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Research

Diagnosing and navigating scale mismatches in a social-ecological system: cross-scale feedbacks and cross-level interactions enable regime shift management in the Great Plains

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ABSTRACT. Institutional fit is a prerequisite for governance of sustainable social-ecological systems. Scale mismatches, which occur when institutional fit is lacking, are common, sometimes leading to irreversible shifts in social-ecological regimes. In the American Great Plains, encroachment of eastern redcedar (*Juniperus virginiana*) threatens to shift the system from grasslands to woodlands, a shift potentially exacerbated by scale mismatches in social-ecological systems governance. We diagnosed this mismatch by examining how ecological change at interacting spatial extents influences management responses and asked whether individual livestock producers attempted to improve institutional fit by elevating management responses from the individual to the collective level. We used Bayesian logistic regression with questionnaire and landcover data to predict whether producers use prescribed burning to manage encroachment. Prescribed burning was most likely when: regional-level encroachment was high and local-level encroachment was low, local-level encroachment was high and regional-level encroachment was low, or producers engaged in local groups. Individuals here navigate scale mismatch by engaging in collective action, leveraging existing individual behaviors while enabling higher-level institutional changes to better align woody encroachment management with its driving processes. Diagnosing scale mismatches and understanding how they are navigated may reveal leverage points for better aligning management with relevant environmental conditions.

Key Words: *collective action; feedbacks; grassland; institutional fit; livestock producer; prescribed burning; rangeland; regime shift; scale; woody encroachment*

INTRODUCTION

The fit of institutions for governing ecosystem processes is a fundamental challenge for society and continues to be the focus of considerable research (Cumming et al. 2006, Folke et al. 2007, Epstein et al. 2015, Cumming and Epstein 2020, Mahajan et al. 2021). The original premise of institutional fit is that institutions should be aligned with ecological processes (e.g., across spatial, temporal, or functional scales) as a precondition for the sustainable management of ecosystems (Huitema et al. 2009, Guerrero et al. 2015). Yet institutional fit remains elusive for many social-ecological systems (SESs), in part because SESs are complex (i.e., characterized by cross-scale/level interactions, nonlinear dynamics, and uncertainty), multiple management goals are often best achieved at different institutional levels with possible tensions between conflicting goals, and institutions are often path-dependent and insensitive to feedbacks (Cash et al. 2006, Folke et al. 2007, Cumming and Epstein 2020). Scale mismatches occur because of a "problem of fit" (Lee 1993, Cumming et al. 2006, Folke et al. 2007). Although scale mismatches are notoriously difficult to circumvent, understanding mismatches is critical for revealing leverage points to better align ecosystem processes with social institutions responsible for managing them.

Studying scale and institutional fit in an SES

Although social and ecological disciplines use scale terms differently, we differentiate between "scale" and "level" following Gibson et al. (2000), whereby scale is the dimension of measurement (e.g., spatial, temporal, administrative) and level is the unit of analysis on that scale (e.g., extent, duration, civil division, respectively). Spatial and temporal dimensions tend to be the focus of many ecological questions, while analytical dimensions of society (e.g., administrative, jurisdictional, institutional) tend to be the focus of many governance questions. Cross-level interactions occur "among levels within a scale," such as when local and regional ecological processes interact with one another; and cross-scale interactions, or feedbacks, occur between scales, such as when the expanding spatial extent of an ecological process results in a change to the administrative extent of an institution (Cash et al. 2006).

Scale considerations are central to the study of SESs. An SES contains coupled social and ecological components that interact across scales and levels to generate emergent properties, such as system resilience (Colding and Barthel 2019). Institutions can inform adaptation, which occurs when the system is maintained, or transformation, which occurs when the system is directed into a different, presumably more desirable regime (Walker et al. 2004, Cote and Nightingale 2012, Chaffin et al. 2016, Blythe et al. 2018, Higuera et al. 2019). Researchers have long argued that changes in spatial, temporal, and functional scales of social and/or ecological processes drive misalignment between institutions and ecosystem processes, with consequences for sustainability (Lee 1993, Cumming et al. 2006, Folke et al. 2007). Institutional fit research has also recognized and diagnosed different types of fit (Cox 2012, Lebel et al. 2013, Epstein et al. 2015), acknowledged the inherently normative, conditional, and political nature of fit (Cash et al. 2006, Folke et al. 2007, Manson 2008, Lebel et al.

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2013, Schultz et al. 2019), and proposed interventions for its improvement (Cash and Moser 2000, Cash et al. 2006, Cumming et al. 2006, Guerrero et al. 2013, 2015, Epstein et al. 2015, Schultz et al. 2019).

To improve institutional fit, further research is needed that clarifies how ecosystem processes across levels affect institutional change (i.e., both cross-scale feedbacks and cross-level interactions). Although it is widely recognized that social institutions have an effect on ecosystem processes, how changes in these ecosystem processes feed back to institutions to inform societal adaptation or transformation is not well-studied (Cash et al. 2006, Cumming and Epstein 2020). The idea that "institutions should be 'managed' by environmental conditions" (Folke et al. 2007) is a self-evident component of adaptation or transformation in a sustainable SES, yet we have few recorded instances (e.g., Bodin et al. 2014) of these tight cross-scale feedbacks from ecosystems to society (Levin 1999, Cumming and Epstein 2020). We also lack empirical analyses of both social and ecological components (e.g., Guerrero et al. 2015) and cross-level interactions of SESs (Cash et al. 2006, Vallury et al. 2022), despite being important for developing flexible and responsive polycentric governance systems that align appropriately with ecosystem processes at multiple levels (Epstein et al. 2015, Cumming and Epstein 2020). And although transformative change, the type often required to align institutions and ecosystems, may not be politically palatable, understanding the extent to which leveraging short-term opportunities toward institutional fit improves sustainability outcomes over the longer-term may help in evaluating the costs and benefits of intervention alternatives (Cumming et al. 2006, Schultz et al. 2019).

Regime shift in the American Great Plains: a problem of fit

The American Great Plains is in a temperate grassland biome (Rossum and Lavin 2000) and provides an opportunity to study the effect of cross-scale feedbacks and cross-level interactions on emergent outcomes, such as institutional fit, in a social-ecological system. Although this region has been in a grassland state for several millennia (Nordt et al. 2008, Cordova et al. 2011), changing relationships among key drivers have enabled eastern redcedar (*Juniperus virginiana*, hereafter "juniper") woodlands to encroach on grasslands (Briggs et al. 2005, Engle et al. 2008, Van Auken 2009) with the potential to force a system-wide regime shift from grasslands to woodlands (Uden et al. 2019), a common threat for global rangelands (Godde et al. 2020). Although juniper seed dispersal occurs predominately at small spatial extents (Fogarty et al. 2022), it is likely bimodal because of animal-aided dispersal occurring across larger extents. Thus, encroachment occurs from both small, local juniper patches across the region and well-established woodlands predominantly in the east that create a higher propagule pressure (Briggs et al. 2005, Van Auken 2009, NRCS 2021).

Studying the factors that enable encroachment at different spatial extents is important. For instance, at large spatial extents (i.e., regional level and up), fire exclusion policies enable fire-sensitive juniper to germinate and spread while climate-change induced drought makes juniper more competitive (Bond and Midgley 2000, Archer et al. 2017). Furthermore, state-endorsed tree planting programs encourage the use of junipers for windbreaks, which introduce patchy seed sources from which trees spread across the state (Taylor et al. 2012, Twidwell et al. 2013a). At small spatial extents (i.e., local level), fire suppression, juniper recruitment from windbreaks, overgrazing, and abiotic factors enable local spread of juniper (Briggs et al. 2005, Taylor et al. 2012, Allred et al. 2012, Twidwell et al. 2014). Together, these processes expand "islands" of juniper in a "sea" of grass into "continents" of encroaching juniper (Briggs et al. 2005, Van Auken 2009, NRCS 2021).

Although these social-to-ecological feedbacks and ecological interactions at different spatial extents have been well-studied from ecological perspectives, we know little about how ecological processes at different levels feed back to the social institutions that are, at least hypothetically, capable of limiting the pace and extent of this regime shift. Indeed, this regime shift is likely exacerbated by decoupled feedbacks from the ecological to the social components of the system (Roberts et al. 2018). Although social-to-ecological feedbacks have effectively excluded fire, and among other factors, enabled the spread of juniper, institutions' sluggish response to ecological changes may miss opportunities to direct the SES toward desired regimes, which severely limits management options (Leverkus et al. 2021).

Among the biggest constraints to social response to ecological change is the institution of private property, which limits juniper management to the voluntary actions at the individual landowner (or manager) level. Opportunities to expand individual-level responses exist when landowners engage in coordinated collective action, defined as two or more actors working together for a public good (i.e., to mitigate encroachment; Sandler 2015, Graham et al. 2019). For example, on private property, prescribed burning, which often requires coordination among adjacent landowners, technical support, equipment sharing, and permits to be effective, safe, and legal, counteracts the ecological repercussions of state tree-planting programs and fire exclusion policies (Twidwell et al. 2013b). Nonetheless, when faced with ecological change at the highest spatial levels, even landowners who coordinate may be ill-equipped to meet the challenge without substantial support at higher levels of the social system. Understanding how ecological feedbacks at different spatial extents affect individual management behaviors may reveal opportunities to increase voluntary management of juniper in the Great Plains.

Here, we diagnose a scale mismatch and highlight extant factors that may enable institutional fit and limit a grassland to woodland regime shift in Nebraska, a state in the center of the American Great Plains. To do so, we examine cross-level interactions (within ecological and social components) and cross-scale feedbacks (from ecological to social components). We use Bayesian hierarchical logistic regression to empirically demonstrate how individuals are navigating scale mismatches, highlight opportunities to leverage, and amplify elements of the system already in social-ecological alignment to limit a system-wide regime shift.

