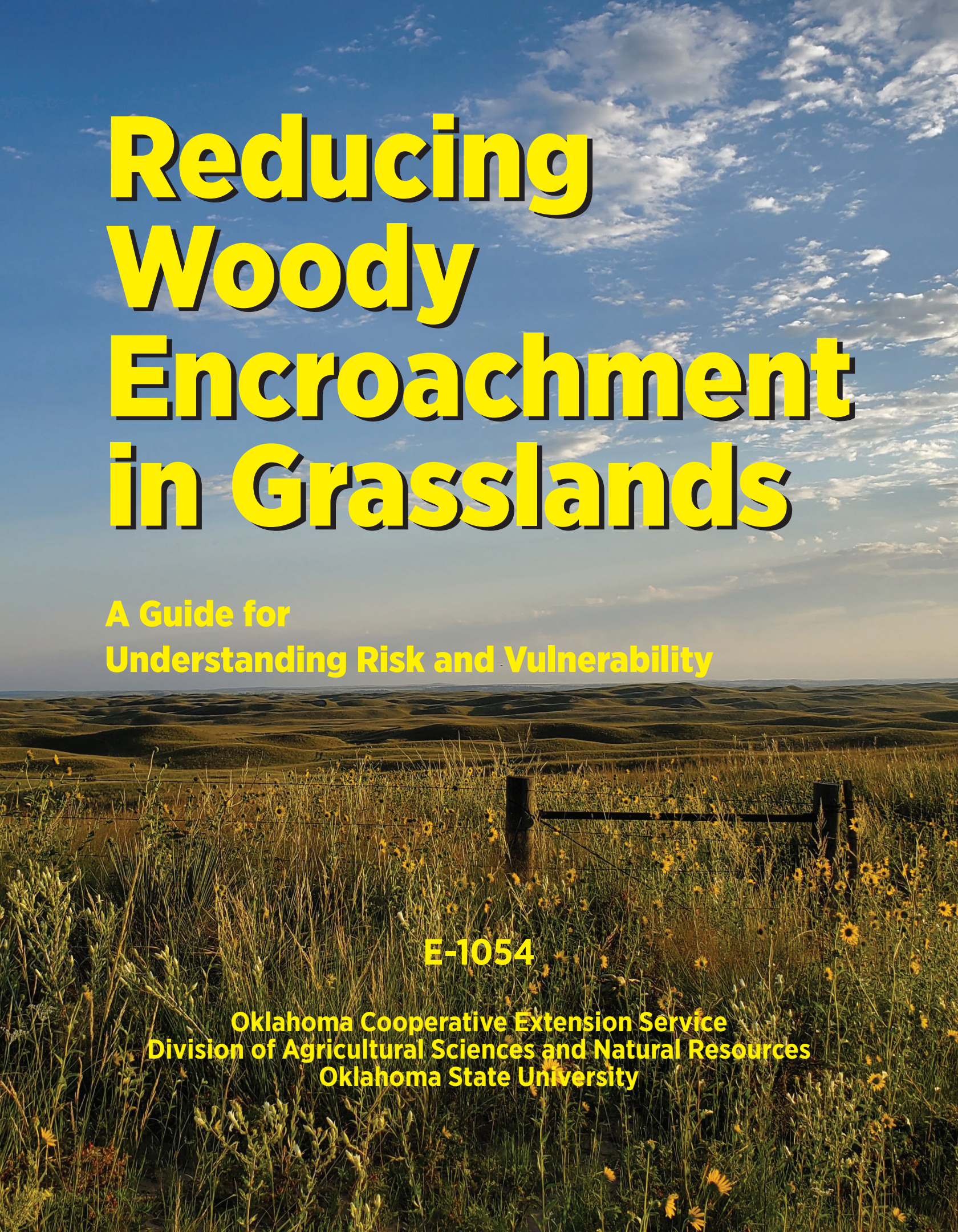
Reducing Woody Encroachment in Grasslands

A Guide for Understanding Risk and Vulnerability



E-1054

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July 2021

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Acknowledgement:
This guide was made possible with financial and technical support from the USDA-Natural Resources Conservation Service 4-State Woody Encroachment Initiative (UNL Award: NR206526XXXXC034), USDA-NRCS Working Lands for Wildlife through Pheasants Forever, USDA-NRCS Central National Technology Support Center, USDA-NIFA Agriculture and Food Research Initiative (AFRI) (UNL Award: M1903198), Nebraska Environmental Trust (UNL Award: 20-139), and Nebraska Game & Parks Commission (UNL Award: W-125-R-2).

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Issued in furtherance of Cooperative Extension work, acts of May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture, Director of Oklahoma Cooperative Extension Service, Oklahoma State University, Stillwater, Oklahoma. This publication is printed and issued by Oklahoma State University as authorized by the Vice President for Agricultural Programs and has been prepared and distributed at a cost of $3.00 per copy. September 2021 GH.

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Woody encroachment has emerged as a global threat to grasslands and the people, plants and animals that depend on them. This guide introduces the principles to manage the risk of woody encroachment and keep grasslands (like this one) intact. (Photo courtesy S. Kelly)

INTRODUCTION

Why use a vulnerability-based approach?

Woody encroachment has emerged as a global threat to grassland biomes and the people, plants and animals that depend on them.[1, 2, 3, 4] Woody encroachment is defined as an increase in density, cover and biomass of woody plants in grassy ecosystems.[5] Managing for woody encroachment has followed a command-and-control philosophy whereby control measures are only put into place after woody encroachment has occurred and caused substantial levels of resource degradation. Rangelands cannot be sustained by this approach.[6, 7] A key failure of the current 'brush management' approach is that it does not address the underlying ecological factors causing encroachment. By the time more mature woody plants are removed, the next generation of encroaching woody plants has been generated – seed has already been spread throughout the landscape and small, inconspicuous seedlings are missed by management activities (e.g., mechanical removal) that only target more mature individuals.[8, 9] Considering the speed at which encroachment is occurring in many regions, like the Great Plains, restoration actions are not keeping pace with rangeland loss and the continued advancement of woody plants. In essence, rangelands have become increasingly vulnerable to encroachment and rangeland management needs to adapt to a more proactive management strategy for woody encroachment that confronts underlying risks and weaknesses before problems arise.[10]

This Guide introduces an integrated framework for reducing grassland vulnerability to woody plant encroachment. Consistent with other vulnerability assessments, this Guide addresses two essential information needs to provide the foundation for more proactive and effective management:

1. Understanding why grasslands are vulnerable or likely to become vulnerable, and
2. Identifying where grasslands are vulnerable or are likely to become vulnerable.

Vulnerability assessments are used to manage risk in the face of unprecedented global change. Originally pioneered to confront natural hazards, food security, poverty and sustainable development, vulnerability assessments have emerged as a primary mechanism for developing adaptation strategies to new and large-scale threats in conservation.[1, 2]

The information within this document will enable managers to better identify the right practices, in the right place and at the right time. Getting there requires addressing common misconceptions within the range management community and leveraging new technologies using the following four-step framework:

- **Understand the ecology of woody plant encroachment:** This framework identifies woody plant encroachment as a five-stage process that results in intact grasslands transitioning to an alternative, woody dominated state. These stages are critical biological indicators that need to be aligned with specific management actions if encroachment is to be managed effectively.
- **Understand the problems of scale:** This framework draws upon the latest science, which recognizes woody encroachment as a biome-scale threat in the Great Plains. Accordingly, this document emphasizes how strategies can be scaled-up to meet their maximum resource potential.
- **Understand risk and vulnerability:** This framework is grounded in risk-based management, careful consideration of what makes grasslands vulnerable to woody encroachment and how to manage risk and vulnerability.
- **Develop a spatial game plan:** This framework recognizes the need for integrated and spatially-explicit management strategies that benefit rangeland resources dependent upon broad-scale functionality.

This document is not a stand-alone tool for managing woody encroachment, and framework improvements are foreseen as scientific knowledge and management success continue to advance. Rather, this document provides critical new approaches that address the shortcomings of the existing rangeland management paradigm. Our understanding of woody encroachment, what is missing from existing approaches and how to improve management has advanced greatly in recent years, and much credit is owed to landowner

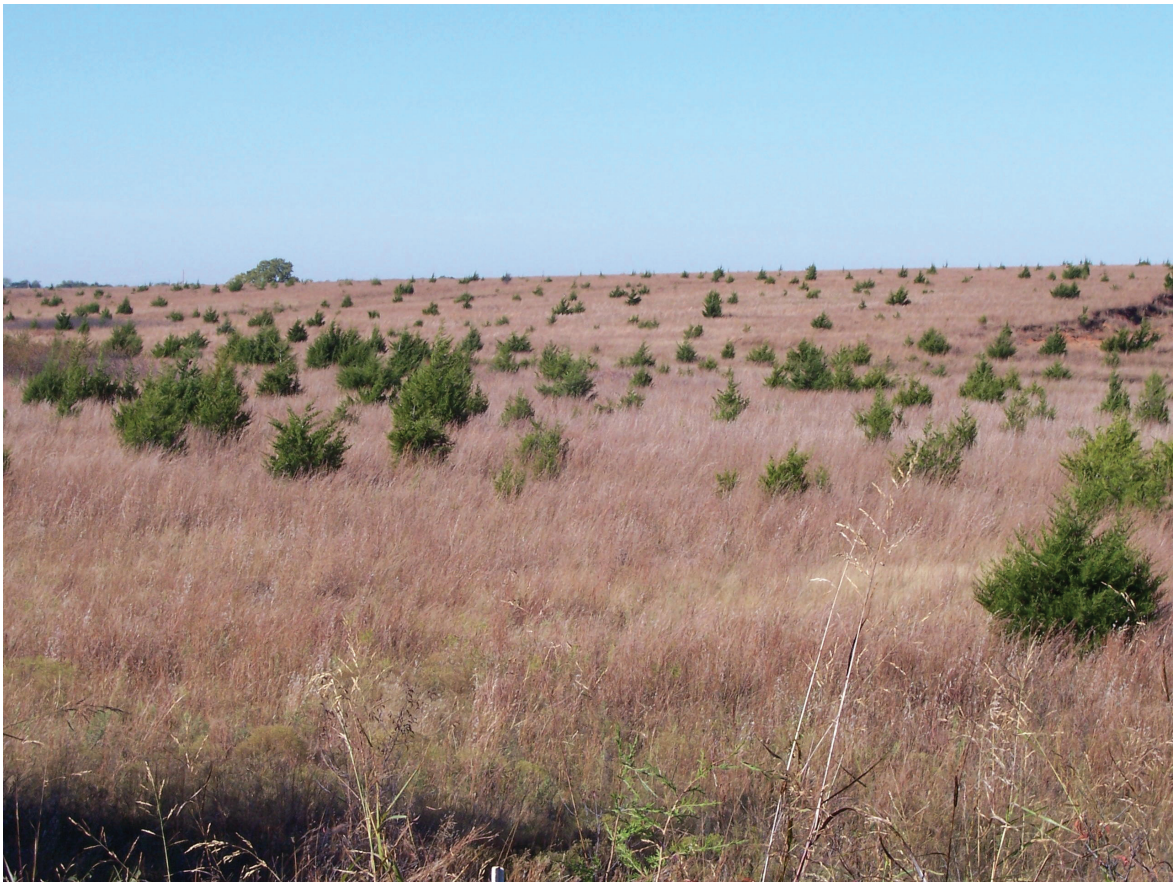
ingenuity, creative implementation of agency conservation incentives programs, new geospatial data platforms and theoretical advancements within the rangeland profession. Drawing upon those advancements, this document provides a roadmap to improve how woody encroachment is managed and, ultimately, how to provide better conservation outcomes and stewardship of rangeland ecosystems.

