Storing Carbon in Sagebrush Rangelands

A Synthesis of Research & Applications to Management

Conducted by the Intermountain West Joint Venture

EXECUTIVE SUMMARY

Because of their extent and variability, rangelands in the United States are receiving increased attention for their potential to sequester carbon as a nature-based climate change solution. Many management practices that may help to sequester or protect stored carbon additionally provide other benefits for communities, livelihoods, and ecosystems. Because carbon sequestration potential and therefore appropriate management actions varies significantly across ecosystems, efforts to scale up carbon sequestration on U.S. rangelands must consider current and relevant science for best outcomes. We synthesized current science on rangeland carbon sequestration to summarize current knowledge, identify opportunities related to the Intermountain West Joint Venture's programs, and assess the potential for management practices to affect carbon storage. We additionally provide recommendations on how this information can be incorporated into IWJV and partner programs and efforts.

As climate changes and drought is more frequent, rangelands will experience variable changes to vegetation, affecting carbon sequestration and storage ability differently over space and time. As arid rangeland systems within the west are already highly limited in productivity, low annual carbon input into carbon stores limits capacity for carbon sequestration. Additionally, variation in carbon sequestration over space and time is largely controlled by variation in weather and other environmental factors that are out of control of managers. As such, in rangeland systems, current and relevant science shows that protecting stored carbon rather than focusing on sequestering new carbon should be the focus of management efforts.

We identified four opportunities to develop strong messages relating to protecting stored carbon in sagebrush rangelands. First, cheatgrass invasion results in marked reductions in carbon stored in plant biomass and soils and may lead to further loss of stored carbon if fire occurs. As such, addressing cheatgrass in rangelands is critical to protecting currently stored carbon and promoting carbon sequestration in the future. Second, wetlands and wet meadows can store significantly more carbon than adjacent arid landscapes, so protecting and restoring these areas will likely contribute to protecting and increasing stored carbon, among other benefits. Third, the effects of grazing on carbon sequestration are highly variable; however, preventing overgrazing and soil erosion will likely help to protect current carbon stores, especially under drought and in mesic areas. Fourth, preventing the conversion or subdivision of rangelands protects stored carbon, thus efforts to limit conversion (e.g., conservation easements) will protect currently stored carbon.

OBJECTIVES AND GUIDING QUESTIONS

The Intermountain West Joint Venture (IWJV) is a science-based landscape-scale conservation organization working in rangelands in the western U.S. A major focus of the IWJV is technical transfer, the approaches we use to inform habitat conservation by providing partners with enhanced access, interpretation, and application of science, local and traditional knowledge, and practices to strengthen on-the-ground outcomes. Carbon sequestration is an emerging topic in rangeland management where technical transfer as needed to inform and support partnership efforts in this area. To identify available information on carbon sequestration and prioritize technical transfer needs, this research synthesis addresses carbon sequestration in Western sagebrush rangelands and grasslands relating to a suite of conservation practices identified by the IWJV as priorities for our partners within the landscapes that we work.

Objectives

Specifically, this research synthesis aims to:

(1) Summarize biological and physical processes by which atmospheric carbon is stored in terrestrial ecosystems, particularly rangelands, and address which climate and biotic factors affect the magnitude of carbon sequestration;

(2) Systematically synthesize current relevant peer-reviewed literature relating to the potential for carbon sequestration on sagebrush rangelands in the Western U.S.; and

(3) Address if, when, and how top conservation threats to sagebrush systems and associated practices supported by the IWJV and our partners contribute to protecting stored carbon or sequestering new carton to support “the right practices in the right places”.

Guiding Questions

The structure of this research synthesis includes four distinct question-driven sections supporting the above objectives:

Section I. Pathways to Carbon Sequestration — How is carbon sequestered in terrestrial ecosystems and what climate and biotic factors affect the magnitude of carbon sequestration?

Section II. Carbon in Rangelands — How much carbon is stored in and sequestered by sagebrush rangelands and grasslands in the Western United States?

Section III. Effects of Climate Change — How do we expect carbon sequestration in sagebrush rangelands and grasslands to be affected by climate change?

Section IV. Effects of Key Threats and Management Practices — How do key threats to sagebrush rangelands and associated management actions within the Partnering to Conserve Sagebrush Rangelands and Water 4 focus areas affect carbon sequestration? Specific threats and areas of focus include:

- *i. Conifer encroachment and conifer removal*
- *ii. Changing wildfire regimes and prescribed fire*
- *iii. Invasive annual grasses and invasives removal*

iv. *Riparian area degradation and wet meadow restoration and flood irrigation*
v. *Overgrazing and prescribed, targeted, and outcome-based grazing*
vi. *Land use conversion and conservation easements*

RESEARCH SYNTHESIS

- Carbon in terrestrial ecosystems is stored temporarily in above- and below-ground plant biomass and more long-term soil organic carbon (SOC).
- Carbon sequestration in plant biomass is influenced by climate, water availability, and plant community composition, where wetter and warmer climates tend to support higher productivity.
- Carbon sequestration in SOC is influenced by climate, water availability, and plant and microbe community composition, where wetter and warmer climates again tend to sequester more carbon.
- Carbon sequestration tends to vary significantly spatially and temporally in rangelands.

Section I. Pathways to Carbon Sequestration

How Is Carbon Stored in Ecosystems?

Carbon sequestration in terrestrial ecosystems (hereafter referred to as "carbon sequestration") has the potential to remove significant carbon dioxide from the atmosphere and store it in vegetation and soil components of terrestrial ecosystems. Enough additional carbon could potentially be sequestered in terrestrial ecosystems globally to reduce carbon dioxide concentrations by 156 ppm (Lal et al. 2018), returning to pre-industrial era levels. How, then, is carbon sequestered by terrestrial ecosystems and can we increase this process to remove more carbon from the atmosphere?

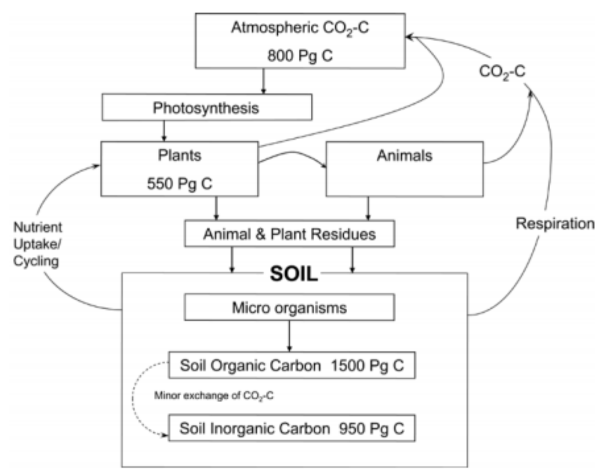

Figure 1. Pathways to carbon sequestration in terrestrial ecosystems. From Morgan et al. 2010.

Plants act as the conduit by which atmospheric carbon enters terrestrial carbon storage both in plant biomass and in soil organic carbon (SOC; Figure 1). As plants undergo photosynthesis, carbon dioxide is removed from the atmosphere to build carbon-based molecules that make up plant biomass—above- and below-ground. Depending on the species, this carbon in biomass may remain sequestered from less than one year (in the case of annual plant species) or for multiple decades (in the case of long-lived tree species). Some portion of carbon sequestered by plants is returned to the atmosphere through plant respiration (decomposition of carbon-based molecules for plant maintenance, growth, and other metabolic functions). Carbon is stored long-term (i.e., longer than the lifespan of the plant) in soil when plant carbon is decomposed into decomposition-resistant soil organic carbon (SOC) by microbes. Soil microbes additionally use and return some of this carbon to the atmosphere via respiration (see Figure 1, Morgan et al. 2010 for further description of these processes). Notably, carbon stored in biomass is only stored temporarily (as when a plant dies, it will mostly be returned to the atmosphere as decomposition occurs).

