Abstract

Patterns of herbicide use have changed dramatically over the past 25 years. While great consideration is often given to shifts in aboveground diversity, the belowground component of ecosystems has been largely neglected. Previous research has revealed a mixed response of edaphic parameters, microbial diversity and function to herbicide application and has spurred calls for further research as well as disentanglement of the direct and indirect effects of herbicide application. With microbes being largely responsible for nutrient cycling and other pivotal ecosystem processes, understanding the direction and magnitude of their responses to vegetation removal in agro-ecosystems is of the utmost concern. In this study, we compare three chemical herbicides, Roundup (glyphosate), Clarity (dicamba), and a tank mix of Aatrex and Calisto (atrazine and mesotrione) to handweeded and nontreated control plots to understand how herbicide application may affect both soil and phyllosphere diversity and function over twenty days post-treatment in *Zea mays* fields.

Our results show that the examined herbicides have limited and short-lasting effects on soil edaphic properties and microbial function measured by extracellular enzyme analysis. Furthermore, weedy vegetation was shown to be a significant predictor of both enzymatic activities and nutrient concentrations, suggesting that the effects of herbicide application are instead mediated via indirect pathways. With this, we suggest that the choice of herbicide in heavily managed agro-ecosystems has little effect on ecosystem function.

Introduction

In 1996, genetically modified herbicide resistant crops were introduced to the United States, prompting a shift in herbicide use patterns. Driven mainly by the use of glyphosate (commonly known as Roundup; a glyphosate-based herbicide, ﻿N-(phosphonomethyl)glycine), herbicide application increased by 239 million kilograms from 1996 to 2011 in the United States alone [1]. In the past, growers were concerned, and rightfully so, with a single parameter: crop yield. However, the birth of the soil health movement has prompted a new way of thinking about production agriculture with a newfound focus on long-term yield and a holo-ecosystem approach. With this new school of thought, researchers and producers alike are realizing the importance of understanding the effects that herbicide and other agricultural amendments might have on soil and the ecosystem services that it provides [9,99].

While commonly applied to control unwanted weedy plant populations, herbicides may also affect soil microbial community structure and function [9,12,13,100,101]. Microbes provide countless benefits in agricultural systems, including: plant growth promotion [102], pathogen suppression [103], nutrient cycling [104–107], as well as aggregate formation and maintenance of soil structure, contributing an estimated $330 to $500 per ha/yr in ecosystem services [108]. Due to the fact that microbes are such important members of agroecosystems, understanding the multifaceted microbial response to herbicide application is necessary in order to optimize agricultural systems for yield and sustainability. Difficulties in elucidating the effects of herbicide application on soil microbes has been demonstrated in reviews of the topic [10–12,109,110] and is underscored by the fact that herbicides are a very broad group of chemicals, and their effects on soil microbes may differ depending on soil [12] and plant characteristics [38] as well as rate of application [12] and mode of action [9]. Furthermore, herbicides have the potential to indirectly affect the soil microbiome through changes to vegetation and subsequent root exudation [111], making it even more difficult to understand how microbial systems might respond.

Studying the effects of herbicide on soil properties and processes is not a new endeavor, with research dating as far back as the 1960’s [100]. Until recently, the methods used to examine the effects of herbicide on soil microbes, like denaturing gradient gel electrophoresis (DGGE) or soil respiration studies, have limited the ability of researchers to uncover fine scale changes in microbiome structure or function following application, and this resulted in the general consensus that herbicides have limited to no effect on soil microbial assemblages [11]. However, over the past ten years, the use of modern molecular tools including high throughput sequencing (HTS), metagenomics and even enzyme assays have afforded researchers a new level of detail when studying the response of soil communities to agricultural amendments. Despite the new level of detail, results from studies examining the effects of herbicide on the soil microbiome remain mixed and only highlight the need for further research [11,14,15,17,112] .

To better understand how herbicide application affects microbial function and diversity in Wyoming, we compared the effects of three different herbicides along with handweeded and nontreated controls on the structure and function of the soil microbiome in *Zea mays* over twenty days post-application. Each of the three examined herbicides act on a different mode of action (Table 1), and as such, we hypothesized that the effects of each herbicide on microbial diversity and function would differ [9]. Specifically, we hypothesized the Aatrex and Calisto tank mix would have effects on nitrogen cycling microbes, as other members of this family of herbicides have been demonstrated to do so [113], and may affect enzymatic activates as it contains organic N in the chemical structure of the herbicide. Roundup Powermax and Clarity are also likely to affect the structure and function of the soil microbial community as they inhibit amino acid synthesis and signaling pathways that are present in both plants and microbes. Furthermore, Roundup and other glyphosate-based herbicides contain organic phosphorus and may affect phosphorus mineralization rates following application. Inclusion of handweeded checks allowed for comparison of the effects of herbicide application to mechanical weed removal. With this experimental design we are able to examine whether shifts in microbial function and diversity are the direct result of herbicide application or whether changes are indirectly mediated through vegetation removal [114].

Methods

*Field experimental design*

In the summer of 2018, 20 experimental plots at the Sustainable Agriculture Research and Extension Center (SAREC) in Lingle, WY (MAT 8.4° C) were planted with *Zea mays* variety ‘P9188AMX’ at 34,000 seeds per acre. Plots were fertilized using a dry fertilizer prior to corn planting according to best practices (40 rock fertilizer- 125Nitrogen-35Phosphorus-0Potassium-35Elemental Sulfur-13Sulfate-2Zinc blend -J.R. Simplot Company, Boise, ID). Plots were irrigated every several days using lateral pivot irrigation according to best practices. The soil at this site has an alkaline pH (~ 8) with CaCO3 content between 1 and 3 %. The soil can be characterized as silty clay loam (27 % - 40 % clay) [115] and is mapped as a well-drained Haverson and McCook loam (i.e. HnA), 0-3% slope (Web Soil Survey, USDA-NRCS). Each plot, 3 m x 10 m, consisted of five evenly spaced rows of *Zea mays*. The experimental design included five different treatments with four replicate plots each, a control (nontreated), handweeded plots, and three different herbicide applications. The three herbicides used in the study were Roundup PowerMax (glyphosate, group 9), Aatrex and Callisto (atrazine and mesotrione tank mix, group 5 and 27 respectively, herein referred to as Aatrex), and Clarity (dicamba, group 4). Herbicides were applied at the following recommended field rates: Roundup PowerMax 2338.5 mL/Ha, Aatrex 1169.25 mL/Ha, Callisto 219.23 mL/Ha, and Clarity 584.62 mL/Ha (Table 1). In the handweeded plots, above ground vegetation was cut using a hoe and left in the plot on the soil surface. Belowground biomass was not disturbed and remained in the soil. A pre-treatment sampling was conducted in early June, on the morning of herbicide application and hand weeding. Following herbicide application and hand weeding, two post-treatment samplings were conducted. The first was 10 days post-treatment and the second at 20 days post-treatment.

