Biochar and woodchip amendments alter restoration outcomes, microbial processes, and soil moisture in a simulated semi-arid ecosystem

Running head: Biochar and woodchip amendments

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Amendments, such as woodchips or biochar, may improve success of arid and semi-arid wildland revegetation limited by unpredictable and insufficient rainfall as well as low soil water holding capacity. In an 116-day greenhouse experiment simulating a nearby savannah, response to four amendment treatments (no treatment, incorporated biochar, incorporated woodchips, and surface woodchips) was tested across two field soils (Chiricahua, Hathaway) and four simulated precipitation treatments (100%, 80%, 60%, and 40% of average), in a replicated design. Soil type, amendment treatments, and simulated precipitation all had significant ($p < 0.01$) effects on aboveground biomass. The surface woodchip treatment averaged the highest biomass production of the amendment treatments (489 kg/ha) and the incorporated woodchips had the lowest (298 kg/ha). Aboveground biomass decreased with decreasing precipitation (533, 468, 350, 216 kg/ha respectively). Biochar amended soils averaged 5 to 10% higher volumetric water content than the woodchip amendments and controls through a 28-day dry down. Microbial nitrogen and phosphorous acquiring activities were higher in Hathaway soils while carbon activities were higher in Chiricahua soils. The surface woodchip treatment resulted in a different species composition than the other amendment and control treatments ($p < 0.01$). None of the amendment treatments ameliorated low precipitation conditions for plants. Contrary to expectations, carbon and phosphorous exoenzyme activities were highest in the lower precipitation treatments (60% and 40%) and nitrogen exoenzyme activities remained high in Hathaway soils regardless of precipitation. Surface application of woodchips increased vegetation as well as carbon and phosphorous exoenzyme activities while incorporating woodchips suppressed vegetation.

Keywords: Sonoran desert, volumetric water content, Arizona, aboveground biomass, drought, exoenzyme and extracellular enzyme activities.

Implications for practice

A thin layer of woodchips on the surface resulted in higher plant density and greater plant growth as well as supported high C and P exoenzyme activities. If woodchips can be readily sourced on site, this practice can enhance vegetation establishment.

Biochar had a neutral effect on revegetation but increased soil water retention and potentially soil carbon storage which seems likely to be a long-term benefit to restoration.

Incorporating woodchips into the soil greatly suppressed vegetation and is not recommended as a restoration practice in this ecosystem.

Introduction

Nearly 10% of the earth's land surface consists of degraded drylands (arid and semi-arid systems) and dryland restoration remains a worldwide priority (FAO 2015). As a primary characteristic of this land type, water limits revegetation (Duniway et al. 2018). During periods with adequate rainfall, revegetation success can occur without needing practices to conserve soil moisture (Fehmi et al. 2014). During periods with rainfall amounts at the lower threshold of plant tolerance, revegetation practices, such as soil amendments have been thought to augment revegetation success (Hueso-González et al. 2018), although there remain many uncertainties in assessing potential revegetation advantages. The decision to use a soil amendment can depend not only on its efficacy, but also on the availability and cost of the amendment material.

Arid and semi-arid former grasslands have been broadly encroached by woody species (Stevens et al. 2017). Site improvement or revegetation projects on these lands result in large amounts of the removed woody material (Redmond et al. 2014). This wood waste represents an ideal source material for a soil amendment to aid revegetation because it is already on site, which limits purchase and hauling costs (Sasatani & Eastin 2018). On-site sourced amendment applications can include chipping the woody material and either applying the chips on the soil surface or incorporating them into the soil through tilling (Benigno et al. 2013). A re-emerging use of woody material is to pyrolyze it into biochar and incorporate it into the soil (Kerre et al. 2016; Blanco-Canqui 2017). These amendments may have the additional advantage of storing carbon in the soil, which may prove to be critical for stabilizing atmospheric CO_2 concentrations (Jackson et al. 2017).

The surface application of wood waste (chipped/ground woody material) derived from the application site should have impacts similar to other mulches and plant litter on revegetation (Robichaud et al. 2013). While thick layers of mulch or litter tend to suppress plant growth, thinner layers have been shown to increase seedling establishment (Hovstad & Ohlson 2008; Breton et al. 2016) which is most often attributed to the combination of decreased surface temperature and decreased evaporation (e.g. Price et al. 1998). Surface application of any mulch during revegetation can change the species composition through the widely varying positive or negative effects of mulch/litter on germination and establishment of the individual species (Loydi et al. 2013). Surface application of woodchips appears to have the additional advantage that woodchips are resistant to decay and less likely to blow away in windy, dry conditions relative to other mulches such as straw (Throop & Belnap 2019).

Incorporating the chipped wood may increase soil moisture through infiltration, absorption, and release (Belden et al. 1990; Benigno et al. 2013), but it also may decrease soil moisture by making a soil excessively well-drained and thereby decreasing moisture retention (Gebhardt et al. 2017). The effect of incorporated woodchips is thought to be relatively long lasting because the woodchips will be somewhat resistant to decay in the soil due to their size and high C:N values (Ofosu-Asiedu & Smith 1973). Woodchip amendments may also result in carbon sinks lasting 30 years or more (Ryals et al. 2015). As the woodchips decay, the soil biotic community may bind-up the nutrients, such as N, needed for vegetation establishment and or growth (Gebhardt et al. 2017).