As such, most efforts to improve carbon sequestration in terrestrial ecosystems should focus on increasing SOC. For most ecosystems, the amount of carbon added to the total stored pool (biomass and SOC) every year (the annual carbon flux) is highly variable over time and space depending on a suite of climate and biological factors (Polley et al. 2010).

Factors Contributing to Carbon Sequestration

Carbon stored in a terrestrial ecosystem each year is a function of carbon stored in plant biomass and in the soil. As plants undergo photosynthesis and respiration, the total amount of carbon stored is referred to as net primary productivity (NPP, units of biomass per area per unit time). Often, NPP is separated into aboveground and belowground components. Soil organic carbon includes carbon stored long-term in organic material in the soil. NPP is strongly influenced by temperature (and therefore climate), water availability, and plant community composition, where wetter and warmer climates tend to support higher productivity (Table 1; Polley et al. 2010; Pineiro et al. 2010). Likewise, carbon sequestration into soil organic carbon is influenced by temperature (and therefore climate), water availability, and plant and microbe community composition. Wetter and warmer climates again tend to sequester more carbon in SOC.

	Direct factors	**Indirect factors**
Plant biomass (above and belowground NPP)	Temperature, water availability, plant community composition, N availability	Climate, potential biota, soil resources
Soil organic carbon	Temperature, water availability, plant and microbe community composition, N availability	Climate, potential biota, soil resources and parent material

Table 1. Factors contributing to stored carbon in plant biomass and soil organic carbon. Direct factors strongly influence components of carbon sequestration; direct factors are influenced by indirect factors (adapted from Piniero et al. 2010).

As these climate and biological factors vary significantly geographically and over time, carbon sequestration in most ecosystems is inherently variable. In arid regions, productivity and therefore carbon sequestration are limited by low precipitation, and are extremely variable within and among years (Pineiro et al. 2010, Gilmanov et al. 2010, Polley et al. 2010). Additionally, interannual changes in biological processes that affect photosynthesis and respiration (such as plant and microbe community composition, nitrogen mineralization rates, etc.) that are driven by environmental variation (such as timing and magnitude of precipitation) may regulate carbon sequestration to a greater degree than these environmental changes alone (Polley et al. 2010). Additionally, large amounts of stored carbon may be lost to the atmosphere as a result of natural and anthropogenic disturbances, such as wildfires, drought, and development (Bachelet et al. 2004, Drewniak et al. 2015). As such, carbon sequestration and loss in terrestrial ecosystems, particularly rangelands, are highly dynamic.

Section II. Carbon in Rangelands

- Rangelands are of interest for carbon storage because of their extent and because they store relatively more carbon in soils than forests.
- Currently, 25% of carbon already stored in western ecosystems is found in grasslands and shrublands, which also sequester 30% of carbon sequestered by ecosystems in the West.
- Monitoring changes in carbon stored in rangeland soils is challenging because the magnitude of the change is small compared to the total amount of stored carbon, and because carbon storage varies significantly over space and time.

Current Carbon Storage and Potential for Sequestration

Rangelands have received increased attention for their potential to store carbon because of their extent in the U.S. and globally. Additionally, some research suggests that grasslands may be more reliable carbon sinks than forests because the majority of carbon is stored in soil and roots belowground, rather than aboveground biomass (Dass et al. 2018). How much carbon is currently stored in our western rangelands? Of the approximately 13,920 teragrams of total carbon (Figure 1) stored in western ecosystems, about a quarter is currently stored in grassland and shrubland ecosystems (Table 2; Zhu and Reed 2012). In the Great Basin alone, about 295 teragrams of carbon is stored aboveground, nearly half in non-forest ecosystems (Fusco et al. 2019b). Of this stored carbon, approximately equal parts are stored in plant biomass (38%) and soil organic carbon (39% in the top 20 cm), with woody debris and other surface pools making up the remaining stored C (Zhu and Reed 2012).

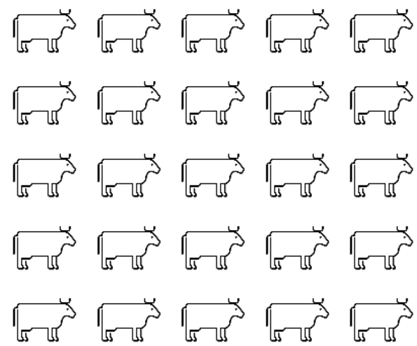

Figure 2. How much is 13,920 teragrams of carbon? About the equivalent weight of 25 billion average-sized beef cows.

Ecosystem	*C stored*	*C flux*
Forests	69%	62%
Grasslands and shrublands	25%	30%
Agricultural lands	4%	7%
Wetlands	<1%	1%

Table 2. Distribution of carbon stored and sequestered in Western U.S. ecosystems. C stored is the percent of current carbon stored by each ecosystem type (reflecting historical sequestration). C flux is the percent of carbon sequestered in each ecosystem annually.

In the Western US, ecosystems sequester the equivalent carbon of about 5% of U.S. fossil fuel emissions per year (Zhu and Reed 2012). Approximately 30% of this carbon is sequestered in grasslands and shrublands (Table 2), with approximately 32% of carbon stored in live biomass, 45% in soil organic matter, and 23% in dead biomass (Zhu and Reed 2012).

Monitoring Carbon Storage

An important factor in assessing both current carbon storage and carbon sequestration is accurately quantifying the magnitude of carbon stored in plant biomass and in the soil and changes to these carbon pools. Generally, carbon in plant biomass can be relatively easily quantified using remote sensing (Dong et al. 2003). For carbon stored in soil, quantification can be relatively challenging in rangelands because change in carbon can be small in comparison to the total amount of stored carbon and thus difficult to measure (Booker et al. 2013, Thomey et al. 2014). As such, quantifying the effects of climate change over short timescales or management practices that have relatively small effects on carbon storage is a challenge (Thomey et al. 2014). Additionally, carbon stored in soils varies substantially spatially and temporally, so intensive sampling can be needed to accurately quantify current stocks and changes to those stocks (Thomey et al. 2014). Most studies only assess soil carbon in the upper layers of the soil profile, which limit inference (Petrokofsky et al. 2012). As such, methodological uncertainty in carbon estimates, particularly in soils, must be considered when planning conservation actions.

Section III. Climate Change Impacts on Carbon Sequestration

- Climate change will likely impact climate and biological factors that influence carbon sequestration.
- Under changing climatic conditions, we expect western rangelands to be warmer and have more frost-free days and more extreme events (e.g., drought, precipitation, wildfires).
- Much research addresses how plants will respond to climate change, although there is still a lot of uncertainty.
- In arid regions, increased aridity is expected, which may decrease plant productivity and therefore carbon sequestration in biomass. In less arid regions, increased productivity could occur as a result of increased precipitation and CO_2 fertilization.
- Significant plant community turnover and ecosystem change could occur, although these changes are very difficult to predict. Sagebrush systems are most vulnerable on the periphery of the range in Southern Utah and Nevada and Eastern Washington.
- As changing climate alters productivity (inputs to carbon storage) and soil microbial respiration (losses of stored carbon), SOC sequestration may be lost or gained. If productivity decreases with aridity, this could result in losses of SOC.

As climate change progresses, understanding how ecosystems and the processes they support will respond is critical. As climate change will impact both the climatic and biological influencers of carbon sequestration, with the potential to either slow or accelerate carbon emissions depending on if ecosystems become net sinks or sources of carbon, understanding impacts of climate change on carbon sequestration is critical. In regions of the Western U.S., increased aridity could result in ecosystems that are currently carbon sinks becoming carbon sources, potentially accelerating climate change (Bachelet et al. 2004, Tan et al. 2015, Maurer et al. 2020).

