Quantifying and predicting fuels and the effects of reduction treatments along successional and invasion gradients in sagebrush habitats

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Abstract

Sagebrush shrubland ecosystems in the Great Basin are prime examples of how altered successional trajectories can create dynamic fuel conditions and, thus, increase uncertainty about fire risk and behavior. Although fire is a natural disturbance in sagebrush, post-fire environments are highly susceptible to conversion to an invasive grass-fire regime (often referred to as a "grass-fire cycle"). After fire, native shrub-steppe plants are often slow to regenerate, whereas nonnative annuals, especially cheatgrass (*Bromus tectorum*) and medusahead (*Taeniatherum caput-medusae),* can establish quickly and outcompete native species. Once fire-prone annuals become established, fire occurrences increase, further promoting dominance of nonnative species. The invasive grass-fire regime also alters nutrient and hydrologic cycles, pushing ecosystems beyond ecological thresholds toward steady-state, fire-prone, nonnative communities. These changes affect millions of hectares in the Great Basin and increase fire risk, decrease habitat quality and biodiversity, accelerate soil erosion, and degrade rangeland resources for livestock production. In many sagebrush landscapes, constantly changing plant communities and fuel conditions hinder attempts by land managers to predict and control fire behavior, restore native communities, and provide ecosystem services (e.g., forage production for livestock).

We investigated successional and nonnative plant invasion states and associated fuel loads in degraded sagebrush habitat in a focal study area, the Morley Nelson Snake River Birds of Prey National Conservation Area (hereafter the NCA), in the Snake River Plain Ecoregion of southern Idaho. We expanded our inference by comparing our findings to similar data collected throughout seven major land resource areas (MLRAs) across the Great Basin (JFSP Project "Fire Rehabilitation Effectiveness: A Chronosequence Approach for the Great Basin" [09-S-02-1]).

We used a combination of field-sampling, experimental treatments, and remotely sensed data to address the following questions: (1) How do fuel loads change along gradients of succession and invasion in sagebrush ecological sites? (2) How do fuel reduction treatments influence fuels in invaded areas formerly dominated by sagebrush? (3) How do fuel loads vary across landscapes and which remote sensing techniques are effective for characterizing them?

For Question 1, we sampled 148 1-ha sites over three years (2012-2014) to quantify and characterize fuel loadings across a comprehensive invasion-successional gradient in the NCA. Fifty-seven of these sites were sampled annually for three years to capture inter-annual variability in plant cover and biomass. To capture invasion and successional gradients, we sampled stratified random locations within unburned, burned-treated, and burned-untreated areas. We found that, although fuel loads and cover types varied across the landscape, herbaceous fuel loads were substantially higher in sites dominated by invasive species than in late-successional sagebrush stands. Moreover, the greatest variability in fine fuel loadings among sample years was found within highly invaded stands, highlighting both the interannual variability in fuel loadings, and the need to track fuel conditions in more degraded landscapes. These findings were consistent with findings from a project examining the effects of seeding treatments on plant cover, composition, and fuel structure across the Great Basin (JFSP Project 09-S-02-1), suggesting broad applicability to sagebrush-steppe ecological sites.

For Question 2, we treated 48 experimental plots in nonnative plant-dominated communities located within three large replicate blocks with a full-factorial, completely randomized combination of the following management practices: mowing, mowing + herbicide, herbicide application, control (no treatment). Half of all plots were seeded with native species. We also out-planted live big sagebrush seedlings in some of the plots the following growing season. We found little or no difference in fuel loadings among treatment types, suggesting that treatment effects on fuels either disappeared within the first year, or were overshadowed by effects of inter-annual variability in precipitation. Seeding treatments did not result in detectable establishment for any species, while out-planted sagebrush seedlings survived for a limited duration during the growing season, likely due to drought conditions. Survival probabilities for sagebrush seedlings did increase with mowing, except when followed by seeding, probably because the soil disturbance from the minimum-till drill led to less bare ground cover (and hence, more competition with ruderal plants). Treatments had no significant effects on soil C decomposition or N mineralization rates. Thus, changes in soil nutrients were unlikely to explain observed treatment effects, or the lack thereof.

For Question 3, we coupled our non-experimental field sites with terrestrial laser scanning, (TLS) sampling, airborne lidar imagery, and multispectral satellite imagery. These data were analyzed to determine which technologies were most effective for capturing key fuel-related vegetation characteristics, and to derive biomass estimates for different plant communities at various spatial scales and resolutions. We found that TLS, airborne lidar, and satellite-based imagery each have unique contributions for characterizing fuel-related vegetation characteristics across the landscape. Lidar (both TLS and airborne) can provide spatially explicit baseline data on the terrain surface and vegetation structure, including shrub biomass and cover. TLS also proved successful at capturing the structural characteristics of low-lying vegetation over plot-sized (1-ha) areas. While less precise than lidar, Landsat 8 satellite imagery was found to accurately map shrub biomass across the NCA. Herbaceous cover and biomass were challenging to map accurately with either satellite or airborne lidar imagery, but we did find that Landsat 8 was more accurate, less costly, and more repeatable than current airborne lidar technology. Fine-scale quantification of herbaceous cover and biomass were best mapped with TLS.

The results of all three of our investigations may be applicable to a variety of sagebrush-steppe conditions, ranging from late-successional sagebrush stands to degraded, annual grass-dominated communities that are increasingly characteristic of much of the Snake River Plain and Great Basin. We provide detailed datasets, analyses, results and interpretations to the public and our agency partners in several publications, database tools, and remotely sensed data products (see Deliverables Crosswalk Table).

Background and Purpose

Variability in plant community dynamics ultimately determines vegetation mosaics, stand structures, productivity, and species composition (Turner et al. 2004). Successional trajectories and plant growth are influenced by a number of factors including land use, fire, nonnative species, edaphic (soil) conditions, and climatic variability. Interactions among these factors can lead to alternative successional pathways and can push systems beyond ecological thresholds from which they may not recover without intensive human intervention (Westoby et al. 1989). Dynamic vegetation traits in turn dictate fuel types, fuel loadings, and fuel continuity across landscapes (Debano et al. 1998). Fuel and fire models can be used to predict fire hazard, fire behavior, and fire effects across landscapes. However, it is difficult to derive accurate predictions if fuel mosaics are either temporally dynamic, poorly measured, or both. A key to understanding and managing fire in large landscapes is to develop adequate models of successional change and plant productivity that are coupled to spatially-explicit, quantitative measures of fuels.

The invasive plant-fire regime in Great Basin sagebrush ecosystems perpetuates and expands the dominance of annual grasses and creates relatively continuous fine fuels that increase rates of fire ignition and facilitate fire spread (Brooks et al. 2004). The result is ongoing vegetation change that creates spatially and temporally (e.g., interannual) dynamic fuel conditions and can lead to more frequent fire and greater area burned over time (Brooks et al. 2015). Despite federal mandates to restore degraded rangelands (Healthy Lands Initiative 2007) and reduce fire risk on public lands (National Fire Plan 2001; Federal Land Assistance, Management, and Enhancement Act of 2009; Secretarial Order 3336 of 2015), there is often little information on how restoration treatments in sagebrush actually influence fuel loads. Various methods have been applied, such as mowing or burning for biomass removal, herbicide application, grazing management, and seeding with native and nonnative species that can compete with nonnative annuals and provide less flammable fuel loads. Despite mixed success in restoring native communities and reducing fire risk (Beyers 2004, Davies et al. 2009, Munson et al. 2014), land management agencies are increasingly engaged in spending substantial amounts of money to apply these techniques via large-landscape restoration projects (e.g., Perryman et al. 2003).