Biochar has been shown to generally increase soil water retention and plant-available water in about 90% of soils (reviewed in Blanco-Canqui 2017). The addition of biochar can also address soil nutrient deficiencies (Gebhardt et al. 2017) by increasing nutrient holding capacity as well as microbial community abundance and diversity (Lehmann et al. 2011). However, biochar may also have a negative effect on revegetation because the nutrients it stores are absorbed from decaying organic matter in soil (sorption of organic matter on the biochar surface) and limit plant availability (Lehmann et al. 2011; Artiola et al. 2012). This temporary reduction in macro- and micro-nutrients may reduce plant establishment, but this effect may be concentrated in a species-specific way with grasses often more affected, both positively and negatively, than forbs (Eschen et al. 2006; Adams et al. 2013). While the addition of any soil amendment will affect a range of soil processes (Ramlow et al. 2018), the critical information from a management perspective is the impact on revegetation.

The primary desired effect of soil amendments in arid and semiarid systems is to improve revegetation success in years where the rainfall would otherwise be inadequate, and to promote plant growth. The objective of this study was to quantify native vegetation establishment and growth responses, as well as microbial exoenzyme activities, to various woody amendment treatments, including surface and incorporated woodchips and incorporated biochar, under a range of precipitation scenarios. We hypothesized that, by retaining moisture near the soil surface, surface woodchips would increase vegetation establishment (density) but not necessarily aboveground biomass and that the positive effect of surface woodchips on establishment would increase with decreasing simulated precipitation. We hypothesized that biochar, through its effect on soil water availability and dissolved nutrients, would improve aboveground biomass and that the positive effect on plant biomass should be proportionally greater with decreasing simulated precipitation. We hypothesized that effects of incorporated woodchips on vegetation would interact across soils with different water holding capacities. Finally, we hypothesized that potential microbial exoenzyme activities would decrease with decreasing precipitation and remain lower in soils with lower water holding capacities.

Methods

The greenhouse experiment included two field soils (Chiricahua and Hathaway), four simulated precipitation treatments (100%, 80%, 60%, and 40% of average), four amendment treatments (no treatment, incorporated biochar, incorporated woodchips, surface woodchips) with 4 replications of each in a factorial randomized complete block design for a total of 160 pots. The greenhouse (32°16’51.77”N, 110°56’13.14”W, 720 m asl) was set up to simulate a nearby field site (31°49’20.48” N 110° 44’03.62” W; 1501 m asl, 35 °C ± 2 °C max temp; night not controlled) comparable to Fehmi and Kong (2012). Our greenhouse would be expected to have difficulty matching a field site’s atmospheric conditions, seed predation, herbivory, and disturbance regimes. A greenhouse offers a viable solution to looking at the potential effects of reduced precipitation across a replicated, factorial array of treatments which would have been prohibitively difficult/expensive to arrange at larger scales on a field site. The greenhouse experiment described here was paired with a field experiment using the same soils and amendment treatments (Espinosa et al. in review) which allows expanded inference beyond a controlled environment.

In late March 2013, the two common soil series: Chiricahua (source 31°50’34.30” N 110°45’05.96” W; 1616 m asl) and Hathaway (source 31°49’20.48” N 110° 44’03.62” W; 1501 m asl) were excavated as a mix of topsoil and the materials within 1.75 m of the surface. This depth mix was intended to match expected conditions after disturbance. These soils were chosen because they were common and different (Table 1) despite the sources being less than 3 km apart. The soils are classified as Ustic Haplargid and Aridic Calciustolls, respectively (Soil Survey Staff 2014; Rasmussen et al. 2015). The Chiricahua had the appearance of a red gravel and was excessively well drained compared to the Hathaway. Both soils support visually similar, grass-dominated sparse woodland vegetation typical for the region.

Whole green *Juniperus monosperma* trees (source 31°49’20.48” N 110° 44’03.62” W; 1501 m asl – source site for the Hathaway soil) were cut and chipped on 14 June 2013 with a Vermeer BC600XL 6” Brush chipper (Pella, Iowa, USA). The particle sizes of the chips varied widely, with much being course sawdust of about 0.5 cm to a maximum fragments size of about 7.5 x 1 cm. The woodchips passed a 2.5 cm sieve and were 37% 2.2 to 1 cm, 35% 1 to 0.4 cm, and 29% < 0.4 cm. The incorporated woodchip treatment added 805.5 g per 22 kg pot of Chiricahua and 635.5 g per 17 kg pot of Hathaway which was at a ratio of 4% air-dry woodchips by weight. At the time of application, the woodchips were about 10.5% water by weight compared to woodchips air dried for 6 months. The incorporated biochar weight added 900 g per 22 kg pot of Chiricahua and 710 g per 17 kg pot of Hathaway. The Biochar was Charcoal Green® Pure Biochar - Mixed Hardwood 0.6-2.5 cm coarse biochar (Crawford, NE, USA). Coarse biochar was chosen to limit dust emissions during soil mixing. During experimental setup, one pot that was supposed to have incorporated wood was instead not amended resulting in 39 pots with incorporated wood and 41 pots with no amendment. The amendments were mixed into the soil with a concrete mixer and then placed in the pots. The surface woodchip treatment used 100 g of green woodchips. This resulted in a single thin layer of woodchips covering approximately 80% of the soil surface.

One hundred seeds of species native to the soil-source location were planted per pot: *Bouteloua curtipendula* (Sideoats grama, 14%), *Bouteloua gracilis* (Blue grama, 14%), *Digitaria californica* (Arizona cottontop, 14%), *Hilaria belangeri* (Curly mesquite, 14%), *Leptochloa dubia* (Green sprangletop, 14%), *Eragrostis intermedia* (Plains lovegrass, 14%), *Elymus elymoides* (Bottlebrush squirreltail, 3%), *Eschscholzia californica* ssp. *Mexicana* (Mexican gold poppy, 8%), *Baileya multiradiata* (Desert marigold, 4%), and *Calliandra eriophylla* (Fairy duster, 1%). These species are commonly found on these soils at the source sites with approximately this same ratio of grasses to forbs. The system is dominated by initial floristics (Egler 1954) where the initially occurring species generally dominate the plant community over long periods. Seeds were purchased from a commercial seed vendor and visually sorted to exclude damaged or broken seed. Seeds were surface broadcast by hand. The surface woodchip treatment was applied after seeding.

