Fuel Response to Mechanical Mastication of Pinyon-Juniper Woodlands in Utah

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Abstract

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Pinyon-juniper woodland encroachment threatens ecosystem function and diversity on sagebrush steppe. Decreased fire frequency likely favors proliferation of pinyon-juniper woodlands and subsequent decline in desirable understory species. Increased tree cover produces hazardous canopy fuel loads that contribute to severe crown fires and threaten life and property at the wildland-urban-interface. Mechanical mastication converts large canopy fuels into small woody debris, altering wildfire dynamics from a potential crown fire to a more controllable surface fire. We measured fuel loading and cover on untreated, masticated, and masticated + burned treatments on 30-m transects within 30 X 33-m subplots, representing 45 different sites throughout Utah. All variables were analyzed using mixed-model analysis of covariance with untreated or pretreatment tree cover as the covariate. Shredding trees reduced large-diameter fuels to primarily 10-hour fuels (6.4-25.4 mm diameter). Reduced fuel sizes, fuel redistribution, and fuelbed compactness resulting from mastication treatments can aid wildfire suppression. Masticated + burned treatments effectively reduced woody surface fuel loading to that of pretreatment conditions. Prescribed burning could be used outside the growing season in cool-weather, high-moisture conditions to remove surface fuels, mitigating lethal soil heating and plant mortality. Shrub loading was not adversely affected by mastication treatments, but was significantly reduced with masticated + burned treatments. Masticated and masticated + burned treatments significantly increased herbaceous fuel loading. Treating at lower tree cover values reduced fuel buildup, and provided more opportunity for a positive herbaceous response. Fuel loading estimates measured in this study were provided to populate fire behavior models for mastication treatments on our study sites when such models become available.

Keywords: mechanical mastication, pinyon-juniper woodlands, fuel loading, fire, decomposition

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1. Introduction

Since European settlement of the western US, changes in fire regimes is thought to have allowed pinyon (*Pinus* L. spp.) and juniper (*Juniperus* L. spp.) woodlands to encroach on thousands of hectares of sagebrush (*Artemisia* L.) steppe (Miller and Wigand 1994). Pinyon-juniper woodland encroachment and infilling are causal factors in the decline of desirable understory species (Pierson et al. 2008; Ross et al. 2012). Loss of desirable understory species results in decreased site resistance to invasion by weeds and decreased site resilience after disturbance (Chambers et al. 2013). Essentially, woodland encroachment threatens the loss of diversity and function in sagebrush steppe ecosystems.

Commonly hypothesized causes of woodland expansion include: decreased fire frequency, overgrazing of rangelands, and climate change (Miller and Wigand 1994). Various pre-settlement conditions were conducive to abundant herbaceous fuels in sagebrush communities, favoring fire continuity, and limiting the distribution and development of woodlands (Gruell 1999; Miller and Tausch 2001). Beginning in the late 1800s, heavy livestock utilization in the western US decreased the abundance of fine herbaceous fuels. Reduction of fine fuels not only decreased fire frequency, but also stimulated greater sagebrush cover (Tausch and Hood 2007). Sagebrush stands created safe-sites for tree seedling establishment (Tausch and Hood 2007), while decreased fire frequency favored unimpeded tree-cover increase.

At present, pinyon and juniper woodlands occupy roughly 30 million hectares of land in the western United States (Miller and Tausch 2001). According to Miller and Tausch (2001), 33% of current pinyon-juniper woodlands are in closed canopy conditions, and such conditions will likely double in the next 40 to 50 years. Without active management, desirable sagebrush community components such as structural diversity, perennial herbaceous production, and wildlife habitat will likely continue to decline in the wake of woodland expansion and infilling (Miller et al. 2008). Tree mastication treatments may aid in reversing the impact of woodland encroachment on sagebrush steppe by maintaining or improving site resistance and resilience (Bybee 2013). Mastication improves site stability by increasing plant cover (Owen et al. 2009), herbaceous loading (Owen et al. 2009; Battagila 2010; Sharik et al. 2010), as well as species diversity (Owen et al. 2009). There is evidence, however, that mastication may increase invasive annual cover (Owen et al. 2009; Sharik et al. 2010). Mastication treatments significantly reduce the amount of bare soil (Battagila 2010), decrease runoff while increasing infiltration (Cline et al. 2010), increase soil moisture, and decrease soil temperature (Owen et al. 2009; Rhoades et al. 2012; Young et al. 2013; Roundy et al. 2014b).

Mastication also aids in the protection of life and property where residential areas border woodland-encroached rangelands. High tree cover produces hazardous canopy fuel loads that contribute to severe crown fires (Tausch 1999), which are difficult for firefighters to suppress due to their high intensity, large flame lengths, frequent spotting, and rapid rate of spread (Rothermel 1983; Scott and Reinhardt 2001). Mastication treatments are often effective means of protecting the wildland-urban-interface from catastrophic fire (Glitzenstein et al. 2006) as well as providing increased firefighter safety (Washa 2011). Mastication substantially reduces woodland density (Sharik et al. 2010) and converts canopy fuels into small surface fuels in order to reduce fire intensity and rate of spread (Bradley et al. 2006; Hood and Wu 2006; Young et al. 2014). Redistribution of vertical tree fuels also potentially reduces the probability of crown ignitions (Battaglia et al. 2010; Kreye et al. 2011).

Despite the apparent advantages to mechanical mastication treatments, effects on fire behavior are not fully understood (Glitzenstein et al. 2006; Battaglia et al. 2010; Kreye et al.

2011, 2012). In natural fuelbeds, fuel loadings by fuel size class (FSC; size classification of fuel based on the fuel diameter) are quantified and used in models to predict potential fire behavior. Finer fuels like 1-hr (0-6 mm diameter) and 10-hr (6-25 mm diameter) tend to dry sooner and burn more easily than coarser 100-hr (25-76 mm diameter) and 1,000-hr (>76 mm diameter) fuels. Regarding fire behavior, finer fuels may contribute more to rate of spread, while coarser fuels are more likely to contribute to burning duration, fire severity, and soil heating (Bradshaw et al. 1983; Pyne et al. 1996; Young et al. 2014).

Masticated fuelbeds differ greatly from natural fuelbeds in fuel shape, loading by FSC, and fuelbed compaction (Kane et al. 2009). Mastication changes natural fuel shape from near cylindrical to hemicylindrical or rectangular, increasing the surface area-to-volume (SA:Vol) ratio, potentially increasing the rate of particle desorption, and increasing the potential rate of combustion (Rothermel 1972, 1983; Kane et al. 2009). From a study involving pinyon-juniper woodlands in Colorado, Battaglia et al. (2010) found that mastication of pinyon-juniper woodlands generates surface fuel loading 3–4 times greater than that of natural fuelbeds, and 70% of masticated materials by mass were composed of 1-hr and 10-hr FSC; natural fuelbeds were composed of merely 30% 1-hr and 10-hr FSC by mass. Bradley et al. (2006) suggests that the short-term effects of increased surface fuel loading may contribute to increased fire severity and intensity potential, but the eventual decomposition and compaction of the fuelbed may decrease fire severity and intensity potential.

Masticated fuelbeds can have high bulk densities – means of 150 $kg \cdot m^{-3}$ reported by Battaglia et al. (2010), 226 $kg \cdot m^{-3}$ reported by Hood and Wu (2006), and 105 $kg \cdot m^{-3}$ reported by Young et al. (2014) – which are more characteristic of duff than of natural woody fuelbeds (Battaglia et al. 2010). The compact nature of masticated fuelbeds may dampen adverse fire behavior (Rothermel 1972; van Wagtendonk 1998; Knapp et al. 2011; Kreye et al. 2011), possibly counteracting any change in fire behavior resulting from alteration of fuel shape (Kane et al. 2009) by increasing fuel moisture at lower fuelbed depths (Kreye et al. 2011) and decreasing the amount of oxygen delivery (Scarff and Westoby 2006; Kane et al. 2009).

Currently, BehavePlus represents the standard approach for fire behavior prediction in natural fuelbed types (Glitzenstein et al. 2006). Approaches to modeling fire behavior on masticated treatments include selecting a surface fire behavior model or developing a custom model based on site fuelbed characteristics (Battaglia et al. 2010). Because masticated fuels form novel fuelbed characteristics, prior research comprised of field and lab-based burning experiments (Glitzenstein et al. 2006; Kobziar et al. 2009; Knapp et al. 2011; Kreye et al. 2011, 2012) suggests that existing models such as BehavePlus (Andrews 2007; Heinsch and Andrews 2010) did not accurately predict all fire behavior characteristics associated with masticated fuels, even when using custom models. Partial modeling accuracy was achieved only under a limited range of conditions (Glitzenstein et al. 2006; Kobziar et al. 2009; Knapp et al 2011), inadequate for general use. Battaglia et al. (2010) proposed several deficiencies in current models that are necessary for predicting fire behavior on mastication treatments. These deficient parameters include: fuel loading, fuelbed bulk density, SA:Vol ratios, and FSC distributions.

This study seeks to improve understanding of mastication as a fuel reduction treatment, and its effect on sagebrush steppe ecosystems. Additionally, our aim was to contribute to the development of fire behavior models for masticated fuels by providing data for several fuel parameters that we measured which could be used to populate models. Although we make broad inferences concerning potential fire behavior based on prior research, we did not conduct fire behavior experiments, nor did we attempt to model fire behavior. Our data represents a robust sample size of 587 subplots on 45 different sites throughout Utah, enabling us to make broad inferences as to mastication's effect on fuel loading in pinyon-juniper encroached rangelands. This study and that of Young et al. (2014) are among the few studies which have quantified fuel loading across a tree cover gradient, providing useful information for managers of pinyon-juniper encroached rangelands. Our objectives were to: 1) determine how pretreatment tree cover affects fuel loading; 2) compare fuel loads between treatments (i.e. masticated, masticated + burned, and control treatments); 3) determine the impact of mastication on fuel loads over time; 4) quantify the fuel load characteristics for our sites that can later be used in fire behavior models when such models become available.

2. Materials and Methods

2.1 Site Description

Our study sites are located throughout Utah (Fig. 1) in the semi-arid Great Basin and Colorado Plateau regions, and are situated between 1,637 and 2,512 m above sea level. Average annual temperature ranges from 4.5 to 11°C, while average annual precipitation ranges from 270 to 482 mm (PRISM Climate Group, 2013). Site soil textures range primarily from a gravelly or cobbly loam to sandy loam (NRCS Soil Survey Geographic Database, 2013). Vegetation composition varied by site with some sites exhibiting abundant perennial grasses, forbs, and shrubs with few trees, while other sites with higher tree cover had a comparatively small understory component (Bybee 2013). Trees found most abundantly on our sites included two-needle pinyon (*Pinus edulis*) and Utah juniper (*Juniperus osteosperma*), with a dominant understory component of mountain and Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *tridentata*, *vaseyana* [Rydb.] Beetle, and *wyomingensis* [Beetle and Young]), yellow rabbitbrush (*Chrysothamnus viscidiflorus* [Hook.] Nutt.), rubber rabbitbrush (*Ericameria nauseosa* [Pall. ex

Pursh] G.L. Nesom and Baird), antelope bitterbrush (*Purshia tridentata* [Pursh] DC.), black sagebrush (*Artemisia nova* A. Nelson), Sandberg bluegrass (*Poa secunda* J. Presl), Indian ricegrass (*Achnatherum hymenoides* [Roem. and Schult.] Barkworth), bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve), crested wheatgrass (*Agropyron cristatum* [L.] Gaertn.), needle and thread (*Hesperostipa comata* [Trin. and Rupr.] Barkworth), and cheatgrass (*Bromus tectorum* L.).

