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Ecosystem carbon in relation to woody plant encroachment and control: Juniper systems in Oregon, USA

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ABSTRACT

The encroachment of western juniper (*Juniperus occidentalis*) trees represents a substantial problem in Oregon rangelands because of the displacement of understory vegetation of importance to wildlife and livestock. Therefore, the control of this species is a common ecological restoration practice. However, western juniper control may also affect the carbon sequestration capacity for an area, although this effect is not well understood. Our study site was a paired watershed in central Oregon where western juniper trees were cut in one watershed (treated, 116 ha) and were left intact in another (untreated, 96 ha). Thirteen years after control, we quantified aboveground carbon stocks for western juniper trees, shrubs, grasses, and litter in both the treated and untreated watersheds. We also quantified belowground carbon stocks (roots and soil) in both watersheds at two soil depths (0 − 25 cm and 25 − 50 cm). Aboveground carbon stocks were 5.8 times greater in the untreated than in the treated watershed. On the other hand, root carbon stocks were 2.6 times greater in the treated than in the untreated watershed. Soil carbon stocks at both 0 − 25 cm and 25 − 50 cm depth were not affected by juniper control. Overall, total ecosystem carbon stocks (average 137.6 Mg C ha^{-1}) were not different between watersheds. Most carbon resided belowground (soil 0 − 50 cm and roots); 84% and 97% of the total ecosystem carbon, respectively, was found in the untreated and treated watershed. Juniper control represents benefits such as habitat restoration for native wildlife, increased forage for livestock, and restoration of hydrological functions. Our study provides basis to suggest that the benefits of juniper control can be attained without substantially affecting the potential for ecosystem carbon sequestration.

1. Introduction

Woody plant encroachment has been documented worldwide over the past 150 years in many ecosystems (Archer et al., 2017). The expansion of woody plants into grasslands and shrublands has important implications for wildlife habitat, fire regimes, forage and livestock production, hydrology and soil erosion, and biodiversity (Archer, 2010; Baruch-Mordo et al., 2013; Eldridge et al., 2011; Ochoa et al., 2018). Woody plant encroachment may also have an impact on carbon pools worldwide by modifying aboveground and belowground net primary productivity and modifying rooting depth, biomass and distribution (Hughes et al., 2006; Boutton et al., 2009). Woodland encroachment commonly results in aboveground carbon stock increases (Barger et al., 2011; Shackleton and Scholes, 2011; Fernandez et al., 2013), but increases in total ecosystem carbon stocks have also been reported (Daryanto et al., 2013; González-Roglich et al., 2014; Pellegrini et al., 2014). González-Roglich et al. (2014) found that an ecosystem encroached by the woody plant *Prosopis caldenia* produced three times greater total ecosystem carbon than an herbaceous-dominated ecosystem. However, thicket encroachment into South African grasslands did not represent significant gains in total ecosystem carbon pools (Coetsee et al., 2013).

Juniper (*Juniperus* spp) encroachment is one of the most large-scale changes that are occurring in North American rangelands (Baker and Shinneman, 2004; Sankey et al., 2010). The spatial distribution of juniper has increased between 30% and 625% since the mid-19th century throughout the Great Basin (Romme et al., 2009; Sankey et al., 2010) and encroachment rates have varied between 1.5% and 2% per year (Sankey and Germino, 2008; Sankey et al., 2010). Western juniper (*Juniperus occidentalis* spp. *occidentalis* Hook.) is an encroaching species into the semiarid shrub-steppes of the western United States that occupies 3.6 million hectares in central and eastern Oregon, northeastern California, southwestern Idaho and northwestern Nevada (Azuma et al., 2005). These woodlands have expanded significantly over the last 130

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years due to a combination of factors including changes in climate, increases in the atmospheric carbon dioxide, introduction of livestock, and reduction of fire occurrences (Soulé et al., 2004; Miller et al., 2005). Documented implications of western juniper encroachment into shrublands and grasslands include a reduced forage base for livestock and habitat deterioration for wildlife species of concern such as the greater sage grouse (*Centrocercus urophasianus*) (Baruch-Mordo et al., 2013; Dittel et al., 2018). Elimination of juniper has resulted in an increase of soil moisture and streamflow compared to encroached areas (Ochoa et al., 2018; Ray et al., 2019).

There is a relative abundance of studies evaluating the ecological repercussions and control benefits of western juniper as well as a clear perception by ranchers that juniper encroachment represents a serious threat (Johnson et al., 2011). As a result, juniper control is a common rangeland management practice (Campbell et al., 2012). However, little is known about the implications of juniper encroachment and control on ecosystem carbon pools. Existing work indicates that western juniper encroachment increases aboveground carbon stocks with respect to non-encroached conditions (Campbell et al., 2012; Throop and Lajtha, 2018). Western juniper encroachment into a sagebrush community increased carbon stocks (aboveground, roots, litter and soil carbon at $0-10$ cm soil depth) from 13.5–30.2 Mg C ha^{-1}, but understory vegetation, such as grasses and shrubs, were not included in total carbon stocks calculation (Throop and Lajtha, 2018). Several studies indicate an increase in surface soil carbon (up to 10 cm depth) associated with western juniper encroachment (Bates et al., 2002; Miwa and Reuter, 2010; Throop and Lajtha, 2018). However, Rau et al. (2011) reported no gains in soil carbon resulting from woody plant (including western juniper) encroachment in the Great Basin of North America. Except for Throop and Lajtha (2018), information on carbon stocks as affected by western juniper control does not exist.

Our study site involved paired watersheds in central Oregon. In one of the watersheds (the treated watershed) western juniper trees were eliminated 13 years prior to sampling whereas in the other watershed the western juniper trees have been left intact (the untreated watershed). Following western juniper control on the treated watershed, changes in vegetation composition have been reported, including western juniper regrowth and greater presence of shrubs and grasses (Ray et al., 2019). Because of the vegetation changes following western juniper control, the potential impact of this management practice on carbon accumulation is difficult to forecast. Evaluations of ecosystem carbon stocks require an understanding of how both aboveground stocks (including understory vegetation) and belowground stocks respond to the presence and control of western juniper trees. Carbon stock evaluations as affected by rangeland management practices are essential in ecological studies, given the significance of promoting carbon sequestration and the extent of rangelands worldwide (Barger et al., 2011; Bikila et al., 2016; Archer et al., 2017). The objective of this study was to determine ecosystem carbon stocks in an encroached juniper watershed and an adjacent watershed where juniper control occurred 13 years prior to determinations. We hypothesized that the treated watershed, after 13 years of mature western juniper control, would store less aboveground and belowground carbon than the untreated watershed, implying lower capacity for soil carbon sequestration resulting from juniper control.