What will climate in western rangelands look like under future climate change? In intermountain west and rocky mountain regions, we can expect to see warmer temperatures, more extreme weather events like drought and extreme precipitation, and more frost-free days (Chambers and Pellant 2008, Halofsky et al. 2018b, 2018a). As topography and other factors affect climate change impacts, these changes will vary somewhat across subregions (see Halofsky, Peterson, Ho, et al. 2018 pg. 40; Halofsky, Peterson, Dante-Wooda, et al. 2018 pg 33 for projections by subregion). We note that even when precipitation is projected to increase, higher temperatures may result in lower soil water deficit (leading to drought). Below, we summarize how these expected changes might result in changes to carbon sequestered in plant biomass and soil organic carbon.

Effects of Climate Change on Plant Biomass

As climate changes, plants will either acclimate, adapt, move, or die, resulting in changes to carbon storage across ecosystems (Corlett and Westcott 2013). Because the impacts of climate change will be variable spatially and temporally, we can expect to see significant variation in how plant productivity—and therefore carbon sequestration in plant biomass—responds (Reddy et al. 2010). In this section, we summarize the general trends in plant response to climate change (by acclimating, adapting, moving, or dying) and impacts on carbon storage in plant biomass, particularly in Western rangelands.

Much recent research has focused on how plants will acclimate to climate change—including responses to changes in carbon dioxide concentration, temperature, and precipitation (Liu et al. 2011, Madani et al. 2018, Maurer et al. 2020, Reich et al. 2020), and overall effects on ecosystem productivity. In general, net primary production (NPP) is expected to increase under warming and elevated CO_2, but decrease when precipitation (both in summer and winter) decrease; additionally, change in these climate factors in concert result in greater effects than when considered alone (Liu et al. 2011, Reich et al. 2020). In arid rangelands systems (such as the Great Basin and desert Southwest), increased aridity (increased temperature, reduced precipitation) is expected, likely reducing both productivity and vegetation cover (Maurer et al. 2020). Research in similar arid Mediterranean rangelands systems suggests that more arid regions are more vulnerable than less arid areas (Golodets et al. 2015). However, in less arid grassland regions, such as the Great Plains, productivity may actually increase under climate change (Hufkens et al. 2016). As such, there is some uncertainty as to how plant biomass will change at the ecosystem level across rangeland systems.

As plants move and die in response to rapid changes in climate, significant species turnover is expected, which will likely affect carbon storage at the ecosystem scale. Because patterns of extinctions and migration are difficult to predict (Kelly and Goulden 2008, Crimmins et al. 2011, Corlett and Westcott 2013), there is uncertainty about impacts in western rangelands (Chambers and Pellant 2008, Halofsky et al. 2018b, 2018a). As abiotic and biotic factors that control ecosystem vulnerability to climate change vary across the multiple ecosystem types that make up Western rangelands, some vegetation types are more vulnerable than others. The U.S. Forest Service (USFS) ranked vulnerability of ecosystem types within the Intermountain West (Nevada, Utah, southern Idaho, eastern California, and western Wyoming were included) based on published literature and expert evaluations, finding that alpine, dry big sagebrush shrublands, and low-elevation riparian areas are most vulnerable (see Table 3, Halofsky et al. 2018 for detailed descriptions of climate impats across ecosystem types). In sagebrush systems, modeling research suggests that sagebrush systems are most imperiled (and likely to shift to other ecosystem types) at the edges of the range in Southern Utah and Nevada and Eastern Washington (Bradley 2010). Likely, these changes will be influenced by other factors, such as changing fire regimes and cheatgrass invasion (Bradley 2010), discussed below. Additional research on *Artemisia tridentata* (Big Sagebrush) suggests that this species may increase productivity in the wet extremes of its range, while declining in the dry extremes (Kleinhesselink and Adler 2018). Multiple studies predict loss in habitat suitable for sagebrush species, and northward shifts into the Great Basin (see page 174, Halofsky et al. 2018), although the authors mention that genetic diversity and haplotype diversity within sagebrush species may help to speed rates of adaptation to changing climate.

Research demonstrates that climate impacts, particularly relating to vegetation changes, are extremely difficult to predict due to limitation in modeling and understanding of plant physiology and response to climate. We caveat that uncertainty is inherent in these predictions, and increased variability is expected. As such, if plants acclimate, adapt, move, or die (or some combination of these four responses) changes in

	Sensitivity rating	Sensitivity score	Adaptive capacity rating	Adaptive capacity score	Combined score	Vulnerability
Alpine	H	5	L	5	10	Very High
Dry big sagebrush shrublands	H	5	L	5	10	Very High
Low-elevation riparian	H	5	L-M	4	9	High-Very High
Subalpine forb communities	H	5	M	3	8	High
Persistent pinyon-juniper woodlands	H	5	M	3	8	High
High-elevation riparian	M-H	4	L-M	4	8	High
Mountain-mahogany woodlands	M	3	L-M	4	7	Moderate-High
Mountain big sagebrush shrublands	M	3	L-M	4	7	Moderate-High
Mountain grasslands	M	3	L-M	4	7	Moderate-High
Salt desert shrublands	M	3	L-M	4	7	Moderate-High
Mid-elevation riparian	M-H	4	M	3	7	Moderate-High
Blackbrush	L-M	2	L	5	7	Moderate-High
Dwarf sagebrush shrublands	M-H	4	M-H	2	6	Moderate
Sprouting sagebrush	M	3	M	3	6	Moderate
Oak-maple woodlands	L-M	2	M	3	5	Low-Moderate
Mountain shrublands	L-M	2	M-H	2	4	Low-Moderate

Table 3. Vulnerability of ecosystem types within the intermountain west to changes due to climate change. Vulnerability was assessed from published literature and expert evaluation. See Halofsky, Peterson, and Ho et al. 2018.

carbon sequestration across Western rangelands may occur. Broadly, although increased productivity in some areas may result in more sequestered in plant biomass (e.g., in grasslands), increased disturbance (e.g., drought and fire) expected under a warming climate will likely result in large to catastrophic loss of carbon during extreme events (Bachelet et al. 2004, Tan et al. 2015). High vulnerability of some ecosystem types may disproportionately affect loss of carbon storage if these ecosystems decline. For example, persistent pinyon-juniper woodlands are ranked highly vulnerable to climate change by the USFS (Table 3), but also store a disproportionate amount of aboveground carbon in rangelands (pinyon-juniper woodlands make up about 17% of land area, but store about 44% of aboveground carbon (Fusco et al. 2019b).

Effects of Climate Change on Soil Organic Carbon

Because soils store nearly four times as much carbon as plant biomass and three times that of the atmosphere (Lal 2004), protecting existing soil carbon stores and sequestering additional soil carbon are both critical through conserving intact landscapes (see Defend the Core, Protect the Core, Mitigate Impacts strategies). As such, there has been significant interest in understanding how soil carbon storage changes with changing climate. Because soil carbon sequestration and storage are primarily driven by a suite of environmental and biological factors (see Table 1) that respond to climate, much research has focused on predicting responses of SOC to climate change. At the global level, models disagree about the effects of climate change on SOC, including whether SOC will be gained or lost and where (Köchy et al. 2015). Overall, if SOC stocks increase or decline will likely depend on changes in productivity over space and time.

The net effect of climate change on SOC is a function of changes in carbon input by plants (productivity) and loss by microbial activity. As reviewed above, effects of climate change on plant productivity will vary. As temperature increases, soil microbial enzymatic activity may increase (particularly when soil moisture also increases), which could lead to increased carbon loss through respiration, but also increased storage as SOC (Qi et al. 2016). However, if decomposition increases more than NPP (biomass inputs into soil), then SOC loss could occur. Additionally, interactions with vegetation change (turnover, changes in productivity, as reviewed above) will likely drive changes in SOC at local to regional scales (Lal 2004). As such, in areas where productivity might decrease, such as where aridity will increase, or at the margins of a species' range, SOC loss may occur, but uncertainty is inherent in these predictions (Köchy et al. 2015).