*Sampling and analysis*

To facilitate sampling, a grid was laid out over each plot and coordinates of sample location were determined using a random number generator. The corn plant closest to the coordinate was selected, and a 0.25 m2 Daubenmire plot was placed so that plant was in the center. Cover classes of the main weeds including, redroot pigweed (*Amaranthus retroflexus*), Nightshade (Solanaceae), lamb’s quarter (*Chenopodium album*), and any graminoid, were recorded for each Daubenmire plot. Total weedy vegetation cover was estimated by summing the various cover classes.

Per treatment plot, three plot replicate soil samples were collected at each of the time points for a total of 180 samples (5 treatments x 4 replicate plots x 3 plot replicates x 3 time points). Each plot replicate soil sample was a composite of three soil cores from a single Daubenmire to ensure sufficient soil for laboratory analyses.Soil samples were collected using flame sterilized soil corer to a depth of 5 cm and stored on ice in sterile Whirl-Pak bags. Using the corn plant in the center of the Daubenmire, a 3 cm x 3 cm sample from three individual leaves of the same corn plant were composited in a sterile Whirl-Pak containing sterile silica beads used as a desiccant. *In situ* soiltemperature was measured at a depth of 2.5 cm using a temperature probe. Soil samples and leaf clippings were transported back to the University of Wyoming on ice for further processing.

In the lab, field-fresh soil samples were stored at 4 °C and processed within 24 hours. Leaf clippings were stored in Whirl-Pak bags on silica beads at – 80 °C until processed. Soil samples were first thoroughly mixed in the Whirl-Pak bag used for collection, after which it was sieved though an ethanol-cleaned 2 mm sieve. Gravimetric moisture content was determined by weight difference of a five gram subsample of sieved field-fresh soil after oven drying at 105° C for 48 hours. Next, ~11 g of sieved soil was weighed out for extraction in 50 mL of 0.5 M K2SO4 for assessment of extractable levels of cations (ammonium, calcium, sodium, and magnesium) and anions (nitrate, nitrite, phosphate, and chloride) on a Thermo scientific Dionex Integrion HPIC system (Thermo Fisher Scientific, Waltham, MA). Briefly, samples were shaken in extractant for 30 minutes, stored at 4 °C overnight and filtered through Fisherbrand Q5 filter paper the next day. Filtered extracts were diluted with nanopore water (1:10) prior to analysis and filtered through a 0.45 μm hydrophilic filter as per [116]. Anions were ran on a Dionex IonPac AS18 4 um 4x150 mm column for 20 minutes with a flow rate of 1.0 mL/min at 35 °C. Cations were ran on a Dionex IonPac CS16-Fast 4um 4x150mm column for 20 minutes with a flow rate of 0.64 mL/min at 40°C. Raw values of anions and cations were reported as ppm and converted to mg/kg dry soil. The remaining soil was then split into two portions, of which one was frozen at -20 °C for microbial analysis (DNA extraction for determination of microbial community structure and extracellular enzyme analysis for microbial function), and the other portion was air-dried. Air dried soil was used to measure pH and electrical conductivity using an Oakton PC700 benchtop meter (OAKTON instruments, Vernon Hills, IL) with a soil to DI water ratio of 1:2 (w:v).

*Extracellular enzyme analysis*

Extracellular enzyme activities (EEA) were measured for seven enzymes involved in the cycling of carbon (C), nitrogen (N), and phosphorus (P) as outlined in [117–121]. The enzymes measured include ß-glucosidase (BG), β-xylosidase (BX), α-glucosidase (AG), cellobiohydrolase (CBH), alkaline phosphatase (PHOS), N-acetyl-ß-glucosaminidase (NAG), and leucine aminopeptidase (LAP). A preliminary assay was performed using four different substrate concentrations (ranging from 200 μM to 4000 μM) at five different measurement times (1, 2, 4, 6, 8 and 10 hours). This was done to ensure non-limiting substrate availability and maximum potential enzyme activity (Vmax) [122]. Three soil samples encompassing the expected variability in enzyme activity were used for these preliminary assays. Briefly, a soil slurry was created by homogenizing 1 g of soil with 100 ml of sodium acetate buffer (50 mM, pH 7.95) for 30 seconds using a Magic Bullet blender (Homeland Housewares LLC). In order to minimize difference between buffer and soil pH, we used a buffer pH 7.95 which represents the mean pH of all soil samples within 1 standard deviation. In a 96-well microplate, 200 μL of soil slurry homogenate was combined with 50 μL substrate and incubated at 20 °C for 1-10 hours. Four technical replicates per soil sample were used to measure fluorescence after addition of substrates. Hydrolytic enzyme activity was measured via fluorescence on a SYNERGY HTX multi-mode reader (BioTek® Instruments Inc., Winooski, VT) at an excitation wavelength of 360 nm and an emission wavelength of 450 nm. Background fluorescence was corrected using a negative control (sample homogenate with buffer), as well as a quench control (sample homogenate with standards). This was done to correct for interference of soil particles with fluorescence intensity. Fluorescence conversions were based on measurements of standards (10 μM): 7-amido-4-methylcoumarin hydrochloride (AMC) for LAP and 4-methylumbelliferone (MUB) for BG, BX, AG, CBH, NAG, and PHOS. Final enzyme activities were calculated using formulas outlined in DeForest [120] and were reported as nmol of substrate converted per hour per g soil dry mass (nmol h-1 g-1). The incubation time and substrate concentration, from the preliminary assay, producing the highest average enzyme activity were selected for each enzyme. This resulted in a single substrate concentration and incubation time to be used for each enzyme across all samples for final enzyme assays. Final enzyme assays for all samples were done in a similar manner as the preliminary assays but using the substrate concentration and incubation time that resulted in the maximum potential enzyme activity (Vmax). One sample from each plot was used for enzyme analysis for a total of 20 sample at each time point and 60 samples across the three time points.

