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Detecting shrub recovery in sagebrush steppe: comparing Landsat-derived maps with field data on historical wildfires

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Abstract

Background: The need for basic information on spatial distribution and abundance of plant species for research and management in semiarid ecosystems is frequently unmet. This need is particularly acute in the large areas impacted by megafires in sagebrush steppe ecosystems, which require frequently updated information about increases in exotic annual invaders or recovery of desirable perennials. Remote sensing provides one avenue for obtaining this information. We considered how a vegetation model based on Landsat satellite imagery (30 m pixel resolution; annual images from 1985 to 2018) known as the National Land Cover Database (NLCD) “Back-in-Time” fractional component time-series, compared with field-based vegetation measurements. The comparisons focused on detection thresholds of post-fire emergence of fire-intolerant *Artemisia* L. species, primarily *A. tridentata* Nutt. (big sagebrush). Sagebrushes are scarce after fire and their paucity over vast burn areas creates challenges for detection by remote sensing. Measurements were made extensively across the Great Basin, USA, on eight burn scars encompassing ~500 000 ha with 80 plots sampled, and intensively on a single 113 000 ha burned area where we sampled 1454 plots.

Results: Estimates of sagebrush cover from the NLCD were, as a mean, 6.5% greater than field-based estimates, and variance around this mean was high. The contrast between sagebrush cover measurements in field data and NLCD data in burned landscapes was considerable given that maximum cover values of sagebrush were ~35% in the field. It took approximately four to six years after the fire for NLCD to detect consistent, reliable signs of sagebrush recovery, and sagebrush cover estimated by NLCD ranged from 3 to 13% (equating to 0 to 7% in field estimates) at these times. The stabilization of cover and presence four to six years after fire contrasted with previous field-based studies that observed fluctuations over longer time periods.

Conclusions: While results of this study indicated that further improvement of remote sensing applications would be necessary to assess initial sagebrush recovery patterns, they also showed that Landsat satellite imagery detects the influence of burns and that the NLCD data tend to show faster rates of recovery relative to field observations.

Keywords: Change point detection, National Land Cover Database, Post-fire monitoring, Sagebrush

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Resumen

Antecedentes: La necesidad de información básica sobre la distribución espacial y la abundancia de especies vegetales para la investigación y el manejo de ecosistemas semiáridos no está frecuentemente cubierta. Esta necesidad es particularmente aguda en grandes áreas impactadas por mega-incendios en ecosistemas esteparios de artemisia (*i.e.*, *sagebrush*), los cuales requieren de información actualizada y frecuente sobre los incrementos de invasoras exóticas anuales o sobre la recuperación de perennes deseables. Los sensores remotos proveen una gran avenida para obtener esta información. Consideramos cómo un modelo de vegetación basado en imágenes Landsat (píxeles de 30 m de resolución e imágenes desde 1985 a 2018) conocido como la Base Nacional de Datos de Cobertura de Tierras (NLCD, National Land Cover Database), componente fraccional de serie de tiempos “Back-in-Time”, comparaba con datos de mediciones de vegetación a campo. Las comparaciones se enfocaron en los límites de detección de la emergencia post fuego de la especie intolerante al fuego *Artemisia* L., principalmente *A. tridentata* Nutt. (artemisia grande). Las especies de artemisia son escasas en el post fuego y su escasez en vastas áreas quemadas crea un desafío para su detección mediante sensores remotos. Las mediciones fueron hechas extensivamente a lo largo de la Gran Cuenca (Great Basin) en los EEUU, sobre cicatrices de fuego que abarcaban unas 500 000 ha con 80 parcelas muestreadas, e intensivamente en 113 000 ha quemadas donde muestreamos la vegetación en 1454 parcelas.

Resultados: Las estimaciones de cobertura de artemisia mediante el NLCD fueron, en promedio, un 6,5 % mayores que las estimaciones basadas en datos de campo, y la varianza alrededor de esta media fue alta. El contraste entre las mediciones de cobertura de artemisia en datos de campo y datos de NLCD en paisajes quemados fue considerable dado que los máximos valores de cobertura de artemisia en el campo fueron de aproximadamente el 35%. Tomó aproximadamente de cuatro a seis años después del fuego para que el NLCD detectara signos consistentes y confiables de recuperación de artemisia, y la cobertura estimada por NLCD varió entre 3 a 13% (equivalente de 0 a 7 % en estimaciones a campo) en ese mismo tiempo. La estabilización de la cobertura y la presencia de cuatro a seis años después de fuego contrastó con previos estudios de campo que observaron fluctuaciones en períodos de tiempo más largos.

Conclusiones: Aunque los resultados de este estudio indicaron que un mejoramiento a futuro en la aplicación de sensores remotos va a ser necesario para determinar los patrones de recuperación inicial de artemisia, también mostraron que las imágenes Landsat detectan la influencia de las quemadas y que los datos de NLCD tienden a mostrar tasas de recuperación más rápidas en relación a las observaciones de campo.

Background

As remote sensing products become more readily available for science and land management applications (*i.e.*, Thackway et al. 2013; Willis 2015), there is a corresponding need to determine how well vegetation maps derived from them match field observations. One compelling application of remote sensing is mapping of plant community recovery patterns after wildfire. Wildfires are increasing in size across the sagebrush steppe in the semiarid western United States (Keane et al. 2009), and the cumulative amount of burned areas increasingly exceeds the field-based monitoring capabilities of landowners and agencies. Initial plant recovery patterns after fire affect the long-term trajectory of ecosystem health and thus are critical to measure for both scientific understanding and enabling timely management interventions. Whether the information required to manage the rapid vegetation changes occurring over these large areas can be gathered with remote-sensing products is an important research question.

