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The Carbon Security Index: A Novel Approach to Assessing How Secure Carbon Is in Sagebrush Ecosystems Within the Great Basin☆

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ABSTRACT

Rangeland carbon is often conceptualized similarly to intensively managed agricultural lands, in that we need to sequester and store more carbon. Unlike intensively managed agricultural lands, rangeland soils cannot sequester more carbon due to pedogenic and climatic limitations that influence plant community and microbial community dynamics. This requires a new paradigm for rangeland carbon that focuses on maintaining carbon security following disturbances like fire and plant community conversions (e.g., annual grasslands and conifer woodlands). To attain this, we propose the creation of a Carbon Security Index (CSI). CSI is a unitless, scalable value that can be used to compare carbon security across rangeland sites and over time and incorporates a plant fractional cover ratio, resistance and resilience, and wildfire probability. Using the Great Basin as a case study, we found that CSI decreased by 53% basin wide from 1989 to 2020. Using the Sagebrush Conservation Design's sagebrush ecological integrity categories across the Great Basin, we found that CSI in "core" areas remained relatively unchanged between 1998 and 2020 (decreased by 1%), whereas "growth opportunity" areas CSI began to change (decreased by 13%) and "other rangeland" areas CSI decreased by 67%. We found that CSI was able to act as an indicator for determining when carbon security would decrease several years prior to a wildfire disturbance, which then rapidly reduced CSI. Finally, we created a carbon security management map to help prioritize potential management for achieving greatest carbon security and locations for restoration. These results show that CSI provides landowners and land managers an opportunity to assess how secure their carbon is on the land and help them prioritize areas for restoration.

Introduction

Research addressing carbon sequestration, storage, and stocks has received considerable attention due to the role these play in climate change mitigation (Esser et al. 2011; Dean et al. 2015; Schlesinger and Amundson 2019; Bossio et al. 2020; Bai and Cotrufo 2022). Nationally and internationally, governments, organizations, and businesses are increasingly addressing climate change through initiatives aimed at reducing carbon emissions while enhancing carbon sequestration and storage via natural climate solutions such as climate-smart agriculture, forest conservation, and ecosystem restoration (Griscom et al. 2017; Bossio et al. 2020; Pathak et al. 2022). However, natural climate solutions are often examined through lenses of reducing carbon emissions in agriculture, prevention of wildland conversion to other uses (e.g., row crop agriculture, urbanization, etc.), or improving an ecosystem's ability to sequester carbon through restoration, afforestation, or reforestation (Griscom et al. 2017; Bossio et al. 2020; Fleischman et al. 2020). Although natural climate solutions are essential for curbing carbon emissions, a greater emphasis on preventing the loss of carbon from intact ecosystems via disturbance and plant community type conversions is urgently needed. Considering the uncertainties in the time necessary to recover lost carbon stores, it is wiser to maintain existing carbon stores than to attempt to recover them once lost.

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Carbon loss after land conversion or disturbance (e.g., wildfire) is considered irrecoverable, because of the immediate loss of aboveground carbon, soil erosion, lack of new belowground inputs, and the slow persistent loss of belowground carbon due to microbial activity (Hasselquist et al. 2011; Aanderud et al. 2019; Goldstein et al. 2020; Nichols et al. 2021). Irrecoverable carbon loss is reported as being most prevalent as aboveground biomass loss in forests and reduction in soil organic carbon in peatlands (Goldstein et al. 2020; Noon et al. 2022). However, here we argue that rangelands have the potential to lose both aboveground and belowground carbon due to disturbances or vegetation community conversions because of water and nutrient limitations that are necessary for carbon recovery (Noy-Meir 1973; Schlesinger et al. 1996; Engel and Abella 2011; Hobley et al. 2018). For example, in the Great Basin desert of the inter-mountain western United States, wildfires have impacted more than 12 million ha of sagebrush (*Artemisia* sp.) steppe between 1989 and 2019 and the annual area burned is increasing (Welty and Jeffries 2021). These wildfires and co-occurring invasion of annual grasses have degraded native sagebrush ecosystems with an estimated loss of up to 50% of aboveground and belowground carbon that is likely irrecoverable without active restoration (Austreng 2012; Nagy et al. 2021). Rangelands comprise ~40% of the terrestrial Earth surface (White et al. 2000) and store 10–30% of the global soil organic carbon, carbon which is secure as long as it remains undisturbed (Anderson 1991; Derner and Schuman 2007; Schlesinger and Bernhardt 2013). However, aboveground disturbances from invasive grasses, woody plant expansion, increased prevalence of wildfires, and land conversions render stored soil organic carbon insecure and potentially irrecoverable over time (Gill and Jackson 2000; Mcculley and Jackson 2012; Rau et al. 2012; Nagy et al. 2021; Zhang et al. 2021; Lohse et al. 2022; Maxwell and Germino 2022). Thus, we are faced with vegetation management and carbon management problems that ultimately distill down to how vegetation management influences carbon dynamics and security.