*Soil and phyllosphere microbiome analysis*

Methods similar to those detailed in chapter two will be utilized to analyze the structure and composition of the soil and phyllosphere microbiomes. Briefly, clippings of *Zea mays* leaves taken at each sampling time point will be extracted using PowerPlant extraction kits (MO BIO, Carlsbad, CA). DNA extracts will be used for assessment of the endo- and epiphytic phyllosphere microbiome. Subsamples of the same soils used for edaphic measurements were extracted using PowerSoil extraction kits (MO BIO, Carlsbad, CA) and will be used for studying soil bacteria and fungi of the top 5 cm.

Both bacterial (16S) and fungal (internal transcribed spacer; ITS) amplicon libraries were prepared in the same fashion, though different primers were used to amplify each region. In order to amplify the V4 region of the bacterial 16S rRNA gene the modified 515F (5’-GTGYCAGCMGCCGC GGTAA-3’) [72] and 806R (5’-GGACTACNVGGGTWTCTAAT-3’) [73] were used. For the ITS1 region of the fungal genome, the primers ITS1F (5'-CTTGGTCATTTAGAGGAAGTAA-3') [123] and ITS2 (3'-CGTAGCTACTTCTTGCGTCG-5') [75] were used. Environmental DNA (eDNA) was normalized to 10 ng/μL prior to amplification. The 15 μL reactions contained 3 μL 5x Kapa HiFi HotStart PCR buffer (Roche, Basel, Switzerland), 0.45 μL 10M dNTPs, 0.3 μL Kapa HiFi HotStart DNA polymerase (Roche, Basel, Switzerland), 3.25 μL HPLC H2O, 6 μL of appropriately paired barcoded primers (3 μL forward and 3 μL reverse), and 2 μL of the diluted 10 μL eDNA sample. In a two-step process, eDNA was amplified and barcoded, then Illumnia adaptors were added. In the amplification and barcoding step, the following PCR conditions were used: 95 °C for 3 min (1 cycle), 15 cycles of 98 °C for 30 sec, 62 °C for 30 sec, 72 °C for 30 sec, and 72 °C for 5 min (1 cycle). PCR was performed in duplicate for each sample and combined to limit PCR biases. PCR products were cleaned using Axygen’s AxyPrep Mag PCR Clean-up Kit according to manufacturer instructions without addition of TE buffer (Axygen Biosciences, Union City, CA). In the second step of the PCR, Illumina barcodes were added to our DNA samples. Each reaction in this step consist of 10 μL of cleaned PCR product from the first step and 5 μL of FlowCell mastermix consisting of 3 μL of 5x Phusion HF buffer (Thermo Fisher Scientific, Waltham, MA, USA), 0.45 μL 10M dNTPs, 0.3 μL Kapa HiFi HotStart DNA polymerase (Roche, Basel, Switzerland), 0.5 μL 10 μM forward (AATGATACGGCGACCACCGAGATCTACACTCGTCGGCAGCGTC) and reverse (CAAGCAGAAGACGGCATACGAGATGTCTCGTGGGCTCGG) FlowCell primers, and 0.75 μL HPLC H2O. In the Illumina adaptor addition step, the following PCR conditions were used: 95 °C for 3 min (1 cycle), 19 cycles of 98 °C for 30 sec, 55 °C for 30 sec, 72 °C for 30 sec, and 72 °C for 5 min (1 cycle). PCR products from the second step were cleaned using GSAF’s modified MagBead protocol and the Axygen’s AxyPrep Mag PCR Clean-up Kit. Following cleaning, sample concentration was checked using a Synergy HTX Take 3 trio plate reader. Samples DNA concentrations were then normalized and combined, and the final library concentration was checked using qPCR. The final library was sent for sequencing at Psomagen genomic sequencing and analysis facility (Rockville, MD) on their NovaSeq6000 using paired end 2 x 250 bp chemistry with a 10% PhiX spike in. Both the fungal and bacterial libraries we sequenced together on a single lane and will be separated bioinformatically.

*Statistical analysis*

While soil samples collected from within the same treatment plot could be considered pseudoreplication and would violate the assumption of independent observations, we argue that pseudoreplication is scale dependent, and the scale that microbes operate on would allow us to assume independence among samples that were collected from the same treatment plot. With aboveground vegetation being a driver of belowground function and vegetation being heterogeneous meter to meter within a single treatment plot, we decided to treat each composite soil sample as an independent sample instead of averaging samples within a plot and losing the ability to assess variation within a treatment plot. This was only of concern for the edaphic measurements, as we used a single sample from each plot for our enzyme analysis.

*Edaphic, enzymatic and vegetation statistical analyses*

All statistical analyses were carried out in R V3.5.2-Eggshell Igloo [44]. Edaphic parameters were examined using multiple model structures. To accomplish this, the entire dataset was subset into either: 1) individual time points containing all five weed removal treatment types or 2) individual weed removal treatments that contained all three time points. In both cases, ANCOVA was used for our statistical analyses. Assumptions of ANCOVA, including normality of residuals and equal variance, were met prior to using this framework. We report a significance level of α = 0.05. As weedy vegetation is a driver of belowground exudation and resource competition, it is likely to contribute to the concentration of nutrients and enzyme activities. As such, it was collected as a covariate and included in our models. The first set of statistical models was used to compare the effects of weed removal treatment within a single time point (Y ~ weed removal treatment + total weedy vegetation, data = time point containing all five treatment types). The second set of models was used to examine the effect of time within a single weed removal treatment (Y ~ time + total weedy vegetation, data = individual treatment type with all three time points). Pairwise differences in edaphic parameters among time points and treatment types were assessed using Tukey’s HSD.

In order to examine changes in extracellular enzyme activities, the dataset was again split by time point and weed removal treatment type with the same comparison methods applied as was done for the edaphic parameters. In addition, using a conservative mixed modeling approach, we examined the effect of time, weed removal treatment, and total weedy vegetation on enzyme activity simultaneously using linear mixed models with fixed effects of weed removal treatment, pre-treatment enzyme activity (to account for initial differences), total weedy vegetation, and a time\*weed removal treatment interaction, with a random effect of sampling time to account for temporal non-independence (Y ~ pre-treatment enzyme activity + treatment + time + total weedy vegetation + treatment\*time + (1|time), data = all data points from time two and three).