Land managers can use estimates of fuel loadings to predict fire behavior, to restore natural communities, and to reduce fuel loads to levels that support natural fire regimes. Guides for quantifying fuel loads in relatively intact sagebrush community types have recently been developed, but such guides are scarce for nonnative successional communities and for areas manipulated for fire suppression or restoration purposes (e.g., post-fire emergency stabilization and burned area rehabilitation, green-stripping) (but see Bourne and Bunting 2011). Moreover, guides for characterizing and quantifying fuel loads (e.g. Scott and Burgan 2005, Sikkink et al.

2009) that are compatible with fire behavior models, such as FARSITE (Finney 2004), typically require substantial on-the-ground surveys that may become outdated as fuel loadings change (inter-annually, and sometimes intra-annually) across landscapes (Varga and Asner 2008). For instance, cheatgrass dominance often varies depending on climatic conditions during the year of fire and temporal patterns in moisture availability after fire (Shinneman and Baker 2009). Thus, to effectively track highly variable fuel conditions, land management agencies and fuels experts would greatly benefit from the ability to rapidly assess fuels and derive spatially-explicit estimates of fuel loads. Recent developments in remote sensing technology, including lidar and multispectral imagery, may be particularly effective and lead to more precise and finer scale maps of fuels via measurements of shrub height and crown area, bulk density (biomass), fuel loadings, and stand density (Streutker and Glenn 2006). Such efforts may also ultimately better capture spatial variability in fuel structure (herbaceous vs. shrub fuel loads) at fine spatial scales, which could help improve the accuracy of inputs and outputs for fire behavior models.

The overarching goal of the proposed study was to explore and develop different approaches to better quantify and predict fuel loadings and the effects of fuels manipulations in sagebrush habitats. To accomplish this goal we addressed three primary research questions:

- **Question 1:** How do fuel loads change along gradients of succession and invasion in sagebrush ecological sites?
- **Question 2:** How do fuel reduction treatments influence fuels in invaded areas formerly dominated by sagebrush?
- **Question 3:** How do fuel loads vary across large landscapes, and which remote sensing techniques are effective for characterizing them?

Below are the key hypotheses we developed to address these questions (hypothesis numbers correspond to research objectives). The null hypothesis (**H_0**) for each is that there will be no differences in the response variables among treatments, along gradients of succession and invasion, or among areas with different past management and disturbance histories.

- **H_1**: Fine fuel loadings will be higher in early-successional/invasive grass-dominated communities than in late successional communities dominated by native species.
- **H_2**: Fine fuel loadings will be lower and native species percent cover will be higher in mowed, herbicide sprayed, and seeded plots than in plots with fewer treatments.
- **H_3**: When environmental settings are equal among sites, higher fine fuel loads will be spatially and positively correlated with greater intensities of past management and disturbance.

Study Description and Location

Study area

Our research was conducted on the Morley Nelson Snake River Birds of Prey National Conservation Area (hereafter the "NCA"), located in the Snake River Plain Ecoregion of Idaho (Fig. 1). The NCA covers 242,773 ha and supports one of the highest densities and diversities of raptor species in the world (Olendorff and Kochert 1977). Contained within the NCA is a 7,994 ha area used by the Idaho Army National Guard as the Orchard Combat and Training Center (OCTC). The Snake River Plain is among the most highly disturbed areas of the Great Basin in terms of altered fire regimes, invasive plant species, and grazing impacts (Leu et al. 2008, Brooks et al. 2015). The NCA provides a relatively large expanse of sagebrush (or potential sagebrush) habitat relative to other areas of the Snake River Plain, but in the last 30 years the NCA has experienced considerable conversion and fragmentation of shrublands due to invasive species and fire. The cumulative result of these disturbances is dynamic plant communities and fuel loadings across the landscape. Fire risk is a major concern for land managers because of large urban areas nearby, endangered plant species endemic to southern Idaho (e.g., *Lepidium papilliferum*), and the importance of the area to raptor species. For instance, in the NCA, where fire was historically rare, more than 50% of the land area has burned between 1980-2003, and roughly one-third has burned two or more times during that period (USDI Bureau of Land Management 2008). Roughly 20% of the NCA has been affected by post-fire treatments (e.g., post-fire drill-seeding of native and nonnative grasses). Only about one-third of the NCA is still occupied by native shrublands, leading to a loss of habitat for imperiled species, reduced livestock forage, escalating fire suppression costs, and risk of fire spread onto adjacent lands.

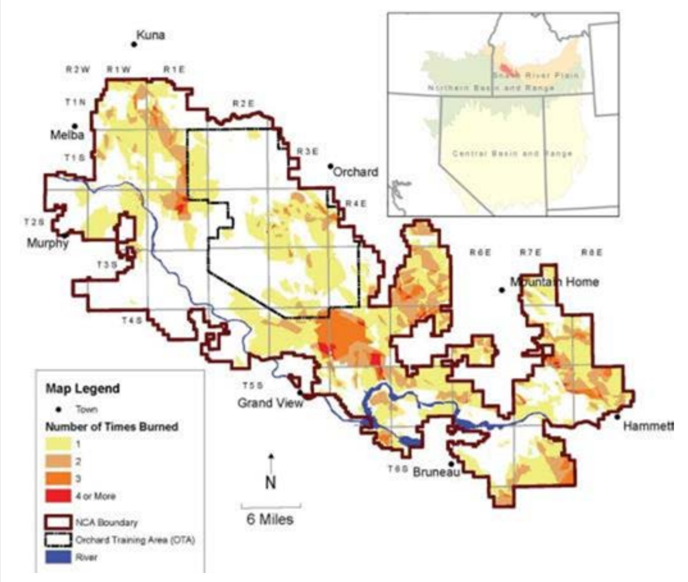

Fig. 1. Number of times burned in the Snake River Birds of Prey National Conservation Area, 1980-2003.

Study design and sampling methods

To address Question 1, we sampled fuel loadings, plant composition, and plant structure at 1,332 points (subplots) located within 148 1-ha plots distributed across the NCA, which included some lands previously treated by land managers. To capture gradients of succession and invasion caused by past wildfire and land use, the 148 1-ha plots were randomly stratified among burned and treated, burned and untreated, and unburned portions of the NCA. Plots were sampled from May through August in 2012-2014. Fifty-seven plots were sampled all three years to better understand the inter-annual variability of vegetation conditions and associated fuels. Within each 1-ha plot, nine subplots were placed on a 3 x 3 grid of evenly distributed points (each point 25 m apart; Fig. 2). At each point, we recorded basic environmental information, used the point-quarter method to sample density and cover of all shrub and bunchgrass species (Pilliod and Arkle 2013), and established a 1 x 1 m quadrat to determine plant species composition, measure plant height by functional group, and obtain plant biomass for fuel-loading estimates. Plant species were identified in the field, while percent cover of each species, as well as litter, bare soil, and rock, was estimated in the lab using SamplePoint software (Booth et al. 2006) and a nadir photo taken from 2-m above each quadrat (Pilliod and Arkle 2013). Within each quadrat, six fuel types were collected: 10-hr down woody debris (DWD), 100-hr DWD, 1000-hr DWD, live shrub, dead shrub, and herbaceous/litter (all live, dead standing, or litter herbaceous material,