Section IV. Effect of Management Practices

- *Conifer encroachment and conifer removal* — Research on both the effect of conifer encroachment and removal on carbon sequestration is limited and variable. Conifer removal may result in reduced carbon storage in biomass and may also decrease SOC loss due to runoff. However, woodland management is a key practice to conserve and restore sagebrush ecosystems and is therefore important beyond carbon storage.
- *Changing wildfire regimes and prescribed fire* — Wildfires result in immediate, significant, and variable loss of carbon in biomass, but the magnitude of this loss depends on fire regime and site ecology. For prescribed fire, limited research indicates that this practice does not reduce stored carbon significantly in the long-term.
- *Invasive annual grasses and invasives removal* — Cheatgrass invasion results in significant reductions in carbon stored in biomass and can contribute to additional loss through the grass-fire cycle. Research on cheatgrass and SOC is limited but indicates that cheatgrass invasion results in loss of SOC as invasion progresses.
- *Riparian area degradation and wet meadow restoration* — Wetlands and wet meadows can store proportionally more carbon than other ecosystem types, despite their relatively low prevalence. Restoration efforts have been shown to increase SOC in wetlands and wet meadows.
- *Overgrazing and prescribed, targeted, and outcome-based grazing* — Significant research addresses the effects of grazing on carbon sequestration, but results are mostly marginal and variable. Low to moderate grazing may increase SOC marginally, but results depend on climate and grassland type. Overgrazing and soil erosion result in loss of SOC and should be avoided.
- *Land use conversion and conservation easements* — Preventing conversion of rangelands to

The IWJV and multiple partners work to implement "the right conservation practices in the right places", leveraging a suite of practices that provide benefits for wildlife, ecosystems, and people. Carbon sequestration and protection of stored carbon are both potential benefits of some conservation practices. This section summarizes current literature addressing the efficacy of some of these practices in protecting or increasing stored carbon in western rangelands.

i. Conifer encroachment and conifer removal

Expansion of native conifer species (juniper (*Juniperus)* and piñon pine (*Pinus)* species) into sagebrush shrub-steppe ecosystems has been identified by multiple agencies as a top threat to sagebrush rangelands (see Working Lands For Wildlife (WLFW) Conservation in the Sagebrush Biome framework and Western Association of Fish and Wildlife Agencies (WAFWA) Sagebrush Conservation Strategy; Natural Resources Conservation Service (NRCS) 2021, Remington et al. 2021). Conifer encroachment has been shown to have broad negative effects on wildlife, plant communities, and ecosystem functions. Conifer encroachment also impacts carbon sequestration via plant biomass and soil organic carbon. Removal of encroaching conifers is increasingly used by managers to address some impacts of conifer expansion. Because conifer encroachment and removal both occur on extensive spatial scales, decision-makers and managers are interested in understanding how management actions affect carbon sequestration and stored carbon.

Broadly, research on the effects of conifer encroachment on carbon sequestration shows variable effects. A synthesis of research on the effects of conifer encroachment on carbon balance indicated that carbon sequestration in plant biomass would generally increase due to increased biomass, but may decrease in very arid regions (<336 mm annual precipitation)(Barger et al. 2011). Responses of soil organic carbon to conifer encroachment varied significantly, from large losses in SOC to significant gains (Neff et al. 2009, Rau et al. 2011b), with no relationship with precipitation (Barger et al. 2011). Additional work suggests that woody plant encroachment may also result in greater loss of SOC due to runoff, including legacy carbon that was previously stabilized in the soil (Puttock et al. 2014), but SOC responses varied from losses to gains (Barger et al. 2011). Research in this area is currently limited, and more work is needed to understand variable responses, although research generally suggests that overall carbon may be lost in areas where woody species are encroaching.

Research on the effects of conifer removal on carbon storage is additionally limited and shows mixed results. Analyses of one site in Walker Butte, OR within the SageSTEP experiment showed that conifer removal can result in reductions in both aboveground and soil carbon storage (Throop and Lajtha 2018). In this study, juniper aboveground biomass accounted for the major differences in carbon storage among encroached versus cut sites, although surface carbon (e.g., litter) and SOC were both reduced when conifers were removed. Other studies have additionally shown that SOC is higher under encroaching trees and shrubs versus interspaces (Neff et al. 2009, DeMarco et al. 2016). In contrast, one study in Oregon compared cut and uncut watersheds and showed no difference in SOC after 13 years, although this study was not properly controlled, so inference is limited (Abdallah et al. 2020). In summary, research is conflicting and limited on the effect of conifer removal on carbon storage in biomass and SOC, likely insufficient to draw broad conclusions on the effect of this management practice. However, woodland management is an important practice in conserving and restoring critical sagebrush ecosystems and is shown to strongly benefit sagebrush obligate wildlife. Therefore, impacts on stored carbon, while difficult to quantify, is only one aspect under consideration when planning woodland management efforts.

ii. Changing wildfire regimes and prescribed fire

Changing wildfire regimes are also a major threat to sagebrush rangelands identified by WLFW and WAFWA sagebrush conservation strategies (Natural Resources Conservation Service (NRCS) 2021, Remington et al. 2021). Change in fire severity and frequency are expected with climate change (Scasta et al. 2016), including within western rangelands. Currently, wildfires return approximately 10 teragrams of carbon per year to the atmosphere, nearly 12% of what is sequestered by terrestrial ecosystems in the Western US. As area burned increases due to climate change, emissions due to wildfires may increase by nearly two-thirds (Zhu and Reed 2012). Additionally, many ecosystems have undergone significant change (e.g., conifer encroachment) due to lack of fire on the landscape. As such, burning is a common management tool to return this important ecosystem process to the landscape. Therefore, understanding how both wildfires and prescribed burning affect carbon storage are important.

Research on the effects of wildfire on stored carbon is relatively robust, but shows that loss of stored carbon due to wildfires is significant (20-40% of fossil fuel combustion) and highly variable (Conard and Solomon 2009). Net effects on carbon storage depend on fire regime (frequency, size, seasonality, and severity; see Figure 3; Conard and Solomon 2009), as well as ecological site type (see (Miller et al. 2013 for further details). Emissions will peak during the fire and slow as additional dead plant material is decomposed and microbial respiration occurs; as vegetation recovers, most systems will again act as carbon sinks, but the timeframe and extent of this recovery depends again on fire regime and ecological site types (Conard and Solomon 2009, Miller et al. 2013). Additionally, carbon storage may be affected if ecosystems undergo state transitions after wildfires (see Figure 4; Miller et al. 2013). For example, sagebrush shrub-steppe ecosystems often become dominated by annual invasive grasses, like cheatgrass, after fire, resulting in reduced capacity for carbon storage (discussed in *Invasive annual grasses* section below).

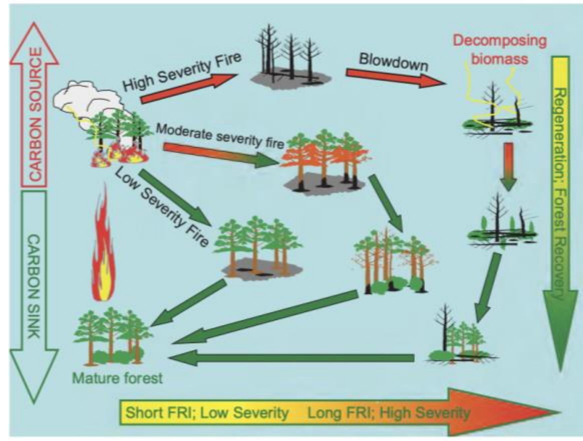

Figure 3. Effects of fire severity on carbon budget over time. From Conard and Solomon (2009).