Who benefits from this guide?

This document was developed for rangeland managers and those involved in rangeland planning. This document is a direct response to land managers, administrators and scientists that have repeatedly called for a unified strategy to confront woody encroachment.

Which systems work with this approach?

This document was developed to provide a scientific foundation for managing rangeland systems that are vulnerable to woody encroachment. We use eastern redcedar (*Juniperus virginiana*) as a featured example because this species is one of the most well-known and studied native invaders in North America. However, principles from this guide are widely applicable across all non-resprouting, seed-obligate woody species and can be generalized to apply to various native or non-native, resprouting or non-resprouting woody invaders.



Rangelands have become increasingly vulnerable to encroachment. Traditional rangeland management has been reactive and has failed to sustain grasslands in the face of woody encroachment. This guide introduces a more proactive strategy that solves current weaknesses in grassland conservation. (Photo courtesy J. Weir)

ECOLOGY OF WOODY PLANT ENCROACHMENT

This framework identifies encroachment of non-resprouting, seed-obligate species, like eastern redcedar as a five-stage process (Figure 1). This makes it easier to identify the biological stages of encroachment and set management targets.[12] In this section, the ecology of woody plant encroachment is broken down and key considerations for management are highlighted.

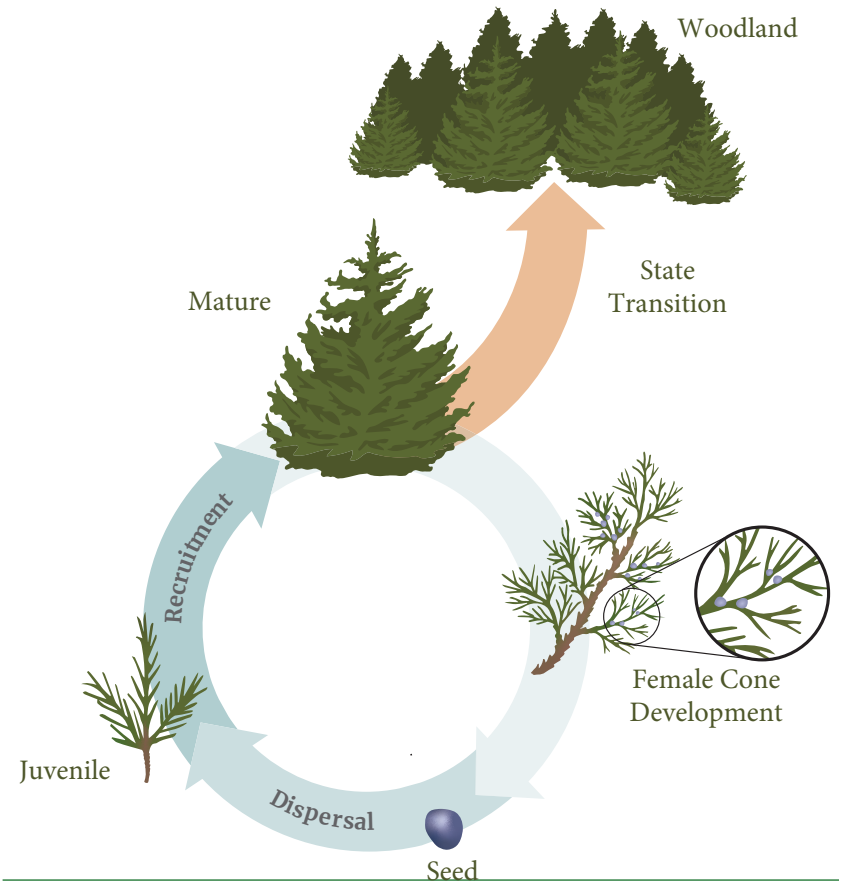


Figure 1. *Life stage transitions of the woody plant encroachment process.*

Five stages of woody plant encroachment

Intact Stage

Intact grasslands are defined as expansive treeless grasslands that are not compromised by incoming seeds of problematic and invasive woody plants. Historically, the vast majority of the Great Plains biome functioned as a network of large, intact grassland ecosystems. By definition, grasslands in this stage are not vulnerable to woody plant encroachment.

Dispersal Stage

Treeless grasslands that have become compromised by incoming seeds. The dispersal stage marks the start of the encroachment process and is short-lived in the absence of management. This stage represents the front lines of the encroachment process.

Recruitment Stage

In the absence of frequent fire, the dispersal stage is quickly followed by the recruitment stage. In the recruitment stage, seeds become seedlings. This is an active stage of the encroachment process marked by high levels of competition between seedlings and grassland plants. [13, 14]

Encroachment Stage

Seedlings become mature, cone-producing plants. Grasslands in the encroachment stage are now seed sources and create their own dispersal and recruitment zones.[15, 16] This is a later stage of the encroachment process where woody plants outcompete and displace grassland plants. Consequences of encroachment start to become realized in the encroachment stage. [17]

State Transition

Land areas in the final stages of woody plant encroachment are no longer grasslands. Instead, the system has transitioned to a woody-dominated ecosystem. This stage is associated with severe changes in rangeland functioning.[3, 18]

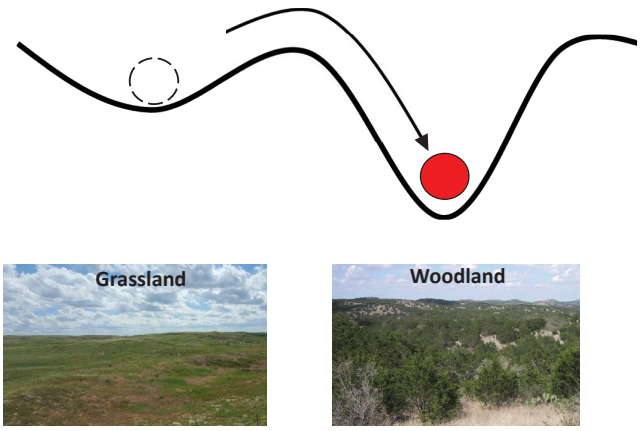


Figure 2. *Graphic illustrates the concept that grassland and woodland ecosystems are alternative states for the same land, and are each maintained by feedback loops that promote exclusion of the other ecosystem.*

Understand that woody plant encroachment erodes resilience and causes a state transition

Like desertification, coral reef bleaching or eutrophication in lakes, woody plant encroachment is a process that causes a state transition from one type of ecosystem to another (Figure 2).[19, 20] The Great Plains' climate supports both grassland and woodland ecosystems.[21, 22] Which of these ecosystems dominates and thrives has been historically-dependent on fire-vegetation feedbacks.[3, 23, 24] Frequent, human-ignited fires gave rise to the Great Plains temperate grassland biome.[25] These fires maintained a grass-dominated biome state, characterized by its expansive, treeless features. Woodland communities in the Great Plains were rare and often limited to areas with limited fire occurrence. In the last century, removal of human management with fire, widespread fire suppression and tree planting in grasslands have given rise to woody plant encroachment and the commonly observed transitions from grass to woody dominance.[3, 26, 27]

When state transitions progress across geographic space, one type of ecosystem becomes geographically larger at the expense of another.[28] This occurs with woody encroachment, and it means that grasses and trees do not co-exist at large scales in the Great Plains.[26] Long-term, as woody transitions occur, they are going to win the battle for geographic space at relatively broad scales at the expense of grasslands. The implications are 1) practices promoting both grass and tree co-existence are unsustainable for regional grassland conservation,[29, 30] 2) grasslands become exceedingly difficult or impossible, from a practical sense, to restore due to the scale of change[31] and 3) it is in society's best interest to prevent such transitions before consequences of large-scale environmental transitions become reality. Currently, no examples of reversing a grassland-to-woodland transition have been documented at large scales.

Understand the social-ecological consequences of woody transitions

Social-ecological systems in the Great Plains are organized around the goods and services provided by grassland systems. Woody transitions are associated with severe changes in the provisioning of these goods and services:

- Woody transitions can cause a permanent, 75% reduction in forage production for livestock and wildlife. [32] This impacts livestock, wildlife and recreation industries.[33]
- Woody encroachment results in reduced revenue generated for K-12 education. In Nebraska, grazing leases generate millions of dollars in revenue for K-12 education each year. Woody encroachment threatens this revenue source due to reduced forage production and increased land management costs. [34]
- Woody transitions have been shown to reduce streamflow and rates of groundwater recharge. Trees simply consume more water than grassland plants, often resulting in reduced freshwater supply in landscapes that have experienced woody transitions. [35]
- Woody plants produce greater fire intensities compared to grassland fuels and encroached grasslands have a higher propensity for extreme wildfire behavior. [36]
- Woody plants displace imperiled grassland species, resulting in the collapse of grassland biodiversity when woody transitions occur. [37]

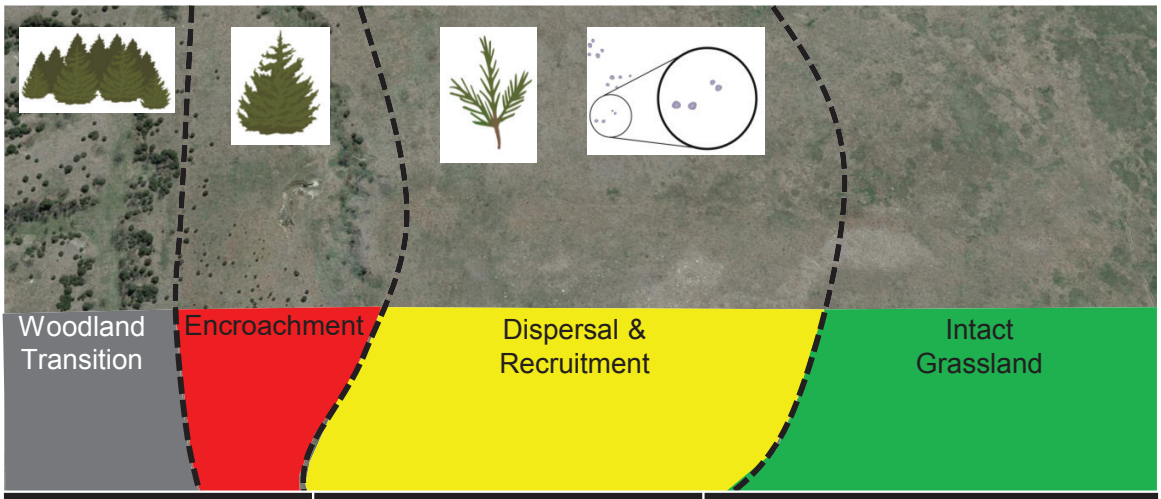
- Woody transitions increase the risk of grassland species becoming regulated as threatened and endangered.
- Many invasive and problematic woody plants contribute to hay fever and seasonal allergies and woody transitions have been linked to heightened threats to human respiratory health. [38]
- In the southern Great Plains, eastern redcedar transitions have been linked to an increased prevalence of important tick-borne pathogens compared to adjacent grasslands.[39]

Understand that woody plant encroachment is spatially contagious

Woody plant encroachment is a spatially-contagious process that is expanding into intact grassland regions. Over decades, this results in spatial collapse of grassland ecosystems and their resources.[27] Today, large grassland regions are actively undergoing a transition to woody dominance, yet components of these landscapes often are in different stages of the encroachment process at any given point in time (Figure 3).