2.2 Treatment Implementation

A Bull Hog® attachment, consisting of a toothed, rotating drum mounted on a tractor masticated trees > 0.5-m tall. Treatments took place on land managed by both the Bureau of Land Management and the United States Forest Service. Sites were selected from mastication fuel control projects that were implemented between 2003 and 2010. Each of our treated sites had comparable untreated areas nearby on the same ecological site type, enabling us to compare treatment with an untreated reference. Masticated + burned sites were selected from five masticated sites that were subsequently burned by wildfires. Post-mastication wildfires occurred between 2003 and 2008 on our selected sites. Also included in our study were four masticated SageSTEP sites (McIver et al. 2010; Fig. 1) which were treated in 2006-2007, and were selected in the same manner as the other masticated sites.

2.3 Study Design

Our 45 sites were designed as blocks to avoid pseudoreplication of subplots (subsamples). Of 587 subplots, untreated control and masticated treatments were each measured on 277 subplots across 45 sites, while masticated and wildfire burned (masticated + burned) treatments were measured on 33 subplots across 5 sites. Subplots were chosen randomly from a pool of potential subplot locations where comparable pretreatment tree-cover values were represented for both untreated and treated areas. In order to analyze the effect of pretreatment tree cover on fuel loads, our subplots were selected across a gradient of pretreatment tree cover values (2 to 90%).

Pretreatment and untreated tree cover for each subplot was quantified using 1-m resolution National Agriculture Imagery Program (NAIP) imagery with object-based-image-analysis software (Feature Extraction ENVI 4.5®; Hulet et al. 2014). Tree cover for one site with no available pretreatment NAIP imagery was quantified by estimating canopy size of each tree in the subplot using the litter layer under the masticated materials as a reference. Sites were sampled once during spring/summer 2011 or 2012, except for our four SageSTEP sites which were part of a previous study (McIver et al. 2010). SageSTEP sites contained masticated-only (no masticated + burned) treatments and were sampled multiple years post-treatment in order to analyze the years-since-treatment (YST) effect.

2.4 Field Measurements

Fuel cover and loading were quantified on untreated, masticated, and masticated + burned treatments sampled on 30-m transects within 30 X 33 m subplots (Fig. 2). Cover was measured only for down and dead woody debris and masticated debris (woody debris). Fuel loading was measured for standing-trees, woody debris (wood on dead plants or on the soil surface) and foliar canopy debris, live shrubs, herbaceous vegetation, and tree litter and duff. Woody fuel loading excluding live shrubs was comprised of biomass values for 1-(≤ 6 mm diameter), 10-(6 - 25 mm diameter), 100-(26 – 76 mm diameter) and 1,000-hr (>76 mm diameter) FSC.

2.41 Woody debris cover

Woody debris cover values were derived from line-point intercept measurements for dead tree and dead shrub branches and twigs as well as masticated tree debris found on the soil surface. Line-point intercept cover data for each subplot was acquired by dropping a pin and recording the material hit every 0.5 m on transects 2, 7, 15, 23, and 28 (300 pin drops per subplot; Fig. 2). Cover values were compared across a tree cover gradient among treatments for 1-6 YST.

2.42 Woody debris loading

For untreated and treated areas, woody debris loading of 1-, 10-, and 100-hr fuels was quantified by collecting fuels within 25 X 25-cm quadrats to be oven-dried, separated by FSC, then weighed. Quadrats were placed each 3rd meter on transects 2, 7, 15, 23 and 28 (50 total quadrats) for subplots with tree cover <15%, and on transects 7, 15, and 23 (30 total quadrats) for subplots with >15% tree cover. We could not discriminate between pre- vs. post-treatment debris in sample collections. Woody debris for treated areas includes both pretreatment woody debris as well as shredded tree debris, notwithstanding there being a relatively insignificant amount of pretreatment woody debris. Loading values within quadrats were scaled up to subplot-wide values. We used a method of 1,000-hr fuel loading estimation involving volume measurements and density values found in the literature (Brown and See 1981; Harmon and Sexton 1996; Bate et al. 2004; Battaglia et al. 2010). Length and two end diameters were measured for each 1,000-hr fuel piece encountered in 2-m wide belt transects using transect locations 2, 7, 15, 23 and 28 for subplots with tree cover <15%, and on transects 7, 15, and 23 for subplots with >15% tree cover. The 1,000-hr fuels were recorded by species and were classified as being either sound or rotten. Biomass was calculated by taking the average of each 1,000-hr fuel end cross section areas, multiplied by the length of the fuel, yielding 1,000-hr fuel volume. Fuel volume was multiplied by the density of either sound or rotten wood (density values utilized by Bate et al. 2004 and Battaglia et al. 2010), yielding fuel biomass. Species-specific loading values were later combined for statistical analysis. The 1,000-hr fuels were sampled in this manner for both untreated and treated areas to limit the amount of biomass collected from the field and oven dried in the lab.

2.43 Standing-tree fuel loading

Standing-tree fuel loading was quantified by using tree measurements from untreated subplots, including tree height, canopy base height, widest canopy diameter, and canopy diameter perpendicular to the widest diameter. These dimensions were applied to species-specific regression equations developed by Tausch (2009), which yielded loading by species and by FSC for each tree. Subplot loading values were derived from the summation of individual tree biomass within each subplot. Species-specific biomass was combined for a total loading by FSC for each untreated subplot.

2.44 Standing and masticated tree biomass partitioning by fuel size class

We used a regression to quantify the relationship between pretreatment tree cover (derived from NAIP imagery) and standing-tree fuel loading in order to quantify standing-tree fuel loading in masticated areas before the areas were treated. Standing tree fuel loading values by FSC were compared with masticated tree debris loading by FSC in order to identify the changes in fuel size partitioning from a standing-tree state to a masticated debris state. Masticated tree debris represents only the debris additions to the pretreatment fuelbed as a result of mastication and does not include pretreatment debris. Because we measured masticated treatment woody debris (inclusion of pretreatment woody debris with masticated tree debris) after treatment and not exclusively masticated tree debris, we subtracted untreated woody debris loading values from the masticated treatment woody debris loading values, yielding the estimated loading by FSC for masticated tree debris. Untreated woody debris loading values and masticated treatment woody debris loading values were derived from the same pretreatment tree cover value for a true comparison.

2.45 Woody debris loading and years-since-treatment

Woody debris loading by FSC before and after treatment was compared across a tree cover gradient, and with the years-since-treatment (YST) effect (1 and 5 or 6 YST) in order to quantify changes in the surface fuel loading over time. YST for woody debris was measured on three SageSTEP sites, all of which were sampled 1 YST; Scipio and Greenville Bench were sampled 5 YST, and Onaqui was sampled 6 YST. We lumped 5 and 6 YST measurements, hereafter compared as 1 and 5 or 6 YST.

2.46 Live shrub loading

Live shrub fuel was sampled on 5 points along transect 15 within a nested circular frame (Bonham 1989; Stebleton and Bunting 2009). Dimensional data was gathered for shrubs >15 cm tall, including height, width at widest point, and the respective perpendicular width. We quantified shrub loading by using dimensional data from our allometric field measurements, allometric equations found in the literature (Wallace and Romney 1972; Green and Flinders 1980; Ross and Walstad 1986; McGinnis et al. 2010; Reiner et al. 2010), and SageSTEP-derived regressions. SageSTEP regressions were developed for common shrub species using allometric field measurements from SageSTEP sites within Utah (Stansbury, Onaqui, Scipio, and Greenville Bench), which measurements were gathered using a destructive sampling technique

(Stebleton and Bunting 2009; Table 1). SageSTEP-derived biomass and dimensional data consisted of a sample size between 15 and 56 individuals per species, similar to sample sizes for regressions found in the literature (Wallace and Romney 1972; Green and Flinders 1980; Ross and Walstad 1986; McGinnis et al. 2010; Reiner et al. 2010).

Allometric equations in the literature used in conjunction with shrub dimension measurements recorded in the field were used to estimate shrub biomass. Of the 40 different shrub species measured, 13 had species-specific equations available (Table 1). Shrubs lacking species-specific equations were assigned equations based on taxonomical relatedness or morphological similarities to a species for which we were able to find a species-specific allometric equation. Two uncommon shrub species which were not identified were assigned allometric equations based solely on morphological characteristics. The nested circular frame method delivered shrub biomass per unit area within frames. Subplot-wide loading estimations were attained by the summation of measured biomass in $kg \cdot ha^{-1}$ each individual shrub we measured. Shrub loading was compared across a tree cover gradient and between treatments.

We were unable to find allometric equations for cactus and yucca (*Yucca angustissima* Engelm. ex Trel.) species (6 total species) agreeable with our methods of measurement. These shrubs were uncommon, and distributed sparsely (≤1% cover) at <1% frequency in our subplots according to line-point cover data. Due to their scarcity, these shrub species were not considered a key fuel component and were excluded from the fuel analysis. Plains pricklypear (*Opuntia polyacantha* Haw.) and broom snakeweed (*Gutierrezia sarothrae* [Pursh] Britton & Rusby) however, were relatively abundant on our study sites. Without adequate dimensional measurements for biomass estimation, we compared plains prickly pear cover values across treatments. Dimensional measurements were not recorded for broom snakeweed in this study, therefore, we compared broom snakeweed cover values across treatments. Neither broom snakeweed nor plains pricklypear were expected to significantly contribute to fuel loading or influence fire behavior. Cover values for all species were derived from line-point-intercept measurements.

2.47 Herbaceous loading

Herbaceous fuel loading was measured by harvesting to 1 cm height in 50 X 50 cm quadrats placed every 2 m on transect 11 (Stebleton and Bunting 2009). Herbaceous fuels were later oven-dried (48 hours at 50 ºC) and then weighed. Herbaceous loading was quantified by the oven-dried weight, scaled-up to the subplot-wide values. Herbaceous loading was compared across a tree cover gradient, between treatments, and across 1-6 YST.

2.48 Tree litter and duff loading

Tree litter and duff samples were collected from under 6 trees >2 m crown diameter for both pinyon and juniper species (where present) within each subplot. Tree litter and duff was sampled with a 25 X 25 cm quadrat at the tree base, 1/3 the canopy radius from the base, and 2/3 the canopy radius from the base for trees with a crown diameter >4 m (Stebleton and Bunting 2009). Six litter and duff samples were weighed in the field for each subplot. We oven-dried and weighed one sample per tree species per subplot in order to obtain percent moisture, which was then used to infer dry biomass weights from sample wet weights of all samples taken in each respective subplot. Quadrat biomass values were multiplied by percent tree cover for subplot-wide tree litter and duff loading. Litter and duff loading was compared across a tree cover gradient and between treatments.

2.5 Data Analysis

Fuel load variables were analyzed using mixed-model analysis of covariance (Table 2) and Proc Glimmix (SAS v9.3, SAS Institute, Inc., Cary, NC). All response variables were square root transformed prior to analysis. Response variables included herbaceous loading, live shrub loading, tree litter and duff loading, woody cover, and biomass by FSC for standing-tree, masticated tree debris, and woody debris. Fixed effects included treatment type (i.e., untreated, masticated, and masticated + burned), FSC, and YST, with pretreatment tree cover as a covariate. Site was considered random. Analysis of covariance is well-suited to allow us to create simple regressions with subplot data to make broad inferences as to site and regional fuel loading responses. Subplots measured across main plot treatments to provide responses associated with a range of covariate values are appropriate data points for analysis of covariance (Littell et al. 2006; Roundy et al. 2014a). When covariate by fixed effects interactions were significant, fixed effects were compared at each 5% increment of tree cover using the Tukey test. We controlled for false positives by using a critical alpha level of 0.01.

Because 1,000-hr fuel measurements were often zero, they were combined with 100-hr fuel measurements to meet the normally distributed residual requirements for analysis. The YST effect was measured only for the masticated and untreated treatment types on three SageSTEP sites as these are the only sites that were sampled across multiple years. The YST effect was only measured for the woody debris cover, woody debris loading, and herbaceous loading response variables.

