Immediate and short-term response of understory fuels following mechanical mastication in a pine flatwoods site of Florida, USA.

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Abstract

Mechanical fuel hazard reduction treatments are widely implemented in fire-prone ecosystems, but research evaluating their effects on fuel dynamics has focused only on woody-dominated post-treatment fuels. In the southeastern US, one of the most fire-prone regions of the world, mechanical fuels reduction is being increasingly used, yet the resulting fuelbeds have yet to be fully characterized for their fire risk. In order to broaden our understanding of the longevity and effectiveness of these treatments, mechanical mastication ("mowing") was examined in a common pine ecosystem of the southeastern US Coastal Plain, where the post-mastication fuel environment was dominated by non-woody fuels. Fuel dynamics differed between recently burned mature stands, mature stands that had not burned for several years, and younger pine plantations. Foliar litter dominated (46–69%) the 17.1–23.1 $Mg \cdot ha^{-1}$ of post-mastication surface fuels across these ecosystems, where pre-treatment understories were dominated by palmetto and gallberry shrubs. Although surface fuels compacted over time, the shrub layer recovered quickly, contributing to the result that stand-alone mechanical treatments did not reduce overall fuel loads. Increases in surface fuels followed by rapid shrub recovery may indicate short-term treatment efficacy, with narrow windows of opportunity for post-treatment fuel reduction burns. The fuelbed characteristics and fuel dynamics observed in these treated sites broaden our understanding of mechanical fuels reduction treatments in general, and provide the critical data for fuel model development.

Keywords: fire management, forest management, fuel models, fuels treatments.

1. Introduction

Altering fuel structure in forest and shrub ecosystems has become a common method aimed at mitigating fire hazard in long-unburned ecosystems. Mechanical mastication (mowing, shredding, chipping, etc.) of the understory rearranges shrubs and small trees into compact surface fuels (Hood and Wu, 2006; Kane et al., 2009; Kobziar et al., 2009) with the intent to reduce subsequent fire behavior. Mastication machinery typically consist of a mastication head, with either rotating blades or a rotating cylinder with fixed or flailing cutters, attached to tracked or rubber-tired ground equipment. The use of such equipment to alter forest fuel structure has become widespread across the USA, with treatments often occurring at large scales.

Recent research describing post-mastication fuel environments has been primarily conducted in the western USA in woody-dominated surface fuels (Hood and Wu 2006; Kane et al., 2009; Kobziar et al., 2009; Battaglia et al., 2010). Pine flatwoods of the southeastern USA, with understories dominated by saw palmetto (*Serenoa repens* (Bartr.) Small) and gallberry (*Ilex glabra* L. (Gray)) shrubs, are unusual shrub ecosystems considering their foliar-dominated fuel characteristics (McNab et al., 1978). Saw palmetto is a shrub palm that grows from horizontal stems with fronds reaching approximately 2 m tall. Historically, fires were frequent (ca. <5 yrs) in pine flatwoods (Abrahamson and Hartnett, 1991) and understory shrubs typically recover quickly following disturbance (Brose and Wade, 2002). Ample ignition sources (both lightning and anthropogenic) in the southeastern USA contribute to continued high fire frequency fire across the region, compelling managers to use prescribed fire, mechanical treatments, or combinations thereof to mitigate wildfire hazard (Brose and Wade, 2002; Watts and Tanner, 2006). With rapid shrub recovery and palmetto dominant in the understory, mechanical mastication in this fuel complex will likely result in unique post-treatment fuelbeds that may deserve special attention for evaluation of effectiveness in reducing wildfire hazard. Rapid understory recovery also provides an opportunity to evaluate expedited fuel dynamics following fuels treatments. In other regions, thoroughly evaluating post- mastication consequences to fuelbeds and wildfire potential may require years to decades, rather than months. Characterizing post-mastication fuelbeds over time in this fuel complex will broaden our understanding of post-treatment fuelbed dynamics, support fuel model development, and provide a range of fuelbed characteristics not likely to occur following mastication in other ecosystems.

Mastication, regionally termed "mowing" and used here throughout, of palmetto/gallberry understories in pine flatwoods is being conducted in large scale applications in northern Florida, USA to reduce fire hazard during post-treatment prescribed burning. Mowing is also being used across the state as a stand-alone treatment where burning is difficult in the wildland-urban interface (WUI), but where altering fuel structure is intended to reduce potential wildfire behavior or enhance suppression efforts (Menges and Gordon, 2010). Treatments are being conducted in mature forests of various ages of "rough", or years since last fire, as well as in pine plantations where understory shrub strata have developed. While many shrub species in this ecosystem, including saw palmetto, sprout or grow new fronds following aboveground damage, the effectiveness of mowing treatments is highly sensitive to time-since-treatment. Increased and continuous surface litter, coupled with a recovered shrub surface fuel load, may result in fuelbeds more conducive to wildfire ignition and spread than untreated stands. In addition, fuel dynamics may differ depending upon the type of stands where treatments are being employed. It is therefore important to evaluate these mowed fuelbeds so that thresholds of fire hazard mitigation effectiveness can be determined. Managers concerned with promoting timber resources can use this information to plan mowing treatments which optimize wildfire risk reduction and minimize the number of entries and total cost.

Evaluating fuel dynamics following mastication treatments will not only provide insight into the post-treatment fire environment, but may serve to provide information useful for other applications. Quantifying biomass change over time can inform our understanding of potential biomass utilization for energy, or how mowing might influence carbon sequestration potential. Post-mowing residues may be left on site or consumed in follow-up prescribed burning treatments. When left on site, extraction for biomass utilization may be feasible. The economic tradeoffs of mowed biomass utilization is dependent on greater understanding of how the biomass changes over time-since-treatment. Also, where mowed residues are left on site, carbon storage potential can be evaluated if we understand the dynamics of surface fuels created from the initial treatment, along with the growth response of shrubs and trees following treatment.

To examine fuel dynamics as a result of mechanically treating understory fuels where rapid vegetation recovery is expected, we evaluated changes to fuel structure and biomass in a pine flatwoods forest in the Osceola National Forest of north-central Florida, The objectives of this *in situ* study were to 1) characterize surface fuels immediately following the mowing of palmetto/gallberry dominated pine flatwoods and 2) quantify changes in fuel/vegetation biomass for up to two years following treatment in three common flatwoods stand types: mature pine, mature/recently burned pine, and pine plantations. Although this study was conducted in one location, we discuss the implications of mowing treatments for fire hazard reduction, as well as biomass utilization or carbon sequestration, in regard to the evidence observed in the sites studied here. Evaluating immediate and longer term changes to fuels in response to mechanical treatments will provide insight into the efficacy of treatment as well as their potential impacts on other ecosystem functions.

2. Methods

2.1 Study Site

Fuel characteristics were measured in mechanically treated sites in the Osceola National Forest (Osceola) in north-central (northern peninsular) Florida, USA. The Osceola encompasses 81,000 ha in parts of Columbia, Baker, Bradford, and Hamilton counties. The terrain is generally flat with underlying marine deposited sandy soils. Climate is characterized by hot humid summers, averaging 27–28°C, with mild winters (12–16°C) and most precipitation occurring during summer months from thunderstorms (Chen and Gerber, 1990). Dominant vegetation communities in the Osceola include mesic and hydric pine flatwoods and interspersed lesser amounts of cypress-hardwood swamps (Myers and Ewel, 1990).

Mechanical fuels treatments in the Osceola were conducted primarily in pine flatwoods communities that have gone unburned for at least 11 years (Malone et al., 2011), and where fuel accumulations pose a hazard within the wildland urban interface (WUI). Pine flatwoods in this region are dominated by slash pine (*Pinus elliottii* var. *elliottii* (Engelm.)) and/or longleaf pine (*Pinus palustris* Mill.) with an understory comprised primarily of saw palmetto and gallberry. Because these systems recover to pre-burn fire hazard levels in less than five years (Davis and Cooper, 1963; Brose and Wade, 2002), management goals are to burn pinelands on an average three-year rotation, although many pine flatwoods areas have not burned in over 5+ years. Challenges to management in the Osceola include very large burn units, extensive WUI including a major interstate highway (I-10) transecting the Forest, wilderness areas isolated by wetlands, and a history of fire exclusion or excessively long fire return intervals in many locations. Thus, mechanical mowing treatments are being used to create firebreaks, reduce the height of understory fuels for re-introduction of prescribed fire, and to reduce fire hazard in areas abutting communities, highways, or large private pine plantations.

For this study, fuels were sampled within two extensive mowing treatments in the southwestern portion of the Osceola. One, a large contiguous area (500 ha) adjacent to Interstate 10 is referred to here as the 'areal' treatment site, and the other, a 100 m wide, 6 km long “buffer” treatment site (60 ha) is adjacent to privately owned pine plantations. Mowing treatments were conducted, in both sites, using a rubber-tired skidder and a tracked vehicle (Gyro-Trac Corp., unknown model), both with front-mounted cylindrical masticating heads. Treatment prescriptions included mowing all shrubs and small-diameter trees (<20 cm) and the resulting debris to be left on site. Each treatment occurred within pine flatwoods ecosystems; however, the areal site was in mature pine (ca. 80 yrs old) flatwoods, while the buffer treatment occurred across three different pine flatwoods stand types: mature (ca. 80 yrs old), mature/burned (ca. 80 yrs old, burned 5 yrs prior to mowing), and a younger pine plantation (27 yrs old). Evaluation of treatment effects on fuelbeds over time was conducted in each of these locations and stand types to increase the scope of the study.

2.2 Areal Treatment Site

To characterize fuelbed properties following mowing in pine flatwoods, fuels and vegetation were sampled from 16 plot locations within the 500 ha areal site (Fig. 1). Plots were allocated using a systematic grid randomly located onto an aerial map of the treatment zone. A grid format was used such that the distance between all grid line intersections was 400 m. Relative plot locations were systematically located using a grid pattern to better facilitate repeated sampling, however, of all possible grid intersections, 16 were randomly selected as sample locations. In addition, sampling locations were only used that occurred within mature pine stands, i.e. if a randomly selected grid intersection occurred within a wetland, it was discarded. Plots were established and vegetation and fuels sampled in January 2010, just prior to mowing to evaluate pre-treatment vegetation and fuel loading. Vegetation and fuels were subsequently measured following treatment.

At each plot location, all trees were measured within a 201 m^2 (8 m radius) circular plot (Fig. 2). Tree diameter at breast height (DBH: measured at 1.37 m above the ground), tree height, and the height to live crown base was measured for all trees ≥2.5 cm DBH, by species and by tree status (live or dead). Shrubs ≥0.5 m tall were sub-sampled within two 4 m^2 rectangular belt transects (1×4 m) located at 4 m north and south of plot center, respectively, each extending to the 8 m plot radius (Fig. 2).

Height and basal diameter were measured for all shrubs. For saw palmetto, a multi-stemmed shrub-form palm, fronds (leaf blade and rachis, Gholz et al., 1999) were tallied for each individual shrub and a representative frond was selected for measurement of basal rachis diameter and frond (palm blade and rachis) length. Biomass of shrub woody stems and foliage were estimated, separately, for the dominant shrub species using published allometric equations (Smith and Brand, 1983; Schafer, 2010), except for saw palmetto. Saw palmetto biomass was estimated from an allometric equation developed in this study from 40 fronds, each collected from 40 different palmetto individuals in an adjacent stand, and regressed against basal rachis diameter and frond length. Gallberry and saw palmetto were the most dominant shrub species in this study, comprising 81% of shrub density in the areal treatment and 51% in the buffer treatment (unpublished data), however lesser occurrences of *Ilex coriacea* ((Pursh) Chapm.), *Vaccinium stamineum* (L.), *V. myrsinites* (Lam.), *Lyonia lucida* ((Lam.) K. Koch), *L. ferruginea* ((Walter) Nutt.), and *Myrica cerifera* ((L.) Small) were also present, however species specific allometric equations were not available for all of these species. Allometric equations for *I. glabra* (Smith and Brand, 1993) were used for *I. glabra* and *I. coriacea*, equations for *Vaccinium* spp. (Smith and Brand, 1993) were used for *V. stamineum*, equations for *Myrica pensylvanica* ((Mirb.) Kartesz) (Smith and Brand, 1993) were used for *M. cerifera*, and equations for *Vaccinium scoparium* (Leiberg ex Coville), a small statured shrub, were used for *V. myrsinites*, a shrub with similar habit. Because these shrub species were not as abundant in this ecosystem and the respective species used as surrogates were similar in form, biomass estimates across sites are probably reasonable for fuels analysis. Specific allometric equations for *Lyonia lucida* and *L. ferruginea* were from Schafer (2010). Herbs, grasses, and vines are a minor component regarding the fuel complex (< 5% of ground cover, Kreye, 2012) and were not quantified for evaluation of fuel dynamics in this study.

Surface fuels were quantified using a non-destructive planar intercept method (Brown 1974). To estimate coarse (CWD) and fine woody debris (FWD), woody fuels were tallied, by diameter classes, along four 10 m transects extending from 4 m N, S, E, and W, respectively, from plot center, and each oriented at a random azimuth (Fig. 2). FWD included 1h (<0.635 cm), 10h (0.635 - 2.54 cm), and 100h (2.54 - 7.62 cm) timelag fuel classes (Fosberg and Deeming, 1971). 1h and 10h fuels were tallied within the last meter of each transect, away from plot center, and 100h fuels were tallied within the last 2 m. CWD (>7.62 cm) was tallied, and diameter measured, along the entire 10 m transect. CWD was further categorized into two decomposition classes: sound and rotten. Woody fuel loading ($Mg \cdot ha^{-1}$) was estimated from tallies using Brown's (1974) equations and fuel characteristics of palmetto/gallberry pine flatwoods from Hough and Albini (1978). Litter depth and duff depth were measured along each planar intercept transect at the transect origin and at 8 m. Litter mass was then estimated from litter depth measurements using reported bulk density ($16.1\ mg \cdot cm^{3}$) of a 20-yr rough (time since last fire) mature flatwoods site in the longleaf pine (LLP 09) photo series for quantifying natural fuels (Ottmar and Vihnanek, 2000). Because duff mass was assumed to be similar following mowing, pre-treatment duff mass was estimated from bulk density values measured from destructive sampling following mowing (described below).

Following mowing treatment (ca. 2 months), all plots were re-sampled using the above methods. To fully describe post-mowing fuelbed characteristics, however, surface fuels (FWD, litter, and duff) were destructively sampled, transported to the laboratory, sorted, oven-dried, and weighed. 1×1 m quadrats were located 1m from the end of two randomly selected fuels transects in each plot (Fig. 2). All FWD and litter were collected from the entire quadrat and duff collected from a 0.25 ×0.25 m nested quadrat. Woody fuel depth and litter depth were measured at four locations within the quadrat and duff depths were measured at four locations within each nested quadrat, prior to the removal of material (Fig. 2). Litter and FWD were separated in the laboratory. FWD was subsequently sorted into timelag classes (1,10, and 100h) and further into fractured and non-fractured particles. Fractured particles were those in which a minimum of 50% of the length was physically altered from mowing (Kane et al., 2009). Litter, FWD, and duff were all oven dried at 65˚C for 72 h. Preliminary analysis of duff samples 'floated' in water for 24 h, to remove mineral soil, indicated little incorporated mineral soil (<5% by weight). The transition from duff to mineral soil is distinct, therefore mineral soil was not removed from duff samples collected from quadrats. At the quadrat level, the relationship between litter mass and average litter depth, as well as the relationship between duff mass and average duff depth, were evaluated using linear regression. The resulting linear regression equations were then used to estimating litter and duff mass from depth measurements using non-destructive planar intercept methods for post-masticated sites in the rest of the study. Average bulk density was calculated for FWD, litter, and duff. It was assumed that duff biomass was not altered during mowing, but that bulk density may have increased from machine operations. Since destructive sampling was not conducted prior to treatment, pre-treatment bulk density was calculated using average pre-treatment duff depth, post-treatment duff depth, and post-treatment bulk density, assuming duff mass had not changed.