Watering began 21 June 2013 when every 15-L pot (30-cm surface diameter) was given 919.5 ml for each of three days. After this initial setup the watering schedule was every third day. Four treatments included: 40% of average rainfall pots (196.16 ml), 60% of average (294.24 ml), 80% of average (392.32 ml), and 100% of average rainfall (490.4 ml) every third day. Average rainfall was calculated on the monsoon share of 320 mm annual precipitation (Fehmi and Kong 2012 but for precipitation patterns see Fehmi et al. 2014). Watering varied by approximately 10% due to the C-frame down spray emitters selected to best simulate the distribution of rainfall across the surface of the pot. An audit after watering had begun determined that 3 pots supposed to be in the 80% treatment were instead in the 40% treatment resulting in 43 pots in 40%, 40 in 60%, 37 in 80% and 40 in 100% of average. Number of individuals (density) of all plant species in each pot was counted on 16 Sep 2013.

Watering ended 17 Sep 2013 after 88 days. All vegetation was clipped to 1 cm on 24 Aug 2013 to prevent shading of adjacent pots. Pots were clipped to the soil surface on 24 Sep 2013 and again on 11 Oct 2013 to ensure collection of any biomass that grew back. Biomass was separated by species, dried at 70 C for at least 48 hours, and weighed.

Volumetric soil water content was measured with a FieldScout TDR 100 Soil Moisture Meter (Spectrum Technologies Inc. Plainfield IL USA) with 10-cm probes. Soil water was measured on 17, 18, 19, 20, 21, 22, 23, 26, Sep and 1, 5, 8, 11, 15 Oct 2013 to capture the dry down at the end of the experiment. The Volumetric Water Content (VWC) data was analyzed for differences between the amendment treatments (effect size) as a linear model. The aboveground biomass effect was estimated but was not included as a covariate in the final model to account for transpiration losses because it is entirely confounded with the amendment treatment beyond easy interpretation. Only VWC data from the 80% and 100% rainfall simulation treatments were used for analysis because the analytical goal was to evaluate the decay function as the pots dried and the signal would be substantially noisier if pots already nearly dry at the beginning were included. A natural log transformation made the VWC approximately normally distributed and consistent with the expected exponential decay model similar to Kurc and Small (2004). Model terms were accepted if their estimate was more than two standard error from zero and terms were considered significantly different if their estimates were more than two standard errors apart, similar to Rondinelli et al. (2015).

On 20 Sep 2013, soils were collected from the top 5 cm of each pot and stored on ice during transport. Then, they were sieved (2 mm) and stored at 4°C until analysis. A supernatant of field moist soil and deionized water in a 1:2 ratio was used to determine soil pH. To estimate potential for carbon

(C), nitrogen (N), and phosphorous (P) cycling, soils were analyzed for seven hydrolytic potential exoenzyme activities (β-Glucosidase (BG), β-D-cellubiosidase (CB), α-Glucosidase (AG), β-xylosidase (XYL), leucine aminopepsidase (LAP), N-acetyl-β-Glucosaminidase (NAG), and Phosphatase (PHOS)) using the 96-well plate fluorimetric technique following Gebhardt et al. (2017) modified from (Saiya-Cork et al. 2002; Steinweg et al. 2013; Steinauer et al. 2015). Values for C exoenzyme activities were analyzed as the sum of BG, CB, AG, and XYL. Values for N exoenzyme activities were analyzed as the sum of LAP and NAG. Microbial exoenzymes indicate microbial nutrient demand as a product of woodchip and biochar (and all organic matter) decomposition (Sinsabaugh et al. 2008). Because microbial nutrient demand is directly tied to environmental nutrient availability, analysis of exoenzymes offers mechanistic insight into the nutrient availability for plant growth (Sinsabaugh et al. 2008).

Biomass, exoenzyme activity, and plant density data were transformed for normality (square root, natural log, and no transform, respectively), if needed based on a Shapiro–Wilk test of their residuals, and analyzed using ANOVA (Type II, Hector et al. 2010). Explanatory variables were soil type, amendment treatment, precipitation, along with their 2- and 3-way interactions. Tukey's Honestly Significant Difference (HSD) was used to determine significance of differences between means. Untransformed data and means were used in figures and reported in the text to best allow real world interpretation. Plant community composition was analyzed using species density per pot in Principle Coordinates Analysis (PCoA), which allowed for the reasonable inclusion of pots with single species as well as pots without any plants (through including "empty" as a species for the analysis). Planted species densities per pot were included separately from volunteer species from the field soil which were aggregated into volunteer forbs and volunteer grasses for the PCoA analysis. The PCoA dispersion was tested using the betadisper function in the vegan package (Anderson 2006) and Tukey's HSD to determine differences between centroids. All data were analyzed in R version 3.2.2 (R Foundation for Statistical Computing, Vienna, Austria).