In heavily managed agricultural lands like row crops, water and nutrients are readily applied to increase carbon sequestration and carbon storage potential (McNunn et al. 2020). Unlike row crop agriculture, water and nutrients cannot be added to rangelands as a carbon management practice because it is not economically or logistically feasible at our management scales. Thus, we need to approach rangeland carbon management differently from agriculture. Currently, carbon management is focused on the amount of carbon sequestered or stored, a feature that is difficult to manage in heterogeneous rangeland soil systems (Jackson and Caldwell 1993; Schlesinger et al. 1996; Six et al. 2002; Maxwell and Germino 2022). Terms like irrecoverable carbon are important for the discussion, but more importantly, we must consider how to secure carbon in disturbance prone rangelands once it is sequestered and stored.

We define carbon security as the indexed value of potential carbon being protected and stored at a location at a given point-in-time. The value of these point-in-time estimates is meant to encapsulate the likelihood of human and non-human based disturbance factors that impact carbon dynamics over space and time. For example, if a rangeland site has low carbon security, stored carbon has a high likelihood of being lost because of the sites' low resiliency to disturbance. If we were to equate this to a financial investment, a low carbon security would be like a high-risk penny stock—one where there are no guarantees of a return and often the companies go bankrupt. In contrast, a rangeland with a high carbon security is resilient to disturbances and the carbon is being replenished throughout its soil profile, this is like a low-risk bond—a bond that has a fixed financial return over a long period of time and will at least return the face value. If we conceptualize carbon as a tenuous but renewable resource with varying degrees of "security" across sites, we can then address carbon on rangeland landscapes as being dynamic and manage for carbon based on the main threats to changes in carbon maintenance.

Over the last 3–5 yr, general user geospatial products (i.e., Rangeland Analysis Platform, Rangeland Cover Map) have made it possible for land managers to observe their management areas not just from the ground but to expand their scale of inference to the landscape level and beyond (Rigge et al. 2019; Jones et al. 2020). The sagebrush biome, which once covered ~1 000 000 km^2 of the western United States and was dominated by *Artemisia tridentata* Nutt., is now half as large because of wildfires, invasive annual grasses, conifer expansion, ecological droughts, and human modification (Knapp 1996; Miller et al. 2019; O'Connor et al. 2020; Palmquist et al. 2021; Doherty et al. 2022; Smith et al. 2022). These recent advances in satellite-based vegetation mapping technology (Allred et al. 2021, 2022) can be used in conjunction with abiotic data (e.g., Chambers et al. 2017; Smith et al. 2023a) to map the relative security of carbon within vegetation communities at broad spatial scales and over time. Such information could, in turn, inform strategically protecting and restoring rangeland carbon stores within the sagebrush biome.

Recently, the Western Association of Fish and Wildlife Agencies created a framework for sagebrush conservation called the Sagebrush Conservation Design (SCD). The SCD is a biome-wide and spatially explicit assessment of the ecological integrity of existing sagebrush habitats (Doherty et al. 2022). Within the SCD framework the sagebrush biome was delineated into three groups: 1) Core Sagebrush Areas—areas of intact sagebrush and perennial bunchgrasses, 2) Growth Opportunity Areas—areas of sagebrush and perennial bunchgrasses with either annual grasses or conifers present, and 3) Other Rangeland Areas—areas where sagebrush has been lost from the landscape. The purpose of this special issue is to use information from the SCD as the foundation for developing a strategic plan for defending and growing Core Sagebrush Areas being impacted by myriad threats (Doherty et al. 2024).

In this paper we apply the concept of carbon security to the Great Basin region by proposing a Carbon Security Index (CSI) for sagebrush steppe rangelands. CSI integrates plant fractional cover, the sagebrush steppe resistance and resilience (R&R) framework (Chambers et al. 2017), and fire probability. Using CSI, we assess dynamics of carbon security in the Great Basin over the last 31 yr (1989–2020) and how it relates to the Great Basin's sagebrush ecological integrity (SEI) metric as defined in the SCD (Doherty et al. 2022). We then used a case study of the 2012 Holloway wildfire to demonstrate how CSI acted as a leading indicator for observing a downward trend in CSI prior to a fire disturbance. Finally, we explored how CSI could be used to inform management of carbon at the landscape scale, presenting a management map that highlights areas of high priority for carbon conservation, restoration, and mitigation.

Methods

Study area and time frame

We focused the CSI and analyses on rangelands in the Great Basin of the western United States as determined by Reeves and Mitchell (2011). The Great Basin is defined by the Northern Basin and Range, Snake River Plain, and Central Basin and Range Environmental Protection Agency Level III ecoregions (Omernik and Griffith, 2014). Data availability for fire probability (Smith et al. 2023a) constrained our initial analysis of CSI from 1989 to 2020 within the Great Basin, and our analyses of the relationship between CSI and SEI (Doherty et al. 2022) was constrained by data availability from 1998 to 2020.

Datasets

We use four datasets for calculating and analyzing CSI within the Great Basin: 1) plant fractional cover from the Rangeland Analysis Platform (version 3; hereafter RAP; Jones et al. 2018; Allred et al. 2021), 2) R&R categories from Chambers et al. (2014, 2017), 3) Great Basin wildfire probability (Smith et al. 2023a), and 4) SEI, where we used both the continuous SEI values and the three management SEI classifications (Doherty et al. 2022). All data were accessed via Google Earth Engine (Gorelick et al. 2017).