For multivariate responses to weed removal treatment or time since treatment, PerMANOVA testing (Adonis) was utilized to determine statistical differences among total enzymatic profiles with a significance level of α=0.05 [81,124]. Non-metric multidimensional scaling was utilized to visualize differences in total enzymatic profiles. Mantel testing was implemented to examine correlations in the distance matrices of edaphic conditions and enzymatic activities.

Differences in the cover of total weedy vegetation, lamb’s quarter, and redroot pigweed across herbicide treatments within a single time point were assessed individually with similar statistical models as were used for comparisons of enzymatic and edaphic properties. As these measurements were collected as cover classes and converted to a continuous covariate, we do not report percent change or means following treatment, only directionality of change.

*Microbiome analyses*

Both multivariate (PerMANOVA) and univariate (indicator species analysis and linear models of alpha diversity) will be used to assess the effects weed removal treatment has on the soil and phyllosphere microbiome.

Results

*Vegetation responses*

As was expected, herbicide application controlled total weedy vegetation at 10 days (time two) and 20 days (time three) post-treatment (p < 0.05). When the cover of weedy species was examined individually, only lamb’s quarter and pigweed had sufficient cover to estimate differences among time points. Like total weedy cover, herbicide application reduced lamb’s quarter and redroot pigweed cover at 10 and 20 days post-application when compared to the nontreated plots. At 10 days post-treatment, the handweeded controls also showed a significant drop in total weedy vegetation, lamb’s quarter, and redroot pigweed cover as compared to the nontreated plots (p < 0.05). However, the observed decreases in cover disappeared at 20 days post-treatment, and weedy vegetation levels were no longer different from the nontreated plots as compared to the nontreated plots.

*Edaphic properties*

Examination of edaphic parameters within in a single time point revealed no significant differences pre-treatment (time one) among the weed removal treatments when the effect of total weedy vegetation was accounted for (Table 2 and Supplementary Tables 1a and 1b). At 10 days (time two) and 20 days (time three) post-treatment, nitrate and total inorganic nitrogen (N) concentration were significantly different (p < 0.05) (Figure 1, Table 2), with weed removal treatment being a significant predictor at both time points but total weedy vegetation being significant only for sampling time two. Plots treated with RoundUp Powermax had higher levels of nitrate and total inorganic N than the handweeded plots at timepoint two and three (p < 0.05). At time three, Roundup treated plots also had significantly higher nitrate concentrations as compared to the nontreated and Aatrex treated plots (p < 0.05). We observed the same trend at sampling time two, but the differences were only marginally significant (p < 0.09). The handweeded plots had lower moisture content as compared to the Aatrex and Clarity plots at time two (p < 0.01), but not at time three. No significant differences in pH, EC, or other nutrients were detected at 10 or 20 days post-treatment.

When examining how our soil variables changed over time within a single weed removal treatment while controlling for total weedy vegetation, multiple differences were observed. Significant models include nitrate, nitrite, ammonium, total inorganic N, phosphate, calcium, magnesium, pH, EC, and gravimetric moisture content (p < 0.05) (Table 3 and Supplementary Tables 2a and 2b). Pairwise contrasts showed time one to have the highest levels of nitrate and total inorganic N across all treatments (p < 0.05) (Figure 1). This was also true for the concentration of magnesium and calcium, with a trend of decreasing concentration over the 20 day sampling period. Total weedy vegetation was only a significant predictor of nitrate concentration in the handweeded plots. Moisture content was also significantly different across time in all treatment types including controls (p < 0.05) and showed the opposite trend of many nutrients, with the later sampling times having higher moisture content in all cases.

Across all treatment types and sampling times, the concentration of nitrate was found to be negatively correlated with total vegetation cover, redroot pigweed cover, and lamb’s quarter cover (p < 0.05, r < -0.14). Ammonium, calcium and magnesium showed the opposite trend and were positively correlated with total vegetation and redroot pigweed cover (p < 0.01, r > 0.19). Only redroot pigweed produced a significant correlation between % cover and phosphate concentration (p < 0.001, r = -0.25).

*Extracellular enzymes*

Our models showed the response of extracellular enzyme activity to weed removal treatment to be limited as well as enzyme and sampling time specific. There were no significant differences in total enzymatic profiles among herbicide treatments at any of the sampling times (p > 0.25, F4,14 < 1.261, R2 < 0.195) (Figure 2). However, total weedy vegetation cover was a significant predictor of differences in enzymatic profiles at the 10 and 20 days post-treatment sample times (p < 0.05, F1,14 > 4.411, R2 > 0.195). With respect to differences in individual enzymes, only alkaline phosphatase (PHOS), ß-glucosidase (BG), and the ratio of N:P cycling enzymes showed a significant differences among herbicide treatments at time point one and two in the global models (p < 0.05) (Figure 3, Table 4, and Supplementary Tables 3a and 3b). Significant pairwise comparisons were limited to PHOS activity and the ratio of N:P cycling enzymes at sampling time one (pre-treatment), with the nontreated plots having higher initial PHOS activity as compared to the handweeded plots, and lower N:P ratio as compared to the handweeded and Aatrex treated plots. While not statistically significant, this trend flipped at sampling time two and three with handweeded plots exhibiting the highest mean PHOS activity across all treatment types (Figure 3a). Likewise, the activity of BG spiked at time two in the handweeded plots compared to the other treatments. However, this trend was not observed in any of the other enzymes examined. While herbicide treatment was not a significant predictor of activity for many enzymes, total weedy vegetation was a significant predictor for BX, AG, and PHOS at time one, and for BG, LAP, and the ratio of C:P cycling enzymes at sampling time two. In all cases, the β coefficients of the regressions were positive indicating that total weedy vegetation had a positive effect on enzyme activity.

