

Managing U.S. Grasslands for Birds, Carbon, and Co-benefits

Natural Climate Solutions
Habitat Management Brief

Brooke L. Bateman, Adam J. Eichenwald,
Joanna Grand, Erika Knight, Amanda M. Long,
Shannon Reault, Meghan Ryan.

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Background



The Importance of Natural Climate Solutions

One of the most powerful tools for addressing the dual crises of climate change and biodiversity loss is nature itself. When managed well, forests, wetlands, coasts, and grasslands can provide healthy habitat for birds, store enough carbon to deliver up to one-third of the climate mitigation the world needs, and help reduce threats like flooding, drought, and extreme heat. There is no viable path to reaching the global targets for limiting temperature rise without putting these natural climate solutions (NCS) to work.

From Canada to Chile, Audubon and partners are implementing NCS at the size and scale needed to address the environmental challenges we face. Through this work, Audubon aims to keep 30 billion tons of carbon stored in forests, wetlands, and grasslands, with additional carbon sequestered each year. Beyond our own conservation actions, we are catalyzing action by others, ensuring bird-friendly NCS are adopted at the scale required to mitigate the climate and biodiversity crises.

FOCUSED ACTION

Audubon's [2021 Natural Climate Solutions Report](#), offered a roadmap for climate-smart conservation by identifying priority locations for protection, better management, and restoration to maximize carbon storage while supporting bird populations. Audubon's [2025 publication in Scientific Reports](#) pinpoints where conservation efforts would provide a triple benefit to protect bird habitat, naturally store carbon, and improve the well-being of local communities that have been under-represented in conservation efforts.

The maps in these two studies provide tools that illuminate where conservation action can

deliver the most meaningful impact. This Natural Climate Solutions Habitat Management Brief augments those data by describing what actions to take.

The following brief highlights which common habitat management practices are likely to benefit grassland birds, support carbon sequestration and storage, and deliver important co-benefits—including water quality, soil health, economic benefits, and improved resilience. Evidence presented was gathered through a literature review; please see the Methods & Areas for Future Research and the Appendix for details.

HABITAT IN FOCUS: U.S. GRASSLANDS

This brief is focused on Central and Western grasslands and rangelands in the United States. Grassland birds are in the steepest decline of any avian group in the U.S., largely due to habitat loss, degradation, and climate change. Improving our understanding of the relationship between common grassland habitat management practices and their impact on grassland birds and carbon will help to halt and ultimately reverse these declines by supporting more intentional, outcome-oriented conservation actions across U.S. grasslands.

How to Use this Brief

This brief is primarily intended for conservation practitioners so that its insights can be integrated into adaptive management strategies, management plans, and regional roadmaps.

The brief also provides insights for policymakers and funders seeking concrete solutions to address climate change and biodiversity loss. For example, strengthening voluntary conservation programs, incentives, and market mechanisms aligned with these findings would support positive outcomes for birds, climate, and communities.

This brief is focused on U.S. Central and Western grasslands and rangelands and leverages a literature review to assess which land management practices benefit grassland birds, increase carbon storage and sequestration, and support other important co-benefits.

 Cover: Cattle in shortgrass prairie on Rockin' 7 Ranch, an Audubon Certified Bird-Friendly ranch in Wyoming.

(this page) Horned Lark on May Valley Ranch, an Audubon Certified Bird-Friendly ranch in Colorado.



Findings

Summary

This brief evaluates eight common grassland management practices for their potential to benefit grassland birds, increase carbon storage and sequestration, and support important environmental and social co-benefits. In Table 1, the practices are classified based on their alignment with the natural climate solutions categories: protect, better manage, and restore. Each practice was scored based on the likelihood and strength of evidence of benefits. Key insights per practice are summarized below, with more detail included in the Appendix.

Across the practices reviewed, most demonstrate the potential to deliver multiple benefits simultaneously. The majority show evidence of “triple-win” performance—benefits to grassland birds, carbon, and co-benefits—under appropriate conditions, with many supporting two outcome areas. Only one practice consistently exhibits high sensitivity to context, suggesting that positive impacts are likely when practices are applied thoughtfully.

The evidence reviewed further underscores that grassland management outcomes are strongly shaped by local ecological, climatic and management context, and that the same practice may produce different results across landscapes depending on how and where it is applied. These findings are intended to support prioritization and decision-making, not to prescribe uniform solutions.

Triple-Win Practices:

For practitioners seeking the greatest likelihood of multiple positive outcomes, four practices show

consistent evidence of benefits across all outcome categories evaluated:

- **Adaptive grazing**
- **Protect wetlands from grazing**
- **Control of invasive species**
- **Plant native species**

These practices offer the highest certainty and lowest-risk pathways to realizing benefits for birds, carbon, and broader grassland resilience.

Double-Benefit Practices:

Three practices show strong evidence of delivering double benefits—supporting birds or increasing carbon storage while also providing clear and well documented co-benefits:

- **Control of woody encroachment**
- **Reduce insecticide use**
- **Prescribed fire in low tree-cover rangelands**

These practices reliably generate meaningful outcomes, with benefits often strengthened when aligned with site conditions, implementation methods, and management intensity.

Highly Context-Dependent Practices:

One practice shows outcomes that are strongly influenced by design, timing, and local conditions, offering meaningful opportunities to support both bird and carbon benefits when implemented thoughtfully. This practice benefits from careful planning and adaptive management to optimize outcomes:

- **Patch-burn grazing**

Across the eight grassland management practices reviewed, most demonstrate the potential to deliver multiple benefits simultaneously—supporting outcomes for grassland birds, climate change, and other important co-benefits.

 Calves on Two Rivers Ranch in the Nebraska Sandhills. Audubon's Conservation Ranching program works with farmers and ranchers to certify grasslands as beneficial bird habitats.