The woody transition process begins when intact grasslands are exposed to dispersing seeds from nearby problematic and invasive woody plants. Over time, these seeds become seedlings, seedlings become mature plants and mature plants produce new dispersing seeds. This describes a process of spatial expansion along the leading front of woody encroachment. Eventually, infilling behind this front leads to an alternative woody dominated state (Figure 1).[16]

In many regions, the process of woody encroachment is intensifying as woody plants become more abundant and widely distributed. In other grassland regions, expansion of woody plants



Stages	Description	Management
Woodland Transition	Woody plant dominance	Heavy machinery - mechanical removal, fire
Encroachment	Scattered producing trees	Hand tools, heavy machinery - mechanical removal, fire
Dispersal & Recruitment	Intact with seedlings or incoming seed	Fire, hand cutting, haying, mechanical removal, browsers
Intact Grassland	Treeless with no seed	Avoid introducing seed

Figure 3. *Consideration of woody encroachment in a landscape context. Figure adapted from USDA-NRCS Working Lands for Wildlife.*

is occurring where it was previously thought to be impossible (e.g., west of the 100th meridian).[40] Individuals and organization are greatly risking rangeland resources when they assume that woody encroachment will not occur in grasslands where woody plants have not occurred in the past. Ecosystem transitions can occur rapidly, and it is in the best interests of rangeland managers to prevent woody expansion and keep rangelands intact.

Understand why stages of woody plant encroachment matter

At any given time, a landscape, or a portion of it, is experiencing a specific stage of encroachment (Figure 3). Managers that are able to correctly identify these encroachment stages are better equipped to halt encroachment and reverse the expansion of more dense and mature stands. Encroachment is a spatial process that occurs over time, with each stage of ecosystem conversion facilitating the next stage. By fully understanding how encroachment occurs, managers are able to use their resources more effectively.

Managing encroachment at large scales relies on the detection of the front lines of encroachment, and then acting early to halt woody expansion and the loss of intact (and more resilient) grasslands (Figure 3). Science shows early action at the front lines of encroachment is a more effective and cost-efficient approach to grassland conservation compared to approaches that focus exclusively on the later stages of the encroachment process (stages associated with spread in Figure 1).[41]

Understand seed dispersal distances drive the advancement of woody encroachment

The front lines of woody encroachment are defined by the dispersal of seed into treeless grasslands (Figure 3). Mature, seed-bearing trees follow. Understanding how far seed will disperse from its source tree is critical to cutting off reproduction and halting woody expansion. A simple rule-of-thumb is to maximize the distance between intact treeless landscapes from seed-bearing trees. Between seed-bearing populations and intact grassland core areas is a Seed-Contaminated Zone (Figure 4). This zone, while not yet a host to seedlings or mature trees, should be considered as part of integrated management plans.

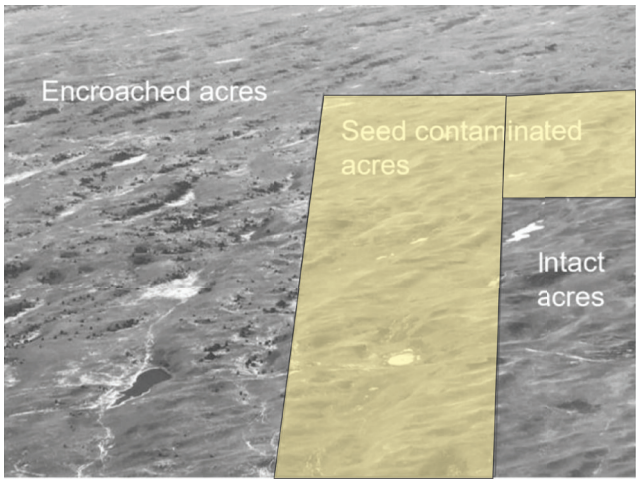


Figure 4. *Seed dispersal drives encroachment into intact grassland landscapes. (Photo courtesy D. Twidwell)*

Research on eastern redcedar encroachment has helped to define this zone. Eastern redcedar can reach maturity within six years, when trees are approximately 5 feet in height. [8] Seed production then increases as trees become larger. A mature eastern redcedar tree can produce more than 1.5 million seeds per year.[42] These seeds ripen in the fall and are dispersed by various animals, with birds serving as the greatest dispersal agents into adjacent grasslands.[15] Once dispersed, seed germination typically occurs within two years. Seeds remaining after this point are not likely to be viable and are not considered to contribute to a soil seed bank. [43]

Research from the Nebraska Sandhills shows that most dispersed seeds germinate near a seed source.[44] Specific to eastern redcedar, available research indicates 90% of recruitment occurs within 100 yards of a seed source (Figure 5), meaning the remaining 10% can be effectively managed with early detection and rapid response tactic.[45] Beyond 100 yards, seed dispersal and recruitment become increasingly rare. However, in regions with longer histories of encroachment, transportation of cattle that have ingested seeds of problematic and invasive woody plants may facilitate long-distance recruitment events,

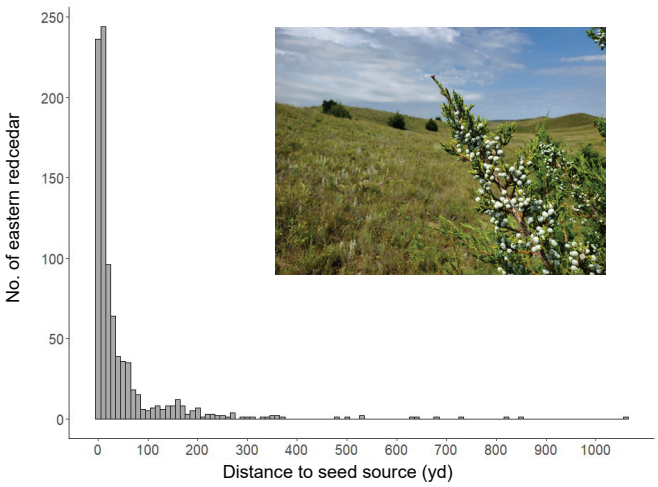


Figure 5. *Effective seed dispersal distances for eastern redcedar in the Nebraska Sandhills. (Photo courtesy D. Fogarty)*

especially for resprouting species like mesquite,[46] although this form of dispersal is not suspected for juniper species.

Available research for eastern redcedar indicates that 90% of recruitment occurs within 100 yards of a seed source. Windbreak photo is from the Nebraska Sandhills, a large grassland region where woody encroachment was incorrectly assumed to be impossible. (Photo S. Kelly)

PROBLEMS OF SCALE

Reconciling scale is one of the central requirements for ecosystem management.[47] This has been one of the central failures of the brush management model in managing woody encroachment.[3, 48] Prior to European settlement, the scale of the control process (fire) far exceeded the scale associated with the dispersal, recruitment and spread of woody plants. Tens of millions of acres likely burned each year in the Great Plains, with large populations of small-mammals acting as an additional constraint on remaining woody plants.[49, 50] Today, with a lack of large-scale management, the scale of dispersal now exceeds the scale of the control process. The expense and effort of mechanical and herbicide treatments has led to control measures being implemented on a scale of dozens of acres at most and generally implemented by individual landowners in a scattered pattern that does not impact broad-scale invasion as well as coordinated action might. This issue has to be reconciled for rangelands to be sustainably managed in the face of woody encroachment.

How extensive is woody plant encroachment?

Woody plant encroachment represents one of the most extensive changes in rangeland vegetation during the 21st century and a national threat to rangelands.[3, 27] Since 1999, woody plants have increased on more than 108 million acres in the western U.S.,[51] an area equivalent to 2.3 times the size of Nebraska. New monitoring data now confirms that rates of grassland lost to woody encroachment now approaches the rate of conversion to agriculture.[52] This rate of conversion is unexpected as woody encroachment has been thought of as a slow driver of unintentional and undesired vegetation change.

What scale of transition is occurring?

Science and technology are now available to track the scale at which state transitions are occurring.[53] In the Great Plains, woody transitions are driving a biome-scale collapse (Figure 6). This is an unprecedented scale of change for rangeland conservation: biomes represent the largest terrestrial unit of biological organization. Woody plant transitions are driving collapse across all scales – from local land units to the entire Great Plains biome. This is consistent with scientific theory. Scientists have emphasized that all scales of ecological organization can be vulnerable to

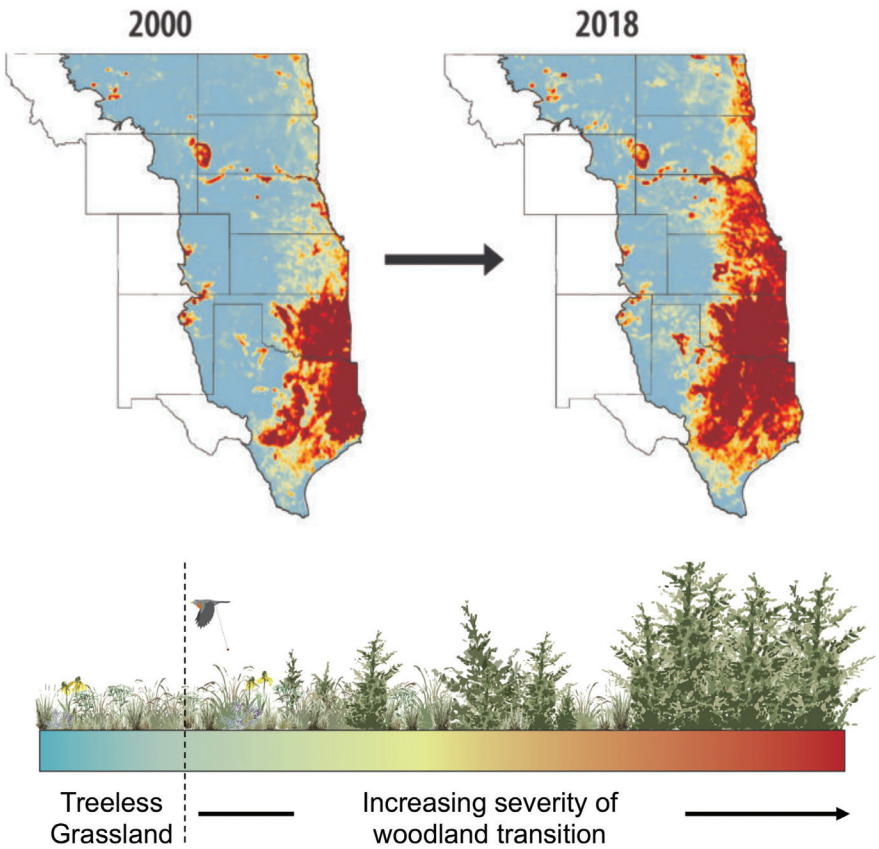


Figure 6. *Woody transitions driving the impending collapse of the Great Plains grassland biome. Maps of geographic change in alternative grassy-woody biome states are available online (https://rangelands.app). Illustration from USDA-NRCS Working Lands for Wildlife.*

collapse, given human pressures driving change during the past century and into the future. Understanding these scales of change, where they are occurring and how quickly, represents the grand challenge for conservation planning and management for the future. Meeting this challenge in the Great Plains requires immediate attention and the inclusion of multi-scale thinking into conservation planning, incentives, and management action.

Given the scale and consequences of woody encroachment, rangeland practitioners can no longer afford to prioritize tools over integrated management strategies. This document introduces the science and rationale for developing landscape strategies and how individual management tools fit within a more sustainable strategy for rangeland conservation.