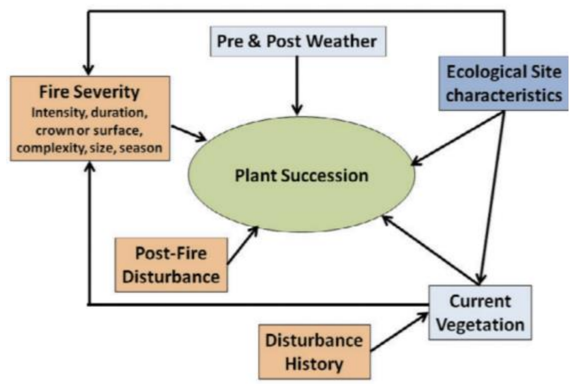

Figure 4. Conceptual model showing factors affecting plant succession (state transitions) after fire. From Miller et al. 2013.

As managers implement prescribed burning to restore the ecological functions of fire to the landscape and to address high fuel loads, these practices will have implications for carbon sequestration. As with wildfires, the effect of prescribed burning on plant biomass depends on fire regime, which can be controlled within management practices and will not be discussed here. For SOC, limited research shows that controlled burning likely has minimal lo ng-term effects SOC. Assessment of prescribed burning to reduce conifer encroachment in the Great Basin showed that although plant biomass carbon was reduced (as intended) by these treatments, there was no effect on soil organic carbon (Rau et al. 2010). Additional work in a Nevada pinyon-juniper woodland showed that SOC increased immediately after burning, but these effects were diminished and nonsignificant over time (Rau et al. 2009). Managers should consider the potential effects of prescribed burning on carbon storage and, perhaps more significantly, the potential to increase cheatgrass invasion and contribute to the grass-fire cycle (see below for further discussion).

iii. Invasive annual grasses and invasives removal

Often identified as the top threat to sagebrush rangelands, the invasive annual grass cheatgrass (*Bromus tectorum)* and other invasive plant species have taken hold across the West (Natural Resources Conservation Service (NRCS) 2021, Remington et al. 2021). Although cheatgrass significantly affects ecosystem structure and function, it strongly affects and is affected by fire regimes (Germino et al. 2016, Nagy et al. 2021). As such, cheatgrass invasion alters carbon storage and sequestration potential. A recent literature review summarizes these effects (Nagy et al. 2021). The authors found that aboveground biomass was on average 55% lower and belowground biomass was on average 62% lower in cheatgrass-invaded versus native sagebrush sites. Additionally, SOC below 20 cm was lost in cheatgrass versus native sagebrush sites greater than five years after fire. However, SOC in the top 10cm of soil was on average higher than in native sagebrush, possibly due to increased litter contribution by cheatgrass, resulting in no significant change in total SOC. Consistent with this synthesis, research in the Great Basin showed that SOC decreases over time and cheatgrass invasion worsens in severity (Rau et al. 2011a). These effects may be worse under drought, resulting in cheat-grass dominated landscapes becoming carbon sources (Prater et al. 2006). Removal of fire-prone invasive species may help to increase carbon storage and additionally is necessary to prevent the loss of additional stored carbon (in biomass and SOC) as the grass-fire cycle continues (Booker et al. 2013, Fusco et al. 2019a, Nagy et al. 2021). As such, removal of cheatgrass and prevention of state transitions of sagebrush and other ecosystem types into cheatgrass-dominated systems should be a major focus of efforts to protect current carbon stores in sagebrush rangelands. Both WLFW and WAFWA sagebrush conservation strategies advocate for robust strategies to address invasive annual grasses, emphasizing the effects on carbon storage. Carbon benefits of cheatgrass removal should be strongly integrated into messaging on invasive annual grasses.

iv. Riparian area degradation and wet meadow restoration

Loss and degradation of riparian areas, such as wetlands and wet meadows, within sagebrush rangelands threatens wildlife habitat and ecosystem services and is an additional focus of both WLFW and WAFWA and sagebrush conservation strategies (Natural Resources Conservation Service (NRCS) 2021, Remington et al. 2021). Although wetlands and wet meadows within sagebrush ecosystems account for a relatively small total area, their potential to store and sequester carbon exceeds drier ecosystems (Norton et al. 2013, Lal et al. 2018, Carter Johnson 2019). As such, prioritizing wetland protection and restoration may be important to contribute to carbon sequestration in the West. Limited but increasing research addresses the impacts of wetland and wet meadow restoration and management on carbon storage. In North America, wetland restoration has the potential to sequester 378 teragrams of carbon, approximately the equivalent of 2.5% of 1990 U.S. annual CO_2 emissions (Euliss et al. 2006). Research in the Canadian Prairie Pothole region has shown that, even considering methane emissions, prairie potholes store and actively sequester carbon, and restoration of these systems increases carbon sequestration (Badiou et al. 2011). Additional work suggested that wetlands do not immediately sequester carbon at rates equivalent to native wetlands, suggesting a need for protection (Galatowitsch and Van Der Valk 1996). Further, extensive work in the intermountain west showed that low-tech riparian and wet meadow restoration increased plant productivity (although carbon storage was not measured) (Silverman et al. 2019). Additionally, heavy grazing has been shown to reduce soil carbon in prairie wetlands (Teuber et al. 2013). As such, first protecting and then restoring wetlands and wet meadows will likely result in positive gains for carbon storage.

v. Overgrazing and prescribed, targeted, and outcome-based grazing

Livestock grazing is extremely prevalent in sagebrush habitats, acting as a disturbance to vegetation, providing important ecosystem functions, and contributing to livelihoods. There has been much interest on the potential for grazing management to contribute to carbon sequestration in rangelands because of their extent both regionally, nationally, and globally. An abundance of literature on this topic both regionally and globally allows for robust synthesis of the effects of grazing on carbon sequestration in rangelands.

Because of the extent of rangelands (covering approximately one-third of land in the U.S., depending on how rangelands are defined (Havstad et al. 2009), marginal changes in carbon storage could add up. Research shows somewhat variable effects of grazing on carbon sequestration depending on site factors like precipitation, but there is generally consensus within the literature that increases in SOC due to grazing are small compared to variation in environmental factors across temporal scales, and that incentives are lacking to make management changes for the purpose of carbon sequestration financially viable (Conant et al. 2001, Pineiro et al. 2010, Booker et al. 2013). However, other ecological and financial benefits of grazing management are numerous, so slight increases in carbon sequestration should be viewed as an additional benefit. Efforts should instead be focused on conserving currently stored carbon within rangelands.

Multiple reviews of the effect of grazing on carbon sequestration similarly conclude that increases are marginal and dependent on climate and grassland type (Conant et al. 2001, Pineiro et al. 2010, Booker et al. 2013, Abdalla et al. 2018). Generally, interannual variation in climate and other environmental factors contributes more to changes in carbon sequestration than does management practices, particularly grazing (MacNeil et al. 2008, Booker et al. 2013). Generally, research shows that more mesic regions may be able to sequester more carbon under grazing management due to greater flux from vegetation to soil (Booker et al. 2013, Abdalla et al. 2018). Some research synthesis also shows that drier sites (<400mm annual precipitation) and wetter sites (>850 mm annual precipitation), but not intermediate sites, that were grazed had higher root carbon contents (a predictor of SOC) than ungrazed sites. Further, C4-dominated grasslands may be more likely to increase SOC in response to grazing than C3 or C3-C4 mixed grasslands (Abdalla et al. 2018).