TABLE 1
Evidence Summary: Grassland Habitat Management Practices

PRACTICE	NCS CATEGORY	GRASSLAND BIRDS	CARBON	CO-BENEFITS
Adaptive grazing	MANAGE			• Biodiversity • Productivity • Resilience • Soil health • Water
Protect wetlands from grazing	PROTECT/RESTORE			• Biodiversity • Soil health • Water
Control of invasive plant species	MANAGE/RESTORE			• Biodiversity • Productivity • Soil health • Water
Plant native species	RESTORE			• Biodiversity • Soil health • Water
Control of woody encroachment	PROTECT/MANAGE			• Biodiversity • Productivity • Soil health • Water
Reduce insecticide use	MANAGE			• Biodiversity • Soil health • Water
Prescribed fire	MANAGE			• Biodiversity • Productivity • Resilience • Soil health
Patch-burn grazing	MANAGE			• Biodiversity • Productivity • Resilience • Soil health

ICON KEY

Likely to be beneficial

Context-dependent

Trade-offs between benefits and harms

Unknown effectiveness

The following practices show the strongest and most consistent evidence of bird benefit: adaptive grazing, protecting wetlands from grazing, reducing pesticide use, controlling invasive plant species and woody encroachment, and native planting. Patch-burn grazing offers trade-offs between benefits and harms to different species. Prescribed fire shows the most variable and context-dependent bird responses.

Carbon outcomes are consistently positive for practices that protect or restore existing vegetation and soil structure. This is particularly true for adaptive grazing, wetland protection, planting native species, removing invasive plant species, and prescribed fire in low tree-cover rangelands.

The carbon dynamics of woody encroachment control are nuanced and context dependent, but they generally shift carbon toward more resilient below-ground reserves without reducing total sequestration capacity. Patch-burn grazing shows more context dependent or inconclusive carbon results, and the direct impact of pesticide reduction on carbon storage is largely unknown.

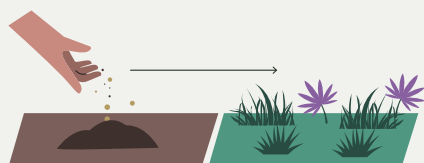
Co-benefits including improved water quality, soil health, biodiversity, resilience, and productivity are evident across nearly all practices. In several cases, they represent the most consistent and well-documented outcome of the practices reviewed.

Adaptive grazing, protecting wetlands from grazing, controlling invasive plant species, and planting native species stand out as the most reliable triple-win practices for birds, carbon, and grassland co-benefits.

sequestering carbon into stable, long-term underground reservoirs.²⁶⁻³¹

Co-benefits: Controlling invasive species, beyond reversing biodiversity loss, restores hydrological health and helps to improve economic outcomes where invasive species have reduced grazing capacity and land values.^{20,32-41} The management of invasive plant species includes prioritizing the defense of intact core habitats and removing small patches before they become unmanageable.³⁴ Strategies should be multi-faceted, integrating biological, mechanical, and chemical controls—including adaptive grazing, mowing, herbicide, prescribed burning, and active reseeded.

Plant Native Species



Birds: Native planting can be beneficial for grassland birds such as the Dickcissel. The most effective approach depends on the context and may include strategies such as integrating strips of native grasses within cropland, interseeding within existing prairie, or combining native seeding and planting with herbicide treatments or composting.^{42,43}

Carbon: Of the reviewed literature, two thirds of studies show a consistent positive relationship between native planting and grassland/rangeland carbon storage. Application methods such as native seed drilling paired with compost application increase the

likelihood and magnitude of carbon sequestration.⁴⁴⁻⁴⁹

Co-benefits: Native planting practices have demonstrated numerous ecological co-benefits, such as increased biodiversity, native plant abundance, and general vegetation health.⁵⁰⁻⁵⁷

Control of Woody Encroachment



Birds: There is strong and consistent evidence that woody plant encroachment (WPE) substantially decreases the density of grassland birds, such as Lesser Prairie-Chicken, Baird's Sparrow, Sprague's Pipit and Greater Sage Grouse. Removing woody plants is a primary mechanism for restoring populations of imperiled grassland-obligate birds.⁵⁸⁻⁶⁷

Carbon: Management of WPE (WPE) is generally found to increase below ground carbon storage in the mid- to long-term by shifting carbon from vulnerable aboveground biomass to stable, belowground pools without reducing total sequestration capacity. While encroachment increases above-ground carbon storage, this carbon is easily lost to wildfire; native grasslands offer deep, resilient sequestration.⁶⁸⁻⁸¹

Co-benefits: Restoring grasslands by removing WPE re-establishes critical hydrological functions, including groundwater recharge and streamflow, while mitigating soil

erosion and stabilizing soil organic matter. These interventions trigger a multi-taxonomic biodiversity rebound and secure the long-term economic viability of rangelands by protecting native forage production. Realizing these benefits requires a multi-faceted strategy that integrates immediate removal—typically through prescribed fire—with long-term stabilization through practices such as adaptive grazing, reseeding, and continued use of prescribed fire. Of note, WPE control frameworks must distinguish undesirable brush encroachment from the vital need to retain legacy native trees, such as open-canopy, low-density oaks in savanna systems that provide multiple benefits for birds, carbon, and more.^{27,61,65,72,73,75,81-92}

Reduce Insecticide Use



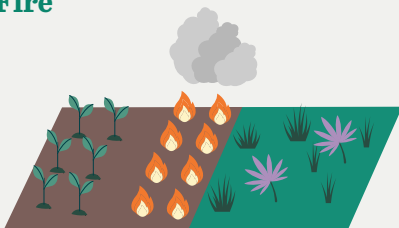
Birds: Reducing use of neonicotinoids and other insecticides lowers mortality and reproductive harm to birds and restores insect prey populations and food webs that support bird populations, such as Eastern and Western Meadowlarks.⁹³⁻⁹⁶

Carbon: The impact of reducing insect pesticide use on carbon dynamics remains poorly understood. While existing literature demonstrates insecticides can alter soil microbial communities and invertebrate populations, key drivers of carbon cycling, there is a

lack of field-based evidence linking these effects to changes in soil organic carbon.^{97,98}

Co-benefits: Reducing neonicotinoid and ivermectin pesticide use improves water quality for livestock and downstream aquatic ecosystems. In addition, reducing neonicotinoids and pyrethroids can improve beneficial insect populations by increasing dung beetle abundance,⁹⁸ wild bee occurrences,⁹⁹ and butterfly abundance and richness.¹⁰⁰ Other management considerations: Improving rangeland conditions can reduce the need for chemical pest control. Insecticides should be used only when warranted based on existing pest populations, and they should be selectively applied to target areas as needed rather than in advance (e.g., avoid seed treatments). Prioritize pest control chemicals that break down quickly, have low toxicity, are applied at the minimum effect rate and after July to avoid peak nesting periods.^{101–103} Other mechanisms to reduce pesticide use, such as integrated pest management, can promote pollinator conservation.⁹⁹