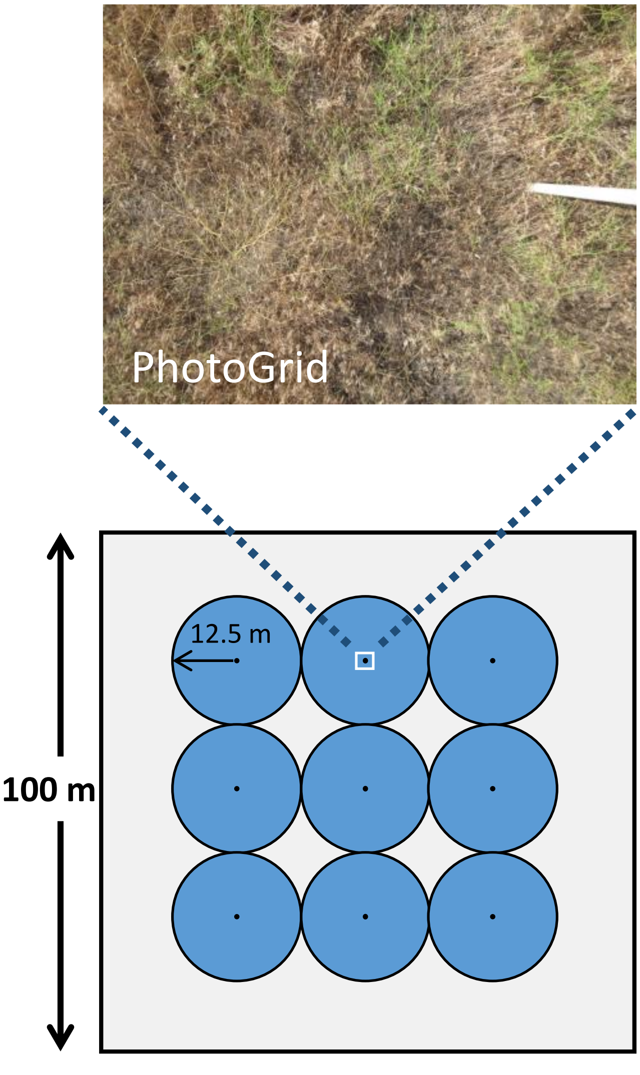

Fig. 2. Sample point distribution within each 1-ha plot. Fuels and species composition were sampled within nine 1 x 1 m quadrats at each point, using field measurements and a photo-grid technique, while the point-quarter method (12.5 m from point center) was used for shrub and bunchgrass cover and density.

including 1-hr DWD). Collected fuels were separated by class into different bags in the field and oven-dried and weighed in the laboratory.

To address Question 2, we experimentally treated 48 1-ha plots in three large replicate blocks using a combination of fuel reduction and restoration treatments. The historical plant community in the selected area was dominated by *A. tridentata* subsp. *wyomingensis*, but multiple fires and past land use resulted in a plant community dominated by cheatgrass, a nonnative tumble-mustard (*Sisymbrium altissimum* L), and Sandberg's bluegrass (*Poa secunda*). We collaborated with land managers to design treatments that reflected typical management actions for fuel reduction objectives. We randomly placed three experimental blocks in this area and sampled them for vegetation characteristics in 2011. After this pre-treatment sampling, the 2011 Bigfoot Fire burned one of the blocks, necessitating selection of an additional location for our third block replicate. This resulted in three experimental blocks and one burned block, all of which were 49 ha in size, with 16 1-ha treatment plots each, and 100 m buffers between plots (Fig. 3). In this report, we only present findings for the three primary experimental blocks (48 1-ha plots) and mention the burned block in "Future Work Needs" (below). The three replicate

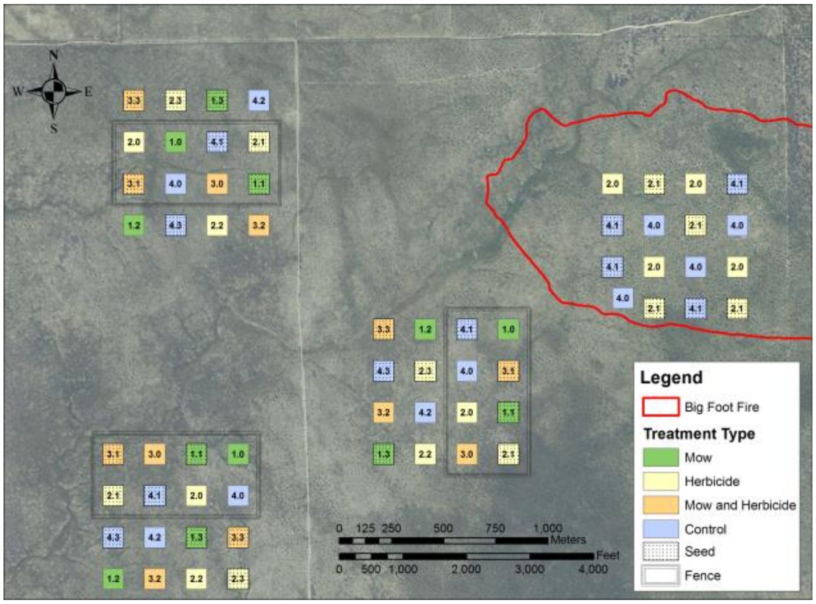

Fig. 3. Layout and design of the experimental study (replicated in three large blocks, and a fourth block that was burned in 2011).

blocks each had 16 treatment combinations applied via a full-factorial, randomized, split-plot block design. The fully crossed treatments included control, mowing, mowing + herbicide, and herbicide application, with native species seeding occurring in half of each treatment. To test the effects of grazing on fuel loadings, half of the blocks were also fenced. However, there was no measurable effect of grazing on herbaceous biomass, so we considered plots both inside and outside fences as replicates and did not include grazing in our analyses.

Vegetation conditions and treatments occurred on the plots in the following sequence. The winter of 2011-12 was wetter than average resulting in tall (~0.5 m), dense standing litter of cheatgrass and exotic forbs by spring 2012. Herbicide plots were prep-mowed in April 2012 (this practice is customarily used to reduce interception of herbicide by standing and senesced vegetation). Mow-only and mow + herbicide plots were mowed in May 2012, after appreciable grass growth. Mowing was to ~10 cm stubble height using a tractor-pulled rotomower. Herbicide plots received 280 g · ha–1 of glyphosate with a boomless sprayer without surfactant in April 2012 following mowing and then 280 g · ha–1 of imazapic with Hasten surfactant via a calibrated boom sprayer in October 2012. Native seeding occurred in November 2012 using a minimum-till drill that simultaneously drilled certain seeds (e.g., grasses and forbs) and imprinted others (i.e., sagebrush and other shrub seeds were lightly pushed into the soil). In addition, seedlings from multiple sagebrush populations were out-planted into each of the 24 1-ha plots within the grazing exclosures. We sampled species composition in all plots in July-August 2011 (prior to treatments), and we sampled composition and fuel loadings on half of the plots in 2012 (due to treatment timing restrictions), and all plots during peak growing season in 2013 and 2014. Sampling within each 1-ha treatment plot used the same sample-point configuration and data collection methods as described for Objective 1 (Fig. 2), except that the point quarter method was not used due to the lack of shrub cover. In addition, we worked with Dr. Marie Anne de Graaff (Boise State University) to explore the impact of fuels treatments on belowground resources (soil carbon and organic matter), by collecting and analyzing soil samples from the experimental plots, and through a controlled laboratory experiment to evaluate soil C decomposition and N mineralization.

For Question 3, we used a combination of terrestrial laser scanning (TLS), airborne lidar (95 km^2 acquired), and multispectral satellite imagery (for the entire NCA) to classify vegetation types and predict biomass of shrubs and other fuel components at various spatial scales and resolutions. These data were trained and validated against our field measurements. We scanned 25, 27, and 10 of our 1-ha (non-experimental) field plots in 2012, 2013, and 2014, respectively, with TLS. Of this dataset 10 of the plots were scanned each year. We then used field data to develop and validate our TLS methodologies. For the airborne lidar classifications and accuracy assessment, we used 46 field plots sampled in 2012 and 2013. For the Landsat 8 classifications and accuracy assessment, we used 141 of the field plots sampled in 2012 and 2013. The random forest (RF) machine learning technique was used for all of these analyses (Breiman 2001).