The goal of conservation is to defend and grow large, intact grasslands. These grasslands minimize the risk of woody encroachment and are most likely to persist for future generations. (Photo courtesy D. Fogarty)

FRAMEWORK FOR MANAGING RISK AND VULNERABILITY

Vulnerability assessments often feature a relatively simple framework for addressing factors contributing to risk, while identifying opportunities for building adaptive capacity. There are three components driving vulnerability: sensitivity, exposure and adaptive capacity (Figure 7).[10] Sensitivity and exposure drive risk. Historically, grasslands in the Great Plains had low risk to woody encroachment because widespread fire reduced their sensitivity to woody establishment and the expansive size of grasslands resulted in minimal exposure to woody seed sources.[25] Adaptive capacity describes the potential to adapt to a threat or problem. For example, a community banding together to confront woody encroachment has increased their adaptive capacity compared to working alone (e.g., landowner prescribed burn associations).[54] Managing to reduce risks and vulnerability to woody encroachment can be achieved by more careful scrutiny of these three factors and how sensitivity, exposure and adaptive capacity has changed in modern rangelands.

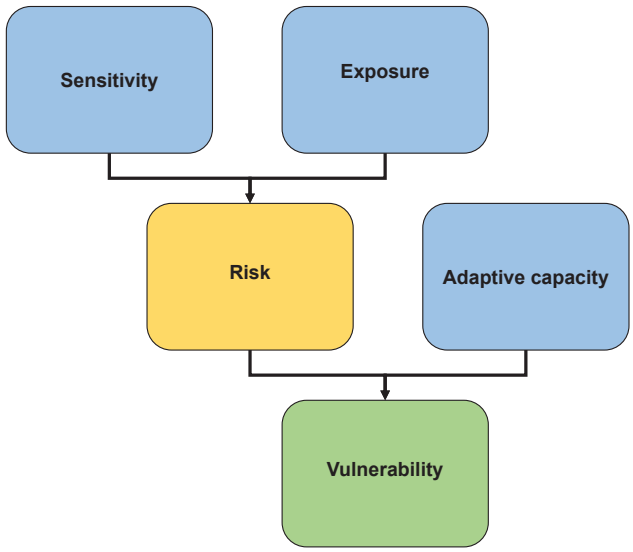


Figure 7. *Components of risk and vulnerability.*[2]

Three Components of vulnerability

Sensitivity

In simple terms, sensitivity can be described as the relative ease that woody plants can establish and spread in grasslands. In general terms, sensitivity to encroachment depicts how fast woody plants are able to advance through the stages of woody encroachment and directly relates to seed production, germination success, recruitment rates, growth rates of individual plants, the rate of population spread across landscapes and the spatial and temporal scales at which grasslands transition to woody dominance. Of course, various biotic and abiotic factors cause sensitivity to vary within and among grasslands.[55] But all grasslands that can support mature woody plants exhibit some degree of sensitivity to woody encroachment, and their level of sensitivity can change over time.

Back when grasslands dominated the interior of North America for centuries prior to European settlement, fire operated as a stabilizing feedback mechanism that reinforced a system with minimal sensitivity to woody encroachment. Additional factors like climate, soils, hydrology and herbivory interacted to make sites relatively more or less suitable for woody plants, thus, more or less sensitive to woody encroachment. But, it was the widespread occurrence of frequent fire events that is widely accepted for giving rise to the Great Plains grassland biome.[24, 25, 26] Grasses and forbs tend to thrive in fire-prone environments, whereas other plant functional groups, such as trees and shrubs, are more susceptible to fire damage and become infrequent occurrences on fire-driven landscapes. In addition, grassland fuels easily ignite and promote more frequent fire occurrences than woody fuels, leading to a grass-fire cycle that is mutually reinforcing.

Exposure

Seed serves are the biological basis for reproduction and spread of seed-obligate encroaching woody species like eastern redcedar. Exposure is driven by seed and subsequent recruitment of woody plants.

Woody plant encroachment cannot occur when grasslands are not exposed to seed sources. Pre-settlement grasslands in the Great Plains were described as expansive treeless ecosystems – meaning these systems occurred at large scales with minimal exposure to woody plant seed sources. Exposure to seed sources likely represents one of the biggest changes in grasslands today.[26] Grassland exposure was rare pre-settlement and restricted mostly to areas that did not support fire and enabled woody plant escape to fire damage.[21]

The degree of exposure a given grassland experiences is dependent on the number of seeds, their dispersal, germination success and persistence in soil seed banks. A female eastern redcedar tree can produce more than 1.5 million seeds per year.[15] Seeds ripen in the fall and are dispersed by birds beyond the canopy into adjacent lands. Research from the Nebraska Sandhills shows most recruitment occurs near seed sources, with 90% of seedling recruitment occurring within 100 yards of a seed source and less than 5% of seedling recruitment occurring more than 200 yards from a seed source (Figure 5).[45] This research suggest long-distance seed dispersal occurs, but rarely results in recruitment. Eastern redcedar seeds are most likely to germinate within two years after ripening, but after this point, they are unlikely to remain viable in a soil seed bank.[43]

Adaptive capacity

Adaptive capacity describes the ability to increase the potential to adapt to a threat or problem. Conservation incentive programs and large-scale collaborative management are examples of building adaptive capacity on private lands.[54, 56] Incentive programs can offset management costs to private landowners, thereby increasing landowner's adaptive capacity, but careful consideration should be taken to avoid the unintended consequences associated with rangeland improvement programs that increase exposure and risk to woody encroachment while providing an alternate, isolated benefit.[29] The rise of landowner-led Prescribed Burn Associations (PBAs) represents one of the most successful examples of building adaptive capacity among landowner groups.[54] PBAs share equipment, experience and funds to coordinate fire management across property lines, increasing their collective abilities to manage the threat of woody encroachment. While adaptive capacity alone may be able to reduce grassland vulnerability to woody encroachment, programs and collaborations will be more effective when combined with strategic approaches that reduce the risks associated with causes of heightened sensitivity and exposure in today's grasslands.

Maintenance requirements increase considerably as grasslands become more sensitive to encroachment and experience greater exposure to woody plants and seed-dispersal agents.

INTEGRATED MANAGEMENT TO REDUCE VULNERABILITY TO WOODY ENCROACHMENT

An integrated management approach is needed to reduce risks of woody encroachment and make sites less vulnerable to its consequences. Only with an integrated management approach is it possible to manage the entire encroachment process (Figure 1). This document introduces a key strategy to prevent, avoid, monitor and suppress the multiple stages of encroachment. It also addresses a central weakness of past management efforts, which focused on a narrow set of criteria, generally the removal of mature trees or patches of trees and brush while ignoring earlier stages of the encroachment process (Figure 8), and did not fully account for the biological realities of how woody encroachment spreads into new grassland environments.

Here, an integrated management approach is introduced and the components needed to more successfully address the woody encroachment problem at large scales are presented. Users of this document should be able to identify the risk, vulnerability, monitoring and management techniques associated with each stage of encroachment. This integrated strategy can then be tailored to the individual contexts and uniqueness of any site. While components are broken down individually, it is important that individual components be considered as part of a more holistic, spatial game plan that considers woody encroachment as a dynamic landscape process.

Woody plant encroachment cannot occur when grasslands are not exposed to seed sources.

An integrated management approach is needed to reduce risks of woody encroachment and make sites less vulnerable to its consequences. (Photo courtesy T. Bidwell)

Box 1. Myth vs. reality of a single restoration

One of the greatest myths that have been perpetuated during the brush management paradigm is that mechanical or chemical removal of encroaching woody plants will restore the system to its previous grassland state. Unfortunately, this does not occur. Single restoration treatments remove mature woody plants and allow grassland plants to recover. [57, 58] However, they do not solve the multiple residual impacts of woody encroachment that set the stage for rapid re-encroachment. [9, 57, 59]

Specifically, a single restoration treatment fails to do three things to prevent rapid re-encroachment: 1) A single treatment leaves behind seeds that allow for rapid re-encroachment of the next generation of woody plants (Figure 8); 2) The size of mechanical removal treatments are small,[41] typically operating on 10s of acres per restoration project, and therefore do not manage sufficient area to reduce exposure to woody seed sources located nearby in the surrounding untreated landscape; and 3) A single restoration is expensive, typically exceeding multiple years' worth of agricultural grazing value, and de-prioritizes cheaper alternatives that target earlier stages of the encroachment process and follow-up treatments critically needed to prevent re-establishment.

Moving forward, a single restoration treatment should be a low priority if a plan is not in place to solve these three pitfalls. Otherwise, a single restoration treatment is short-lived and more expensive to solve the problem of woody encroachment in the long run because managers are forced into a perpetual cycle of restoration over time. In contrast, an integrated approach is needed that leverages multiple treatments to strategically target woody encroachment as a dynamic landscape process. This reduces future risk and vulnerability and removes the perpetual restoration burden to landowners.

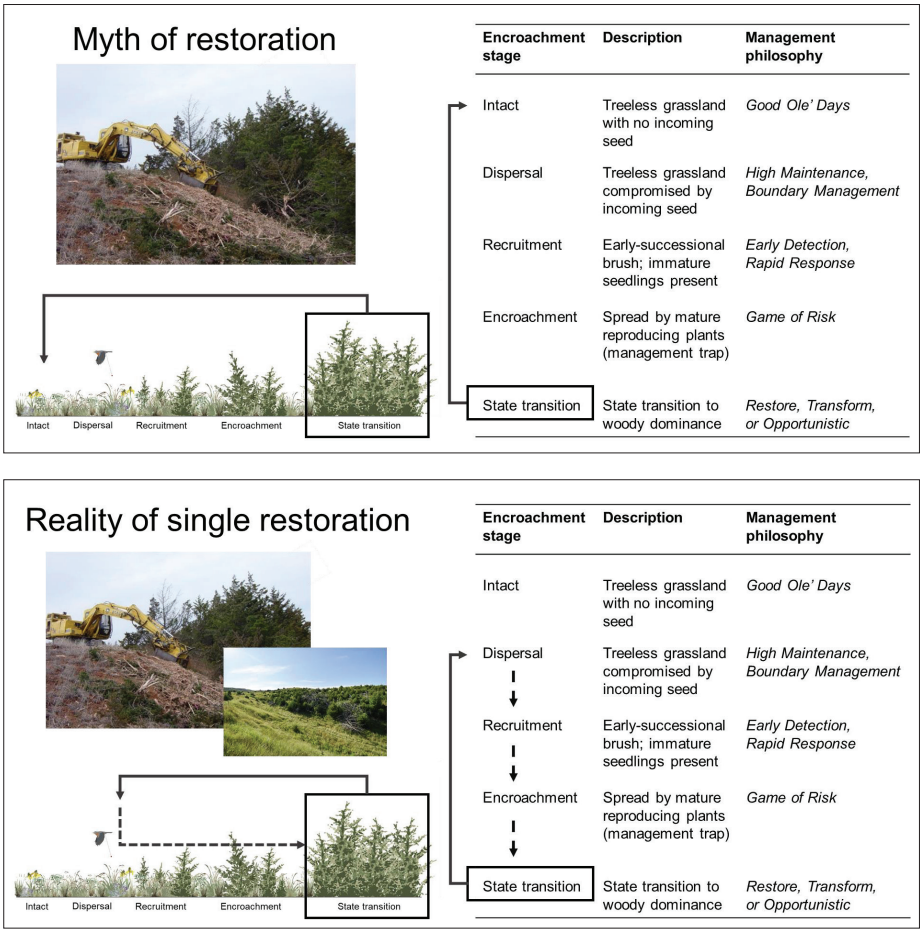


Figure 8. *Myths vs. realities of a single restoration treatment. A single restoration treatment has long been recommended as a best practice for managing woody encroachment under the premise of restoring grassland dominance. However, a single treatment by itself does not return the system to the previous intact grassland state. The most likely outcome of a single restoration is the recovery of woody plants over time and the re-establishment of a woody state. More investments are required to prevent the system from rapidly becoming a woody-dominated state again than if grasslands are kept intact. Eastern redcedar illustration adapted from USDA-NRCS Working Lands for Wildlife. (Tree removal photo J. Weir; reinvasion photo E. McCready)*

Managing stages of the woody encroachment process

Intact stage – no seed contamination or encroachment

- **Intact grasslands have minimal vulnerability to woody plant encroachment because they have no exposure to the source of the encroachment problem (seed).** Intact grasslands are treeless at large scales, and grasslands are no longer intact when they become contaminated by seed or when they become hosts to seedling recruitment.
- **Historically, the vast majority of grasslands within the Great Plains functioned as intact grassland ecosystems.** Today, the intact grasslands that remain represent the most resilient grasslands to woody encroachment. These grasslands serve as a place to anchor large-scale conservation efforts. Keeping large-scale grasslands intact and re-building intact grasslands to anchor future grassland conservation efforts, represents the best opportunity for grasslands to persist in the face of large-scale collapse.