When the examining the effect of time within in a single weed removal treatment, there were only a few significant differences in enzyme activities over the 20 day sampling period. The Aatrex, Clarity, and nontreated plots showed no significant differences in individual enzyme activities or overall enzymatic profiles over time (p > 0.05). Only the handweeded plots showed a significant difference in total enzymatic profile over the 20 day sampling period (p < 0.01, F2,11 = 6.88, R2 = 0.607). Pairwise comparisons revealed time one to be significantly different from time two (p < 0.05) and marginally significant from time three (p = 0.055). Phosphatase activity was the most variable of the measured enzyme activities over time, showing a statistically significant increase in activity at 10 days after treatment followed by a reduction 20 days after treatment for both the handweeded and Roundup Powermax plots (p < 0.05). No correlation was found between phosphate ion concentration and PHOS activity when considering all plots (p > 0.9, r = 0.011). In addition to PHOS activity, both the handweeded and Roundup treated plots had similar trends over time for BG, AG, BX, and the ratio of C:N cycling enzymes, with the lowest activity at time one, the highest at time two and a return to pretreatment levels at sampling time three (Figure 4). However, this was only statistically significant for the handweeded plots (p < 0.05) (Table 5 and Supplementary Tables 4a and 4b).

Our conservative linear mixed models of the entire dataset revealed enzyme specific results with respect to the significance of weed removal treatment, initial enzyme activity, total weedy vegetation, and the interaction of time and weed removal treatment. BG, LAP and the ratio of C:P cycling enzymes were predicted by total weedy vegetation (p < 0.05). These enzyme also had positive β-coefficients for weedy vegetation cover, indicating that higher weed cover led to higher enzyme activity. Both BG and LAP were also predicted by the interaction of treatment and time (p < 0.05), though this was only marginally significant for BG (p = 0.055) (Figure 3b & 3c). PHOS activity at time one was deemed a significant predictor of PHOS activity at time two and three (p < 0.05). Both herbicide treatment (p = 0.057) and the treatment by time interaction (p = 0.052) were marginally significant for predicting PHOS activity as well (Figure 3a). All other mixed models for enzyme activity produced no significant predictors (Supplementary Table 5).

Finally, mantel testing of edaphic conditions and enzymatic activities showed that distance matrices of nutrient availability and total enzymatic profile were not correlated (p > 0.75, r = -0.037).

Discussion

Our examination of soil properties and microbial function following the application of chemical herbicide and mechanical removal of weedy vegetation revealed few statistically significant differences among weed removal treatments over the twenty days post-treatment. Our results suggest that the soil environment in agroecosystems is both resistant and resilient to herbicide application. We show that the examined edaphic parameters and most enzyme activities, other than PHOS, were not different among treatments at sampling time one (pre-treatment), suggesting that our initial conditions were similar across plots and that any observed differences at sampling times two and three are a result of herbicide application and/or changes in weedy vegetation. The latter of which found more support from the significance of total weedy vegetation as a predictor in our models and the observed correlations between vegetation cover and soil nutrient concentrations. With this, it appears that the act of killing vegetation, instead of the direct effects of herbicide [38], may be the primary driver of edaphic and functional shifts in agroecosystems.

By splitting our dataset by weed removal treatment, we examined the effect of time since treatment on edaphic parameters and found changes in the concentrations of nutrients like ammonium, phosphate, nitrate, magnesium and calcium, though these changes were correlated with weedy vegetation cover. As a general trend, the concentrations of nutrients decreased as time progressed. However, phosphate proved to be an exception to this trend, increasing over the twenty days in all treatments except for the nontreated plots, which showed a stable concentration. With weedy vegetation being significantly correlated with many nutrient concentrations, it is likely that competition for nutrients among plants and microbes is driving the observed decreases as opposed to application of herbicide. The general trend of increased phosphatecould be explained by increases in mineralization of plant matter inputs across the weed removal plots, or in the Roundup Powermax treated plots, as a sign of organophosphate degradation [125]. However, as the trend of increased extractable phosphate was observed in all treatments except the nontreated plots, we suggest that the effects of herbicide treatment are indirectly mediated through increased litter inputs and shifts in decomposition. For example, roots and small aboveground structures would come into contact with the soil and begin to be broken down, each providing organic matter inputs. During initial stages of decomposition, soluble organic carbon can be carried by moisture pulses from irrigation into the soil profile and would feed microbial activity, potentially explaining the increase in activity we observed at time two [126].

Given our results, we hypothesize that observed differences in nitrate and total inorganic N concentrations may be mediated indirectly through differences in total weedy vegetation cover among treatments occurring at sampling times two and three [38,111,127]. In a previous study by Hagner et al. [114], the authors examined the effects of glyphosate on soil N. Their results also showed no difference in inorganic N between their treated vegetation plots (handweeded and Roundup treatments) over twenty weeks. They did however report significant differences between the handweeded plots and the nontreated plots. The authors showed nitrate levels, as measured by resin ion exchange strips, to be higher in their handweeded plots as compared to the nontreated. Our results showed nitrate levels to be lowest in our handweeded and nontreated plots, with concentrations being higher in our Roundup plots. While our results differ slightly form Hagner et al., we show that nitrate concentrations were significantly correlated with vegetation cover, and at 20 days post-treatment, the handweeded plots experienced an increase in weedy vegetation cover and *Zea mays*. The change in vegetation over 20 days likely explains the discrepancy and accounts for the observed decrease in nitrate concentration. Other potential explanations include the fact that Hagner et al. disrupted the soil in their Roundup plots by hoeing to mimic the soil disturbance of the handweeded plots, and this physical disturbance may affect cycling of N. Given the lack of difference between their handweeded and Roundup treated plots and the observed correlations between nitrate concentration and vegetation cover in our experiment, we suggest that differences in inorganic nitrogen between glyphosate, handweeded, and nontreated plots are indirectly mediated through changes in vegetation instead of a direct effect of herbicide application. Experimental designs like ours and the one implemented by Hagner et al. [114] allow for direct and indirect effects of herbicide application and vegetation removal to be accounted for when considering the implications of weed removal treatment.

Differences in N cycling under Aatrex and other atrazine based herbicides treatment over time have also been observed in previous work, with a general trend of short term reduction in the rate of N mineralization following application [128]. In line with that, we showed a decrease in the inorganic N pool over the twenty days post-application in the Aatrex treated plots, providing support for our hypothesis and further evidence that this herbicide has short term effects on N cycling. However, this trend of decreased inorganic N was observed in other treatments as well, and together with the observed correlations with total weedy vegetation, it is difficult to tell whether this effect is direct or indirect as the crop, Zea mays, and other weedy vegetation may also be partially responsible for a reduction in inorganic N via uptake and immobilization in plant biomass. Other similar herbicides, members of the ﻿triazine family, have also been shown to inhibit nitrification and decrease the abundance of specific ammonia oxidizers, leading to short term alterations to N cycling [113]. Our sequence data may allow for further exploration of the mechanisms responsible for these shifts in N cycling.