One year following mowing (spring 2011), plots were re-sampled using the destructive sampling to determine changes in surface fuel loading and whether litter or duff bulk density changed as surface fuels settled over the first year following treatment. One 25×25 cm quadrat was randomly located at each plot. Litter and duff depths were measured and debris collected, oven dried, and weighed as above. Linear regression was also used to determine if the relationship between litter depth and litter mass, and duff depth and duff mass had changed.

2.3 Buffer Treatment Site

A 100 m wide, 6 km long buffer site was masticated along the southwestern boundary of the Osceola adjacent to private pine plantations during the summer of 2009. Shrub vegetation and surface fuels were sampled immediately prior to treatment, and at 2, 8, 16, and 24 months following treatment using the same non-destructive sampling methods described above. Trees were sampled using the same methods as in the areal site, but were only measured prior to treatment, post-treatment, and two years following treatment. The 8-mos sampling period was conducted at the beginning of the growing season (March 2010), 16-mos sampling after the growing season (October 2010), and 24-mos in August 2011. Pre-treatment sampling plots were systematically located within the linear buffer and subsequently re-sampled following treatment. Allocation of plots within stand types (mature N=12, mature/burned N=9, plantation N=6) were weighted based on the linear distance of stand types along the buffer. Plots were allocated so that the total number of plots within any one stand type was divisible by three. Plots were spatially arranged in triplets at 15, 45, and 75 m from the buffer edge, but arranged at a 45˚ angle between plots in reference to the edge of the buffer. They were spatially established by locating the center of the stand type unit, to reduce edge influence from adjacent stand types, and were arranged so that an equal number of plots were located on either side of the center of the unit.

Shrub biomass and pre-treatment litter and duff biomass in the buffer site were estimated using the same methods described above. . Two and eight month post-treatment litter and duff mass were estimated from depth measurements using the regression equations developed from destructive sampling in the areal site just after treatment, while litter and duff mass at 16 and 24 months following treatment were estimated from depth measurements using the regression equations developed from destructive sampling at one year following treatment in the areal site.

2.4 Data Analysis, Areal Treatment Zone

Mean, range, and standard deviation were reported for all fuelbed characteristics measured from destructive sampling. Linear regression was used to evaluate the relationships between litter depth and litter mass, as well as duff depths and duff mass, for both post- and one year post-treatment, from destructive sampling. From non-destructive sampling, overstory characteristics (tree density, basal area (BA), quadratic mean diameter (QMD), tree height, and tree crown base height (CBH)), shrub characteristics (density, height, biomass), biomass of surface fuels (1h, 10h, 100h, 1000h, litter, duff), and fuel depths (FWD, litter, duff) were each compared between pre- and post-treatment using a repeated measures analysis of variance (ANOVA) with plot as the subject. Tests for differences among the means were conducted at the $\alpha=0.05$ level. Assumptions of normality and equal variance were tested with the Shapiro-Wilk and Modified-Levene Tests, respectively. When model assumptions were not met, data were log or square-root transformed to meet assumptions. As mentioned above, saw palmetto frond biomass was regressed against frond length and frond basal rachis diameter, separately, using linear regression to establish an allometric equation to estimate biomass from non-destructive sampling.

2.5 Data Analysis, Buffer Site

Overstory tree characteristics (density, BA, QMD, height, CBH) were compared across stand types (mature, mature-burned, plantation) and time since treatment using analysis of variance (ANOVA). Shrub biomass (woody stems and foliage), surface fuel biomass (litter, 1h, 10h, and 100h woody), and total fuel biomass (shrub and surface fuel) were compared across stand types and time since treatment using ANOVA. Duff and 1000h fuels were not considered as surface fuel in this particular analysis, but were evaluated separately since they contribute to smoldering combustion and not flaming combustion at the fire's front. Shrub characteristics (shrub stem biomass, shrub foliar biomass, shrub height, and shrub density) were each compared across stand types and time since treatment using ANOVA. Biomass of all surface fuels, including duff and 1000h fuels, were each compared across stand type and time since treatment using ANOVA. For all ANOVA analyses, statistical significance was test at the α=0.05 level, and the Tukey-Kramer post-hoc comparison of the means test was used to determine differences among groups. Each ANOVA was conducted as a within-subjects (repeated measures) analysis with time since treatment as the within-subject variable and each plot as the subject. When model assumptions were not met, data were log or square-root transformed to meet assumptions.

3. Results

3.1 Areal Treatment Site

Surface fuel loading immediately following understory mowing in pine flatwoods ranged from 9.6 to 35.6 $Mg \cdot ha^{-1}$, from destructive sampling, with foliar litter accounting for over two-thirds of mass, on average (Table 1). Litter depth and mass averaged 5.4 cm and 12.6 $Mg \cdot ha^{-1}$, respectively. Of the fine woody fuels collected, only 20% of the 3.1 Mg·ha-1 of 1h fuels, and only 25% of the 2.1 Mg·ha^{-1} of 10h fuels, on average, were fractured following mowing. Only two plots had 100h fuels within sampling quadrats, one plot with a fractured particle and one with an unfractured particle. Average duff depth and mass was 3.6 cm and 41.9 Mg·ha^{-1}, respectively.

Destructive sampling allowed for the development of biomass equations to be used for subsequent non-destructive sampling. Post-mowing litter mass was correlated with litter depth measurements (R^2=0.93, p<0.001) and a regression equation was developed to estimate mass from depth measurements. One year following treatment, litter mass per unit depth was slightly higher (14%) than immediately post-treatment, however less variation in litter mass was explained by depth (R^2=0.74, p<0.001). Duff mass was well explained by duff depth following-treatment (R^2=0.94, p<0.001) and at one year post-treatment (R^2=0.97, p<0.001), however, regression models indicate an almost 20% increase in bulk density one year following treatment. Regression figures and associated equations for litter and duff biomass are included in Appendix A. From the 40 saw palmetto fronds collected for allometry, frond mass was best predicted by total frond length (R^2=0.92, p<0.001) and a regression equation was developed to estimate biomass from non-destructive measurements (Fig. 3).

Non-destructive sampling revealed the transformation of shrub and small tree biomass into compact fine surface fuels via understory mowing. Pre-treatment overstory in the areal site consisted of 358 trees per ha (tph), 18.8 m^2 per ha of basal area (BA), and a quadratic mean diameter (QMD) of 25.8 cm. Average tree height was 16.7 m and crown base height (CBH) was 12.0 m (Table 2). Following mowing, tree density was slightly reduced (p=0.002) whereas QMD, tree height, and CBH increased (p<0.005 for all). Since only small trees were removed during treatment, BA did not differ following treatment (p=0.577). Shrub density (>0.5 m tall) was reduced to <15% of pre-treatment values (p<0.001) and those remaining, mostly near tree boles, were somewhat shorter than the average shrub height prior to mowing (p=0.015) (Table 2). As a result of treatment, shrub biomass was reduced by almost 95% (p<0.001). From non-destructive sampling (planar intercept method) of surface fuels, estimated biomass of both 1h and 10h woody fuels increased following mowing (1h, p=0.022; 10h, p<0.001), however 100h and 1000h woody fuels did not change. Mowing reduced litter depth slightly, from 7.8 to 6.0 cm (p=0.005), but increased litter mass from 9.0 to 13.4 $Mg \cdot ha^{-1}$ (p<0.001). Duff depth was also reduced following treatment (p<0.001), from 5.8 to 3.8 cm, but duff mass was unchanged (p=0.982). Average depth of fine woody debris (1h,10h, and 100h) was 7.3 cm and did not change following treatment (p=0.361).

3.2 Buffer Treatment

Mowing in the buffer site reduced overstory tree density in all stand types (mature, mature-burned, plantation), but only significantly reduced basal area in the mature stands (Table 3). While density did not statistically differ between pre- and post-mowing in the plantation stands, density was lower 2 years following mowing. Quadratic mean diameter (QMD) in mature and mature-burned stands significantly increased, however QMD was not affected by mowing in the plantation. Average tree height increased in both mature stand types following mowing, but not in the plantation, however height did statistically increase in plantation stands two years later. In both mature and mature-burned stands, CBH was increased after treatment, but CBH increased again two years later in the recently burned stands. CBH only differed two years following treatment.

Shrub biomass (> 0.5m tall) was reduced by ~90% following treatment, but by 16 months was already increasing across all stand types (Fig. 4, Table 4). An interaction between time since treatment (TST) and stand type suggested that changes in shrub biomass following treatments differed among stand types. Plantations had less initial shrub biomass than both mature stand types, while mature/burned stands recovered to greater biomass after 16 months than both the unburned stand types. Surface fuels increased by about 10 $Mg \cdot ha^{-1}$ in unburned mature stands and plantations, but only increased by 4 $Mg \cdot ha^{-1}$ in the recently burned stands. Although total fuel loading (shrubs and surface fuels) was unchanged in mature/burned stands, total fuel increased in unburned mature stands and especially in plantations.

Regarding specific shrub characteristics, shrub foliage, which should translate into surface litter following mowing, was reduced by 2.0 and 3.0 $Mg \cdot ha^{-1}$ in mature and mature/burned stands, respectively, similar to the 2.2 and 2.9 $Mg \cdot ha^{-1}$ increases in surface litter observed in those sites (Fig. 5 and 6). In plantation stands, however, shrub foliage was only reduced by 1.1 $Mg \cdot ha^{-1}$, but surface litter increased by 5.9 $Mg \cdot ha^{-1}$. Values, by stand type and time since treatment (TST), of specific shrub characteristics (foliage and stem biomass, shrub height, and shrub density) and biomass of surface fuel classes (litter, 1h, 10h, 100h, 1000h sound, 1000h rotten, and duff) are listed in Appendix B. Shrub stems, which should translate into 1 or 10h woody surface fuels (shrub basal diameters were <1.0 cm), were reduced by 2.9, 1.6, and 0.3 $Mg \cdot ha^{-1}$ in mature, mature/burned, and plantation stands, respectively (Fig. 5), however 1h woody fuels increased by 2.8, 1.9, and 2.5 $Mg \cdot ha^{-1}$, and 10h fuels increased by 4.2, and 2.9 $Mg \cdot ha^{-1}$ in the unburned mature and plantation stands, respectively, with no change in recently burned mature stands (Fig. 6). Therefore, more litter was added to surface fuels in plantations than what was accounted for by mowed shrub foliage and substantially more fine woody material was added to the forest floor than the shrub stems that were treated. And in unburned mature stands, 1h and 10 h fuel increases, combined, exceeded that of shrub stem biomass mowed, however 1h woody fuel additions were close to the biomass of stems treated in both the unburned and burned mature stands. Average shrub heights did not differ following treatment, however shrub density was substantially reduced (Fig. 5), but had recovered to pre-treatment densities by 16 months in the unburned stands (mature and plantations), but not in the mature/burned stands, where pre-treatment shrub density was very high prior to treatment.

While mowing treatments increased surface fuels immediately, biomass of fine fuels changed over time following treatment. As mentioned above, surface fuels increased just following treatments in all stand types, but 1h fuels subsequently decreased at 8 and 16 months post-treatment (Fig. 6). And 10h woody fuels were only higher than pre-treatment loading after 8 months in the unburned plantations. 100h surface fuels were not as abundant as 1h and 10h fuels across planar intercepts and did not statistically differ across time since treatment ($p=0.500$), however these larger fuels were greater in biomass in the unburned mature and plantation stands compared to the recently burned mature stands. Surface litter increased just following treatment, as mentioned above, however mowing in unburned plantation stands resulted in greater surface litter mass than unburned mature stands ($p=0.006$), even though pre-treatment litter did not differ.

1000 h surface fuels, which contribute to flaming and smoldering combustion, were rare prior to treatment in all stand types. Sound 1000h fuels increased following mowing in all stand types, and expectedly 1000h rotten fuels did not (Fig.7). 1000h sound fuels increased more in unburned mature stands than in mature-burned stands, and increased even more in plantation stands, where there were none prior to treatment. While 1000h sound fuels were observed in mature/burned stands after treatment, but not before, they were still infrequent (0.4 $Mg \cdot ha^{-1}$). Duff, which also contributes to smoldering combustion, was not changed just after treatment in both unburned and recently burned mature stands, however duff mass increased just after treatment in plantations and increased after 8 months in mature-burned stands, with no subsequent changes in either stand types. It should be pointed out, however, that duff mass was estimated with the assumption that duff bulk density increased immediately following mowing, but was no different between 2 and 8 mos after treatment, then subsequently increased, but with no changes between 16 and 24 mos.

4. Discussion

Surface fuelbeds following understory mowing in this palmetto/gallberry pine flatwoods site were dominated by foliar litter, with a lower proportion of fine woody fuels. This is in contrast to many other post-masticated sites that have been studied, where fine woody fuels dominate (Glitzenstein et al., 2006; Kane et al., 2009; Kobziar et al., 2009; Battaglia et al., 2010) (see Appendix C for comparisons across studies). Few studies have addressed mastication in shrub or forest ecosystems of the southeastern USA, especially in pine flatwoods (Glitzenstein et al., 2006; Menges and Gordon, 2010). Of those studies, none describe detailed fuelbed characteristics, but instead address a treatment effect on other attributes. Since pine flatwoods are typically burned on a frequent interval, stands that are in need of mechanical treatment from lack of fire may have not burned in as little as five years. Small trees are not abundant, resprouting shrubs are short-statured, and saw palmetto, a dominant shrub, is primarily foliar. Therefore, litter dominated surface fuels following mastication is much different than in other ecosystems where treatments occur in older shrublands and forests with substantial under- and mid-story tree density (Glitzenstein et al., 2006; Kane et al., 2009; Kobziar et al., 2009). Understanding their characteristics and temporal dynamics enhances our general understanding of mechanical fuel treatments and provides insight for fire hazard reduction and potentially other important management considerations such as biomass utility for energy production or carbon sequestration.

Evidence of increased bulk density of litter and duff one year following treatment in these pine flatwoods stands may be critical for post-treatment prescribed fire use where reduction of surface fuels is desired. Compaction may result in increased moisture retention (Kreye et al., 2012), but also long duration heating when burned (Busse et al., 2005; Kreye et al., 2011; Kreye et al., 2013). Meeting management goals when burning in these fuelbeds may require special attention to moisture dynamics to ensure desired fuel consumption while minimizing potential effects. Long duration heating in compact surface fuels (Kreye et al., 2011; Kreye et al., 2013) may result in ignition of duff and potential overstory mortality if conditions are dry (Varner et al., 2007; Kreye, 2012). If surface fuels are slow to lose moisture (Kreye et al., 2012), however, desired fuel consumption may not occur even if flammability of shrubs is high enough to carry fire (Gagnon et al., 2010). Effective burning regimes in these novel fuelbeds may require additional knowledge to ensure that management objectives are met.

Shrubs were reduced from mowing in the three buffer stand types, however shrub recovery was evidenced as quickly as 16 months following treatment. Treatment effectiveness in this site may be short-lived due to rapid recovery of shrub biomass combined with treatment-associated accumulation of surface fuels. Even shortly after treatments occurred, total fuel contributing to flaming combustion (shrubs, litter, and fine woody materials) was greater in the unburned mature and plantation stands in this study. Greater total fuel loads following treatment likely results from the small trees that were masticated during treatment, but were not counted as pre-treatment fuels. Understory trees were not considered combustible fuel since they are not primary drivers of fire behavior in this shrub-dominated ecosystem (Hough and Albini, 1978). There were fewer understory trees in the recently burned mature stands and total fuel loading was not increased by mowing. Areas that have gone unburned for several years are likely to be primary targets for these treatments. The conversion of shrubs and understory trees into surface fuels may minimize crown fire potential, but at the cost of increasing surface fire behavior, including both flaming and smoldering combustion. Although a window of opportunity likely exists to conduct post-treatment burning prior to shrub recovery, the addition of surface fuels may be an important consideration in evaluating potential ecological consequences when these dense surface fuels burn.