2. Materials and methods

2.1. Study area

This study was conducted at the Camp Creek Paired Watershed Study site (lat 43.96 N, long 120.34 W) in Crook County, central Oregon, USA (Fig. 1). The study site comprises an area of approximately 212 ha and includes two adjacent watersheds, one treated (116 ha) and the other untreated (96 ha) with elevations ranging from 1370 m to 1524 m (Ochoa et al., 2018). In the treated watershed, approximately 90% of the western juniper trees were cut in 2005 using chain saws, leaving only old-growth trees intact (Ray et al., 2019). The felled trees and debris that resulted from juniper cutting were scattered and left on the ground. The average slope for each watershed is around 25% with similar distribution of aspects (Fisher, 2004). Prior to juniper elimination from the treated watershed, juniper occupied 27% cover in the whole area (Ray et al., 2019), which is near the 30% cover described for Phase (III) juniper sites (Miller et al., 2005). In addition, prior to juniper elimination there were no statistically significant differences in vegetation cover (including juniper, shrubs, and grasses) between the treated and untreated watersheds (Fisher, 2004). After elimination, juniper cover in the treated watershed was 1% (Durfee et al., 2019; Ray et al., 2019).

The average annual precipitation of the study site is 358 mm. The study area comprises mostly three major soil series; Westbutte, Madeline, and Simas; Westbutte very stony loam and Madeline loam, the two major soil types, were found to comprise approximately 70% to 74% of the study area (Fisher, 2004). Simas, gravelly silt loam accounts for the final portion with additional soil series occupying < 1% The Westbutte series is classified as loamy-skeletal, mixed, superactive, frigid Pachic Haploxerolls. The Madeline series is classified as clayey, smectitic, frigid Aridic Lithic Argixerolls. The Simas series is classified as fine, smectitic, mesic Vertic Palexerolls. The untreated watershed is primarily composed of 48% Madeline, 26% Westbutte, and 21% Simas series while the treated watershed is composed of 50% Westbutte, 20% Madeline, and 3% Simas series (Fisher, 2004).

The most common tree in the area is western juniper (*Juniperus occidentalis*). The most common shrub species are mountain big sagebrush (*Artemisia tridentata, spp vaseyana*), antelope bitterbrush (*Purshia tridentata*), rubber rabbitbrush (*Ericameria nauseosa*), and green rabbitbrush (*Chrysothamnus viscidiflorus*). For the purposes of this study, western juniper is considered a tree, not to be confused with shrubs in any context or determination. The most common perennial grasses of the area are Idaho fescue (*Festuca idahoensis*), bluebunch wheatgrass (*Pseudoroegneria spicata*), Sandberg bluegrass (*Poa secunda*), prairie junegrass (*Koeleria macrantha*), and Thurber's needlegrass (*Achnatherum thurberianum*). Forbs are not common, representing < 3% of plant cover in the area (Ray et al., 2019).

2.2. Field sampling layout

The treatments of study were: 1) untreated = no manipulation of vegetation, i.e., western juniper trees, shrubs, and grasses were left intact in the untreated watershed and 2) treated = western juniper trees were cut in 2005 (shrubs and grasses were left intact). The trees were manually cut with chainsaws to ground level and the resulting debris was scattered and left on the ground. Cattle grazing has occurred in both watersheds before and after juniper elimination in the treated watershed. In each watershed (treated and untreated), 20 plots (replications) of 20 m X 20 m were established (Fig. 2). The 20 plots were systematically randomized in a 4 × 5 grid (sensu Keith, 2017) trying to represent most of the terrain within each watershed (Fig. 1). The samples were first located on a digital map and then the plots were found on the terrain with the help of a GPS unit. The sampling was random because we did not control the specific areas where the plots were located. The distance between plots within the predefined grid was 130 m among columns and 180 m among rows. The 20 m × 20 m plots were used to sample western juniper trees. Then, a 10 m × 10 m plot within each 20 m × 20 m plot was established for estimating shrub biomass (Fig. 2). In addition, four plots of 2 m × 2 m within each 20 m × 20 m plot were established for grass and litter biomass evaluations.

2.3. Data collection

We followed the Intergovernmental Panel on Climate Change (IPCC) guidelines for developing greenhouse gas (GHG) emission inventories