Prescribed Fire



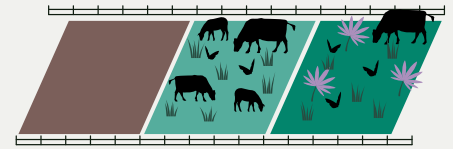
Birds: Prescribed fire is a foundational management tool, and the key questions relate to appropriate implementation. In

fire-dependent prairie systems, the absence of fire is itself a driver of degradation. Bird responses to prescribed fire are highly variable and species-dependent, meaning burns should be paired with ongoing monitoring of abundance (and nesting success if high predation is suspected) rather than assumed to be uniformly beneficial.^{104–107}

Carbon: While prescribed burns release carbon in the short term, when implemented in rangelands with low tree densities (<26% tree cover), they support better long-term carbon storage than either wildfire or fire suppression by protecting soil carbon reserves and reducing the risk of severe, high-intensity fires.^{109,110} Note that this threshold is specific to the rangeland carbon literature and does not reflect fire's role in other fire-dependent systems.

Co-benefits: Prescribed fire can meaningfully suppress invasive plant species and restore native vegetation; in oak savanna in particular, fire is the primary lever for reversing woody encroachment and restoring characteristic structure.^{111–113} Durable results typically require repeated burns, strategic timing, and integration with complementary practices like managed grazing.^{114,115} Prescribed fire also supports soil health,¹¹⁶ and reduces wildfire risk by decreasing fuel loads, lowering the likelihood of high-severity fire events that are more damaging to both ecosystems and communities.¹¹⁷ Together, these outcomes contribute directly to productivity, biodiversity, and long-term ecosystem resilience.

Patch-Burn Grazing



Birds: Patch-burn grazing (PBG)—a management strategy that concentrates grazing within rotationally burned portions of pasture—delivers benefits for some grassland birds at the pasture scale, generally improving habitat availability and breeding site selection.^{118–120} However, species requiring tall or dense structure for nest concealment (e.g. Lark Bunting) have shown significant declines in patch-burned relative to unburned pastures regardless of time since burn.¹²¹ Fragmentation, high stocking rates, predation, parasitism, and drought can constrain or offset avian diversity benefits. In highly fragmented landscapes, low stocking rates and periodic rest from grazing in unburned areas may be required to achieve a diverse bird community.^{121,122}

Carbon: When implemented within appropriate scales, stocking rates, and landscape context, PBG impacts on carbon are neutral to positive, with limited or no negative impacts on soil carbon stocks.^{120,123,124}

Co-benefits: Potential co-benefits of PBG include improved forage quality, invasive species control, vegetation beta diversity (turnover in species composition across patches) and structural heterogeneity, microbial abundance, ecosystem function, productivity, and drought resilience.^{124–128}



Recommendations

CONSERVATION PRACTITIONERS & LAND STEWARDS

These findings are not a prescriptive playbook, but a synthesis of where the evidence most consistently points across U.S. grasslands. Used alongside local knowledge and tailored to local context, they can help practitioners prioritize actions with a higher likelihood of delivering multiple benefits.

We recommend that practitioners prioritize actions with the highest likelihood of multiple benefits, while remaining responsive to local conditions and producer goals.

1 Lead with practices that show the strongest, most consistent multi-benefit outcomes

Adaptive grazing, protecting wetlands from grazing, control of invasive plant species, and planting native species offer the most reliable pathways to triple-wins—simultaneous benefits for birds, carbon storage, and overall grassland resilience. These areas provide a strong ecological foundation and should be prioritized as core components of broader grassland management strategies.

2 Pair high-confidence actions with Double-Benefit practices to expand gains

Several practices show strong evidence of either bird or carbon benefits, alongside clear and well-documented co-benefits. Controlling woody encroachment, reducing insecticide use, and prescribed fire in low tree-cover rangelands often deliver meaningful additional outcomes when tailored to site conditions.

These practices can complement triple-win practices and help scale benefits across working grasslands.

3 Let local context guide implementation, particularly for bird outcomes

Across nearly all practices evaluated, bird responses are more variable than carbon or co-benefits. Practitioners should expect differences among species and guilds and design management with focal species, habitat structure, and timing in mind. Aligning practices with local ecological conditions can help strengthen positive outcomes for grassland birds.

4 Apply Highly Context-Dependent practices with clear objectives and adaptive management

Patch-burn grazing can deliver bird and carbon benefits when thoughtfully designed. These practices are most effective when guided by clear ecological objectives, implemented with flexibility in intensity, scale and timing, and supported by ongoing monitoring to guide adjustments over time.

5 Elevate co-benefits in producer engagement

Co-benefits such as improved water quality, soil health, drought resilience, and productivity are among the most consistent outcomes across practices. Centering these benefits can strengthen alignment between conservation goals and producer priorities.

 Audubon Range Ecologists have helped producer Ed Brown, right, improve bird-friendly grazing practices at his Two Rivers Ranch in the Nebraska Sandhills.

POLICYMAKERS, FUNDERS, AND CONSERVATION INVESTORS

These findings highlight where public and private investments can most reliably deliver climate, biodiversity, and community benefits across U.S. grasslands. Rather than suggesting one-size-fits-all solutions, they point to opportunities for aligning policy and investment with practices that consistently generate multiple benefits, while maintaining the flexibility needed to respond to diverse ecological and management contexts.

We recommend aligning conservation policy and investments with practices most likely to deliver multiple benefits—while preserving flexibility and supporting producer-led solutions across diverse landscapes.

1 Prioritize support for high-confidence, multi-benefit practices

Public and private investments are likely to achieve greater returns by emphasizing practices with strong evidence of multi-benefit outcomes—particularly adaptive grazing, protecting wetlands from grazing, control of invasive species, and planting native species. Additional support for double-benefit practices—including woody encroachment control, reduced insecticide use, and prescribed fire in appropriate contexts—can further expand climate and biodiversity gains.

2 Build flexibility into program design

Because outcomes are shaped by local ecological and management conditions, conservation programs are often more effective when they allow for regionally appropriate implementation and encourage adaptive management rather than rigid prescriptions.

3 Treat co-benefits as core outcomes

Improved soil health, drought resilience, and productivity are core benefits of many practices reviewed. Recognizing these benefits explicitly in conservation programs can strengthen cross-sector value, increase producer participation, and enhance durability of investments.