METHODS

Study area

Our study area is Nebraska, USA, in the American Great Plains. Nebraska consists of grassland ecoregions characterized by substantial row crop agriculture and ranching (Chapman et al. 2001). Wide-spread juniper encroachment has resulted in high severity transition areas in over a third of the state (NRCS 2021) such that juniper distribution is expected to double by 2050

(Shrestha et al. 2025). Land managers use a variety of encroachment interventions, including prescribed burning to kill junipers in the seedbank (Twidwell et al. 2021). Though prescribed burning is the most effective option for managing widespread encroachment, numerous institutional barriers limit its implementation and effectiveness, such as a persistent fire removal paradigm, lack of coordination/consistency across levels of government, and an absence of regulation to manage encroachment (Twidwell et al. 2013b, Leis et al. 2017, Roberts et al. 2018).

Scale mismatches may be a critical barrier to managing juniper encroachment and limiting the extent of a wide-spread regime shift in Nebraska (Roberts et al. 2018). Because Nebraska is almost exclusively private land (97.4%; Headwaters Economics 2019), policy makers frequently treat juniper encroachment as a landowner issue (D. Twidwell, *personal communication*). The vast majority of management actions must be funneled through individual landowners even though the encroachment extends well-beyond state boundaries. Although individuals may be temporarily successful at limiting encroachment on their own properties, actors in Nebraska have failed to collectively halt encroachment occurring across the state. Indeed, both the ecological process (i.e., woody encroachment) and the most effective control (i.e., fire) require action beyond property boundaries, presenting an institutional fit conundrum. Although collective efforts at higher levels of the social system do exist to support individuals seeking to manage encroachment, including federal initiatives, conservation non-profit organizations, prescribed burn associations, and informal rangeland management groups, their success is predicated on voluntary landowner involvement.

Data collection and measures

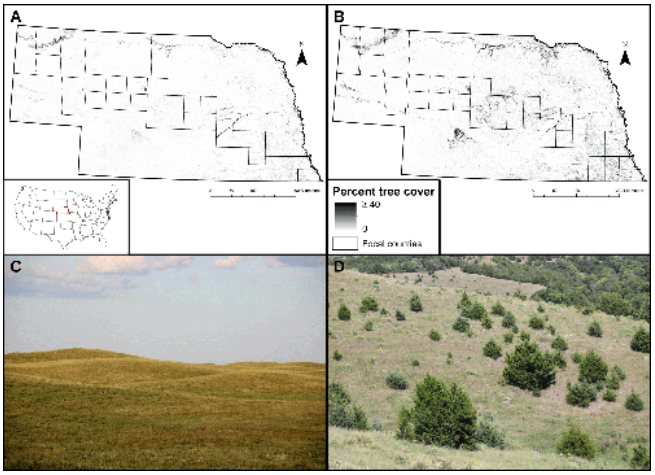
Social data

In 2021, we administered a mail-back and online questionnaire (Appendix 1) to livestock producers in Nebraska using a modified tailored design (Dillman et al. 2014) with informed consent (ethics approval: UNL IRB #20086, UM IRB #235-19). Our study area included 31 counties across a gradient of juniper encroachment (Fig. 1). We purchased our sample from Farm Market iD, obtaining addresses within our study counties for all National Agricultural Survey respondents with > 8 hectares of pasture/rangeland (N = 6546). After taking a simple random sample of 4500 from this population and removing duplicates, our sample size was 4494 individuals (see Appendix 2). We asked respondents how often they used prescribed burning to manage juniper encroachment on their operation in the last three years and their level of involvement in local rangeland management groups (Bennett et al. 2014, Cinner et al. 2015, Marshall et al. 2016; Table 1) to test whether group involvement has an effect on prescribed burning implementation

Ecological data

We calculated encroachment variables based on percent tree cover in the Rangeland Analysis Platform v2.0 (Allred et al. 2021). We calculated the mean percent tree cover at each respondent's location by averaging the percent tree cover across all rangeland

Fig. 1. Percent tree cover in 1990 (A) and 2020 (B) in greyscale; sampled counties are highlighted and represent a gradient of juniper encroachment. Photos of 0% tree cover (C) and 5–10% tree cover in the foreground (D). Data are from the RAP v2.0 (Allred et al. 2021).



pixels within a 1 km radius (i.e., local level) and a 100 km radius (i.e., regional level) of their geolocated address in 1990 and in 2020 (Fig. 1). We masked pixels classified as cropland, development, or water in the 2016 National Land Cover Database, as well as those within a 60-meter buffer of National Wetland Inventory features. To calculate our encroachment variables at the local and regional level, we subtracted the 1990 mean percent tree cover values from those in 2020 for each respondent and standardized each variable. We chose a 1 km radius because it approximates the average farm size in Nebraska (USDA NASS 2022) and a 100 km radius because it encompasses average commute distances for every county in the state (Index Mundi 2018). Thus, individual producers have likely been exposed to encroachment at each of these levels. Furthermore, because regional-level encroachment was not highly correlated with local-level encroachment ($r = 0.36$), we were able to include both variables in a model to test the effects of local- and regional-level encroachment on prescribed burning implementation. Because the process of encroachment is so persistent over time, endogeneity between our social and ecological variables was mitigated by calculating encroachment as percent tree cover change over 30 years, rather than at one year. An alternative approach would be to use tree cover data from 2017 and behavior data from 2018–2020, but this approach would not entirely mitigate endogeneity because those using prescribed burning in 2018–2020 are likely to have used it in previous years. Nonetheless, for those who engaged in prescribed burning, 87% had local-level encroachment increase over 30 years, which would not be the case if prescribed burning were substantively reducing local-level encroachment (and thus presenting an endogeneity problem for our analysis).

Because junipers encroach from both patches (or "islands") and woodland "continents," operators experience encroachment at both local and regional levels that may vary in severity. Different

Table 1. Variables included in model and the variable scale, source, mean and standard deviation (SD). Prescribed burning is the response variable and all others are explanatory variables.

Variable	Scale	Scale description	Source	Mean (SD)
Prescribed burning	0, 1	0 = Never; 1 = Rarely, occasionally, or more frequently	Survey to producers: Please rate how often you have used prescribed burning to manage [juniper encroachment] on your operation in the past three years.	0.46 (0.5)
Group involvement	0, 1	0 = No rangeland management groups exist and/or I am not involved with any of them; 1 = I am involved with at least one group	Survey to producers: What's the extent of your involvement with rangeland management groups?	0.07 (0.25)
Local-level encroachment	Continuous	Ranges from -10% to 29%	Rangeland analysis platform: Percent tree cover in 1990 and 2020 for a 1 km radius around each respondent	2.5 (4.0)
Regional-level encroachment	Continuous	Ranges from -0.1% to 10%	Rangeland analysis platform: Percent tree cover in 1990 and 2020 for a 100 km radius around each respondent	3.3 (2.5)

combinations of severity at the local and regional level may result in different types of decision making by operators. Thus, we included an interaction term in our model, which tests whether the effect of local-level encroachment on an individual's behavior depends on the extent of regional-level encroachment. In other words, does increasing local-level encroachment consistently increase prescribed burning, or does the effect of local-level encroachment on an individual's behavior depend on what's happening at the regional level as well?

Theoretical framing

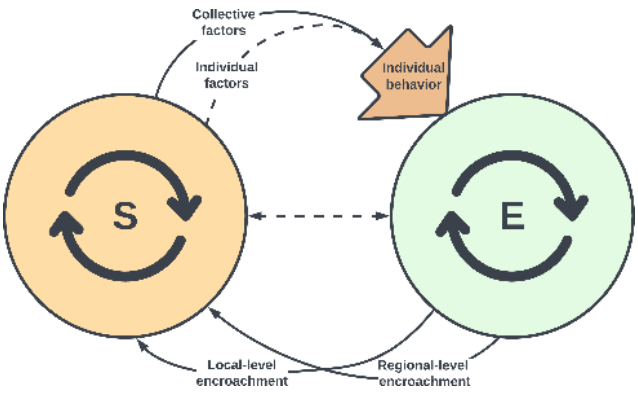
In Nebraska's Great Plains SES, relationships within the social component of the system lead to collective and individual factors that must be funneled through individual behavior because almost all of Nebraska is private land (Fig. 2). Individual behaviors often resist regime shifts in the ecological component of the system through management actions. In turn, relationships within the ecological component result in local- and regional-level landscape changes that interact with one another to influence the social component of the system. We focused our inquiry on the cross-scale feedbacks that connect social and ecological components and cross-level interactions within components. We tested the relative effects of local- and regional-level encroachment, the interactions across these spatial levels, and coordinated collective factors (i.e., group involvement) on individual behavior (i.e., the probability that a producer uses prescribed burning to manage juniper encroachment). Though individual factors were not studied here, we show them in our conceptual diagram for completeness.

We diagnosed the scale mismatch by testing the effects of encroachment at different spatial levels and the interaction of these levels on each behavior.

H1: We hypothesized that a scale mismatch exists because regional-level encroachment has a larger effect on individual behavior than local-level encroachment and the effect of local-level encroachment on an individual's behavior is dependent on the extent of regional-level encroachment.

If social and ecological components were aligned, local-level encroachment would have a larger effect on individual behavior than regional-level encroachment and the interaction would have no effect because individual behavior would be responsive to on-property encroachment with little effect of regional-level encroachment.

Fig. 2. Conceptual diagram of our theoretical framing. In Nebraska's Great Plains social-ecological system, collective and individual social factors (S) are funneled through individual behavior in a landscape dominated by private land to influence the ecological (E) component, while local- and regional-level encroachment interact to influence the social component. The dashed arrows represent the many other connections between social and ecological components not studied here.



We also examined whether individuals navigate scale mismatches by attempting to improve institutional fit.

H2: We hypothesized that individuals who leverage collective efforts improve institutional fit because those who participate in higher-level management groups are more likely to manage encroachment than individuals who do not participate in these groups.

We suspect that individuals attempt to match the level of management with that of ecosystem processes by expanding from individual management to coordinated collective management. If supported, our results would indicate that voluntary, coordinated collective action helps individuals navigate the institution of private property rights that constrains effective management of woody encroachment across property boundaries.