Vulnerability Ranking:

Keeping intact grasslands intact is the easiest way to manage vulnerability at large scales.

Managing intact stage

Encroachment stage	Description	Management philosophy
Intact	Treeless grassland with no incoming seed	*Good Ole' Days*
Dispersal	Treeless grassland compromised by incoming seed	*High Maintenance, Boundary Management*
Recruitment	Early-successional brush; immature seedlings present	*Early Detection, Rapid Response*
Encroachment	Spread by mature reproducing plants (management trap)	*Game of Risk*
State transition	State transition to woody dominance	*Restore, Transform, or Opportunistic*

Figure 9. *Managing woody encroachment the easy way: Keep intact grassland intact and avoid seed source contamination from problematic and invasive woody species. Eastern redcedar illustration adapted from USDA-NRCS Working Lands for Wildlife.*

- **Monitoring should be done to evaluate the proximity of intact grassland sites to seed sources as well as their proximity to the expanding, alternative woody biome state.** Monitoring should provide answers to the following questions: How close is my property to a seed source? Where is the regional threat of encroachment coming from and how quickly is it expanding? Answers to these questions allows increased time to prepare for future changes in risk as woody encroachment continues to expand its footprint into new areas in the Great Plains.
- **Scientific confidence is highest for conservation efforts that prioritize the conservation of intact grasslands, avoid seed source contamination and prevent woody encroachment**. That confidence increases with the size of intact grasslands. Intact grasslands represent the "good ole' days" of grassland management (Figure 9). Managing for woody encroachment is not necessarily needed, allowing time and money to be prioritized towards other practices like fire management to benefit grassland plants, wildlife, and livestock.

Dispersal stage – start of the encroachment process

- **Grasslands in the dispersal stage are contaminated by seed.** This is the beginning of the encroachment process. Grasslands in this stage are treeless but have experienced seed contamination due to exposure from nearby seed sources. For eastern redcedar, seed dispersal is most important within the first 100 yards to 200 yards of a seed source (given the limited knowledge that currently exists on effective recruitment distances; Figure 5). In the absence of fire, these areas transition to the next phase of the encroachment process.
- **No monitoring data exists to track this stage of encroachment.** Distance-based measures can be used, along with field inventory or remote sensing data, when information is available on seed dispersal distances (e.g., Figure 5).
- **Best management practices in the dispersal stage are those reduce vulnerability of the site.** Scientific confidence is highest for approaches that use integrated management to 1) prevent future seed contamination by removing sources of seed exposure within the area or on neighboring sites and 2) deplete the existing seed bank (Figure 10). This two-part process is the only way to maintain a site with minimal vulnerability to future woody encroachment.
- **If unable to remove sources of seed exposure, then the next best approach is to implement a *High Maintenance, Boundary Management* philosophy that holds the line and prevents woody expansion.** Only fire can accomplish the goal of preventing seed germination and seedling occurrence. No other management option consumes seeds within the grass layer before germination. Fire thereby reduces the sensitivity of the system to woody encroachment by reducing or eliminating the seed pool. This should be viewed as a high maintenance scenario, because fire needs to occur on a frequent basis to keep pace with pressures from the dispersal of nearby seed sources. In many cases, fire is required annually to prevent seed germination,

Vulnerability Ranking:

Vulnerability is moderate in the absence of fire because the system has experienced heightened exposure (due to novel introductions of seed sources) and no disturbance-based feedback (i.e. fire) is in place to lower the sensitivity of the system to prevent or suppress further encroachment.

Vulnerability is lower if fire is in place to manage the increased exposure to woody encroachment. Fire reduces sensitivity of the system and offsets the increased risk driven by heightened exposure via seed dispersal. But, the vulnerability of the system has increased compared to an intact grassland because of the novel introduction of seed sources and the potential to escape fire damage.

Vulnerability decreases when management removes nearby seed sources and depletes the remaining seed bank.

Managing seed dispersal stage

Encroachment stage	Description	Management philosophy
Intact	Treeless grassland with no incoming seed	*Good Ole' Days*
Seedbank depletion ↑		
Dispersal	Treeless grassland compromised by incoming seed	*High Maintenance, Boundary Management*
Recruitment	Early-successional brush; immature seedlings present	*Early Detection, Rapid Response*
Encroachment	Spread by mature reproducing plants (management trap)	*Game of Risk*
State transition	State transition to woody dominance	*Restore, Transform, or Opportunistic*

Figure 10. *Seed source removal and seedbank depletion are required to transition a site back to an intact grassland. Eastern redcedar illustration adapted from USDA-NRCS Working Lands for Wildlife. (Photo J. Weir)*

although less frequent fire return intervals may be required where dispersal and/or seed germination is rare.

- **Scientific confidence is low to moderate** for strategies that do not keep grasslands intact and instead attempt to control dispersal. Confidence declines as the size of the dispersal zone becomes larger, which in turn, leads to more area being managed to prevent active stages of encroachment that are associated with greater risk. Even with fire, the spread and intensity of fire varies within burns, and this variability creates opportunities for seeds to escape fire mortality and germinate. Over time, individual trees that escape damage from multiple fire events become future seed sources and expand the amount of area experiencing seed contamination.

Recruitment stage – start of spatial expansion

- **Recruitment is a stage of spatial expansion – where self-sustaining woody populations expand from parental sources to eventually grow to maturity and become potential future seed sources.** Grasslands in the recruitment stage contain young woody plants too small for reproduction.
- **Historically, exposure to woody seed sources was rare and grasslands were less**

Vulnerability Ranking:

Vulnerability is high because of active recruitment of seedlings and future generations of seed-bearers. Removing seedlings does not alter vulnerability of the site. It does not change exposure or sensitivity. The site still has high exposure to nearby seed sources and there is anecdotal evidence that sensitivity of the site increases over time as a result of positive feedbacks where woody plants promote future woody plants, thereby fostering greater rates of future seedling establishment.

Vulnerability can only be reduced with an integrated, spatially targeted approach that considers adjacent encroachment stages in the landscape.

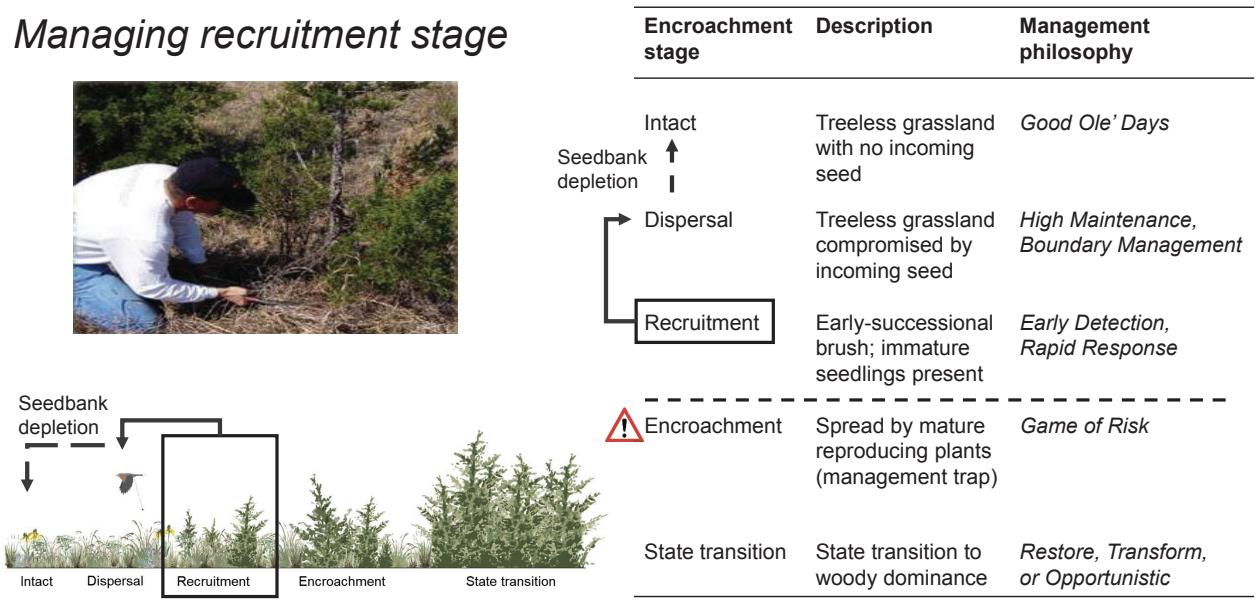


Figure 11. *Managing the recruitment stage is done with Early Detection, Rapid Response management to prevent seedlings from reaching reproductive maturity. This is a high risk stage requiring intensive maintenance. Best management practices at this stage are those that transition the system to a less vulnerable state. Eastern redcedar illustration adapted from USDA-NRCS Working Lands for Wildlife. (Photo J. Weir)*

sensitive to seedling establishment due to widespread and frequent fire occurrence. Consequently, few landscapes within Great Plains grasslands were susceptible to seedling recruitment.

- **Monitoring the recruitment stage is limited to field inventory.** Remote sensing products available today are unable to detect small tree canopies and seedlings obscured by herbaceous vegetation. Field inventory should confirm that no seed-bearing trees occur at this stage.
- **Best management practices in the recruitment stage are those that reduce vulnerability of the site (Figure 11).** Scientific confidence is highest for approaches that use integrated management to 1) remove existing seedlings, 2) prevent future seed source contamination by removing sources of seed exposure on neighboring sites and 3) deplete the existing seedbank (Figure 11). Priority should be given to sites that are adjacent to larger, more intact grassland landscapes.
- ***Early Detection, Rapid Response* should be the focus if unable to implement best practices that remove sources of seed exposure.** The goal is to create a recruitment trap that prevents seedlings from achieving reproductive maturity. Creating a recruitment trap can be accomplished with various routine treatments that control seedlings and small trees (e.g., fire, hand cutting, haying and targeted browsing).
- **This stage of encroachment denotes a highly vulnerable system.** The system is one stage away from becoming a source of exposure for other grassland sites. Failure at this stage results in reproductively viable individuals and the expansion of seed sources. Eastern redcedar can reach reproductive maturity in six years,[8] and many seedlings go undetected in the herbaceous layer for several years before undergoing exponential growth to larger size classes.[60]
- **Scientific confidence is low to moderate** for strategies that wait to act until the recruitment stage. Exposure to seed sources leads to a persistent seedbank and the need for regular, intensive management to keep seedlings within a recruitment trap and prevent reproduction. Multiple lines of evidence suggest a high probability of management failure long-term. Evidence suggests rates of seedling establishment can increase through time, reducing the

effectiveness of some treatments used in this stage (e.g., hand cutting, browsing). Consequently, even with intensive management, the system exists in a state of high risk where any management failures result in the system transitioning to the Encroachment stage.