4 Invest in monitoring, technical assistance, and targeted research

Variability in outcomes and strong context dependence underscores the importance of practice-level monitoring and evaluation, and the value of research aimed at improving implementation effectiveness and regional outcomes. Strengthening local technical assistance—including support for Technical Service Providers qualified by Natural Resources Conservation Service (NRCS) and other trusted non-profit organizations—can help translate science into successful on-the-ground implementation.

5 Support management pathways rather than single practices

Evidence suggests that conservation success often comes from sequences and combinations of actions over time, not isolated practices. Programs that support flexible, producer-led management pathways allow practices to build on one another, reflecting how grassland systems function and how management decisions are made in practice. Longer-term, flexible program frameworks can better enable sustained, multi-benefit outcomes.

Audubon Conservation Ranching

The Audubon Conservation Ranching program works with farmers and ranchers to protect and enhance bird habitat across United States grasslands through market-connected conservation. The program certifies lands managed

with bird-friendly practices and connects participating producers to consumers and companies seeking to support biodiversity, healthy grasslands, and resilient working lands.

The practices highlighted in this brief—including adaptive grazing, restoring native plant species, protecting wetlands from grazing, and managing invasive species and woody

encroachment—align with the program's science-based approach to sustaining grassland ecosystems while supporting agricultural productivity. By pairing conservation outcomes with economic opportunity, Audubon Conservation Ranching demonstrates how working lands can support birds, store carbon, and strengthen rural resilience.



Learn more: audubon.org/ranching



Methods & Areas for Future Research

Evidence for each practice was gathered through structured literature searches in Web of Science and Google Scholar, supplemented by NRCS and U.S. Geological Survey (USGS) white papers where published literature was limited. Searches combined practice-specific keywords with carbon, bird, location, and ecosystem terms; results were saved and organized by practice in Zotero, manually filtered for relevance, and synthesized after reviewing the available literature to a point of thematic saturation. Findings for each practice were then summarized and classified across grassland bird, carbon, and co-benefit outcomes, using an icon system reflecting the strength and direction of available evidence.

Several evidence gaps exist across the practices evaluated. The relationship between grassland management and soil carbon dynamics is understudied or methodologically limited for

some practices evaluated here, making it difficult to draw firm conclusions across all practices. Pesticide research presents a clear example: while the harms of neonicotinoid and ivermectin use are reasonably well documented, limited regulatory pressure and the difficulty of isolating pesticide effects in large, heterogeneous landscapes have left the question of what reduction or recovery looks like in U.S. grassland contexts largely unanswered. Bird responses to many practices are highly variable and species-dependent, underscoring the value of site-level monitoring paired with any management change. More broadly, field-based research directly examining these relationships in U.S. grassland and rangeland contexts is limited and expanding that evidence base will be essential to refining guidance and building confidence in these practices as natural climate solutions.

 **Western Meadowlark on Rockin' 7 Ranch, an Audubon Certified Bird-Friendly ranch in Wyoming.**

Acknowledgements

We thank all of our Audubon colleagues who shepherded this report forward and provided feedback that improved this report throughout the process, especially Dan Devine, Chris Wilson, Thomas Schroeder, Nat Miller, Anthony Hauck, Megan Moriarty, Glynnis Breen, Sarah Rose, Sam Wojcicki, and Chad Wilsey. We also thank all of the individuals outside of Audubon who contributed their time and expertise to review an earlier draft and provided comments that improved it.

PHOTOS: EVAN
BARRIENTOS/AUDUBON
(COVER, P2, P10);
SHEA EVANS (P3,8).
ILLUSTRATIONS: JULIE
ROSSMAN/AUDUBON;
ANNALISE KRISTENSEN/
AUDUBON.

Literature Cited

1. Derner, J. D. et al. Adaptive grazing management in semiarid rangelands: An outcome-driven focus. *Rangelands* 44, 111-118 (2022).
2. Morris, C. How Biodiversity-Friendly Is Regenerative Grazing? *FRONTIERS IN ECOLOGY AND EVOLUTION* 9, (2021).
3. Shrestha, B. M. et al. Adaptive Multi-Paddock Grazing Lowers Soil Greenhouse Gas Emission Potential by Altering Extracellular Enzyme Activity. *Agronomy* 10, 1781 (2020).
4. di Virgilio, A., Lambertucci, S. & Morales, J. Sustainable grazing management in rangelands: Over a century searching for a silver bullet. *AGRICULTURE ECOSYSTEMS & ENVIRONMENT* 283, (2019).
5. Teague, W. et al. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. *AGRICULTURE ECOSYSTEMS & ENVIRONMENT* 141, 310-322 (2011).
6. Wang, T., Jin, H., Kreuter, U. & Teague, R. Understanding producers' perspectives on rotational grazing benefits across US Great Plains. *RENEWABLE AGRICULTURE AND FOOD SYSTEMS* 37, 24-35 (2022).
7. Schmid, R. B., Welch, K. D., Teague, R. & Lundgren, J. G. Adaptive Multipaddock (AMP) Pasture Management Increases Arthropod Community Guild Diversity Without Increasing Pests. *Rangeland Ecology & Management* 94, 141-148 (2024).
8. Augustine, D. J. et al. Adaptive, Multipaddock Rotational Grazing Management: A Ranch-Scale Assessment of Effects on Vegetation and Livestock Performance in Semiarid Rangeland. *Rangeland Ecology and Management* <https://doi.org/10.1016/j.rama.2020.07.005> (2020) doi:10.1016/j.rama.2020.07.005.
9. Dobkin, D. S., Rich, A. C. & Pyle, W. H. Habitat and avifaunal recovery from livestock grazing in a riparian meadow system of the northwestern Great Basin. *Conserv. Biol.* 12, 209-221 (1998).
10. Nelson, K. S., Gray, E. M. & Evans, J. R. Finding solutions for bird restoration and livestock management: comparing grazing exclusion levels. *Ecol. Appl.* 21, 547-554 (2011).
11. Poessel, S. A., Hagar, J. C., Haggerty, P. K. & Katzner, T. E. Removal of cattle grazing correlates with increases in vegetation productivity and in abundance of imperiled breeding birds. *Biological Conservation* 241, 108378 (2020).
12. Popotnik, G. J. & Giuliano, W. M. Response of birds to grazing of riparian zones. *J. Wildl. Manage.* 64, 976-982 (2000).
13. Berzins, L. L., Harris, M. E. & McKellar, A. E. Aerial insectivores breeding in agricultural landscapes: Highlighting the value of wetlands and heterogeneous habitats. *Ornithological Applications* 128, 1-16 (2026).
14. Macdade, L. S., Rodewald, P. G. & Hatch, K. A. Contribution of Emergent Aquatic Insects to Refueling in Spring Migrant Songbirds. *Auk* 128, 127-137 (2011).
15. Ascenzi, I., Hilbers, J. P., van Katwijk, M. M., Huijbregts, M. A. J. & Hanssen, S. V. Increased but not pristine soil organic carbon stocks in restored ecosystems. *Nat. Commun.* 16, 637 (2025).
16. Booth, D. T., Likins, J. C., Cox, S. E., Norton, J. B. & Anderson-Sprecher, R. C. Grazing Increases Soil Warming in Headwater Wetlands: Importance to Land Managers and Water Users. *Ecosystems* 25, 1052-1065 (2022).
17. Willard, S. et al. Examining climate benefits from rangeland and pasture management practices in the United States: opportunities, tradeoffs, and information gaps. *npj Sustain. Agric.* 3, 63 (2025).
18. Kauffman, J. B., Thorpe, A. S. & Brookshire, E. N. J. Livestock Exclusion and Belowground Ecosystem Responses in Riparian Meadows of Eastern Oregon. *Ecological Applications* 14, 1671-1679 (2004).
19. Kidd, S. A. & Yeakley, J. A. Riparian Wetland Plant Response to Livestock Exclusion in the Lower Columbia River Basin. *naar* 35, 504-514 (2015).
20. Coon, J. J. et al. Bird and arthropod response to herbicide and grazing: Trade-offs and time lags in invasive plant management. *Ecosphere* 16, e70355 (2025).