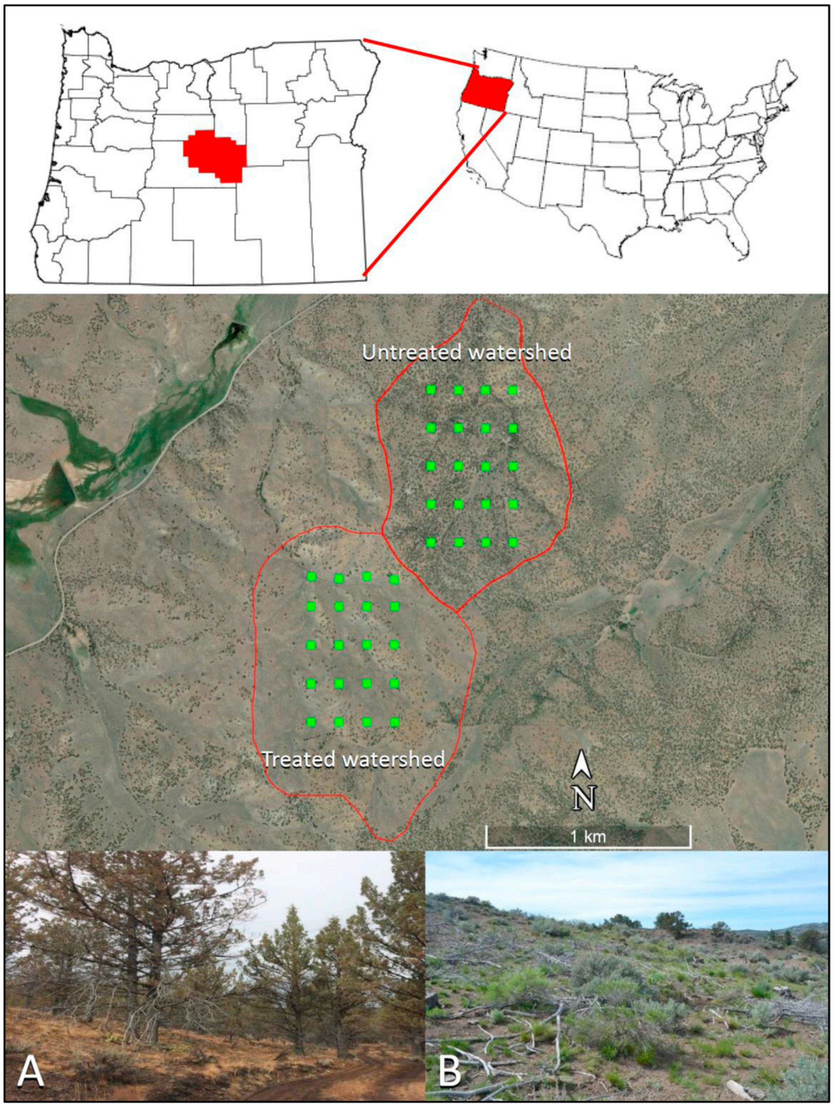

Fig. 1. Map of the study area showing untreated and treated watersheds, indicating locations of systematically randomized plots used in this study. Photograph A shows intact western juniper (*Juniperus occidentalis*) trees in the untreated watershed, while photograph B shows cut western juniper trees in the treated watershed.

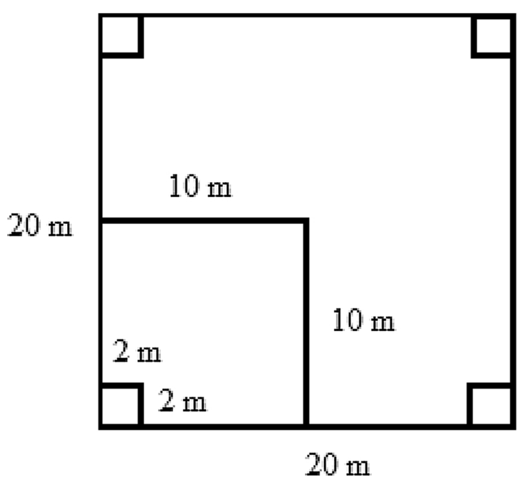

Fig. 2. Plots used in the study for biomass evaluations. The 20 m × 20 m plots were used for western juniper (*Juniperus occidentalis*) sampling, the 10 m × 10 m plots were used for shrub sampling, and the 2 m X 2 m plots were used for grass and litter sampling.

for forestlands. We estimated carbon content in western juniper and understory biomass using a component of the tiered approach to develop carbon inventories suggested by the IPCC: Tier 3 estimates carbon biomass taking into consideration management practices and long-term effects (Eggleston et al., 2006).

2.4. Aboveground biomass and litter sampling

Aboveground biomass for western juniper trees was estimated in each 20 m × 20 m plot of the untreated watershed using allometric equations developed by Sabin (2008) for western juniper trees of comparable dimensions in eastern Oregon. Based on the best-reported fitting equation, canopy diameter was recorded in two opposite directions for all trees within each plot (Sabin, 2008). Then, canopy area was calculated using the average diameter for each tree. Subsequently, aboveground biomass (kg) was estimated using the equation $y = 9.7164x + 37.506$, where x is the tree canopy area (m^2). The allometric equation that we used has been previously used by Campbell et al. (2012) to estimate aboveground biomass in other areas of Oregon.

Aboveground biomass for regrowth western juniper trees in the treated watershed was obtained by counting the number of individuals within a given plot, cutting and collecting a representative individual from within a given plot, obtaining its dry weight at the lab, and extrapolating biomass weight by area. When mature trees were found inside the treated watershed plots (since 10% of the mature juniper trees were left intact), they were also included in the carbon quantification. The biomass of those trees was calculated as in the untreated plots. The shrub biomass (in both watersheds) was obtained in a similar manner as regrowth juniper trees, except that for shrubs one representative individual was collected for each shrub species found within the sampling plot. For grasses, eighty 2 m × 2 m plots were established in each watershed. Grass aboveground biomass was estimated in both watersheds by harvesting all live standing tissue for dry matter analysis. Non-grass herbs were not common, but when they were present, we sampled them as we did grasses and their biomass was lumped into that of grasses. Litter was sampled from the same plots that were used for grass sampling. All dead lying tree, shrub, and grass materials were considered litter. Because all the litter was dry and detached from the soil, we picked it all to obtain its weight it and returned it to its original place.

2.5. Belowground biomass sampling

Root biomass was estimated by the trench method, as in Komiyama et al. (1987). In the untreated watershed, root biomass was estimated for random stands of mature western juniper trees, shrubs, and grasses, while in the treated watershed, it was estimated for random stands of regrowth juniper, remaining tree stumps, shrubs, and grasses. Three trenches for each plant type in each watershed were dug to a depth of 50 cm using an excavator (Bobcat Inc. West Fargo, North Dakota, USA). The trench width was 61 cm while the trench length was about 3 m (the exact length for each trench was measured and recorded). Twenty-one trenches (9 in the untreated watershed and 12 in the treated watershed) were dug in total. The trenches were dug first for the top 25 cm and then for the subsequent 25 cm, maintaining the soil from each depth separated. After obtaining the substrate from each trench and soil depth, the roots were carefully separated from the soil using a sieve prior to subsequent rinsing.

2.6. Plant dry matter and carbon concentration determinations

Dry matter of aboveground and belowground biomass was obtained by placing biomass samples in an oven at 60 °C until constant weight. The carbon concentrations for aboveground biomass were determined in five samples for western juniper and the main shrub species found in the area. Five samples were considered enough because carbon concentration variation is considered low in relation to that of other nutrients (Martin et al., 2015). Evidence that carbon concentration variation is low and that our sampling protocol was adequate was the low variation obtained in all the plant carbon measurements (Table 1). Carbon concentrations for root samples were determined for western juniper and the shrub species without distinguishing shrubs species (it was difficult to separate shrub roots by species). Likewise, carbon concentrations were also determined for samples of grasses and litter without distinguishing species. These determinations were conducted at the Central Analytical Laboratory of the Crop and Soil Science Department at Oregon State University (Corvallis, OR) using a CNS automatic analyzer (Elementar Vario MMARCO CNS, Elementar Analysen Systeme GmbH, Hanau, Germany).