As for differences in soil function based on extracellular enzymatic activities, we showed that there was no difference in total enzymatic profile between treatments at sampling time one, indicating that our plots were relatively homogeneous prior to treatment. However, at the ten day post-treatment sampling, weed removal treatment did not affect enzymatic profiles, but total weedy vegetation was a significant predictor of enzymatic profile, again providing support to the idea that the effects of herbicide application on soil function may be indirectly mediated through changes in vegetation [38,111]. As plant diversity has been shown to influence microbial diversity, albeit the effect on bacteria and fungi is not equal, with a larger effect of vegetation being reported for fungal communities [129], it is not surprising that total weedy vegetation influences microbial enzymatic profile [37]. These results directly refute our hypothesis that each mode of action would result in a unique total enzymatic functional profile.

When examining changes in enzyme activities over the 20 days post-treatment within a single treatment type, we found phosphatase (PHOS) activity to be significantly different within the Roundup Powermax and handweeded plots. In these treatments, PHOS activity displayed a humped pattern, with an increase in enzyme activity at day 10 and a drop at day 20. It is possible that the increase in anthropogenic soil P and chemical by-products of microbial degradation of glyphosate [130] led to the significant decrease in activity observed in the Roundup Powermax treated plots between sampling times two and three. As extracellular enzymes are costly to produce for microbes, it could be hypothesized that the production and secretion of alkaline phosphatase might increase following the addition of an organophosphorus compound like Roundup (glyphosate) but decrease once there is sufficient P in the soil [131], as was shown with the increasing trend of soil phosphate over the twenty day period. However, given the lack of correlation between phosphate concentration and PHOS activity and observing the same patterns in the handweeded plots, we hypothesize forces besides herbicide application may be responsible, e.g. redroot pigweed cover, that was shown to be negatively correlated with phosphate concentration.

Though not following the same humped pattern that we observed, others have found the response of PHOS to glyphosate based herbicides in clay-loam soils to be related to time since application, with alkaline phosphatase being more sensitive [132] than other members of the phosphatase enzyme family. Further, Cherni et al. [133] used a controlled mesocosm experiment to examine the effect of Roundup on phosphatase activity and showed no differences between the recommended field rate group (1 L/HA) and controls and only a mild increase in activity in the 10X field rate application (10 L/HA), suggesting that the application of glyphosate based herbicide at rates of up to 10X field rate has limited effects on PHOS activity. As our application rate was only slightly above the 1X and well below the 10X rates used by Cherni et al. [133] it is not surprising that the effects of Roundup Powermax on PHOS activity were minimal and short lived. Others have also shown a high glyphosate dose requirement in order to observe significant effects on microbial activity [89,134,135], and hypothesize that at these high rates, increased microbial activity following herbicide application is a result of detrimental effects on lithotrophic microbes [127]. If true, this would shift the competitive balance among microbes, with heterotrophic microbes being favored. However, given that we observed increased activity in several extracellular enzymes, both in the handweeded and Roundup (glyphosate) treated plots at 10 days post-application, we do not believe that a shift in competitive balance among litho- and heterotrophs as a result of herbicide application is responsible, but rather an increase in available above- and belowground plant detritus. With the observed hump shape in enzyme activities and a return to pre-treatment levels, it could be hypothesized that labile litter inputs would stimulate decomposition, but once the detritus became more recalcitrant or its C:N ratio increased, it may no longer be favorable for decomposition, resulting in the observed decrease in extracellular enzyme activity from 10 to 20 days post-application.

Based on our conservative mixed models, four enzymes or enzyme ratios produced significant models, however, each model had different significant predictors, suggesting that soil enzyme activity may respond to herbicide application and environmental ques in an enzyme specific fashion. In particular, the activity of BG, LAP and the ratio of C:P cycling enzymes were shown to be predicted by total weedy vegetation. As both BG and LAP are produced by both plants as well as microbes, it is not surprising that their activities are predicted by total weedy vegetation cover [136–138]. It is also possible that the mechanical disruption of soil during the enzyme assay prep could have also led to intracellular enzymes, contained in plant material, to be released into the soil slurry [139]. Though we observed differences in PHOS activity in our experiment, our mixed modeling found the activity of PHOS at time one to be a significant predictor of activities at time two and three, suggesting the existence of a legacy effect in PHOS activity. Thus, our ability to say whether PHOS activity was affected by weed removal treatment is limited.

Our results suggests that herbicide application has limited effects on soil nutrient concentrations and microbial function over 20 days post-application, and the observed differences are most likely mediated through indirect effects. While our experiment examined several herbicides and compared them to both handweeded and nontreated controls, the differences recovered were mostly limited to the Roundup Powermax and handweeded treatment plots. Our findings are not all that surprising due to the high degree of functional redundancy in the soil microbiome [140,141] and the fact that we used a relatively low rate of herbicide in our applications. With respect to herbicide application in agricultural systems, it appears that direct effects on microbial function are few and short lasting and that in heavily managed, traditional agricultural systems, the choice of herbicide has little direct effect on soil function and that the observed effects are instead mediated though indirect pathways, like shifts in vegetation cover.

Our ongoing work examining changes to the soil and phyllosphere microbiomes can be expected to produce more significant results. In general, we hypothesize an increase in saprophytic microbes will follow treatment in the handweeded and herbicide treated plots. This increase would be due to senescence of root tissues and nutrient inputs from the herbicide itself providing a pulse of labile organic matter. As for changes specific to weed removal treatment, glyphosate based herbicides, like Roundup Powermax, affect aromatic amino acid synthesis through disruption of the Shikimate pathway, which is found in both plants and microorganisms, and thus can be expected to have both direct and indirect effects on microbial assemblages. Clarity (dicamba) treated plots are also expected to experience both direct and indirect effects of herbicide application as dicamba mimics auxin, a plant-microbe signaling molecule that also affects gene regulation in microbes [142]. We further hypothesize the atrazine and mesotrione tank mix will have effects on nitrogen cycling microbes, as other members of this family of herbicides have been demonstrated to do so [113]. Furthermore, it should be noted that recent research has shown prolonged herbicide application results in increased antibiotic resistance genes and mobile genetic elements in microbial populations. As such, even if no effects on enzymatic function or microbial taxonomic assemblages are detected, the effects of herbicide on human and livestock health may be dramatic, suggesting that we may need to revisit how we assess the safety of herbicides [101].