21. Flanders, A. A. et al. Effects of Invasive Exotic Grasses on South Texas Rangeland Breeding Birds. *Auk* 123, 171-182 (2006).
22. Fuhlendorf and Samuel D. and Harrell and Wade C. and Engle and David M. and Hamilton and Robert G. and Davis and Craig A. and Leslie and Jr. and David M. Should heterogeneity be the basis for conservation? Grassland bird response to fire and grazing. *ECOLOGICAL APPLICATIONS* (2006).
23. Lloyd, J. D. & Martin, T. E. Reproductive Success of Chestnut-Collared Longspurs in Native and Exotic Grassland. *The Condor* 107, 363-374 (2005).
24. Nelson, S. et al. Contrasting impacts of invasive plants and human-altered landscape context on nest survival and brood parasitism of a grassland bird. *LANDSCAPE ECOLOGY* 33, 1799-1813 (2018).
25. Scheiman, D., Bollinger, E. & Johnson, D. Effects of leafy spurge infestation on grassland birds. *JOURNAL OF WILDLIFE MANAGEMENT* 67, 115-121 (2003).
26. Bradley, B. A., Houghton, R. A., Mustard, J. F. & Hamburg, S. P. Invasive grass reduces aboveground carbon stocks in shrublands of the Western US. *Global Change Biology* 12, 1815-1822 (2006).
27. Dickens, S., Allen, E., Santiago, L. & Crowley, D. Extractable nitrogen and microbial community structure respond to grassland restoration regardless of historical context and soil composition. *AOB PLANTS* 7, (2015).
28. Maxwell, T. M., Quicke, H. E., Price, S. J. & Germino, M. J. Annual grass invasions and wildfire deplete ecosystem carbon storage by >50% to resistant base levels. *Commun Earth Environ* 5, 669 (2024).
29. Nagy, R. C. et al. A synthesis of the effects of cheatgrass invasion on US Great Basin carbon storage. *Journal of Applied Ecology* 58, 327-337 (2021).
30. Skersiene, A., Slepeliene, A., Stukonis, V. & Norkeviciene, E. Accumulation of SOC and Carbon Fractions in Different Age Red Fescue Permanent Swards. *Land* 12, 1025 (2023).
31. Wisconsin Reed Canary Grass Management Working Group. Reed Canary Grass (*Phalaris arundinacea*) Management Guide: Recommendations for Landowners and Restoration Professionals. https://www.nrcs.usda.gov/sites/default/files/2022-09/Reed%20Canary%20Grass%20Management%20Guide_0.pdf (2009).
32. Bais, H. P., Vepachedu, R., Gilroy, S., Callaway, R. M. & Vivanco, J. M. Allelopathy and Exotic Plant Invasion: From Molecules and Genes to Species Interactions. *Science* 301, 1377-1380 (2003).
33. Ceradini, J. P. & Chalfoun, A. D. When perception reflects reality: Non-native grass invasion alters small mammal risk landscapes and survival. *Ecol Evol* 7, 1823-1835 (2017).
34. DiTomaso, J. M. Invasive weeds in rangelands: Species, impacts, and management. *Weed Science* 48, 255-265 (2000).
35. Gasch, C. K. et al. Kentucky bluegrass invaded rangeland: Ecosystem implications and adaptive management approaches. *Rangelands* 42, 106-116 (2020).
36. Hall, L., Mull, J. & Cavitt, J. Relationship between cheatgrass coverage and the relative abundance of snakes on Antelope Island, Utah. *Western North American Naturalist* 69, (2009).
37. Lacey, J. R., Marlow, C. B. & Lane, J. R. Influence of Spotted Knapweed (*Centaurea maculosa*) on Surface Runoff and Sediment Yield. *Weed Technology* 3, 627-631 (1989).
38. Leitch, J. A., Leistritz, F. L. & Bangsund, D. A. Economic Effect of Leafy Spurge in the Upper Great Plains: Methods, Models, and Results. *Agricultural Economics Reports* <https://ideas.repec.org/p/ags/nddaer/23196.html> (1994).
39. Liao, C. et al. Altered ecosystem carbon and nitrogen cycles by plant invasion: a meta-analysis. *New Phytologist* 177, 706-714 (2008).
40. Litt, A. R. & Steidl, R. J. Insect assemblages change along a gradient of invasion by a nonnative grass. *Biol Invasions* 12, 3449-3463 (2010).
41. Reed, H. E., Seastedt, T. R. & Blair, J. M. Ecological Consequences of C4 Grass Invasion of a C4 Grassland: A Dilemma for Management. *Ecological Applications* 15, 1560-1569 (2005).
42. Coon, J. J., Nelson, S. B. M., Bradley, I. A., Rola, K. E. & Miller, J. R. Increased abundance and productivity of a grassland bird after experimental control of invasive tall fescue. *Restor. Ecol.* 30, e13709 (2022).
43. Schulte, L. A. et al. Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn-soybean croplands. *Proc. Natl. Acad. Sci. U. S. A.* 114, 11247-11252 (2017).
44. Conant, R. T., Cerri, C. E. P., Osborne, B. B. & Paustian, K. Grassland management impacts on soil carbon stocks: a new synthesis. *Ecol. Appl.* 27, 662-668 (2017).
45. Hernandez-Ramirez, G., Sauer, T. J., Chendev, Y. G. & Gennadiev, A. N. Nonlinear turnover rates of soil carbon following cultivation of native grasslands and subsequent afforestation of croplands. *Soil* 7, 415-431 (2021).
46. Luong, J. C., Mejia-Muñoz, J. & Krone, P. Compost and Native Seeding Interactively Increase Bulk Soil Carbon, but Compost Addition Favors Nonnative Plants. *Rangeland Ecol. Manage.* 103, 104-112 (2025).
47. Phillips, C. B. Legume Establishment in Native Warm-Season Grass Pastures. (Virginia Tech, 2023).
48. Stricker, E. & O'Connell, M. Amendments and seeding did not augment erosion control structure effectiveness in dry rangelands. *Ecosphere* 16, e70105 (2025).