Encroachment stage – a later stage of the encroachment process

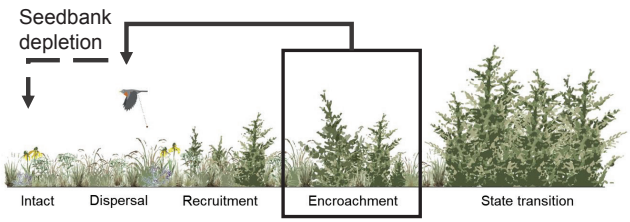
- **The encroachment stage is identified by the presence of seed-bearing trees.** This is a later life stage of woody encroachment and greatly increases grassland vulnerability compared to earlier stages.
- **Grasslands in the encroachment stage are the source of risk to other grassland sites.** Until this point in the encroachment process, grasslands were only vulnerable to encroachment. A single eastern redcedar tree can produce more than 1.5 million seeds in a year, and these seeds are dispersed into nearby grasslands.[15]

Vulnerability Ranking:

Vulnerability is severe because of self-sustaining and expanding woody populations. Mature seed sources signal a late phase of the encroachment process and a stage that requires costly long-term restoration and rehabilitation.

Vulnerability can only be reduced with an integrated, spatially targeted approach that transitions the system to an earlier stage in the encroachment process and prevents re-encroachment.

Managing encroachment stage



Encroachment stage	Description	Management philosophy
Intact	Treeless grassland with no incoming seed	*Good Ole' Days*
Seedbank depletion ↑		
Dispersal	Treeless grassland compromised by incoming seed	*High Maintenance, Boundary Management*
Recruitment	Early-successional brush; immature seedlings present	*Early Detection, Rapid Response*
Encroachment	Spread by mature reproducing plants (management trap)	*Game of Risk*
State transition	State transition to woody dominance	*Restore, Transform, or Opportunistic*

Figure 12. *Best management practices in the encroachment stage are those that implement a rehabilitation strategy to reduce vulnerability to surrounding and more intact grassland sites. This stage poses a risk to neighboring grassland sites and reducing this risk requires multiple treatments over time to eliminate sources of seed contamination and deplete the seedbank. Eastern redcedar illustration adapted from USDA-NRCS Working Lands for Wildlife. (Photo J. Weir)*

- **A variety of platforms are emerging to monitor the encroachment stage.** For example, the Rangeland Analysis Platform (RAP) (https://rangelands.app/) can be used to track annual tree cover from local to regional scales. Combined with field inventory, tools like the RAP improve early detection capabilities. Field inventory is more important at the early stages of encroachment, especially when woody plants remain small or sparse and go undetected with remote sensing technology.[56]
- **Best management practices in the encroachment stage are those that reduce vulnerability to surrounding and more intact grassland sites (Figure 12).** This requires integrated management that 1) removes all mature woody plants (using an initial restoration treatment) and 2) follows up with regular, intensive management to avoid re-establishment of mature individuals. This occurs only when 1) fire exceeds intensity thresholds needed to trigger high mortality or 2) by clear-cutting (using various mechanical removal techniques: shearing, dozing, mulching, chainsaws, etc.). In either case, no seed-bearing tree should be left behind. Non-clear cuts, selective removal practices or mature trees escaping fire damage will leave behind reproducing individuals and do not reduce vulnerability to surrounding and more intact grassland sites.
- **Efforts to maintain this stage at equilibrium (where grasses and encroaching trees coexist) are unlikely to be successful.** This stage tends to progress to a woody-dominated state. As a result, managing this stage is a low priority if managers are unable to transition the system to an earlier stage of the encroachment process and maintain initial investments (Figure 12). Efforts to maintain this stage should prioritize cheap treatments that can be implemented at large scales (e.g., fire) to avoid a state transition.
- **Scientific confidence is low for strategies prioritizing this stage over earlier action.** Restored grasslands are highly sensitive following years of encroachment. Research shows rapid re-establishment and recovery of woody plants following restoration, causing restoration treatments to be short-lived (Box 1).

State transition and grassland collapse – a stage renowned for lost resources

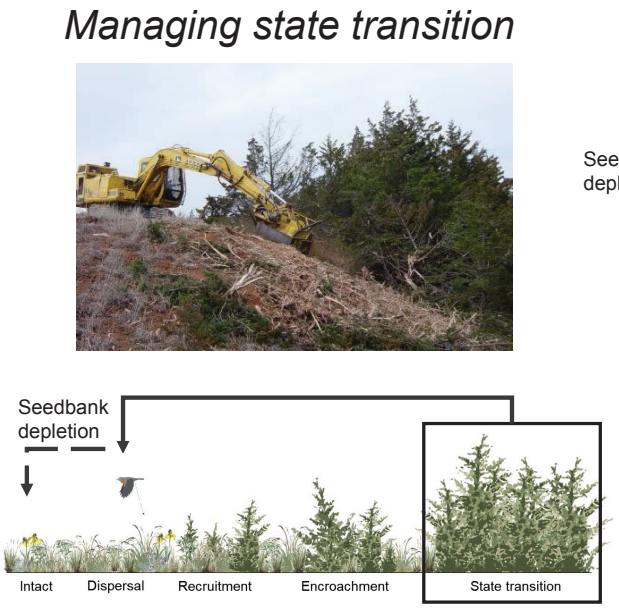
- **The final stage of woody encroachment refers to the collapse of the grassland ecosystem and a transition to woody plant dominance.** A transition to an alternative ecological state represents one of the most severe changes that occurs in ecosystems. In this case, a transition from grass-to-woody dominance is associated with severe changes in rangeland functioning and the collapse of a suite of ecosystem services that affect human well-being.
- **Techniques have been developed to monitor the leading edge of state transitions and track large-scale loss of grassland to expanding woody regimes.** Products providing early warning of large-scale woody transitions are now available on the Rangeland Analysis Platform (RAP) from 1990–2020 (updated annually). Combined with cover data and field inventory, warnings of large-scale transitions can be operationalized at site-scales to target management actions.
- **Best management practices in this stage are those that reduce vulnerability to surrounding and more intact grassland sites.** Because this stage serves as a source of risk to surrounding and intact grassland landscapes, the greatest benefit to large-scale conservation is to strategically reduce the amount of core grassland area at risk to this stage. A secondary mission is to protect local, but critical resource values. Both of

Vulnerability becomes irrelevant at this point in the encroachment process.

A state transition is associated with severe changes in rangeland functioning:

- Grasslands are taken out of agricultural production
- Forage production declines by 75%
- Wildfire danger increases
- Streamflow and aquifer recharge decrease
- Grassland biodiversity collapses
- Grassland species are at greater risk of becoming threatened and endangered
- Human respiratory health risks increase due to increased allergens

**List of consequences are specific to Eastern redcedar (http://cedarliteracy.unl.edu)*



Encroachment stage	Description	Management philosophy
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Encroachment	Spread by mature reproducing plants (management trap)	*Game of Risk*
State transition	State transition to woody dominance	*Restore, Transform, or Opportunistic*

Figure 13. *Best management practices in the state transition stage are dependent upon a site's context within the broader landscape. When restoration provides clear benefits to the broader landscape, best practices are those that transition the system to an earlier stage in the encroachment process that lacks seed sources and focuses on maintaining the investment. Eastern redcedar illustration adapted from USDA-NRCS Working Lands for Wildlife. (Photo J. Weir)*

these require a strategic spatial game plan to prioritize expensive restoration treatments, with the aim of transitioning the system to an earlier stage of the encroachment process (Figure 13). This requires integrated management that 1) removes all mature woody plants using an initial restoration treatment and 2) follows up on the initial restoration investment to avoid re-establishment of reproductively mature individuals. After restoration, these sites are more prone to re-encroachment compared to nearby sites that have not previously undergone a state transition to woody dominance. Additionally, management costs are highest in the state transition stage and managers should only target this stage when there are clear and sustainable benefits to the broader landscape.

- **Buy time, be opportunistic or accept new reality.** When immediate restoration is not in the best interest of an integrated landscape management plan, the best practice represents a choice between: 1) buying time until the site can be connected to neighboring intact grasslands, 2) being opportunistic and taking advantage of unforeseen events that facilitate restoration (e.g. wildfire) or 3) accepting the reality of losing large grassland landscapes and transforming resource values to avoid the most severe consequences to human life and property. In the first choice, the goal is to manage to buy time and sustain what resources remain until the site can be re-incorporated into a broader network of intact grassland sites. This should be accomplished with treatments like prescribed fire that can be implemented cheaply, at large scales, and target multiple stages of encroachment. In the second choice, large-scale disturbances, such as wildfire, create unforeseen opportunities for restoration to be cheaper and more effective.[62] The third choice recognizes large-scale restoration may not be a viable option. In turn, management efforts should focus on limiting consequences of this transition (e.g., heightened wildfire danger) while transforming values to squeeze resource benefits out of the alternative, woody dominated state (e.g., recreational deer hunting).

Integrating practices to reduce vulnerability on landscapes

It is important to consider how individual practices alter vulnerability to woody encroachment, and how they need to be combined to manage woody encroachment as a dynamic landscape process. No *silver bullet* exists. Control treatments differ in their ability to manage a specific stage of the encroachment process, some are more useful than others in certain situations, and each has obstacles that limit their ability to be scaled up.[12, 63]

Only fire has the potential to manage the entire process of woody encroachment – which is likely why woody plants were so rare historically (Table 1). Hand cutting, haying or goats can target early stages of encroachment (seedlings), whereas heavy mechanical machinery and most chemical applications target mature, established trees. Note that mechanical removal, haying and hand cutting change risk only by altering exposure (e.g., by removing current or future seed sources; Table 1). Of course, these treatments have minimal impact to a site's vulnerability if exposure is also driven by nearby seed sources located off-site. In contrast, herbivory alters only the sensitivity of a site (e.g., by altering recruitment potential; Table 1).[26] Only fire has the potential to alter both sensitivity and exposure, but some individuals frequently escape fire damage and require supplemental integrative management approaches, seeking to reduce both sensitivity and exposure.[41, 63, 64] Given the extent of woody encroachment in today's rangelands, only an integrative management approach is likely to reduce the high risk and vulnerability that currently characterize most grassland landscapes.

Table 1. *The ability for range management to target stages of the woody encroachment process for non-resprouting Juniperus species (e.g., eastern redcedar) and change sensitivity and exposure – which drives risk in grassland systems.*

Practice	*Woody encroachment stages*				*State transition*	*Components of risk*	
	Intact	*Dispersal*	*Recruitment*	*Encroachment*		*Sensitivity*	Exposure
Prescribed fire	X	X	X	X	X	↓	↓
Hand tool removal			X	X			↓
Haying			X				↓
Goats			X			↓	
Mechanical				X	X		↓
Grazing management						↑↓	

Only fire has the potential to manage the entire process of woody encroachment. (Photo courtesy C. Bielski)

PUTTING IT ALL TOGETHER AS A SPATIAL GAME PLAN

An eight-step approach is introduced to help managers begin to manage woody encroachment as a dynamic landscape process. These steps draw upon all preceding sections in this document and leverage a proven process of co-production whereby landowner-science partnerships are used to customize solutions to woody encroachment and scale-up management on private lands.[65] Additional considerations, beyond those included in this eight-step approach, should be included to accommodate local site needs.