In all cases when addressing Questions 1 through 3, the potential influences of successional and invasion gradients on community characteristics (e.g., herbaceous biomass) were analyzed by using continuous variables that represented the percent cover of native shrub and nonnative herbaceous species. However, some results presented used convenient breakpoints in these gradients to better illustrate key findings. When appropriate, we also expanded our inference by comparing our findings to similar data collected throughout seven major land resource areas (MLRAs) across the Great Basin (JFSP Project “Fire Rehabilitation Effectiveness: A Chronosequence Approach for the Great Basin” [09-S-02-1]). MLRAs represent geographically based resource units, defined by patterns of physiography, geology, climate, soil, water, and biological characteristics, as well as land use (USDA Natural Resource Conservation Service 2006).

Key Findings

Question 1: How do fuel loads change along successional and invasion gradients in sagebrush ecological sites?

a) Successional stage (based on prevalence of shrub cover) had a large effect on herbaceous biomass in the NCA and in seven MLRAs across the Great Basin. Herbaceous biomass was substantially lower in later successional plots (e.g., shrub canopy cover >10%). On average, areas with ≥10% shrub cover had 57% less herbaceous biomass (average = 85.3 g/m^2) than areas with <10% shrub cover (average = 148.9 g/m^2). This pattern of decreasing herbaceous biomass with increasing shrub cover was observed across the full range of shrub cover (0-54%) sampled. The effects of shrub cover on herbaceous biomass were most pronounced in the Central Nevada Basin and Range MLRA and weakest in the Fallon-Lovelock MLRA. When shrubs were absent from plots, increasing bunchgrass cover did not have a strong effect on herbaceous biomass, likely because nonnative annuals accounted for more biomass when bunchgrasses were sparse.

b) An invasion gradient (i.e., increasing prevalence of nonnative plants) had a stronger effect on herbaceous biomass than did successional stage. In some invasion-prone areas (e.g., Snake River Plain), cover of nonnative forbs (*S. altissimum, Salsola tragus*) contributed substantially more herbaceous biomass than did cheatgrass. However, the highest herbaceous biomass loads were in plots containing both cheatgrass and nonnative forbs.

c) Shrub biomass, not surprisingly, was greatest in plots with high shrub cover and tall shrubs. However, even when nonnative plants were present, they had no detectable effect on shrub biomass.

d) Across all MLRAs, down woody debris (DWD; 10-hr, 100-hr, 1000-hr) was more abundant in late successional areas than in recently burned locations. Within unburned areas, 10-hr DWD was about 5 times more prevalent than 100-hr DWD and 1000-hr was rare. Overall, DWD of all size classes was infrequently encountered and did not contribute appreciably to fuel loads regardless of the successional or invasion stage of the area sampled.

e) Within the NCA (where plant cover and biomass were measured annually at the same locations), inter-annual variability in herbaceous biomass was substantial and correlated with precipitation amounts among years. For example, between 2012 and 2014, herbaceous biomass decreased by 45% (on average) as below average precipitation fell during 2013 and led to not only reductions in cover of annuals, but also reductions of perennial grass cover (e.g., *P. secunda*). However, herbaceous biomass did not vary much between wet and dry years in sites with relatively high shrub cover (>20%) compared to sites with little or no shrub cover (<5%). Changes in community composition were also evident over this time period, particularly in invaded areas, with decreased dominance of *B. tectorum*, *S. altissimum*, and *P. secunda* and increased cover of soil, litter, *S. tragus*, *Ceratocephala testiculata*, and *Descurainia sophia*.

Question 2: How do fuel reduction treatments influence fuels in invaded areas formerly dominated by sagebrush?

a) The effects of mowing, herbicide application, and mowing+herbicide on herbaceous biomass (and community composition) were minimal, especially when compared to changes through time observed at control plots. Across the experimental blocks, 10-hr fuels were infrequently present and highly variable, and there was no detectable effect of treatment on this fuel type. There were very few 100-hr and 1000-hr fuels in these plots.

b) There were differences in vegetation characteristics across all plots among years. Herbaceous biomass averaged 90.5 g/m^2 (+/- 6.7 g/m^2 SE) in 2013 and 61.5 g/m^2 (+/- 6.2 g/m^2 SE) in 2014 across experimental plots. Mean cover of nonnative annual grass decreased markedly across all plots from 27.7% (+/- 3.5% SE) in 2011 (prior to treatments) to 2.3 (+/- 0.6% SE) in 2014, likely due to below average precipitation in 2013. We measured a less dramatic change in native perennial grass, with mean cover across plots decreasing from 21.9% (+/- 2.4% SE) in 2011 to 14.0% (+/- 1.6% SE) in 2014.

c) Mowing prior to out-planting did result in greater initial big sagebrush seedling survival probabilities, likely related to changes in bare soil cover (Brabec et al. 2015). Local big sagebrush populations also had greater initial seedling survival than populations from more distant regions of the Great Basin (Brabec et al. 2015).

d) Experimental seeding of native grass, forb, and shrub species did not result in detectable seedling establishment for any seeded species. This was likely due to low precipitation during the winter and spring following seeding (Brabec et al. 2015). This underscores the difficulty associated with establishing plant species in degraded areas of the sagebrush steppe, where both inter-specific competition and annual variability in precipitation make germination and establishment unpredictable. Seeding, even with a low-till rangeland drill, decreased bare ground cover significantly across all treatment types, probably by causing an increase in nonnative annual species (Brabec et al. 2015).

e) Plots exposed to grazing during the study did not differ in herbaceous biomass or community composition from plots that were not grazed during the study. However, we consider these findings preliminary and inconclusive given several design issues (see interpretation) and the short duration of this study. Prior to the experiment, plots had similar grazing regimes.

f) Fuel reduction treatments had no significant direct impacts on soil microbial functioning as measured by microbial CO_2 respiration rates or nitrogen mineralization rates. Indirect effects, through impacts on plant community composition, are possible but not observed here.

Question 3: How do fuel loads vary across landscapes and which remote sensing techniques are effective for characterizing them?

a) Models using descriptors of vegetation heights from TLS were developed to predict the canopy cover fraction of shrubs (R2 = 0.72, RMSE = 7.3%), annual grasses (R2 = 0.61, RMSE = 23.7%), perennial grasses (R2 = 0.28, RMSE = 12.9%), forbs (R2 = 0.53, RMSE = 6.1%), bare earth or litter (R2 = 0.40, RMSE = 20.9%), and the biomass of shrubs (R2 = 0.64, RMSE = 191.7 g) and herbaceous vegetation (R2 = 0.55, RMSE = 106.3 g). Our models usually demonstrated good correlation between predictions and manual measurements (R2 > 0.5), but low predictive precision (RMSE ranging from 55% to 195% of average manual measurements; Anderson 2014; Anderson et al., in review).

b) TLS scanning of 1-ha plots provides a 3-dimensional map of plant cover, height, and spatial distribution, which can be used to predict fuels at points within the 1-ha area, fuels across the 1-ha area, and fire behavior based on a 3D, spatially-explicit fire behavior model for sagebrush and grassland sites (this is being pursued by our collaborators at the Missoula Fire Lab; Anderson 2014; Anderson et al., in review).