49. Walston, L. J. et al. Modeling the ecosystem services of native vegetation management practices at solar energy facilities in the Midwestern United States. *Ecosyst. Serv.* 47, 101227 (2021).
50. Avila-Sanchez, J. S. et al. Rangeland Ecology & Management Highlights. *Rangelands* 43, 127–130 (2021).
51. Dhar, A., Wilkinson, S. R. & Naeth, M. A. Reclaiming Disturbed Sites: Influence of Planting Time, First-Year Mowing, and Seed Mix Richness Over 8 Years. *Appl. Veg. Sci.* 28, (2025).
52. Hall, C. D. Native grass and forb establishment in post-agricultural soil. (University of Denver, 2013).
53. Holfus, C. M. Restoration of Annual Grass-invaded Landscapes in the Sagebrush Steppe using Perennial Grass Seed Technologies and Wyoming Big Sagebrush Transplanting. https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/08612w639 (2021).
54. McFarlane, S. L., Kochanski, J. M., Gratton, C. & Damschen, E. I. Intervention intensity predicts the quality and duration of prairie restoration outcomes. *Restoration Ecology* 31, e13993 (2023).
55. Porensky, L. M., Perryman, B. L., Williamson, M. A., Madsen, M. D. & Leger, E. A. Combining active restoration and targeted grazing to establish native plants and reduce fuel loads in invaded ecosystems. *Ecol. Evol.* 8, 12533–12546 (2018).
56. Scott, S. V. Effects of biochar, subsoiling, and native seeding on the establishment of pollinator habitat in log landings. (University of Missouri-Columbia, 2024).
57. Trowbridge, C. C. Long-term effects of prairie restoration: community structure and native plant population dynamics 6 years after experimental management. (University of British Columbia, 2015).
58. Andersen, E. & Steidl, R. Woody plant encroachment reduces density of most grassland specialists in a desert grassland but has limited influence on nest survival. *ORNITHOLOGICAL APPLICATIONS* 125, (2023).
59. Bernath-Plaisted, J. S. et al. Review of Conservation Challenges and Possible Solutions for Grassland Birds of the North American Great Plains. *Rangeland Ecology & Management* 90, 165–185 (2023).
60. Coffman, J., Bestelmeyer, B., Kelly, J., Wright, T. & Schooley, R. Restoration Practices Have Positive Effects on Breeding Bird Species of Concern in the Chihuahuan Desert. *RESTORATION ECOLOGY* 22, 336–344 (2014).
61. Frost, J. & Powell, L. Cedar Infestation Impacts Avian Communities along the Niobrara River Valley, Nebraska. *RESTORATION ECOLOGY* 19, 529–536 (2011).
62. Holmes, A., Maestas, J. & Naugle, D. Bird Responses to Removal of Western Juniper in Sagebrush-Steppe. *RANGELAND ECOLOGY & MANAGEMENT* 70, 87–94 (2017).
63. Johnson, D. The Effects of Management Practices on Grassland Birds. Professional Paper <https://pubs.usgs.gov/publication/pp1842> (2019) doi:10.3133/pp1842.
64. Lautenbach, J. et al. Woody Vegetation Removal Benefits Grassland Birds on Reclaimed Surface Mines. *JOURNAL OF FISH AND WILDLIFE MANAGEMENT* 11, 89–98 (2020).
65. Olsen, A. et al. Reversing Tree Encroachment Increases Usable Space for Sage-Grouse during the Breeding Season. *WILDLIFE SOCIETY BULLETIN* 45, 488–497 (2021).
66. Pulliam, J. P., Somershoe, S., Sather, M. & McNew, L. B. Habitat Targets for Imperiled Grassland Birds in Northern Mixed-Grass Prairie. *Rangeland Ecology & Management* 73, 511–519 (2020).
67. Silber, K., Hefley, T., Castro-Miller, H., Ratajczak, Z. & Boyle, W. The long shadow of woody encroachment: An integrated approach to modeling grassland songbird habitat. *ECOLOGICAL APPLICATIONS* 34, (2024).
68. Mushinski, R., Zhou, Y., Hyodo, A., Casola, C. & Boutton, T. Interactions of long-term grazing and woody encroachment can shift soil biogeochemistry and microbiomes in savanna ecosystems. *GEODERMA* 441, (2024).
69. Abdallah, M., Mata-González, R., Noller, J. & Ochoa, C. Ecosystem carbon in relation to woody plant encroachment and control: Juniper systems in Oregon, USA. *AGRICULTURE ECOSYSTEMS & ENVIRONMENT* 290, (2020).
70. Asner, G., Archer, S., Hughes, R., Ansley, R. & Wessman, C. Net changes in regional woody vegetation cover and carbon storage in Texas Drylands, 1937–1999. *GLOBAL CHANGE BIOLOGY* 9, 316–335 (2003).
71. Cable, J., Ogle, K., Tyler, A., Pavao-Zuckerman, M. & Huxman, T. Woody plant encroachment impacts on soil carbon and microbial processes: results from a hierarchical Bayesian analysis of soil incubation data. *PLANT AND SOIL* 320, 153–167 (2009).
72. Creamer, C., Filley, T., Boutton, T., Oleynik, S. & Kantola, I. Controls on soil carbon accumulation during woody plant encroachment: Evidence from physical fractionation, soil respiration, and $\delta^{13}\text{C}$ of respired CO_2 . *SOIL BIOLOGY & BIOCHEMISTRY* 43, 1678–1687 (2011).
73. Creamer, C. et al. Degree of woody encroachment into grasslands controls soil carbohydrate and amino compound changes during long term laboratory incubation. *ORGANIC GEOCHEMISTRY* 52, 23–31 (2012).
74. DeMarco, J., Filley, T. & Throop, H. Patterns of woody plant-derived soil carbon losses and persistence after brush management in a semi-arid grassland. *PLANT AND SOIL* 406, 277–293 (2016).
75. Ding, J. & Eldridge, D. Ecosystem service trade-offs resulting from woody plant removal vary with biome, encroachment stage and removal method. *JOURNAL OF APPLIED ECOLOGY* 61, 236–248 (2024).