Analysis

We compared the relative importance of local- and regional-level encroachment, their interaction, and group involvement

on prescribed burning behavior using a Bayesian hierarchical logistic regression model with weakly informative priors:

$$y_i \sim Bern(p_i) \quad (1)$$

$$logit(p_i) = \alpha_i + x_i'\beta \quad (2)$$

$$\alpha_i \sim N(0, \sigma) \quad (3)$$

$$\sigma \sim Exponential(1) \quad (4)$$

$$\beta \sim (0,1) \quad (5)$$

where y_i, a binary indicator of whether the respondent i reported participating in prescribed burning, occurs with probability p_i and is a function of the covariate values ($\boldsymbol{x_i'}$), the regression coefficients (β), and a varying intercept (α_j) depicting the Natural Resource District (NRD) of the individual. NRDs are administrative units that manage natural resources in Nebraska, including implementing cost-share programs for planting juniper and other tree species. We used brms (Bürkner 2021), an R (R Core Team 2023) interface to the Stan probabilistic programming language (Stan Development Team 2024). We examined prior predictive densities to evaluate the effects of our prior specification, evaluated model diagnostics for appropriate model specification, checked for multicollinearity, chain convergence, and assessed model fit and classification accuracy with leave-one-out (LOO) cross-validation (Appendix 2).

RESULTS

Overview of sample

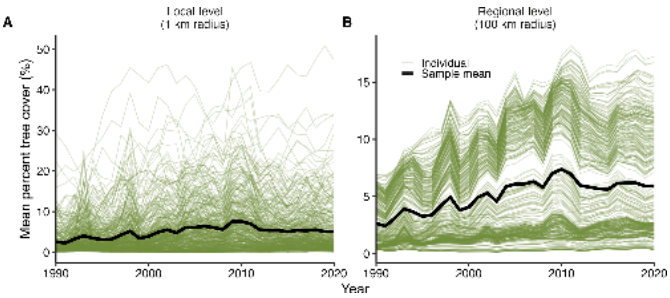
Social data

We had 573 responses and 176 refusals to our survey (response rate of 12.8%) and no significant differences in age, gender, education, and income between paper vs. email respondents. There were no significant differences between respondents and non-respondents for hectares in production for beef, dairy, pasture/range, soybeans, and wheat, but respondents had significantly fewer planted hectares, less gross farm income (GFI), and fewer hectares in corn production than non-respondents. After removing incomplete responses for the variables in this analysis, our final sample had 396 respondents. Although our respondent profile (Appendix 2) was more affluent, more educated, and had a larger operation than the average Nebraskan producer (Nebraska Investment Finance Authority 2021, USDA NASS 2022), it is consistent with livestock producers (i.e., our sample frame) compared to other producers. Forty-six percent used prescribed burning to manage juniper encroachment and 7% were involved in rangeland management groups (Table 1).

Ecological data

Average mean percent tree cover for respondents in 1990 was about the same at the local and regional levels (2.5 and 2.6%, respectively) and more than doubled by 2020 (5.0 and 5.9%, respectively; Fig. 3). Respondents experienced considerably more variability in mean percent tree cover at the local level (0 to 30% in 1990, 0 to 47% in 2020) compared to the regional level (0.4 to 7% in 1990, 0.3 to 17% in 2020).

Fig. 3. Mean percent tree cover at the (A) local and (B) regional level for each individual respondent. Each green line represents the mean percent tree cover on an individual's operation over time. The black line indicates the sample mean across respondents. Data are from the RAP v2.0 (Allred et al. 2021).



Model fit

The difference in expected log predictive density (ELPD LOO) between the fit and null models was -37.8, indicating that the fit model performed better than the null model (Table A2.1). With a classification threshold of 0.5 (≥ 0.5 is a 1, and < 0.5 is a 0), model accuracy was 67%. Chains converged well and posterior predictive checks suggest that the model is well-specified (Figs. A2.4, A2.7). Multicollinearity was not an issue (Fig. A2.5). NRD-level effects varied but all credibility intervals (CI) spanned zero, except for the Upper Niobrara-White NRD (log odds [LO] = -0.73, CI = [-1.66, -0.005]; Fig. A2.3).

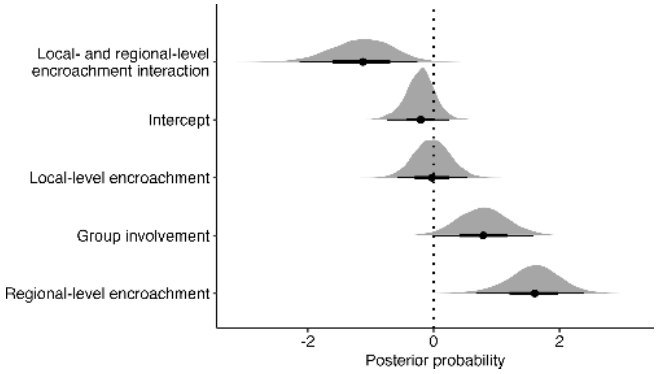
Model results

We found strong support for H1: regional-level encroachment (log odds [LO] = 1.59, CI = [0.67, 2.39]) had a larger, more certain effect on individual behavior than local-level encroachment (LO = -0.03, CI = [-0.58, 0.54]) and the effect of local-level encroachment on behavior was dependent on the extent of regional-level encroachment (LO = -1.15, CI = [-2.13, -0.26]; Figs. 4, 5, Table 2). This interaction term indicates that the probability of using prescribed burning was highest when local-level encroachment was high and regional-level encroachment was low, or when local-level encroachment was low and regional-level encroachment was high. On the other hand, the probability of using prescribed burning was lowest when local- and regional-level encroachment was high, or when local- and regional-level encroachment was low. In other words, producers were most likely to use prescribed burning when they were on one of two "islands" (i.e., juniper patch surrounded by grassland or grass patch surrounded by woodland) and least likely when they were on one of two "continents" (i.e., grassland or woodland; Figs. 4, 5). We also found support for H2: producers involved in groups, compared to producers not involved, were more likely to use prescribed burning (LO = 0.79, CI = [0.01, 1.59]; Figs. 4, 5, Table 2).

DISCUSSION

Our results demonstrate opportunities to leverage ongoing efforts to improve social-ecological alignment for the scale mismatch occurring between ecological and social processes in one of the largest grassland SESs in the world, the American Great Plains

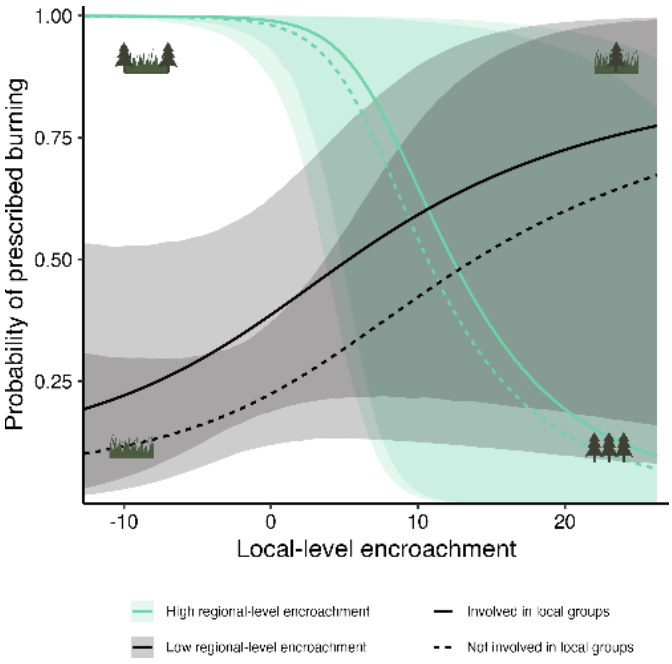
Fig. 4. Posterior probabilities of each variable predicting prescribed burning. The grey shaded area is the density distribution of the posterior probabilities, the point is the median, the thick bars cover the middle 66% of the density distribution, and the thin bars cover the middle 95% of the density distribution.



biome. By examining cross-level interactions and cross-scale feedbacks, we diagnosed this mismatch by illustrating that individual producers were more likely to manage this regime shift when local shift signals were low but regional signals that extended well beyond their own operations were high, or when local signals were high and regional signals were low. Additionally, we argue that a subset of individual producers navigated this mismatch by aligning management responses with ecological processes through coordinated collective action, a rare example of ecological feedbacks inspiring social processes toward sustainable SES management. These results suggest policy levers for enhancing management in strategic locations and at higher social levels to improve social-ecological alignment as a precondition for more effective system-wide management.

These results provide insight into the types of places that are prime for interventions targeting voluntary behavior change. The effects of regional-level encroachment and cross-level interaction terms on the probability of management behaviors demonstrate that individual producers responded to environmental change beyond the boundaries of their own properties by taking into account changing conditions on the surrounding landscape and incorporating that information into decisions about how to manage their own operation. Indeed, we found that producer behavior was unrelated to local-level encroachment alone. Producers on juniper and grassland islands (i.e., low local-level and high regional-level encroachment or vice versa) were the most likely to manage encroachment with prescribed burning. Interestingly, these results are consistent with research finding that conservation professionals, who integrate landscape-level information, have higher perceptions of encroachment risk than producers, who focus on managing an individual operation and are only responsive to encroachment once it exceeds a certain threshold (Legatzke et al. 2026). These results highlight places where ecological feedbacks are most likely to affect individual behavior. With the help of diagnostic tools available online (Allred et al. 2021), practitioners may be able to identify and strategically contact individuals prime for prescribed burning, such as producers on grassland or juniper islands.

Fig. 5. The effect of the interaction of local- and regional-level encroachment on prescribed burning. Because our encroachment variables are on a continuous scale, we had to make dichotomous predictions for one of the spatial levels to illustrate the interaction. We defined "high encroachment" as the largest difference in tree cover (i.e., 10%) and "low encroachment" as the smallest difference in tree cover (i.e., 0%) experienced by respondents at the 100 km level between 1990 and 2020. Lines indicate the mean prediction while translucent colors represent the 95% credibility intervals around the mean. Solid lines indicate the prediction for individuals involved in local groups while dashed lines indicate the prediction for individuals not involved in local groups. The distance between the solid and dashed lines illustrates the group effect. Icons illustrate juniper and grassland "islands" and "continents."