The dynamics of forest fuels is an important consideration for evaluating the effectiveness and potential consequences of fuels treatments. Several studies have addressed changes to fuel properties following burning treatments (Agee et al., 1977; Knapp et al., 2005; Sah et al., 2006), however little attention has been given to post-treatment fuel dynamics following mechanical treatments (Stephens et al., 2012). Immediate post-treatment fuel conditions may be short-lived and subsequent changes to fuel loading and structure may be more critical for evaluating treatment effectiveness. The immediate effect of converting standing live fuels into surface fuelbeds is a dramatic shift in both fuel arrangement and bulk density, however, vegetation recovery and subsequent surface fuel compaction will need to be considered. Where mastication treatments inhibit vegetation recovery, fires may be limited to low intensities and slow spread rates (Knapp et al., 2011). And while compacting fuels may enhance moisture retention (Kreye et al., 2012; Kreye et al., In Press), the loss of shrub cover may actually result in drier surface fuels following mastication treatments (Kreye, 2012). The rate in which surface fuels decompose will be an important component in post-treatment fuel dynamics. In sites similar to this study, Kreye (2012) observed ~25% of litter and ~15% of fine woody mass lost to decomposition after one year. In locations where shrubs recover rapidly, e.g. from resprouting as in this study, fire hazard reduction, however, may be short-lived, with shrubs quickly regaining influence over fire spread and intensity (Kreye, 2012). Both decomposition rates (Gholz et al., 1985) and vegetation response (Kane et al., 2010) may vary greatly across regions and in different forest types. Their contribution to the dynamics of forest fuels following mechanical treatments will be important considerations to evaluate the efficacy of such treatments aimed at mitigating fire hazard.

In addition to improving our understanding of fuel dynamics, the translation of understory shrubs and small trees into forest floor surface debris, observed here, provides insight into potential biomass for energy utilization. While this *in situ* study occurred in one location of the Southeastern Coastal Plain, differences in post-treatment surface biomass observed across the different stand types may provide coarse biomass estimates following mowing in common pine flatwoods forests of the region. Equations developed here to estimate surface biomass using non-destructive sampling, primarily from bulk density estimates of litter and duff, may not be appropriate in all flatwoods sites, however this method could be used to estimate biomass in other sites. Non-destructive estimates of litter, duff, and fine woody biomass, from the commonly used intercept method (Brown 1974), were close to those estimated destructively, however non-destructive intercept sampling estimated a greater biomass (+48%) of 10h fuels compared to destructive sampling. This has been observed in other masticated flatwoods sites of the Southeast (Glitzenstein et al. 2006). More importantly, however, these findings highlight that total understory biomass may actually increase following treatments due to stimulated regrowth of shrubs. If used as a stand-alone treatment, mowing may increase carbon storage where shrubs and small trees are converted to surface debris, but where shrubs resprout vigorously and grow rapidly following treatment (Gholz et al., 1999; Lavoie et al., 2010).

Further work evaluating the decomposition rates of mowed debris, the long-term effects on soil carbon, and how these treatments influence the long-term growth of shrubs and overstory trees will provide further insight into carbon dynamics across fuels treatment regimes (Gholz et al., 1985; Gonzales-Benecke et al., 2010; Lavoie et al., 2010).

The site we observed in this study indicates that mowed surface fuels in pine flatwoods are unique in their high proportion of litter and their rapid vegetation recovery; results which differ from previously published fuels treatments effects. While shrubs are reduced following mowing, the effectiveness of treatments at altering fire behavior may be short-lived, so follow-up prescribed burning will likely need to occur soon after treatment. The addition of surface fuels, however, especially in unburned pine flatwoods, may present fire managers with potential problems if burning in these compact fuelbeds results in damage to fine roots or basal cambial tissue of residual trees (Varner et al., 2007; O'Brien et al., 2010), compromising the long-term stability or resilience of treated sites. Considerations regarding surface, duff, and soil moisture will need to be taken into account to minimize overstory tree mortality and to ameliorate smoldering emissions. This study provides insight into how forest fuels may respond in the short-term to mechanical treatments. Additional studies in flatwoods ecosystems across its expansive range will help elucidate the effects of these treatments more generally in a region where they are being widely applied. Due to the high proportion of fine fuels and rapid understory recovery observed in this ecosystem, however, the expedited dynamics of fuels characteristics following mowing may provide additional insight as to how forest fuels may respond in the longer-term in other more slowly recovering ecosystems where larger diameter woody fuels may decay slowly and shrub recovery is delayed. Complimentary research evaluating post-treatment fire behavior in these fast recovering ecosystems may also provide much needed insight into the efficacy of treatments at mitigating fire hazard where mechanical fuel treatments are being applied.

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Fig. 1. Mechanical fuels treatments (500 ha areal treatment and 60 ha buffer treatment) where mowing was implemented in palmetto/gallberry pine flatwoods in Osceola National Forest in north-central Florida, USA.

Fig. 2. Fuels and vegetation sampling in the areal mowing treatment site. Fuel/vegetation measurement sampling followed the same protocol in the Buffer site, excluding the forest floor biomass plots.

Fig. 3. Saw palmetto allometry used for estimation of biomass from non-destructive sampling. Frond includes rachis and lamina.

Fig. 4. Shrubs (a), surface fuels (b) (litter, 1h,10h, and 100h fuels), and total fuel (c) (shrub + surface) loading ($Mg{\cdot}ha^{-1}$) following mowing treatment in 3 stand types (mature, mature/burned (burned 5 yrs prior to mowing), and plantation) of palmetto/gallberry pine flatwoods in north-central Florida, USA. 0 time since treatment= pre-treatment. Error bars are reflective of the variation across the treated sites.

Fig. 5. Shrub foliage (a) and shrub stem (b) biomass, shrub height (c), and shrub density (d) following mowing treatment in 3 stand types (mature, mature/burned (burned 5 yrs prior to mowing), and plantation) of palmetto/gallberry pine flatwoods in north-central Florida, USA. 0 time since treatment= pre-treatment. Error bars are reflective of the variation across the treated sites.

Fig. 6. Surface fuel components, 1h (a), 10h (b), 100h (c), and litter (d), following mowing treatment in 3 stand types (mature, mature/burned (burned 5 yrs prior to mowing), and plantation) of palmetto/gallberry pine flatwoods in areal and buffer sites in the Osceola National Forest of north-central Florida, USA. 0 time since treatment= pre-treatment. Error bars are reflective of the variation across the treated sites.

Fig. 7. Large woody fuels, 1000h-S (sound) (a) and 1000h-R (rotten) (b), and duff (c) biomass following mowing treatment in 3 stand types (mature, mature/burned (burned 5 yrs prior to mowing), and plantation) of palmetto/gallberry pine flatwoods in buffer and areal sites of the Osceola National Forest in north-central Florida, USA. 0 time since treatment= pre-treatment. Error bars are reflective of the variation across the treated sites.

Appendix A. Litter (top) and duff (bottom) mass as a function of depth following mowing treatments in palmetto/gallberry pine flatwoods in north-central Florida, USA. Measurement taken just after mowing (left) and one year following mowing (right).

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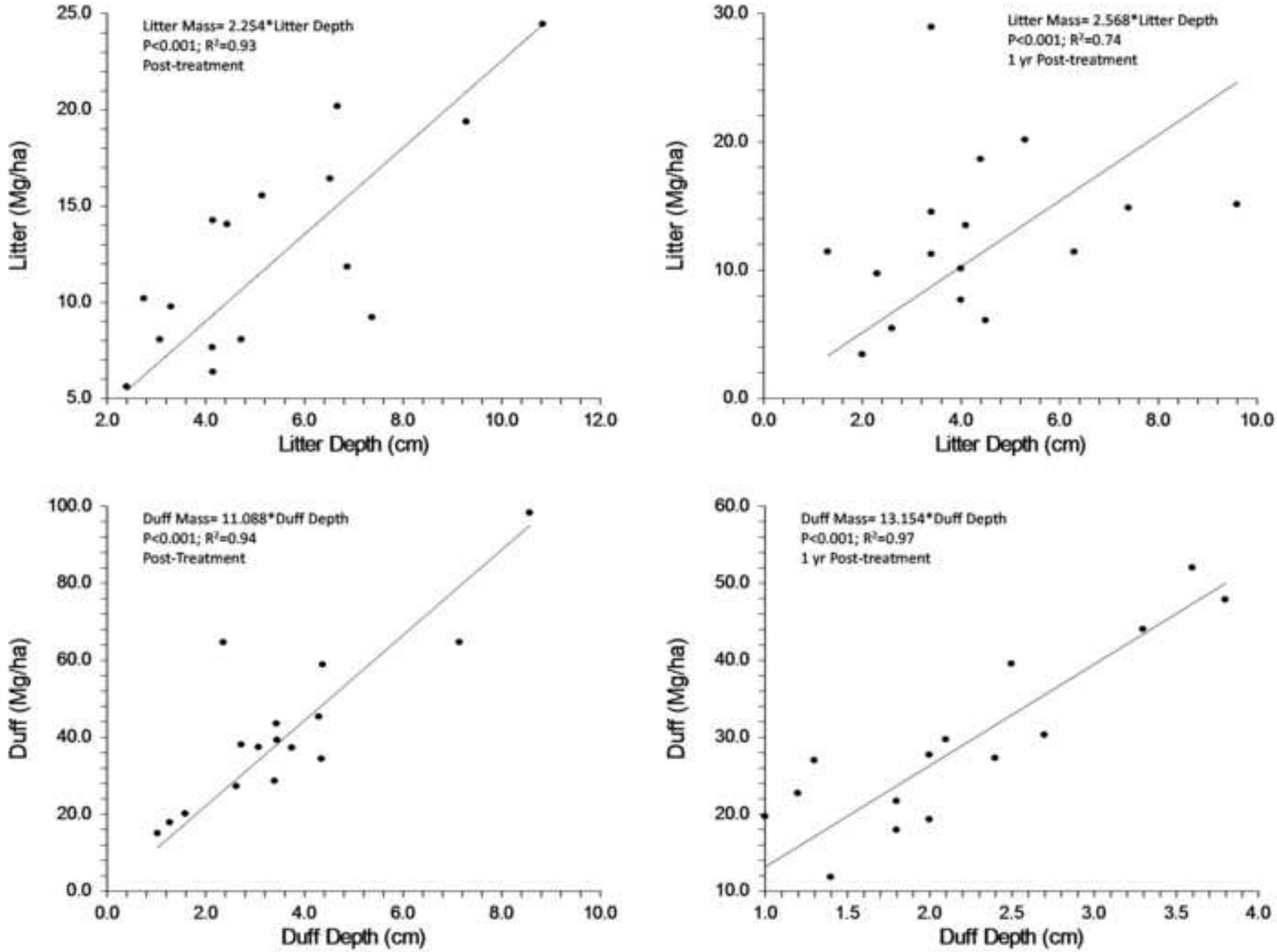

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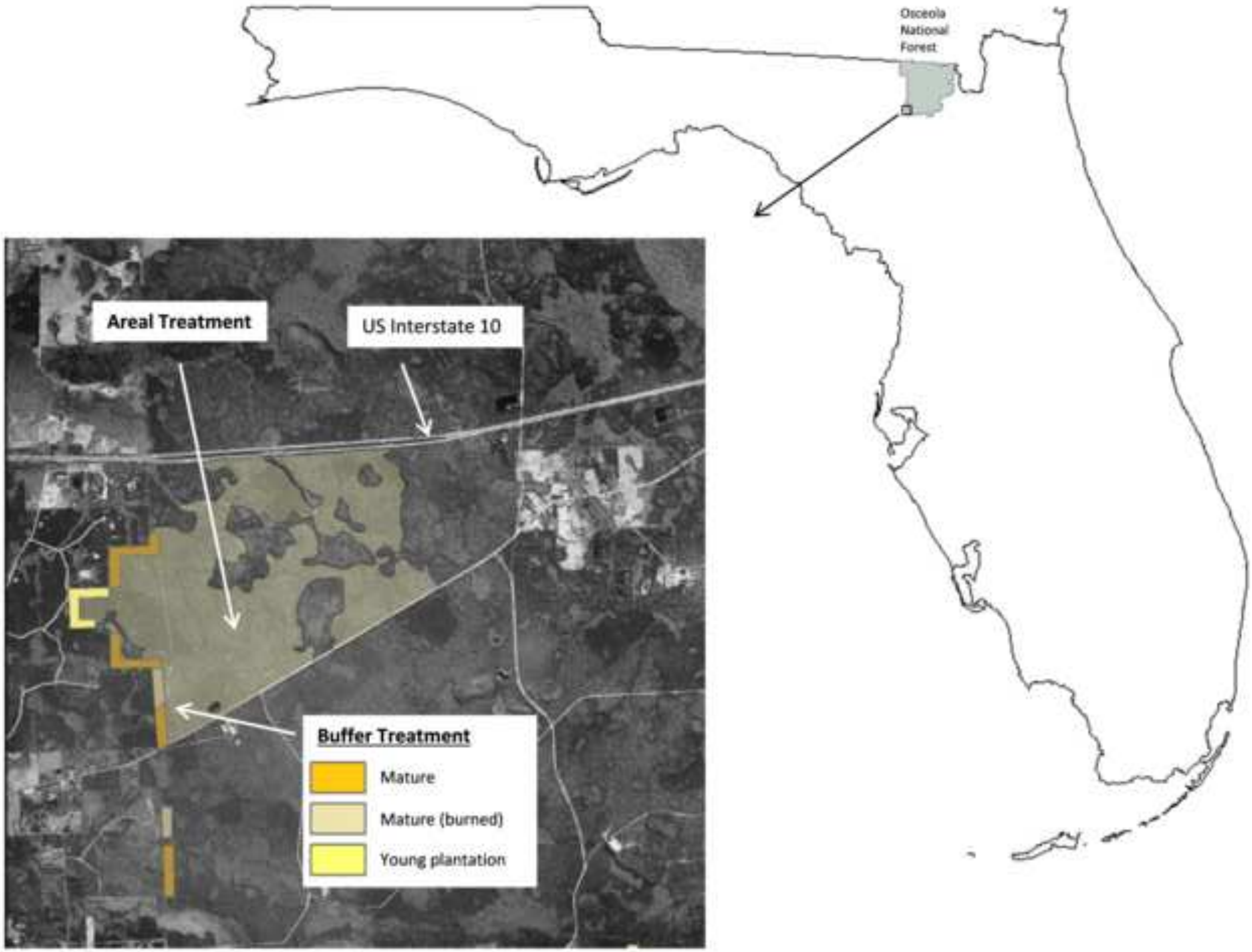