Creation of CSI

CSI is an additive model made up of three unitless terms that provides a range of values from −2 to 2:

$$CSI = Preferred\ Rangeland\ Cover\ Index + Resistance\ Resilience - P(Fire) \quad (1)$$

The first term in the CSI model is another index called the Preferred Rangeland Cover Index, meant to characterize the degree of compositional departure from an intact plant community. For our purposes in this paper, we are addressing sagebrush plant communities within the Great Basin.

$$PRCI = \frac{(PFG + SHR) - (AFG + TRE)}{PFG + SHR + AFG + TRE + BGR} \quad (2)$$

The preferred plant community (the first term in the numerator) could be whatever fractional cover type is of interest, but given our focus on sagebrush plant communities we are interested in the perennial forb and grass cover fraction (PFG) and shrub cover fraction (SHR). These groups comprise the largest fractional cover categories of Core Sagebrush Areas in the Great Basin (Doherty et al. 2022), and are resilient to disturbances while providing consistent inputs to soil organic carbon in the upper 1-m of soil (Rau et al. 2011a; Austreng 2012; McAbee et al. 2017; Germino et al. 2019; Miller et al. 2019; Johnson et al. 2022). The annual forb and grass cover fraction (AFG) as well as the tree cover fraction (TRE) are penalized in our model because of positive feedbacks from the annual grass-fire cycle and the increased fire severity risks associated with 1 000-h and 10 000-h fuels (i.e., greatest potential carbon loss) that impact ecosystem health (Rau et al. 2011a, 2011b; Nagy et al. 2021; Mahood et al. 2022; Maxwell and Germino 2022). The denominator aggregates all the fractional cover values including bare ground (BGR). Bare ground is included only as a denominator because soil carbon stocks are relatively consistent through time and bare ground is an inherent part of semiarid and arid rangelands that can be accentuated because of disturbances (Conant et al. 2017; Jones et al. 2018). What we are left with is a unitless index term that has a range of values between −1 and 1 that will be incorporated into CSI.

The second term in the CSI model is R&R as defined by Chambers et al. (2014, 2017, 2019), which uses soil temperature and soil moisture regimes to delineate landscape resiliency to disturbance and resistance to invasive annual grasses. The current iteration of R&R is a categorical variable with three categories: high, moderate, and low. For each R&R category we assigned values of 0.75 (high), 0.50 (moderate), and 0.25 (low) to help characterize the relative likelihood of carbon recovery after disturbance. This term is meant to incorporate the abiotic or climatic characteristics of a site within CSI. For example, a sagebrush and bunchgrass community in a high R&R location will likely be able to recover after a fire disturbance because it is relatively resistant to annual grass invasions; additionally, these sites are likely to have higher carbon accumulation rates because of increased soil moisture (Aanderud and Richards 2009; Flerchinger et al. 2020; Maxwell and Germino 2022). Sagebrush sites with low R&R are less likely to recover after a disturbance and have a higher potential for invasive annual grasses because of their higher soil temperatures and lower soil moisture, which in turn translate to lower carbon accumulations (Prater et al. 2006; Mahood et al. 2022; Maxwell and Germino 2022).

The last term in the CSI model is relative fire probability. Wildfire plays a major role in governing carbon dynamics in Great Basin rangeland, and by extension belowground carbon inputs for soil organic carbon (Cleary et al. 2010; Lohse et al. 2022). Currently, we are using the dynamic fire probability model from Smith et al. (2023) developed specifically for the Great Basin. Values from this model are not absolute probabilities, but range from 0 to 1 and characterize conditions at the beginning of the year (predominantly fine fuel accumulation from the previous two growing seasons, but also abiotic inputs) that influence the likelihood of a large (>400 ha) wildfire as the result of exposure to ignition.

Statistical analyses

We used linear regression to estimate trend in average CSI from 1989 to 2020 at the scale of the entire Great Basin. We then used the SCD's categorical designations derived from SEI—"Core Sagebrush Areas" (hereafter Core; intact sagebrush ecosystem), "Growth Opportunity Areas" (hereafter Growth; partially intact sagebrush ecosystem), and "Other Rangeland Areas" (hereafter Other; degraded sagebrush ecosystem)—to address how our concept of carbon security relates to the SCD framework in the Great Basin. First, we verified that the two indices (SEI and CSI) were sufficiently independent to warrant comparisons between them. To accomplish this, we randomly sampled 30-m pixels ($N = 6\,643$) from 2020 in the Great Basin and extracted CSI and SEI values from each pixel. Some similarity was expected due to shared parameters (e.g., fractional plant cover); however, because of the presence of nonshared parameters and major differences in how fractional cover variables were weighted and aggregated, the two indices were only moderately correlated (Pearson's correlation coefficient, $r = 0.45$; $P < 0.001$). Notably, CSI was far more variable in areas with very low SEI scores (Fig. 1). Satisfied that the two indices were nonredundant, we used linear regression with CSI as our response variable to test for differences in trends in carbon security among SEI categories. Independent variables included *year* (limited to 1998–2020 due to the period covered by the SCD), *SEI* category (core, growth, and other), and the interaction *year* × *SEI*. Terms were deemed significant at $\alpha = 0.05$. Means and trend testing for *year* × *SEI* trends were made using marginal means.