Step 1: Assess the context and scale of woody plant encroachment.

The first step in the planning process is to assess baseline information for the area of interest. This step can be completed with science partners or resource professionals to better understand the scale and context of woody encroachment for the area. Baseline information provides critical context that matters throughout the planning process. Consider the following questions:

1. Is your site embedded within a grassland or woodland landscape?
2. What is the proximity of your site to nearby and expanding woody dominated landscapes?
3. What is the rate of woody encroachment on your site and within your region?
4. Where are seed sources located on your property?
5. Are seed sources present on neighboring properties?
6. What areas of your site are most vulnerable to encroachment?
7. What resources are at risk?

Eight Steps for a Spatial Game Plan

1. Assess the context and scale of woody plant encroachment
2. Determine potential to partner with neighbors
3. Determine current stages of woody encroachment and vulnerability
4. Determine realistic scale for establishing core areas to anchor conservation efforts
5. Develop integrated management plan to defend the core
6. Develop integrated management plan to grow the core
7. Develop integrated management plan to mitigate impacts
8. Monitor outcomes, adapt over time and grow landowner coalitions

Step 2: Determine your potential to partner with neighbors.

Efforts to counteract woody plant encroachment are more successful when neighbors work together across property lines, including private and public land partnerships (Figure 15).[54] Collaborating across property boundaries builds adaptive capacity and reduces vulnerability to woody encroachment (Figure 7). Time, money and labor are more efficiently expended when management is structured based on the ecology of encroachment rather than based on pasture or property lines. This is important because large-scale grassland cores are more

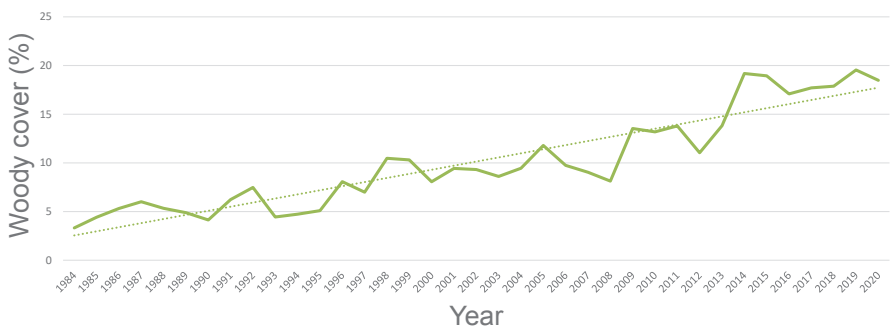


Figure 14. *Example of a diagnostic tool available from the Rangeland Analysis Platform (RAP; https://rangelands.app/) to monitor changes in vegetation cover.*

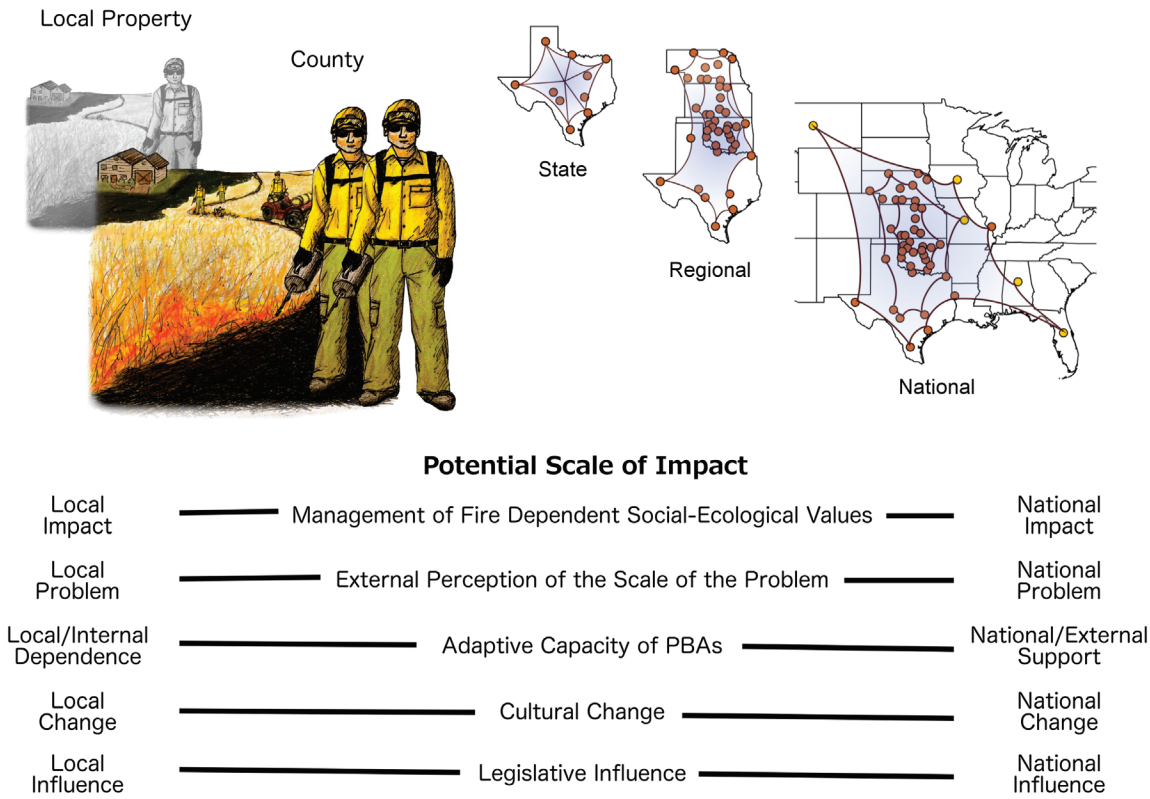


Figure 15. *Expected trajectory of impact as partnerships for managing woody encroachment develop and grow. (Figure is from Weir et. al, 2016).*[54]

resilient to threats and more likely to withstand pressures of woody encroachment as other surrounding areas continue to transition to woody dominance.

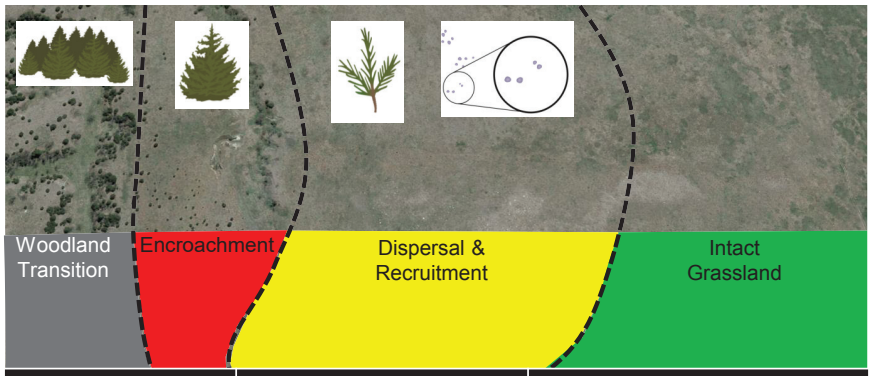
Step 3: Map the stages of encroachment and vulnerability in the landscape.

Mapping encroachment allows for customized solutions where the right management action is targeted in the right place to reduce grassland vulnerability to woody encroachment. Maps delineate a landscape as being one of the following: intact core area, seed dispersal zone, recruitment zone, encroachment zone and zone where the system transitioned to an alternative woody state (Figure 16). For most applications, precise and detailed maps are not necessary to improve how woody plant encroachment is managed. Instead, the point of this step is to determine the vulnerability that exists in the landscape, identify how far encroachment has progressed in different areas and target the right management options in the right place. Even mental maps can achieve this aim.

Starting with the state transition stage is recommended, then work backwards to map the stages of woody plant encroachment and understand vulnerability. There is no correct scale or spatial extent to delineate each zone. Even a small patch is important to map and identify because these locations alter the vulnerability of areas around it.

Zones causing other sites to be vulnerable to encroachment (seed source zones):

1. Identify state transition zone(s). This zone is defined by an area of severe woody infestations. The zone includes areas where dense woody stands have displaced grass productivity. These areas are easily recognizable onsite. At large scales, maps are available in the Rangeland Analysis Platform to aid large-scale conservation planning.
2. Identify encroachment zone(s). The encroachment zone is defined by an area that contains reproductively mature woody plants but which have not yet caused a collapse of the grassland ecosystem. This stage is usually identified by trees spreading from the



Stages	Description	Management
Woodland Transition	Woody plant dominance	Heavy machinery - mechanical removal, fire
Encroachment	Scattered producing trees	Hand tools, heavy machinery - mechanical removal, fire
Dispersal & Recruitment	Intact with seedlings or incoming seed	Fire, hand cutting, haying, mechanical removal, browsers
Intact Grassland	Treeless with no seed	Avoid introducing seed

Figure 16. *Example of mapping various stages of encroachment to better target management and reduce future vulnerability. Figure is from USDA-NRCS Working Lands for Wildlife Framework.*

state transition zone. These areas are easily identified on-site and maps of tree cover are available on the Rangeland Analysis Platform that identify areas with mature encroachment.

Zones vulnerable to encroachment:

3. Identify dispersal and recruitment zone(s). This zone is defined by effective recruitment – where seed dispersal has given rise to immature woody plants not yet capable of cone production. Use the location of the encroachment zone to identify candidate areas where seedling recruitment is likely. The majority of eastern redcedar recruitment occurs near a seed source (which occurs in the encroachment and state transition zones). Use field inventory to monitor for the presence of seedlings and to track whether management is keeping seedlings in a recruitment trap.
4. Identify the intact zone(s). This zone is defined by the absence of effective recruitment – likely because the area is sufficiently far away from seed sources. If previous zones were identified correctly, than the only area remaining should be intact. Use field inventory to confirm the remaining area(s) are indeed treeless and not host to seedling recruitment.
5. Refine maps based on management history. Previous treatments or disturbances may have left behind seeds and seedlings in areas that are now located far from existing seed sources. Use field inventory to ensure these areas are accounted for in the planning process.

Step 4: Establish core areas.

Core areas are intact grasslands that serve as anchor points for conservation efforts. The more area existing as intact grassland cores, the less grassland area vulnerable to woody encroachment. Maximizing the amount of intact core area is therefore the priority, but groups should set realistic targets to avoid being overextended and unable to hold the line against woody expansion. In areas without intact cores, or where only a small amount of land area is not compromised by encroachment, it may take multiple years to remove woody plants from candidate areas and to deplete the seedbank before core areas are established. Over time, these grassland cores are grown by strategically targeting management to reduce vulnerability and through the addition of landowner partners.

Step 5: Defend the core.