In addition to ecological factors, intensity of grazing may affect SOC. Low to moderate intensity grazing are more likely to increase SOC over high intensity grazing (Abdalla et al. 2018). Excluding grazing, however, usually does not result in increased SOC over moderate levels of grazing (Derner et al. 2019). Additionally, reducing overgrazing (particularly when drought occurs) may help to increase carbon storage (Conant and Paustian 2002). Because soil erosion can result in loss of SOC (Booker et al. 2013), avoiding practices that result in soil erosion is critical to protecting currently stored carbon.

Some authors agree that although much focus has been on increasing carbon sequestration, where increases may be marginal and highly variable, we should instead focus on protecting currently stored carbon (Derner and Schuman 2007, Booker et al. 2013). Conversion of grasslands or shrublands to agriculture and development results in significant loss of SOC, and although restoration can increase SOC, reaching previous levels may take hundreds of years (Knops and Tilman 2000). Therefore, maintaining land under proper livestock grazing management rather than converting it to other uses is preferable for carbon storage. Additionally, grazing may help to prevent cheatgrass invasion and subsequent state transitions (Booker et al. 2013), which has benefits for carbon balance.

vi. Land use conversion and conservation easements

Because the conversion of rangelands to other uses (croplands, development) results in loss of stored carbon and prevents or limits future sequestration, management practices that prevent these transitions have a critical role in preserving stored carbon (Drewniak et al. 2015, Holechek et al. 2020). From the 1700s onward, more than 3 million km^2 of land in the U.S. was converted to agricultural lands, which released over 10,000 teragrams of carbon into the atmosphere (Havstad et al. 2009). Today, rangelands generally provide more carbons sequestration benefits than croplands or otherwise developed lands. Brief or perpetual, protected areas, particularly conservation easements, can provide binding incentives to prevent the conversion of rangelands into cropland and developments (Havstad et al. 2007, Holechek et al. 2020). Conservation easements are a common tool in many programs aimed at improving carbon storage on working lands. Protection of stored carbon is just one benefit of conservation easements, but messaging on this benefit could be increased.

OPPORTUNITES FOR THE IWJV — TAKEWAYS

The purpose of this report was to address current knowledge on carbon storage in sagebrush rangeland and assess the potential for management practices to affect carbon storage. After identifying carbon sequestration as a potential opportunity for the IWJV and our programs and partners, this is the second step in technical transfer surrounding this topic – reviewing current information to inform additional technical transfer steps. From this analysis, we have identified a vision for using this information in our work and several concrete opportunities to apply current science to our work.

Vision for Incorporating Carbon Sequestration into IWJV Work

1. *Strengthen current programs* — Rather than identifying new directions for the IWJV, this information helps us to strengthen framing and communication surrounding our current work (see Opportunities, below). Appropriately using the latest science and language surrounding carbon sequestration, an emerging priority at the national level, will launch the IWJV into a leadership role among partners at a time where others are still getting up to speed on how carbon sequestration is relevant to their work. Providing guidance and talking points, particularly for the BLM, will help our partners to efficiently strengthen their messages relating to co-benefits of conservation practices.
2. *Synergize messages with partners* — As two new major frameworks for conservation in the Sagebrush Biome have emerged during the writing of this report (Natural Resources Conservation Service (NRCS) 2021, Remington et al. 2021), using messaging consistent with these frameworks is key. Both frameworks focus entirely or in part on the five main threats to the sagebrush biome identified in this report. Additionally, as advocated above, they integrate carbon storage co-benefits of conservation actions relating to major sagebrush threats into their strategies and communications (see, for example, WLFW's *Healthy Rangelands Store Critical Carbon Above and Below the Surface)*.
3. *Articulate co-benefits of current conservation practices* — Four main opportunities for protecting and increasing carbon storage emerged from our analysis. We find these the most promising areas within our program purview to integrate carbon sequestration into our work.
    - **a.** *Invasive annual grasses and invasive removal* — Cheatgrass invasion results in marked reductions in carbon stored in plant biomass and soils and may lead to further loss of stored

carbon if fire occurs. As such, addressing cheatgrass in rangelands is critical to protecting currently stored carbon and promoting carbon sequestration in the future.

   b. *Riparian area degradation and wet meadow restoration* —Wetlands and wet meadows can store significantly more carbon than adjacent arid landscapes, so protecting and restoring these areas will likely contribute to protecting and increasing stored carbon, among other benefits.

   c. *Overgrazing and prescribed, targeted, and outcome-based grazing* — The effects of grazing on carbon sequestration are highly variable; however, preventing overgrazing and soil erosion will likely help to protect current carbon stores, especially under drought and in mesic areas.

   d. *Land use conversion and conservation easements* — Preventing the conversion of rangelands into croplands or developments protects stored carbon, so efforts to do this (e.g., conservation easements, conservation incentive programs) will protect currently stored carbon.

4. *Follow the relevant science* — Carbon sequestration is a hot topic in conservation. While critically important to preventing and mitigating climate change, not all ecosystems are suitable for contributing substantially to carbon sequestration, and not all management practices that help to sequester carbon are appropriate in all ecosystems. In rangelands, the focus of carbon-related efforts should be protecting stored carbon and remaining carbon neutral rather than sequestering new carbon for the reasons outlined in this report. Following the science that is relevant to arid rangeland systems is critical to crafting strong messages around carbon and avoiding misinformation pitfalls.

LITERATURE CITED

Abdalla, M., A. Hastings, D. R. Chadwick, D. L. Jones, C. D. Evans, M. B. Jones, R. M. Rees, and P. Smith. 2018, February 1. Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. Elsevier B.V.

Abdallah, M. A. B., R. Mata-González, J. S. Noller, and C. G. Ochoa. 2020. Ecosystem carbon in relation to woody plant encroachment and control: Juniper systems in Oregon, USA. Agriculture, Ecosystems and Environment 290:106762.

Bachelet, D., R. P. Neilson, J. M. Lenihan, and R. J. Drapek. 2004. Regional differences in the carbon source-sink potential of natural vegetation in the U.S.A. Environmental Management 33:S23–S43.

Badiou, P., R. Mcdougal, D. Pennock, and B. Clark. 2011. Greenhouse gas emissions and carbon sequestration potential in restored wetlands of the Canadian prairie pothole region. Wetlands Ecology and Management.

Barger, N. N., S. R. Archer, J. L. Campbell, C. Y. Huang, J. A. Morton, and A. K. Knapp. 2011, December 1. Woody plant proliferation in North American drylands: A synthesis of impacts on ecosystem carbon balance. Blackwell Publishing Ltd.

Booker, K., L. Huntsinger, J. W. Bartolome, N. F. Sayre, and W. Stewart. 2013. What can ecological science tell us about opportunities for carbon sequestration on arid rangelands in the United States? Global Environmental Change 23:240–251.

Bradley, B. A. 2010. Assessing ecosystem threats from global and regional change: hierarchical modeling of risk to sagebrush ecosystems from climate change, land use and invasive species in Nevada, USA. Ecography 33:198–208.

Carter Johnson, W. 2019. Ecosystem Services Provided by Prairie Wetlands in Northern Rangelands. Rangelands 41:44–48.

Chambers, J. C., and M. Pellant. 2008. Climate Change Impacts on Northwestern and Intermountain United States Rangelands. https://doi.org/10.2111/1551-501X(2008)30[29:CCIONA]2.0.CO;2 30:29–33.

Conant, R. T., and K. Paustian. 2002. Potential soil carbon sequestration in overgrazed grassland ecosystems. Global Biogeochemical Cycles 16:90-1-90–9.

Conant, R. T., K. Paustian, and E. T. Elliott. 2001. GRASSLAND MANAGEMENT AND CONVERSION INTO GRASSLAND: EFFECTS ON SOIL CARBON. Ecological Applications 11:343–355.