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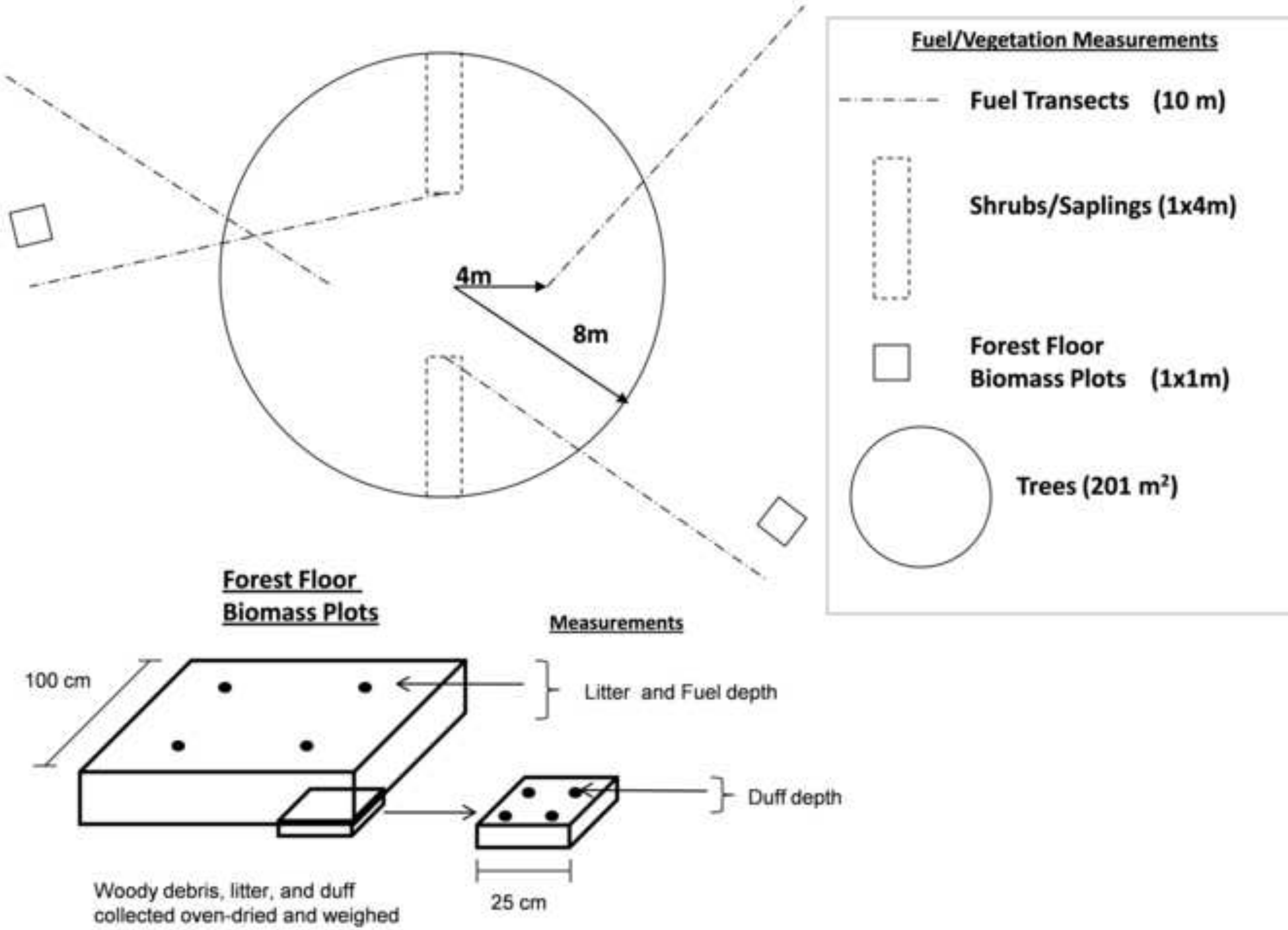

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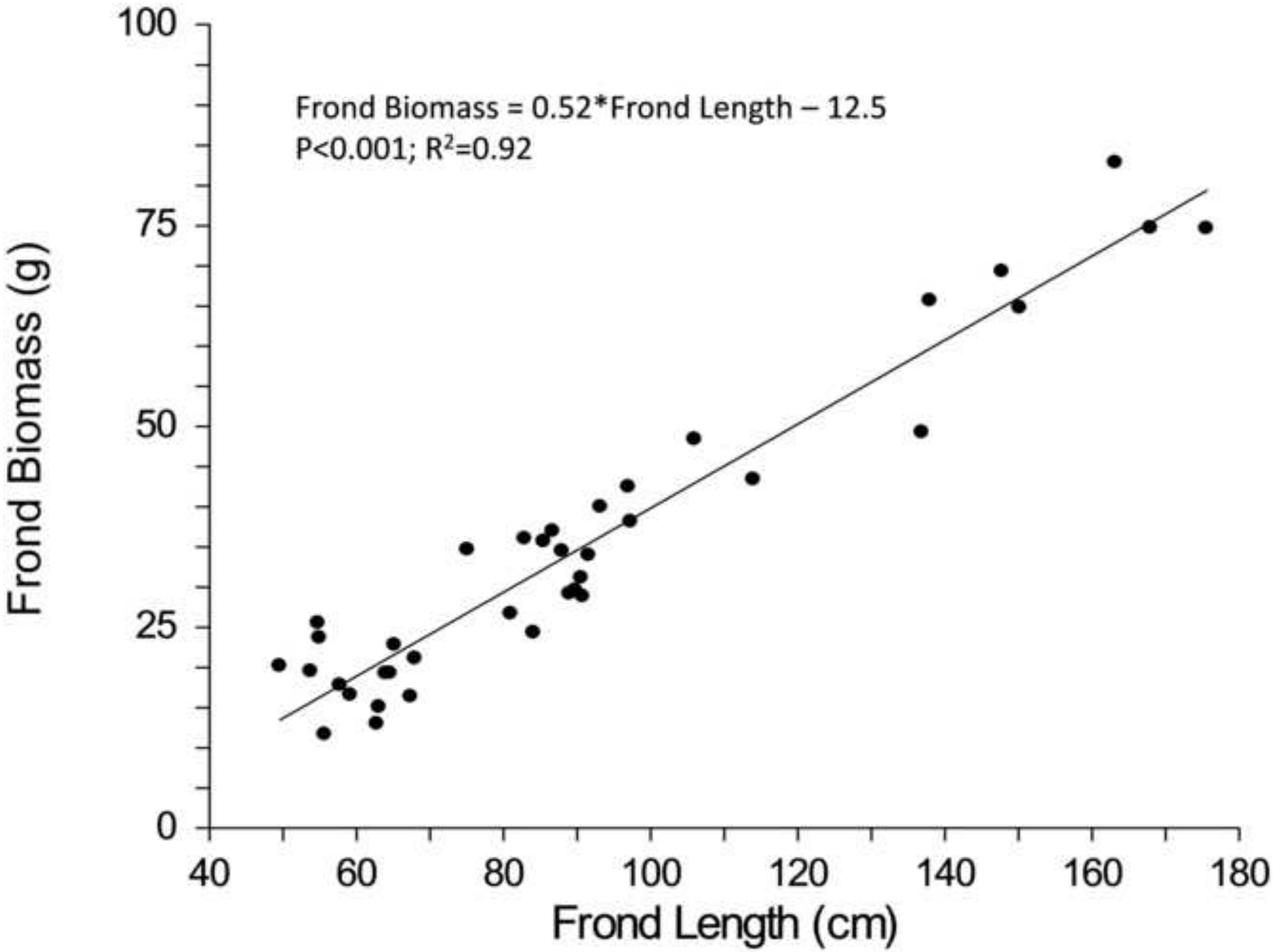

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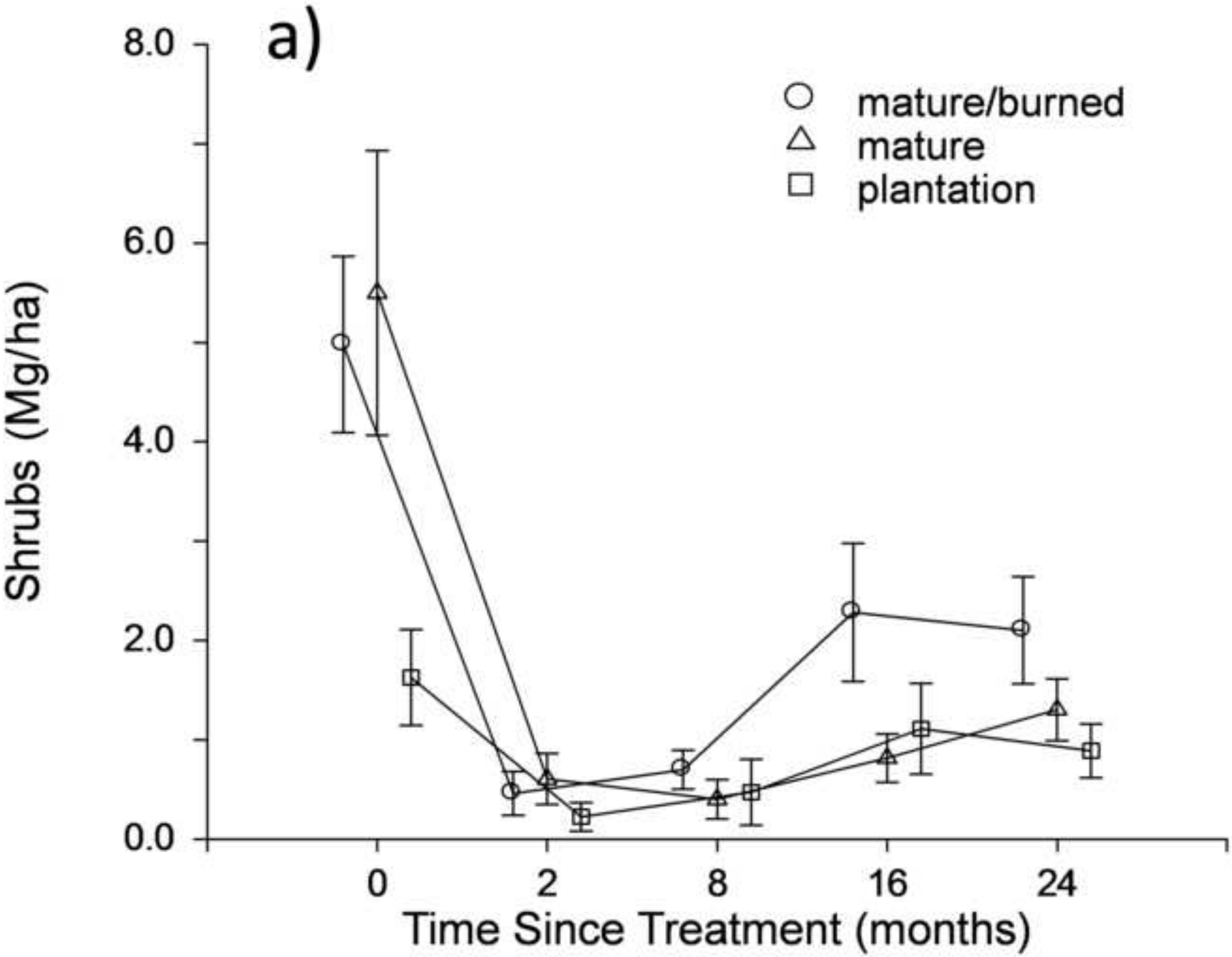

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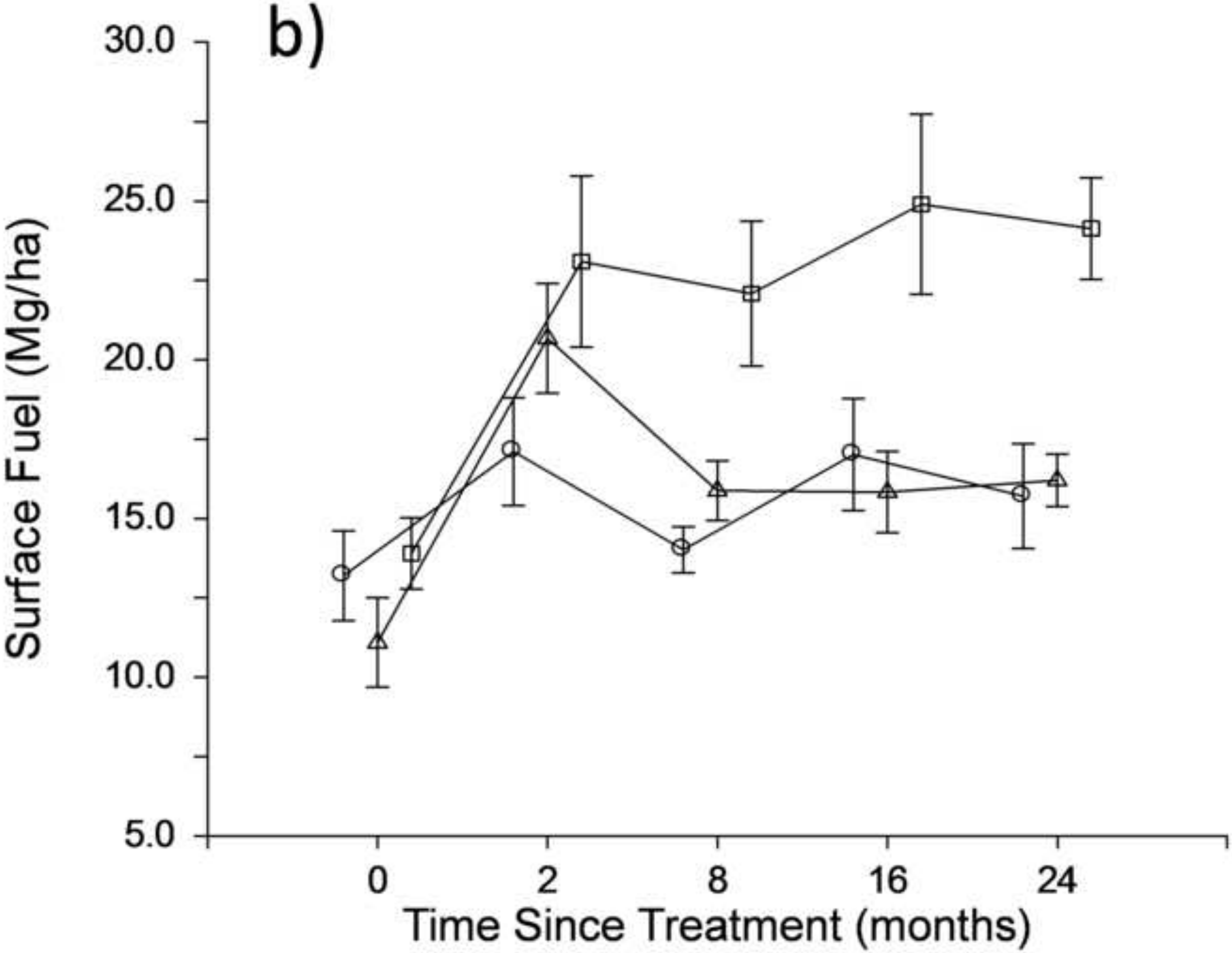