c) Airborne lidar data explained approximately 75% of the variance of field shrub biomass (R2=0.76) with a RMSE of ~150 g/m^2 (Dhakal in prep; Glenn et al, in review).

d) Vegetation metrics derived from Landsat 8 imagery explained approximately 60% and 50% of the variance of shrub and herbaceous biomass, respectively (R2 = 0.60, RMSE = 126 g/m^2 for shrub and R2 =0.50, RMSE = 0.65 g/m^2 for herbaceous). The vegetation metrics were able to explain 63% and 69% of the field shrub and herbaceous cover measurements with RMSE of 7 to 13% (Glenn et al, in review).

e) Multispectral imagery (Landsat 8) was overall better suited than lidar to model (estimate) vegetation cover across a large scale (e.g. the entire NCA). However, lidar estimated shrub cover and biomass better than Landsat 8 (Dhakal in prep; Glenn et al, in review).

f) The Landsat model calculated from imagery with multiple acquisition dates was more efficient in characterizing vegetation. The model was able to use phenological transitions of the vegetation to more accurately classify plant species.

g) Neither Landsat nor airborne lidar were satisfactorily efficient to model the herbaceous biomass on the NCA. The low stature of the herbaceous component may limit the application of these aerial and satellite-based technologies for fuel loading estimation.

h) Based on our imputed map (estimations based on the relationship we found between Landsat and field measurements), the NCA contains ~ 344,925,600 g of herbaceous biomass and ~ 313,420,200 g of shrub biomass. Similarly, more than 70% of the NCA has shrub biomass less than 100 g/m^2 and 50% with less than 100 g/m^2 of herb biomass. More than 68% of NCA has shrub cover of 10% or less.

Management Implications

Our work focused on developing a better understanding of dynamic fuel loadings across a range of invasion and successional conditions in sagebrush ecological sites, using a combination of field measurements, experimental manipulation, and remotely sensed data analysis. As a result, we developed new information and new tools to improve the accurate assessment of fuel-loadings across time and space, and provided a better understanding of the potential efficacy of fuel reduction and restoration efforts in already degraded sagebrush-steppe plant communities. Information such as this is critical for agencies involved in fire management and suppression to be able to understand, evaluate, and predict fuel conditions, fire risk, and fire behavior across the large landscapes they manage. Moreover, targeted fuel reduction is a high priority for U.S. Department of Interior land management agencies under Secretarial Order 3336, not only to reduce immediate fire risk, but also to increase ecological resistance and resilience and prevent future conversion to fire-prone grasslands.

Information derived from our field and remotely sensed data analyses allowed us to quantify fuel loadings across successional and invasion gradients. As expected, we were able to show that herbaceous (fine) fuel loadings were substantially higher in degraded or early-successional systems compared to late-successional sagebrush stands with greater native shrub cover. However, we also demonstrated how these fuel loadings and cover types can vary across the landscape and over time. For instance, we showed that the greatest variability in fine fuel loadings among sample years within our study landscape was within plots dominated by invasive annual species, rather than intact shrublands, highlighting the importance of tracking fuel conditions in degraded landscapes to better ascertain regional fire risk and fire-behavior potential.

Our work resulted in data and various tools to better track and estimate these fuel loadings. For example, the NCA fuels database (see Deliverables Crosswalk Table) we developed allows fuels experts to quickly obtain fuel and vegetation information under a variety of conditions, by querying based on species cover, plant height, and environmental variables (e.g., soil types, elevation, precipitation). Using this database, land managers can export fuels datasets for analysis (e.g. to summarize fuel conditions, or derive inputs for fire-behavior models), or print out fuel field guides for a variety of vegetation conditions, complete with photos and fuel loadings for each fuel class. In addition, site-specific fuel loading comparisons can be made among years with different precipitation amounts. Thus, the database permits both easy access to fuel information for field estimates and also summarizes fuel conditions across a range of potential conditions that are reflective of our large study area.

Our analysis of remotely sensed data provides potentially useful data and tools for fuel estimates. One such tool is TLS, an emerging ground-based technology with potential for quick and highly accurate field assessments of vegetation conditions. TLS has high potential for efficient repeat monitoring of fuels using ground-control procedures and, although this involves a large upfront investment cost, the longer-term costs of repeat monitoring are minimal. We determined that TLS may be used at a range of scales (1 m^2 to 100 m^2) to extend manual measurements of grassland and shrubland vegetation for quantifying fuel loads, with scale dependent upon the level of precision that is needed (e.g., for fuels data for fire-behavior modeling). The TLS methods we developed also showed that low-lying vegetation structural characteristics can be modeled without classifying and delineating individual plants.

The ability to quantify and track fuel loadings over large landscapes is also critical to land managers and fire management efforts. We explored the efficacy of different remote sensing technologies to achieve this objective. Our results demonstrate that using lidar, with at least 8 points per m^2, can provide spatially-explicit baseline data on the terrain surface and vegetation structure, including shrub biomass and cover. Although this technique has high precision, its utility is likely limited due to cost. In contrast, freely available Landsat 8 imagery may be more appropriate for mapping shrubs across large landscape such as the NCA, where precision may be traded for large-scale information. Although herbaceous cover is still challenging to map with Landsat, it is still more accurate than lidar because the height of the herbaceous cover is within the error of the lidar technology. The low cost and frequent acquisition interval of Landsat 8 data allows for intra-annual or annual vegetation/fuels mapping, which our work suggests may be needed to capture dynamic fuel loads in the Great Basin.

Reducing risk of undesirable fire through targeted fuel reduction, increasing native species diversity, and increasing ecological resistance and resilience are high priorities for the Bureau of Land Management and other land managers (Secretarial Order 3336, 2015). Although success of restoration treatments is often uncertain in invaded systems, restoring pre-invasion community structures should reduce fine fuel loads and fuel continuity. Studies have shown that a combination of mowing and herbicide may be effective at reducing cheatgrass (Davidson and Smith 2007; Morris et al. 2009), although effects on native forb species are less well known (e.g. Baker et al. 2009). Restoration actions to improve forage production, such as planting competitive nonnative forage grasses, are often successful; however, restoration actions to restore native species and communities in the face of ongoing threats such as invasive species and fire is more challenging and has been the focus of considerable research (Davies and Bates 2014; Knutson et al. 2014).

Our experimental blocks were located in a portion of the NCA landscape that had lost its native shrub cover, retained some of its native bunchgrass cover (*P. secunda*), and contained high cover of nonnative grasses and forbs. Our results largely showed that despite treatment, there was little or no effective difference among blocks in terms of fuel loadings. Although somewhat disappointing, this is a potentially important finding, because any initial differences in fuel loadings immediately after treatment had effectively disappeared within the first year. Although our treatment effects and resulting fuel loadings may have been influenced by drought conditions the year after seeding, water stress and climatic extremes may become more common in the Great Basin under climate change (Strzepek et al. 2010). Thus, these results are potentially relevant to help guide other restoration efforts in sites with a well-established, nonnative grass-forb component, which are becoming increasingly common across much of the Snake River Plain and northern Great Basin. Our findings further suggest that effectively decreasing fuel loadings will likely require repeated treatments over time.