Tables

Table 1. Weed removal treatment name, chemical agent, modes action, and application rates used in experimental design.

|  |  |  |  |
| --- | --- | --- | --- |
| **Weed removal treatment** | **Chemical agent** | **Mode of action** | **Application rate** |
| Clarity ® | dicamba | Auxin mimic | 584.6 mL/Ha |
| Aatrex ® and Calisto ® | atrazine and mesotrione tank mix | Photosystem II and carotenoid pigment synthesis inhibitor | 1169.25 mL/Ha and 219.25 mL/Ha |
| RoundUp Powermax ® | glyphosate | EPSPS synthase inhibitor | 2338.49 mL/Ha |
| Handweed | NA | Mechanical removal | NA |
| Nontreated | NA | NA | NA |

Table 2.Summary statistics of edaphic parameters across treatment types at each sampling time. Values are represented as mean (standard deviation). Significant global ANOVA models for the effect of herbicide treatment are indicated in bold. Letters indicate significant pairwise differences among treatments.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Sampling Time One | | | | | | |
|  | Nontreated | Handweeded | Aatrex | Clarity | Roundup Powermax | p-value (F) |
| *Nitrite..mg.g.dry.soil.* | 0.001 (0.001) | 0 (0) | 0.001 (0.002) | 0.001 (0.001) | 0.01 (0.05) | 0.51, (F 4,50 = 0.83 ) |
| *Nitrate..mg.g.dry.soil.* | 0.197 (0.173) | 0.346 (0.263) | 0.187 (0.17) | 0.287 (0.26) | 0.424 (0.467) | 0.24, (F 4,54 = 1.43 ) |
| *Ammonium..mg.g.dry.soil.* | 0.004 (0.003) | 0.004 (0.001) | 0.004 (0.002) | 0.005 (0.002) | 0.012 (0.026) | 0.44, (F 4,54 = 0.96 ) |
| *total\_inorganic\_N* | 0.206 (0.181) | 0.356 (0.275) | 0.206 (0.172) | 0.292 (0.261) | 0.483 (0.552) | 0.24, (F 4,50 = 1.42 ) |
| *Phosphate..mg.g.dry.soil.* | 0.05 (0.018) | 0.043 (0.009) | 0.048 (0.011) | 0.042 (0.008) | 0.043 (0.007) | 0.37, (F 4,54 = 1.1 ) |
| *Magnesium..mg.g.dry.soil.* | 1.462 (0.353) | 1.374 (0.323) | 1.577 (0.343) | 1.457 (0.259) | 1.464 (0.245) | 0.63, (F 4,54 = 0.65 ) |
| *Calcium..mg.g.dry.soil.* | 0.524 (0.152) | 0.542 (0.153) | 0.589 (0.138) | 0.524 (0.092) | 0.47 (0.114) | 0.31, (F 4,54 = 1.23 ) |
| *GravimetricMoistureContent* | 0.103 (0.018) | 0.098 (0.012) | 0.093 (0.017) | 0.101 (0.023) | 0.094 (0.025) | 0.61, (F 4,54 = 0.68 ) |
| *pH* | 7.88 (0.88) | 7.88 (0.22) | 7.9 (0.174) | 7.84 (0.145) | 1.76 (0.082) | 0.67, (F 4,14 = 0.60) |
| *EC* | 923.3 (233.93) | 976.3 (436.1) | 840.75 (345.55) | 1023.5 (463.0) | 1240.5 (173.37) | 0.57, (F 4,14 = 0.75) |
|  |  |  |  |  |  |  |
| Sampling Time Two | | | | | | |
|  | Nontreated | Handweeded | Aatrex | Clarity | Roundup Powermax | p-value (F) |
| ***Nitrate..mg.g.dry.soil.*** | **0.136 (0.123)ab** | **0.11 (0.062)a** | **0.244 (0.12)ab** | **0.155 (0.11)ab** | **0.277 (0.194)b** | **0.04, (F 4,53 = 2.68 )** |
| *Ammonium..mg.g.dry.soil.* | 0.004 (0.003) | 0.004 (0.006) | 0.004 (0.004) | 0.003 (0.002) | 0.005 (0.004) | 0.34, (F 4,53 = 1.16 ) |
| ***total\_inorganic\_N*** | **0.141 (0.122) ab** | **0.115 (0.07) a** | **0.249 (0.13) ab** | **#VALUE! ab** | **0.285 (0.191) b** | **0.04, (F 4,53 = 2.76 )** |
| *Phosphate..mg.g.dry.soil.* | 0.053 (0.026) | 0.052 (0.013) | 0.056 (0.015) | 0.043 (0.007) | 0.055 (0.016) | 0.21, (F 4,53 = 1.51 ) |
| *Magnesium..mg.g.dry.soil.* | 1.241 (0.711) | 0.749 (0.614) | 0.994 (0.743) | 1.194 (0.659) | 1.199 (0.761) | 0.23, (F 4,53 = 1.45 ) |
| *Calcium..mg.g.dry.soil.* | 0.528 (0.379) | 0.301 (0.32) | 0.379 (0.342) | 0.5 (0.332) | 0.49 (0.355) | 0.27, (F 4,53 = 1.33 ) |
| ***GravimetricMoistureContent*** | **0.185 (0.033) ab** | **0.21 (0.022) a** | **0.16 (0.022) b** | **0.168 (0.025) b** | **0.177 (0.03) ab** | **<0.001, (F 4,53 = 5.46 )** |
| *pH* | 7.78 (0.106) | 7.79 (0.099) | 7.635 (0.186) | 7.855 (0.178) | 7.737 (0.084) | 0.38, (F 4,14 = 1.12) |
| *EC* | 979.25 (155.2) | 1092 (185.8) | 1031 (88.44) | 881.75 (185.0) | 1209 (333.18) | 0.32, (F 4,14 = 1.29) |
|  |  |  |  |  |  |  |
| Sampling Time Three | | | | | | |
|  | Nontreated | Handweeded | Aatrex | Clarity | Roundup Powermax | p-value (F) |
| ***Nitrate..mg.g.dry.soil.*** | **0.01 (0.013)b** | **0.03 (0.02)b** | **0.038 (0.041)b** | **0.062 (0.04)ab** | **0.12 (0.132)a** | **0.01, (F 4,53 = 3.77 )** |
| *Ammonium..mg.g.dry.soil.* | 0.003 (0.002) | 0.002 (0.002) | 0.002 (0.002) | 0.001 (0.001) | 0.002 (0.002) | 0.23, (F 4,53 = 1.44 ) |
| ***total\_inorganic\_N*** | **0.014 (0.013)b** | **0.033 (0.02)b** | **0.041 (0.041)b** | **0.065 (0.04)ab** | **0.123 (0.133)a** | **0.01, (F 4,53 = 3.72 )** |
| *Phosphate..mg.g.dry.soil.* | 0.048 (0.015) | 0.056 (0.011) | 0.068 (0.027) | 0.058 (0.019) | 0.064 (0.024) | 0.8, (F 4,53 = 0.41 ) |
| *Magnesium..mg.g.dry.soil.* | 0.992 (0.589) | 0.754 (0.57) | 0.767 (0.606) | 0.766 (0.602) | 0.763 (0.664) | 0.58, (F 4,53 = 0.72 ) |
| *Calcium..mg.g.dry.soil.* | 0.285 (0.213) | 0.188 (0.199) | 0.193 (0.204) | 0.189 (0.2) | 0.166 (0.192) | 0.41, (F 4,53 = 1 ) |
| *GravimetricMoistureContent* | 0.217 (0.026) | 0.207 (0.028) | 0.197 (0.032) | 0.2 (0.025) | 0.189 (0.016) | 0.77, (F 4,53 = 0.46 ) |
| *pH* | 8.06 (0.218) | 8.093 (0.15) | 8.08 (0.116) | 8.052 (0.184) | 8 (0.219) | 0.94, (F 4,14 = 0.19) |
| *EC* | 730.25 (228.1) | 681.25 (93.4) | 564.5 (140.91) | 790.75 (241.1) | 930.5 (393.63) | 0.36, (F 4,14 = 1.16) |

