Carbon and ecohydrological priorities in managing woody encroachment: UAV perspective 63 years after a control treatment

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Keywords: vegetation change, chaparral, pinyon-juniper, shrub height, shrub biomass, drone, carbon

Abstract

Woody encroachment, including both woody species expansion and density increase, is a globally observed phenomenon that deteriorates arid and semi-arid rangeland health, biodiversity, and ecosystem services. Mechanical and chemical control treatments are commonly performed to reduce woody cover and restore ecohydrologic function. While the immediate impacts of woody control treatments are well documented in short-term studies, treatment impacts at decadal scales are not commonly studied. Using a controlled herbicide treatment from 1954 in the Sierra Ancha Experimental Forest in central Arizona, USA, we quantify woody encroachment and associated aboveground carbon accumulation in treated and untreated watersheds. Woody encroachment and aboveground carbon are estimated using high resolution multispectral images and photogrammetric data from a fixed-wing unmanned aerial vehicle (UAV). We then combine the contemporary UAV image-derived estimates with historical records from immediately before and after the treatment to consider long-term trends in woody vegetation cover, aboveground carbon, water yield, and sedimentation. Our results indicate that the treatment has had a lasting impact. More than six decades later, woody cover in two treated watersheds are still significantly lower compared to two control watersheds, even though woody cover increased in all four drainages. Aboveground woody carbon in the treated watersheds is approximately one half that accumulated in the control watersheds. The historical records indicate that herbicide treatment also increased water yield and reduced annual sedimentation. Given the sustained reduction in woody cover and aboveground woody biomass in treated watersheds, we infer that the herbicide treatment has had similarly long lasting impacts on ecohydrological function. Land managers can consider legacy impacts from control treatments to better balance carbon and ecohydrological consequences of woody encroachment and treatment activities.

1. Introduction

Woody encroachment into rangelands has been commonly observed around the world (Archer et al 2017, Stevens et al 2017). In the western US, for example, pinyon–juniper has encroached into rangelands at varying rates (Sankey and Germino 2008) resulting in woody cover increases of up to 600% in the 20th century (Romme et al 2009). Encroachment can accumulate large amounts of woody biomass and associated above- and below-ground carbon (Strand et al 2008, Rau et al 2011, Sankey et al 2013, Fusco et al 2019). Recent estimates have demonstrated that woody encroachment in the western US has resulted in twice the total aboveground carbon than previously estimated (Fusco et al 2019). However, the magnitude of the carbon increase varies among ecosystems due to edaphic variables and plant
species mix. Detailed carbon accounting is missing in many regions, especially in dryland ecosystems. Consequently, woody contribution to global carbon pools and fluxes is unclear.

Land managers face competing priorities in managing woody encroachment (Archer and Predick 2014, Bestelmeyer et al. 2018). In addition to managing for increased carbon pools and sequestration, land managers have to consider the ecohydrological and biodiversity consequences: (a) Woody encroachment increases plant water use and evapotranspiration, which subsequently reduces downslope stream water yield, an important resource in arid and semi-arid ecosystems (Ingebo and Hibbert 1974). (b) Woody encroachment reduces herbaceous cover and forage for livestock and wildlife, and increases bare ground, erosion, and connectivity of sediment and runoff, which spatially redistributes sediment and nutrients across the landscape (Ludwig et al. 2005, D’Odorico et al. 2010, Gonzales et al. 2018, Wang et al. 2019, Williams et al. 2020, Sankey et al. 2021). Taken together, woody encroachment and management thereof encompass four critical elements of the ecosystem: vegetation cover, carbon accumulation, water yield, and sediment yield (figure 1).

Many encroached areas are treated with controlled burning, mechanical thinning, or herbicide applications to increase water yield, reduce sediment runoff, and improve herbaceous cover and livestock forage (Romme et al. 2009). Following treatments, the decrease in shrub canopy cover and increase in bare ground cover initially result in enhanced sediment availability and increased soil erosion (Pierson et al. 2015, Dukes et al. 2018, Sankey et al. 2021). However, herbaceous vegetation recovers over time, reduces bare ground, improves water infiltration, and decreases water runoff, soil erosion, and sedimentation (Williams et al. 2019). The vegetation structure change, therefore, leads to shifts in hydrologic and sediment connectivity across spatial scales and improves ecohydrologic function (Peters et al. 2020, Williams et al. 2020). Due to the spatial extent of woody-encroached areas, which span hundreds of millions of hectares in USA drylands as well as all other major drylands worldwide (Knapp et al. 2008, Eldridge et al. 2011), the control treatment impacts have large implications for vegetation, water, sediment, and carbon budgets at the national scale (Puttock et al. 2014).

Using high resolution unmanned aerial vehicle (UAV) multispectral images and photogrammetric data, we quantify and compare woody vegetation cover and aboveground carbon in treated and control watersheds known as Natural Drainages in central Arizona, USA. We then combine the contemporary UAV observations of woody and herbaceous cover with historically documented trends in water and sediment yield before and after the treatment. While most ecohydrological studies document short-term impacts, the carefully-controlled historic experiments performed 63 years ago at the Natural Drainages provide a unique opportunity to compare the long-term impacts of the competing management priorities. Our detailed UAV-derived estimates of woody and herbaceous cover compliment the historical field-based records collected throughout the 20th century (figure 1) given the comparable level of details in both estimates of vegetation cover, which subsequently impacts water and sediment yield.