2.7. Soil sampling

Soil samples were collected from all systematically randomized plots (20 plots in each watershed) (Fig. 1) using a cylindrical soil step probe of 1.6 cm inner diameter (AMS, Inc; American Falls, Idaho, USA). Soil samples were collected from under the canopy of mature western juniper trees in the untreated watershed and near stumps of cut western juniper trees (areas that would have been under canopy prior to tree

Table 1
Mean (± SE) of carbon concentration (%) obtained by laboratory analysis of western juniper (*Juniperus occidentalis*), main shrub species, grasses, and litter of the study area, central Oregon, USA. Root carbon analysis by species was not performed on shrubs.

Biomass samples	Aboveground carbon %	Root carbon %
Mature western juniper	51.2(0.50)	44.4(1.10)
Regrowth western juniper	51.1(0.44)	45.2(0.87)
Shrubs (average)	46.2(0.97)	38.8(1.92)
Artemisia tridentata	47.7(0.35)	
Purshia tridentata	46.7(0.10)	
Eriogonum fasciculatum	43.3(0.71)	
Ericameria nauseosa	47.0(0.43)	
Grasses	39.7(0.58)	37.6(1.61)
Western juniper stumps	–	45.0(1.26)
Litter (mainly western juniper debris)	46.4(0.50)	–

*For all live species (juniper, shrubs, and grasses), the aboveground carbon analysis was made in leaves and stems or twigs.

cutting) in the treated watershed. Our sampling was done from areas 50 cm to the trunk or stump but we did not follow any specific direction within the canopy because a previous study found no differences in soil organic matter in relation to soil sample orientation under tree canopies (Rossi and Villagra, 2003). Soil samples were also obtained from interspaces of both watersheds. Thus, there were two sampling contexts in each plot, under-canopy/near stumps and interspace. Two soil samples were collected from each sampling context of each plot at two soil depths (0 – 25 cm and 25 – 50 cm). In total, eight soil samples were collected for each plot (2 samples x 2 conditions x 2 depths). For the whole study, we analyzed 320 soil samples for carbon at the Central Analytical Laboratory in the Crop and Soil Science Department at Oregon State University, Corvallis, OR, USA. The soil samples were sieved (2 mm mesh) to avoid gravel or rocks, oven-dried at 40 °C for 48 h, weighed, and analyzed using a CNS automatic analyzer (Elementar Vario MMARCO CNS, Elementar Analysen Systeme GmbH, Hanau, Germany). Although we analyzed total soil carbon, the soils of the study area contain very little to no inorganic carbon, especially in the upper layers (Soil Survey Staff, 2019), therefore, our analysis reflect soil organic carbon.

2.8. Soil bulk density and carbon calculation

Soil cores for determining bulk density were obtained from four plots selected from the middle of the 20 plots in each watershed. A soil core sampler was used to collect core samples (5 cm diameter x7.5 cm length) in under-canopy zones of mature western juniper trees in the untreated watershed, near-stump zones of cut western juniper trees in the treated watershed, and in interspace zones of both watersheds. We tried to avoid rocky areas for the bulk density sampling because those were not representative of the whole area. Because of this, the samples that were obtained did not contain large pebbles and our samples were not sieved. One core sample was obtained in each zone of each plot at two soil depths (0 – 25 cm and 25 – 50 cm). Soil core samples were oven-dried at 105 °C for 48 h and weighed. Bulk density was calculated as the ratio of the mass of oven-dried soil sample to core volume (g cm^{-3}). The soil carbon mass per area (Mg C ha^{-1}) was computed by the following formula: Soil C (Mg ha^{-1}) = BD (g cm^{-3}) x C % x d (cm). Where: d = soil depth (cm), BD = bulk density in g cm^{-3}, and C % = percentage carbon content of the sample.

In determining soil carbon stocks per plot, we adjusted for the areas under canopy cover (or near tree stumps) and interspace because the soil carbon concentrations were demonstrably different between those areas. The cover of under-canopy and interspace zones were determined for each 20 m × 20 m plot of the untreated watershed. Canopy cover was calculated based on individual tree canopy area estimates in each plot using the canopy diameter measurements. The sum of all tree canopy areas was divided by the total plot area to determine plot-scale canopy cover. The interspace cover at plot scale was estimated by subtracting tree canopy area from the total plot area. We considered that the under-canopy cover in the treated watershed prior to tree elimination was similar to that of the untreated watershed because this was previously evaluated for our study area (Fisher, 2004). Mean soil carbon concentration (Mg C ha^{-1}) for each plot zone-cover (under-canopy/near-stump and interspace zones for both watersheds) was multiplied by the total areas of the relevant plot zone-cover in order to estimate zone-cover specific soil carbon stocks (Edmondson et al., 2014). Finally, the values for both zones were summed for each plot to represent soil carbon stocks per plot.

2.9. Data analysis

Single factor analysis of variance with two-sample t-tests (treated vs. untreated) were applied to test for differences in each analyzed variable using the R Statistical Software (Core Team, 2019). The number of sample replications by treatment varied by analyzed variable; for aboveground biomass of juniper and shrubs n = 20, for grasses and litter n = 80, for root biomass by plant type n = 3, for soil carbon n = 20. Because of the large-scale (around 100 ha watersheds) nature of our study, we only had one treated and one untreated area. Our comparisons are valid, however, because we properly randomized our sampling, have a high number of replications, and have pre-treatment information (Wester, 1992).

3. Results

3.1. Carbon concentration of biomass samples

The carbon concentrations that we obtained were used to calculate carbon pools and they were not intended to test for carbon content differences among species or plant parts. Yet, it was evident that grasses had less carbon than woody plants (Table 1).

3.2. Tree density and cover

Tree density was evaluated for the determination of tree carbon stocks. Tree density was greater ($P < 0.05$) in the untreated (327 individuals ha^{-1}) than in the treated (210 individuals ha^{-1}) watershed (Fig. 3). The density values on the treated watershed mainly reflect small regrowth trees that resulted after juniper control. In the calculation of soil carbon stocks at the watershed scale, juniper cover and interspace cover in the untreated watershed were evaluated. Interspace cover was 68.5% while western juniper canopy cover was 31.5%, similar to that reported by Ray et al. (2019).