In addition to addressing how CSI related to SEI categories, we also used CSI to illustrate the influence of fire on carbon security using the 187 000 ha Holloway fire (2012) in southeast Oregon and northern Nevada as a case study. The Holloway fire was chosen because it was large enough to encompass a variety of abiotic conditions, reflected in the presence of large areas of high, moderate, and low R&R categories. Within the fire perimeter (from the Monitoring Trends in Burn Severity dataset; Eidenshink et al. 2007) we aggregated CSI among R&R categories through time. We then fit a piecewise linear regression, using the R packaged "segmented" (Muggeo 2008), to model CSI as a function of R&R category and year while allowing for breaks in slope associated with the fire. When building piecewise linear models an a priori breakpoint is required for the model to begin estimation; we initialized the breakpoint at 2012, the year of the wildfire. Breakpoints estimated by the model were rounded to the nearest year.

To map CSI we used the distribution of a random sample of 30-m pixel CSI values ($N = 6\,643$) from 2020 in the Great Basin (the same used in the determination of the relationship between CSI and SEI) to define three carbon security management levels:

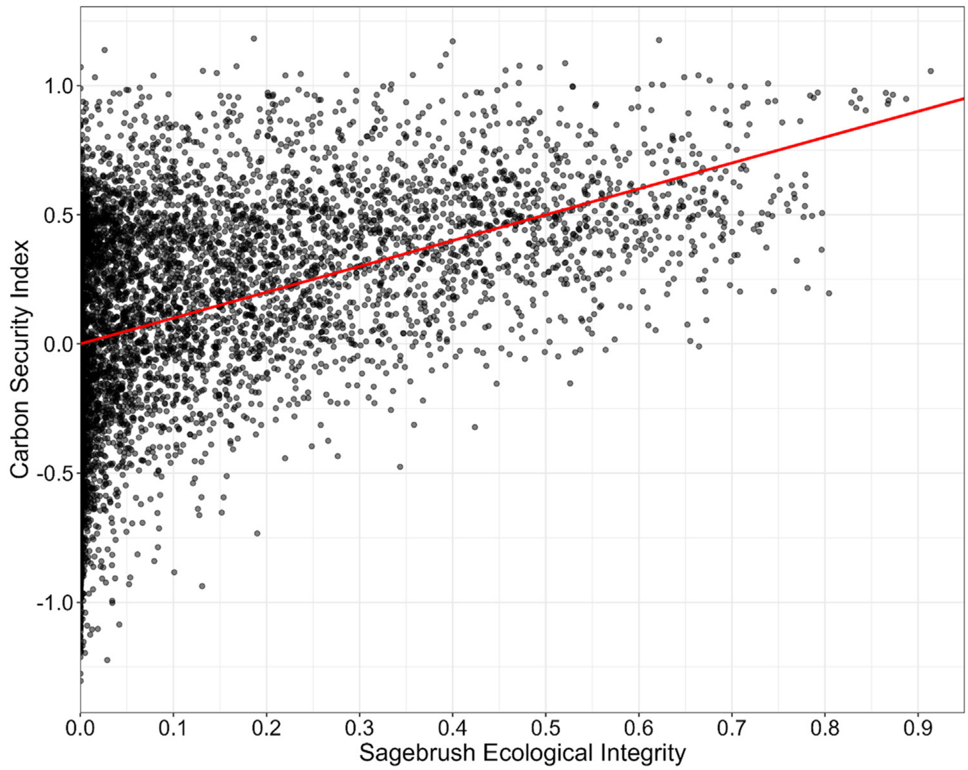

Figure 1. A moderate positive correlation (Pearson's correlation coefficient, $r = 0.45$; $P < 0.001$) among 6 643 randomly sampled 30-m spatial points within the Great Basin from 2020 between the carbon security index and sagebrush ecological integrity models. The red line represents a 1:1 line.

Protect, Restore, and Mitigate. Breaks between these levels were based on the first and third quartiles of the distribution. CSI values of >0.45 were considered "Protect," which means to protect these areas from processes that involve carbon loss. Sites assigned to "Protect" will have high cover of shrubs, perennial grasses and forbs with little to no tree or annual grass and forb cover; these areas are expected to have the highest carbon security and thus stored carbon. CSI values between −0.15 and 0.45 were considered "Restore," indicating areas that should be considered for increasing carbon inputs (e.g., through restoring the native plant communities). "Restore" sites may have lower cover of shrubs, perennial grasses and forbs, and/or increased cover of trees or annual grasses and forbs; these sites have lost some carbon security due to their elevated potential for disturbance and degradation. CSI values of <−0.15 were considered "Mitigate," indicating areas where management should address imminent threats of fire, erosion, and conversion to annual grasses to prevent continued loss of carbon. "Mitigate" sites have low to no shrub and perennial grass and forb cover, whereas high cover of trees and annual grasses and forbs result in high fire probability; these sites have low carbon security and a greater potential for losses of carbon.