Defending the core is the top priority; these lands represent grasslands that are the least vulnerable to encroachment and require minimal maintenance compared to all other

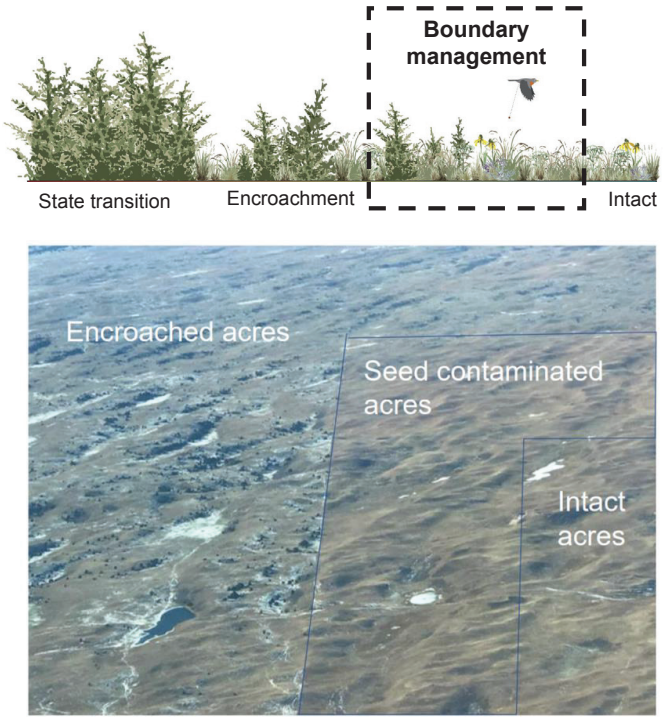


Figure 17. *Defending the core requires management in the boundary zone that separates seed sources from intact grasslands. Eastern redcedar illustration adapted from USDA-NRCS Working Lands for Wildlife. (Photo D. Twidwell)*

areas. Protecting grassland cores prevents threat expansion. As woody threats expand, more area becomes vulnerable to encroachment, necessitating more expensive control treatments than if the threat had been prevented in the first place.

Defending core areas can be thought of as boundary management. At the front lines of the encroachment process, management is needed to disrupt the geographic expansion of seed dispersal and subsequent seedling recruitment to prevent future seed sources. Seedlings can reach reproductive maturity in as little as six years,[8] so frequent and intensive management is likely needed to ensure these areas do not become an encroachment zone.

Managing to halt encroachment is relatively new, so there are opportunities to explore novel and innovative solutions. Integrating hand removal of seedlings into daily ranch operations is one example of how landowners have defended core areas in regions with relatively slow rates of seedling recruitment. Another example includes the use of prescribed fire on a more frequent rotation than in other areas of the landscape to maintain boundaries where recruitment occurs more rapidly. In either example, managers should be on the lookout for individual plants that escape initial treatment.

Defending cores improves upon traditional guidance that has always chased woody expansion. Yet, core areas may be small, fragmented and have complex boundaries that incur high maintenance costs. Thus, in the grand scheme of grassland conservation, core areas are meant to be grown over time to restore grassland productivity and reverse trends of woody encroachment.

Step 6: Grow the core

Growing cores expands the size of intact grassland area using integrated management that spatially targets restoration actions (Figure 18). Growing grassland cores requires management of mature encroachment stages. Seed sources

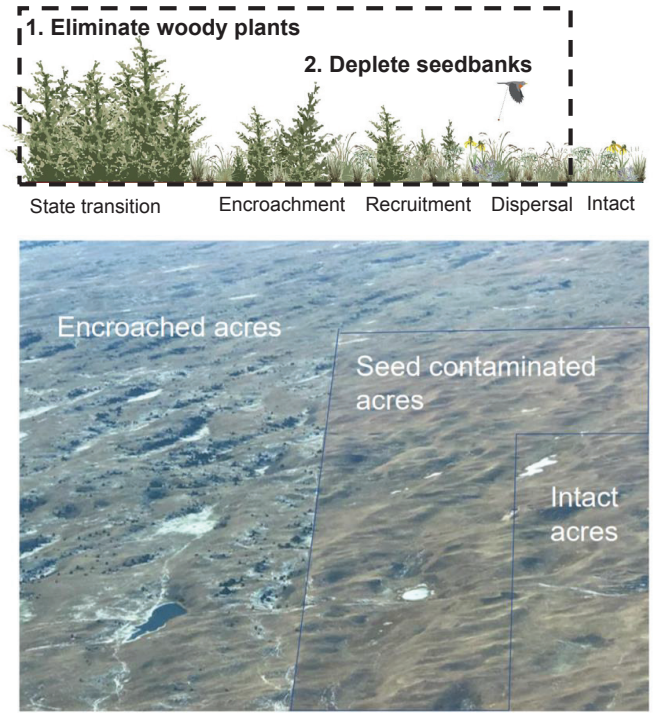


Figure 18. *Growing the core requires integrated management across multiple stages of the encroachment process to remove woody plants and prevent re-encroachment. Over time, this approach minimizes vulnerability by removing the source of the threat and transitioning lands back to an intact grassland. Eastern redcedar illustration adapted from USDA-NRCS Working Lands for Wildlife. (Photo D. Twidwell)*

need to be eliminated and follow-up treatments are necessary to block future recruitment. The following questions may help practitioners grow grassland core area:

Where to grow the core?

- Where are the most cost-effective areas to grow the core?
- Where can cores be grown quickly to maximize intact grassland area?
- Where will growing the core provide the greatest benefit to conservation outcomes?
- Where can high-maintenance zones be eliminated?
- Can complex management boundaries be simplified?
- Can growing the core be used to create larger and simpler management units (e.g., large burn units with natural or permanent fire breaks)?
- Can growing the core connect multiple properties?
- Where can multiple cores be connected to restore intact grassland ecoregions?

How to grow the core?

Managers should consider new and innovative approaches to integrate management techniques, grow core grassland area and increase their capacity for large-scale management. For example, brush management incentives have been integrated with fire using a cut-and-stuff strategy. In this case, isolated eastern redcedar trees were selectively cut, then stuffed beneath larger patches of trees to manipulate the intensity of prescribed fire and increase eastern redcedar mortality. This approach provides a more economical solution than brush management alone, and allows producer groups to scale-up the impact of their treatments.

Step 7: Mitigate impacts

The strategy described in this guide prioritizes large-scale intact grasslands, but also recognizes the need to lessen severe impacts within heavily infested landscapes. Strategies for mitigating impacts within infested areas is highly dependent on local context. Actions should take into account the long-term vision for the landscape and whether 1) opportunities might exist for the area to be incorporated as part of a grassland core in the future or 2) local assets require protection and intensive management to offset consequences of encroachment.

Step 8: Monitor outcomes, adapt over time and grow landowner coalitions.

Large-scale management is most successful when applied within a framework that facilitates learning, adaptation and growth of capacity. Monitoring the outcomes of management allows managers to learn, build on success, reduce sources of uncertainty and identify where future adaptation is needed. Multiple geospatial data products are coming online to track important outcomes (e.g., rangeland productivity in the Rangeland Analysis Platform). Documenting outcomes helps grow landowner coalitions, garner external support and increase the potential for large-scale impact.

Brush management incentives are integrated with fire using the cut-and-stuff strategy. In this case, isolated eastern redcedar are selectively cut and stuffed beneath larger patches of trees to manipulate the intensity of prescribed fire and increase eastern redcedar mortality. (Photo courtesy C. Bielski)

Box 2. Top tips for a winning strategy

Strategies that minimize risk and vulnerability are built for long-term success. Guiding principles are provided below to help managers develop a spatial game plan that minimizes the risk of woody encroachment.

Maximize distance from seed sources to minimize exposure:

1. Establish and grow the core – eliminate seed sources. Eliminate sources of exposure for as large of an area as possible. This is the most reliable way to reduce risk and vulnerability. The absence of seed sources at large-scales increases the probability of long-term success and should be prioritized over all other approaches for intact grassland landscapes.

2. Follow up: deplete seedbanks after seed sources are eliminated. Implement follow-up treatments to remove seedlings and deplete seedbanks after seed sources have been eliminated. Monitor these areas on an annual basis for the presence of seedlings to ensure grassland areas do not contain residual seed. Without this step, vulnerability remains high and woody plants re-establish with time.

Manage sensitivity when exposure cannot be eliminated:

3. Defend the core with fire. Fire is a natural process that enhances grassland resilience and reduces its sensitivity to woody encroachment. When sources of seed contamination cannot be eliminated, prescribed fire is the most cost effective way to manage risk at the core's boundaries. The goal here is to create a recruitment barrier that prevents new seed sources from emerging and contaminating areas further into grassland cores.

Identify high-maintenance zones:

4. Protect the core — no seed bearing trees allowed. Recognize high-risk boundaries around the core and identify these as high-maintenance zones. These grassland areas have high exposure to seed sources and are at high risk for recruitment when fire is absent or where individual trees escape fire damage. Areas should be monitored and maintained annually to ensure they never contain new seed-bearing trees.

Buy time and be opportunistic to build new cores:

5. Buy Time. In heavily infested areas, consider how to affordably buy time and prevent the issue from worsening. This represents a high-risk zone that is difficult to restore at large scales without anchoring management to larger intact grassland landscapes. Management efforts should avoid tendencies for high cost treatments to impact small acreages when greater priorities exist to secure less vulnerable sites.

6. Be opportunistic – restore areas burned by wildfire. Managers have implemented restoration following wildfire to offset costs of restoring large landscapes. This has led to large landscapes being restored in areas considered previously to be too heavily infested to restore. Without rapid and intensive management, however, relatively rapid rates of re-encroachment is observed and opportunities for restoration are lost.

Box 3. STOP: AVOID THIS

1. Avoid scattered, random acts of conservation. Scattered treatments result in short-lived projects and do not reduce risk and vulnerability. Clustered and spatially targeted treatments reduce exposure and anchor upon previous management investments.

2. Avoid leaving mature seed sources behind. Leaving behind seed sources fails to reduce exposure. Leaving trees does not reduce risk to future woody encroachment, meaning costly treatments will be needed again in the near future.

3. Avoid believing the myth of restoration. Sites remain highly vulnerable to woody plant encroachment after a single restoration treatment. Follow-up management is required in these areas to prevent re-encroachment due to residual seeds and seedlings that escaped the initial restoration treatment. No pathway exists to restore grassland using a single action.

4. Avoid narrow targets during restoration. Restoration requires integrating management across all stages of woody encroachment. Fixating on a single stage during the restoration process leaves sites vulnerable to encroachment. This happens when actions prioritize the removal of mature trees over preventative management of seed dispersal and seedling recruitment.

5. Avoid waiting until later stages of encroachment. Waiting to act results in the need for expensive restoration treatments that often exceed a site's grazing value. Moreover, waiting to act results in a larger land base that is vulnerable to woody encroachment.

6. Avoid assuming re-encroachment is encroachment again. Re-encroachment occurs faster than initial rates of encroachment. Expect for restored lands to require greater management inputs compared to lands undergoing encroachment for the first time.

7. Avoid chasing the problem. Strategies that do not recognize the leading edge of encroachment chase the encroachment process over time. Restoring heavily infested areas, while ignoring pathways for new recruitment and future encroachment problems, have not worked at large scales.

8. Avoid making the tool the goal. Implementing a treatment is not a goal. Dollars spent and acres treated are not goals. Set management goals based on desired outcomes (e.g., reducing vulnerability, conserving intact grasslands, preventing grazing losses, increasing grassland birds). These goals should account for scale – from individual properties to regional conservation.

9. Avoid a single silver bullet. Traditional brush management results in the management of brush. Sites remain highly vulnerable to encroachment. An integrated approach, not a silver bullet, is needed to recreate grasslands with minimal vulnerability to sustain large-scale grassland ecosystems.

10. Avoid denial. Woody plant encroachment is happening in areas where it has never happened before. Research shows that exposure to seed sources is the most important determinant of whether encroachment occurs in the future. Avoid repeating mistakes of past rangeland managers and assuming, "It won't happen to me."

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NOTES

EXTENSION