Results

The main effects of soil type, amendment treatments, and the levels of simulated precipitation on aboveground plant biomass were all significant ($p < 0.01$; Table S1), whereas none of the two-or the three-way interactions were significant ($p > 0.12$). The Chiricahua soil yielded significantly more aboveground biomass (462 kg/ha) than the Hathaway soil (313 kg/ha; Fig. 1a). The surface woodchip treatment was the most productive of the amendment treatments (489 kg/ha) and the incorporated woodchips were the least productive (298 kg/ha; Fig. 1b). Biochar (379 kg/ha) and the un-amended pots (383 kg/ha) were not significantly different. The simulated precipitation levels (40%, 60%, 80%, and 100%) yielded aboveground biomass in rising order (216, 350, 468, 533 kg/ha respectively; Fig. 1c) but the 80% and 100% levels were not significantly different. The expected interaction between amendment treatments, especially between biochar and precipitation was not observed ($p = 0.54$) for aboveground biomass.

The volumetric water content (VWC), based on the combined 80% and 100% precipitation treatments, showed that the soils had different drying rates ($e^{0.624} \pm e^{0.025}$, estimate ± se). Individual models for each soil indicated that biochar increased soil water retention for both soils (Fig. 2, $e^{0.302} \pm e^{0.038}$ for Chiricahua, $e^{0.398} \pm e^{0.031}$ for Hathaway). One day after cessation of watering, the difference between the biochar and no treatment for the Chiricahua soil was 3.8 % higher VWC (Fig. 2A). The difference in Hathaway soil was 7.6 % higher VWC (Fig. 2B) and differences persist for both soils throughout the 28-day observation period. The incorporated woodchip and surface woodchip treatments had more complex responses with the incorporated woodchips increasing the VWC in the excessively well-drained Chiricahua soil (*$e^{0.245}$* ± *$e^{0.036}$*) and having no effect in the Hathaway soil (*$e^{0.003}$* ± *$e^{0.031}$*), while the surface woodchips had no effect on Chiricahua soil (*$e^{-0.001}$* ± *$e^{0.036}$*) but reduced VWC in Hathaway soil (*$e^{-0.155}$* ± *$e^{0.031}$*). The effect of plant biomass on soil drying was significant and on the order of a 1% reduction in VWC per each 208 kg/ha equivalent of biomass one day after cessation of watering of the 80% and 100% precipitation pots.

The Chiricahua and Hathaway soils differed in properties such as clay content, nutrient content, and CEC that, along with amendment treatment, had the potential to influence microbial activities (Table 1). The exoenzyme activities of N and P mineralization were significantly higher, and C exoenzyme activities significantly lower, in the control, non-amended Hathaway soils compared to Chiricahua soils (Table 2). For the C and P exoenzyme activities, the main effects of soil type, amendment treatments, and the levels of simulated precipitation on were all significant ($p \leq 0.01$; Tables S2, S3, S4) as well as the interaction between soil type and amendment treatment. For this interaction, the amendments had a significant effect on C and P exoenzyme activities, with highest C exoenzyme activities in surface woodchip application (79.92 ± 11.21, mean ± SE) and lowest in biochar (29.09 ± 3.28) in the Chiricahua soil. Highest P exoenzyme activities occurred in surface woodchip application (67.66 ± 6.43 Chiricahua and 84.74 ± 8.62 Hathaway) and lowest in biochar (28.36 ± 2.86 Chiricahua and 81.97 ± 7.67 Hathaway; Table 2).

The simulated precipitation levels also had a significant effect on C and P exoenzyme activities, with highest activities for both C and P in the 60% simulated precipitation (Table 3). N exoenzyme activities were higher in Hathaway soils than Chiricahua soils regardless of simulated precipitation (Table 4). The interaction between amendments and simulated precipitation levels was only significant for N exoenzyme activities, which were highest in surface woodchips at 40% precipitation (Table 4, Table S3) and otherwise increased with increasing precipitation. There were no significant three-way interactions among soil type, amendment, and simulated precipitation levels for any of the exoenzyme activities.

The plant community response, as shown through evaluation of the species composition and the Principle Coordinates Analysis (Fig. 3), showed that the seeded and volunteer plants could survive and grow to maturity across every treatment combination in this study, albeit quite variably in the 40% and 60% simulated rainfall treatments. The study design included soils with different properties (Table 1), nonetheless, the soils did not result in a different plant community level response ($p = 0.20$; Fig. 3A). Volunteer forbs did not occur in the Chiricahua soil, which supported only a single occurrence of a seeded forb (*Baileya multiradiata).* Seven volunteer forbs occurred in the Hathaway soil along with 10 *B. multiradiata* plants making forbs uncommon overall.

The amendment treatments (Fig. 3B) show that the surface woodchip treatment resulted in a different species composition than the other amendment treatments ($p < 0.01$) including unamended controls. The biochar and the no amendment treatments had nearly identical plant communities. The incorporated woodchips had the largest envelope with the centroid being separated from the rest due to having numerous no-establishment and low species abundance pots. The simulated rainfall treatments did not form statistically distinct groups ($p > 0.42$; Fig. 3C). This was again due in part to pots without plant establishment. Five pots in the 40% precipitation incorporated woodchip treatment had no vegetation establishment (three in Chiricahua, two in Hathaway). In the 40% precipitation biochar treatment in the Hathaway soil, one pot had no establishment and another had only a single volunteer grass.

Only the amendment and precipitation treatments were significant for pot densities ($p < 0.01$; Table 5S) while the soils and interactions were not significant ($p > 0.45$). The surface woodchip treatment resulted in a significantly ($p < 0.01$) higher average number of individual plants per pot (13.28 ± 0.64) compared to the biochar (7.48 ± 0.73), incorporated woodchips (5.51 ± 0.63) and no amendment (8.68 ± 0.67) treatments. The densities increased as the precipitation increased with 40% (6.70 ± 0.73), 60% (7.80 ± 0.72), 80% (10.16 ± 0.92), and 100% (10.63 ± 0.69) increasing in stepwise fashion and each being significantly different ($p \leq 0.01$) from the non-neighboring levels. Volunteer grasses were common and dominated by *Panicum hirticaule* (58%) followed by *Aristida adscensionis* (29%) and *Eragrostis cilianensis* (8%). Neither *Elymus elymoides* nor *Eschscholzia californica*, both part of the seed mix, occurred in any of the pots.