3. Results

3.1 Standing and Masticated Tree Biomass Partitioning By Fuel Size Class and Fuel Position

The effects of mastication on fuel size biomass partitioning are apparent. According to equations derived from Tausch (2009), standing-tree biomass by FSC on our study sites was partitioned as 35%, 13%, and 52% for 1-, 10-, and 100+1,000-hr fuels respectively. Mastication essentially converted large standing-tree fuels (100- and 1,000-hr) to 10-hr surface fuels. This is well-illustrated in figure 3 which compares biomass partitioning by FSC of standing trees and masticated tree debris (not including pretreatment woody debris). Mastication modified the FSC partitioning to 40%, 45%, and 15% for 1-, 10-, and 100+1,000-hr fuels respectively. Loading of standing-tree 1 and 100 + 1,000-hr fuels was greater than the size class equivalents for the masticated treatment across tree cover values of 5-80% and 0-80% respectively ($P < 0.01$). Standing-tree and masticated tree debris loading increased with tree cover for all FSC ($P < 0.01$). We did see a substantial decrease in masticated tree debris loading compared to standing-tree loading estimates.

3.2 Woody Debris Loading

Mastication of canopy fuels substantially increased woody debris loading. Mastication treatment woody debris loading was greater than untreated for 1-and 10-hr fuels across 0-90% tree cover, and for 100 + 1,000-hr fuels across 20-90% tree cover ($P < 0.01$). Loading by FSC estimates can be found in appendix A. Masticated woody debris loading increased with tree cover ($P < 0.01$; Fig. 4a). Loading of untreated woody debris did not vary among FSC ($P > 0.01$).There was a significant loss in woody debris loading between the 1st and 5th or 6th YST for masticated areas on three SageSTEP sites ($P < 0.05$) at greater than 30% pretreatment tree cover (Fig. 5).

Masticated + burned treatments effectively removed woody debris from our sites, yielding less woody debris loading than masticated treatments for 1-hr, 10-hr, and 100+1000-hr fuels across pretreatment tree covers of 0-60, 10-60, and 40-60% respectively ($P < 0.01$; Fig. 4b). Masticated + burned woody debris loading was not different than untreated areas for any FSC ($P > 0.01$), and yielded no difference in loading among FSC ($P > 0.01$). In masticated + burned treatments, 1-hr fuel loading increased with tree cover ($P < 0.01$) while 100+1,000-hr and 10-hr classes did not change with tree cover ($P > 0.01$). Total woody debris loading for untreated areas ranged from 1,209 to 3,092 $kg \cdot ha^{-1}$ for tree cover values 0 to 90% with a mean of 2,814 $kg \cdot ha^{-1}$, while masticated areas ranged from 3,608 to 36,780 $kg \cdot ha^{-1}$ for tree cover values 0 to 90% with a mean of 12,346 $kg \cdot ha^{-1}$. Masticated + burned loading ranged from 1,014 to 2,144 $kg \cdot ha^{-1}$ for tree cover values of 0 to 60% with a mean of 1,962 $kg \cdot ha^{-1}$.

3.3 Woody Debris Cover

Woody debris cover increased with tree cover on the masticated treatment ($P < 0.01$), while woody cover did not change with tree cover in untreated and masticated + burned treatments ($P > 0.01$). Masticated + burned treatments yielded less woody debris cover than masticated treatments at tree cover above 10% ($P < 0.01$), and masticated + burned woody debris cover was not different from untreated areas ($P > 0.01$). Woody debris cover did not vary among YST for masticated treatments or untreated areas ($P > 0.01$).

3.4 Live Shrub Loading

Mastication treatments did not adversely affect live shrub loading as shrub biomass on masticated areas did not differ from untreated areas ($P > 0.01$). Shrub loading decreased with increasing tree cover in untreated and masticated areas ($P < 0.001$). Untreated areas ranged from 4,675 to 9 $kg \cdot ha^{-1}$ for tree cover values of 0 to 80% with a mean of 2,313 $kg \cdot ha^{-1}$, while masticated areas ranged from 4,256 to 1 $kg \cdot ha^{-1}$ for tree cover values 0 to 80% with a mean of

2,028 kg · ha^{-1}. Shrub loading on mastication + burned treatments ranged from 584 to 38 kg · ha^{-1} for tree cover values of 0 to 70% with a mean of 351 kg · ha^{-1} and was not influenced by pretreatment tree cover ($P > 0.01$). Mastication + burned treatments reduced shrub loading across 0-35% tree cover compared with masticated or untreated areas ($P < 0.01$; Fig. 6). Regarding shrub species for which we were unable to attain loading estimates, mastication treatments did not adversely affect cover, while mastication + burned treatments substantially reduced cover. Where present, plains prickly pear had 0. 4, 0. 4, and 0% cover for untreated, masticated and masticated + burned treatments respectively. Where present, broom snakeweed had 1, 1.4, and 0.4% cover for untreated, masticated, and masticated + burned treatments respectively.

3.5 Herbaceous Loading

Herbaceous loading decreased with increasing tree cover in untreated areas, ranging from 210 to 5 kg · ha^{-1} for tree cover values from 0 to 90% with a mean of 137 kg · ha^{-1} ($P < 0.001$). Herbaceous loading increased with increasing tree cover in mastication treatments, ranging from 298 to 646 kg · ha^{-1} for tree cover values from 0 to 90% with a mean of 445 kg · ha^{-1} ($P < 0.001$). Herbaceous loading in masticated + burned treatments did not change in response to changes in pretreatment tree cover, ranging from 714 to 804 kg · ha^{-1} for tree cover values 0 to 80% with a mean of 794 kg · ha^{-1} ($P > 0.01$; Fig. 6; Appendix A). Untreated areas exhibited no difference in herbaceous loading across YST ($P < 0.001$). Herbaceous loading for masticated treatments was greater than on untreated areas the first YST across 20-30% pretreatment tree cover and for the second through sixth YST across 10-60% tree cover ($P < 0.001$; Fig. 7). Finally, the amount of pretreatment herbaceous loading positively influenced the amount of post-treatment loading ($P < 0.001$).

3.6 Tree Litter and Duff Mound Loading

Litter and duff mound loading increased with increasing tree cover, ranging from 2,400 to 62,000 kg · ha^{-1} for tree cover values 0 to 90%, with a mean of 17,200 kg · ha^{-1} ($P < 0.001$) on untreated areas. Litter and duff mound loading on masticated areas was less than on untreated areas across 15-90% tree cover ($P < 0.01$), ranging from 1,500 to 39,400 kg · ha^{-1} for tree cover values 0 to 90% with a mean of 11,200 kg · ha^{-1} (Fig. 6; Appendix A).

4. Discussion

4.1 Tree Cover Effect

This study illustrates that with increasing tree cover, tree fuel loading increases while shrub and herbaceous fuel loading decrease in untreated areas. Roundy et al. (2014a) advised that perennial herbaceous cover is critical to resisting weed dominance, maintaining high infiltration rates, and mitigating soil erosion. Woodland encroachment and infilling act as ecosystem stressors, which may reduce both resistance to invasive weeds and site resilience after fire (Brooks and Chambers 2011). Mastication increases herbaceous fuels, and thus may aid in avoiding biotic and abiotic thresholds by resisting weed dominance and erosion (Roundy et al. 2014a). We found that the amount of pretreatment herbaceous loading influenced the amount of post-treatment loading; therefore, masticating woodland-encroached rangelands prior to closed-canopy development would prompt a positive post-treatment perennial herbaceous response.

4.2 Responses to Alteration of Woody Debris Loading

One of the most apparent results of mechanical mastication is the conversion of large standing-tree fuels (100 and 1,000-hr) into primarily 10-hr surface fuels (Knapp et al. 2011; Fig. 3). This alteration of both fuel size and distribution has numerous ecological and management implications. The subsequent massive increase in fine woody surface fuels could reduce bare soil and runoff, and may increase infiltration rates (Cline et al. 2010; Pierson et al. 2013). Mastication treatments have also been shown to increase time of available soil moisture, and decrease soil temperature (Owen et al. 2009; Rhoades et al. 2012; Young et al. 2013; Roundy et al. 2014b). Mastication treatments may aid in suppressing or preventing severe crown fires that threaten life and property at the wildland-urban-interface (Glitzenstein et al. 2006) by reducing fire intensity and rate of spread (Bradley et al. 2006; Hood and Wu 2006; Young et al. 2014). Mastication interrupts contiguous canopy fuels which may increase firefighter safety (Washa 2011) and ease of fire suppression. Unfortunately, we lack complete understanding of fire characteristics associated with masticated fuels as current fire behavior modeling capabilities are limited (Glitzenstein et al. 2006; Kobziar et al. 2009; Knapp et al. 2011; Kreye et al. 2011, 2012) and fire behavior characteristics are highly variable with fluctuating environmental conditions (Rothermel 1972).

Fire in heavy fuel loads may imperil site stability due to lethal soil heating, and residual plant mortality, especially with masticated fuel depths of ≥7.5 cm (Busse et al. 2005). Conversely, increased soil moisture as a result of mastication could protect soil from excessive heating (Busse et al. 2005). Soil heating is highly dependent upon the masticated fuelbed depth and soil water content at the time of the fire (Busse et al. 2005, 2010). Busse et al. (2010) found that soil moisture has a strong influence on heat transfer, and volumetric soil moisture content ≥20% suppressed lethal soil heating (>60°C) in a variety of soil types below 2.5 cm depth, while drier soils exceeded 60°C at a depth of 10 cm. Our study found that masticated + burned treatments effectively returned woody surface fuels to pretreatment loading conditions. Interestingly, we observed that with the masticated + burned treatment, the 1-hr FSC loading increased with increasing pretreatment tree cover while larger fuel loading did not change with tree cover. As Bradley et al. (2006) suggested, perhaps the apparently low consumption of 1-hr fuels was actually much higher, and included larger fuels that were only partially consumed. Prescribed burning could be used outside of the growing season in cool-weather, high-soil moisture conditions to safely remove surface fuels, mitigating the potential for lethal soil heating and plant mortality (Bradley et al. 2006; Harrod et al. 2008; Bates and Svejcar 2009). Further, treating prior to closed-canopy development will mitigate heavy woody fuel loading.

We observed a significant YST by FSC interaction ($P < 0.05$) in loss of woody fuel biomass between the 1^{st} and the 5^{th} or 6^{th} YST. Loss of woody biomass increased much more over time for 1-hr, compared to larger FSC. Although we did not directly measure decomposition rates, there are several possible explanations for this rapid loss in woody loading over time. The analysis of standing-tree biomass coupled foliar biomass (scales and needles) with the woody 1-hr FSC. In dry coniferous systems, foliar litter decomposition rates generally increase in response to cutting trees (Bates et al. 2007). Decreasing competitors for water resources by killing trees increases soil water availability (Bates et al. 2000; Roundy et al. 2014b) and may also increase decomposition (De Santo et al. 1993). Bates et al. (2007) found that loss of litter biomass was 60% greater where trees were cut compared to untreated areas; They attributed this loss to increased decomposition associated with addition of canopy foliar litter to the fuelbed, decreasing the C:N ratio, and thereby favoring increased microbial activity. Conversely, Gallo et al. (2006) suggests that in arid systems, decomposition is not strongly correlated with the C:N ratio, but is a function of solar radiation and temperature. In the province of Chubut, Argentina, Austin and Vivianco (2006) found that litter biomass was reduced 40% during an 18 month period in full sun, and attenuation of solar radiation caused a 60 % reduction in litter decomposition. Further, several studies have found photodegradation to be very influential in organic matter decomposition in semi-arid and arid environments (Austin and Vivianco 2006; Gallo et al. 2006, 2009; Vanderbilt et al. 2008). Thus, decomposition of the litter portion of 1-hr fuels certainly contributed to the rapid loss in total loading.

We would expect highly lignified woody debris to decompose slower than foliar litter. Numerous decomposition studies have identified lignin concentration as a key predictor of decomposition rates (Murphey et al. 1998). Conversely, Schaefer et al. (1985) found no correlation between biomass loss and lignin concentration. In arid systems, Gallo et al. (2009) suggests that photoacceleration of decomposition depends primarily on exposed surface area-to-mass ratio of the litter rather than biochemical composition. Perhaps increased woody debris SA:Vol ratios via mastication treatments and subsequent exposure to greater solar radiation facilitated significant decomposition by photodegradation. Over time, we would expect that decomposition and compaction will reduce fuel loading and fuelbed fire intensity (Bradley et al. 2006).