Conard, S. G., and A. M. Solomon. 2009. Chapter 5 Effects of Wildland Fire on Regional and Global Carbon Stocks in a Changing Environment Author's personal copy. Page *in* A. Bytnerowicz, M. Arbaugh, A. Riebau, and C. Andersen, editors. Developments in Environmental Science. Elsevier.

Corlett, R. T., and D. A. Westcott. 2013, August 1. Will plant movements keep up with climate change? Elsevier Current Trends.

Crimmins, S. M., S. Z. Dobrowski, J. A. Greenberg, J. T. Abatzoglou, and A. R. Mynsberge. 2011. Changes in climatic water balance drive downhill shifts in plant species' optimum elevations. Science 331:324–327.

Dass, P., B. Z. Houlton, Y. Wang, and D. Warlind. 2018. Grasslands may be more reliable carbon sinks than forests in California. Environmental Research Letters 13:074027.

DeMarco, J., T. Filley, and H. L. Throop. 2016. Patterns of woody plant-derived soil carbon losses and persistence after brush management in a semi-arid grassland. Plant and Soil 406:277–293.

Derner, J. D., D. J. Augustine, and D. A. Frank. 2019. Does Grazing Matter for Soil Organic Carbon Sequestration in the Western North American Great Plains? Ecosystems 22:1088–1094.

Derner, J. D., and G. E. Schuman. 2007. Carbon sequestration and rangelands: A synthesis of land management and precipitation effects. Journal of Soil and Water Conservation 62.

Dong, J., R. K. Kaufmann, R. B. Myneni, C. J. Tucker, P. E. Kauppi, J. Liski, W. Buermann, V. Alexeyev, and M. K. Hughes. 2003. Remote sensing estimates of boreal and temperate forest woody biomass: Carbon pools, sources, and sinks. Remote Sensing of Environment 84:393–410.

Drewniak, B. A., U. Mishra, J. Song, J. Prell, and V. R. Kotamarthi. 2015. Modeling the impact of agricultural land use and management on US carbon budgets. Biogeosciences 12:2119–2129.

Euliss, N. H., R. A. Gleason, A. Olness, R. L. McDougal, H. R. Murkin, R. D. Robarts, R. A. Bourbonniere, and B. G. Warner. 2006. North American prairie wetlands are important nonforested land-based carbon storage sites. Science of the Total Environment 361:179–188.

Fusco, E. J., J. T. Finn, J. K. Balch, R. Chelsea Nagy, and B. A. Bradley. 2019a. Invasive grasses increase fire occurrence and frequency across US ecoregions. Proceedings of the National Academy of Sciences of the United States of America 116:23594–23599.

Fusco, E. J., B. M. Rau, M. Falkowski, S. Filippelli, and B. A. Bradley. 2019b. Accounting for aboveground carbon storage in shrubland and woodland ecosystems in the Great Basin. Ecosphere 10:e02821.

Galatowitsch, S. M., and A. G. Van Der Valk. 1996. Vegetation and environmental conditions in recently restored wetlands in the prairie pothole region of the USA. Vegetatio 126:89–99.

Germino, M. J., J. C. Chambers, and C. S. Brown, editors. 2016. Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US. Springer International Publishing, Cham.

Gilmanov, T. G., L. Aires, Z. Barcza, V. S. Baron, L. Belelli, J. Beringer, D. Billesbach, D. Bonal, J. Bradford, E. Ceschia, D. Cook, C. Corradi, A. Frank, D. Gianelle, C. Gimeno, T. Gruenwald, H. Guo,

N. Hanan, L. Haszpra, J. Heilman, A. Jacobs, M. B. Jones, D. A. Johnson, G. Kiely, S. Li, V. Magliulo, E. Moors, Z. Nagy, M. Nasyrov, C. Owensby, K. Pinter, C. Pio, M. Reichstein, M. J. Sanz, R. Scott, J. F. Soussana, P. C. Stoy, T. Svejcar, Z. Tuba, and G. Zhou. 2010. Productivity, respiration, and light-response parameters of world grassland and agroecosystems derived from flux-tower measurements. Rangeland Ecology and Management 63:16–39.

Golodets, C., M. Sternberg, J. Kigel, B. Boeken, Z. Henkin, · No'am, G. Seligman, E. D. Ungar, C. Golodets, · M Sternberg, J. Kigel, B. Boeken, Z. Henkin, N. G. Seligman, and E. D. Ungar. 2015. Climate change scenarios of herbaceous production along an aridity gradient: vulnerability increases with aridity. Oecologia 1:971–979.

Halofsky, J. E., D. L. Peterson, K. S. Dante-Wooda, L. Hoang, J. J. Ho, and L. A. Joyce. 2018a. Climate change vulnerability and adaptation in the Northern Rocky Mountains - Part 1.

Halofsky, J. E., D. L. Peterson, J. J. Ho, J. Little, Natalie, and L. A. Joyce. 2018b. Climate change vulnerability and adaptation in the Intermountain Region [Part 1]. Halofsky, Jessica E.; Peterson, David L.; Ho, Joanne J.; Little, Natalie, J.; Joyce, Linda A., eds. 2018. Climate change vulnerability and adaptation in the Intermountain Region. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO.

Havstad, K. M., D. P. C. Peters, R. Skaggs, J. Brown, B. Bestelmeyer, E. Fredrickson, J. Herrick, and J. Wright. 2007. Ecological services to and from rangelands of the United States.

Havstad, K., D. C. Peters, B. Allen-Diaz, B. T. Bestelmeyer, D. Briske, J. Brown, M. Brunson, J. E. Herrick, P. Johnson, L. Joyce, R. D. Pieper, A. J. Svejcar, J. Yao, J. Bartolome, and L. Huntsinger. 2009. The western United States rangelands, a major resource. Page Grassland, Quietness and Strength for a New American Agriculture.

Holechek, J. L., H. M. E. Geli, A. F. Cibils, and M. N. Sawalhah. 2020. Climate Change, Rangelands, and Sustainability of Ranching in the Western United States. Sustainability 12:4942.

Hufkens, K., T. F. Keenan, L. B. Flanagan, R. L. Scott, C. J. Bernacchi, E. Joo, N. A. Brunsell, J. Verfaillie, and A. D. Richardson. 2016. Productivity of North American grasslands is increased under future climate scenarios despite rising aridity. Nature Climate Change 6:710–714.

Kelly, A. E., and M. L. Goulden. 2008. Rapid shifts in plant distribution with recent climate change. Proceedings of the National Academy of Sciences of the United States of America 105:11823–11826.

Kleinhesselink, A. R., and P. B. Adler. 2018. The response of big sagebrush (*Artemisia tridentata*) to interannual climate variation changes across its range. Ecology 99:1139–1149.

Knops, J. M. H., and D. Tilman. 2000. DYNAMICS OF SOIL NITROGEN AND CARBON ACCUMULATION FOR 61 YEARS AFTER AGRICULTURAL ABANDONMENT. Ecology 81:88–98.

Köchy, M., A. Don, M. K. Van Der Molen, and A. Freibauer. 2015. Global distribution of soil organic carbon-Part 2: Certainty of changes related to land use and climate 1:367–380.

Lal, R. 2004, November 1. Soil carbon sequestration to mitigate climate change. Elsevier.

Lal, R., P. Smith, H. F. Jungkunst, W. J. Mitsch, J. Lehmann, P. K. Ramachandran Nair, A. B. McBratney, J. C. De Moraes Sá, J. Schneider, Y. L. Zinn, A. L. A. Skorupa, H. L. Zhang, B. Minasny, C. Srinivasrao, and N. H. Ravindranath. 2018. The carbon sequestration potential of terrestrial ecosystems. Journal of Soil and Water Conservation 73:145A-152A.

Liu, F., X. Ben Wu, E. Bai, T. W. Boutton, and S. R. Archer. 2011. Quantifying soil organic carbon in complex landscapes: An example of grassland undergoing encroachment of woody plants. Global Change Biology 17:1119–1129.