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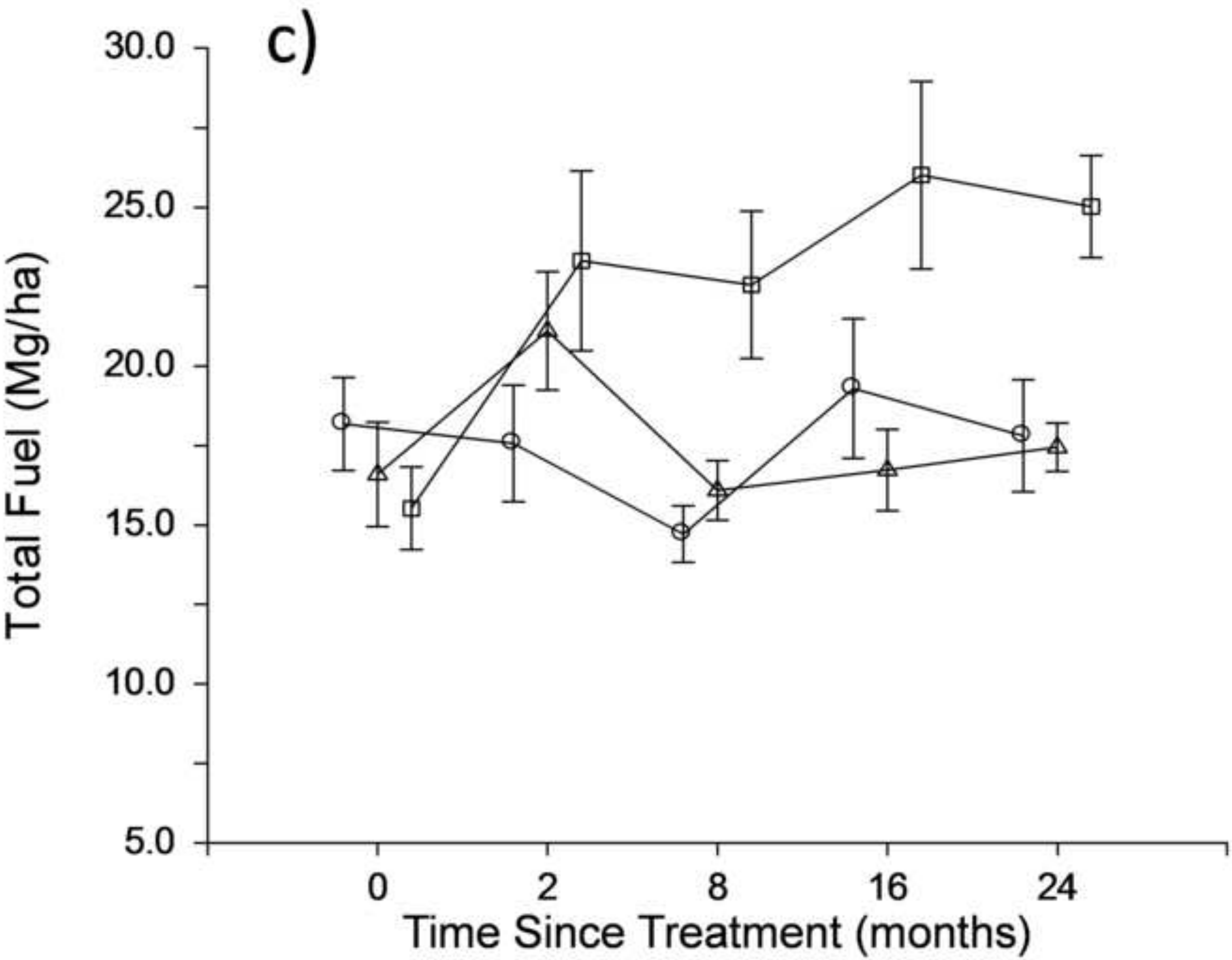

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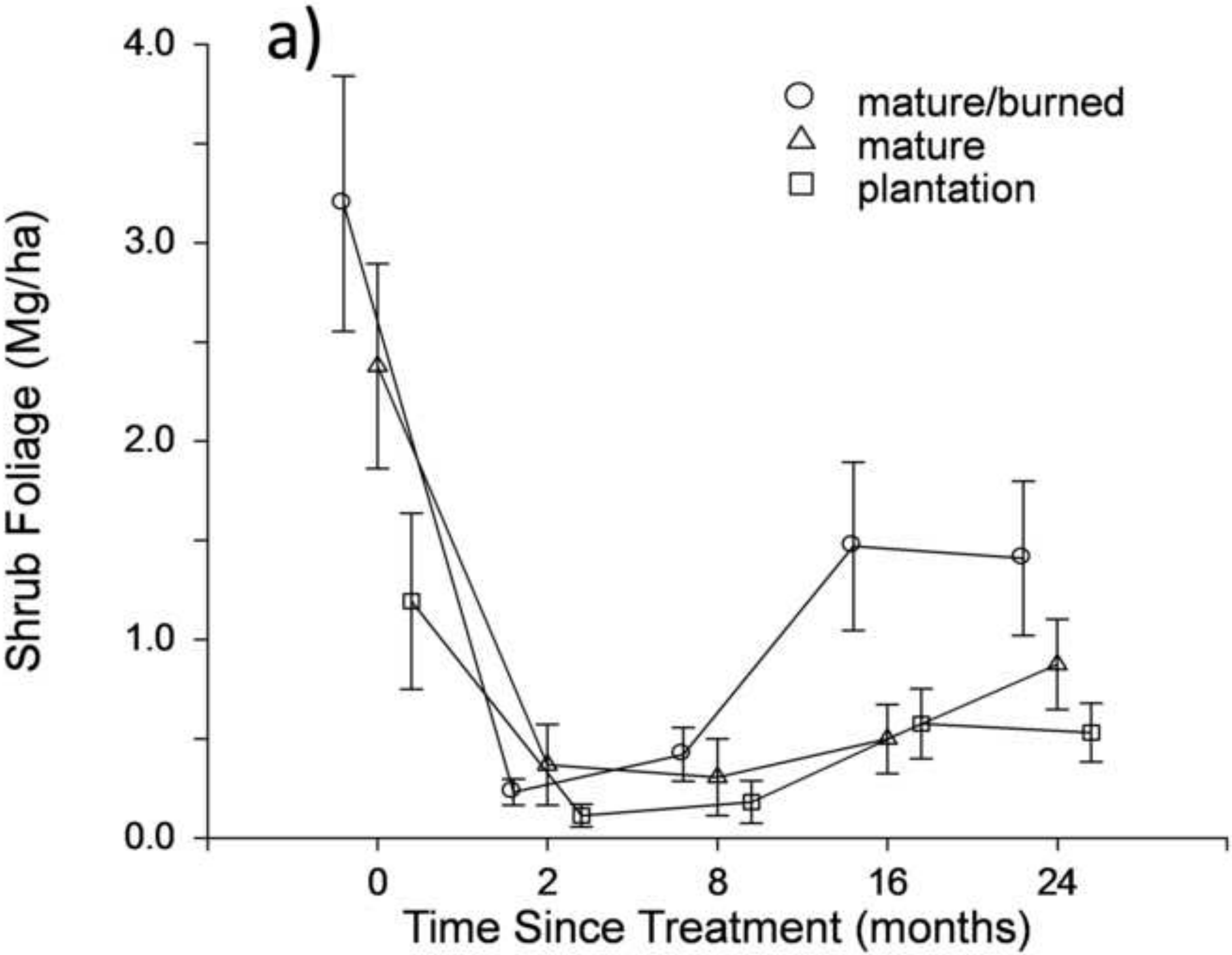

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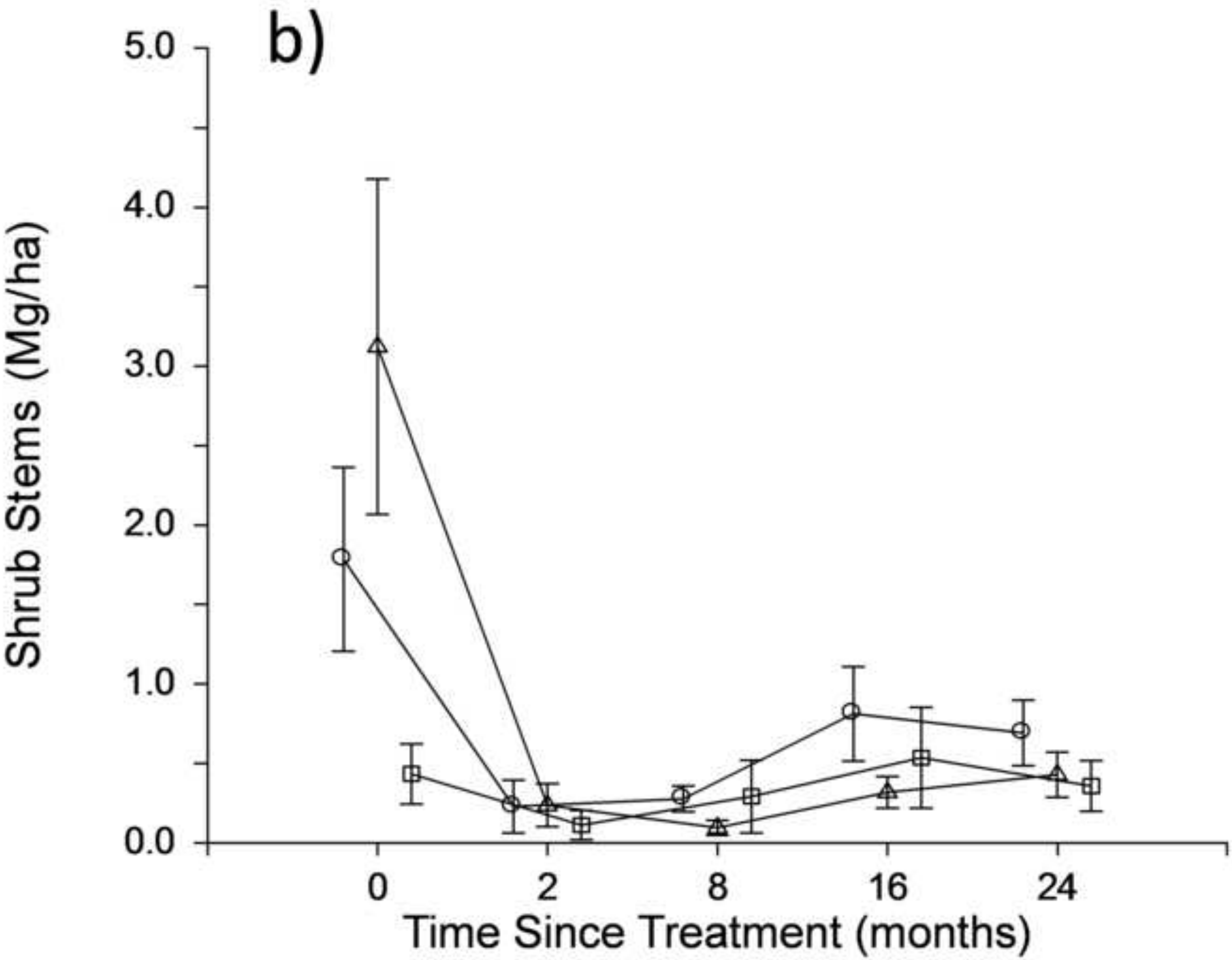

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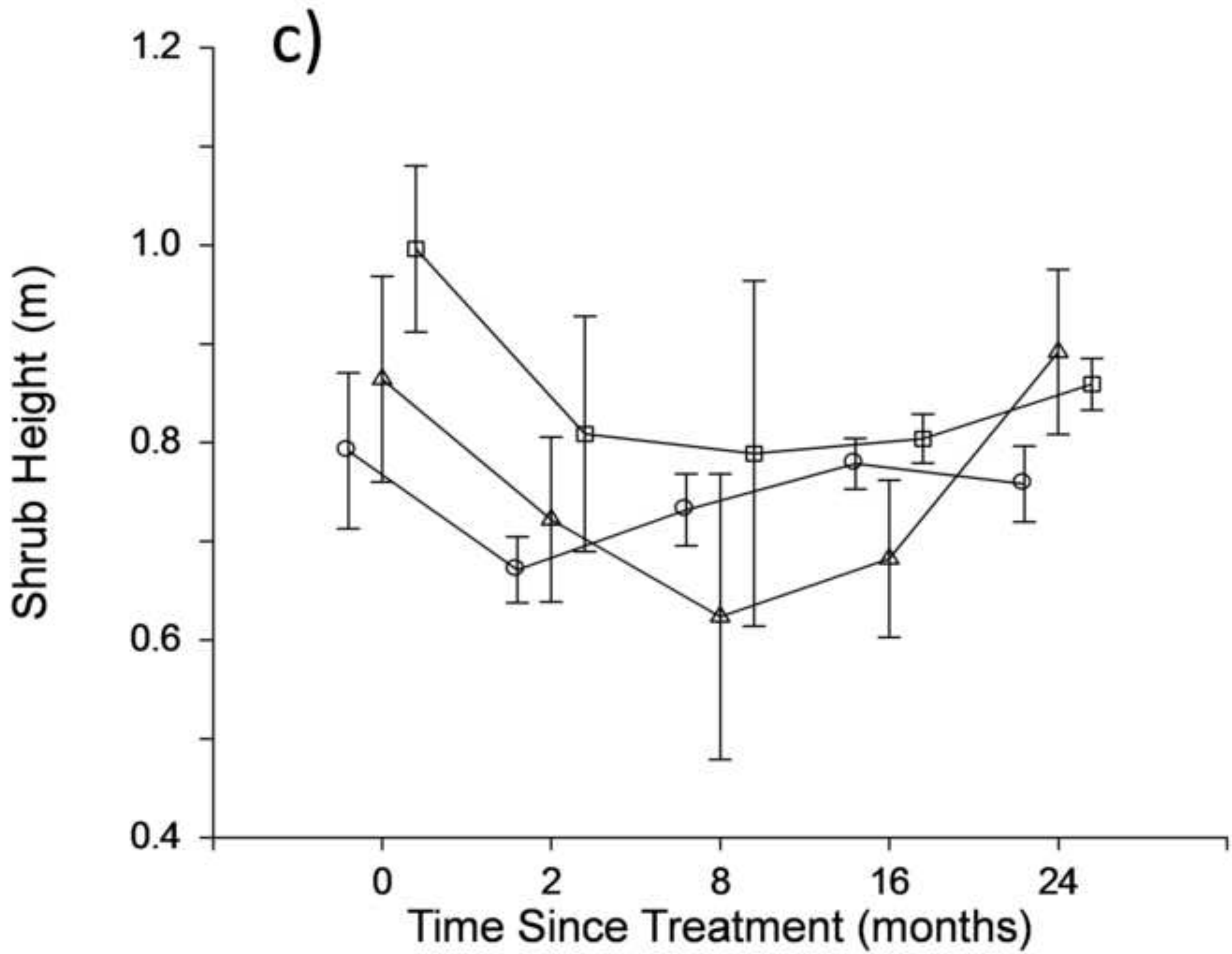

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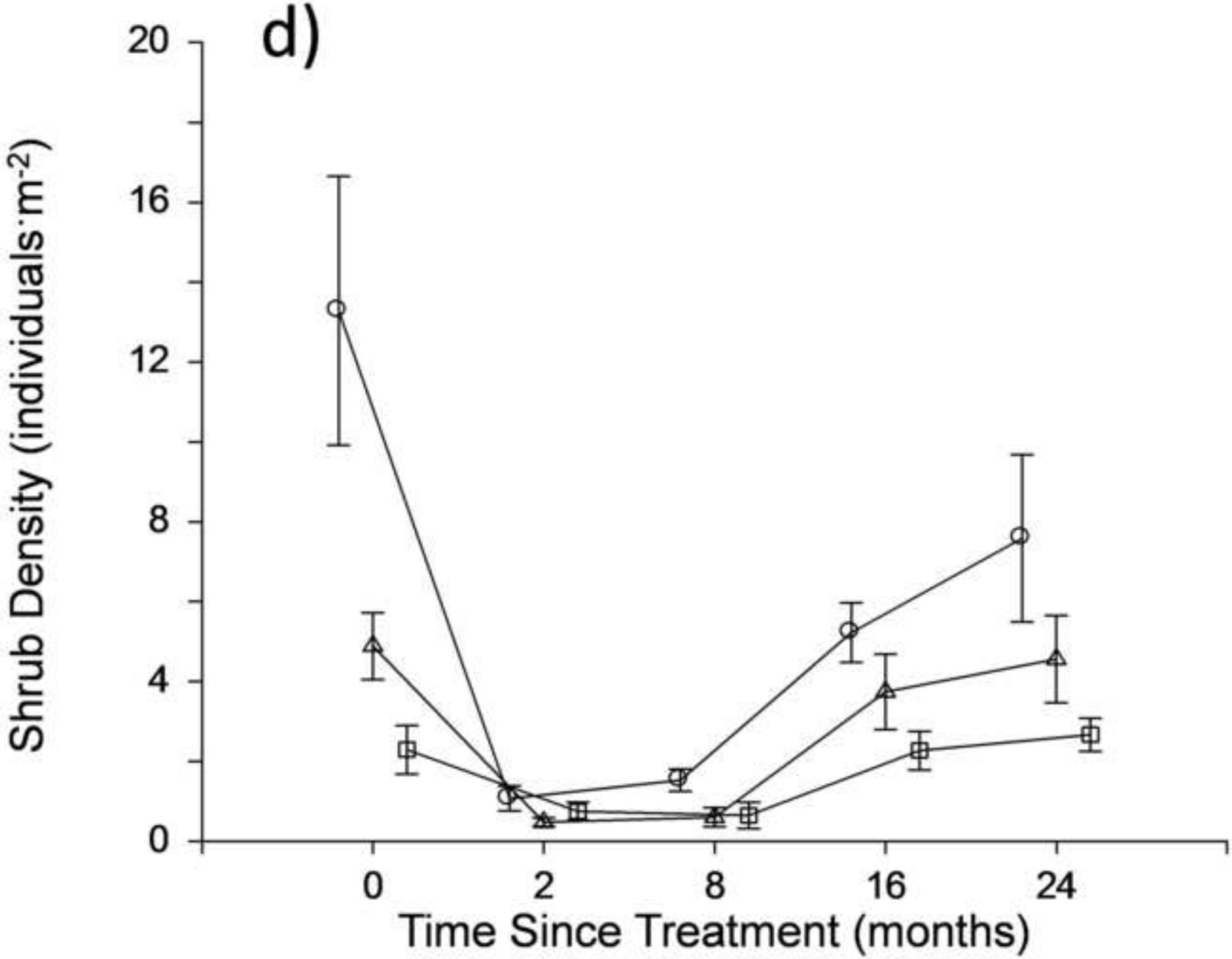