4.3 Vegetation and Tree Litter and Duff Response to Treatment

Because sagebrush (*Artemisia* spp.) has great ecological significance for various wildlife species (Davies et al. 2011; Pyke 2011), it is important to note that mastication treatments did not adversely affect live shrub loading. Masticated + burned treatments significantly reduced shrub loading across 0-35% tree cover compared to untreated areas. Management goals could dictate the type of treatment necessary to enhance understory health. Mastication treatments could be used to maintain or increase shrub loading at sites with lower tree cover values, while high tree cover sites with very little shrub presence could be masticated and burned to remove woody surface fuels and increase site herbaceous loading.

Masticated and masticated + burned treatments greatly increased herbaceous loading compared to untreated areas. Figure 6 demonstrates the ability of herbaceous vegetation to monopolize resources made available by killing trees with the mastication treatment; this phenomenon is most pronounced at higher pretreatment tree cover values. Figure 6 also demonstrates that the loading of herbaceous fuels did not change in response to changes in pretreatment tree cover for the masticated + burned treatment. This pattern of loading is likely due to the burning of residual shrubs at lower tree cover values, making all resources available to herbaceous vegetation, regardless of pretreatment tree cover. Relative to mean loading values reported by Battaglia et al. (2010), our mean herbaceous loadings exhibited half the amount reported for untreated areas, and slightly greater than mean herbaceous loadings reported for masticated areas.

Masticating trees frees water and nutrient resources for first-colonizing vegetation. As earlier stated, perennial herbaceous cover is critical to resisting weed dominance, maintaining high infiltration rates, and mitigating soil erosion (Roundy et al. 2014a). If perennial herbaceous residuals are sufficiently abundant after treatment to monopolize freed resources, site degradation (e.g., exotic annual dominance, bare ground, decreased soil aggregation, and soil compaction or loss; Pellant et al. 2005) may be avoided. This study did not measure separate loading values for cheatgrass, and we are thereby unable to determine how cheatgrass loading may have contributed to our total loading estimates. However, a companion study (Bybee 2013) measured cheatgrass cover on our sites and concluded that cheatgrass cover increased with increasing pretreatment tree cover following mastication. Therefore, treating at lower tree cover values may reduce the likelihood of cheatgrass dominance and the crossing of ecological thresholds.

This study found that herbaceous loading for mastication treatments increased each successive YST at all tree cover values (Fig. 7). This increasing loading trend is most pronounced at higher tree cover values and illustrates that it can take years for vegetation to monopolize resources made available by killing trees. Litter and duff loading was similar to that reported by Battaglia et al. (2010) for untreated and similar to that reported by Battaglia et al. (2010) and Hood and Wu (2006) for masticated areas. The observed decrease in tree litter and duff mound loading with the masticated treatment is likely the result of photodegradation of litter materials due to increased exposure to solar radiation (Austin and Vivianco 2006; Gallo et al. 2006, 2009; Vanderbilt et al. 2008).

5. Conclusions and Management Implications

This study offers useful information for land managers regarding pinyon-juniper woodland ecosystem dynamics, as well as the fuel response resulting from two treatment options. As pinyon-juniper woodland encroachment threatens diversity and function in sagebrush steppe ecosystems, mastication treatments have proven to be an effective tool in restoring diversity and function. Masticated and masticated + burned treatments greatly increased herbaceous vegetation loading, while the masticated treatment did not adversely affect shrub loading on our study sites. Reduced woody fuel sizes and fuel redistribution resulting from mastication treatments can aid wildfire suppression by reducing fire intensity and rate of spread as well as by interrupting contiguous canopy fuels. Our findings support the conclusion that masticated fuels may present less fire risk over time by means of decomposition. Additionally, masticating woodland-encroached rangelands prior to closed-canopy development would reduce woody fuel buildup, and provide more opportunity for a positive herbaceous vegetation response. We found that masticated + burned treatments effectively removed woody fuels. Perhaps future research could help identify safe and effective methods of masticated fuel removal via prescribed burning. Other valuable future research should strive to gain a greater understanding of fire behavior in masticated treatments. This study provides fuel loading estimates for our sites in order to populate fire behavior models for mastication treatments when such models become available.

Literature Cited

Andrews, P. L. 2007. BehavePlus fire modeling system: past, present, and future. In: Proceedings of 7th Symposium on Fire and Forest Meteorological Society, 23-25 October, Bar Harbor, Maine, 13p.

Austin, A. T. and L. Vivanco. 2006. Plant litter decomposition in a semi-arid ecosystem controlled by photodegradation. Nature 442:555-558.

Bate, L. J., T. R. Torgersen, M. J. Wisdom, and E. O. Garton. 2004. Performance of sampling methods to estimate log characteristics for wildlife. Forest Ecology and Management 199:83-102.

Bates, J. D., R. F. Miller, and T. J. Svejcar. 2000. Understory dynamics in cut and uncut western juniper woodlands. Journal of Range Management 53:119-126.

Bates, J. D., T. S. Svejcar, and R. F. Miller. 2007. Litter decomposition in cut and uncut western juniper woodlands. Journal of Arid Environments 70:222-236.

Bates, J. D. and T. J. Svejcar. 2009. Herbaceous succession after burning of cut western juniper trees. Western North American Naturalist 69:9-25.

Battaglia, M. A., M. E. Rocca, C. C. Rhoades, and M. G. Ryan. 2010. Surface fuel loadings within mulching treatments in Colorado coniferous forests. Forest Ecology and Management 260:1557-1566.

Bonham, C. D. 1989. Measurement for Terrestrial Vegetation. New York, NY: John Wiley and Sons. Inc. 338p.

Bradley, T., J. Gibson, and W. Bunn. 2006. Fire severity and intensity during spring burning in natural and masticated mixed shrub woodlands. In: P. L. Andrews and B. W. Butler [eds.]. Fuels management—how to measure success: conference proceedings; 28-30 March 2006; Portland, OR, USA. Fort Collins, CO, USA: USDA Forest Service, RMRS-P-41. p. 333-340.

Bradshaw, L. S., J. E. Deeming, R. E. Burgan, and J. D. Cohen. 1983. The 1978 national fire-danger rating system: technical documentation. Ogden, UT, USA: USDA Forest Service, INT-GTR-169. 44p.

Brooks, M. L. and J. C. Chambers. 2011. Resistance to invasion and resilience to fire in desert shrublands of North America. Rangeland Ecology and Management 64:431-438.

Brown, J. K. and T. E. See. 1981. Downed dead woody fuel and biomass in the Northern Rocky Mountains. Intermountain Forest and Range Experiment Station, INT-GTR-117.

Busse, M. D., K. R. Hubbert, G. O. Fiddler, and C. J. Shestak. 2005. Lethal soil temperatures during burning of masticated forest residues. International Journal of Wildland Fire 14:267-276.

Busse, M. D., C. J. Shestak, K. R. Hubbert, and E. E. Knapp. 2010. Soil physical properties regulate lethal heating during burning of woody residues. Soil Science Society of America 74:947-955.

Bybee, J. 2013. Understory vegetation response to mechanical mastication of piñon and juniper woodlands. MS Thesis, Brigham Young University, Provo, Utah. 28 p.

Chambers, J. C., B. B. Bradley, C. D'Antonio, M. J. Germino, J. B. Grace, S. P. Hardegree, R. F. Miller, and D. A. Pyke. 2013. Resilience to disturbance and resistance to alien grass invasions in the cold desert of western North America. Ecosystems 17:360-375.

Cline, N. L., B. A. Roundy, F. B. Pierson, P. Kormos, and C. J. Williams. 2010. Hydrologic response to mechanical masticated in a juniper woodland. Rangeland Ecology and Management 63:467-466.

Davies, K. W., C. S. Boyd, J. L. Beck, J. D. Bates, T. J. Svejcar, and M. A. Gregg. 2011. Saving the sagebrush sea: an ecosystem conservation plan for big sagebrush plant communities. Biological Conservation 144:2573-2584.

De Santo, A. A., B. Berg, F. A. Rutigliano, A. Alfani, and A. Fioretto. 1993. Factors regulating early-stage decomposition of needle litters in five different coniferous forests. Soil Biology and Biochemistry 10:1423-1433.

Gallo, M. E., A. Porras-Alfaro, K. J. Odenbach, and R. L. Sinsabaugh. 2009. Photoacceleration of plant litter decomposition in an arid environment. Soil Biology and Biochemistry 41:1433-1441.

Gallo, M. E., R. L. Sinsabaugh and S. E. Cabaniss. 2006. The role of ultraviolet radiation in litter decomposition in arid ecosystems. Applied Soil Ecology 34:82-91.

Glitzenstein, J. S., D. R. Streng, G. L. Achtemeier, L. P. Naeher, and D. D. Wade. 2006. Fuels and fire behavior in chipped and unchipped plots: implication for land management near the wildland/urban interface. Forest Ecology and Management 236:18-29.

Green, J. S. and J. T. Flinders. 1980. Habitat and dietary relationships of the Pygmy Rabbit. Journal of Range Management 33:136-142.

Gruell, G. E. 1999. Historical and modern roles of fire in pinyon-juniper. Proceedings: ecology and management of pinyon-juniper communities within the interior West; 1997 September 15-18; Provo, UT. Proc. RMRS-P-9. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Harmon, M. E. and J. Sexton. 1996. Guidelines for measurement of woody detritus in forest ecosystems. US Long Term Ecological Research Network, Albuquerque, NM, 42p.

Harrod, R. J., D. W. Peterson, and R. D. Ottmar. 2008. Effects of mechanically generated slash particle size on prescribed fire behavior and subsequent vegetation effects. Final Report to the Joint Fire Science Program, Project Number 03-3-2-06.

Heinsch, F. A. and P. L. Andrews. 2010. BehavePlus fire modeling system, version 5.0: design and features. General Technical Report RMRS-GTR-249. Fort Collins, CO, USA: USDA Forest Service.

Hood, S. and R. Wu. 2006. Estimating fuelbed loadings in masticated areas. In: P. L. Andrews and B. W. Butler [eds.]. Fuels management—how to measure success: conference proceedings; 28-30 March 2006; Portland, OR, USA. Fort Collins, CO, USA: USDA Forest Service, RMRS-P-41. p. 333-340.

Hulet, A., B. Roundy, S. Petersen, R, Jensen, and S. Bunting. 2014. Cover estimations using object-based image analysis rule-sets developed across multiple scales in pinyon-juniper woodlands. Rangeland Ecology and Management –in press.

Kane, J. M., J. M. Varner, and E. E. Knapp. 2009. Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and south-western Oregon, USA. International Journal of Wildland Fire 18:686-697.

Knapp, E. E., J. M. Varner, M. D. Busse, C. N. Skinner and C. J. Shestak. 2011. Behaviour and effects of prescribed fire in masticated fuelbeds. International Journal of Wildland Fire 20:932-945.

Kobziar, L. N., J. R. McBride, and S. L. Stephens. 2009. The efficacy of fire and fuels reduction treatments in a Sierra Nevada pine plantation. International Journal of Wildland Fire 18:791-801.

Kreye J. K., J. M. Varner, and E. E. Knapp. 2011. Effects of particle fracturing and moisture content on fire behaviour in masticated fuelbeds burned in a laboratory. International Journal of Wildland Fire 20:308-317.

Kreye J. K., J. M. Varner, and E. E. Knapp. 2012. Moisture desorption in mechanically masticated fuels: effects of particle fracturing and fuelbed compaction. International Journal of Wildland Fire 21:894-904.

Littell, R. C., G. A. Milliken, W. W. Stroup, R. D. Wolfinger, and O. Scabenberger. 2006. SAS® for Mixed Models, Second Edition, Cary, NC:SAS Institute, Inc. 813p.