2. Methods

2.1. Study setting and historical water and sediment records

The Natural Drainages are four adjacent watersheds in the chaparral vegetation cover type, which covers approximately one half of the National Forest lands (~4 million ha) in Arizona. Chaparral cover type in Arizona is historically dominated by turkey oak (Quercus turbinella), manzanita (Arctostaphylos spp), desert ceanothus (Ceanothus greggii), and sumac (Rhus spp), while perennial grass cover co-occurs at varying abundance, typically on elevations between 1300–1800 m. Much of the contemporary chaparral cover type also includes juniper (Juniperus monosperma) and pinyon (Pinus monophylla). Ranging in size from 3.7 to 7.9 ha, the Natural Drainages experimental sites were first established in 1934 within the century-old Sierra Ancha Experimental Forest (SAEF) to assess livestock grazing effects on vegetation, streamflow, and sediment (figure 1). Known as the drainages A, B, C, and D, the Natural Drainages are individual watersheds contained within well-defined ridges that separate each adjacent watershed. The Natural Drainages all occur on easterly aspects of 15%–25% slope on 1380–1515 m elevation (Ingebo and Hibbert 1974).

Streamflow, runoff, and sediment have been measured in Natural Drainages since 1935 using 90° V-notch weirs and stage recorders in each watershed (figure 1). Perennial herbaceous cover has also been measured since 1935 in 1 m² quadrats, while shrubs have been monitored in 5 m² quadrats (Rich and Reynolds 1963). All four drainages were closed to livestock grazing between 1934 and 1938, but 80% and 40% of the grasses were grazed on drainages A and D, respectively, between 1939 and 1954. No livestock grazing has occurred in any of the drainages since 1954.

In 1954, the US Forest Service treated Natural Drainages with herbicide application to control woody encroachment and to increase water yield from streamflow owing to surface water runoff (Rich and Reynolds 1963, Ingebo and Hibbert 1974). Two of the drainages, A and C, were sprayed with 6.6% 2,4-D and 2,4,5 T in diesel oil during the summer...
1954, while drainages B and D were designated as control drainages (Pond 1964). In the treated drainages A and C, the basal 13 cm of all shrubs and trees were sprayed until all woody species were totally killed. No other landscape-scale disturbance or treatments have occurred since 1954 in any of the drainages.

Prior to the treatment, crown and basal intercepts of all woody species were measured in all four drainages along ten 12 m line transects in 1950 and 1954. Pre-treatment total vegetation cover ranged 32%–40% (Rich and Reynolds 1963). Among them, shrub cover varied 19%–21% (Cable 1957) (figure 1). The most abundant pre-treatment shrub species was turbinella oak at 15%–22% cover across the four drainages. Other common shrub species included two sumac species (Rhus trilobata; Rhus ovata) and desert ceanothus (Ceanothus greggii) (Pond 1964). Following the treatment, the same measurements were made in 1957 and 1959 (Pond 1964).

Historical studies and post-treatment records, which began in 1954 and terminated in 1971 (Ingebo and Hibbert 1974), demonstrate the following ecohydrological impacts of the herbicide treatment (figure 1):

(a) Treated drainages had three times more herbaceous and sub-shrub (Eriogonum wrightii; Menodora scabra; Lotus rigidus; Lotus wrightii) cover and production compared to the control drainages on all slopes and quartzite-derived soils, a common parent material in Natural Drainages. (b) No significant differences were observed in herbaceous and sub-shrub cover and production on the diabase-derived soils, the other common parent material in Natural Drainages. (c) The herbaceous cover increase resulted in 72% decrease in annual sedimentation. (d) The two treated drainages showed a 22% increase in streamflow compared to pre-treatment baseline data. (e) The streamflow increases were attributed to the lower evapotranspiration demands by the herbaceous cover that replaced the woody vegetation.

2.2. Contemporary estimates of woody and herbaceous vegetation cover

We flew a Sensefly eBee Ag fixed-wing UAV platform (Sensefly, Lausanne, Switzerland) (figure 1) with a multispectral sensor (multiSPEC4C) in four spectral bands (spectral range center): green (550 nm), red (660 nm), red edge (735 nm), and near-infrared (790 nm). We completed three flights on 29 July 2017 at 80 m altitude above ground, which resulted in image pixel resolution of 13 cm and covered a total area of ~30 ha (figure 2). The multispectral image was processed with a photogrammetric method known as Structure-from-Motion (SfM) (Westoby et al 2012, Sankey et al 2017, Shin et al 2018, Solazzo et al 2018, Belmonte et al 2020) to generate 3D point cloud data using Pix4D software (Sensefly, Lausanne, Switzerland). The resulting average point density was 115 m$^{-2}$. The Pix4D software reported...
that the final orthomosaicked image from the fixed-wing UAV had a root mean squared error (RMSE) of 1.8, 1.6, and 2.9 m in the X, Y, and Z dimensions, respectively. However, our comparison of the UAV image with ground-based GPS locations (<30 cm post-processing accuracy) of calibration targets indicated <1 m accuracy in the X and Y dimensions.