Producers who were involved in rangeland management groups were more likely to use prescribed burning, the most effective tool for managing encroachment across wide spatial extents, suggesting that coordinated collective action is important for institutional alignment and potentially transformative regime shift management. In a landscape dominated by private property, practitioners and some producers are increasingly recognizing the need to coordinate across property boundaries, with controlled-burn cooperatives of private landowners and other organizations playing coordination roles (Twidwell et al. 2013b, Leis et al. 2017, Legatzke et al. 2025). Because prescribed burning is a collective action requiring more than one person to accomplish, such groups provide the social support necessary to safely manage a burn across property boundaries or to prevent fire from crossing boundaries inadvertently. This social support includes technical and policy knowledge, appropriate equipment, and coordination with spatially adjacent landowners (Twidwell et al. 2013b). Group involvement may also be indicative of collective uncoordinated social factors, not measured here, like normative influences and

Table 2. Posterior log odds estimates, 95% credibility intervals (CI), and standard deviations for the fixed effects in the model.

Variable	Estimate (95% CI)	Standard deviation
Intercept	-0.22 (-0.74, 0.25)	0.25
Group involvement	0.79 (0.01, 1.59)	0.4
Local-level encroachment	-0.03 (-0.58, 0.54)	0.29
Regional-level encroachment	1.59 (0.67, 2.39)	0.43
Interaction of local- and regional-level encroachment	-1.15 (-2.13, -0.26)	0.48

information access through social connections, that can affect individuals' conservation behaviors (Willcox et al. 2012, Niemiec et al. 2016, Lubeck et al. 2019, Nesbitt et al. 2024).

Our results suggest low-risk opportunities for policy makers to improve institutional fit. The effect of group involvement on the probability of individuals using prescribed burning suggests that individuals attempted to "level-up" management responses to match the spatial extent of an ecological process, providing insight into policy opportunities that can be institutionalized to work within the framework of private property. Although a land tenure system dominated by private property limits the ability of higher social levels to manage widespread ecological changes directly—whether changes are undesirable like regime shifts or invasive species spread, or desirable like conservation—the history of fire management and tree planting in Nebraska, including their success at eliminating fire and creating woodlands, highlights that higher social levels have and can bolster adaptation and transformation through social-to-ecological feedbacks (Taylor et al. 2012, Russell-Smith and Thornton 2013, Nebraska Association of Resources Districts 2022). Investing in pre-existing groups with resources, capacity building, and networking is an obvious, low-risk policy opportunity. In particular, incentivizing more meaningful two-way interactions between producers and governance networks may facilitate better knowledge integration across society (Legatzke et al. 2025). To further expand collaborative efforts, lessons can be learned from other collaborative governance contexts navigating scale mismatches. For example, policy tools that address mismatches in forest governance include allowing flexible longer-term funding arrangements to support collaboration, providing technical capacity, and stipulating minimum spatial extents for work being done by collaboratives (Schultz et al. 2019). Using a suite of complementary policy tools and considering cross-level interactions among institutions is also important in this context and many others facing regime shifts and scale mismatches (Cash et al. 2006, Schultz et al. 2019, Mahajan et al. 2021, Salerno et al. 2021). For instance, aligning programs, policies, and institutions at district, state, and national levels that directly conflict with one another with respect to Great Plains management (Roberts et al. 2018, Hogan et al. 2022, Legatzke et al. 2025) will further support institutional fit and SES governance.

Limitations

These results should be interpreted while considering the limits to our research that we encountered. Our sample demographic had a higher education and income level than the sample frame population (Nebraska Investment Finance Authority 2021), our response rate was low despite being typical for research within this demographic (Ulrich-Schad et al. 2022), and we did not sample the entire population of Nebraska. Inferences here are limited to producers in sampled counties and caution should be used when inferring to the largest operations. Nonetheless, our results are consistent with the experiences of producers and conservation professionals with whom we have engaged. Although we partially mitigated for endogeneity by using a 30 year encroachment variable and suspect that endogeneity is not an issue here (see methods), temporally overlapping data may have weakened our results. Future research should employ more temporally resolute data for when producers did and, importantly, did not use prescribed burning (e.g., When did you start using prescribed burning on your operation? In which of the last 10 years have you used prescribed burning on your operation?) to more fully mitigate endogeneity.

Future research

This research is an early step to understand how cross-level interactions and cross-scale feedbacks influence management of a SES, yet the approach and results highlight important scale considerations for future researchers and several possible avenues for future inquiry. Though our study did not assess underlying socio-cognitive mechanisms, both cognitive risk assessment and perceived normative pressure have been shown to have large effects on individual behavior in the context of agriculture (Grothmann and Patt 2005, Willcox et al. 2012, Azadi et al. 2019), weed management (Niemiec et al. 2016, Lubeck et al. 2019), environmental campaigns (Griskevicius et al. 2008), and other conservation domains (Lubell et al. 2007, Nesbitt et al. 2021). Future research could determine how different socio-cognitive mechanisms influence individuals exposed to different spatial configurations of ecological change to better inform targeted policy interventions. For instance, though most studies that examine how environmental change influences behavior consider change at one spatial extent, this and other research (Legatzke et al. 2026) show that individuals respond differently to change at multiple levels.

In the context of the Great Plains, it may be helpful to investigate how policy interventions at higher social levels (e.g., eliminating cost-share tree planting programs, increased prescribed burn permitting) influence voluntary individual management behavior. Understanding the role of non-profit organizations, particularly in the context of building networks and providing resources and information, may highlight how organizations at levels beyond the individual step in when state and municipal levels of government are risk averse to transformative institutional change (Legatzke et al. 2025). Though we show how ecological feedbacks affect individual behavior, circumventing institutional change to some degree, an unanswered question is the extent to which those individual behaviors, relative to ecological feedbacks, eventually force higher-level institutional change.

CONCLUSION

Scale mismatches severely limit our ability to manage SESs and prevent wide-spread regime shifts. Our research demonstrates that scale mismatches are occurring in the American Great Plains such that individual landowners, not a coordinated government response, are attempting to manage a regime shift occurring across the region. We highlight opportunities to enhance

institutional fit by leveraging existing efforts in the short term, such as focusing interventions in locations where voluntary action is most likely and eliminating barriers to coordinated action through policies that build capacity and align agency programs. Although widespread prescribed burning may not be currently possible given the institutional frameworks staunchly in place, understanding the extent to which low-risk opportunities can be promoted through incentivizing voluntary behavior is essential for charting a path toward longer-term sustainability outcomes and transformative institutional change (Cumming et al. 2006, Schultz et al. 2019). Although few studies explicitly examine how cross-scale and -level dynamics influence the resilience of social-ecological systems (Siders 2019, Vallury et al. 2022), we examine both by assessing the effects of cross-level ecological interactions and coordinated efforts on individual human behavior. Furthermore, we focus on understanding how the spatial extent of ecological processes influences that of social processes responsible for managing them, a rare example of ecological to social cross-scale feedbacks, and provide recommendations for improving institutional fit in this SES in Nebraska. Research on institutional fit helps identify where mismatches occur and provides policy makers with quantitative evidence and strategic guidance on how to resolve mismatches toward more sustainable management of our SESs.

Author Contributions:

HKN, ALM, DRU, MAW, BCC, TMF, and CRA conceived the ideas and designed the methodology. HKN and DRU collected the data. HKN, DRU, and MAW analyzed the data. HKN led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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Data Availability:

Data are available at https://doi.org/10.5281/zenodo.13942540. Statistical procedures and script are available at https://github.com/nesbitthollyPHDScalarMismatches.git.

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NEBRASKA RANGELAND VEGETATION CHANGE SURVEY

Working in Nebraska

1. Which of these options makes up the **largest proportion** of your operation?
(*Please choose only **one** option.)*

- ○ Cattle ranching
- ○ Other livestock (for example: dairy, pigs, poultry), please specify: _____
- ○ Farming
- ○ Specialty farm products (for example: bees), please specify: _____
- ○ Other, please specify: _____

2. How many years have you personally been ranching or farming?
Please enter a numeric value. _____ years

3. Please estimate the acreage of your operation in 2020.
Please enter a numeric value. If none, please enter a zero.

Owned acres _____ Acres rented from others _____

4. In what county in Nebraska is the largest proportion of your operation located?

_____

Cover photo: © Dillon Fogarty

Vegetation transitions and other changes on the landscape

The following questions ask about your experiences with changes on the landscape, including **"vegetation transitions"** on your operation. Specifically, we would like to know if you have noticed transitions from a mostly grassy landscape to one with more shrubs and trees.

5. Please indicate how strongly you agree or disagree with the following statements about **landscape changes in your area**. *(For each row, please choose only **one** option.)*

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
In my time managing my operation, I have noticed...					
...that vegetation has transitioned from mostly grasses to mostly shrubs/trees.	○	○	○	○	○
...more variability in precipitation.	○	○	○	○	○
...increased problems with invasive species on the landscape.	○	○	○	○	○
...more flooding at certain times of year.	○	○	○	○	○
...more severe drought at certain times of year.	○	○	○	○	○

6. Please indicate how strongly you agree or disagree with the following statements about **the general effects of vegetation transitions from mostly grasses to mostly shrubs/trees**. *(For each row, please choose only **one** option.)*

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Vegetation transitions will harm the profitability of rangelands in the long term.	○	○	○	○	○
Vegetation transitions will harm rangeland ecosystems.	○	○	○	○	○
Vegetation transitions are not a significant challenge to future agricultural productivity.	○	○	○	○	○

7. Please rate how often you have taken the following actions to **manage vegetation transitions on your operation *in the past three years***. *(For each row, please choose only **one** option.)*

	Never	Rarely	Occasionally	Always as appropriate
Chemical application	◯	◯	◯	◯
Prescribed burning	◯	◯	◯	◯
Rotational grazing	◯	◯	◯	◯
Mechanical removal	◯	◯	◯	◯
Other vegetation controls	◯	◯	◯	◯

8. For this question, imagine for a moment that vegetation transitions are occurring on your operation. Please indicate how strongly you agree or disagree with the following statements about **managing vegetation transitions from mostly grasses to mostly shrubs/trees on your operation**. Please respond to these questions as if **vegetation transitions are occurring on your operation**. *(For each row, please choose only **one** option.)*