Satellite imagery has been used to assess coarse ecosystem recovery of burned areas, such as changes to normalized difference vegetation index (NDVI) or band reflectance over time (White et al. 1996; Hope et al. 2007; Van Leeuwen 2008; Johnston et al. 2018). However, the primary information needs of land managers are often about species composition of recovering plant communities. Semiarid rangelands pose a unique set of challenges for remote sensing because major functional differences exist between key species that are often not accompanied by strong spectral differences (Mansour et al. 2012). In the vast sagebrush steppe ecosystems of western North America, which have experienced ~50% contraction in recent decades due to the fire–invasive–annual–grass cycle (Miller et al. 2011), extensive and intensive restoration interventions are executed to assist recovery of desirable perennials such as sagebrush (*Artemisia tridentata* Nutt.), and to decrease exotic invasive species (Pilliod et al. 2017). The planning, application, and assessment of these land treatments and natural recoveries

require frequent measurement of plant communities over large areas.

New remote sensing platforms such as the National Land Cover Database (NLCD) “Back-in-Time” fractional component cover time-series (Rigge et al. 2019; Homer et al. 2020) provide yearly updates on plant community composition derived from Landsat satellite imagery (annual images from 1985 to 2018, at 30 m pixel resolution). The NLCD estimates sagebrush cover and other dominant functional groups that can potentially meet managers’ information needs. However, a tradeoff in performance between spatial extent and local accuracy is unavoidable for NLCD and similar digital products, such as the Rangeland Analysis Platform (Jones et al. 2018). While field surveys with high sampling power can detect sagebrush re-emergence after wildfire and form the benchmark for local accuracy (as in Germino et al. 2018), less detection ability is expected from estimates made from aerial imagery (Applestein et al. 2018). The scale tradeoffs occur along a spectrum of reduced extent and greater local accuracy beginning with aircraft-based photography (Moffet et al. 2015), followed by high-resolution satellite imagery like Worldview (Xian et al. 2019), and lastly vegetation models based on moderate-resolution satellite imagery like Landsat (30 m resolution) or coarse-resolution MODIS (250 m resolution; Van Leeuwen 2008).

Few studies offer insight as to how well cover of vegetative species or functional types in large managed landscapes, such as megafire scars, can be assessed from platforms such as NLCD. This is a critical information gap for species such as sagebrush, which is central to one of the largest restoration programs globally. Despite the importance of post-fire sagebrush recovery, efforts to monitor it in the field are not yet spatially or temporally adequate, nor are they likely to be with the currently available ground-based sampling approaches (see Germino et al. 2018 for an exception).

Field monitoring of sagebrush is usually done either in a few locations and years after wildfires for restoration or research projects (among the most intensive are three to five plots per burn area in Knutson et al. 2014 and Shriver et al. 2018), or routinely throughout its range with sampling that is even sparser in space and time (e.g., US Bureau of Land Management AIM monitoring program, <https://landscape.blm.gov/geoportal/catalog/AIM/AIM.page>). Species such as sagebrush confer some advantages for detection by remote sensing; most notably, the green-gray sagebrush foliage is contrasted by the high albedo of surrounding vegetation, which is senesced for at least six months of each year (Clark et al. 2001). However, there are also major challenges to quantifying spatial patterns of post-fire sagebrush cover, most notably that burned sagebrush steppe ecosystems have

large amounts of bare soil, scarce plant cover, and spectrally indeterminate vegetation, which makes discriminating between phenologically concurrent species or between plant and soil cover difficult (Huang et al. 2009; Fairweather et al. 2012). The relative scarcity of sagebrush cover is particularly acute post fire, when plants are smaller and sparser during the initial stages of burned-area recolonization. One previous study found sagebrush measured in the field to be well below 10% ($R^2 = 0.03$) of the sagebrush cover estimated by NLCD, at the eastern fringe of sagebrush’s range in South Dakota, USA, although agreement was greater when assessing the presence or absence of sagebrush (Parsons et al. 2020). Other studies have shown greater concordance, including a field accuracy assessment across the geographic extent of the NLCD data (Rigge et al. 2020) and a long-term field monitoring study of sagebrush in Wyoming, USA (Shi et al. 2020). However, none of these studies have specifically examined post-fire regeneration. Determining the threshold abundance of sagebrush required to generate an adequate signal for it to be detected by NLCD is a critical first step in evaluating the suitability of such map products for evaluating recovery of burned sagebrush steppe ecosystems.

To determine whether NLCD sagebrush cover layers can be applied as an extension of field monitoring for addressing management questions, we asked the following: (1) over what time period does NLCD display a post-fire sagebrush (*Artemisia* spp.) regeneration signal, and does this signal match field data? Is the regeneration signal consistent from year to year? (2) How do estimates of post-fire sagebrush cover from NLCD compare with field data, across historical burn scars in western North America? (3) What is the minimum level of sagebrush cover measured in the field that can be detected by the NLCD sagebrush product? We predicted that the NLCD would underestimate sagebrush abundances in the first few years after fire, compared to benchmark estimates from the field where detection of sagebrush at the plot level should be greater.

Methods

NLCD Back-in-Time data

Methodology used to produce the NLCD data is described in Rigge et al. 2019. The NLCD data is given as sagebrush cover as whole-integer percentage. Post-processing of NLCD prior to its release for public use includes two screening steps for potential high or low sagebrush cover anomalies, specifically (1) flagging pixels where sagebrush cover decreases from one year to the next, and only allowing cover to remain constant or increase over years after fire; and (2) flagging any predicted cover values that were greater than would be predicted from:

$$\text{Sagebrush cover} = -0.0333 \times y^2 + 2.333 \times y - 0.0001, \tag{1}$$

where y is the number of years since fire. Flagged data values are reduced to the value predicted by this equation. Only 1.01% of the spatially extensive data (6% of pixels in the second post-fire year) and none of the spatially intensive data were affected by this correction; the correction was thus deemed to have little impact on the overall analysis.