Discussion

We tested the potential for woodchip and biochar amendments to increase revegetation success under increasingly drier conditions in a semi-arid system. In all scenarios except for the lowest precipitation treatments, we expected the amendments to have an increasingly positive effect on aboveground biomass as the amount of simulated precipitation decreased. This expected interaction between the amendments and the simulated precipitation did not occur and instead only the main effects of the amendment treatments and levels of simulated precipitation had a significant effect on aboveground biomass.

The woodchips spread on the soil surface were expected to aid in plant establishment (Hovstad & Ohlson 2008; Breton et al. 2016) through the physical effect of the woodchips insulating the soil surface, retaining moisture, and improving germination and establishment conditions (e.g. Bulmer 2000; Hueso-González et al. 2018). Surface woodchips were then expected to have a limited effect on plant growth as the plants matured. Instead, the surface woodchips resulted in significantly greater aboveground biomass, a result that is consistent with higher plant cover with surface woodchips compared to incorporated woodchips in a 22-month field experiment using the same soils and amendments (Espinosa et al. in review). Surface woodchips also resulted in greater plant density and greater plant community similarity that was also unique compared to the other treatments. High activities of C and P exoenzymes with surface woodchips, and high N activities with surface woodchips at 40% precipitation, suggest higher rates of nutrient cycling compared to soils with other amendments. Greater plant density may have also allowed more resource capture early, possibly N, due to higher root distribution through the soil (de Vries & Bardgett 2016) resulting in higher biomass. This effect may have been augmented by a non-significant trend toward higher species richness that might have also aided resource capture and biomass production (Tilman et al. 1996; Cardinale et al. 2007).

The effect of plant establishment may have been amplified by resources released by the decay of the chips themselves. The surface woodchips might be thought to have a slower and smaller decay rate compared to incorporated woodchips due to less of the chip being in contact with the soil, similar to the decay rates observed by Biederman and Whisenant (2011), but photodegradation may be an important factor in the hot dry regional conditions (Barnes et al. 2012). Results from a semi-arid site in Colorado USA (Miller & Seastedt 2009) found no change in soil N availability in the first two years after surface woodchip application and an increase after 3 years. In our experiment, surface application of woodchips did not significantly alter N acquiring exoenzyme activities compared to the un-amended control except in the most water-limited treatment of 40% precipitation, though C and P activities were significantly higher with surface woodchip application.

Surface woodchip application decreased soil water retention in Hathaway soil but had no effect on volumetric water content in the more well-drained Chiricahua soil. One potential explanation is that greater plant biomass in the surface woodchip treatment led to greater water loss through transpiration. A more complex effect may also be occurring such as observed by Fehmi and Kong (2012) who, in soils from the same source areas, ascribed surface mulch (straw) as allowing larger soil moisture losses to evaporation through hydraulic connectivity to the atmosphere. The surface woodchips may prevent a surficial dry layer from forming, which would break the hydraulic connection to deeper layers. This effect can occur in well drained soils and may not occur on finer-grained soils (Jalota et al. 2001). This may explain why there was no observed soil moisture effect of surface woodchips in the Chiricahua soil where the biomass was greater but the soil has a finer texture. Overall, the positive effect of surface woodchips on aboveground biomass, and exoenzyme activities involved with C degradation and P mineralization appears important because it represents a viable management technique to improve revegetation efforts.

While biochar increased soil water retention, this did not result in the expected increase in aboveground biomass; the overall effect was not significantly different from the no amendment treatment response. This was similar to the findings of Gebhardt et al. (2017) for the one of same soil types (Hathaway) and Espinosa et al. (in review) for a field experiment with both soil types. Perhaps a strong effect of biochar might not be expected at higher levels of simulated precipitation, but, contrary to our results, an effect would be expected where water was the limiting factor on plant growth in the 40% and 60% of average rainfall treatments. Another explanation might be that the biochar could shift the limiting factor from water to nutrients, such as N, and that the advantage of higher soil moisture would be tempered by suppression from lack of the next most limiting nutrient. Since exoenzyme production is N-demanding (Allison & Vitousek 2005), low N environments might limit production. This might hold some explanatory power given that we found C and P exoenzymes were lowest in biochar, consistent with Espinosa et al. (in review).

Biochar has been shown to decrease plant growth by decreasing the availability of micronutrients either through direct binding or indirectly through raising soil pH (Haider et al. 2017). In our experiment, soil pH was not significantly different among treatments ($p > 0.24$, data not shown). The biochar treatment did yield the lowest potential exoenzyme activities of C and P, which might be due to the initial sorption of elements or enzymes to biochar (Bailey et al. 2011; Swaine et al. 2013) that might be subsequently released as biochar degrades. The duration of this experiment may not have been long enough to detect this and other biochar effects that might change over the extended growing season as found by Artiola et al. (2012). The large granule size of the biochar may have had an inhibiting effect on either root uptake of water or root distribution near the biochar. As reviewed in Wang et al. (2016), complex interactions of positive and negative effects occur with biochar addition. Biochar addition may have a longer-term positive impact on plant establishment and aboveground biomass, but in the short-term it had no significant effect on establishing and maintaining vegetation in our study. Nonetheless, the potential for long-term C storage of the biochar seems to offer substantial promise for mitigating increased atmospheric CO_2 (Li et al. 2018) and the increased water content holds promise for greater future plant biomass. Field studies using locally sourced biochar and with 5-10 year observation period are recommended as future work.