	Strongly disagree	**Somewhat disagree**	**Neither agree nor disagree**	**Somewhat agree**	**Strongly agree**
If I take actions to manage vegetation transitions, it will inspire other producers to do so.	○	○	○	○	○
I doubt that other producers and I can collectively prevent vegetation transitions at a regional scale.	○	○	○	○	○
If nearby producers take actions to manage vegetation, it will also reduce the chance of vegetation transitions on my operation.	○	○	○	○	○
I can easily change practices on my operation to manage vegetation transitions.	○	○	○	○	○
I do not think I can personally do anything about vegetation transitions on my operation.	○	○	○	○	○
I believe my actions on my operation can significantly reduce vegetation transitions happening on the greater landscape.	○	○	○	○	○

9. Please indicate how strongly you agree or disagree with the following statements about **trying different ranching/farming practices on your operation to prevent vegetation transitions from mostly grasses to mostly shrubs/trees**. *(For each row, please choose only **one** option.)*

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I frequently look for information about new ranching/farming techniques to prevent vegetation transitions on my operation.	○	○	○	○	○
I implement test plots to evaluate new ranching/farming practices to prevent vegetation transitions on my operation.	○	○	○	○	○
I am willing to adopt management practices on my operation to prevent vegetation transitions on my neighbors' properties.	○	○	○	○	○

10. Recent advances in digital technology make it possible to map different types of vegetation across the landscape. In some areas, these maps can provide information about how quickly vegetation is transitioning from grasses to shrubs/trees. This vegetation mapping can be used as an "early warning system" to help producers get ahead of vegetation transitions and ensure operation profitability. The next three questions ask about your views regarding this mapping technology.

Please indicate how strongly you agree or disagree with the following statements about **information provided by technology**. *(For each row, please choose only **one** option.)*

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I am willing to consider using vegetation mapping to manage vegetation transitions on my operation.	○	○	○	○	○
I would like more access to vegetation maps to help me manage vegetation transitions on my operation.	○	○	○	○	○
I would attend a workshop to learn more about using vegetation mapping to manage vegetation transitions.	○	○	○	○	○

11. Please indicate how strongly you agree or disagree with the following statements about **managing risk on your operation related to vegetation transitions from mostly grasses to mostly shrubs/trees**. *(For each row, please choose only **one** option.)*

	Strongly disagree	**Somewhat disagree**	**Neither agree nor disagree**	**Somewhat agree**	**Strongly agree**
I like to experiment with new management practices to overcome risks to my operation from vegetation transitions.	○	○	○	○	○
Through effective planning, I can overcome risks to my operation from vegetation transitions.	○	○	○	○	○
I am willing to participate in **state funded** land conservation programs to reduce financial risks associated with vegetation transitions.	○	○	○	○	○
I am willing to participate in **federally funded** land conservation programs to reduce financial risks associated with vegetation transitions.	○	○	○	○	○
I am willing to participate in **privately funded** land conservation programs to reduce income risks associated with vegetation transitions.	○	○	○	○	○
If needed, I can rely on other producers in my community for assistance managing risks created by vegetation transitions on my operation.	○	○	○	○	○
The risks of adopting new technology to manage vegetation transitions on my operation outweigh the benefits.	○	○	○	○	○

12. Please indicate how strongly you agree or disagree with the following statements about **other people's efforts to manage vegetation transitions from mostly grasses to mostly shrubs/trees**. *(For each row, please choose only **one** option.)*

	Strongly disagree	**Somewhat disagree**	**Neither agree nor disagree**	**Somewhat agree**	**Strongly agree**
Most producers like me believe it's important to prevent vegetation transitions.	◯	◯	◯	◯	◯
Most producers like me are taking actions to prevent vegetation transitions.	◯	◯	◯	◯	◯
I trust the government to effectively manage vegetation transitions.	◯	◯	◯	◯	◯
I believe current efforts to manage vegetation transitions in my area are **not** working well enough.	◯	◯	◯	◯	◯

About your professional social network

We would like to ask you about the people who you go to for advice about rangeland management and the operations of your ranch or farm. Please list these people, but only use their **first names or initial**s to maintain privacy.

No one but the research team will see the names or initials you list and **we will never** use this information to identify or contact individuals.

As you answer these questions, **don't feel pressure to fill all 15 slots.** It's fine if people fit into multiple categories, but please make sure you ***only list each person once.***

13. First, think of the people with whom you work on your operation. Please list up to four people with whom you work.

Next, think of the people with whom you communicate about operating your ranch or farm. Please list up to four people with whom you communicate about your operation. Please consider people you have not already listed.

Next, think of the people to whom you go for rangeland management and operations advice. Please list up to four people with whom you consult for this information. Please consider people you have not already listed.

Finally, scan your list of contacts and decide: is anyone significant missing? If so, please add any additional people who should be included in your network of contacts regarding management activities on your operation.

The next few questions are about the people you just named. First, we will ask some questions about them, and then we will ask questions about your relationship with each person.

14. What is each person's **primary** occupation? *(For each person, please choose only **one** option.)*

	Rancher, farmer, or producer	Scientist or researcher	Government agency manager or conservationist	Other conservation professional	Farm financier	Other
1	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○
4	○	○	○	○	○	○
5	○	○	○	○	○	○
6	○	○	○	○	○	○
7	○	○	○	○	○	○
8	○	○	○	○	○	○
9	○	○	○	○	○	○
10	○	○	○	○	○	○
11	○	○	○	○	○	○
12	○	○	○	○	○	○
13	○	○	○	○	○	○
14	○	○	○	○	○	○
15	○	○	○	○	○	○

15. How many years have you known each person? Please enter a numeric value for each person.

If you've known a person for less than one year, please write 1.

	Years known
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	

16. What kinds of information do you mainly receive from each person?

*(For each person, please select **all options** that apply.)*

Information about...

	Ranch or farm operations	Ranch or farm technology	Conservation practices (prescribed burning, weed control, etc.)	Financial or insurance programs (CRP, EQIP, etc.)	Non-operations
1	☐	☐	☐	☐	☐
2	☐	☐	☐	☐	☐
3	☐	☐	☐	☐	☐
4	☐	☐	☐	☐	☐
5	☐	☐	☐	☐	☐
6	☐	☐	☐	☐	☐
7	☐	☐	☐	☐	☐
8	☐	☐	☐	☐	☐
9	☐	☐	☐	☐	☐
10	☐	☐	☐	☐	☐
11	☐	☐	☐	☐	☐
12	☐	☐	☐	☐	☐
13	☐	☐	☐	☐	☐
14	☐	☐	☐	☐	☐
15	☐	☐	☐	☐	☐

17. How frequently do you interact with each person? Please include both face-to-face and electronic interactions.

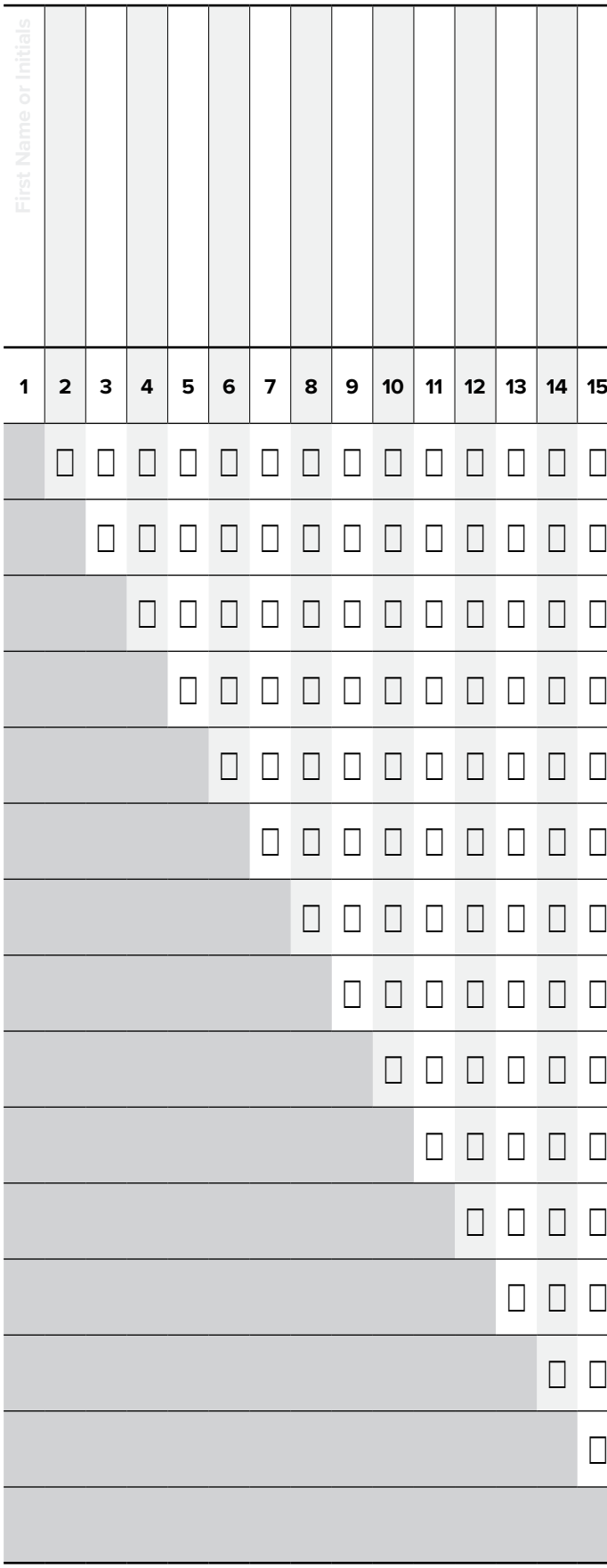
*(For each person, please choose only **one** option.)*

	Daily	2-3 times per week	Weekly	2-3 times per month	Monthly	Less than once per month
1	○	○	○	○	○	○
2	○	○	○	○	○	○
3	○	○	○	○	○	○
4	○	○	○	○	○	○
5	○	○	○	○	○	○
6	○	○	○	○	○	○
7	○	○	○	○	○	○
8	○	○	○	○	○	○
9	○	○	○	○	○	○
10	○	○	○	○	○	○
11	○	○	○	○	○	○
12	○	○	○	○	○	○
13	○	○	○	○	○	○
14	○	○	○	○	○	○
15	○	○	○	○	○	○

This question is to find out whether your social contacts know each other. Feel free to copy the list of your contacts into the header row of the table opposite. Make sure that the names and numbers match.