Change point detection in spatially extensive analysis

We calculated the mean NLCD percent sagebrush cover and proportion of pixels with sagebrush present (defined as having sagebrush cover $\geq 1\%$) from one year prior to fire through 26 years after fire (or however many years were available, if fewer than 26) in ArcGIS (version 10.5.1; ESRI, Redlands, California, USA) using the zonal statistics tool (for cover) and tabulate zones tool (for presence) on all seeded and unseeded areas within the fire boundary, separately. We then ran the `strucchange` package in R (Zeileis et al. 2002) to use Chow’s (1960) method for determining temporal change points in year-to-year fluctuations of post-fire sagebrush cover and presence

(analyzed separately), to determine in which post-fire year sagebrush stopped increasing (or decreasing). Chow’s method identifies structural change points by considering whether slopes of two linear regressions significantly differ before and after each potential change point (“points” are years after fire). In our application, Chow’s F-test was used to determine how significant the difference in slope (change in sagebrush over time) was before, compared to after, each time point.

Spatially extensive analysis

Our extensive analysis required subject sites that had burned and had existing field data on sagebrush recovery and, moreover, were representative of big sagebrush sites in terms of soils and climate. Additionally, burned areas were selected to include a range of different fire years and sizes (Fig. 1, Table 1). A broad digital search revealed eight areas in sagebrush steppe that burned between 1990 and 2007 and ranged in size from 4400 to 252 800 ha in the Central Great Basin, Northern Great Basin, and Snake River Plain Ecoregions (Environmental Protection Agency; level three), USA, where sagebrush recovery had been measured in the field using standardized belt-transect techniques by Knutson et al. (2014), Shriver et al. (2018), and Barnard et al. (2019; Fig. 1,

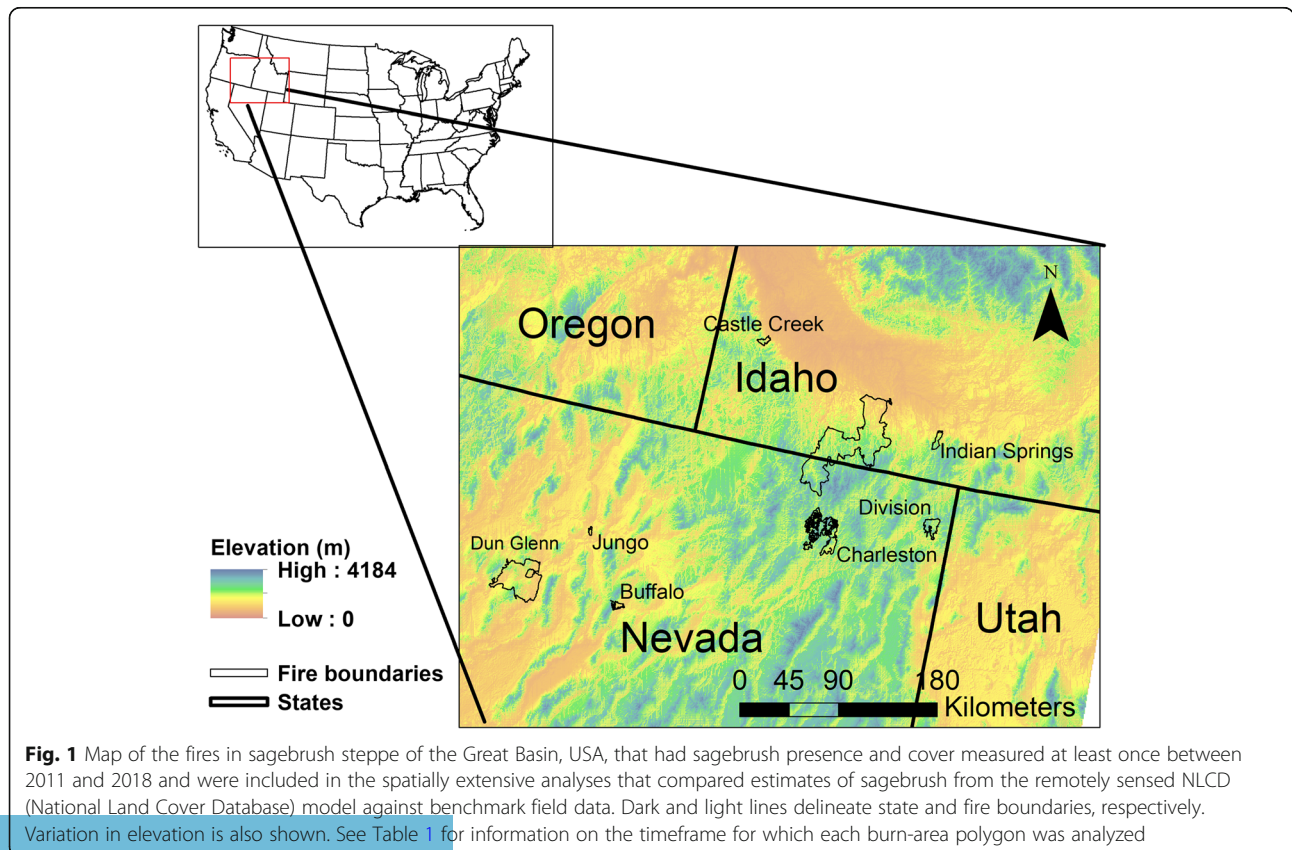


Table 1 Characteristics of areas burned in sagebrush steppe of the Great Basin, USA, that had sagebrush presence and cover measured at least once between 2011 and 2018 and were included in the spatially extensive or spatially intensive analyses that compared estimates of sagebrush from the remotely sensed NLCD (National Land Cover Database) model against benchmark field data. Points refer to field plots, which were the spatial basis of comparison to the NLCD model estimates. “Year monitored” refers to both NLCD and field sampling occurring in each noted year