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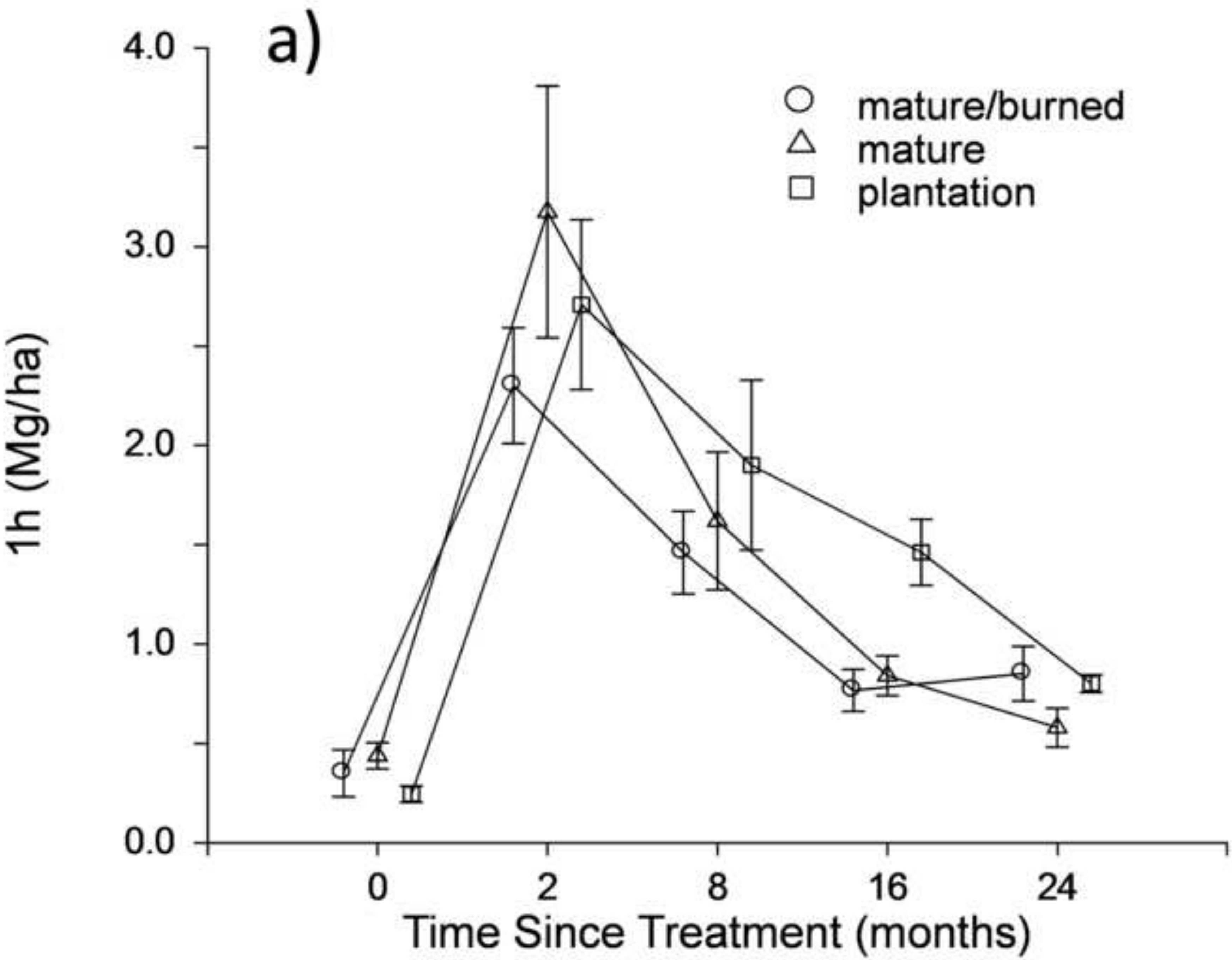

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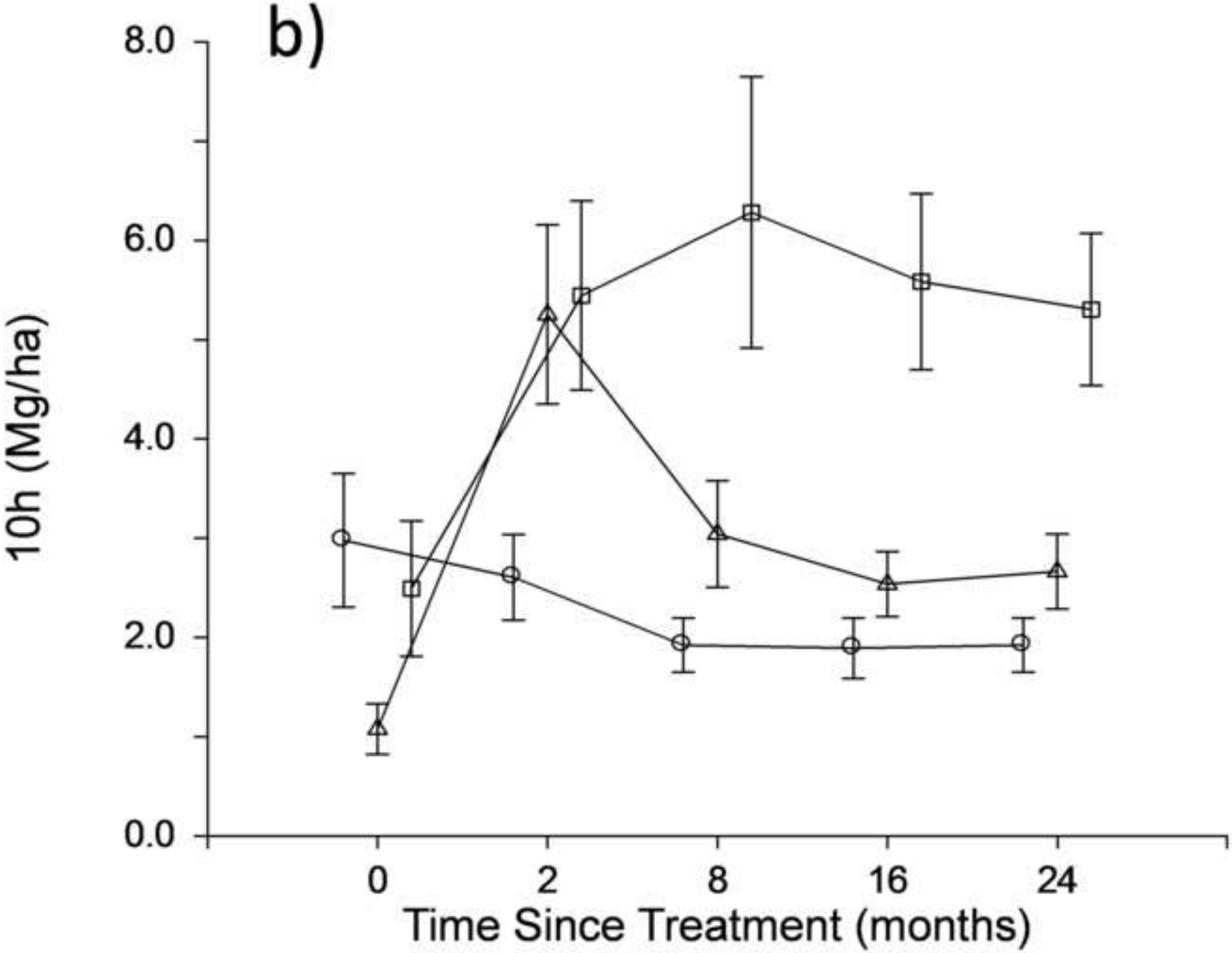

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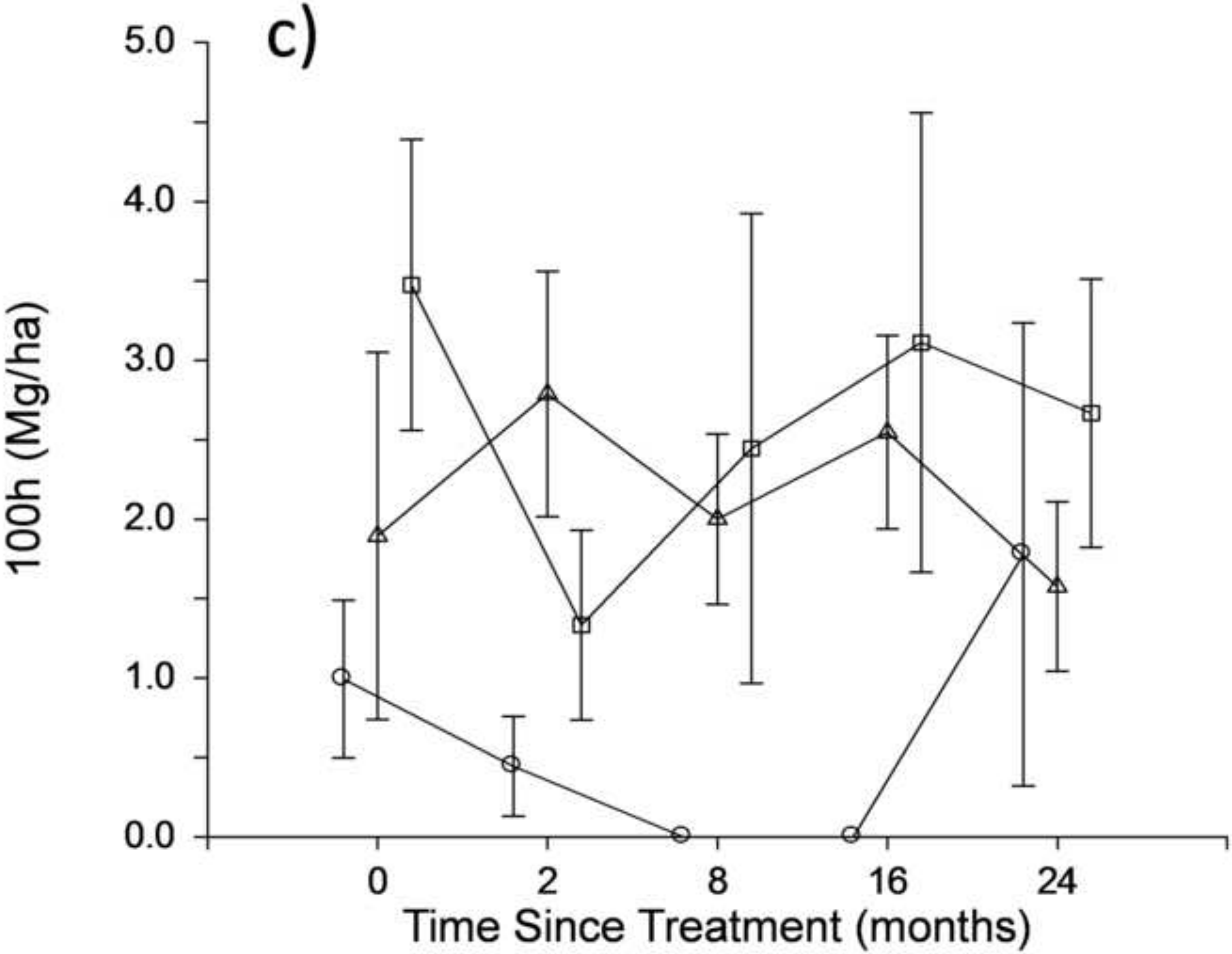

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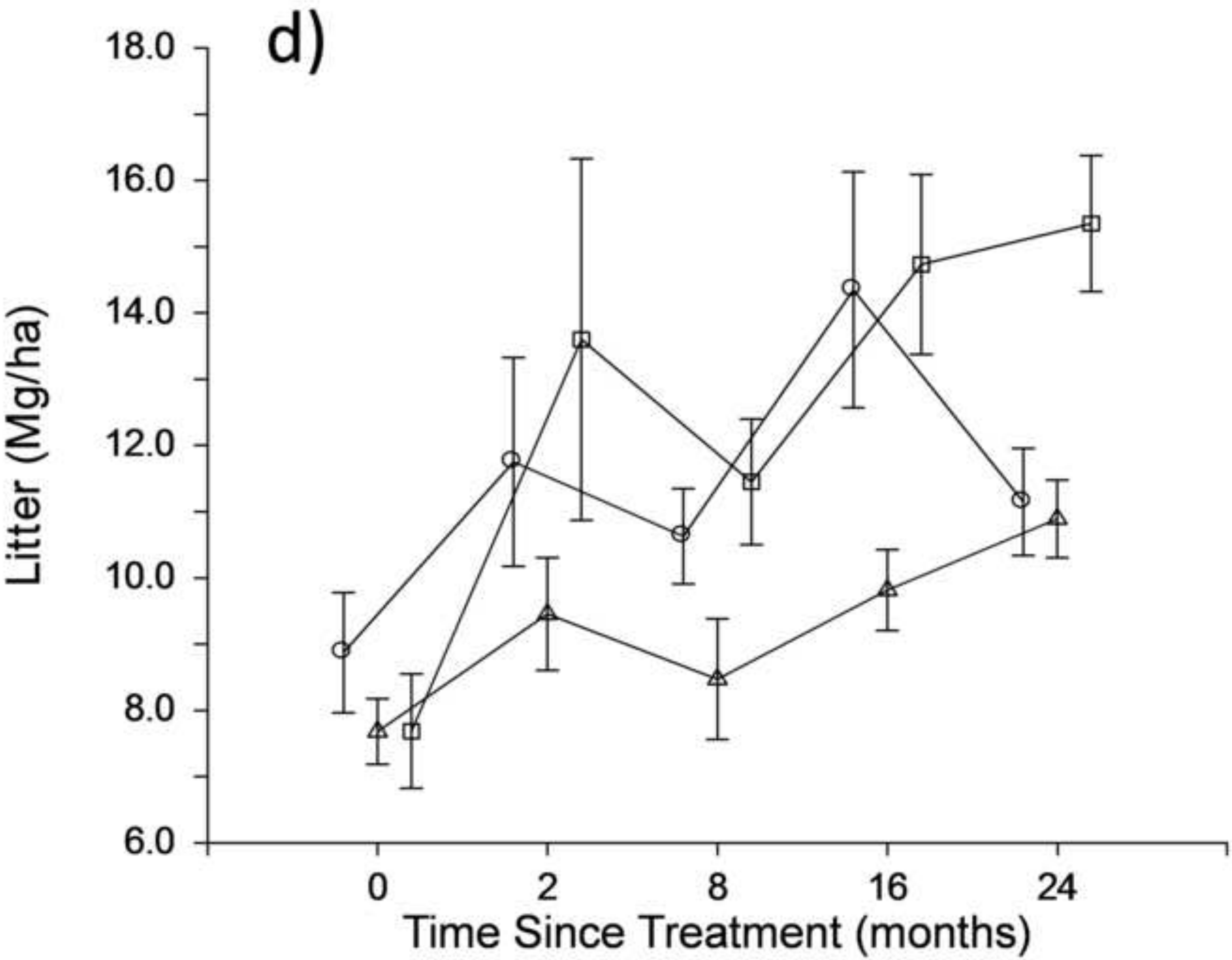