We classified the ground versus vegetation returns in the 3D point cloud data and then used the vegetation point cloud in ENVI 5.2 software and BCAL lidar module (Harris Geospatial, Boulder, CO, USA) to calculate the maximum vegetation height as well as the vegetation height range in 13 cm raster cells, consistent with the pixel size of the multispectral data. These vegetation height raster bands were then combined with the original four spectral bands of the multispectral image to take advantage of the woody vegetation height information in classifying the rangeland cover types (Sankey et al 2019, 2021). In addition, we calculated the normalized difference vegetation index (NDVI) using the red edge and near infrared bands and calculated the mean texture of the NDVI values as a co-occurrence measure (Haralick et al 1973). The NDVI band and its mean texture band were also added to the multispectral image to generate a final eight-band image composite.

A classification and regression tree (CART) model was used in ENVI 5.2 software to classify the final
eight-band multispectral image. Our preliminary analysis indicated that the CART model produced much more accurate results than the supervised classification models in ENVI, which used the available bands weighted equally as inputs. In contrast, the CART model selects input bands weighted by their importance as input variables. The final CART model included the maximum vegetation height, green, red, red edge, and NIR bands, the NDVI band and its mean texture as predictor variables. Our training data consisted of 400–1100 corresponding image pixels at locations where field-based GPS samples were mapped for the dominant species depending on their relative abundance. The differentially-corrected Trimble GeoXH GPS locations had <30 cm accuracies.

We classified the following dominant target cover types: pinyon–juniper (*Pinus monophylla–Juniperus monosperma*), manzanita (*Arctostaphylos pungens*), turbinella oak (*Quercus turbinella*), bare ground, herbaceous and other vegetation. Given the fine spatial resolution of the multispectral image, shadows associated with each large woody plant was also classified as a separate class 'shadow'. Wright buckwheat (*Eriogonum* spp), hollyleaf buckhorn (*Rhamnus* spp), yucca (*Yucca* spp), desert ceanothus (*Ceanothus* spp), and sacahuista (*Nolina* spp) were other less common, small sub-shrubs observed in the field. We combined these less common sub-shrubs into a single cover type 'other vegetation'. Due to their spectral and field-observed similarities, pinyon versus juniper could not be separately classified and were combined into a single class pinyon–juniper.

We also generated a binary classification of total woody cover versus non-woody cover. The total woody cover included pinyon–juniper, manzanita, and turbinella oak, whereas the non-woody cover class included the other vegetation, herbaceous vegetation, and bare ground classes. We then estimated total woody cover and non-woody cover in percent within 5 × 5 m cells (≈1275 pixels within each cell) in all four drainages. By counting and summarizing the total number of pixels classified as woody cover within each 5 m cell (≈3000 cells per drainage), we estimated the woody and non-woody percent cover. The mean and standard deviation of the woody cover were then calculated for each drainage and compared using a one-way analysis of variance test with Tukey’s pairwise multiple comparisons in R software.

2.3. Ground-based validation data for woody cover estimates

In spring and fall 2018, we identified and mapped with a Trimble GeoXH GPS all shrub and sub-shrub species in the historical 5 m² plots (*n* = 24 plots) distributed across the Natural Drainages. We assessed the UAV image classification accuracies using 60–220 pixel samples per class at the corresponding locations (*N* = 1096). More abundant species were represented by greater numbers of samples in the accuracy assessment. We also measured the location, aboveground height, and canopy diameter of 30 individual shrubs randomly distributed throughout the Natural Drainages. Using these field-based measurements, we evaluated the accuracy in the UAV SfM-derived shrub height estimates, which were an important input for the shrub species classification and aboveground shrub biomass estimates.

2.4. Contemporary estimates of aboveground carbon

The UAV-based dominant species map delineated each of our target species at the individual crown level, whereas the UAV SfM-derived canopy height model provided estimates for each shrub. Using these outputs, we estimated total aboveground biomass (AGB) within each drainage and converted the total biomass estimates to aboveground carbon estimates. To estimate AGB of the dominant woody species, we used the following allometric equations (equations (1)–(3)) established for juniper, manzanita, and turbinella oak, respectively:

\[
AGB_{\text{juniper}} = 11.06x CA
\]

where CA is individual juniper tree crown area, which has a correlation coefficient of 0.92 with AGB for juniper with a RMSE of 41.23 kg (Cunliffe et al 2020);

\[
AGB_{\text{manzanita}} = 1.1627x CA^{1.1036}
\]

where CA is individual manzanita shrub crown area, which has a strong correlation with AGB, but not with shrub height, and RMSE of 0.67 kg (Huff et al 2017);

\[
\log AGB_{\text{turbinella} \text{oak}} = 0.7005 + 0.0018 \left( CH^2 \right) - 0.0317 \left( BR \times \text{CH} \right) + 6.29588 \left( \log \text{BR} \right)
\]

where CH is the individual turbinella oak canopy height and BR is the basal radius, which predict AGB with a correlation coefficient of 0.95 and a RMSE of 0.16 Log(g) (McCraw 1985). We used the mean BR value of 1.125 cm and standard deviation of 0.66 cm, which we estimated from data reported by McCraw (1985), since our remote sensing-based measurements did not include basal radius.