18. Please look across each person's ROW. If the person in the row and the person above know each other, place a check in the appropriate box. For example, say you named John, Paul, George and Ringo as your social contacts. For this question, you would go across John's ROW and put checks under Paul, George and Ringo, because John and Paul know each other, John and George know each other, and John and Ringo know each other. For your contacts who don't know each other, leave the boxes between them blank.

Take your time and be as accurate and complete as possible.



	First Names or Initials
Person 1	
Person 2	
Person 3	
Person 4	
Person 5	
Person 6	
Person 7	
Person 8	
Person 9	
Person 10	
Person 11	
Person 12	
Person 13	
Person 14	
Person 15	

19. Due to COVID-19, communication with the people I listed above has been...

*(Please choose only **one** option.)*

- ◯ ...very negatively affected.
- ◯ ...somewhat negatively affected.
- ◯ ...unaffected.
- ◯ ...somewhat positively affected.
- ◯ ...very positively affected.

20.a. Are there groups of people in your area that regularly meet to discuss rangeland management? *(Please choose only **one** option.)*

- ◯ No ➔ skip to **Question 21**
- ◯ Yes ➔ continue to **Question 20.b**

20.b. What's the extent of your involvement with these group(s)? *(Please choose only **one** option.)*

- ◯ I am not involved in any groups. ➔ skip to **Question 21**
- ◯ I am heavily involved with at least one group. ➔ continue to **Question 20.c**
- ◯ I am moderately involved with at least one group. ➔ continue to **Question 20.c**
- ◯ I am minimally involved with at least one group. ➔ continue to **Question 20.c**

20.c. What's the longest amount of time you have been involved in any of these groups? *(Please choose only **one** option.)*

- ◯ Less than 1 year
- ◯ 1-3 years
- ◯ 4-10 years
- ◯ 11-20 years
- ◯ More than 20 years

Economic decision making

In this section, we want to understand a little about your approach to decision making. We will ask you five questions about a hypothetical opportunity to win a cash payment. In each question, you will be asked to choose one of two options.

21. Option A guarantees a payment of $25,000 in all five choices, while in option B there is a 50-50 chance of winning a certain amount. **Which option would you choose for each question?**

Although this is a hypothetical exercise and no real payments are involved, please think carefully before making your choice for each question. *(For each numbered row, please choose only **one** option.)*

Question	Option A		Option B
1.	○ $25,000	OR	○ 50% chance of $48,000, and 50% chance of $1000
2.	○ $25,000	OR	○ 50% chance of $50,000, and 50% chance of $1000
3.	○ $25,000	OR	○ 50% chance of $52,000, and 50% chance of $1000
4.	○ $25,000	OR	○ 50% chance of $54,000, and 50% chance of $1000
5.	○ $25,000	OR	○ 50% chance of $56,000, and 50% chance of $1000
6.	○ $25,000	OR	○ 50% chance of $58,000, and 50% chance of $1000

About you

This final section asks about you and your operation.

22. Approximately what percentage of your household income came from agriculture in 2019? *(Please choose only **one** option.)*

- ○ 0-19%
- ○ 20-39%
- ○ 40-59%
- ○ 60-79%
- ○ 80-100%

23. In what year were you born? _____

24. Which best describes your gender? *(Please choose only **one** option.)*

- ○ Male
- ○ Female
- ○ Other

About you *(continued)*

25. What is the highest level of school you have completed? *(Please choose only **one** option.)*

- ○ Grade school
- ○ High school / GED
- ○ Some college or vocational training
- ○ 2-yr college
- ○ 4-yr college
- ○ Postgraduate

26. What was your total household income before taxes in 2019? *(Please choose only **one** option.)*

- ○ Less than $25,000
- ○ $25,000 - $49,999
- ○ $50,000 - $99,999
- ○ $100,000 - $149,999
- ○ $150,000 - $249,999
- ○ Greater than $250,000

Thank you for taking this survey. If you have any comments, please let us know here:

Please use the postage-paid envelope to mail the completed survey back to us.

Return address:

Center for Resilience in Agricultural Working Landscapes
203 Keim Hall
University of Nebraska-Lincoln - East Campus
Lincoln, NE 68583

Appendix 2

Supplementary material for Nesbitt et al. 2026 (Diagnosing and navigating scale mismatches in a social-ecological system in Ecology and Society)

Holly K. Nesbitt

January 22, 2026

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Survey details

Individuals unaffiliated with the research group piloted the questionnaire.

We purchased producer address information from Farm Market iD, an agricultural data marketing company, requesting addresses within our study counties for all National Agricultural Survey respondents with >20

acres of pasture/rangeland (N = 6546 with mailing addresses, 3448 for whom we had emails). After taking a simple random sample of 4500 from this population and removing duplicates, our sample size was 4494 individuals, 2409 for whom we had emails. Using a modified tailored design (Dillman, Smyth, and Christian 2014), we sent three survey invitation emails followed by three paper mailings; all mailings were spaced 2-3 weeks apart.

We asked respondents how often they used prescribed burning (i.e., response variable) to manage juniper encroachment on their operation in the last three years on a 4-point ordinal scale, which we dichotomized (never = 0, rarely/occasionally/frequently = 1) (Table 1). To measure coordinated collective factors, we asked respondents about their level of involvement in local rangeland management groups (Bennett et al. 2014; Cinner et al. 2015; Marshall et al. 2016). To generate the group involvement variable, we combined responses from two questions about whether those groups existed and, if so, individuals' level of involvement to create a dichotomized variable (Table 1).

Respondent profile

Our respondents were 91% male and 8% female with the remaining identifying as other or preferring not to disclose. Respondents most commonly had a 4-year college degree (26%) or some college or vocational training (25%) and had household income of $50-99,999/year (35%) or $100-149,999/year (19%). The average age of respondents was 64 at the time the survey was administered. Respondents owned between 0 and 84,000 acres (median = 460) and rented between 0 and 20,000 acres (median = 340).

Justification for 1 km radius and 100 km radius for percent tree cover calculations

We chose a 1 km radius because it results in an area of 3.14 km2 (776 acres), which somewhat approximated the average farm size in Nebraska of 1000 acres (USDA NASS 2021). We chose a 100 km radius because it encompasses average commute distances for every county in the state, which range from 25-70 km (Index Mundi 2018). Because change in mean percent tree cover calculated at a 100 km radius was not highly correlated with change in mean percent tree cover calculated at a 1 km radius (r = 0.36), we were able to include both variables in a model while avoiding multicollinearity.

Visualizations of the variables in the model

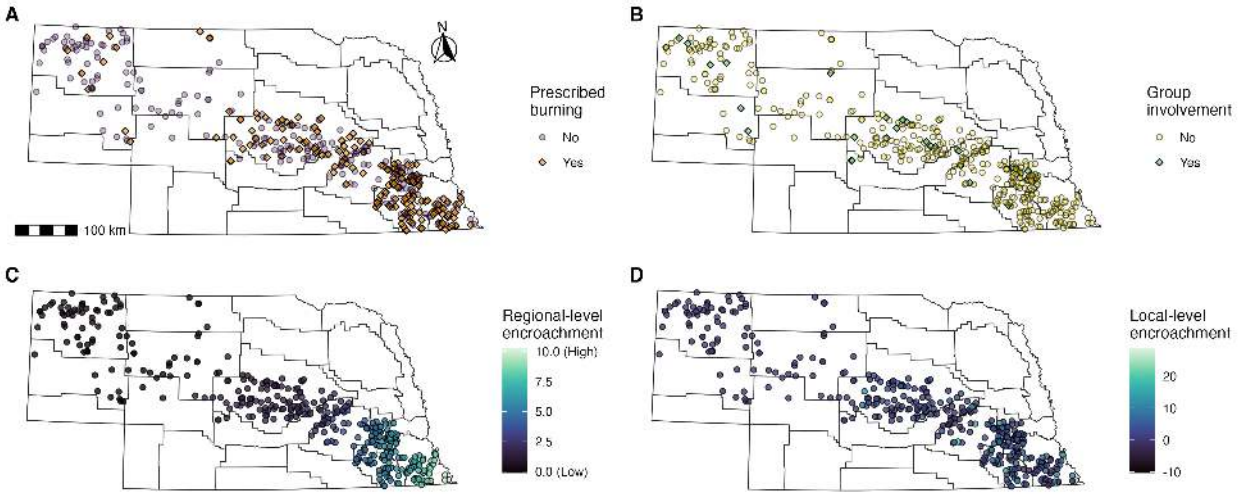


Figure A2.1: Maps of respondent locations (points) across Nebraska's Natural Resource Districts (polygons) showing whether respondents engaged in prescribed burning (A), were involved in groups (B), and the extent of regional- (C) and local-level encroachment (D) around them.

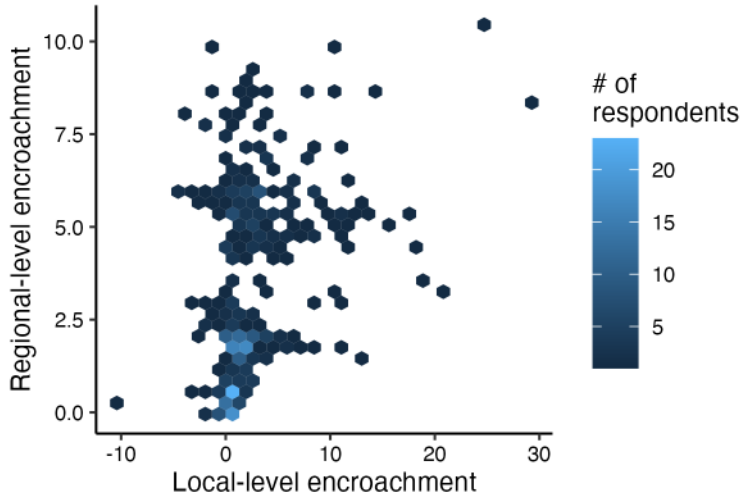


Figure A2.2: The number of respondents experiencing different combinations of local- and regional-level encroachment. The lighter the color, the more respondents experienced that particular combination.