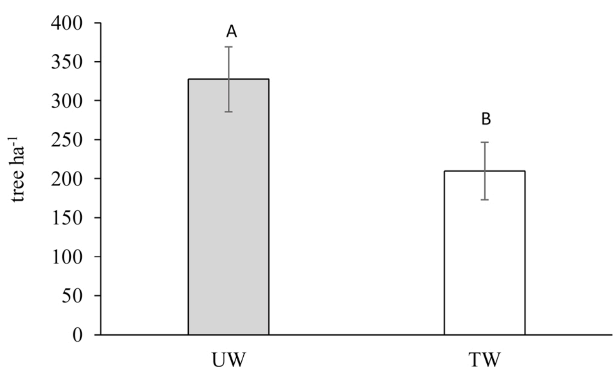

Fig. 3. Tree density (tree ha^{-1}) across management practices (UW = untreated watershed, mature trees; TW = treated watershed, regrowth trees after 13 years of control). The data are means (± standard error) by management practice based on 20 sampling plots.

Table 2
Mean (± SE) aboveground carbon stocks (Mg C ha^{-1}) for plant groups (western juniper [*Juniperus occidentalis*] trees, shrubs, grasses) and litter by management practice in central Oregon, USA. The management practices are 1) Untreated (western juniper intact) and 2) Treated (western juniper cut). The trees in the Treated management watershed are regrowth western juniper after 13 years of juniper removal.

Management Practice	Trees	Shrubs	Grasses	Litter
Untreated	21.98(2.77)^a	0.10(0.02)^b	0.06(0.006)^a	0.32(0.05)^b
Treated	1.05(0.71)^b	0.81(0.12)^a	0.04(0.004)^b	1.98(0.24)^a
P value	< 0.05	< 0.05	< 0.05	< 0.05

Different lowercase letters (a, b) along columns indicate significant differences between management practices for a given plant group or litter ($P < 0.05$).

3.3. Aboveground carbon stocks

Aboveground tree carbon stocks were greater ($P < 0.05$) in the untreated watershed than in the treated watershed (Table 2). Mature western juniper trees contained 21 times more carbon than regrowth trees. Similarly, grass carbon stocks were 50% greater ($P < 0.05$) in the untreated watershed than in the treated watershed. In contrast, the shrub and litter carbon stocks were greater ($P < 0.05$) in the treated watershed than in the untreated watershed. Shrubs and litter had 8.1 and 6.2 times more carbon in the treated than the untreated watershed, respectively. Sagebrush was the main shrub species in both watersheds.

3.4. Belowground carbon stocks

Root carbon stocks (0 – 50 cm soil depth) for mature trees (intact vs. stumps) and shrubs were not significantly different ($P > 0.05$) between treated and untreated watersheds (Table 3). It was noticeable that root carbon stock for regrowth juniper on the treated watershed was only slightly lower (14%) than in mature intact trees. Root carbon for grasses was eight times greater ($P < 0.05$) in the treated than the untreated watershed.

More soil carbon ($P < 0.05$) was stored under mature western juniper tree canopies of the untreated watershed and near western juniper tree stumps of the treated watershed than the corresponding interspaces in each watershed (Fig. 4). Under-canopy zones of mature western juniper and near-stump zones of cut western juniper had about twice the soil carbon stocks of the interspaces. Soil carbon stocks were similar under the canopies of mature western juniper and near-stump zones of cut western junipers. Likewise, soil carbon stocks were similar in untreated and treated watershed interspaces.

Table 3
Mean (± SE) root carbon stocks at 0 – 50 cm soil depth (Mg C ha^{-1}) for plant groups (mature juniper [*Juniperus occidentalis*] trees, regrowth juniper trees, shrubs, and grasses) by management practice in central Oregon, USA. The management practices are 1) Untreated (western juniper intact) and 2) Treated (western juniper cut). The comparison of mature trees included root determination near existing juniper trees (untreated watershed) and near juniper tree stumps (treated watershed).

Management Practice	Mature trees	Regrowth trees	Shrubs	Grasses
Untreated	1.50(0.09)^a	–	1.49(0.10)^a	0.58(0.10)^b
Treated	1.92(0.24)^a	1.29(0.20)	1.26(0.09)^a	4.76(0.84)^a
P value	0.70 ns		0.47 ns	< 0.05

Different lowercase letters (a, b) along columns indicate significant differences between management practices for a given plant group ($P < 0.05$). ns = not significant.

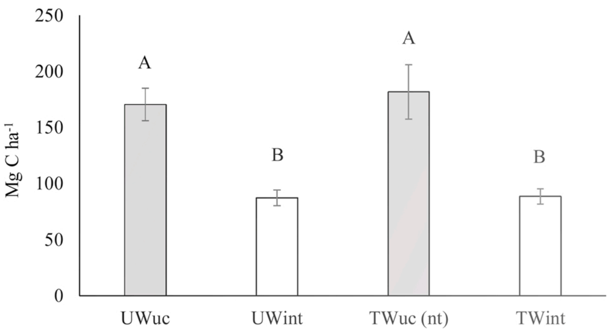

Fig. 4. Soil carbon stocks at 0 − 50 cm soil depth (Mg C ha^{-1}) by watershed and treatments (UWuc = untreated watershed and under tree canopies; UWint = untreated watershed and interspaces beyond tree canopies; TWuc (nt) = treated watershed and under tree canopies (near the tree stumps); TWint = treated watershed and interspaces beyond the tree stumps. Data are means ± standard error.

3.5. *Total carbon stocks by management practice*

Total aboveground carbon stocks differed by watershed ($P < 0.05$) (Table 4). The untreated watershed had 5.8 times more total aboveground carbon than the treated watershed. Root carbon stocks were also significantly different ($P < 0.05$) by watershed. Yet, contrary to aboveground biomass, roots in the treated watershed stored 2.6 times more carbon than those in the untreated watershed. In contrast to the total aboveground carbon stocks, total belowground carbon stocks (root and soil) did not differ ($P > 0.05$) by watershed. Moreover, total belowground carbon stocks were 5.4 and 33.1 times greater than their corresponding total aboveground carbon stocks in the untreated and treated watersheds, respectively. Total carbon stocks, including both total belowground and aboveground carbon, were not significantly ($P > 0.05$) different between the untreated and treated watersheds.