AGB was estimated for each individual plant and then summed to determine a total AGB per species in metric tons per hectare (Mg ha⁻¹) in each of the control and treated drainages. Uncertainty of AGB was estimated following the approach of Sankey et al (2013). In short, 1000 realizations of the AGB model solutions for each individual plant of each species were run in which the predictor variables (e.g. CA, CH, BR) were allowed to vary from the observed value based on a specified distribution and standard deviation. The standard deviations were
Figure 3. Regression relationship between the field-measured and UAV SfM-derived shrub height in Natural Drainages.

estimated from the following reported values in the literature: CA$_\text{Juniper}$ RMSE of 127 and 102 cm for control and treated areas, respectively (Sankey et al. 2013), CA$_\text{Manzanita}$ RMSE of 8 and 7 cm for control and treated areas, respectively (Sankey et al. 2019), CH$_\text{Turbinella oak}$ RMSE of 76 cm (figure 3), and BR$_\text{Turbinella oak}$ range of 0.66 cm (McCraw 1985). Realizations also incorporated an error term for the specific allometric equations using the respective RMSE values reported with the equations (McCraw 1985, Huff et al. 2017, Cunliffe et al. 2020).

Individual tree/shrub biomass was then converted to carbon (C) by multiplying the AGB by a factor of 0.5 following Strand et al. (2008), Sankey et al. (2013) and Cunliffe et al. (2020), who estimated juniper C content using AGB. The resulting C storage map was then overlaid with the dominant species map to estimate total aboveground C storage within each drainage and to compare treated versus control drainages.

3. Results

The UAV image was successfully classified with an overall accuracy of 93% (table 1). The dominant woody species were all classified with high producer’s accuracies, especially manzanita. When we compared the SfM-derived individual shrub height estimates to the field-based measurements, the coefficient of determination was 0.72 with a RMSE of 0.76 m (figure 3). Given this correlation, we used the SfM-derived shrub heights in our UAV image classification and AGB estimates, which integrated both the individual crown area and height.

Historical studies indicate that: (a) pre-treatment total shrub cover was 19%–21% among all four drainages (Cable 1957), (b) the 1954 chemical control treatment reduced shrub cover to 0% in the two treated drainages, and (c) consequently, post-treatment historical total shrub cover was 0% and ~20% on treated and control drainages, respectively. In comparison, our contemporary UAV-derived total woody cover was ~11% and ~25% in treated and control drainages, respectively (figure 4), indicating 11% and 5% increases in woody cover over the 63 year period, respectively. Total non-woody cover in the UAV image was on average 89% and 75% in treated and control drainages, respectively, with 20% and 16% herbaceous cover.

The dominant woody species in the UAV image showed varying levels of abundance. Among them, manzanita and turbinella oak covered the largest areas at 22.5% and 6% of the total area, respectively, in the Natural Drainages (figure 4). In comparison, historical studies suggest that the most abundant pretreatment shrub species was turbinella oak. It averaged 41.5% of the total woody cover (Cable 1957) and 8% of the total area and has had a relatively stable abundance over time. The historical studies also show sporadic manzanita, pinyon, and juniper were recorded (Ingebo and Hibbert 1974), which suggests that these are newly arrived woody species within the study area that have greatly expanded over the last 63 years (figure 3).
When we compared the UAV-derived total woody cover among the four drainages, the treated drainages A and C had significantly lower total woody cover compared to the control drainages \( (p < 0.001) \) (figure 5). Specifically, the control drainages B and D had twice as much total woody cover compared to the treated drainages 63 years after the treatment.

The total AGB of juniper in the treated and control drainages were 5.4 and 9.1 Mg ha\(^{-1}\), respectively (figure 6). The juniper biomass estimates translate to 2.7 and 4.5 Mg ha\(^{-1}\) in total C in treated and control drainages, respectively. The total AGB of turbinella oak was 0.02 and 0.04 Mg ha\(^{-1}\) in treated and control drainages, respectively, which is equivalent to total C of 0.01 and 0.02 Mg ha\(^{-1}\), respectively. The total manzanita AGB was 1 and 1 Mg ha\(^{-1}\) in treated and control drainages, respectively (figure 6), which translate to 0.5 and 0.5 Mg ha\(^{-1}\) of total C, respectively. Taken together, the control drainages had accumulated much larger C at 5.1 Mg ha\(^{-1}\) compared to the treated drainages, which included a total C of 3.2 Mg ha\(^{-1}\) (figure 6). This difference is largely associated with juniper biomass difference, since the other woody species are smaller in stature and similar in distribution between the control and treated drainages, while juniper AGB comprises a large component of the total C estimates.

### 4. Discussion

#### 4.1. Woody control impacts on vegetation and aboveground carbon

This study links contemporary UAV data with historical records to create a six-decades-long monitoring dataset, which reveals three important findings. First, our results demonstrate that the herbicide treatment from 1954 has had a land-use legacy impact on the vegetation. The herbicide-treated drainages today still have significantly lower total woody cover compared to the control drainages (figure 5). Although the herbicide was only applied to turbinella oak and other woody species that were dominant 63 years ago, the impact of the treatment appears also notable on currently dominant woody species including the newly arrived pinyon pine and juniper trees. While many woodlands undergo burning and thinning treatments at large scales, they are not often continuously controlled and monitored and only a few other studies have documented legacy effects (Browning and Archer 2011). The Natural Drainages in SAEF is unique in that no other disturbance events and treatments have occurred since 1954 and provide a rare opportunity to examine the long-term impacts from the treatment. Dryland management must consider legacy land uses in making decisions regarding community structure, ecological productivity, and ecosystem services (Browning et al 2015).

