to forage quality, forage quantity, and water regulating services. The concept of ecosystem services as a cascade from ecosystem structure and processes to the services and benefits directly available to people suggests that landowners may have greater uncertainty about how changes to more distal regulating and supporting services can ultimately impact their well-being (Potschin and Haines-Young 2011). Landowners focused on livestock production may be accustomed to adapting to changes in provisioning services related to forage quality and quantity, and farmers and ranchers likely recognize the predominant role of soil water in regulating primary productivity potentially lending greater certainty to these services. Close associations between water-related services and fodder production services have been found in grasslands elsewhere, such as the ecosystem service bundles provided by grassland agricultural systems in Northern Europe and South Africa (Bengtsson et al. 2019).

Synergies or win-wins among ecosystem services are ideal; however, social, economic, and ecological goals are often at odds in working landscapes making ecosystem service trade-offs a common reality and increasingly important to understand (Swinton et al. 2007, Godfree et al. 2017). The vignette experiment enables nuanced insights about landowners' preferences and evaluations of trade-offs. Although the importance of provisioning services to agricultural landowners has been well documented in prior research (Roche et al. 2015, Swinton et al. 2015, York et al. 2019), our scenario modeling suggests that, while important, forage-related services do not exclusively dominate landowners' decision-making about ecosystem services. In addition to loss aversion, landowners' concern over losing regulating and supporting services may reflect holistic considerations about the sustainability of their operation, overall ecological health, or some combination. However, the potential benefits of enhanced regulating and supporting services were outweighed by diminished provisioning services. This echoes previous research that producers are unlikely to accept diminished personal profitability to provide environmental benefits for the public at large (Swinton et al. 2015). We found that provisioning services may be more focal and important when landowners make decisions related to achieving enhanced outputs; but, a wider range of supporting and regulating services may become important when landowners make decisions related to preventing diminished ecological conditions.

Despite the unacceptability of negative impacts to ecosystem services, landowners' thresholds to take action against a new, invasive grass species are high. In our study, the worsening ecological conditions mirroring impacts of Kentucky bluegrass across stages of invasion resulted in movement toward a management intention to control the species, but are limited to a slight intention to reduce or control the species under conditions of advanced invasion. This corresponds to previous findings that individuals are not likely to engage in preventative management against invasive species until they personally experience negative impacts (Johnson et al. 2011). The lack of early, proactive action reflects an inherent human tendency to minimize threats and downplay initial warnings because people consistently underestimate the likelihood that they will experience negative outcomes (Sharot 2011, Van Bavel et al. 2020). Additionally, early action and containment require immediate costs, while the benefits of such action remain speculative (Mooney 2005). As personal losses are experienced and the frame of reference shifts from the status quo to one of loss, however, landowners may be more willing to accept the operational risks associated with shifting management to focus on control efforts (Kahneman and Tversky 1979, Holmes et al. 2011). Although full-time agricultural producers of large operations tend to have a greater capacity to adapt to change than part-time or small-scale agricultural landowners (Swinton et al. 2015, York et al. 2019), our study involving large-acreage production-oriented landowners indicates that they may still have high thresholds for taking management action to reduce or control an invasive species.

Implications for landscape-scale management.— Along with individual reluctance to change current management, the ability to manage invasives across a landscape is complicated by a number of issues. First, species invasions often happen insidiously with limited initial impact and without clear responsibility (Mooney 2005). Decision-making is complicated by scientific uncertainty about immediate, near-term, and longer-term impacts to the land and a landowner's livelihood. As seen with Kentucky bluegrass, invasives may initially provide some benefits but can undermine resilience and enhance vulnerability if the species becomes more problematic at later stages of invasion (Shackleton et al. 2007, Shackleton et al. 2019*c*). Second, the involvement of a large number of individual decision makers, each with their own land management goals, risk thresholds, attitudes, and preferences, can complicate cooperative conservation efforts. Collective action may be further undermined by free riders that benefit from the invasive species management efforts of others but do not equally contribute, or holdouts who decide not to participate (Goldman et al. 2007). This ultimately creates a source-sink dynamic in which non-participants serve as sources for neighboring landowners controlling invasives on their land (Epanchin-Niell et al. 2010). Third, this heterogeneity across private landowners also increases coordination costs and reduces the effectiveness of local institutions attempting to address the issue. Spread of invasive species such as Yellow starthistle (*Centaurea solstitialis*) and eastern red cedar (*Juniperus virginiana*) may continue despite explicit programs and other resources focused on control (Epanchin-Niell et al. 2010, Wilcox et al. 2018).