Fire name	Burn year	Year monitored	Fire size (ha)	Points (n)
Spatially extensive analysis				
Castle Creek	1990	2011, 2016	4 452	14
Indian Springs	1990	2014	7 303	5
Buffalo	1995	2011, 2017	5 425	20
Division	1996	2011	15 158	12
Dun Glenn Complex Poker Brown	1999	2015	101 044	5
Jungo Complex	2000	2014	36 336	4
Charleston	2006	2015	66 385	15
Murphy	2007	2015	252 794	5
Spatially intensive analysis				
Soda	2015	2016, 2018	110 069	1454

Table 1). Soils across the large areas evaluated were generally loams, ranging from clay loam to sandy loam, and generally had mesic-aridic to frigid-aridic soil temperature–moisture regimes, with the majority of the ~250 to 400 mm of mean annual precipitation occurring in cool winter or spring months. Field plots were located on flat or hilly terrain that did not exceed ~15% slope.

Burned areas were selected to include a range of different fire years and sizes from those that had previously been monitored for post-fire sagebrush recruitment. All burned areas were partially seeded with sagebrush by aircraft and had their sagebrush density and cover measured either once or twice between 2011 and 2017 (data reported in Knutson et al. 2014; Shriver et al. 2018, 2019; and Barnard et al. 2019). Polygons of seeded areas were obtained from the Land Treatment Digital Library (Pilliod and Welty 2013). We excluded areas that were strip seeded (regular alternations of seeded and unseeded swaths) and instead only used areas that were seeded homogeneously. We also removed areas that reburned within ten years of the initial fire dates to ensure enough recovery time. Next, we created polygons for the unseeded burned areas by selecting all areas that had not been seeded with sagebrush (with a buffer of 60 m).

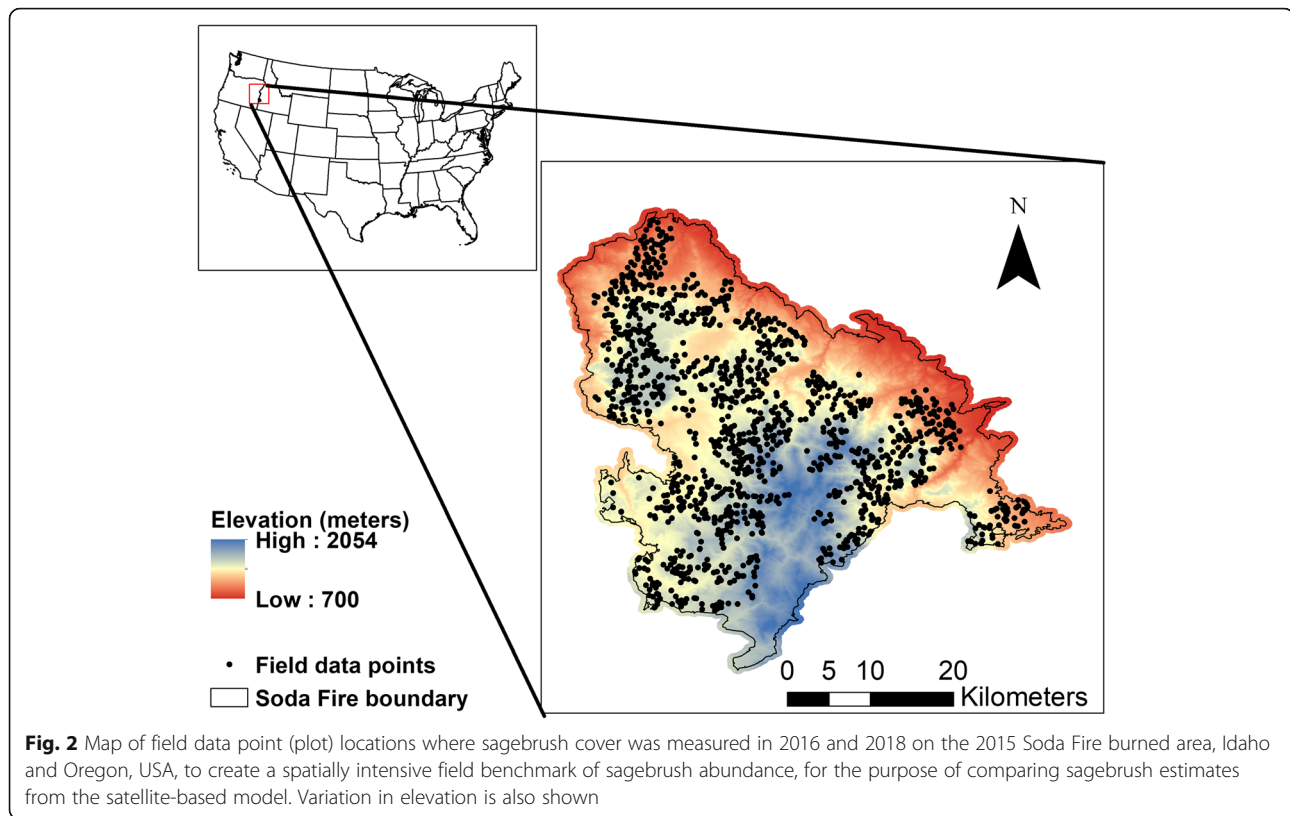
Eighty field plots were established using a stratified random approach across 489 000 ha among the eight extensive burned areas by the authors of the data we used (Knutson et al. 2014; Shriver et al. 2018; Barnard et al. 2019). Plots were either located in burned+unseeded areas, burned+seeded areas, or unburned+unseeded areas located 150 to 2000 m outside the fire perimeter (described in detail in Arkle et al. 2014). At each plot, sagebrush cover was recorded from line-point-intercept

using 150 points along three 50 m belt transects that were arranged in a spoke design (Herrick et al. 2005). Recordings of sagebrush included *Artemisia tridentata* Nutt., *A. arbuscula* Nutt., and *A. tripartita* Rydb. GPS accuracy of plot location was ~3 m. We used the extract multi tool in ArcGIS to obtain the 30 m NLCD pixel value of sagebrush cover at the center of the field plots for the time point that coincided with the field-monitoring year.