3.6. *Belowground carbon stocks by soil depth*

Root carbon stocks for western juniper mature trees, stumps, and regrowth trees did not vary significantly ($P > 0.05$) by depth (Table 5). In contrast, root carbon stocks for shrubs in both watersheds were 3.5–10.5 times greater ($P < 0.05$) in the top soil layer (0–25 cm depth) than in the bottom soil layer (25–50 cm depth). In a similar fashion, root carbon stocks for grasses in the treated watershed were 19 times greater ($P < 0.05$) in the top than in the bottom soil layer. In the untreated watershed, grass root carbon did not vary significantly ($P > 0.05$) by depth.

Soil carbon stocks in under-canopy zones were about 70% and 60% greater ($P < 0.05$) in the top than in the bottom soil layer for untreated and treated watershed areas, respectively (Table 5). Soil depth did not produce significant difference ($P > 0.05$) in interspace soil carbon stocks in both watersheds.

Table 5
Mean (± SE) belowground carbon stocks (Mg C ha^{-1}) from roots of different plant types and from soil from different areas by soil layer depth and management practices in central Oregon, USA. The management practices are 1) Untreated (western juniper [*Juniperus occidentalis*] intact) and 2) Treated (western juniper cut). Regrowth trees were only evaluated in the treated watershed.

Compartment		Soil layer depth (cm)	Untreated Watershed	Treated Watershed
Root	Mature Juniper Tree[a]	0-25	0.68(0.11)^{Aa}	1.36(0.17)^{Aa}
	Regrowth	25-50	0.82(0.02)^{Aa}	0.56(0.16)^{Aa}
	Juniper Tree	0-25	–	0.97(0.07)^{A}
		25-50	–	0.32(0.14)^{A}
Soil[c]	Shrub	0-25	1.36(0.07)^{Aa}	0.98(0.06)^{Aa}
	Grass	25-50	0.13(0.04)^{Ba}	0.28(0.05)^{Ba}
	Under	0-25	0.57(0.10)^{Ab}	4.52(0.84)^{Aa}
	canopy[b]	25-50	0.02(0.004)^{Ab}	0.24(0.05)^{Ba}
	Interspace	0-25	106.8(10.44)^{Aa}	111.4(15.12)^{Aa}
		25-50	63.8(5.93)^{Ba}	70.3(9.98)^{Ba}
		0-25	47.4(3.66)^{Aa}	48.0(4.13)^{Aa}
		25-50	39.7(4.47)^{Aa}	40.5(2.83)^{Aa}

Different capital letters (A, B) along columns indicate significant differences between soil depths for a given management practice and plant type or soil area ($P < 0.05$).
Different lowercase letters (a, b) along rows indicate significant differences between management practices for a given soil depth and plant type or soil area ($P < 0.05$).
[a] Roots from mature trees in the treated watershed were extracted from the base of stumps of cut juniper.
[b] Soil carbon under tree canopies in the treated watershed was determined from areas near the base of stumps of cut juniper.
[c] Soil carbon was not adjusted by the amount of surface under canopy cover (or near tree stumps) and interspace because the purpose of this table is to show the absolute differences between these two areas.

4. Discussion

This study reports quantitative estimates of ecosystem carbon stocks in encroached juniper systems following juniper control. Given the importance and extent of juniper control as a common rangeland management practice in western USA, it is essential to shed light on the environmental implications of such practice. The vegetation differences between treated and untreated watersheds that we report are attributed to juniper control because prior to it there were no statistically significant differences in vegetation cover (including juniper, shrubs, and grasses) between the same treated and untreated watersheds (Fisher, 2004)

4.1. *Effects of management practices on aboveground carbon stocks*

As hypothesized, the treated watershed had less aboveground

Table 4
Mean (± SE) total aboveground, total belowground carbon stocks (0 − 50 cm soil depth) and total carbon stocks (Mg C ha^{-1}) by management practices in central Oregon, USA. The management practices are 1) Untreated (western juniper [*Juniperus occidentalis*] intact) and 2) Treated (western juniper cut). Root carbon stocks in the untreated watershed represent the sum of root carbon in mature western juniper, shrubs, and grasses, while root carbon stocks in the treated watershed represents the sum of regrowth western juniper, western juniper stumps, shrubs and grasses.

Management practices	Root carbon	Soil carbon	Total belowground carbon	Total aboveground carbon	Total carbon stocks
Untreated	3.57(0.30)^{b}	117.08(9.60)^{a}	120.65(9.60)^{a}	22.46(2.77)^{a}	143.11(11.53)^{a}
Treated	9.23(0.83)^{a}	119.06(11.85)^{a}	128.29(11.85)^{a}	3.88(0.66)^{b}	132.17(12.12)^{a}
P value	< 0.05	0.90 ns	0.62 ns	< 0.05	0.52 ns

Different lowercase letters (a, b) along columns indicate significant differences between management practices for a given variable ($P < 0.05$). ns = not significant.
*Soil carbon stocks were calculated by adjusting the amount of surface under canopy cover (or near tree stumps) and interspace because the soil carbon concentrations were demonstrably different between those areas.

carbon after 13 years of juniper control than the untreated watershed. This was attributed to the elimination of mature western juniper trees, which represented the bulk of the aboveground carbon. Thirteen years after mature juniper control, the regrowth juniper trees were abundant on the treated watershed, as seen by their high density, but their aboveground biomass accumulation was only about 5% of that of mature trees. Therefore, the contribution of regrowth trees to the carbon accrual was small. Juniper control caused a clear increase in shrub presence, as it has been previously reported in different areas of Oregon (Bates et al., 2017; Dittel et al., 2018; Ray et al., 2019), but similar to regrowth juniper trees, the contribution of shrub aboveground biomass was small because of the dwarfing effect of mature juniper trees. As expected, litter carbon stocks were much higher in the treated than in the untreated watershed due to the juniper cut-and-leave operation. Litter carbon in the treated watershed was the largest pool, accounting for 51% of the total aboveground carbon in it. An unexpected result was that grass carbon stocks were lower in the treated watershed than in the untreated watershed; previous reports have found higher grass presence after juniper cutting (Bates et al., 2017; Dittel et al., 2018; Ray et al., 2019). It is possible that the lower grass stocks at the treated watershed resulted from uneven cattle grazing, heavier on the treated watershed, during the year of evaluations.

Aboveground carbon stocks usually increase due to woody species encroachment through time while elimination of woody vegetation would decrease those stocks (Barger et al., 2011; Eldridge et al., 2011). Such a response was observed in our juniper study site, despite the positive response of shrubs and the litter accumulation resulting from juniper control. Throop and Lajtha (2018) also reported a decrease in aboveground carbon stocks following western juniper control.