McGinnis, T. W., C. D. Shook, and J. E. Keeley. 2010. Estimating aboveground biomass for broadleaf woody plants and young conifers in Sierra Nevada, California, forests. Western Journal of Applied Forestry 25:203-209.

McIver, J. D., M. Brunson. S. C. Bunting, J. C. Chambers, N. Devoe, P. Doescher, J. Grace, D. Johnson, S. Knick, R. Miller, M. Pellant, F. Pierson, D. Pyke, K. Rollins, B. Roundy, E. Schupp, R.Tausch, and D. Tuner. 2010. The sagebrush steppe treatment evaluation project (SageSTEP): a test of state-and-transition theory. Fort Collins, CO, USA: US Department of Agriculture, Forest Service, RMRS-GTR-237. 16p.

Miller, R. F. and R. J. Tausch. 2001. The role of fire in pinyon and juniper woodlands: a descriptive analysis. In: K. E. Galley and T. P. Wilson [eds.]. Proceedings of the invasive species workshop: the role of fire in the control and spread of invasive species. Fire conference 2000. Tallahassee, FL, USA: Tall Timbers Research Station, Miscellaneous Publication 11. p. 15-30.

Miller, R. F., R. J. Tausch, E. D. McArthur, D. D. Johnson, and S. C. Sanderson. 2008. Age structure and expansion of piñon-juniper woodlands: a regional perspective in the Intermountain West. Res. Pap. RMRS-RP-69. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 15p.

Miller, R. F., T. J. Svejcar, and J. A. Rose. 2000. Impacts of western juniper on plant community composition and structure. Journal of Range Management 53:574-585.

Miller, R. F. and P. E. Wigand. 1994. Holocene changes in semiarid pinyon-juniper woodlands: responses to climate, fire, and human activities in the U.S. Great Basin. Bioscience 44:465-474.

Murphy, K., J. M. Klopatek, and C. C. Klopatek. 1998. Effects of litter quality and climate on litter decomposition along an elevation gradient in Northern Arizona. Ecological Applications 8:1061-1071.

NRCS Soil Survey Geographic Database, 2013. Natural Resource Conservation Service, http://www.nrcs.usda.gov, Retrieved 22 January, 2014.

Owen, S. M., C. H. Sieg, C. A. Gehring, M. A. Bowker. 2009. Above- and belowground responses to tree thinning depend on the treatment of tree debris. Forest Ecology and Management 259:71-80.

Pellant, M., P. Shaver, D. A. Pyke, and J. E. Herrick. 2005. Interpreting indicators of rangeland health. BLM Technical Reference 1734-6. United States Bureau of Land Management, Washington, D.C. 136p.

Pierson, F. B., P. R. Robichaud, C. A. Moffet, K. E. Spaeth, S. P. Hardegree, P. E. Clark, and C. J. Williams. 2008. Fire effects on rangeland hydrology and erosion in a steep sagebrush-dominated landscape. Hydrological Processes 22:2916-2929.

Pierson, F. B., C. J. Williams, S. P. Hardegree, P. E. Clark, P. R. Kormos, and O. Z. Al-Hamdan. 2013. Hydrologic and erosion responses of sagebrush steppe following juniper encroachment, wildfire, and tree cutting. Rangeland Ecology and Management 66:274-289.

Pierson, F. B., C. J. Williams, P. R. Kormos, S. P. Hardegree, P. E. Clark, and B. M. Rau. 2010. Hydrologic vulnerability of sagebrush steppe following pinyon and juniper encroachment. Rangeland Ecology and Management 63:614-629.

PRISM Climate Group, 2013. Oregon State University, http://prism.oregonstate.edu, Retrieved 22 January 2014.

Pyke, D. A. 2011. Restoring and rehabilitating sagebrush habitats. S. T. Knick, J. W. Connelly [eds.]. Greater sage-grouse: ecology and conservation of a landscape species and its habitats. Studies in Avian Biology, Vol. 38. Berkeley, CA: University of California Press. p. 531-548.

Pyne, S. J., P. L. Andrews, and R. D. Laven. 1996. Introduction to wildland fire. 2nd ed. New York, NY, USA: John Wiley and Sons, Inc. 769p.

Reiner, A. L., R. J. Tausch and R. F. Walker. 2010. Estimation procedures for understory biomass and fuel loads in sagebrush steppe invaded by woodlands. Western North American Naturalist 70:312-322.

Rhoades, C., M. Battaglia, M. E. Rocca, and M. G. Ryan. 2012. Short- and medium-term effects of fuel reduction mulch treatments on soil nitrogen availability in Colorado conifer forests. Forest Ecology and Management 276: 231-238.

Ross, D. W. and J. D. Walstad. 1986. Estimating aboveground biomass of shrubs and young ponderosa and lodgepole pines in south-central Oregon. Research bulletin: Oregon State University, Forest Research Laboratory, 57.

Ross, M. R., S. C. Castle, and N. N. Barger. 2012. Effects of fuels reductions on plant communities and soils in a Piñon-juniper woodland. Journal of Arid Environments 79:84-92.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service Research Paper INT-115.

Rothermel, R. C. 1983. How to predict the spread and intensity of forest and range fires. USDA Forest Service General Technical Report INT-143.

Roundy, B. A., R. F. Miller, R. J. Tausch, K. Young, A. Hulet, B. Rau, B. Jessop, J. C. Chambers, and D. Egget. 2014a. Understory cover responses to piñon-juniper treatments across tree dominance gradients in the Great Basin. Rangeland Ecology and Management –in press.

Roundy, B. A., K. Young, N. Cline, A. Hulet, R. F. Miller, R. J. Tausch, J. C. Chambers, and B. Rau. 2014b. Piñon-juniper reduction increases soil water availability of the resource growth pool. Rangeland Ecology and Management –in press.

Scarff, F. R. and M. Westoby. 2006. Leaf litter flammability in some semi-arid Australian woodlands. Functional Ecology 20:745-752. doi:10.1111/J.1365-2435.2006.01174.X.

Schaefer, D., Y. Steinberger, and W. G. Whitford. 1985. The failure of nitrogen and lignin control of decomposition in a North American desert. Oecologia (Berlin) 65:382-386.

Scott, J. H. and E. D. Reinhardt. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59p.

Sharik, T. L., W. Adair, F. A. Baker, M. Battaglia, E. J. Comfort, A. W. D'Amato, C. Delong, R. J. DeRose, M. J. Ducey, M. Harmon, L. Levy, J. A. Logan, J. O'Brien, B. J. Palik, S. D. Roberts, P. C. Rogers, D. J. Shinneman, T. Spies, S. L. Taylor, C. Woodall, and A. Youngblood. 2010. Emerging themes in the ecology and management of North American forests. International Journal of Forestry Research 11p. http://dx.doi.org/10.1155/2010/964260.

Stebleton, A. and S. Bunting. 2009. Guide for Quantifying Fuels in the Sagebrush Steppe and Juniper Woodlands of the Great Basin. Technical Note 430. Bureau of Land Management, Denver, CO, BLM/ID/PT-09/002+2824. 81p.

Tausch, R. J. 1999. Transitions and thresholds: Influences and implications for management in pinyon and Utah juniper woodlands. In: S. B. Monsen and R. Stevens [eds.]. Proceedings: ecology and management of pinyon-juniper communities within the interior west; 15-18 September 1997; Provo, Utah, USA. Ogden, UT, USA: USDA Forest Service, RMRS-P-9. p. 361-365.

Tausch, R. J. 2009. A structurally based analytic model for estimation of biomass and fuel loads of woodland trees. Natural Resource Modeling 22:463-488.

Tausch, R. J. and S. Hood. 2007. Pinyon/juniper woodlands. In: S. Hood and M. Miller [eds.]. Fire ecology and management of the major ecosystems of southern Utah. Fort Collins, CO, USA: US Forest Service, RMRS-GTR-202. p. 57-71.

van Wagtendonk, J.W. 1998. Fuel bed characteristics of Sierra Nevada conifers. Western Journal of Applied Forestry 13:73-84.

Vanderbilt, K. L., C. S. White, O. Hopkins, and J. A. Craig. 2008. Aboveground decomposition in arid environments: results of a long-term study in central New Mexico. Journal of Arid Environments 72:696-709.

Wallace, A. and E. M. Romney. 1972. Radioecology and ecophysiology of plants at the Nevada Test Site. National Technical Information Services, USAEC Report TID-25954.

Washa, J. B. 2011. Hazardous Fuels Treatment Effectiveness on Utah BLM Lands. Proceedings: Association for Fire Ecology; 14-17 November 2011, Snowbird Resort, Salt Lake City, Utah.

Young, K. R., B. A. Roundy, S. C. Bunting, and D. L. Eggett. 2014. Utah juniper and two-needle piñon reduction alters fuel loads. International Journal of Wildland Fire –in review.

Young, K. R., B. A. Roundy, and D. L. Eggett. 2013. Tree reduction and debris from mastication of Utah juniper alter the soil climate in sagebrush steppe. Forest Ecology Management 310:777-785. http://dx.doi.org/10.1016/j.foreco.2013.09.024 .

Tables and Figures

Table 1. Shrub biomass regression equations sources

Scientific Name	Common Name	Ind. Measured	Equation Source
Artemisia tridentata Nutt. ssp. *wyomingensis* Beetle & Young	Wyoming big sagebrush	5,947	Sage STEP regressions
Chrysothamnus viscidiflorus (Hook.) Nutt.	Yellow rabbitbrush	2,625	Sage STEP regressions
Artemisia nova A. Nelson	Black sagebrush	1,199	Sage STEP regressions
Artemisia arbuscula Nutt.	Little sagebrush	517	Sage STEP regressions
Amelanchier alnifolia (Nutt.) Nutt. ex M. Roem.	Serviceberry	500	Green and Flinders (1980)
Purshia tridentata (Pursh) DC.	Antelope bitterbrush	446	Sage STEP regressions
Ephedra nevadensis S. Watson	Nevada jointfir	261	* Reiner et al. (2010)
Ericameria nauseosa (Pall. ex Pursh) G.L. Nesom & Baird	Rubber rabbitbrush	257	Sage STEP regressions
Artemisia tridentata Nutt. ssp. *vaseyana* (Rydb.) Beetle	Mountain big sagebrush	235	Sage STEP regressions
Symphoricarpos oreophilus A. Gray	Mountain snowberry	211	* Ross and Walstad (1986)
Ephedra viridis Coville	Mormon tea	132	Reiner et al. (2010)
Cercocarpus montanus Raf.	Mountain mahogany	128	* McGinnis et al. (2010)
Eriogonum microthecum Nutt.	Slender buckwheat	86	Reiner et al. (2010)
Quercus turbinella Greene	Sonoran scrub oak	69	* McGinnis et al. (2010)
Rhus aromatica Aiton	Fragrant sumac	59	* McGinnis et al. (2010)
Tetradymia spinosa Hook. & Arn.	Shortspine horsebrush	47	* Green and Flinders (1980)
Purshia stansburiana (Torr.) Henrickson	Stansbury cliffrose	41	* Sage STEP regressions
Quercus gambelii Nutt.	Gambel oak	40	* McGinnis et al. (2010)
Tetradymia glabrata Torr. & A. Gray	Littleleaf horsebrush	36	* Green and Flinders (1980)
Coleogyne ramosissima Torr.	Blackbrush	34	* McGinnis et al. (2010)
Opuntia polyacantha Haw.	Plains pricklypear	30	NA
Tetradymia canescens DC.	Spineless horsebrush	22	Green and Flinders (1980)
Fraxinus anomala Torr. ex S. Watson	Singleleaf ash	13	* McGinnis et al. (2010)
Grayia spinosa (Hook.) Moq.	Spiny hopsage	12	Wallace and Romney (1972)
Krascheninnikovia lanata (Pursh) A. Meeuse & Smit	Winterfat	12	* Green and Flinders (1980)
Atriplex canescens (Pursh) Nutt.	Fourwing saltbush	8	* Sage STEP regressions
Atriplex confertifolia (Torr. & Frém.) S. Watson	Shadscale saltbush	5	Sage STEP regressions
Shepherdia rotundifolia Parry	Roundleaf buffaloberry	5	* McGinnis et al. (2010)
Yucca angustissima Engelm. ex Trel.	Narrowleaf yucca	4	NA
Cercocarpus ledifolius Nutt.	Curl-leaf mountain mahogany	3	* McGinnis et al. (2010)
Cylindropuntia echinocarpa (Engelm. & J.M. Bigelow) F.M. Knuth	Wiggins' cholla	3	NA
Mahonia fremontii (Torr.) Fedde	Fremont's mahonia	3	* McGinnis et al. (2010)
Ribes cereum Douglas	Wax currant	3	* Ross and Walstad (1986)
Ceanothus greggii A. Gray	Desert ceanothus	2	* McGinnis et al. (2010)
Prunus fasciculata (Torr.) A. Gray	Desert almond	2	* McGinnis et al. (2010)
Unknown Shrub 239	-	2	* McGinnis et al. (2010)
Pediocactus simpsonii (Engelm.) Britton & Rose	Mountain ball cactus	1	NA
Ribes aureum Pursh	Golden currant	1	* Ross and Walstad (1986)
Sambucus racemosa L.	Red elderberry	1	* McGinnis et al. (2010)
Unknown Shrub 235	-	1	* McGinnis et al. (2010)

Species order is determined by the total number of individuals measured in the field from high to low. Under the Equation Source column, an asterisk (*) denotes that no species-specific equation was found for the given species and an equation was used based on taxonomical relatedness and/or morphological similarities to a species for which the equation was intended. NA signifies that there were no adequate regression equations found for the particular species that was compatable with our field measurements.