We used a linear regression and Tukey’s post-hoc contrasts (Tukey 1949) to compare the difference in sagebrush cover estimates between the NLCD cover and the field data cover measurements between different treatment types (burned+seeded, burned+unseeded, and unburned+unseeded plots) and time since fire. We then used linear regression to assess the correspondence between field data cover estimates and NLCD cover estimates for all data.

Spatially intensive analysis

To determine minimum sagebrush detection level, we compared sagebrush cover estimated by NLCD against field estimates made on 1454 plots dispersed in a stratified random fashion using ArcGIS across the 2015 Soda Fire burned area (113 000 ha; Table 1, Fig. 2), with measurements and comparisons made in 2016 and again in 2018. Data for 2016 and methods are described in Germino et al. (2018). Sagebrush cover was determined by first measuring the density of sagebrush using a frequency-density approach, and then estimating cover from the density value. The frequency-density approach entailed counting the number of sagebrush present in a 1 m² quadrat, provided at least three seedlings were detected. If fewer than three seedlings were detected, the



search area was expanded to a 5.5 m radius circular area, and again incrementally to 9, 13, or 18 m radii areas if necessary. The heights of all sagebrush were recorded as being in one of the following height bins: <5, 5 to 15, 15 to 30, 30 to 75, 75 to 120, or >120 cm.

Next, sagebrush cover was determined by summing the product of the number of plants and average crown area for plants in each height bin:

$$Cover = Density \text{ (plants } m^{-2}) \times Mean \text{ crown area (} m^2 \text{plant}^{-1}) \times 100 \tag{2}$$

Mean crown areas were determined for each sagebrush height class based on regressions of crown area and height measurements made on a centrally located common garden in the Soda Fire burned area (Davidson et al. 2019). Crown area was determined for each of 1321 plants measured multiple times over the course of three years (6899 individual data points) in the garden by measuring diameter of the foliar extent in two dimensions and then assuming the crown to be circular (*i.e.*, area = πr^2). To assess accuracy of this method, we compared sagebrush cover derived from this method for each plot to an ocular estimate of sagebrush cover taken in 2019 ($R = 0.35$, $P < 0.0001$, $y = -0.42 + 0.45x$). The coordinates of each plot (~3 m accuracy) were used to

identify the corresponding NLCD pixel to create a basis for comparison.

We compared the Soda Fire monitoring sagebrush cover estimates from 2016 and 2018 with NLCD data. We created a contingency table using sagebrush cover bins (0%, >0 to 1%, >1 to 5%, or >5%) and calculated a Cohen’s kappa metric (Cohen 1960) to assess agreement between sagebrush cover field estimates and NLCD data.

Results and discussion

Change point detection for spatially extensive data

For the burned areas assessed, NLCD sagebrush regeneration signal for both cover and presence did not fluctuate strongly after reaching a stabilizing point four to six years after fire (Figs. 3 and 4). Once the NLCD dataset showed that sagebrush occurrence was similar to pre-fire levels (as measured by the proportion of pixels containing sagebrush), this signal tended to stay consistent. One exception was the Jungo Fire (Figs. 3 and 4), both unseeded and seeded areas, that had a transient decrease in sagebrush occurrence 13 years after fire. Previous field studies have shown strong fluctuations in sagebrush population density (and frequently in cover) for up to 40 years post fire that reflect ecologically important processes (Shriver et al. 2019). It is likely that these fluctuations are not well captured by the spatial or spectral scale of the NLCD data.