The greater total aboveground carbon stocks observed in the untreated watershed were within the ranges of aboveground biomass carbon stocks (10–65 Mg C ha^{-1}) reported for southern Great Plains encroached by mesquite (*Prosopis* spp) (Hibbard et al., 2001; Knapp et al., 2008); Great Basin encroached by western juniper (Tiedemann and Klemmedson, 1995); and Great Plains encroached by *Juniperus virginiana* (Knapp et al., 2008; McKinley and Blair, 2008). Compared to mature western juniper trees, the contribution of shrubs, grasses and litter to total aboveground carbon stocks in the untreated watershed was minimal. Combined, the total aboveground carbon stocks of those three pools was 0.48 Mg C ha^{-1}, representing 2.2% of the tree contribution in the untreated watershed.

4.2. Effects of management practices on belowground carbon pools

Regardless of soil depth, this study showed a clear increase (2.6-fold) in root carbon stocks 13 years post juniper control in the treated watershed. The change was mainly due to the large increase in grass roots following juniper control, despite the observed slight decrease in grass aboveground biomass. Other studies have found grass biomass production surges post juniper control (Bates et al., 2017; Dittel et al., 2018; Ray et al., 2019) but grass root responses have not been previously documented. Because of their typically large root:shoot ratio, perennial grasses can store large amounts of carbon belowground (Evans et al., 2013). In our study, grass roots contributed slightly more than the other plants types (juniper and shrubs) combined to the total root carbon stocks in the treated watershed. The important contribution of grass roots to carbon stocks was previously reported by Sharrow and Ismail (2004) who found that soil organic carbon in pastures was greater than in tree plantations and agroforests.

Soils under-canopy and near-stump zones of cut western juniper had soil carbon stocks twice as great as those of interspace zones across the watersheds, which is consistent with previous studies on woody plant canopies (Throop and Archer, 2008; Neff et al., 2009; Miwa and Reuter, 2010; DeMarco et al., 2016; Zhou et al., 2017). Our results also indicate that soil carbon near-stump zones of cut western juniper remained elevated even 13 years following tree elimination and did not differ from soil carbon under-canopy zones of mature western juniper of the untreated area. Another study has found that soil carbon remains elevated under mesquite (*Prosopis velutina*) canopies 8 years after cutting (DeMarco et al., 2016). However, 40 years after mesquite cutting, a loss of soil carbon was observed (McClaran et al., 2008) indicating the recalcitrant nature of woody biomass in arid soils (Zhang and Wang, 2015).

Total soil carbon stocks at 50 cm depth, including both under-canopy and interspace areas, remained unchanged 13 years after juniper elimination with an average of 118 Mg C ha^{-1}. This is similar to results by Throop and Lajtha (2018) who suggested that the lack of degradation of organic material in western juniper settings might reflect stabilized carbon pools. Our results did not support our hypothesis of lower soil carbon following juniper control. It is possible that after a longer time (40 more years) of woody plant control a decrease in soil carbon may occur, as has been reported in other systems (McClaran et al., 2008; Neff et al., 2009; DeMarco et al., 2016). Yet, that decrease would be reflected mainly on the areas under the juniper canopy, which amount to about 30% of the whole area. The other 70% of the area, the juniper interspaces, would be much less affected by the juniper control. In fact, an increase in soil carbon is more likely in these areas because of the increase in grass and shrub roots following juniper control. Thus, the replacement of mature juniper roots by those of understory vegetation might compensate potential losses of soil carbon in the long term. As stated by Barger el al. (2011), the control of woody vegetation might shift the vegetation growth to more dynamic, younger, and more productive plant populations (grasses and shrubs in our case).

Soil organic carbon stocks integrate long-term contribution from roots and aboveground plant matter; thus, it is expected that soil carbon stock would be negatively affected by elimination of vegetation, i.e., woody plant control (Archer et al., 2017). However, changes in soil carbon are much slower than those aboveground, which explains that soil carbon is negatively affected by woody plant control only after > 40 years of the practice in the Sonoran Desert (McClaran et al., 2008). The aridity level in our study area of central Oregon is lower than in the Sonoran Desert. Therefore, it is more likely to expect carbon sequestration following woody plant control and long-term plant succession in our study area than in the Sonoran Desert (Archer et al., 2017). Although our study is still of short duration (13 years post juniper control), our plant succession results, with positive biomass gain in understory vegetation, led us to hypothesize that juniper control is not likely to result in significant net carbon losses.

4.3. Total carbon stocks and management practices

Total carbon stocks in both management practices did not differ and showed an average carbon level of 137.6 Mg C ha^{-1}. The encroachment of western juniper increased aboveground carbon stock, but the belowground carbon stock (0 − 50 cm soil depth) was not affected by the management practices of untreated and treated watersheds. These findings partially supported our hypothesis, indicating that the treated watershed stored less aboveground carbon relative to the untreated watershed. Even though woody encroachment in globally extensive arid environments usually increases aboveground carbon stocks, its impact on belowground carbon stock is uncertain, varying with spatial scale, species composition, and environmental conditions (Barger et al., 2011; Eldridge et al., 2011; DeGraaff et al., 2014). In our study, the gain of understory plant roots associated with western juniper cut led to partially counteract the losses of aboveground carbon in the treated watershed.

In both treated and untreated watersheds, the large majority of the total carbon pool was stored belowground (roots and soil). According to the present study, 84% and 97% of the total carbon stocks in the untreated and treated watershed, respectively, are allocated belowground (0 − 50 cm soil depth). Our results are comparable to those of Sharrow and Ismail (2004) who reported that 88% and over 90% of the total carbon stocks were stored in the soil (0 – 45 cm depth) for agroforest and grasses-dominated pastures, respectively. In addition, rangeland ecosystems were reported to contain 85.8% of the total carbon stocks in the soils (0 – 30 cm depth) (Bikila et al., 2016). Cold desert ecosystems such as the sagebrush steppe in North America generally have very low ratios of aboveground to belowground biomass, and belowground herbaceous biomass tends to substantially contribute to belowground carbon pools (Jackson et al., 2000).