Secondly, woody cover in the control drainages has also increased compared to the historical estimates from prior to the herbicide treatment. This estimate indicates woody encroachment rates in no-action management scenario and is consistent with woody encroachment rates documented in chaparral ecosystems (Gibson et al 2019) and other rangelands across the western US (Romme et al 2009). Taken together, the historical records (Pond 1964, 1971) and the UAV image-derived estimates indicate that turbinella oak has continuously had a strong and relatively stable presence at 6%–8% cover in this ecosystem for over a century, but manzanita and pinyon–juniper are newly dominating species, which are now more common and as abundant as turbinella oak across the study area. We also note that the soil parent material appears to play a major role in these observed patterns in woody species distribution (figure 4). Turbinella oak, a deep-rooted sprouter that spreads clonally, is currently distributed across much of the diabase soil parent material and fractured bedrock within Natural Drainages, whereas the seeder species of manzanita and pinyon–juniper are found on the quartzite-derived soil parent material (figure 4). This is consistent with previous observations in our study region (Leonard et al 2015, Gibson et al 2019).

Third, the control drainages B and D have approximately twice as much AGB in comparison to

| Target cover types | Turbinella oak | Manzanita | Herb. | BG | Shadow | Sample size | Producer’s accuracy | User’s accuracy |
|--------------------|----------------|-----------|-------|----|--------|-------------|-------------------|----------------|
| Pinyon–juniper (PJ) | 205            | 16        | 15    | 236| 99.5%  | 86.8%       |
| Turbinella oak     | 1              | 194       | 12    | 207| 88.1%  | 93.7%       |
| Manzanita          | 4              | 171       | 5     | 180| 85.0%  | 95.0%       |
| Herbaceous and     | 6              | 1         | 193   | 200| 96.0%  | 94.6%       |
| other vegetation   |                |           |       |    |        |             |
| (Herb.)            |                |           |       |    |        |             |
| Bareground (BG)    | 1              | 209       |       | 210| 98.1%  | 99.5%       |
| Shadow (Shad.)     | 60             |           |       | 60 | 100%   | 100%        |
| Total samples      | 1093           |           |       |    |        | Overall accuracy 93.1% |

Table 1. UAV image-derived vegetation cover type classification accuracies.

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the treated drainages. In particular, the long-living species of juniper and turbinella oak, which can live >200 years, demonstrate the substantial impacts from the treatment, while shorter-living manzanita demonstrate similar AGB in treated versus control drainages. Land managers interested in herbicide treatment should consider the long-lasting C footprints at the decadal scale. Furthermore, regional- and continental-scale US carbon estimates continue to have large uncertainties due to the incomplete C stock estimates in non-forested and dryland ecosystems (Fusco et al 2019). Local-scale C stock estimates such as ours can help complete regional-scale estimates in dryland ecosystems. Although many allometric relationships have been developed for the dominant species, some of the current allometric relationships need to be further refined to improve our estimates at the species and individual canopy levels. For example, the currently available turbinella oak allometric model...
Figure 5. Total woody cover in the treated drainages A and C versus the control drainages B and D, where total woody cover is significantly different (indicated by different letters).

Figure 6. Total AGB (Mg ha$^{-1}$) for each dominant woody species as well as their sum at the drainage-scale in treated and control drainages. AGB was first estimated for each individual plant per species and then summed to determine the total AGB in the control and treated drainages. We estimated the uncertainty in the total AGB estimate using simulations and the uncertainty is shown with the error bars.

was based on a small dataset and was very sensitive to small changes in height and basal radius over a small range of both variables, which was evidenced by the small AGB values with large uncertainty (standard deviation) in our estimates for that species (figure 6). Furthermore, our C stock estimates do not include potential changes in aboveground herbaceous biomass and associated belowground root biomass and soil carbon, while previous studies indicate that belowground carbon pools can be much larger than aboveground carbon stock (Fusco et al 2019).
Ground-based plant AGB estimates are often time-consuming and labor-intensive. We demonstrate that UAV data provide a potential alternative means to estimate C at a landscape scale (e.g. 35 ha) and monitor woody encroachment similarly to previous lidar-based studies (Sankey et al 2013) and photogrammetry studies (Cunliffe et al 2020). While airborne lidar data provide similar accuracies (Sankey et al 2017, 2018), the UAV SfM data provide a cheaper alternative to acquire 3D data over larger areas (Shin et al 2018, Sankey et al 2019). The UAV-derived individual shrub crown and height estimates (figure 3) can be particularly important for the SAEF, where individual shrub canopies were permanently marked in the 1920s and have been monitored over the last century. In UAV data applications for such estimates, the accuracies and errors should be carefully considered. While the initial UAV data error reported by the Pix4D software indicated errors of up to 2.9 m in the X, Y, and Z dimensions, our comparison of the UAV data with ground-based measurements and GPS data indicated errors of <1 m in the X and Y dimensions and 0.76 m in the Z dimension. Some of the errors might be attributed to the fact that our UAV images and field-based GPS data were collected several months apart, although this time difference might have negligible impacts on the long-living species in the chaparral ecosystem. Such errors and differences have important implications for estimating and monitoring short stature woody vegetation as well as small variability in topography.