Model specification

Priors

We expected that larger numbers are less likely for the parameter estimate for all of our variables, so we used a normal distribution centered at 0 with a standard deviation (sd) of 1.
We expected a narrow distribution of estimates for the intercept, so we used a student-t distribution with degrees of freedom (df) of 7, median (mu) of 0, and a scale parameter (sigma) of 1.5.
The standard deviation must be above 0, so we used an exponential distribution with a rate of 1 which truncates estimates above 0.

```
prior1 <- c(# expect that larger numbers would be less likely
            set_prior("normal(0,1)", class = "b", coef = "group_involve2"),
            set_prior("normal(0,1)", class = "b", coef = "trees1_9020"),
            set_prior("normal(0,1)", class = "b", coef = "trees100_9020"),
            set_prior("normal(0,1)", class = "b", coef = "trees100_9020:trees1_9020"),
            # expect a narrow distribution
            set_prior("student_t(7, 0, 1.5)", class = "b", coef = "Intercept"),
            # truncates above 0
            set_prior("exponential(1)", class = "sd"),
            # truncates above zero, allows SD to be wider for NRD effects
            set_prior("exponential(0.5)", class = "sd", coef = "Intercept", group = "nrd"))
```

Model controls

We ran 4 chains for 4000 iterations (1000 warmup, 3000 sampling). We used 2 cores and 2 chains. We used the Bernoulli family (with the logit link) to model a logistic regression.

```
output <- capture.output(burn <- brm(b_burn01 ~
                  0 + Intercept +
                  trees100_9020 +
                  trees1_9020 +
                  trees100_9020*trees1_9020 +
                  group_involve2 +
                  (1|nrd),
              data = dat90_20_z,
              warmup = 1000, iter = 3000,
              cores = 2, chains = 4,
              control = list(adapt_delta = 0.96),
              prior = prior1,
              seed = 123,
              family = bernoulli,
              sample_prior = T))
```

NRD-level effects

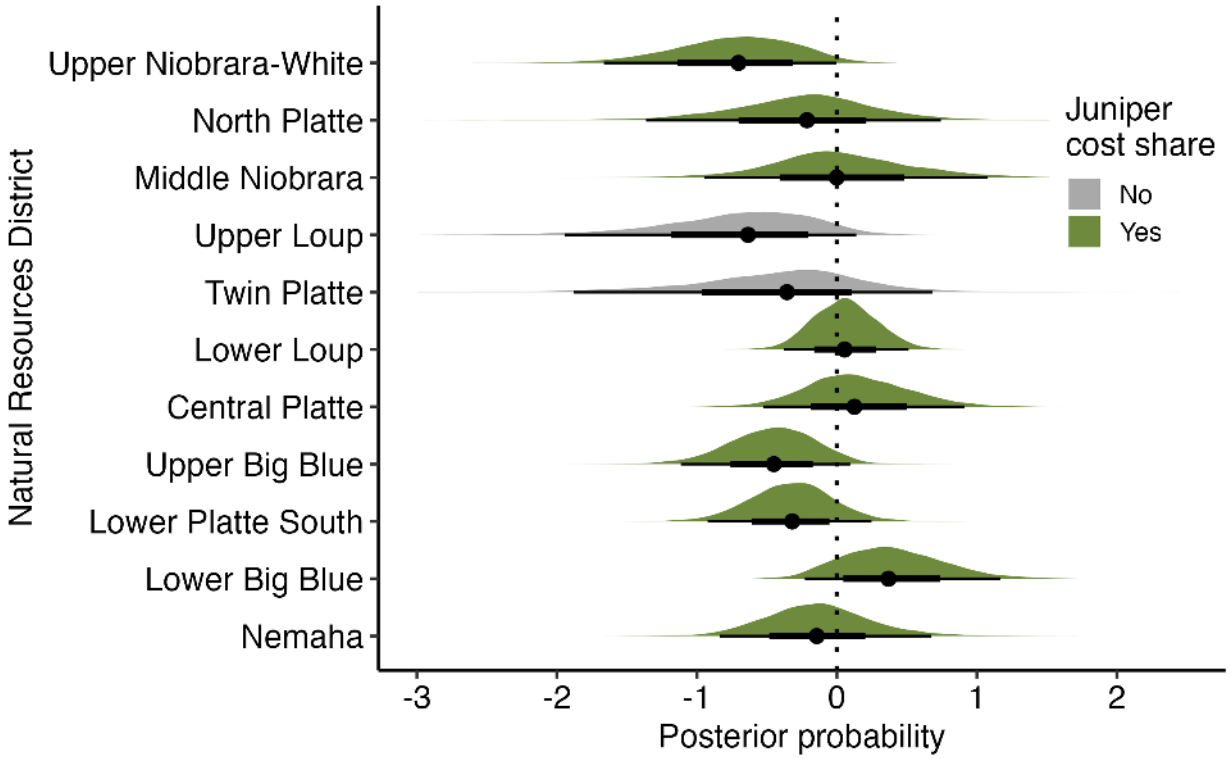


Figure A2.3: The effect of Natural Resources Districts (NRDs) on prescribed burning. NRDs are plotted in order from the northwest corner of the state (Upper Niobrara-White) to the southwest corner of the state (Nemaha) following the juniper encroachment gradient. NRDs with juniper cost share programs have a green density distribution and NRDs that have eliminated juniper cost share programs have a grey density distribution. The point is the median, the thick bars cover the middle 66% of the density distribution, and the thin bars cover the middle 95% of the density distribution.

Diagnostics and model checks

Posterior predictive check

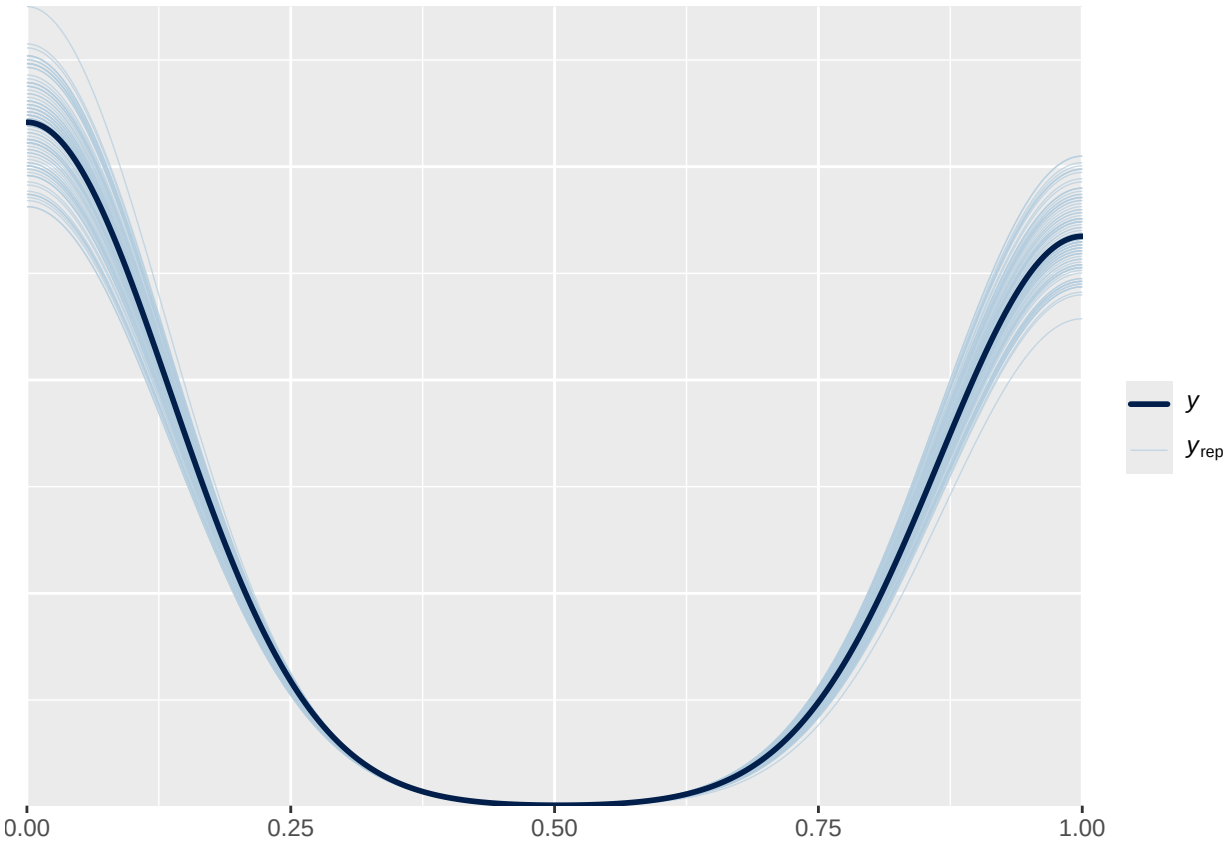


Figure A2.4: Posterior predictive check. The generated data (blue lines) match the real data closely (black thick line), indicating that the model is correctly specified.