Aboveground biomass in the incorporated woodchip amendment treatment was significantly lower than in all other amendment treatments though this result cannot be attributed to lower soil water content as predicted. In fact, incorporated woodchip amendment led to an increase in water content in the well-drained Chiricahua soil compared to the no amendment treatment, and no water content differences were found in the Hathaway soil. Evidence from the same Hathaway soil and woodchip species (*Juniperus monosperma*) as our experiment, indicates that incorporating woodchips into soil can stimulate microbial activity and potentially reduce plant available nitrogen (Gebhardt et al. 2017; Espinosa et al. in review). Microbial respiration rates have been shown to be higher with incorporation of woodchips in these same soils, possibly reflecting higher cycling rates, shifts in communities, and/or waste heterotrophic respiration (Espinosa et al. in review). The addition of woodchips has been shown to significantly increase the relative amount of dissolved organic carbon to total dissolved nitrogen in these soils despite the relatively large chip size and recalcitrant Juniper chips (Gebhardt et al. 2017; Espinosa et al. in review). The effect of vegetation growing poorly in soil mixed with woodchips has been observed in the 22-month field experiment using the same soils and amendments (Espinosa et al. in review) and elsewhere (e.g. Venner et al. 2011 in British Columbia, Canada; Eldridge et al. 2012 in Colorado, USA). These effects may be driven by local site factors and many woodchip applications are accompanied with fertilization (Larney & Angers 2012). Incorporating woodchips into soil may have a long-term positive effect as the woodchips decay and release nutrients despite significantly suppressing vegetation in the short term. However, any later advantage may not offset the profound disadvantage of increasing the chance of revegetation failure in the first year.

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Table 1. Pretreatment properties of the two soils.

	Chiricahua	Hathaway
Texture classification	Sandy loam	Sandy loam
Loss on Ignition[a] (%)	3.5 ± 0.01	4.3 ± 0.05
Rock Fragments[a] (%)	72 ± 3.2	43 ± 3.6
Sand (%)	69.1	59.7
Silt (%)	24.4	30.9
Clay (%)	6.4	9.4
NO_3 (ppm)	5.7	3.4
PO_4 (ppm)	10	1.9
K (ppm)	150	190
pH	6.1	7.7
CEC (meq/100g)	11.5	22.1

[a] Loss on ignition (LOI) and rock fragment values are mean of three replicates reporting 1 standard deviation.

Soil Type	Amendment	Exoenzyme Activities (nmol activity g^{-1} SOM h^{-1}) Carbon	Nitrogen	Phosphorous
Chiricahua	None	54.66_{ab} (9.99)	52.30_{b} (4.98)	59.63_{c} (5.78)
	Biochar	29.09_{bc} (3.28)	63.67_{b} (4.83)	28.36_{d} (2.86)
	Incorporated Woodchips	40.65_{b} (4.49)	50.66_{b} (2.22)	32.87_{d} (3.03)
	Surface Woodchips	79.92_{a} (11.12)	54.83_{b} (4.47)	67.66_{bc} (6.43)
Hathaway	None	17.83_{cd} (1.11)	120.07_{a} (11.46)	92.30_{ab} (7.31)
	Biochar	13.35_{d} (0.99)	95.97_{a} (10.33)	81.97_{abc} (7.67)
	Incorporated Woodchips	22.54_{c} (1.85)	130.68_{a} (3.17)	107.77_{a} (9.93)
	Surface Woodchips	17.12_{cd} (1.21)	122.68_{a} (10.78)	84.74_{abc} (8.62)

Table 2. Mean (standard error of the mean) calculated from un-transformed data are presented to better allow real-world interpretation. A natural log transformation was used for analysis. Different letters within columns designate significant differences ($p < 0.05$) based on Tukey's HSD test.

		Exoenzyme Activity (nmol activity g^{-1} SOM h^{-1}) Carbon	Phosphorous
Simulated Precipitation	40%	40.47_{a} (5.68)	73.57_{a} (5.86)
	60%	42.93_{ab} (7.51)	75.28_{a} (7.07)
	80%	28.17_{ab} (4.00)	64.88_{b} (6.15)
	100%	25.94_{b} (2.40)	63.58_{ab} (6.06)

Table 3. Mean (standard error of the mean) calculated from un-transformed data are presented to better allow real-world interpretation. A natural log transformation was used for analysis. Different letters within columns designate significant differences ($p < 0.05$) based on Tukey's HSD test. There was no significant interaction with soil type and the results of both soils are presented together.

		Nitrogen Exoenzyme Activity (nmol activity g^{-1} SOM h^{-1})	
		Chiricahua	Hathaway
Simulated Precipitation	40%	49.56_b (5.21)	139.87_a (11.09)
	60%	50.84_b (3.37)	99.79_a (7.61)
	80%	61.96_b (4.09)	112.31_a (12.95)
	100%	60.28_b (4.01)	115.66_a (11.95)

Table 4. Mean (standard error of the mean) calculated from un-transformed data are presented to better allow real-world interpretation. A natural log transformation was used for analysis. Different letters within the table designate significant differences ($p < 0.05$) based on Tukey's HSD test. This interaction was significant due to the high activity in the 40% precipitation in the Hathaway soil which does not match the otherwise common increase in activity with increased precipitation.