All data analyses and graphical visualizations were completed in the Google Earth Engine code editor (Gorelick et al. 2017), ArcGIS Pro (Esri, 2023 Redlands, CA, USA), and program R with R Studio (R Core Team, 2022 Vienna, Austria; R Studio team, 2023 Boston, MA, USA). Post hoc tests were completed using the R package emmeans (Lenth 2022).

Results

Great Basin

From 1989 to 2020, mean CSI in the Great Basin has decreased overall by 53% (Fig. 2; $P < 0.001$, adj. $R^2 = 0.525$; Table S1; available online at doi:10.1016/j.rama.2024.08.005). The reduction is predominately caused by a reduction in the PRCI component and an increase in the fire probability component (Fig. 2, bottom left panel inset). When we tested for trends by SEI category, we observed no significant downward trend in CSI for core areas (1% reduction). Growth opportunity and other rangeland areas had significant reductions in CSI between 1998 and 2020, 13% and 67% respectively (Fig. 2; growth opportunity: $P < 0.001$; other rangeland: $P < 0.001$; Table S2; available online at doi:10.1016/j.rama.2024.08.005). There was also a significant difference between the slope and intercept of other rangeland and core areas (Fig. 2; $P = 0.0454$; Table S2). There were no differences between intercepts and slopes for core and growth opportunity areas or growth opportunity and other rangeland areas from 1998 to 2020.

Holloway fire

Prior to the estimated breakpoints, low R&R sites within the Holloway fire boundary had a moderate reduction in mean CSI with an estimated breakpoint of 2009 ($P = 0.037$), whereas moderate and high R&R sites had smaller reductions in mean CSI prior to their estimated breakpoints of 2008 (Fig. 3, Table S3; available online at doi:10.1016/j.rama.2024.08.005). After the mean breakpoints all R&R categories were statistically different from one another ($P < 0.001$), and all postbreakpoint CSI slopes were statistically different from their prebreakpoint slopes ($P < 0.001$). These differences in slopes resulted in large reductions of mean CSI values (Fig. 3, Table S3).

Discussion

As a first-in-kind creation, the novelty of the CSI is its ability to shift the prevailing paradigm from sequestration to security of stored carbon in rangelands. CSI is attractive for its integration