Most organic carbon in terrestrial ecosystems is contained in the soil (Schlesinger, 1997). We found that soil carbon was the single greatest carbon pool in both watersheds, representing 81% (untreated watershed) and 90.1% (treated watershed) of the total ecosystem carbon stocks. Consequently, any anthropogenic activities that might have negative impacts on soils, such as grazing-induced erosion (Carbajal-Morón et al., 2017) would have major implications in reducing carbon stocks in these systems. Even without considering erosion, inadequate management practices such as overgrazing may lead to carbon losses in the upper soil layers (Daryanto et al., 2013; Bikila et al., 2016).

The aboveground biomass in arid and semi-arid woodlands is viewed as an unstable organic carbon pool because of the frequency of wildfire in these systems (15–90 years), the threat of exotic grass invasion, and the poor recovery of important shrubs such as sagebrush following fires (Rau et al., 2011; Canadell and Raupach, 2008; Reed-Dustin et al., 2016; Mata-González et al., 2018). Therefore, it is imperative to protect the stable belowground carbon pool in juniper-managed areas to mitigate climate change and global warming. Degradation of the belowground carbon pool will eventually result in a reduction of total carbon stocks in the system.

Elimination of juniper encroachment has well documented benefits such as habitat restoration for native wildlife, increased forage base for livestock, increased soil moisture and restoration of watershed hydrological functions (Baruch-Mordo et al., 2013; Dittel et al., 2018; Ochoa et al., 2018; Ray et al., 2019). Our study provides basis to suggest that the benefits of juniper control can be attained without substantially affecting the potential for carbon sequestration of these systems.

4.4. Effects of soil depths on belowground carbon within management practices

The shrubs and grasses in our study area had generally greater root carbon stocks in the top soil layer (0 – 25 cm) than in the bottom soil layer (25 – 50 cm). In fact, about 95% of grass root carbon stocks in the treated watershed was concentrated in the top soil layer. This is in agreement with reports for Great Basin vegetation (Rau et al., 2009) and in general with estimations of global carbon stock distribution with soil depths (Jobbágy and Jackson, 2000). Grasses have a dense, fibrous root system of shallow depth in the top 20 – 30 cm of the soil profile, where water and nutrients are at maximum concentrations (Archer et al., 2017). In contrast to shrubs and grasses, root carbon stocks for juniper trees were more homogeneously distributed with depth down to 50 cm, coinciding with results by Young et al. (1984). Western juniper develops a large extension of lateral roots (Mollnau et al., 2014) with their greatest proportion found within 0 – 50 cm soil depths (Young et al., 1984). The main lateral roots grow to radii that are at least equal to the height of a tree and extend beyond the dripline determined by the extension of the canopy (Young et al., 1984) but with large restriction of roots to surface soils (Miller et al., 2005). Woody species roots are typically more lignified and deeper rooted than the grasses they displace (Boutton et al., 1999; Barger et al., 2011).

The top soil layer contained more soil carbon in both under-canopy and near-stumps zones of western juniper. The mechanism responsible for the increase in soil carbon at 0 – 25 cm was likely the concentration of organic matter inputs from litterfall and the incorporation and redistribution of soil carbon into near surface soils (Jobbágy and Jackson, 2000; Eggleston et al., 2006; Zhou et al., 2017). Although it decreased with depth, substantial soil carbon under-canopy and near-stumps zones of western juniper existed below 25 cm soil depth. That was consistent with results of soil carbon sequestration occurring deeper than 30 cm following woody encroachment (Chiti et al., 2017; Zhou et al., 2017). Our results showed that 38% of the soil carbon stocks in under-canopy and near-stump zones was present in the 25 – 50 cm soil layer. In contrast, the interspace areas did not show difference in carbon stocks with soil depth, reflecting the lower organic matter inputs that these areas receive.

Carbon stocks of surface soil layers are more prone to be affected by management or vegetation changes than deeper layers (Bikila et al., 2016; Throop and Lajtha, 2018). Our evaluation of total carbon stocks as affected by juniper control included the 0 – 50 cm soil layer because juniper roots may influence changes at that depth (Young et al., 1984). However, there were no differences in soil carbon stocks due to juniper control (between watersheds) at either the 0 – 25 cm or the 25 – 50 cm soil layers.

4.5. Limitations of the study

This study had the advantage of analyzing juniper elimination at the whole watershed (approximately 100 ha each) scale. Yet, because of its large scale, the replication of the study is limited to one watershed per treatment and the interpretation and extrapolation of the results should be done cautiously. In addition, our vegetation and soil sampling occurred in the 20 replicated plots scattered through the watersheds. However, root sampling was done in only three trenches per vegetation type in each watershed because of the difficulty of moving an excavator throughout the whole study area (more than 200 ha). Root sampling is always a difficult task and in some cases, roots are only estimated based on biomass modeling.

5. Conclusions and implications

Juniper encroachment is considered an important contributor to rangeland degradation in North America and thus its control is a common restoration practice with ecological benefits to native wildlife and livestock. Yet, the implications of juniper control in terms of ecosystem carbon stocks are largely unknown. This motivated our study. We hypothesized that a treated watershed, after 13 years of mature western juniper elimination, would store less aboveground and belowground carbon than an untreated watershed, implying lower capacity for soil carbon sequestration resulting from juniper control. Although aboveground carbon stock was reduced in the treated western juniper area, the belowground carbon stock was not, rendering no significant effects on total carbon stocks (aboveground and belowground) caused western juniper control. A greater root carbon accumulation in the treated area than in the untreated area partially offset the losses in aboveground carbon due to juniper control.

The greatest ecosystem carbon accumulation resides belowground (over 90%). Therefore, changes in the 10% aboveground biomass can be of less relative significance in the short term. However, our 13-year post treatment study, is still of short duration to contemplate soil carbon changes. It is not known if juniper control may result in lower soil carbon stock in decades to come but our vegetation succession results do not anticipate that.

Protecting the belowground carbon source is paramount. This study indicates that cutting western juniper did not affect belowground carbon pools, at least after 13 years of cutting. Western juniper elimination facilitates the recovery of shrubs and grasses and permits the restoration of watershed hydrological functions. Therefore, evidence supports that juniper control can help to improve the habitat quality for wildlife such as sage grouse and the forage productivity for moderate cattle grazing while maintaining the carbon sequestration potential of the system. We would like to emphasize, however, that studies of longer duration and mechanistic models are needed to forecast and better understand carbon stocks as affected by land management in these dynamic systems.

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.

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