As a result of these issues, invasive species management strategies employing an invasive-by-invasive approach may struggle to succeed, particularly in regions where landcover at the landscape scale is the emergent property of a large number of individual decision makers (Epanchin-Niell et al. 2010). The question for invasive species management then becomes how to effectively engage and motivate private landowners. We consider three pathways: incentive programs, collaboration networks, and transdisciplinary research.

Incentive programs have been commonly employed in working landscapes to encourage land management to control invasives (Roberts et al. 2018) and other beneficial land management actions (Claassen and Ribaudo 2016). Incentive programs can address the inertia of private landowners to take action by subsidizing the private costs for providing public benefits, yet they suffer from the collective action problem of needing to achieve high participation to accomplish landscape-level effects (Graham et al. 2019). Further, such programs are rarely designed to encourage the necessary cross-boundary and cross-scale cooperation (Goldman et al. 2007).

Collaborative, multi-scalar networks that complement incentive programs represent a promising path forward for invasive species management by encouraging collaboration, establishing norms, and promoting social learning. Although private landowners typically define the system of interest as the land they own, their scope of influence extends beyond property boundaries. Collaborative networks can build a community of practice that supports the autonomy of landowners while helping them develop common knowledge and expectations that allow them to act in service of a shared purpose across boundaries (Butler and Goldstein 2010). Collaborative networks can serve as the intersection of top-down policy to control behavior and bottom-up efforts of individuals and institutions to self-organize. Middle-out organizations complement top-down and bottom-up approaches to governance by uniting professional expertise and local knowledge through information exchange and greater access to funding (Epanchin-Niell et al. 2010).

Transdisciplinary research efforts can be integrated into collaborative networks or operate independently as a way to advance shared knowledge about global change drivers such as invasive species. Built from the same theoretical foundation as collaboration, transdisciplinary research seeks to produce actionable scientific knowledge through collaboration between scientists and those making management decisions (Enquist et al. 2017). For instance, the Collaborative Adaptive Rangeland Management (CARM) experiment is a transdisciplinary effort to compare non-traditional grassland management focused on a multifunctional landscape to status quo approaches. The CARM experiment has increased stakeholder trust and engagement, and helped foster appreciation for multiple ways of knowing about grasslands and their management (Wilmer et al. 2018).

Collaborative engagement is key to developing both shared understanding and a shared vision within and beyond landowners' property boundaries because perceptions of invasive species impacts can vary between and among decision makers based on social, cultural, and spatial contexts (Crowley et al. 2017, Vaz et al. 2017, Shackleton et al. 2019*c*, Tebboth et al. 2020). Collaborative efforts through learning networks, adaptive management, or transdisciplinary research can lead to more effective coordinated efforts to eradicate an invasive species or guide transformation to a future where the invasive is integrated into the landscape while supporting livelihoods (Shackleton et al. 2007, Epanchin-Niell et al. 2010, Tebboth et al. 2020). Integration of invasives often occurs when a species is perceived to have some degree of utility, such as suitability as forage for livestock or as biofuel (Kelley et al. 2013, Tebboth et al. 2020). Overall, the trust and social learning across institutions and at multiple scales that collaborative networks facilitate can result in increased support for management and more coordinated action for invasive species management.

Conclusion

Ecological transformation and novelty are not new; however, the current anthropogenic drivers of unprecedented global change have heightened the expansion of invasive species (Crutzen 2006, Ewel et al. 2013, Jackson 2013). The spread of invasive grasses in the northern Great Plains of the USA, as with the spread of invasive species worldwide, is both an ecological and a social process.

Anticipating human contributions to disruptive environmental change and the social tipping points that may encourage sustainable transformations are priorities for earth system science and global sustainability (Reid et al. 2010). In working landscapes, private landowners can profoundly impact the ability to control or eradicate an invasive species (Wilcox et al. 2018). Our work provides insight into the links between potential ecological outcomes, ecosystem service trade-offs, and how landowners intend to respond. Consistent with attitude theory, we found that landowners consider the impacts of an invasive species on ecosystem services as part of their judgment and decision-making process (Fishbein and Ajzen 2010). We found that negative ecological impacts may need to be quite severe before prompting landowners to take management actions focused on control, even when all ecosystem services are considered important.

Agricultural landowners are gatekeepers of transformation across large spatial scales. Individual landowners in the northern Great Plains will likely, although perhaps inadvertently, facilitate the spread of invasive grasses such as Kentucky bluegrass when they are perceived to provide some benefits. Successful conservation and agricultural outcomes may be enhanced through collaborative management efforts focused on generating stakeholder buy-in and consensus to provide for desired ecosystem services through either the control of, or co-existence with, the invasive species.

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.3652/full