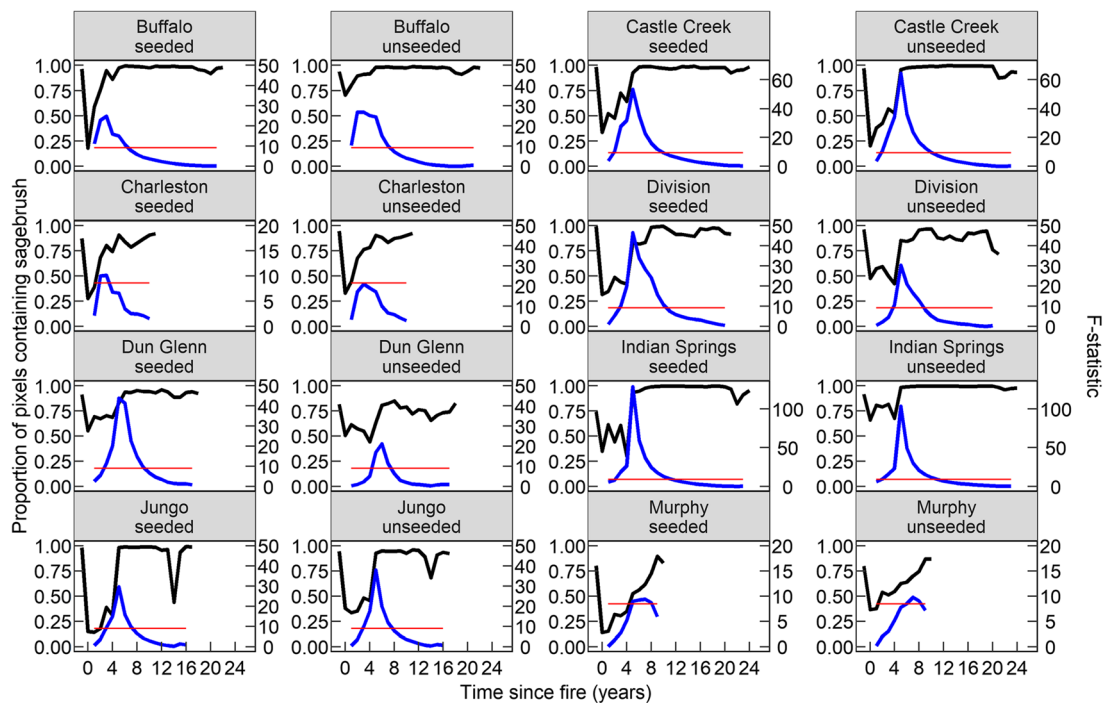


Fig. 3 Proportion of pixels containing sagebrush according to the National Land Cover Database (NLCD; black line) and corresponding F-statistic from the Chow test that indicates how the temporal trend before each post-fire year differs from the temporal trend after the year (blue line). The red line shows the significance level for the Chow F-statistic; F-statistic values greater than the red line are significant. The maximum F-statistic values in each panel indicate the year when the most change has occurred from before compared to after the year, and thus generally correspond with inflections between the initial post-fire increase in sagebrush followed by a period of stabilization, having little or no directional change in sagebrush from year to year. Values at <0 years since fire are pre-fire conditions. Each panel shows a different fire and treatment (seeded or unseeded) for the areas burned in sagebrush steppe of the Great Basin, USA, that had sagebrush presence and cover measured at least once between 2011 and 2018

Sagebrush cover estimated by NLCD tended to decrease from 4 to 16% of ground area before each fire (year -1 on abscissa of Fig. 4) to <1 to 8% the year after each fire, and then recovered progressively toward pre-fire abundances in subsequent years. Temporal patterns of sagebrush recovery and Chow F statistics were consistent between seeded and unseeded areas, indicating that naturally regenerating areas displayed spectral signals similar to managed areas, although some important distinctions are notable. For example, sagebrush presence in unseeded areas of the Buffalo Fire burn area did not appear to decrease as appreciably after fire (at year 0 compared to year -1 on abscissa of Fig. 4) compared to seeded areas. This may reflect manager’s decisions to seed in areas that experienced greater loss of sagebrush. The differences between field and observed data at specific measurement years were appreciable and reflected a substantial overestimate by NLCD (Fig. 4). The exceptions included seeded areas of the Indian Springs and Jungo fires, where field data better matched NLCD cover estimates (see asterisk symbols in Fig. 4).

Comparison between spatially extensive field data and NLCD data

Estimates of sagebrush cover made by NLCD and in the field were positively related ($P = 0.0004$), although there was a high level of unexplained variation in the relationship ($R^2 = 0.15$) and a relatively large y -intercept (6.5% cover) revealed a tendency for sagebrush cover to appear appreciably abundant in NLCD estimates in areas for which field data revealed no sagebrush cover (Fig. 5). Seeding treatment and time since fire can sometimes strongly affect the abundance of sagebrush (e.g., Germino et al. 2018), and we asked if the relationships would differ between NLCD and field estimates for these different spatial and temporal windows, but there was no such variation in the relationship (Table 2). We expected that there would be lower-accuracy sagebrush detection primarily in the initial years after fire because dispersed small seedlings would likely not be spectrally detected in a 30 m pixel. However, NLCD also overestimated sagebrush cover compared with field estimates in later years after fire. After the detection threshold of four to six years post fire, NLCD estimates of sagebrush