Table 2. Mixed-model analysis of covariance Type III F-Test

Analysis	**Effect**	**Num DF**	**Den DF**	**F-value**	**p-value**
Woody Debris Cover:	TRT	1	86	80.02	<0.0001
Untreated and Masticated	TC	1	355	233.16	<0.0001
R^2=0.93	TC*TRT	1	355	204.75	<0.0001
Woody Debris Cover:	TRT	2	13	2.27	0.1425
Untreated, Masticated, and Masticated+Burned	TC	1	22	7.69	0.0111
R^2=0.91	TC*TRT	2	22	10.62	0.0006
Woody Debris Cover:	PWC	1	295	5.3	0.0221
1-6 Years-Since-Treatment	TRT	1	118	24.96	<0.0001
R^2=0.90	TC	1	295	87.94	<0.0001
	YST	1	3	1.24	0.3467
	TC*TRT	1	295	64.47	<0.0001
	YST*TRT	1	3	0.41	0.5681
	TC*YST	1	295	3.75	0.0538
	TC*YST*TRT	1	295	0	0.992
Standing Tree and Masticated Tree Debris	TRT	1	77	43.9	<0.0001
R^2=0.88	FSC	2	132	5.91	0.0035
	TC	1	948	1446.64	<0.0001
	TRT*FSC	2	154	45.73	<0.0001
	TC*TRT	1	948	38.85	<0.0001
	TC*FSC	2	948	13.82	<0.0001
	TC*TRT*FSC	2	948	31.88	<0.0001
Woody Debris:	TRT	1	76	13.8	0.0004
Untreated and Masticated	FSC	2	152	15.87	<0.0001
R^2=0.80	TC	1	916	237.65	<0.0001
	TRT*FSC	2	152	15.16	<0.0001
	TC*TRT	1	916	126.72	<0.0001
Woody Debris:	TRT	2	10	4.27	0.0457
Untreated, Masticated, and Masticated+Burned	FSC	2	20	2.17	0.1404
R^2=0.76	TC	1	132	3.83	0.0523
	TRT*FSC	4	20	3.12	0.0381
	TC*TRT	2	132	12.94	<0.0001
	TC*FSC	2	132	4.14	0.018
Woody Debris:	YST	1	23	0	0.9996
1 and 5 or 6 Years-Since-Treatment	FSC	2	27	9.43	0.0008
R^2=0.89	YST*FSC	2	19	0.22	0.8047
	TC	1	37	0	<0.0001
	TC*YST	1	36	0	0.9528
	TC*FSC	2	82	1.38	0.2572
	TC*YST*FSC	2	82	0.92	0.4045

Table 2 Continued

Analysis	Effect	Num DF	Den DF	F-value	p-value
Shrub:	TRT	1	86	0.3	0.5828
Untreated and Masticated	TC	1	350	235.46	<0.0001
R^2=0.65	TC*TRT	1	350	0.31	0.5781
Shrub:	TRT	2	13	12.44	0.001
Untreated, Masticated, and Masticated+Burned	TC	1	22	31.34	<0.0001
R^2=0.67	TC*TRT	2	22	4.66	0.0205
Herbaceous:	TRT	1	86	4.07	0.0467
Untreated and Masticated	TC	1	348	2.54	0.1121
R^2=0.74	TC*TRT	1	348	62.31	<0.0001
Herbaceous:	TRT	2	13	4.5	0.0327
Untreated, Masticated, and Masticated+Burned	TC	1	22	0.08	0.7854
R^2=0.78	TC*TRT	2	22	5.09	0.0152
Herbaceous:	PHB	1	329	42.28	<0.0001
1-6 Years-Since-Treatment	TRT	1	117	0.2	0.6529
R^2=0.75	TC	1	329	26.66	<0.0001
	YST	1	3	0.05	0.8433
	TC*TRT	1	329	0.03	0.8529
	YST*TRT	1	3	0.76	0.4479
	TC*YST	1	329	27.57	<0.0001
	TC*YST*TRT	1	329	10.21	0.0015
Litter and Duff:	TRT	1	88	1.88	0.1735
Untreated and Masticated	TC	1	374	696.65	<0.0001
R^2=0.81	TC*TRT	1	374	8.29	0.0042

Acronyms defined	
Num DF=Numerator degrees of freedom	**YST**=Years-since-treatment
Den DF=Denominator degrees of fredom	**FSC**=Fuel size class
TRT=Treatment	**PWC**=Pretreatment woody cover
TC=Tree cover	**PHB**=Pretreatment herbaceous biomass

The 2- and 3-way interactions not shown were not significant and were excluded from the models

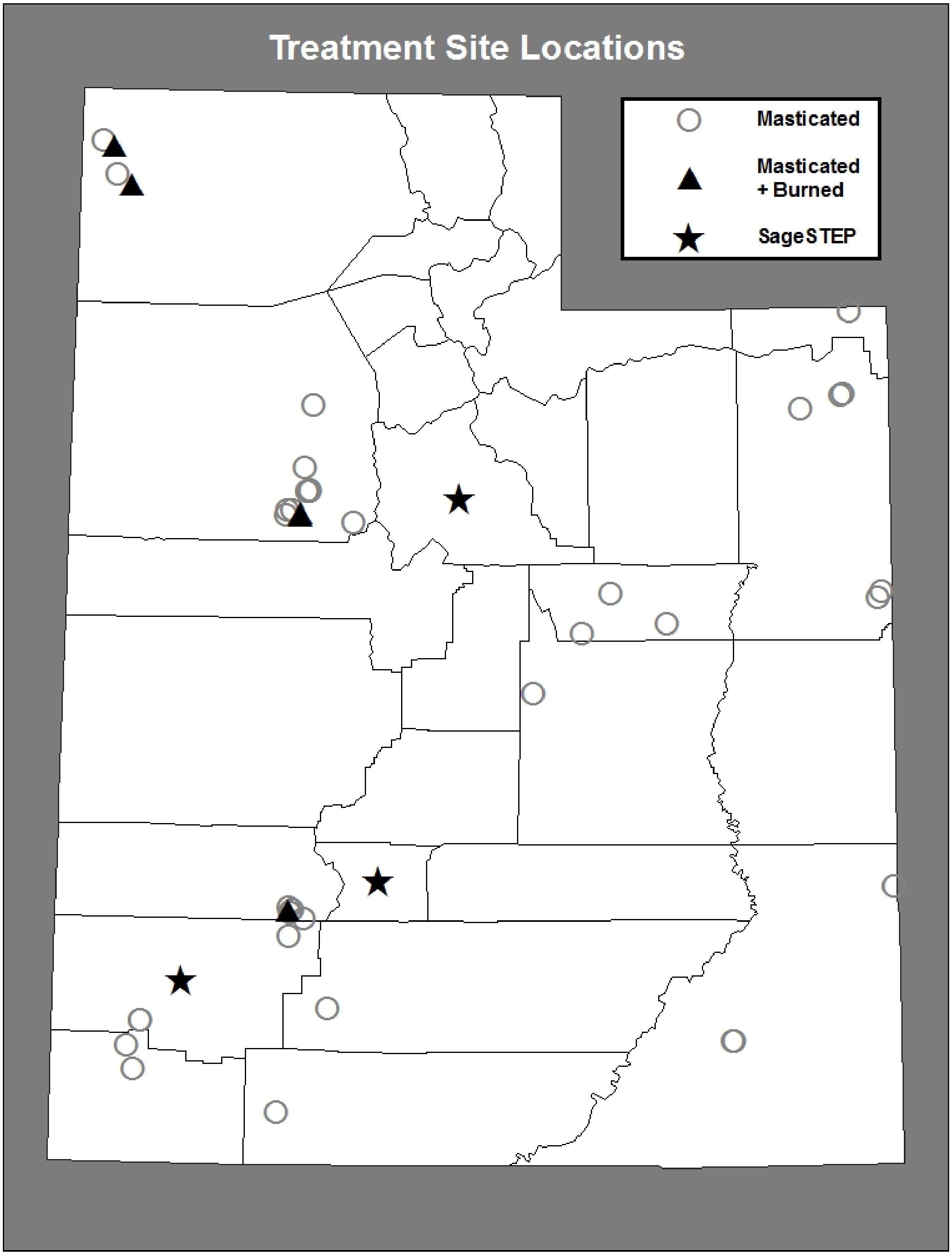

Figure 1. Map of Utah with locations for masticated only (including SageSTEP sites) as well as masticated + burned sites.

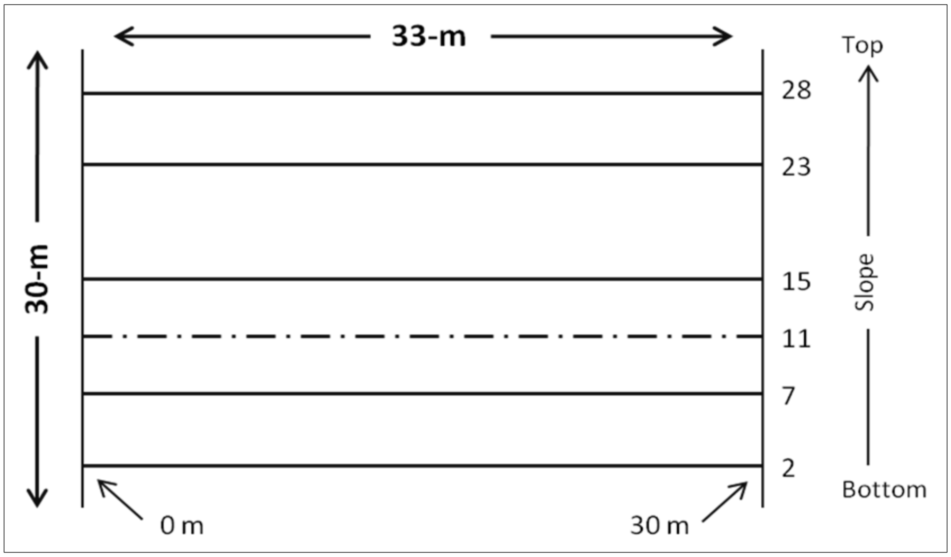

Figure 2. Subplot transect design. Numbers on the right vertical axis (2, 7, 11, 15, 23, and 28) denote the transect number within the subplot. Horizontal solid lines represent transects where vegetation parameters were measured. The dashed horizontal line represents the only transect where herbaceous vegetation was harvested.