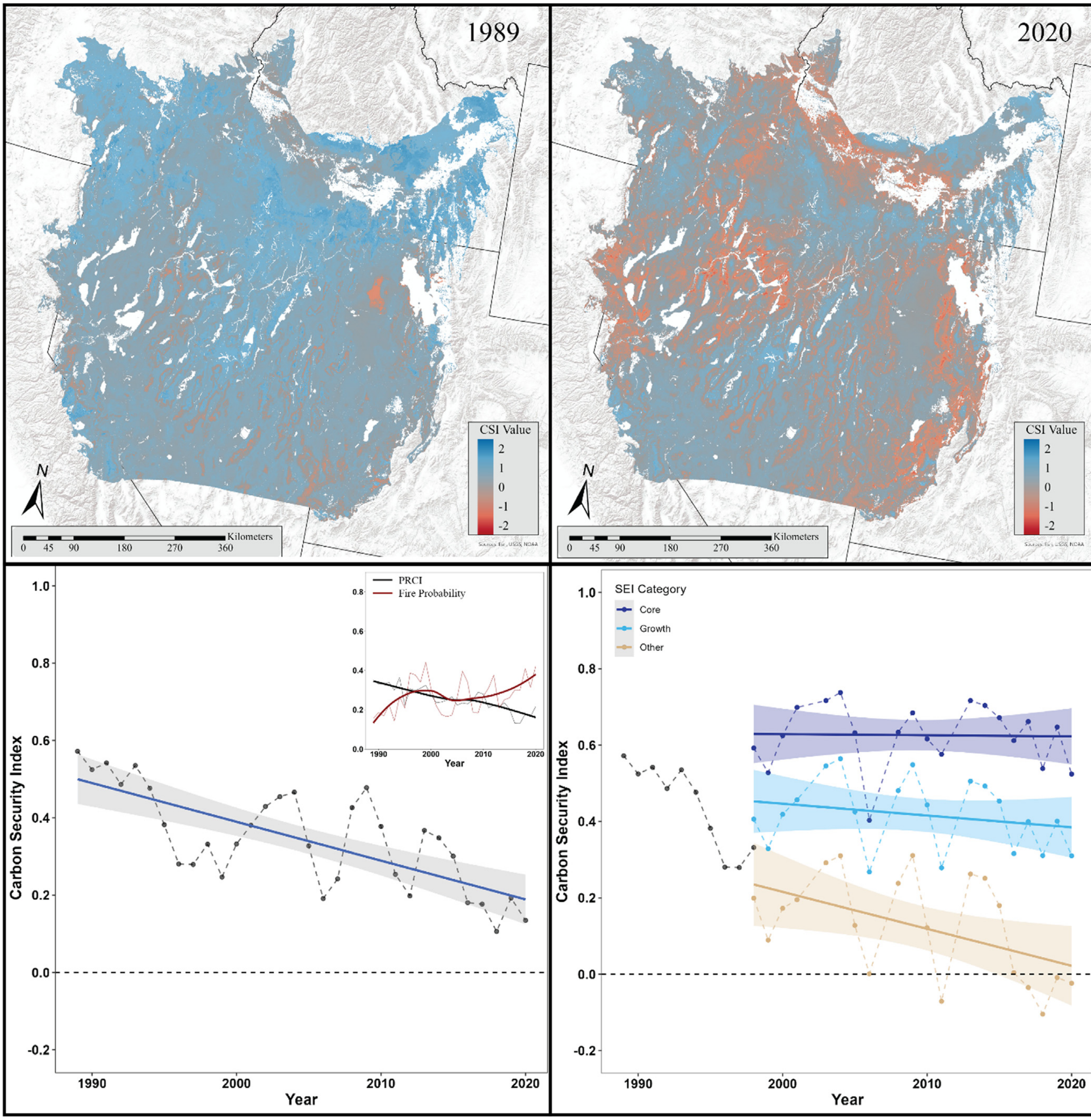

Figure 2. Calculated Carbon Security Index (CSI) at 30-m resolution for the Great Basin desert in 1989 (upper left), and 30-m CSI in 2020 (upper right). Temporal trends in mean CSI across the Great Basin from 1989 to 2020 (bottom left) and Great Basin mean CSI variation from 1998 to 2020 for the three sagebrush ecological integrity (SEI) categories (bottom right). Solid lines are the model estimated means, whereas shading indicated the 95% confidence intervals around the estimated mean. The points are the calculated CSI values. The inset in the bottom left panel shows temporal trends of the Preferred Rangeland Cover Index (PRCI; black line) and the Fire Probability (red line) across the Great Basin from 1998 to 2020.

of vegetation and carbon management to estimate carbon security trajectories across large and complex landscapes over management timeframes. This information can in turn be used to make determinations about the most productive spatial array of carbon conservation assets and their management. Within the Great Basin, for example, our analysis indicates a 53% reduction in CSI from 1989 to 2020 (Fig. 2). The overall reduction in CSI captures well-documented and increasing trends in annual grass and conifer cover (Smith et al. 2022; Boyd et al. 2024; Reinhardt et al. 2024).

Changes in CSI from increased annual grass cover is often the result of increased wildfire activity, which reduces native sagebrush cover and sometimes perennial grass density (Boyd et al. 2015; Pilliod et al. 2017; Bates et al. 2020; Smith et al. 2023a, 2023b). The loss of sagebrush and perennial grasses reduces the carbon inputs at deeper soil depths (>40 cm), which will likely result in continued loss of soil carbon over time (Bradley et al. 2006; Rau et al. 2011a; Nagy et al. 2021; Mahood et al. 2022; Maxwell and Germino 2022;). Additionally, conifers, such as West-