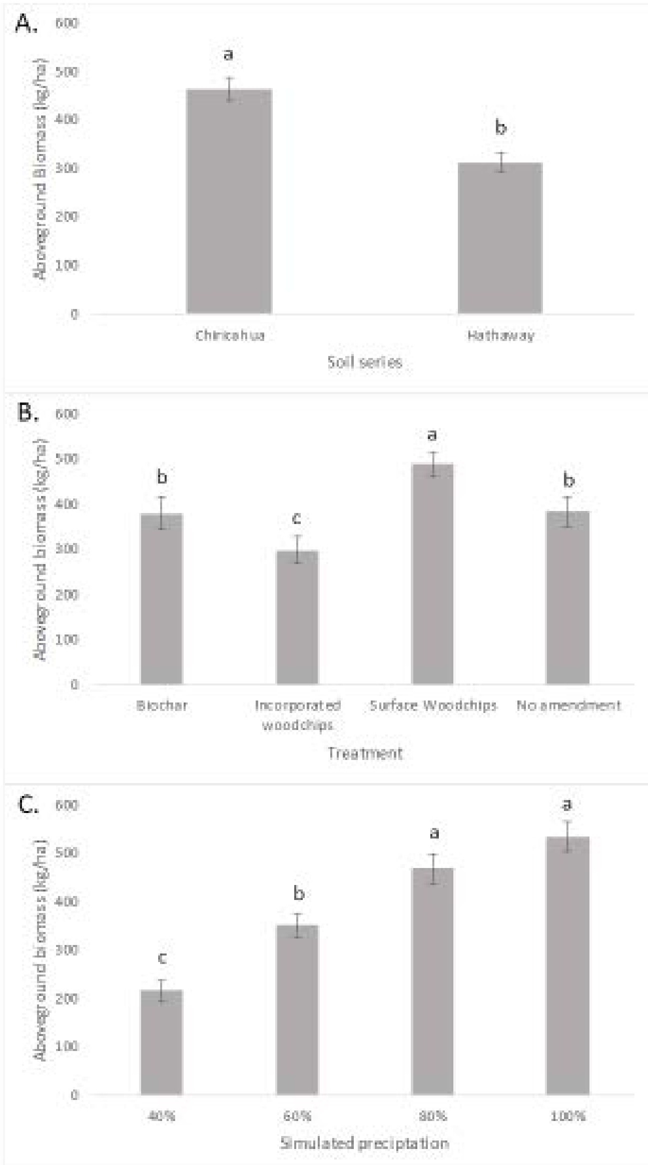

Figure 1. Aboveground biomass, untransformed data presented. Error bars represent ± SE. Columns denoted with different letters within a panel indicate a significant difference ($p < 0.05$) based on Tukey's HSD test. A) by soil type. The difference between soils is significant ($p < 0.01$). B) by amendment treatment. All differences are significant ($p < 0.01$) except for between biochar and no amendment. C)

by simulated precipitation level. All differences are significant ($p < 0.01$) except for between 100% and 80%.