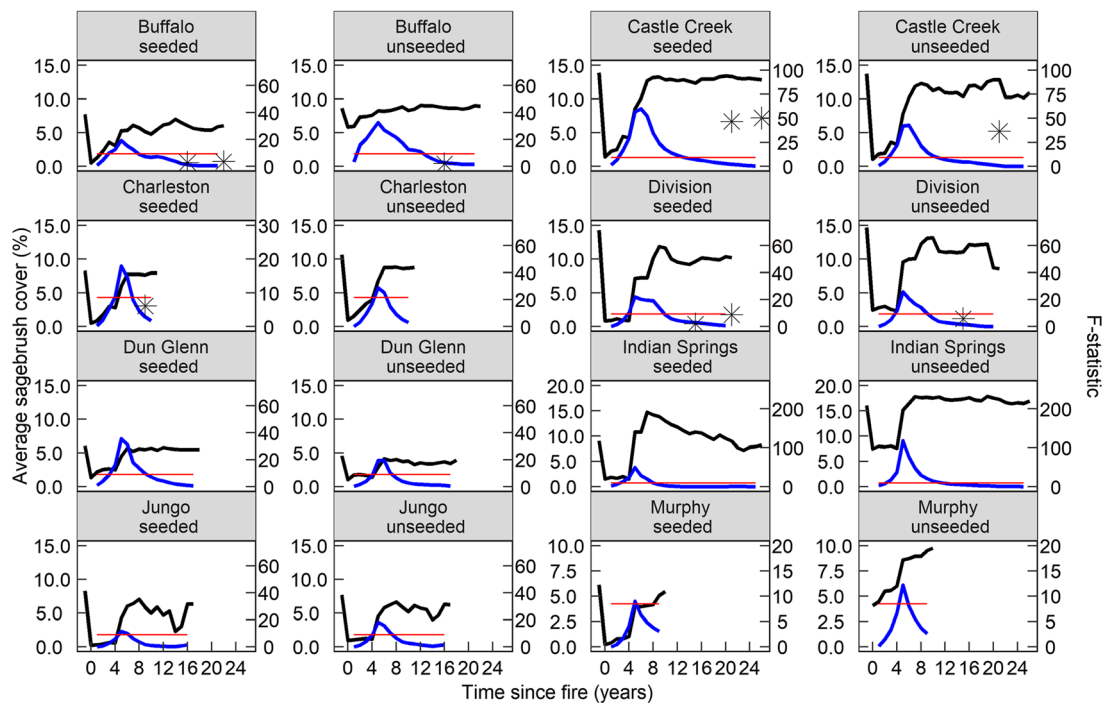


Fig. 4 Average percent sagebrush cover (%) according to the National Land Cover Database (NLCD; black line) and corresponding F-statistic from the Chow test that indicates how the temporal trend before each post-fire year differs from the temporal trend after the year (blue line). The red line shows the significance level for the Chow F-statistic; F-statistic values greater than the red line are significant. The maximum F-statistic values in each panel indicate the year when the most change has occurred from before compared to after the year, and thus generally correspond with inflections between the initial post-fire increase in sagebrush followed by a period of stabilization, having little or no directional change in sagebrush from year to year. Field data (when available) is shown with asterisks (*) at the years in which monitoring was done and is given as an average of the monitoring cover. Values at <0 years since fire are pre-fire conditions. Each panel shows a different fire and treatment (seeded or unseeded) for the areas burned in sagebrush steppe of the Great Basin, USA, that had sagebrush presence and cover measured at least once between 2011 and 2018

cover ranged from 3 to 13% in years with corresponding field estimates (Fig. 4) while field estimates ranged from 0 to 7% (Fig. 5).

The 6.5% overestimation of NLCD sagebrush cover compared to field data is on one hand contrary to the expectation that underestimation and lack of detection would be more likely in remotely sensed estimates of a scarce shrub. On the other hand, the 6.5% difference is within a similar range of error reported by other readily available rangeland remote sensing products, such as the Rangeland Analysis Platform, which reportedly had a mean absolute error of 6.9% overall (Jones et al. 2018). The correlation we found between NLCD and field estimates of sagebrush cover was greater than the correlation R^2 of 0.03 found by Parsons et al. (2020) in South Dakota on unburned areas. The South Dakota analysis was conducted in a landscape where the growth habitat of short-stature sagebrush individuals was interspersed with dense grass, atypical of the sagebrush biome as a whole, although likely more analogous to our post-fire study systems than “typical” intact sagebrush stands. The scale of our field data (three 50 m transects

radiating out from a common origin) was larger than the 30 m pixel size of the NLCD data. Typically, accuracy assessments on remote sensing products rely on ground-truthing data that align exactly with imagery pixel scales, but the ground-truthing accuracy data may differ in plot size and measurement method from those used by managers for monitoring land treatment effects. As land managers increasingly use remote sensing products, there is a critical question about whether and how these products are comparable to regularly used field monitoring techniques, such as the AIM protocol (Herrick et al. 2005).

Minimum NLCD detection level for spatially intensive field data

There was no evidence of a minimum detectable percent sagebrush cover in the field that would be a detection threshold for the NLCD data. The category of sagebrush cover for each sampled pixel on the Soda Fire burn area estimated by NLCD was greater than the corresponding field data in both 2016 (Cohen’s kappa = -0.02, $P = 0.2$) and 2018 (Cohen’s kappa = -0.002, $P = 0.7$; Table 3). A

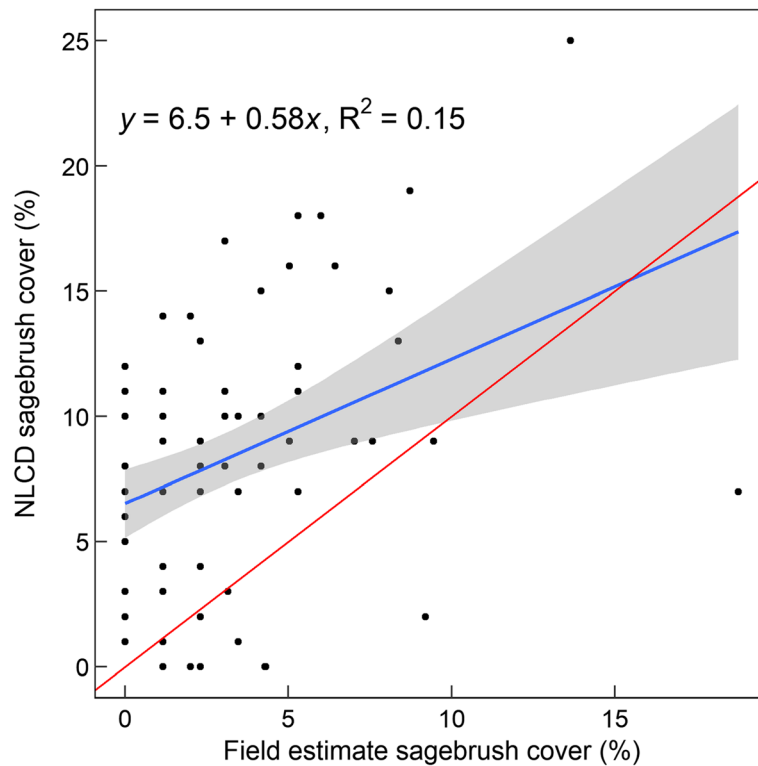


Fig. 5 Linear regression of sagebrush cover estimated in the field (abscissa) and the National Land Cover Database (NLCD; ordinate) in the spatially extensive dataset (Fig. 1) for the burned areas in sagebrush steppe of the Great Basin, USA, that had sagebrush presence and cover measured at least once between 2011 and 2018. The blue line and equation show the least-squares regression fit, with 95% confidence intervals in gray. For comparison, the red line depicts perfect agreement between estimates (which was not observed)