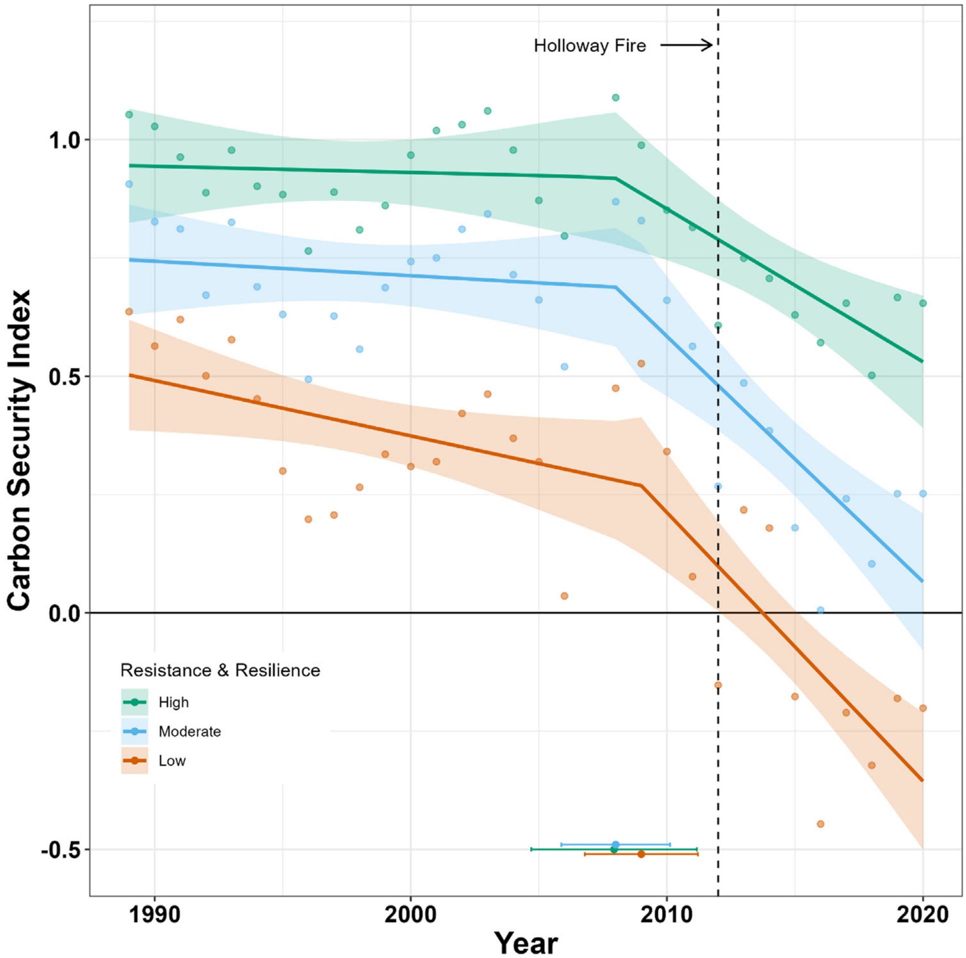

Figure 3. Carbon Security Index time series from 1989 to 2020 separated by resistance and resilience categories (high = green, moderate = blue, and low = red) parameterized for the Holloway fire. Solid lines represent the piecewise linear regression modeled means, whereas the shading indicates the 95% confidence interval for each mean. The points along the lines are the actual Carbon Security Index calculated values. The three points with standard error bars at the bottom of the figure are the piecewise linear regression estimated breakpoints for each resistance and resilience category and indicate the start of a large decrease in carbon security.

ern juniper (*Juniperus occidentalis*), have expanded from their historic ranges (Miller et al. 2006, 2019). Unlike annual grass conversions, conifers sequester and store large quantities of carbon belowground and in aboveground biomass (Rau et al. 2009, 2011b; Fusco et al. 2019; Abdallah et al. 2020). However, larger amounts of aboveground biomass in conifers can increase vulnerabilities of carbon loss to wildfires, as up to 70% of the sequestered carbon can be rapidly released upon burning (Rau et al. 2010, 2011b). This potential for large carbon losses after fire reduces the carbon security of the landscape when conifers are present. Such reductions in carbon security because of conversions to annual grassland or conifer expansion need to be considered when thinking about how we manage carbon in sagebrush ecosystems.

Comparing CSI and SEI (Fig. 1) directly to one another, we found that there was greater variation in CSI where SEI took on a value of zero. This pattern emerges because SEI is multiplicative; if any component's weighted score is zero then the final SEI value is zero and the area is classified as "other rangeland" (Doherty et al. 2022). For example, if a wildfire reduces sagebrush cover to zero then the SEI value is zero, even if high perennial bunchgrass and forb cover remain. Under the same scenario, CSI would remain relatively high because perennial grasses sequester and store carbon throughout the soil profile even in the absence of sagebrush (Figs. 1 and 3; Acker 1992; Cleary et al. 2010). These differences between SEI and CSI can be harnessed for a more complete picture of areas that could be prioritized for restoration with sagebrush ecosystem because of their carbon security potential and ability to resist annual grass invasion.

We found that averaged CSI in places that have remained sagebrush "core areas" has not declined more than 1% in 22 yr, whereas areas currently classified as "growth opportunity" experienced a 13% reduction in CSI over that same period (Fig. 2). This is an encouraging finding because the carbon security in these areas is being maintained or has only been reduced minimally, in association with relatively intact perennial grass and shrub plant communities that incorporate carbon into deeper soil depths (>40 cm) (Rau et al. 2011a). Areas currently classified as "other rangelands" have experienced a 67% loss in carbon security over the last 22 yr as they have transitioned to degraded annual grasslands or woodlands (Fig. 2). The decrease of CSI in "other rangelands" needs to be addressed because of how CSI and SEI models diverge as discussed in the previous paragraph. There is a high likelihood that a portion of "other rangelands" in the Great Basin have high CSI because they are devoid of sagebrush cover but maintain high perennial bunchgrass cover and low annual grass cover, perhaps due to high R&R. The ongoing, large-scale loss of core and growth opportunity areas means that carbon security losses are likely occurring on a similar scale (Doherty et al. 2022). Thus, if we want to man-