4.2. Woody control impacts on ecohydrology

The legacy impacts on woody cover and AGB have important consequences for water and sediment yield (figure 7). First, woody encroachment increases plant water use and evapotranspiration (Qiao et al 2017). In the control drainages A and C, where woody cover and AGB are twice as high compared to the treated drainages, plant water use and evapotranspiration likely continued to be greater over the last six decades. The increases in plant water use and evapotranspiration significantly reduce streamflow and groundwater recharge in woody-encroached rangelands (Wilcox et al 2008, Kormos et al 2017). The herbicide treatment at our study area altered these trends and increased water yield by as much as 22% (Ingebo and Hibbert 1974), which was also consistent with other studies in our region (Ffolliot and Thorud 1974, Hibbert et al 1974). A long-term study conducted nearby, which included initial impacts from wildfire followed by periodic herbicide treatments to suppress regrowth of shrub species, demonstrated initial average increases in water yield of 300%–700% in the first few years after treatment and average of 36% increase over the 18 years following treatment (Hibbert 1982). Although we lack recent quantitative
estimates of water yield, we infer that the treated watersheds within the Natural Drainages have likely have benefitted water yield for at least part of the last six decades because our UAV-based estimates indicate that: (a) woody cover and AGB in the treated drainages are still half of those at the control drainages, and (b) total herbaceous and bare ground cover in treated drainages are still greater than those in the control drainages. This trend is overall consistent with the historical records (Pond 1964, Indego and Hibbert 1974), which demonstrated that the treated drainages had lower woody cover and greater herbaceous cover and thus greater streamflow.

Secondly, the herbicide treatment has likely had sustained impact on sediment yield over time. The historical records indicate that annual sediment yield decreased on average by 72% following treatment (Ingebo and Hibbert 1974). Post-treatment herbaceous cover reduces undercanopy bare ground and sediment runoff (Williams et al. 2019). We infer that the treated drainages at our study site have likely continued to have lower sediment yield because: (a) our UAV-based estimates indicate that the herbaceous cover in the treated drainages continued to be high and greater than that in the control drainages, and (b) this trend is consistent with the post-treatment historical observations. In contrast, sediment yield in the control drainages likely increased over the six decades because our UAV images indicate that woody cover increased in control drainages compared to the historical vegetation cover estimates. Over time, woody encroachment results in increased bare ground under and between tree canopies and subsequent sediment runoff (Pierson et al. 2015). The increasing woody cover thus increases sediment connectivity and deteriorates ecohydrologic function (Turnbull et al. 2012).

Finally, the long-term impacts from woody control treatment presented here can be useful for land managers, since most observational studies are limited to shorter time periods (figure 7). Rangeland managers around the world are facing a unique challenge because woody encroachment has been shown to deteriorate rangeland health, biodiversity, and ecohydrologic resources, but it also provides opportunities for increased C accumulation (Strand et al. 2008, Sankey et al. 2013). Policy makers tasked to manage for increased productivity and C accumulation can expect to double the C storage over several decades by not chemically or mechanically treating woody encroachment. In contrast, our contemporary and historical records demonstrate that given the right circumstances, managers can expect greater water yield and herbaceous forage in the decades following a landscape-scale woody control treatment (Hibbert 1983). To simultaneously create both impacts, land managers might consider a mosaic of controlled and treated landscapes, where woody species are treated in favorable locations for increased water yield and forage production, while other woody patches are left to accumulate C.

5. Conclusion

We re-visited historical records on woody and herbaceous cover and subsequent control treatment impacts in central AZ. Combined with the contemporary UAV images, these records illustrate that woody encroachment into rangelands left uncontrolled has accumulated large aboveground C storage at decadal scales. In contrast, herbicide control has had lasting impact on woody cover and provided some ecohydrological benefits. Land managers and policy makers can compare and contrast such benefits with risks to carefully balance impacts to C and ecohydrology associated with woody encroachment. Historical and contemporary observational datasets collected at similar scales and spatial resolutions can be effectively linked to provide site-specific records to inform decision making.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Acknowledgments

We would like to thank Scott Massed, Zach Ventrella, and Wade Gibson for their fieldwork efforts as well as Patrick Shin for his assistance with UAV data collection. Joel B Sankey was supported by the U.S. Geological Survey Ecosystems Mission Area. This manuscript is submitted for publication with the understanding that the United States Government is authorized to reproduce and distribute reprints for Governmental purposes. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. government. This study was funded by the US Forest Service cooperative agreement award #17-CS-11221634-148.