Despite no detectable differences in fuel loadings, we were able to document other treatment outcomes that should be useful for land managers considering fuel reduction or native plant restoration treatments in degraded sagebrush. We were unable to successfully reintroduce native grasses, forbs, and sagebrush species, most likely due to severe growing season drought conditions that immediately followed fall seeding of the previous year, a pattern that has been observed elsewhere (Owen et al. 2011). However, we were able to document that probability of mortality in sagebrush seedlings decreased with mowing, but increased where (unsuccessful) native plant seeding followed mowing. In fact, native plant seeding led to a reduction in bare soil cover across all treatment types, possibly due to higher cover of cheatgrass, even with the use of minimum-till drill technology. Owen et al. (2011) also found that a one-time application of imazapic combined with seeding shrubs was only slightly effective in rehabilitating areas with high cheatgrass cover and, more importantly, the treatments also resulted in short-term impacts to non-target species. Finally, the treatments had no significant effects on C decomposition rates or N mineralization rates. This suggests that direct impacts of our treatments on soil microbial functioning are negligible and that treatment effects will likely be significant only indirectly through impact on plant communities. Again, these results may be relevant to help guide restoration for other highly invaded sites in similar environmental settings of the Snake River Plain and elsewhere in the Great Basin.

Relationship to Recent Studies

Question 1

Our findings are most relevant to the JFSP Project “Fire Rehabilitation Effectiveness: A Chronosequence Approach for the Great Basin” (09-S-02-1). This study evaluated whether fuel loads would differ in seeded compared with unseeded burned areas of the Great Basin. Similar to our major findings, they concluded that seeding recently burned areas had minimal effect on fuel load (biomass) within the first 13 years with the exception that drill seeding did significantly reduce 10-hour fuel biomass compared to burned unseeded areas (Pyke et al. 2013). More importantly, they found that precipitation had no interactive effect with seeding effects on fuel loads, which helps broaden the inference of our findings from southwestern Idaho. However, Pyke et al. (2013) did conclude that while herbaceous biomass in unburned and burned-seeded areas were statistically the same up to 1250 m, above that elevation herbaceous biomass in unburned areas declined more precipitously than in burned areas. Similarly, fuel continuity was also influenced by elevation such that perennial grass cover in burned and seeded areas increased with elevation (and precipitation) and seeding in burned areas led to similar annual interspace conditions as in unburned areas at the highest precipitation sites.

Question 2

In a recent study (JFSP 08-1-5-20) in south-central Washington, Davies et al. (2012) found that plant communities at the lowest elevations, which were comparable to our study system on the NCA, were particularly susceptible to conversion from sagebrush shrublands to grasslands dominated by weedy, early-successional species. They found that cheatgrass dominance was reduced by herbicide application (glyphosate, imazapic) relative to untreated areas and these treatments allowed resprouting species like *Phlox longifolia* and *Poa secunda* to increase as a result of competitive release from the loss of shrubs and reduction in cheatgrass (Davies et al. 2012). We did not have a similar release in native species, demonstrating the potential variability of ecosystem response to treatments within highly-invaded sagebrush communities.

Question 3

There have been several recent studies on quantifying biomass and cover in shrublands. One such study was located in the sagebrush-steppe (Mitchell et al. 2015). They found that a combination of hyperspectral (optical passive) and lidar data were beneficial in quantifying shrub cover with relationships between field and remote sensing data with r^2 = ~0.7 and RMSE < ~7%. These results are similar to our findings though we hypothesize that our relationships were slightly worse using the coarser-scale satellite imagery (Landsat 8). Zandler et al (2015) quantified shrub biomass in Tajikistan using satellite imagery from Landsat 8 and RapidEye. They report a high RMSE (992 kg/ha), yet were detecting dwarf shrubs similar in structure to low sagebrush (*Artemisia arbuscula*). Greaves et al. (2015) used TLS to quantify shrub biomass in the Arctic, resulting in strong relationships between harvested material and TLS-based volume estimates of biomass (explaining at least 90% of the variance with relatively low RMSEs). Their study was conducted at close range (~ 2 to 50 m ranges), indicating that our TLS-based estimates at the NCA may improve over shorter distances. Overall, our findings are quite similar to these recent studies. Together these studies demonstrate that as technology improves and we continue to develop techniques to analyze the data, we have capabilities through a combination of ground-based, airborne, and satellite platforms to monitor drylands for fuel characteristics and at a range of spatial scales.

Future Work Needs

As a result of this research we have several ongoing and future projects:

- Effects of greenstrips – We sampled vegetation and fuel conditions inside of and adjacent to greenstrips on the NCA. Expanding this dataset to include fuel moisture time-series data and data on greenstrips throughout the Great Basin could provide resource managers with information on the effects of greenstrips on vegetation, fuels, and fuel moisture across the region. Further, we have created a fairly comprehensive fire polygon GIS database. We plan to use these GIS data to examine how frequently, and in what locations, greenstrips have been effective at altering spread or behavior of actual wildfires.

- Fire frequency, recentness, and community composition – The NCA provides sagebrush ecological sites with some of the highest fire return intervals in the Great Basin. Some locations have up to eight recorded wildfire polygons. Across this gradient of fire frequency, some areas have burned only recently, whereas others first burned several decades ago. This provides an opportunity to test relationships between number of times burned, year of first fire, and time since last fire, on plant communities and fuel characteristics in this fire-prone landscape.
- Additional experimental treatments – The experimental design we implemented on treatment blocks will provide opportunities for future research on restoration effectiveness under differing treatment conditions. Work could include additional drill or aerial seedings, herbicide applications, mowing treatments, additional sagebrush, grass, or forb out-plantings, and tests of genetic source on survival or treatment effectiveness.
- Burned block – The experimental block that burned in the 2011 Bigfoot fire provided a unique opportunity for additional research. Sampling at the burned block has been the same as across the experimental blocks, including the collection of 2011 pre-treatment data. The treatments differ in that the entire block was fenced following the 2011 fire, and treatments only include herbicide (seeded and unseeded) and control (seeded and unseeded) plots. Preliminary results from this treatment block suggest that the wildfire, followed by two relatively dry years, resulted in fairly substantial (at least 20%) reductions in herbaceous biomass and a transition from non-native to native plant community composition, likely because of removal of non-native plants (and their seeds) combined with persistence of some native plants that were able to produce seed the

following year. Results from soil sampling conducted at the burned block showed no significant treatment effect on CO2 respiration rates or nitrogen mineralization.

- Insects – Funding provided by the Bureau of Land Management National Landscape Conservation System supported a study of insect community responses to herbicide applications on our experimental blocks, including the additional burned block. Samples collected the year of treatment 2012 and again in 2014 will provide additional information about short-term ecological effects of herbicide applications on insects, including herbivores, detritivores, predators, and pollinators.
- Fire behavior models – TLS scans provide 3-dimensional maps of shrubs, grasses, and forbs across 1-ha areas. Our collaborators at the USFS Missoula Fire Science Lab (Russ Parsons et al.) are using these data as inputs to 3-dimensional fire behavior models (developed for forest fire behavior) to generate for the first time, fine-scale, site-specific models of fire behavior in sagebrush and grassland habitats. Since we acquired TLS data across successional gradients and on the same plots in years with differing precipitation, we will be able to examine effects of factors such as post-wildfire seeding treatments and inter-annual variability in precipitation on modeled fire behavior. The USFS (Matt Reeves et al.) is also using our data to help develop and test the Rangeland Vegetation Simulator, a program that permits modeled simulations of rangeland management scenarios and their potential effects on vegetation succession, fuel-loadings, and fire potential over time.
- Additional remotely sensed data analysis – While this study allowed 3 field seasons to study changes across the landscape, the environmental conditions and especially the limited precipitation prevent significant change detection with remote sensing. Future

studies could compare fine-scale cover and biomass changes using TLS, and determine how the distribution of these changes affects fire-behavior models at the 1-ha plot level.

Literature Cited

Anderson, K. 2015. Vegetation measurements in sagebrush steppe using terrestrial laser scanning. M.S. Thesis. Idaho State University.