MacNeil, M. D., M. R. Haferkamp, L. T. Vermeire, and J. M. Muscha. 2008. Prescribed fire and grazing effects on carbon dynamics in a northern mixed-grass prairie. Agriculture, Ecosystems and Environment 127:66–72.

Madani, N., J. S. Kimball, A. P. Ballantyne, D. L. R. Affleck, P. M. Van Bodegom, P. B. Reich, J. Kattge, A. Sala, M. Nazeri, M. O. Jones, M. Zhao, and S. W. Running. 2018. Future global productivity will be affected by plant trait response to climate OPEN. Scientific Reports 8:2870.

Maurer, G. E., A. J. Hallmark, R. F. Brown, O. E. Sala, and S. L. Collins. 2020, March 1. Sensitivity of primary production to precipitation across the United States. Blackwell Publishing Ltd.

Miller, R. F., J. C. Chambers, D. A. Pyke, F. B. Pierson, and C. Jason Williams. 2013. A review of fire effects on vegetation and soils in the great basin region: Response and ecological site characteristics. Page A Review of Fire Effects on Vegetation and Soils in the Great Basin Region: Response and Ecological Site Characteristics.

Morgan, J. A., R. F. Follett, L. H. Allen, S. Del Grosso, J. D. Derner, F. Dijkstra, A. Franzluebbers, R. Fry, K. Paustian, and M. M. Schoeneberger. 2010. Carbon sequestration in agricultural lands of the United States. Journal of Soil and Water Conservation 65.

Nagy, R. C., E. J. Fusco, J. K. Balch, J. T. Finn, A. Mahood, J. M. Allen, and B. A. Bradley. 2021. A synthesis of the effects of cheatgrass invasion on US Great Basin carbon storage. Journal of Applied Ecology 58:327–337.

Natural Resources Conservation Service (NRCS). 2021. A framework forr conservtion action in the Sagebush Biome. Washington, D.C. .

Neff, J. C., N. N. Barger, W. T. Baisden, D. P. Fernandez, and G. P. Asner. 2009. Soil carbon storage responses to expanding pinyon-juniper populations in southern Utah. Page Ecological Applications.

Norton, J. B., H. R. Olsen, L. J. Jungst, D. E. Legg, and W. R. Horwath. 2013. Soil carbon and nitrogen storage in alluvial wet meadows of the Southern Sierra Nevada Mountains, USA.

Petrokofsky, G., H. Kanamaru, F. Achard, S. J. Goetz, H. Joosten, P. Holmgren, A. Lehtonen, M. C. Menton, A. S. Pullin, and M. Wattenbach. 2012. Comparison of methods for measuring and assessing carbon stocks and carbon stock changes in terrestrial carbon pools. How do the accuracy and precision of current methods compare? A systematic review protocol. Environmental Evidence 1:6.

Pineiro, G., J. M. Paruelo, M. Oesterheld, and E. G. Jobbágy. 2010. Pathways of grazing effects on soil organic carbon and nitrogen. Rangeland Ecology and Management 63:109–119.

Polley, H. W., W. Emmerich, J. A. Bradford, P. L. Sims, D. A. Johnson, N. Z. Saliendra, T. Svejcar, R. Angell, A. B. Frank, R. L. Phillips, K. A. Snyder, J. A. Morgan, J. Sanabria, P. C. Mielnick, and W. A. Dugas. 2010. Precipitation regulates the response of net ecosystem CO2 exchange to environmental variation on united states rangelands. Rangeland Ecology and Management 63:176–186.

Prater, M. R., D. Obrist, J. A. Arnone, and E. H. DeLucia. 2006. Net carbon exchange and evapotranspiration in postfire and intact sagebrush communities in the Great Basin. Oecologia 146:595–607.

Puttock, A., J. A. J. Dungait, C. J. A. Macleod, R. Bol, and R. E. Brazier. 2014. Woody plant encroachment into grasslands leads to accelerated erosion of previously stable organic carbon from dryland soils. Journal of Geophysical Research: Biogeosciences 119:2345–2357.

Qi, R., J. Li, Z. Lin, Z. Li, Y. Li, X. Yang, J. Zhang, and B. Zhao. 2016. Temperature effects on soil organic carbon, soil labile organic carbon fractions, and soil enzyme activities under long-term fertilization regimes. Applied Soil Ecology 102:36–45.

Rau, B. M., D. W. Johnson, R. R. Blank, and J. C. Chambers. 2009. Soil carbon and nitrogen in a Great Basin pinyon-juniper woodland: Influence of vegetation, burning, and time. Journal of Arid Environments 73:472–479.

Rau, B. M., D. W. Johnson, R. R. Blank, A. Lucchesi, T. G. Caldwell, and E. W. Schupp. 2011a. Transition from sagebrush steppe to annual grass (Bromus tectorum): Influence on belowground carbon and nitrogen. Rangeland Ecology and Management 64:139–147.

Rau, B. M., D. W. Johnson, R. R. Blank, R. J. Tausch, B. A. Roundy, R. F. Miller, T. G. Caldwell, and A. Lucchesi. 2011b. Woodland expansion's influence on belowground carbon and nitrogen in the Great Basin U.S. Journal of Arid Environments 75:827–835.

Rau, B. M., R. Tausch, A. Reiner, D. W. Johnson, J. C. Chambers, R. R. Blank, and A. Lucchesi. 2010. Influence of prescribed fire on ecosystem biomass, carbon, and nitrogen in a pinyon juniper woodland. Rangeland Ecology and Management 63:197–202.

Reddy, A. R., G. K. Rasineni, and A. S. Raghavendra. 2010. The impact of global elevated CO 2 concentration on photosynthesis and plant productivity †. Page CURRENT SCIENCE.

Reich, P. B., S. E. Hobbie, T. D. Lee, R. Rich, M. A. Pastore, and K. Worm. 2020. Synergistic effects of four climate change drivers on terrestrial carbon cycling. Nature Geoscience 13:787–793.

Remington, T. E., P. . Deibert, S. E. Hanser, D. . Davis, L. A. Robb, and J. . Welty. 2021. Sagebrush Conservation Strategy—Challenges to Sagebrush Conservation.

Scasta, J. D., J. R. Weir, and M. C. Stambaugh. 2016. Droughts and Wildfires in Western U.S. Rangelands. Rangelands 38:197–203.

Silverman, N. L., B. W. Allred, J. P. Donnelly, T. B. Chapman, J. D. Maestas, J. M. Wheaton, J. White, and D. E. Naugle. 2019. Low-tech riparian and wet meadow restoration increases vegetation productivity and resilience across semiarid rangelands. Restoration Ecology 27:269–278.

Tan, Z., S. Liu, T. L. Sohl, Y. Wu, and C. J. Young. 2015. Ecosystem carbon stocks and sequestration potential of federal lands across the conterminous United States. Proceedings of the National Academy of Sciences of the United States of America 112:12723–12728.

Teuber, L. M., N. Hölzel, and L. H. Fraser. 2013. Livestock grazing in intermountain depressional wetlands-Effects on plant strategies, soil characteristics and biomass. Agriculture, Ecosystems and Environment 175:21–28.

Thomey, M. L., P. L. Ford, M. C. Reeves, D. M. Finch, M. E. Litvak, and S. L. Collins. 2014. Review of Climate Change Impacts on Future Carbon Stores and Management of Warm Deserts of the United States.

Throop, H. L., and K. Lajtha. 2018. Spatial and temporal changes in ecosystem carbon pools following juniper encroachment and removal. Biogeochemistry 140:373–388.

Zhu, Z., and B. C. Reed. 2012. Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of the Western United States. U.S. Geological Survey Professional Paper 1797,.