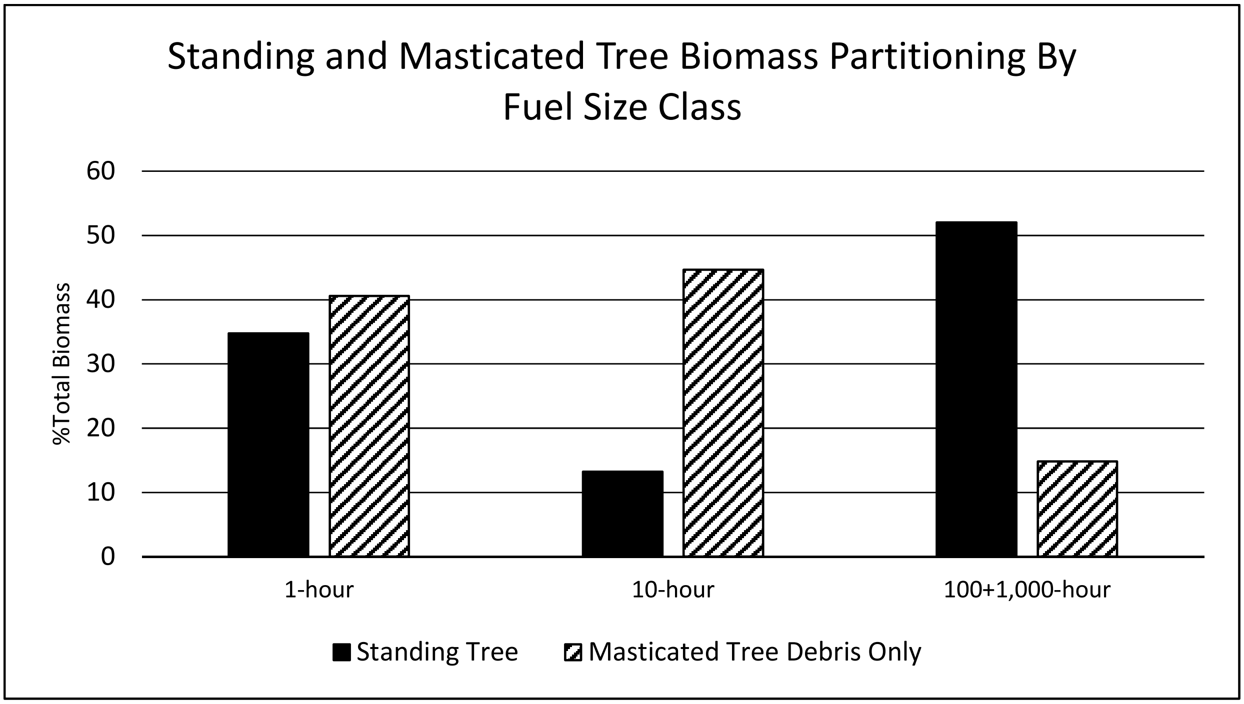

Figure 3. Standing and masticated tree biomass partitioning by fuel size class. Masticated tree debris represents only the debris additions to the pretreatment fuelbed as a result of mastication and does not include pretreatment woody debris.

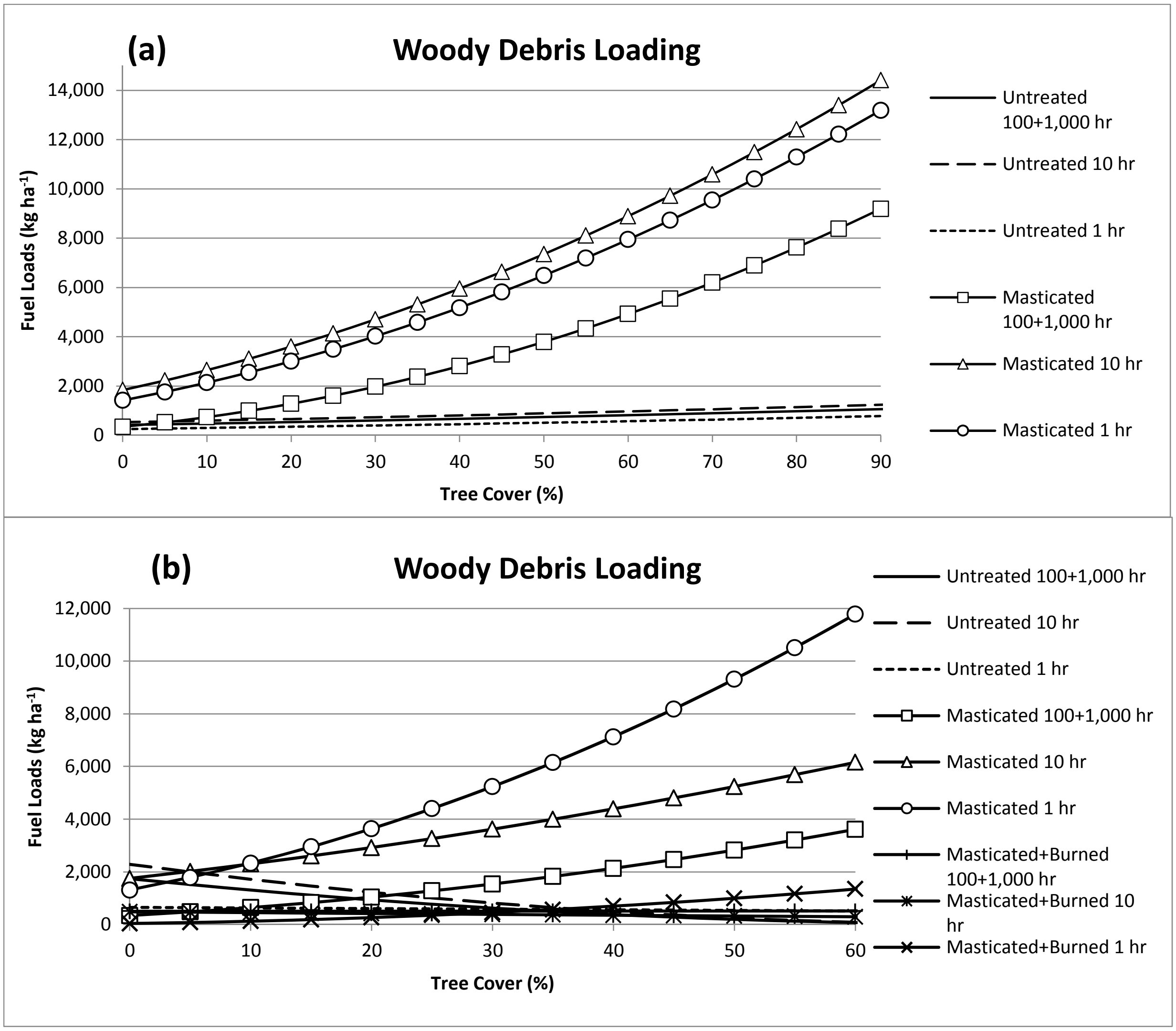

Figure 4. Fuel load response to treatments across a gradient of tree cover values. (a) Represents a comparison between untreated woody debris loading (pretreatment woody debris) and masticated treatment woody debris loading (including pretreatment woody debris and masticated tree debris) across 45 sites. (b) Represents a comparison between untreated woody debris loading (pretreatment woody debris), masticated treatment woody debris loading, and masticated + burned treatment woody debris loading across 5 sites. Tree cover values on the x-axis are not modeled, but actual tree cover values measured using NAIP imagery and Feature Extraction ENVI 4.5® software.

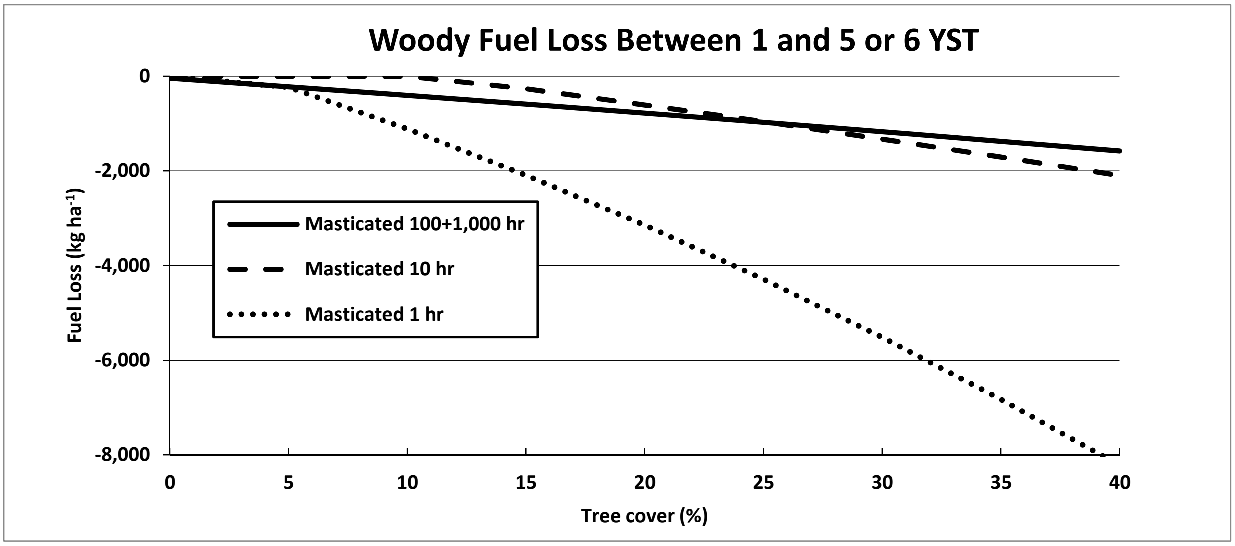

Figure 5. Woody debris fuel loss as calculated by the difference in fuel loading between 1 and 5 or 6 Years-Since-Treatment (YST). These data are representative of 3 SageSTEP sites, namely Greenville Bench, Scipio, and Onaqui.