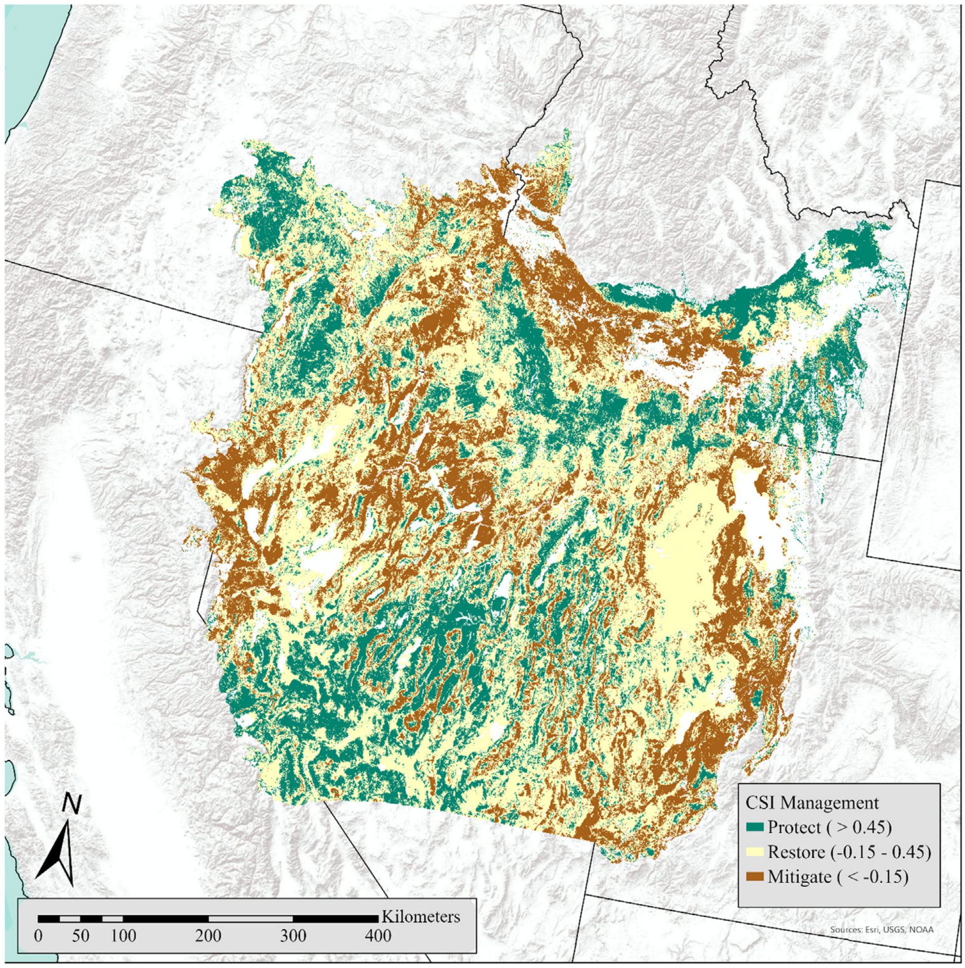

Figure 4. Carbon Security Index (CSI) management map for the Great Basin in 2020.

age landscapes for carbon we should focus on protecting core and growth opportunity areas to reduce the likelihood of losing carbon stores in these sagebrush rangelands.

Disturbances like wildfires have wide-ranging impacts including changes in plant communities, soil erosion, soil properties, etc. (Ravi et al. 2007; Rau et al. 2010; Hasselquist et al. 2011; Bates et al. 2020), ultimately affecting all aspects of carbon security. We used CSI to track the trajectory of carbon security among the different R&R categories before and after the 2012 Holloway fire in southern Oregon and northern Nevada. We found that high and moderate R&R sites prior to the fire had little change in CSI, whereas low R&R sites had a greater reduction in CSI (Fig. 3; Table S3; see slope estimates). Since the fire, CSI values have declined at a significantly faster rate among all R&R categories (slope values: high, −0.031 [95% CI, −0.05 to −0.01]; moderate, −0.049 [95% CI, −0.08 to −0.03]; low, −0.045 [95% CI, −0.08 to −0.03]). Perhaps more notable, however, is that the breakpoints for all R&R categories were estimated at between 2 and 3 yr prior to the fire (Fig. 3). This was a serendipitous, if informal, demonstration of the utility of CSI as a leading indicator as opposed to a lagging index of changes in the past. To return to our stock market analogy, CSI is intended to fill a niche similar to a volatility index, which uses recent market dynamics to make near-term forecasts of the trajectory of the market. CSI was designed to be sensitive to changes in vegetation composition and fire probability that are a bellwether for events that affect carbon fluxes and pools, like wildfires.

Management implications

Mapping carbon security in rangelands is crucial to provide a tool for evaluating how changes in the landscape influence potential carbon resiliency over time. CSI provides a quantitative methodology for evaluating carbon security from ecoregional to pasture scales, enabling ranchers, land managers, and planners to strategically allocate carbon management. However, making management decisions on the basis of a spatially and temporally dynamic continuous index presents its own challenges. To help reduce complexity, we present a carbon security management map (Fig. 4) that divides the landscape into three categories: Protect, Restore, and Mitigate (Fig. S1; available online at doi:10.1016/j.rama.2024.08.005). The carbon security management map can be layered upon other SCD geospatial layers (see other articles in this special issue) to get a more complete picture of how to holistically defend and grow the Core in the face of ongoing and future threats while simultaneously maximizing carbon security in a dynamic environment. Our findings indicate that CSI in Core and Growth areas largely align with managing for carbon security on Great Basin sagebrush rangelands.

CSI is not a carbon accounting index. Although knowing the quantitative amounts of carbon is an important component of carbon management so too is the security of the carbon in a disturbance prone environment. CSI will not replace intensive carbon sampling required for estimating carbon pools and stock, but CSI can provide insight into location selection for intensive carbon sampling. The concept of carbon security provides an alternative framework for planning and decision making in highly dynamic dryland ecosystems such as sagebrush rangelands where the prevailing focus on carbon sequestration and storage are limited currently by our lack of data and understanding of the complex heterogeneity of these landscapes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Rory C. O'Connor: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chad S. Boyd:** Writing – review & editing, Writing – original draft, Conceptualization. **David E. Naugle:** Writing – review & editing, Writing – original draft, Conceptualization.

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Data availability

Carbon Security Index data for the Great Basin from 1989 to 2020. Data are in the form of a Google Earth Engine asset. https://gee-community-catalog.org/projects/csi/.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2024.08.005.

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