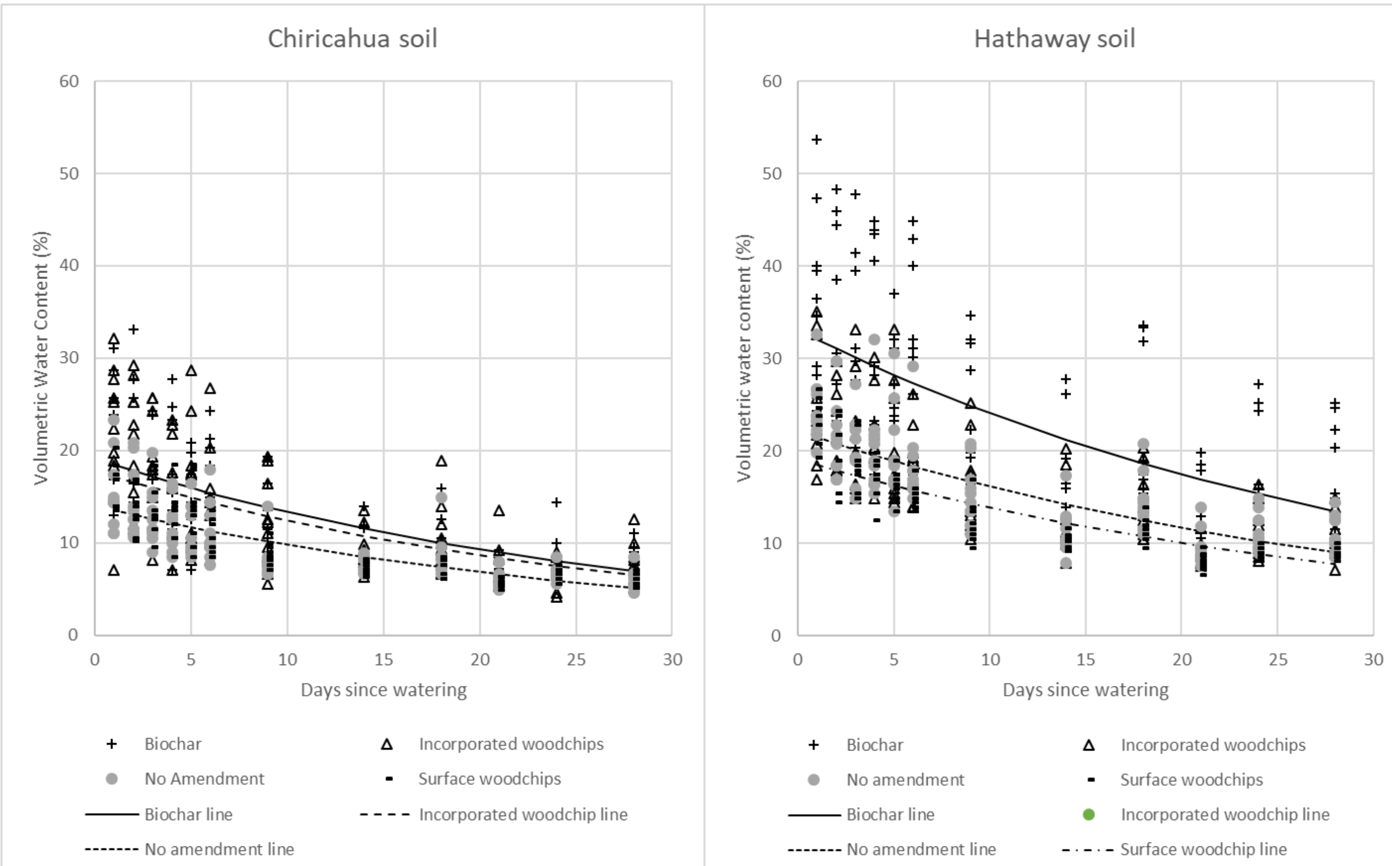

Figure 2. Volumetric water content data from the 80 and 100% precipitation treatments. Lines are from the linear models and have been back transformed into the units shown. The line for surface wood for the Chiricahua soil and for incorporated wood in the Hathaway soil were not significantly different from the no treatment lines ($p > 0.90$) and are not shown. For line fitting, water conted was natural log transformed so equations of presented lines are: Chiricauhua – Biochar $e^{2.95 - 0.036day}$, – Incorporated wood $e^{2.89 - 0.036day}$, – No amendment $e^{2.65 - 0.036day}$, $R^2 = 0.62$; Hathaway – Biochar $e^{3.40 - 0.032day}$, – Surface wood $e^{2.95 - 0.032day}$, – No amendment $e^{3.10 - 0.032day}$, $R^2 = 0.68$.

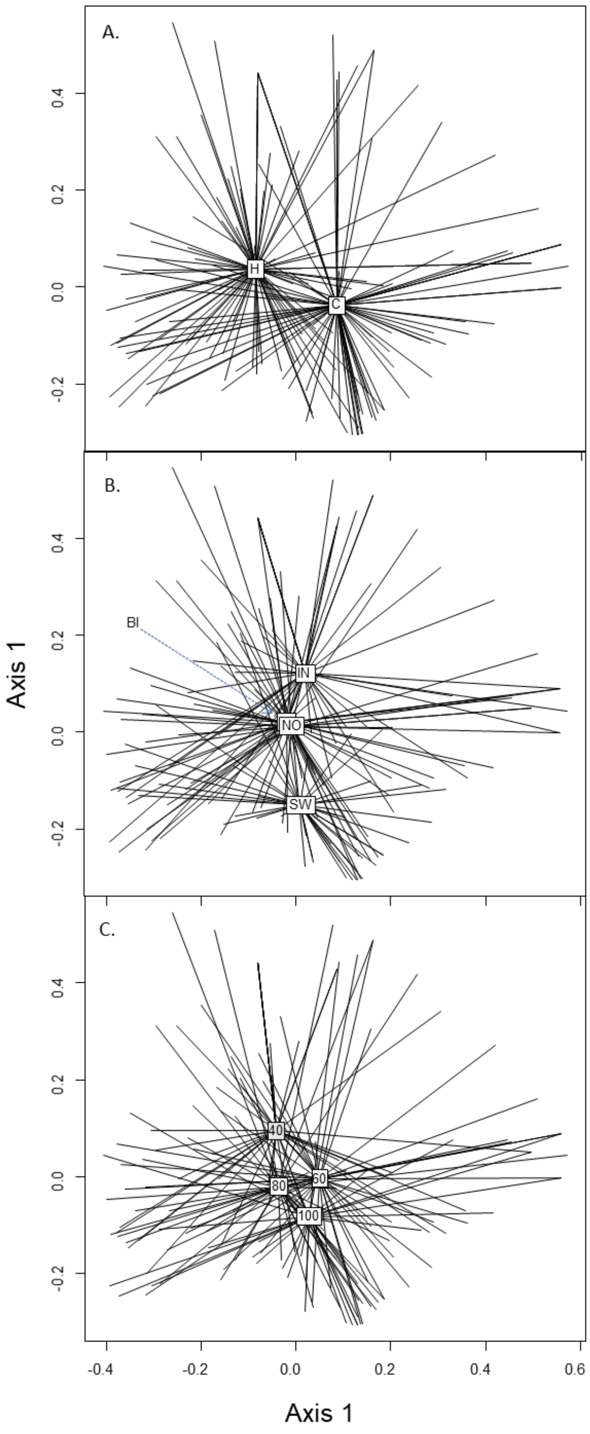
A.
H
C
B.
BI
IN
NO
SW
C.
40
80
60
100
0.4
0.2
0.0
-0.2
Axis 1
-0.4
-0.2
0.0
0.2
0.4
0.6
Axis 1

Figure 3. Visualization of Principle Coordinates Analysis of plant species composition similarities in response to the main effects of soil types (A), amendment treatments (B), and simulated precipitation treatments (C). A) the two soil types with C standing for Chiracauhau and H standing for Hathaway. B) the amendment treatments with BI standing for Biochar, IN standing for incorporated wood, NO standing for no treatment, and SW standing for Surface Wood chips. The BIochar centroid is obscured by the NO amendment centroid due to them being nearly the same. C) The simulated precipitation treatments with 40 standing for 40% of average, 60 standing for 60% of average, 80 standing for 80% of average, and 100 standing for 100% of average.