76. Gan, L. & Hu, X. Woody plant encroachment allocated more photosynthetic carbon belowground through soil pores in grasslands. *CATENA* 258, (2025).
77. Hughes, R. et al. Changes in aboveground primary production and carbon and nitrogen pools accompanying woody plant encroachment in a temperate savanna. *GLOBAL CHANGE BIOLOGY* 12, 1733–1747 (2006).
78. Li, H. et al. Effects of shrub encroachment on soil organic carbon in global grasslands. *SCIENTIFIC REPORTS* 6, (2016).
79. McCulley, R. & Jackson, R. Conversion of Tallgrass Prairie to Woodland: Consequences for Carbon and Nitrogen Cycling. *AMERICAN MIDLAND NATURALIST* 167, 307–321 (2012).
80. Neff, J., Barger, N., Baisden, W., Fernandez, D. & Asner, G. Soil carbon storage responses to expanding pinyon-juniper populations in southern Utah. *ECOLOGICAL APPLICATIONS* 19, 1405–1416 (2009).
81. Puttock, A. et al. Changes in ecosystem structure, function and hydrological connectivity control water, soil and carbon losses in semi-arid grass to woody vegetation transitions. *EARTH SURFACE PROCESSES AND LANDFORMS* 38, 1602–1611 (2013).
82. Anadón, J. D., Sala, O. E., Turner, B. L. & Bennett, E. M. Effect of woody-plant encroachment on livestock production in North and South America. *Proceedings of the National Academy of Sciences* 111, 12948–12953 (2014).
83. Brudvig, L. & Asbjornsen, H. The removal of woody encroachment restores biophysical gradients in Midwestern oak savannas. *JOURNAL OF APPLIED ECOLOGY* 46, 231–240 (2009).
84. Daryanto, S., Fu, B. & Zhao, W. Evaluating the use of fire to control shrub encroachment in global drylands: A synthesis based on ecosystem service perspective. *SCIENCE OF THE TOTAL ENVIRONMENT* 648, 285–292 (2019).
85. Keen, R. et al. Impacts of Riparian and Non-riparian Woody Encroachment on Tallgrass Prairie Ecohydrology. *ECOSYSTEMS* 26, 290–301 (2023).
86. Limb, R., Engle, D., Alford, A. & Hellgren, E. Plant Community Response Following Removal of *Juniperus virginiana* from Tallgrass Prairie: Testing for Restoration Limitations. *RANGELAND ECOLOGY & MANAGEMENT* 67, 397–405 (2014).
87. Martin, R., Asner, G., Ansley, R. & Mosier, A. Effects of woody vegetation encroachment on soil nitrogen oxide emissions in a temperate savanna. *ECOLOGICAL APPLICATIONS* 13, 897–910 (2003).
88. Noden, B. H., Tanner, E. P., Polo, J. A. & Fuhlendorf, S. D. Invasive woody plants as foci of tick-borne pathogens: eastern redcedar in the southern Great Plains. *Jvec* 46, 12–18 (2021).
89. Reisinger, A. J., Blair, J. M., Rice, C. W. & Dodds, W. K. Woody Vegetation Removal Stimulates Riparian and Benthic Denitrification in Tallgrass Prairie. *Ecosystems* 16, 547–560 (2013).
90. Sankey, T., Leonard, J., Moore, M., Sankey, J. & Belmonte, A. Carbon and ecohydrological priorities in managing woody encroachment: UAV perspective 63 years after a control treatment. *ENVIRONMENTAL RESEARCH LETTERS* 16, (2021).
91. Scott, R., Huxman, T., Williams, D. & Goodrich, D. Ecohydrological impacts of woody-plant encroachment: seasonal patterns of water and carbon dioxide exchange within a semiarid riparian environment. *GLOBAL CHANGE BIOLOGY* 12, 311–324 (2006).
92. Veach, A., Dodds, W. & Jumpponen, A. Woody plant encroachment, and its removal, impact bacterial and fungal communities across stream and terrestrial habitats in a tallgrass prairie ecosystem. *FEMS MICROBIOLOGY ECOLOGY* 91, (2015).
93. Kraus, J. M. et al. Cross-Ecosystem Fluxes of Pesticides from Prairie Wetlands Mediated by Aquatic Insect Emergence: Implications for Terrestrial Insectivores. *Environmental Toxicology and Chemistry* 40, 2282–2296 (2021).
94. Li, Y., Miao, R. & Khanna, M. Neonicotinoids and decline in bird biodiversity in the United States. *Nature Sustainability* 1–9 (2020) doi:10.1038/s41893-020-0582-x.
95. Frank, S. D. & Tooker, J. F. Neonicotinoids pose undocumented threats to food webs. *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA* 17, 22609–22613 (2020).
96. Stanton, R. L., Morrissey, C. A. & Clark, R. G. Analysis of trends and agricultural drivers of farmland bird declines in North America: A review. *Agriculture, Ecosystems & Environment* 254, 244–254 (2018).
97. Pecenka, J. & Lundgren, J. Effects of herd management and the use of ivermectin on dung arthropod communities in grasslands. *Basic and Applied Ecology* 40, (2019).
98. Torabian, S., Leffler, A. & Perkins, L. Effects of ivermectin on soil nutrient cycling, plant biomass, and dung beetle abundance. *The Rangeland Journal* 45, 224–234 (2024).
99. Guzman, L. M. et al. Impact of pesticide use on wild bee distributions across the United States. *Nat Sustain* 7, 1324–1334 (2024).
100. Van Deynze, B., Swinton, S. M., Hennessy, D. A., Haddad, N. M. & Ries, L. Insecticides, more than herbicides, land use, and climate, are associated with declines in butterfly species richness and abundance in the American Midwest. *PLoS One* 19, e0304319 (2024).
101. McEwen, L. C., Knittle, C. E. & Richmond, M. L. Wildlife Effects from Grasshopper Insecticides Sprayed on Short-Grass Range. *Journal of Range Management* 25, 188–194 (1972).