Multicollinearity

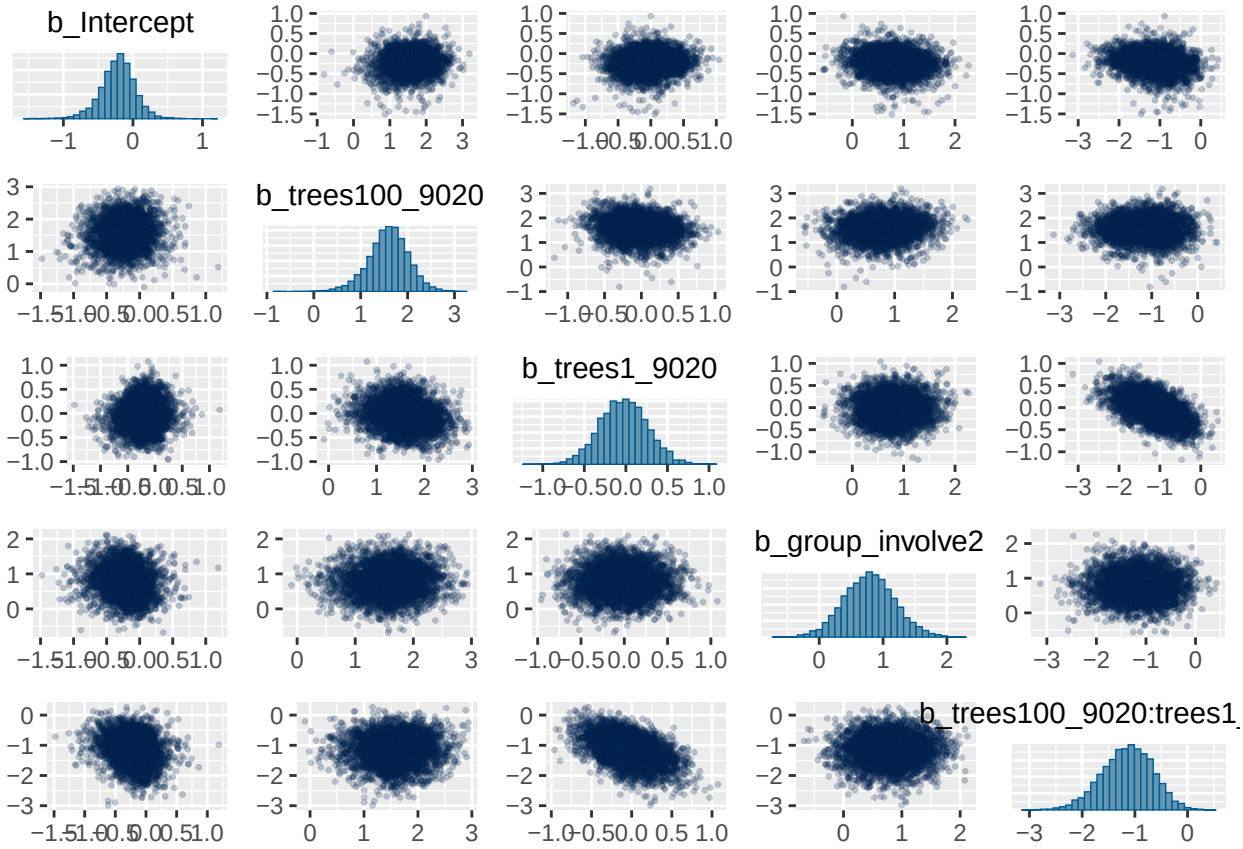


Figure A2.5: Scatter plots of generated data. Plots indicate that multicollinearity is not an issue.

Marginal posterior distributions

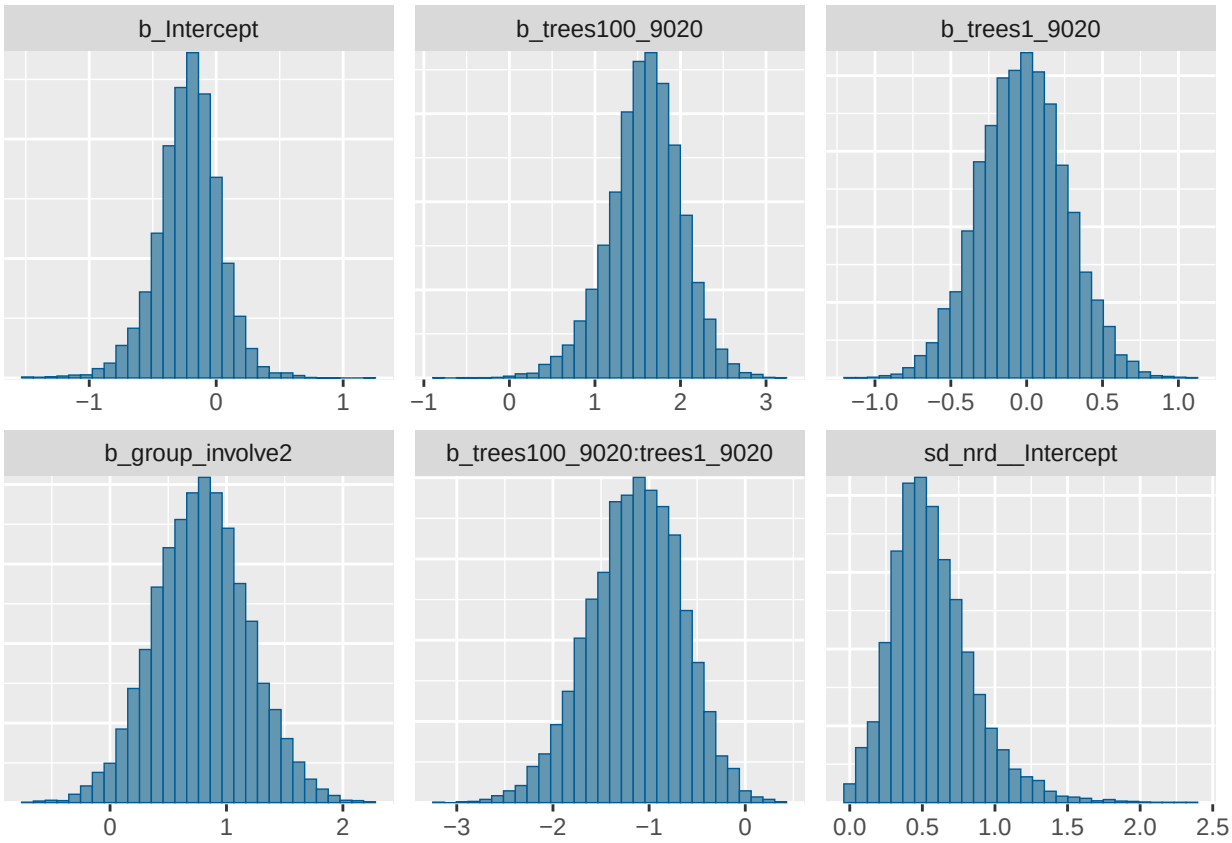


Figure A2.6: Histograms showing the marginal posterior distributions. Histograms are unimodal and centered, indicating that model estimates match the distribution. Distribution spread, indicating estimate uncertainty, is reasonable.

Chain convergence

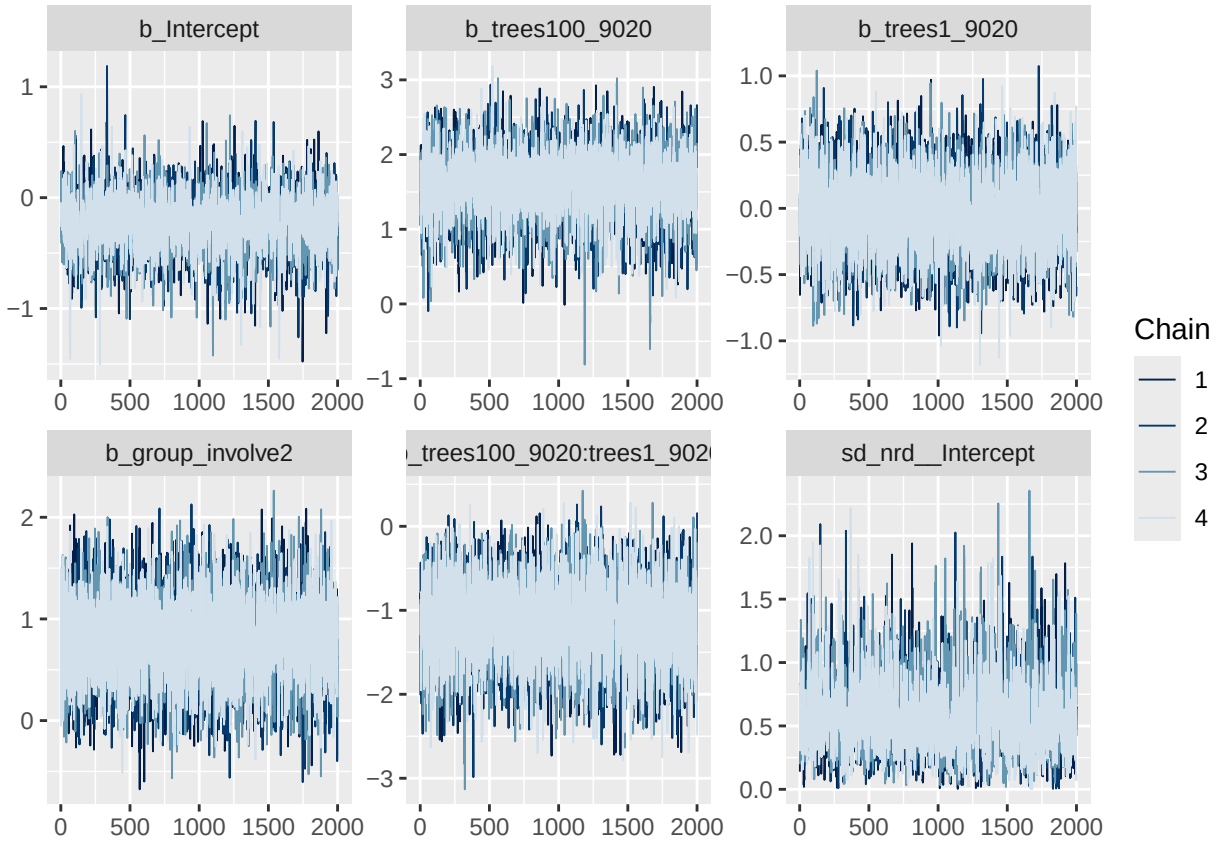


Figure A2.7: Caterpillar plots of model runs. Caterpillar plots indicate that chains converged.

Model fit and classification accuracy

Table A2.1: Model fit and classification accuracy. n = sample size, ELPD = expected log predictive density, LOO = leave-one-out cross validation.

Term	Value
n	396
ELPD LOO	-37.8 (7.8)
LOO classification accuracy	67%

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