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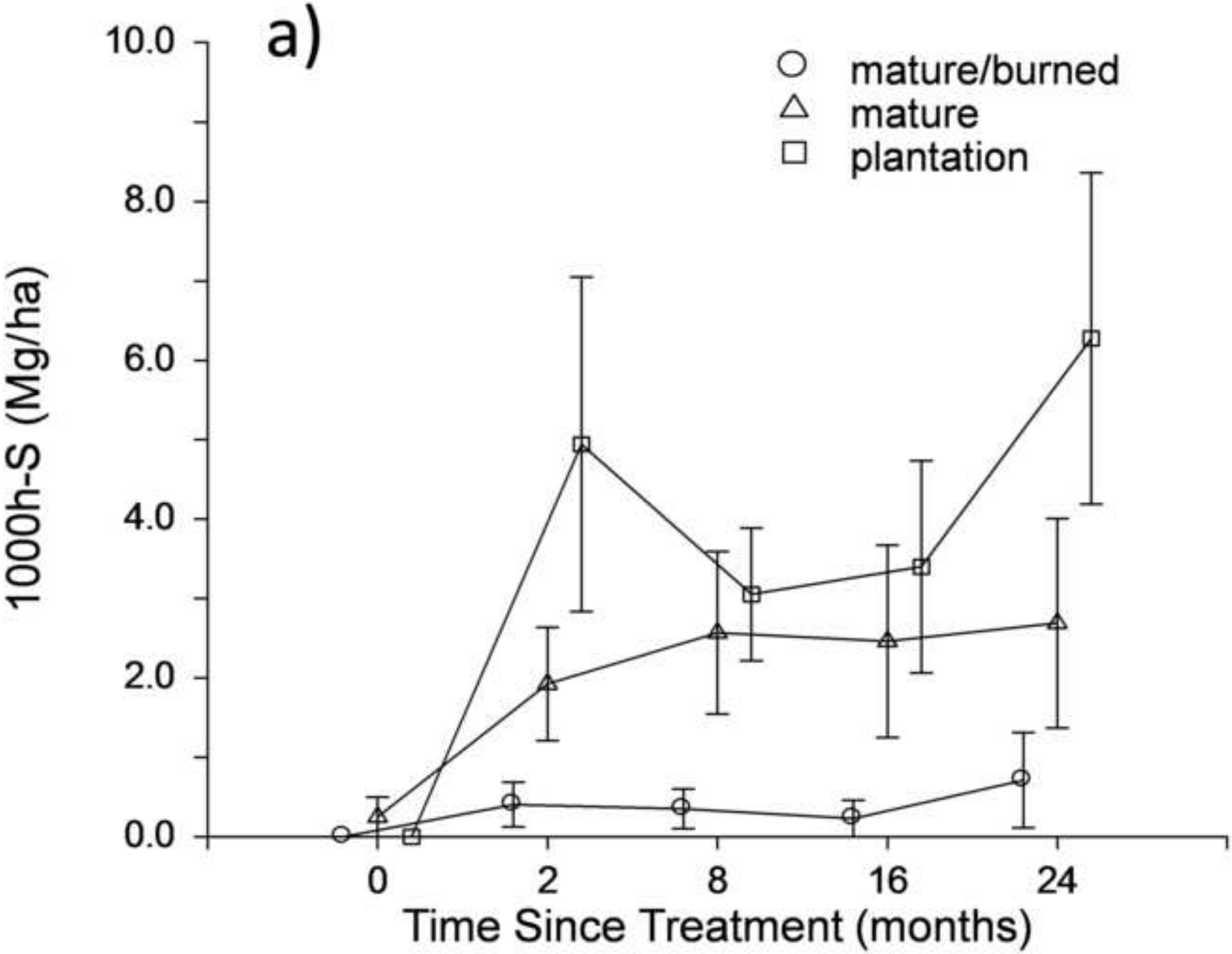

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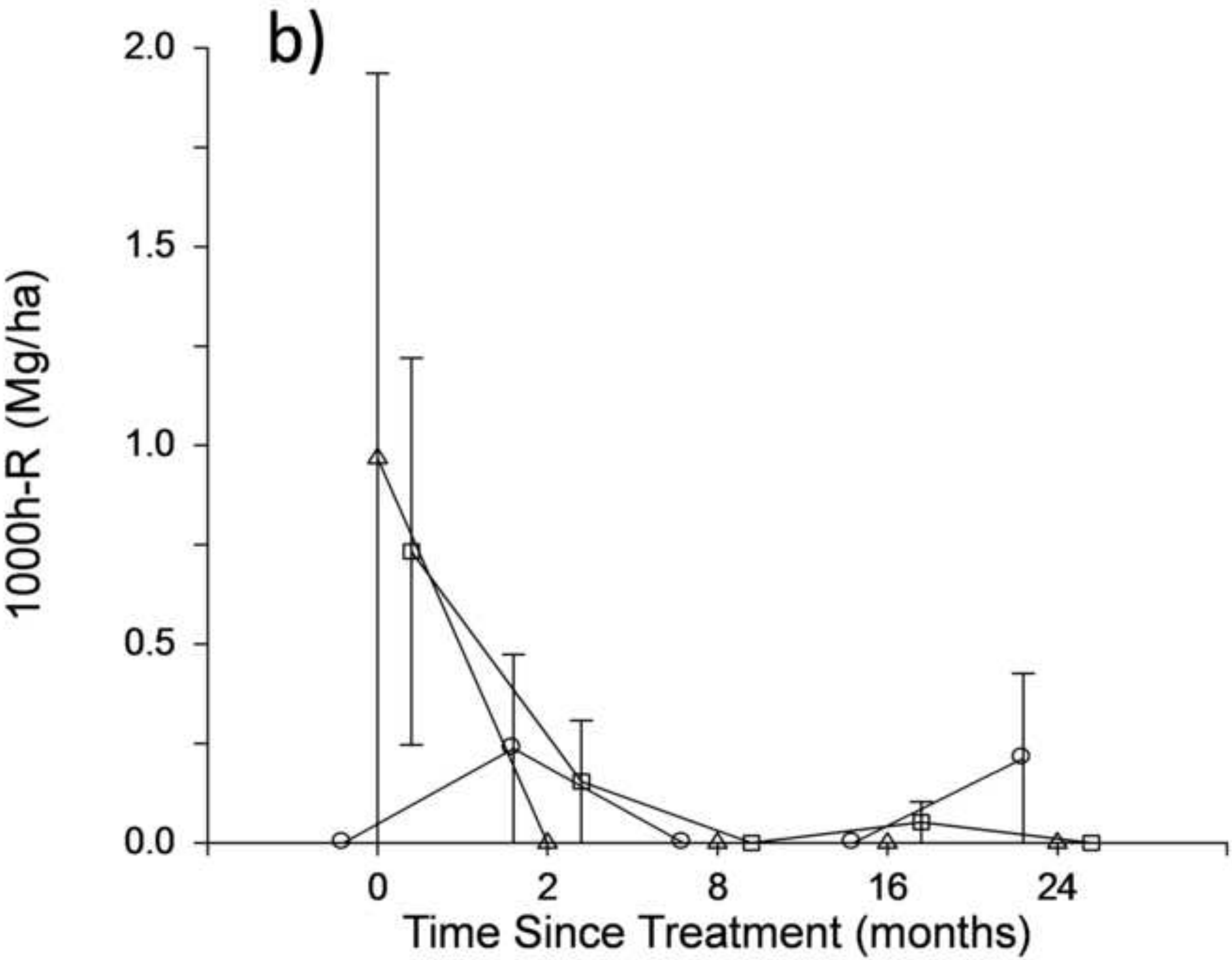

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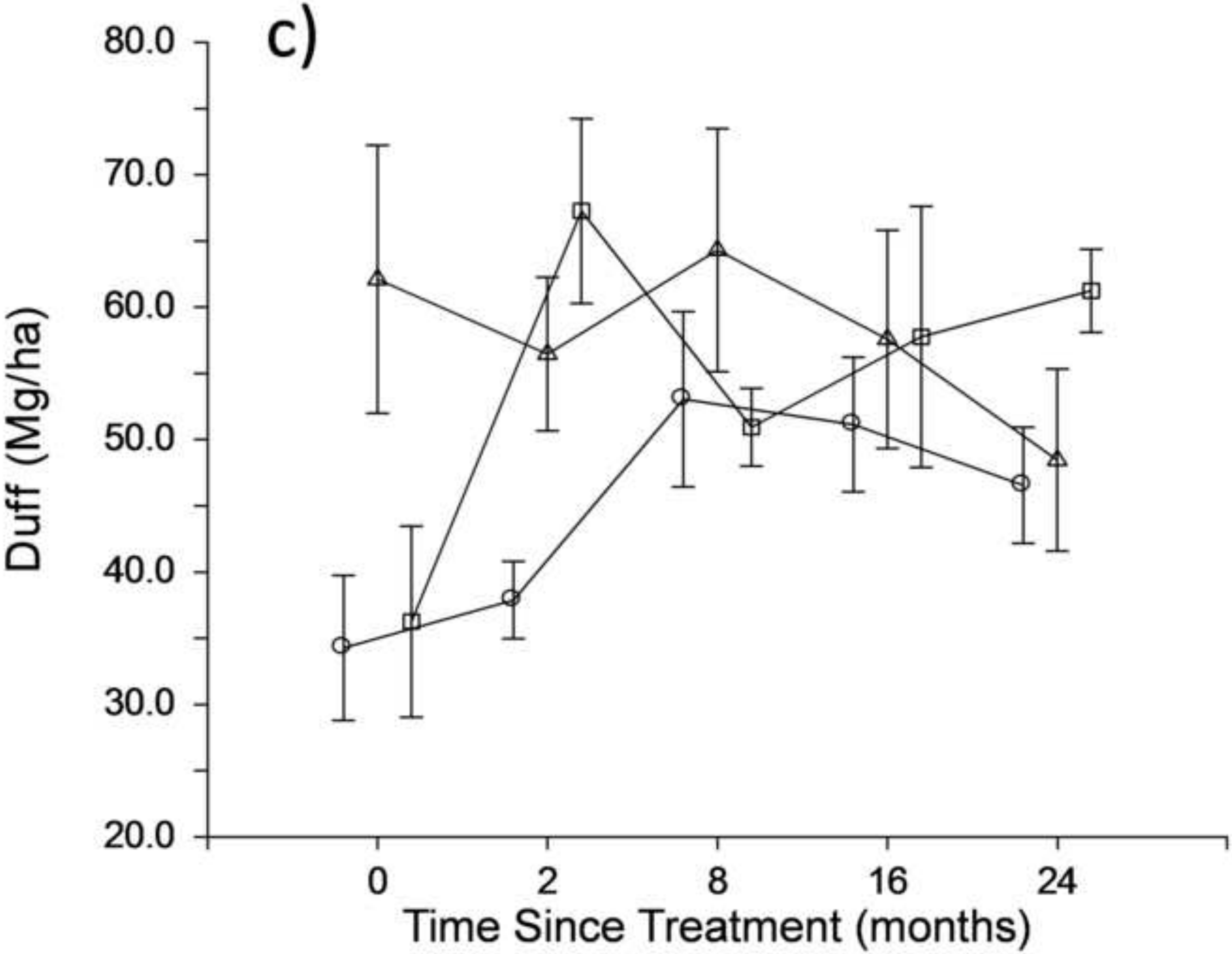

Table 1 Surface fuel characteristics just following (ca. 2 mos) mowing treatment in a 500 ha palmetto/gallberry pine flatwoods in north-central Florida, USA from destructive sampling. Values in parentheses are standard deviation (sd).

	Fuel Load ($Mg \cdot ha^{-1}$)		Fuel Depth (*cm*)		Fractured[a] (%)		Fuelbed Proportion[b] (%)	
	range	mean (sd)	range	mean (sd)	range	mean (sd)	range	mean (sd)
Litter	5.6 - 24.4	12.6 (5.5)	2.4-10.9	5.4 (2.4)	na		40-88	69 (13)
1h	1.4 - 6.0	3.1 (1.2)	-	-	6-33	20 (8)	7-29	18 (7)
10h	0.6 - 6.3	2.1 (1.5)	3.0-12.8[c]	7.4 (3.0)[c]	0-65	25 (20)	4-32	11 (7)
100h	0.0 - 5.9	0.4 (1.5)	-	-	0-100	50 (71)	0-24	2 (6)
Total	9.6-35.6	18.2 (6.6)	3.9-13.2	8.1 (2.8)	na		100	100
Duff	15.0-98.2	41.9 (21.3)	1.0-8.6	3.6 (2.0)	na		na	

[a] Percent of woody fuels (1,10, and 100h), by weight, that has been fractured at least 50% of its particle length,

[b] Proportion, by mass, of the total fuelbed associated with flaming combustion(does not include duff), [c] Depth of all fine woody debris (1h, 10h, and 100h)

Table 2 Overstory, understory, and surface fuel characteristics of a 500 ha mowing treatment in palmetto/gallberry pine flatwoods of north-central Florida, USA. Surface fuels sampled non-destructively (planar intercept method). Values in parentheses are standard errors.

	Trees					Shrubs[a]		
	Density	BA□	QMD□	Height	CBH□	Density	Height	Biomass
	trees·ha^{-1}	*m*^{2}*·ha*$^{-1}$	*cm*	*m*	*m*	*ind·m*$^{-2}$	*m*	*Mg·ha*$^{-1}$
Pre-Treatment	358 (39)^{A}	18.8 (2.3)^{A}	25.8 (1.0)^{A}	16.7 (0.9)^{A}	12.0 (0.8)^{A}	4.2 (0.5)^{A}	1.12 (0.02)^{A}	3.68 (0.49)^{A}
Post-Treatment[b]	277 (38)^{A}	18.6 (2.4)^{A}	29.8 (1.2)^{B}	20.7 (0.9)^{B}	14.7 (0.7)^{B}	0.6 (0.2)^{B}	0.75 (0.14)^{B}	0.24 (0.08)^{B}
	Surface Fuel Loading							
	1h	10h	100h	1000h-S	1000h-R	Litter	Duff	
	----------*Mg·ha*$^{-1}$----------							
Pre-Treatment	1.7 (0.3)^{A}	1.4 (0.1)^{A}	0.3 (0.1)^{A}	0.3 (0.3)^{A}	0.2 (0.2)^{A}	9.0 (0.9)^{A}	42.0 (3.6)^{A}	
Post-Treatment[b]	2.7 (0.5)^{B}	3.1 (0.5)^{B}	0.6 (0.3)^{A}	0.4 (0.2)^{A}	0.3 (0.2)^{A}	13.4 (1.2)^{B}	42.0 (4.3)^{A}	
	Fuel Depth							
	FWD[c]	Litter	Duff					
	----------*cm*----------							
Pre-Treatment	7.2 (1.7)^{A}	7.8 (0.8)^{A}	5.8 (0.5)^{A}					
Post-Treatment[b]	7.3 (0.9)^{A}	6.0 (0.5)^{B}	3.8 (0.4)^{B}					

[a] Shrubs >0.5 m in height, [b]ca. 2 mos following treatment, [c] Fine woody debris (1h, 10h, and 100h fuels)

Note: Values sharing letters within columns are not statistically different (α=0.05)

□ Basal area (BA), quadratic mean diameter (QMD), crown base height (CBH).