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References

Archer S R, Andersen E M, Predick K I, Schwinning S, Steidl R J and Woods S R 2017 Woody plant encroachment: causes and consequences Rangeland Systems: Processes, Management and Challenges ed D D Briske (Berlin: Springer) pp 25–84
Archer S R and Predick K I 2014 An ecosystem services perspective on brush management: research priorities for competing land-use objectives. J. Ecol. 102 1394–407

Belmonte A, Sankey T, Kolb T, Bradford J, Biederman J and Goetz S 2020 UAV-derived estimates of forest structure for assessing restoration practices in ponderosa pine forest ecosystems Remote Sens. Ecol. Conserv. 6 187–91

Bestelmeyer B, Peters D C, Archer S R and Webb N P 2018 The grassland-shrubland regime shift in the southwestern United States: misconceptions and their implications for management Bioscience 68 678–90

Browning D and Archer S 2011 Protection from livestock fails to deter shrub proliferation in a desert landscape with a history of heavy grazing Ecol. Appl. 21 1629–42

Browning D, Rango A, Karl J, Laney C and Vivoni E 2015 Emerging technological and cultural shifts advancing drylands research and management Front. Ecol. Environ. 13 52–60

Cable D R 1957 Chemical control of chaparral shrubs in central Arizona J. For. 55 899–903

Canliffe A, McIntire C, Boscetti F, Sauer K, Litvak M, Anderson K and Braizer R 2020 Allometric relationships for predicting aboveground biomass and sapwood area of Oneseed Juniperus (juniperus monosperma) trees Front. Plant Sci. 11 1–12

D’Odorico P, Porporato A, Ridolfi A, Rinaldo L and Cunliffe A, McIntire C, Boschetti F, Sauer K, Litvak M, Cable D R 1957 Chemical control of chaparral shrubs in central Arizona Tech. Bull. 215

D’Odorico P, Porporato A, Ridolfi A, Rinaldo L and Rodriguez-Iiturbe I 2010 Ecohydrology of terrestrial ecosystems Bioscience 60 898–907

Dukes D, Gonzales H B, Ravi S, Grandstaff D E, Van Pelt R S, Li J, Wang G and Sankey J B 2018 Quantifying postfire aeolian sediment transport using rare earth element tracers J. Geophys. Res. Biogeosci. 123 288–99

Eldridge D, Bowler M, Maestre F, Roger E, Reynolds J F and Whitford W G 2011 Impacts of shrub encroachment on ecosystem structure and functioning: towards a global synthesis Ecol. Lett. 14 709–22

Ffolliott P and Thorud D 1974 Vegetation for Increased Water Yield in Arizona Tech. Bull. 215 (Tucson, AZ: University of Arizona, Agricultural Experiment Station) 38 p 4448

Fusco E J, Rau B M, Falkowski M, Filippelli S and Bradley B A 2019 Accounting for aboveground carbon storage in shrubland and woodland ecosystems in the Great Basin Ecosystem 10 02821

Gilson W M, Moore M M, Leonard J M, Grady K C and Springer J D 2019 Eighty-two years of plant functional type, composition, and cover changes in an Arizona interior chaparral community Poster Presentation at the 8th Int. Fire Ecology and Management Congress (Tucson, AZ, 18–22 November 2019)

Gonzalez H B, Ravi S, Li J and Sankey J B 2018 Ecohydrological implications of aeolian sediment trapping by sparse vegetation in drylands Ecohydrology 11 1886

Haralick R, Shanmugan K and Dinstein I 1973 Textural features for image classification IEEE Trans. Syst. Man Cybern. 3 610–21

Hibbert A R 1983 Water yield improvement potential by vegetation management on western rangelands J. Am. Water Resour. Assoc. 19 375–81

Hibbert A R, Davis E A and Knipe O D 1982 Water Yield Changes Resulting from Treatment of Arizona Chaparral USDA Forest Service, Gen. Tech. Rep. PSW-58 (Berkeley, CA: Pacific Southwest Forest and Range Experiment Station)

Hibbert A, Edwin D and Scholl D 1974 Chaparral Conversion Potential in Arizona: Part I: Water Yield Response and Effects on Other Resources Res. Pap. RM-126. (Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station) vol 36 p 1144

Huff S, Ritchie M and Temezen H 2017 Allometric equations for estimating aboveground biomass for common shrubs in northeastern California For. Ecol. Manage. 398 48–63

Ingebo P A and Hibbert A R 1974 Runoff and Erosion after Brush Suppression on the Natural Drainage Watersheds in Central Arizona Research Note RM-275 (Department of Agriculture, U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station) p 7

Knapp A K et al 2008 Shrub encroachment in North American grasslands: shift in growth form dominance can rapidly alter control of ecosystem C inputs Global Change Biol. 14 613–25

Kormos P, Marks D, Pierson F, Williams J, Hardegree S, Havens S, Hedrich A, Bates J and Szewcz T 2017 Ecosystem water availability in juniper versus sagebrush snow-dominated rangelands Rangeland Ecol. Manage. 70 116–28

Leonard J M, Medina A L, Neary D G and T ecle A 2015 The influence of parent material on vegetation response 15 years after the Dude Fire, Arizona Forests 6 613–35

Ludwig J, Wilcox B, Breshears D, Tongway D and I meson A 2005 Vegetation patches and runoff-erosion as interacting ecohydrological processes in semiarid landscapes Ecoology 862 86–97

McCraw P 1985 Biomass prediction of two Arizona chaparral species: Shrub live oak and birchleaf mountain mahogany Graduate thesis Arizona State University