negative Cohen’s kappa indicates disagreement between the two data sources. Sagebrush cover estimated by NLCD tended to be one or two categories greater than field-based measurements (Table 3). The NLCD tended to have commission errors rather than omission errors. In 2016, the NLCD cover data misclassified sagebrush

absences (0% cover) as presences (>0% sagebrush cover) four times more often than it correctly classified absences and in 2018, misclassification of absences was 20 times more frequent than correct absence classifications (Table 3). Out of 731 plots where sagebrush was detected in the field in 2016, only 93 incorrect omissions

Table 2 Coefficient values for a linear regression considering the effects of treatment (burned+seeded, burned+unseeded, unburned+unseeded) and time since fire on the difference in sagebrush cover in sagebrush steppe of the Great Basin, USA, between 2011 and 2018, that was estimated by the remotely sensed NLCD (National Land Cover Database) model compared to benchmark field data. The intercept is given as the coefficient estimate for burned+seeded. Tukey’s post-hoc contrasts between different treatment types are given below the regression coefficients. SE standard error

	Estimate	SE	t-value	P-value
Linear regression coefficients				
Intercept	2.8553	1.7306	1.65	0.103
Burned+unseeded	2.1752	1.7079	1.274	0.207
Unburned+unseeded	2.2871	1.633	1.401	0.165
Time since fire	0.1185	0.102	1.162	0.249
Tukey’s contrasts				
Burned+seeded versus burned+unseeded	-2.175	1.71	-1.274	0.4144
Burned+seeded versus unburned+unseeded	-2.287	1.63	-1.401	0.3457
Burned+unseeded versus unburned+unseeded	-0.112	2.19	-0.051	0.9986

Table 3 Contingency table for the number of plots on the Soda Fire burned area, Idaho and Oregon, USA, that had estimated sagebrush cover (%) in four different abundance categories, for estimates made in the field (rows) and National Land Cover Database (NLCD) remotely sensed sagebrush cover (columns) in 2016 and 2018. Total plot numbers are given in the bottom row and last column

Year	Field estimate (%)	Estimate from NLCD, remote sensing				Total plots (n)
		0%	>1%	>1 to 5%	>5%	
2016	0	139	446	135	3	723
	>0 to 1	90	335	268	3	696
	>1 to 5	2	10	13	0	25
	>5	1	5	4	0	10
	Total plots (n)	232	796	420	6	1454
2018	0	26	94	297	139	556
	>0 to 1	23	96	441	210	770
	>1 to 5	1	1	15	6	23
	>5	0	0	5	4	9
	Total plots (n)	50	191	758	359	1358

were found in the NLCD data. Out of 802 plots where sagebrush was detected in the field in 2018, only 24 incorrect omissions were found in the NLCD data (Table 3).

The high commission error indicates that regeneration of non-sagebrush vegetation may be incorrectly detected and classified as sagebrush cover at the aggregated plot scale by the NLCD data, particularly because commission error sharply increased between 2016 and 2018 as post-fire regeneration of all vegetative cover increased. Other shrubs were not a dominant functional group during this time range, but perennial grass cover did increase in many plots throughout the three-year period. Obtaining very low or high cover values in remote sensing products, especially those produced using regression trees, is difficult because of noise and the tendency of regression toward the mean. Accordingly, 0% sagebrush cover measured in the plots is likely to be mapped as 1 to 10% cover in the NLCD pixels. A large number of our Soda Fire plots had sagebrush cover between 0 and 1% for all three years post fire, which points to this temporal window being a difficult time period in which to classify sagebrush cover.

Conclusion

As wildfires increase in size every year across the vast domain of sagebrush steppe, there is a growing management need for spatially extensive data that can inform post-fire vegetative recovery. Remote sensing products such as the NLCD fractional component dataset offer one potential source of data that could be used to assess sagebrush recovery and treatment effectiveness. Similar to other comparisons between field data and remote sensing data, this study shows evidence of a “false

moderating effect” (Rigge et al. 2020), for which very low abundances are overpredicted and high abundances are underpredicted. Very low sagebrush abundances are common in early years post fire. This study shows that current NLCD sagebrush cover data may yield somewhat different results than typical ground-survey field data used for post-fire monitoring. Comparisons of entire polygons containing many pixels may yield a different level of agreement; however, field data are rarely sampled adequately enough to enable such a comparison. Our results show that, while further improvement of post-fire remote sensing products is warranted, NLCD sagebrush cover data do detect the influence of burns, but data tend to show faster rates of recovery relative to field observations. It should be noted that NLCD Back-in-Time data include cover components for other functional groups, including annual herbaceous cover, and future research should examine the initial post-fire recovery patterns of these components. Finer resolution remote-sensing data, including LiDAR-derived estimates, have shown promise for higher accuracy characterization of small-scale sagebrush biomass and cover, although underestimation is likely (Mitchell et al. 2011). Continued large-scale field monitoring efforts are warranted to obtain this initial post-fire sagebrush cover data to track recovery trajectories.

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Authors’ contributions

Both authors conceived of and wrote the paper. MJG provided supervision and acquired the funding. CA performed the analyses including statistics and graphing. Both authors read and approved the final manuscript.

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Availability of data and materials

All data used in this study can be found in the original citations and references provided.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Both authors give consent for publication.

Competing interests

The authors have no competing interests to declare.

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