Anderson et al. (In review). Using terrestrial laser scanning and a machine learning algorithm to quantify vegetation biomass and cover in shrub- and grass-dominated drylands. Methods in Ecology and Evolution.

Baker, W.L., J. Garner, P. Lyon. 2009. Effect of Imazapic on cheatgrass and native plants in Wyoming big sagebrush restoration for Gunnison sage-grouse. Natural Areas Journal 29:204-209.

Beyers, J.L. 2004. Postfire seeding for erosion control: Effectiveness and impacts on native plant communities. Conservation Biology 18:947-956.

Bourne, A. and S. Bunting. 2011. Guide for Quantifying Post-treatment Fuels in the Sagebrush Steppe and Juniper Woodlands of the Great Basin. Technical Note 437. Bureau of Land Management, Denver, CO, BLM/ID/PT-11/003+2824. 115p

Brabec, M.M, M.J. Germino, D.J. Shinneman, D.S. Pilliod, S.K. McIlroy, R.S. Arkle. 2015. Challenges of establishing big sagebrush (*Artemisia tridentata*) in rangeland restoration: effects of herbicide, mowing, whole-community seeding, and sagebrush seed sources. Rangeland Ecology and Management 68:432-435.

Breiman, L. 2001. Random Forests. Machine Learning 45:5–32.

Brooks, M.L., C.M. D'Antonio, D.M. Richardson, J.B. Grace, J.E. Keeley, J.M. DiTomaso, R.J. Hobbs, M. Pellant, D. Pyke. 2004. Effects of invasive alien plants on fire regimes. BioScience 54:677-688.

Brooks, M. L., J. R. Matchett, D. J. Shinneman, P. S. Coates. 2015. Fire patterns in the range of greater sage-grouse, 1984-2013-Implications for conservation and management. Page 66. U.S. Geological Survey Open-File Report 2015-1167.

Davies, K.W., J.D. Bates, D.D. Johnson, A.M. Nafus. 2009. Influence of mowing *Artemisia tridentata* ssp. *wyomingensis* on winter habitat for wildlife. Environmental Management 44:84-92.

Davies, G.M., J.D. Bakker, E. Dettweiler-Robinson, P.W. Dunwiddie, S.A. Hall, J. Downs, J. Evans. 2012. Trajectories of change in sagebrush steppe vegetation communities in relation to multiple wildfires. Ecological Applications 22:1562-1577.

Davies, K.W., J.D. Bates. 2014. Attempting to restore herbaceous understories in Wyoming big sagebrush communities with mowing and seeding. Restoration Ecology 22:608-615.

Davison, J.C., E.G. Smith. 2007. Imazapic provides 2-year control of weedy annuals in a seeded Great Basin fuelbreak. Native Plants Journal 8:91-96.

Debano, L.F., D. Neary, P. Ffolliett. 1998. Fire's effects on ecosystems. John Wiley & Sons, New York.

Finney, M.A. 2004. FARSITE: Fire Area Simulator-model development and evaluation. Res. Pap. RMRS-RP-4, USDA Forest Service, Rocky Mountain Research Station, Ogden, UT.

Greaves, H.E., L.A. Vierling, J.U. Eitel, N.T. Boelman, T.S. Magney, C.M. Prager, K.L. Griffin. 2015. Estimating aboveground biomass and leaf area of low-stature Arctic shrubs with terrestrial LiDAR. Remote Sensing of Environment 164:26-35.

Glenn, N.F., A. Neuenschwander, L.A. Vierling, L.P. Spaete, A. Li, D.J. Shinneman, D.S. Pilliod, R.S. Arkle, and S.K. McIlroy (In review) Landsat 8 and ICESat-2: Synergies for vegetation dynamics in dryland ecosystems: Landsat 8 Special Issue in Remote Sensing of

Environment.

Knutson, K.C., D.A. Pyke, T.A. Wirth, R.S. Arkle, D.S. Pilliod, M.L. Brooks, J.C. Chambers, J.B. Grace. 2014. Long-term effects of seeding after wildfire on vegetation in Great Basin shrubland ecosystems. Journal of Applied Ecology 51:1414-1424.

Leu, M., S.E. Hanser, S.T. Knick. 2008. The human footprint in the West- A large-scale analysis of anthropogenic impacts. Ecological Applications 18:1119-1139.

Mitchell, J.J., R. Shrestha, L.P. Spaete, N.F. Glenn. 2015. Combining Airborne Hyperspectral and LiDAR Data across Local Sites for Upscaling Shrubland Structural Information: Lessons for HyspIRI. Remote Sensing of Environment. Accessed July 5. doi:10.1016/j.rse.2015.04.015.

Morris, C., T.A. Monaco, C.W. Rigby. 2009. Variable impacts of imazapic rate on downy brome (*Bromus tectorum*) and seeded species in two rangeland communities. Invasive Plant Science and Management 2:110-119.

Munson, S.M., A.L. Long, C. Decker, K.A. Johnson, K. Walsh, M.E. Miller. 2015.

Repeated landscape-scale treatments following fire suppress a non-native annual grass and promote recovery of native perennial vegetation. Biological Invasions 17:1915-1926.

Olendorff, R.R., M. Kochert. 1977. Land management for the conservation of birds of prey. Proceedings of the World Conference on Birds of Prey.

Owen, S.M., C.H. Sieg, C.A. Gehring. 2011. Rehabilitating downy brome (*Bromus tectorum*)-invaded shrublands using imazapic and seeding with native shrubs. Invasive Plant Science and Management 4:223-233.

Perryman, B.L., R.E. Wilson, W.I. Morrill. 2003. Viewpoint: Eastern Nevada landscape coalition position. Rangelands 25:30-34.

Pilliod, D.S., R.S. Arkle. 2013. Performance of quantitative vegetation sampling methods across gradients of cover in Great Basin plant communities. Rangeland Ecology and Management 66: 634-647.

Pyke, D.A., D.S. Pilliod, J.C. Chambers, M.L. Brooks, and J.B. Grace. 2013. Fire rehabilitation effectiveness: a chronosequence approach for the Great Basin. Joint Fire Science Report 09-S-02-1.

Scott, J. H., R.E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Shinneman, D.J., W.L. Baker. 2009. Environmental and climatic variables as potential drivers of post-fire cover of cheatgrass (*Bromus tectorum*) in seeded and unseeded semiarid ecosystems. International Journal of Wildland Fire 18:191-202.

Sikkink, P.G., D.C. Lutes, R.E. Keane. 2009. Field guide for identifying fuel loading models. RMRS-GTR-225. USDA Forest Service, Rocky Mountain Research Station. Fort Collins, CO.

Strzepek, K., G. Yohe, J. Neumann, B. Boehlert. 2010. Characterizing changes in drought risk for the United States from climate change. Environmental Research Letters 5:044012.

Streutker, D.R., N.F. Glenn. 2006. LiDAR measurement of sagebrush steppe vegetation heights. Remote Sensing of Environment 102:135–145.

Turner, M.G., D.B. Tinker, W.H. Romme, D.M. Kashian, M.L. Creighton. 2004. Landscape patterns of sapling density, leaf area, and aboveground net primary production in postfire lodgepole pine forests, Yellowstone National Park (USA). Ecosystems 7:751-775.

USDA Natural Resources Conservation Service. 2006. Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. U.S. Department of Agriculture Handbook 296.

USDI Bureau of Land Management. 2008. Snake River Birds of Prey National Conservation Area Proposed Resource Management Plan and Final Environmental Impact Statement, Boise, ID.