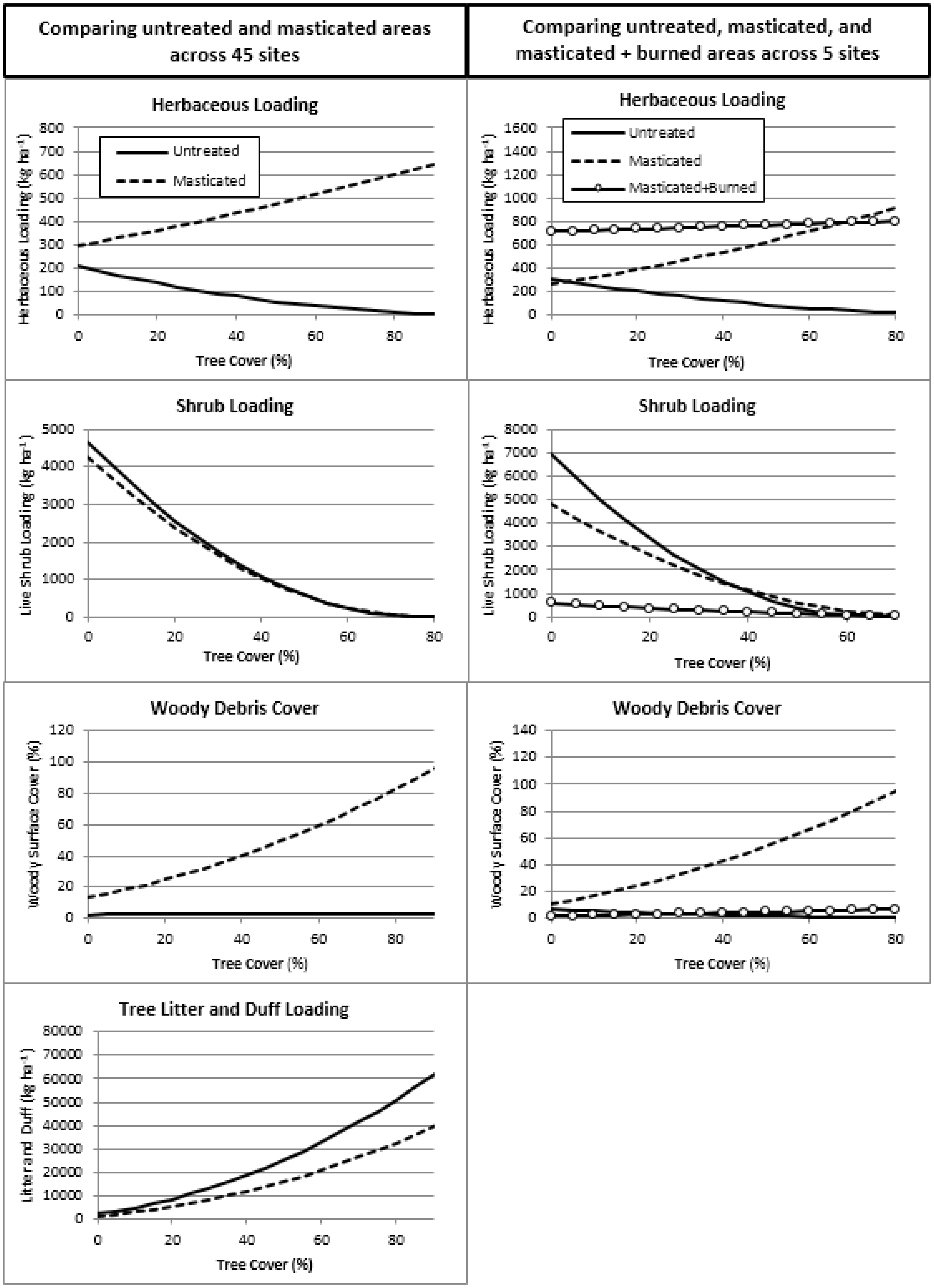

Figure 6. Treatment comparison estimates for herbaceous loading, shrub loading, tree litter and duff loading, and woody debris cover across a tree cover gradient. Graphs shown on the left compared untreated and masticated areas across 45 sites while graphs on the right compared untreated, masticated, and masticated + burned areas across 5 sites.

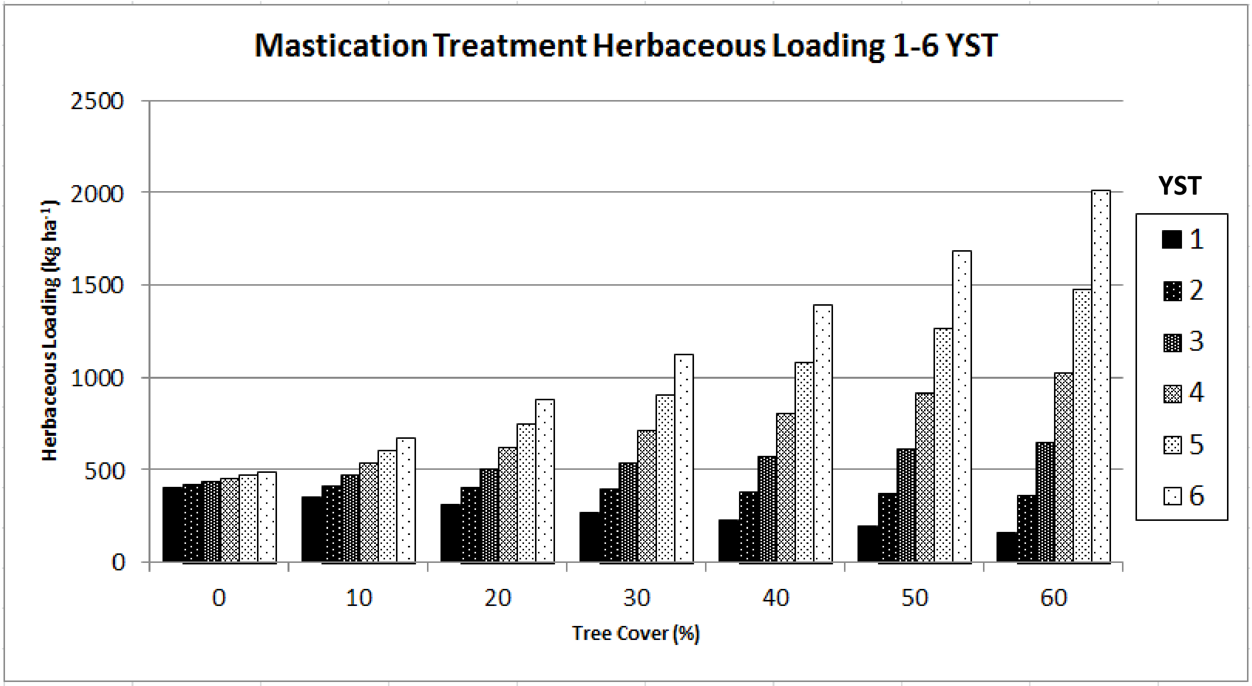

Figure 7. Years-since-treatment (YST) 1-6 effect for herbaceous fuel loading on 3 SageSTEP sites (Greenville Bench, Scipio, and Onaqui).

Appendix A. The following tables represent loading values for various fuel types across a range of tree cover (TC) values, and between fuel size classes, treatments, and years-since-treatment (YST). Hyphenated portions of the tables for the given fuel and treatment type represent tree cover values for which we did not gather data, and are subsequently beyond our models' power of inference. Because 1,000-hr fuel measurements were often zero, they were combined with 100-hr fuel measurements to meet the normally distributed residual requirements for analysis. The combination of 100 and 1,000-hr fuels may not be appropriate for fire behavior models. In order to separate loading values by FSC, we provide relative proportions of each based on mean biomass across all sites using raw data. By biomass, 31% of the mean fuel proportion is composed of 100-hr fuels and 69% is composed of 1,000-hr fuels.

Table 1. Woody debris fuel loading estimates (kg ha^{-1})

	Untreated				Masticated				Masticated+Burned			
TC (%)	1 hr	10 hr	100+1,000 hr	Total	1 hr	10 hr	100+1,000 hr	Total	1 hr	10 hr	100+1,000 hr	Total
0	253	534	422	788	1,420	1,838	350	3,258	34	480	500	514
5	275	566	450	841	1,761	2,224	529	3,985	71	462	501	533
10	298	598	479	896	2,139	2,646	745	4,786	121	445	502	566
15	322	632	509	953	2,554	3,106	997	5,660	184	428	502	612
20	346	666	540	1,012	3,006	3,602	1,286	6,607	260	411	503	671
25	372	701	571	1,073	3,494	4,135	1,612	7,629	349	395	504	744
30	398	737	604	1,135	4,019	4,704	1,974	8,723	452	379	505	831
35	425	774	637	1,200	4,581	5,310	2,373	9,891	568	363	505	931
40	454	812	672	1,266	5,179	5,953	2,809	11,133	697	348	506	1,045
45	483	851	707	1,334	5,815	6,633	3,282	12,448	839	333	507	1,172
50	513	891	743	1,403	6,487	7,350	3,791	13,836	995	318	508	1,313
55	544	931	781	1,475	7,195	8,103	4,338	15,298	1,163	304	509	1,467
60	575	973	819	1,548	7,941	8,893	4,921	16,834	1,345	290	509	1,635
65	608	1,015	858	1,623	8,723	9,720	5,540	18,443	-	-	-	-
70	642	1,059	898	1,700	9,542	10,583	6,197	20,125	-	-	-	-
75	676	1,103	938	1,779	10,398	11,483	6,890	21,881	-	-	-	-
80	712	1,148	980	1,860	11,290	12,420	7,620	23,711	-	-	-	-
85	748	1,194	1,023	1,942	12,220	13,394	8,386	25,614	-	-	-	-
90	785	1,241	1,066	2,026	13,185	14,405	9,190	27,590	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-
100	-	-	-	-	-	-	-	-	-	-	-	-

Table 2. Masticated treatment woody debris YST fuel loading estimates (kg ha^{-1})

	Masticated 1-YST				Masticated 5 or 6-YST			
TC (%)	1 hr	10 hr	100+1,000 hr	Total	1 hr	10 hr	100+1,000 hr	Total
0	1,271	1,062	11	2,333	928	1,230	39	2,158
5	2,156	1,591	139	3,746	1,337	1,622	151	2,959
10	3,273	2,226	411	5,499	1,821	2,068	335	3,889
15	4,623	2,967	828	7,591	2,379	2,568	592	4,947
20	6,206	3,815	1,390	10,021	3,011	3,123	922	6,134
25	8,021	4,770	2,096	12,791	3,718	3,731	1,325	7,450
30	10,068	5,831	2,946	15,899	4,500	4,394	1,799	8,894
35	12,348	6,998	3,941	19,345	5,356	5,111	2,347	10,466
40	14,862	8,271	5,081	23,133	6,286	5,882	2,967	12,168
45	-	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-
100	-	-	-	-	-	-	-	-

Table 3. Tree litter & duff fuel loading estimates (kg ha^{-1})

TC (%)	Untreated	Masticated
0	2,351	1,457
5	3,550	2,217
10	4,994	3,135
15	6,685	4,212
20	8,622	5,448
25	10,805	6,843
30	13,234	8,396
35	15,909	10,108
40	18,830	11,979
45	21,997	14,009
50	25,410	16,198
55	29,070	18,545
60	32,975	21,051
65	37,126	23,716
70	41,524	26,540
75	46,167	29,522
80	51,057	32,664
85	56,193	35,964
90	61,574	39,422
95	-	-
100	-	-

Table 4. Live shrub fuel loading estimates (kg ha^{-1})

TC (%)	Untreated	Masticated	Masticated+ Burned
0	4,675	4,256	584
5	4,085	3,733	523
10	3,535	3,243	466
15	3,024	2,788	412
20	2,554	2,367	361
25	2,123	1,981	314
30	1,732	1,629	270
35	1,381	1,311	230
40	1,069	1,028	192
45	797	779	158
50	565	565	127
55	373	385	100
60	221	239	76
65	108	128	55
70	35	52	38
75	2	9	-
80	9	1	-
85	-	-	-
90	-	-	-
95	-	-	-
100	-	-	-

Table 5. Herbaceous fuel loading estimates (kg ha^{-1})

TC (%)	Untreated	Masticated	Masticated+ Burned
0	210	298	714
5	191	314	719
10	173	330	725
15	155	347	730
20	139	364	736
25	123	381	741
30	108	399	747
35	95	417	752
40	82	436	758
45	70	455	764
50	59	475	769
55	49	495	775
60	40	515	781
65	32	536	786
70	25	557	792
75	18	579	798
80	13	600	804
85	8	623	-
90	5	646	-
95	-	-	-
100	-	-	-

Table 6. Herbaceous YST fuel loading estimates (kg ha^{-1})

	Untreated						Masticated					
TC (%)	1-YST	2	3	4	5	6	1	2	3	4	5	6
0	353	349	344	340	336	331	406	422	438	454	471	488
5	313	313	314	314	314	315	381	416	454	493	534	576
10	276	280	284	289	293	298	356	411	470	533	600	670
15	240	249	257	265	273	282	333	406	487	575	670	772
20	208	219	230	242	254	266	310	401	503	618	744	881
25	177	191	205	220	236	251	288	396	521	662	821	997
30	150	165	182	199	218	237	267	391	538	709	903	1,121
35	124	141	160	180	200	222	247	386	556	757	988	1,251
40	101	119	139	161	184	209	227	381	574	806	1,078	1,389
45	80	99	120	143	168	195	209	376	592	857	1,171	1,534
50	62	81	102	126	153	182	191	371	610	909	1,268	1,686
55	46	64	86	111	139	170	174	366	629	964	1,369	1,845
60	32	50	71	96	125	158	157	361	648	1,019	1,474	2,012
65	-	-	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-
100	-	-	-	-	-	-	-	-	-	-	-	-