Peters D, Okin G, Herrick J and Zhang J 2020 Modifying connectivity to promote state change reversal: the importance of geomorphic context and plant-soil feedbacks Ecology 101 e03069

Pierson F, Williams J, Kormos P, Al-Hamdan O, Hardegree S and Clark P 2015 Short-term impacts of tree removal on runoff and erosion from pinyon- and juniper-dominated sagebrush hillslopes Rangeland Ecol. Manage. 68 408–22

Pond F W 1964 Response of grasses, forbs, and halshrubss to chemical control of chaparral in central Arizona J. Range Manage. 17 200–3

Pond F 1971 Chaparral: 47 Years Later Res. Pap. RM-69 (Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station) vol 11 p 1905

Puttock A et al 2014 Woody plant encroachment into grasslands leads to accelerated erosion of previously stable organic carbon from dryland soils J. Geophys. Res. 119 2345–57

Qiao L, Zou C B, Stebler E and Will R E 2017 Woody plant encroachment reduces annual runoff and shifts runoff mechanisms in the tallgrass prairie, USA Water Resour. Res. 53 4838–49

Rau B, Johnson D, Blank R, Tausch R, Roundy B, Miller R, Caldwell T and Lucchesi A 2011 Woodyland expansion's influence on belowground carbon and nitrogen in the Great Basin U.S. J. Arid Environ. 75 827–35

Rich I R and Reynolds H G 1963 Grazing in Relation to Runoff and Erosion on Some Chaparral Watersheds of Central Arizona J. Range Manage. 16 322–26

Romme W et al 2009 Historical and modern disturbance regimes, stand structures, and landscape dynamics in piñon-juniper vegetation of the Western United States Rangeland Ecol. Manage. 622 03–22

Sankey J B, Sankey T, Li J, Ravi S, Wang G, Caster J and Kasprak A 2021 Quantifying plant-soil-nutrient dynamics in rangelands: fusion of UAV hyperspectral-LiDAR, UMW multispectral-photogrammetry, and ground-based LiDAR-digital photography in a shrub-encroached desert grassland Remote Sens. Eviron. 253 112223

Sankey T, Donager J, McVay J and Sankey J 2017 UAV lidar and hyperspectral fusion for forest monitoring in the southwestern USA Remote Sens. Environ. 195 30–43

Sankey T and Germínio M 2008 Assessment of juniper encroachment with the use of satellite imagery and geospatial analysis Rangeland Ecol. Manage. 61 412–8

Sankey T, Leonard J and Moore M 2019 Unmanned aerial vehicle-based rangeland monitoring; examining a century of vegetation change Rangeland Ecol. Manage. 72 858–63

Sankey T, McVay J, Swetnam T, Mcclaran M, Heilman P and Nicholls M 2018 UAV hyperspectral and lidar data and their fusion for arid and semi-arid land vegetation monitoring Remote Sens. Ecol. Conserv. 1 20–25
Sankey T, Shreshtha R, Sankey J and Hardegree S 2013 Lidar-derived carbon estimates in woody encroachment J. Geophys. Res. 118 1144–55
Shin P, Sankey T, Moore M and Thode A 2018 Evaluating unmanned aerial vehicle images for estimating forest canopy fuels in a ponderosa pine stand Remote Sens. 10 1266–88
Solazzo D, Sankey J B, Sankey T T and Munson S M 2018 Mapping and measuring aeolian sand dunes with photogrammetry and LiDAR from unmanned aerial vehicles (UAV) and multispectral satellite imagery on the Paria Plateau, AZ, USA Geomorphology 319 174–85
Stevens N, Lehmann C, Murphy B and Durigan G 2017 Savanna woody encroachment is widespread across three continents Global Change Biol. 23 235–44
Strand E K, Vierling L A, Smith A M and Bunting S C 2008 Net changes in aboveground woody carbon stock in western juniper woodlands 1946–1998 J. Geophys. Res. Biogeosci. 113 1–13
Turnbull L et al 2012 Understanding the role of ecohydrological feedbacks in ecosystem state change in drylands Ecohydrology 5 174–83
Wang G, Li J, Ravi S, Theiling B P and Sankey J B 2019 Fire changes the spatial distribution and sources of soil organic carbon in a grassland-shrubland transition zone Plant Soil 435 309–21
Westoby M, Brasington J, Glasser N F, Hambrey M J and Reynolds J M 2012 ‘Structure-from-motion’ photogrammetry: a low-cost, effective tool for geoscience applications Geomorphology 179 300–14
Wilcox B, Huang Y and Walker J 2008 Long-term trends in streamflow from semiarid rangelands: uncovering drivers of change Global Change Biol. 14 141676–89
Williams J, Pierson F, Nouwakpo S, Al-Hamdani O, Kormos P and Weltz M 2020 Effectiveness of prescribed fire to re-establish sagebrush steppe vegetation and ecohydrologic function on woodland-encroached sagebrush rangelands, Great Basin, USA: part I: vegetation, hydrology, and erosion responses Catena 185 103477
Williams J, Pierson F, Nouwakpo S, Kormos P, Al-Hamdani O and Weltz M 2019 Long-term evidence for fire as an ecohydrologic threshold-reversal mechanism on woodland-encroached sagebrush shrublands Ecohydrology 12 e2086