U.S. Department of the Interior, 2015a, Secretarial Order 3336—Rangeland Fire Prevention, Management, and Restoration, accessed September 2015, at http://www.fws.gov/greatersagegrouse/documents/Threats/20150106DOI-Fire-Order.pdf

Varga T, G. Asner. 2008. Hyperspectral and LiDAR remote sensing of fire fuels in Hawaii Volcanoes National Park. Ecological Applications 18:613–623.

Westoby, M., B. Walker, I. Noy-Mier. 1989. Opportunistic management for rangelands not at equilibrium. Journal of Range Management 42:266-274.

Zandler, H., A. Brenning, and C. Samimi. 2015. Quantifying Dwarf Shrub Biomass in an Arid Environment: Comparing Empirical Methods in a High Dimensional Setting. Remote Sensing of Environment 158 (March):140–55. doi:10.1016/j.rse.2014.11.007.

Samimi. 2015. Quantifying Dwarf Shrub Biomass in an Arid Environment: Comparing Empirical Methods in a High Dimensional Setting. Remote Sensing of Environment 158 (March): 140–55. doi:10.1016/j.rse.2014.11.007.

Deliverables Crosswalk Table

Proposed	**Delivered**	**Status**
Workshops, training sessions for fuels and fire modelers	Hudak and Glenn. May 2014. Lidar Data Processing for Fuel Applications. Association of Fire Ecology Meeting in Missoula, MT. Approximately 20 participants from university and governmental agencies were trained in processing lidar to generate topographic and vegetation metrics for fuel modeling.	Completed
	Glenn et al. May 2014. Point Cloud Processing – ALS, TLS, zCloud Tools. NSF Critical Zone Observatory Community lidar Workshop at Boulder, CO. Approximately 34 participants were given hands-on instruction on Lidar processing, including change detection.	Completed

	Glenn et al. May-June 2014. Developing vegetation metrics from lidar and spectral imagery. Approximately 20 participants (from the Czech Republic) trained in lidar data (airborne, terrestrial) processing, as well as spectral image processing for ecological applications.	Completed
	Glenn et al. March 2015. Developing terrain and vegetation products from lidar. 25 student participants trained in 2-day workshop located at UNAM, Mexico City, Mexico.	Completed
	Spaete et al. September 2015. Demonstration and hands-on workshop on using ground based lidar for developing vegetation and landscape metrics for characterizing sage grouse habitat. 20 participants of sage grouse workshop in Iceland.	Completed

	Project final workshop. November 9, 2015. Great Basin Fire Science Exchange Webinar.	Scheduled
Published fuels guide Datasets, models	Shinneman et al. (in prep). Fuels Guide and Database for Western Rangelands	Distributed for review in beta version to fuels experts at the BLM. Final version will be released as a U.S. Geological Survey data series after peer-review.
Information exchange meetings (with resource managers and fuels and fire modeling experts)	Mar 2015. Meeting with BLM fuels and fire managers to obtain additional input on fuels database and fuels guide.	Completed
	Feb 2015. Meeting with Dr. Russ Parsons, to discuss fire modeling applications of our fuels data	Completed
	Jun 2014. Meeting with BLM resource managers to discuss role of forage kochia as fire breaks and effects on fuel loadings	Completed

	Mar 2012. Meeting and information exchange with fire and fuel modeling experts at the U.S. Forest Service Fire Lab in Missoula, MT	Completed
	May 2012. Meeting and poster presentation of project to the BLM Executive Leadership Team Meeting	Completed
	Jan 2012. Meeting and presentation for the BLM and USDA ARS to discuss project objectives	Completed
	May 2011. Meeting with BLM and OTA staff to discuss plans and determine approaches to setting up treatment blocks and treatment techniques.	Completed
	2013-2015. Numerous updates and meetings with the Great Basin Research and Management Partnership Morley Nelson Birds of Prey	Completed

	National Conservation Area Science Working Group.	
Invited papers/presentations	*Presentations:* Shinneman, et al. Oct 2014. Assessing fuel loads across successional and invasion gradients in degraded sagebrush landscapes. Society for Ecological Restoration Regional Conference, Redmond, OR.	Completed
	Dhakal et al. Oct 2014. Using multispectral imagery, lidar and field measurements for aboveground biomass in the sagebrush-steppe, Morley Nelson Snake River Birds of Prey National Conservation Area. Society for Ecological Restoration Regional Conference, Redmond,	Completed

	OR. Awarded 2nd place student presentation award.	
	Shinneman, et al. Jul 2014. Wildfire patterns and interactions with vegetation within the range of the sage grouse. Sagebrush Restoration/Rehabilitation Science Coordination in the Great Basin, Washington, D.C.	Completed
	Shinneman, et al. May 2014. Assessing fuel loads across successional and invasion gradients in degraded sagebrush landscapes. Large Wildland Fires: Social, Political and Ecological Effects. Association of Fire Ecology Meeting, Missoula, Montana.	Completed
	Anderson, et al. May 2014. Using terrestrial laser scanning to model fuel characteristics in shrub-	Completed

	steppe. Large Wildland Fires: Social, Political and Ecological Effects. Association of Fire Ecology Meeting, Missoula, Montana.	
	Germino et al. Dec 2013. Post-fire sagebrush establishment across the landscape: experimental tests to inform restoration success. Great Basin Consortium Conference, Reno, NV.	Completed
	Shinneman et al. Mar 2012. Quantifying and predicting fuels and the effects of reduction treatments along successional and invasion gradients in sagebrush habitats. Presentation to the Missoula Fire Sciences Lab, Missoula MT.	Completed
	Dhakal et al. Feb 2015. Estimating Aboveground Biomass of Sagebrush Using Airborne Laser	Completed

	Scanning and Random Forest Regression Great Basin Consortium Conference, Boise, ID.	
	Dhakal et al. Dec 2015. Improved Radiometric Capabilities of Landsat 8, Coupled with lidarlidar, Estimate Semi-arid Rangeland Biomass and Cover. AGU Fall Meeting, San Francisco, CA	Abstract Submitted
Refereed publications	Brabec et al. Challenges of establishing big sagebrush (*Artemisia tridentata*) in rangeland restoration: effects of herbicide, mowing, whole-community seeding, and sagebrush seed sources. Rangeland Ecology & Management 68:432-435.	Completed
	Anderson, K. 2015. Vegetation measurements in sagebrush steppe using terrestrial laser scanning. M.S. Thesis. Idaho State University.	Completed

	Anderson et al. (In review). Using terrestrial laser scanning and a machine learning algorithm to quantify vegetation biomass and cover in shrub- and grass-dominated drylands Methods in Ecology and Evolution.	Completed (in review)
	Glenn et al. (In review) Landsat 8 and ICESat-2: Synergies for vegetation dynamics in dryland ecosystems: Landsat 8 Special Issue in Remote Sensing of Environment.	Completed (in review)
	Pilliod et al. (In prep.) Ecological responses to fuel reduction and native species restoration in degraded sagebrush steppe rangelands	Draft
	Shinneman et al. (In prep.) Predicting fuel loadings in degraded sagebrush landscapes along successional and invasion gradients	Draft

	Dhakal, S. (In prep). Assessing the Limitations and Capabilities of Lidar and Landsat to Estimate Aboveground Vegetation Biomass and Cover in a Rangeland Ecosystem using a Machine Learning Algorithm. M.S. Thesis. Boise State University.	Draft
	Dhakal, S. (In prep) Airborne lidar Based Estimation and Scaling of Semiarid Biomass Using Random Forest Variable Selection	Draft
	Dhakal, S. (In prep) Imputation of Vegetation Biomass and Cover for Large Scale Mapping in a Semi-arid Rangeland Using Airborne lidarlidar, Landsat 8 and Machine Learning Algorithm	Draft
Final Joint Fire Science Report		Completed