102. Norelius, E. E. & Lockwood, J. A. The effects of reduced agent-area insecticide treatments for rangeland grasshopper (Orthoptera: Acrididae) control on bird densities. *Arch Environ Contam Toxicol* 37, 519–528 (1999).
103. Shaffer, J. A. & DeLong, J. P. The Effects of Management Practices on Grassland Birds — An Introduction to North American Grasslands and the Practices Used to Manage Grasslands and Grassland Birds. Professional Paper <https://pubs.usgs.gov/publication/pp1842A> (2019) doi:10.3133/pp1842A.
104. Grant, T., Madden, E., Shaffer, T. & Dockens, J. Effects of Prescribed Fire on Vegetation and Passerine Birds in Northern Mixed-Grass Prairie. *JOURNAL OF WILDLIFE MANAGEMENT* 74, 1841–1851 (2010).
105. Madden, E., Hansen, A. & Murphy, R. Influence of prescribed fire history on habitat and abundance of passerine birds in northern mixed-grass prairie. *CANADIAN FIELD-NATURALIST* 113, 627–640 WE-Science Citation Index Expanded (SCI-EXPANDED) AN-WOS:000084720700010 (1999).
106. Petersen, K. & Best, L. Effects of prescribed burning on nongame birds in a sagebrush community. *Wildlife Society Bulletin* 15, 317–329 WE-Science Citation Index Expanded (SCI-EXPANDED) AN-WOS:A1987J742800001 (1987).
107. Shochat, E. et al. Ecological traps in isodars: effects of tallgrass prairie management on bird nest success. *OIKOS* 111, 159–169 (2005).
108. Skagen and Susan K. and Augustine and David J. and Derner and Justin D. Semi-arid grassland bird responses to patch-burn grazing and drought. *Journal of Wildlife Management* (2018).
109. Rau, B. et al. Developing a model framework for predicting effects of woody expansion and fire on ecosystem carbon and nitrogen in a pinyon-juniper woodland. *JOURNAL OF ARID ENVIRONMENTS* 76, 97–104 (2012).
110. Xu, S. et al. Fire frequency and type regulate the response of soil carbon cycling and storage to fire across soil depths and ecosystems: A meta-analysis. *SCIENCE OF THE TOTAL ENVIRONMENT* 825, (2022).
111. Berleman, S., Suding, K., Fry, D., Bartolome, J. & Stephens, S. Prescribed Fire Effects on Population Dynamics of an Annual Grassland. *RANGELAND ECOLOGY & MANAGEMENT* 69, 423–429 (2016).
112. Ellsworth, L. M. & Kauffman, J. B. Plant community response to prescribed fire varies by pre-fire condition and season of burn in mountain big sagebrush ecosystems. *Journal of Arid Environments* 144, 74–80 (2017).
113. Peterson, D. & Reich, P. Prescribed fire in oak savanna: Fire frequency effects on stand structure and dynamics. *Ecological Applications* 11, 914–927 (2001).
114. Toledo, D. et al. Fire and Drought Effects on Kentucky Bluegrass in a Northern Great Plains Grassland. *RANGELAND ECOLOGY & MANAGEMENT* 105, 56–64 (2026).
115. Havstad, K. M. & James, D. Prescribed burning to affect a state transition in a shrub-encroached desert grassland. *JOURNAL OF ARID ENVIRONMENTS* 74, 1324–1328 (2010).
116. Rau, B.M., Chambers, J.C., Blank, R.R., Johnson, D.W., 2008. Prescribed Fire, Soil, and Plants: Burn Effects and Interactions in the Central Great Basin. *Rangeland Ecology & Management* 61, 169–181. <https://doi.org/10.2111/07-0371>
117. Twidwell, D. et al. The rising Great Plains fire campaign: citizens’ response to woody plant encroachment. *Frontiers in Ecology and the Environment* 11, e64–e71 (2013).
118. Erickson, A. N. Responses of grassland birds to patch-burn grazing in the Flint Hills of Kansas. (Kansas State University, 2017).
119. Rischette, A. C., Duquette, C. A., Hovick, T. & Geaumont, B. A. Patch-burn grazing provides resources for upland-nesting ducks. *Avian Conserv. Ecology* 18, (2023).
120. Sipe, H. A. Exploring complexity, uncertainty, and risk in avian reintroduction decisions through structured decision making. (University of Washington, 2023).
121. Augustine and David J. and Derner and Justin D. Patch-burn grazing management, vegetation heterogeneity, and avian responses in a semi-arid grassland. *Journal of Wildlife Management* (2015).
122. Pillsbury, F. C., Miller, J. R., Debinski, D. M. & Engle, D. M. Another tool in the toolbox? Using fire and grazing to promote bird diversity in highly fragmented landscapes. *Ecosphere* 2, (2011).
123. Gerhard, L., Gasch, C. K. & Sedivec, K. Soil properties are resilient despite grass invasion, fire, and grazing. *Agroecosystems Geosci & Env* 5, e20257 (2022).
124. Spiess, J. W. Patch-Burn Grazing in Southwestern North Dakota: Assessing Above-and Belowground Rangeland Ecosystem Responses. (North Dakota State University, 2021).
125. Duquette, C. et al. Heterogeneity-based management restores diversity and alters vegetation structure without decreasing invasive grasses in working mixed-grass prairie. *Land* 11, 1135 (2022).
126. Ricketts, A. M. & Sandercock, B. K. Patch-burn grazing increases habitat heterogeneity and biodiversity of small mammals in managed rangelands. *Ecosphere* 7, e01431 (2016).
127. Scasta, J. D. et al. Patch-burn grazing (PBG) as a livestock management alternative for fire-prone ecosystems of North America. *Renewable Agriculture and Food Systems* 31, 550–567 (2016).
128. Weir, J. R. et al. Patch burning: integrating fire and grazing to promote heterogeneity. <https://digitalcommons.unl.edu/usfwspubs/440/> (2013).