Table 3 Overstory characteristics following mowing treatments in three stand types of palmetto/gallberry pine flatwoods of north-central Florida, USA.

	Stand Type: mature	Stand Type: mature-burned	Stand Type: plantation	Stand Type	TST[a]	Stand Type × TST
					p value	
Tree Density		*trees·ha^{-1}*		<0.001	<0.001	<0.001
Pre-Treatment	941 (179)^{A}	365 (36)^{A}	1120 (185)^{A}			
Post-Treatment	327 (58)^{B}	216 (30)^{B}	804 (82)^{AB}			
2yrs Post-Treatment	290 (46)^{B}	216 (30)^{B}	713 (71)^{B}			
Basal Area		*m^{2}·ha^{-1}*		0.029	<0.001	0.043
Pre-Treatment	28.3 (3.3)^{A}	17.9 (2.2)^{A}	34.0 (5.9)^{A}			
Post-Treatment	23.2 (2.9)^{B}	17.3 (2.4)^{A}	27.5 (2.2)^{A}			
2yrs Post-Treatment	23.4 (2.8)^{B}	18.2 (2.3)^{A}	26.3 (2.5)^{A}			
QMD		*cm*		0.004	<0.001	<0.001
Pre-Treatment	21.8 (1.7)^{A}	25.6 (2.1)^{A}	20.7 (0.4)^{A}			
Post-Treatment	32.2 (2.0)^{B}	32.8 (2.2)^{B}	21.0 (0.5)^{A}			
2yrs Post-Treatment	33.6 (1.7)^{B}	33.9 (2.2)^{B}	21.8 (0.6)^{A}			
Height		*m*		0.211	<0.001	<0.001
Pre-Treatment	12.9 (0.8)^{A}	16.2 (1.4)^{A}	18.9 (0.4)^{A}			
Post-Treatment	20.3 (1.4)^{B}	21.7 (0.4)^{B}	19.0 (0.2)^{A}			
2yrs Post-Treatment	22.0 (1.1)^{B}	22.8 (0.5)^{B}	21.9 (0.5)^{B}			
CBH		*m*		0.158	<0.001	<0.001
Pre-Treatment	8.3 (0.7)^{A}	10.5 (0.8)^{A}	13.6 (0.5)^{A}			
Post-Treatment	13.3 (1.1)^{B}	13.2 (0.4)^{B}	13.6 (0.3)^{A}			
2yrs Post-Treatment	14.8 (1.1)^{B}	15.7 (0.4)^{C}	15.7 (0.4)^{B}			

[a] Time Since Treatment

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

Table 4 Biomass of shrubs, surface fuels, and total (shrubs and surface fuels) following mowing of understory shrubs and small trees in pine flatwoods of the Osceola National Forest in north-central Florida, USA.

	Stand Type					
	Mature	Mature/Burned	Plantation	Stand Type	TST[a]	Stand Type × TST
		$Mg \cdot ha^{-1}$			*p value*	
Shrubs				0.098	<0.001	0.008
Pre-Treatment	5.5 (1.4)^{A}	5.0 (0.9)^{A}	1.6 (0.5)^{A}			
2 months	0.6 (0.3)^{B}	0.5 (0.2)^{B}	0.2 (0.1)^{B}			
8 months	0.4 (0.2)^{B}	0.7 (0.2)^{B}	0.5 (0.3)^{B}			
16 months	0.8 (0.2)^{C}	2.3 (0.7)^{C}	1.1 (0.5)^{C}			
24 months	1.3 (0.3)^{C}	2.1 (0.5)^{C}	0.9 (0.3)^{C}			
Surface Fuels[b]				<0.001	<0.001	0.103
Pre-Treatment	11.1 (1.4)^{A}	13.2 (1.4)^{A}	13.9 (1.1)^{A}			
2 months	20.7 (1.7)^{B}	17.1 (1.7)^{B}	23.1 (2.7)^{B}			
8 months	15.9 (0.9)^{B}	14.0 (0.7)^{B}	22.1 (2.3)^{B}			
16 months	15.8 (1.3)^{B}	17.0 (1.8)^{B}	24.9 (2.8)^{B}			
24 months	16.2 (0.8)^{B}	15.7 (1.6)^{B}	24.1 (1.6)^{B}			
Total Fuel[c]				0.007	0.004	0.009
Pre-Treatment	16.6 (1.6)^{A}	18.2 (1.5)^{A}	15.5 (1.3)^{A}			
2 months	21.1 (1.9)^{B}	17.6 (1.8)^{A}	23.3 (2.8)^{AB}			
8 months	16.1 (0.9)^{A}	14.7 (0.9)^{A}	22.5 (2.3)^{AB}			
16 months	16.7 (1.3)^{AB}	19.3 (2.2)^{A}	26.0 (2.9)^{B}			
24 months	17.4 (0.8)^{AB}	17.8 (1.8)^{A}	25.0 (1.6)^{B}			

[a] Time Since Treatment, [b] includes litter, 1h, 10h, and 100h fuels; [c] shrubs and surface fuels

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

Appendix B.1 Shrub foliage and stem biomass, shrub height, and shrub density following mowing of understory shrubs and small trees in pine flatwoods of the Osceola National Forest in north-central Florida, USA.

	Stand Type					
	Mature	Mature/Burned	Plantation	Stand Type	TST[a]	Stand Type × TST
	Mg·ha^{-1}			*p value*		
Shrub Foliage				0.049	<0.001	0.306
Pre-Treatment	2.4 (0.5)^{A}	3.2 (0.6)^{A}	1.2 (0.4)^{A}			
2 months	0.4 (0.2)^{B}	0.2 (0.1)^{B}	0.1 (0.1)^{B}			
8 months	0.3 (0.2)^{B}	0.4 (0.1)^{B}	0.2 (0.1)^{B}			
16 months	0.5 (0.2)^{C}	1.5 (0.4)^{C}	0.6 (0.2)^{C}			
24 months	0.9 (0.2)^{C}	1.4 (0.4)^{C}	0.5 (0.1)^{C}			
Shrub Stems				0.308	<0.001	0.002
Pre-Treatment	3.1 (1.1)^{A}	1.8 (0.6)^{A}	0.4 (0.2)^{A}			
2 months	0.2 (0.1)^{B}	0.2 (0.2)^{B}	0.1 (0.1)^{B}			
8 months	0.1 (0.0)^{B}	0.3 (0.1)^{BC}	0.3 (0.2)^{BC}			
16 months	0.3 (0.1)^{B}	0.8 (0.3)^{C}	0.5 (0.3)^{AC}			
24 months	0.4 (0.1)^{B}	0.7 (0.2)^{C}	0.4 (0.2)^{AC}			
Shrub Height	*m*			0.347	0.078	0.788
Pre-Treatment	0.86 (0.10)^{A}	0.79 (0.08)^{A}	1.00 (0.08)^{A}			
2 months	0.72 (0.08)^{A}	0.67 (0.03)^{A}	0.81 (0.12)^{A}			
8 months	0.62 (0.14)^{A}	0.73 (0.04)^{A}	0.79 (0.17)^{A}			
16 months	0.68 (0.08)^{A}	0.78 (0.03)^{A}	0.80 (0.02)^{A}			
24 months	0.89 (0.08)^{A}	0.76 (0.04)^{A}	0.86 (0.03)^{A}			
Shrub Density	*individuals·m^{-2}*			0.018	<0.001	0.018
Pre-Treatment	4.9 (0.8)^{A}	13.3 (3.4)^{AC}	2.3 (0.6)^{A}			
2 months	0.5 (0.1)^{B}	1.1 (0.3)^{B}	0.8 (0.2)^{B}			
8 months	0.6 (0.2)^{B}	1.5 (0.3)^{BC}	0.6 (0.3)^{B}			
16 months	3.7 (0.9)^{A}	5.2 (0.7^{BC}	2.3 (0.5)^{A}			
24 months	4.6 (1.1)^{A}	7.6 (2.1)^{C}	2.7 (0.4)^{A}			

[a] Time Since Treatment

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

Appendix B.2 Biomass of litter and fine woody fuels (1h, 10h, 100h) following mowing of understory shrubs and small trees in pine flatwoods of the Osceola National Forest in north-central Florida, USA.

	Stand Type					
	Mature	Mature/Burned	Plantation	Stand Type	TST[a]	Stand Type × TST
	$Mg \cdot ha^{-1}$			*p value*		
1h woody				0.546	<0.001	0.090
Pre-Treatment	0.4 (0.1)^{A}	0.4 (0.1)^{A}	0.2 (0.0)^{A}			
2 months	3.2 (0.6)^{B}	2.3 (0.3)^{B}	2.7 (0.4)^{B}			
8 months	1.6 (0.4)^{C}	1.5 (0.2)^{C}	1.9 (0.4)^{C}			
16 months	0.8 (0.1)^{D}	0.8 (0.1)^{D}	1.5 (0.2)^{D}			
24 months	0.6 (0.1)^{D}	0.9 (0.1)^{D}	0.8 (0.0)^{D}			
10h woody				<0.001	<0.001	<0.001
Pre-Treatment	1.1 (0.3)^{A}	3.0 (0.7)^{A}	2.5 (0.7)^{A}			
2 months	5.3 (0.9)^{B}	2.6 (0.4)^{A}	5.4 (1.0)^{B}			
8 months	3.0 (0.5)^{A}	1.9 (0.3)^{A}	6.3 (1.4)^{B}			
16 months	2.5 (0.3)^{A}	1.9 (0.3)^{A}	5.6 (0.9)^{B}			
24 months	2.7 (0.4)^{A}	1.9 (0.3)^{A}	5.3 (0.8)^{B}			
100h woody				<0.001	0.500	0.060
Pre-Treatment	1.9 (1.2)^{A}	1.0 (0.5)^{A}	3.5 (0.9)^{A}			
2 months	2.8 (0.8)^{A}	0.4 (0.3)^{A}	1.3 (0.6)^{A}			
8 months	2.0 (0.5)^{A}	0.0 (0.0)^{A}	2.4 (1.5)^{A}			
16 months	2.5 (0.6)^{A}	0.0 (0.0)^{A}	3.1 (1.5)^{A}			
24 months	1.6 (0.5)^{A}	1.8 (1.5)^{A}	2.7 (0.8)^{A}			
Litter				0.006	<0.001	0.201
Pre-Treatment	7.7 (0.5)^{A}	8.9 (0.9)^{A}	7.7 (0.9)^{A}			
2 months	9.5 (0.9)^{BC}	11.8 (1.6)^{BC}	13.6 (2.7)^{BC}			
8 months	8.5 (0.9)^{B}	10.6 (0.7)^{B}	11.4 (0.9)^{B}			
16 months	9.8 (0.6)^{C}	14.3 (1.8)^{C}	14.7 (1.4)^{C}			
24 months	10.9 (0.6)^{C}	11.1 (0.8)^{C}	15.3 (1.0)^{C}			

[a] Time Since Treatment

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

Appendix B.3 Biomass of 1000h (sound and rotten) woody fuels and duff following mowing of understory shrubs and small trees in pine flatwoods of the Osceola National Forest in north-central Florida, USA.

	Stand Type					
	Mature	Mature/Burned	Plantation	Stand Type	TST[a]	Stand Type × TST
	---------------------*Mg·ha*$^{-1}$	----------------------		-------------------*p value*	----------------------	
1000h-Sound				0.002	<0.001	0.138
Pre-Treatment	0.2 (0.2)^{A}	0.0 (0.0)^{A}	0.0 (0.0)^{A}			
2 months	1.9 (0.7)^{B}	0.4 (0.3)^{B}	4.9 (2.1)^{B}			
8 months	2.6 (1.0)^{B}	0.4 (0.2)^{B}	3.1 (0.8)^{B}			
16 months	2.5 (1.2)^{B}	0.2 (0.2)^{B}	3.4 (1.3)^{B}			
24 months	2.7 (1.3)^{B}	0.7 (0.6)^{B}	6.3 (2.1)^{B}			
1000h-Rotten				0.874	0.269	0.755
Pre-Treatment	1.0 (1.0)^{A}	0.0 (0.0)^{A}	0.7 (0.5)^{A}			
2 months	0.0 (0.0)^{A}	0.2 (0.2)^{A}	0.2 (0.2)^{A}			
8 months	0.0 (0.0)^{A}	0.0 (0.0)^{A}	0.0 (0.0)^{A}			
16 months	0.0 (0.0)^{A}	0.0 (0.0)^{A}	0.1 (0.1)^{A}			
24 months	0.0 (0.0)^{A}	0.2 (0.2)^{A}	0.0 (0.0)^{A}			
Duff				0.179	0.048	0.004
Pre-Treatment	62.1 (10.1)^{A}	34.3 (5.5)^{A}	36.3 (7.2)^{A}			
2 months	56.5 (5.8)^{A}	37.9 (2.9)^{A}	67.3 (7.0)^{B}			
8 months	64.3 (9.2)^{A}	53.1 (6.6)^{B}	50.9 (2.9)^{AB}			
16 months	57.6 (8.2)^{A}	51.1 (5.1)^{B}	57.8 (9.9)^{AB}			
24 months	48.5 (6.9)^{A}	46.6 (4.4)^{AB}	61.2 (3.1)^{B}			

[a] Time Since Treatment

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05

Appendix C A comparison of post-mastication surface fuels across different ecosystems in the western US and the pine flatwoods system (this study) of the southeastern USA.

Study	Ecosystem	Location	Litter	Duff	1-h	10-h	100-h	1000-h
			$Mg \cdot ha^{-1}$					
Kane et al., 2009	Black oak/madrone	Oregon	10.3	6.7	12.3	24.6	8.6	5.3
	Ponderosa pine	California	8.6	12.4	7.6	21.4	8.1	2.2
	Manzanita shrubland	California	2.6	7.5	6.2	13.8	3.6	0.0
	Manzanita shrubland	California	0.6	19.6	23.5	34.8	5.1	0.0
	Ponderosa pine	California	2.9	15.0	4.7	8.2	1.3	3.1
	Ceanothus shrubland	California	5.4	5.7	5.2	11.1	6.6	0.0
	Ponderosa pine	California	9.9	25.9	15.7	25.0	4.8	1.3
	Manzanita shrubland	California	5.6	27.9	13.2	21.7	2.1	0.0
	Ponderosa pine	California	4.8	5.9	4.4	9.4	1.6	0.0
	Black oak/pine	California	3.3	7.0	11.8	16.4	3.5	0.0
Hood and Wu, 2006	Jeffrey pine/white-fir	California	56.0		39.9			
	Ponderosa pine/ Gambel oak	Colorado	43.0		39.0			
	Pinyon pine/juniper	Colorado	17.0		56.0			
Kobziar et al., 2009	Ponderosa-Jeffrey pine (plantation)	California	23.7	39.2	2.6	11.2	10.9	16.2
Battaglia et al., 2010	Lodgepole pine	Colorado	10.2	11.5	16.9	19.3	5.2	5.3
	Mixed conifer	Colorado	27.7	19.2	23.0	24.5	10.8	5.0
	Ponderosa pine	Colorado	13.6	10.5	8.0	18.0	7.4	5.3
	Pinyon pine/juniper	Colorado	8.6	4.9	7.81	12.0	4.2	3.2
This Study	Pine flatwoods (mature)[1]	Florida	12.6	41.9	3.1	2.1	0.4	n/a
	Pine flatwoods (mature)[2]	Florida	9.5	56.5	3.2	5.3	2.8	1.9
	Pine flatwoods (mature/burned)[2]	Florida	11.8	37.9	2.3	2.6	0.4	0.6

	Pine flatwoods (plantation)[2]	Florida	13.6	67.3	2.7	5.4	1.3	5.1

[1]Fuel loads determined from destructive sampling. [2]Fuel loads estimated from non-destructive (planar intercept) sampling