Table 3.Summary statistics of edaphic parameters across sampling times and split by treatment types. Values are represented as mean (standard deviation). Significant global ANOVA models for the effect of time since treatment are indicated in bold. Letters indicate significant pairwise differences among sampling times.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Nontreated | | | | |
|  | Time one | Time two | Time three |  |
|  | mean (sd) | mean (sd) | mean (sd) | p-value (F) |
| ***Nitrate mg/g dry soil*** | **0.19 (0.17)a** | **0.24 (0.12)a** | **0.04 (0.04)b** | **0.01, (F 2,32 = 5.76 )** |
| *Ammonium mg/g dry soil* | 0 (0) | 0 (0) | 0 (0) | 0.18, (2,32= 1.81 ) |
| ***Total inorganic N*** | **0.2 (0.06)a** | **0.25 (0.13)a** | **0.04 (0.04)b** | **0.01, (F 2,31 = 5.74 )** |
| *Phosphate mg/g dry soil* | 0.05 (0.01) | 0.06 (0.01) | 0.07 (0.03) | 0.74, (F 2,32= 0.3 ) |
| ***Magnesium mg/g dry soil*** | **1.58 (0.34)a** | **0.99 (0.74)a** | **0.77 (0.61)a** | **0.02, (F 2,32 = 4.7 )** |
| ***Calcium mg/g dry soil*** | **0.59 (0.14)a** | **0.38 (0.34)a** | **0.19 (0.2)a** | **0.02, (F 2,32 = 4.23 )** |
| ***Gravimetric moisture content*** | **0.09 (0.02)a** | **0.16 (0.02)b** | **0.2 (0.03)c** | **<0.001, (F 2,8 = 35.76)** |
|  |  |  |  |  |
| Handweeded | | | | |
|  | Time one | Time two | Time three |  |
|  | mean (sd) | mean (sd) | mean (sd) | p-value (F) |
| ***Nitrate mg/g dry soil*** | **0.35 (0.26)a** | **0.11 (0.06)b** | **0.03 (0.02)b** | **<0.001, (F 2, 31 = 13.01)** |
| *Ammonium mg/g dry soil* | 0 (0) | 0 (0.01) | 0 (0) | 0.28, (F 2, 31 = 1.34 ) |
| ***Total inorganic N*** | **0.356 (0.27)a** | **0.12 (0.07)b** | **0.03 (0.02)b** | **<0.001, (F 2, 30 = 12.65)** |
| ***Phosphate mg/g dry soil*** | **0.04 (0.01)a** | **0.05 (0.01)ab** | **0.06 (0.01)a** | **<0.001, (F 2, 31 = 7.21 )** |
| ***Magnesium mg/g dry soil*** | **1.37 (0.32)a** | **0.75 (0.61)b** | **0.75 (0.57)b** | **0.01, (F 2, 31 = 5.91 )** |
| ***Calcium mg/g dry soil*** | **0.54 (0.15)a** | **0.3 (0.32)b** | **0.19 (0.2)b** | **<0.001, (F 2, 31 = 7.48 )** |
| ***Gravimetric moisture content*** | **0.1 (0.01)a** | **0.21 (0.02)b** | **0.21 (0.03)b** | **<0.001, (F 2, 8 = 88.39)** |
|  |  |  |  |  |
| Aatrex | | | | |
|  | Time one | Time two | Time three |  |
|  | mean (sd) | mean (sd) | mean (sd) | p-value (F) |
| ***Nitrate mg/g dry soil*** | **0.19 (0.17)a** | **0.24 (0.12)a** | **0.04 (0.04)b** | **<0.001, (F 2,32 = 9.44 )** |
| ***Ammonium mg/g dry soil*** | **0 (0)a** | **0 (0)ab** | **0 (0)b** | **0.05, (F 2,32 = 3.31 )** |
| ***Total inorganic N*** | **0.206 (0.172)a** | **0.25 (0.13)a** | **0.04 (0.04)b** | **<0.001, (F 2,31 = 9.83 )** |
| *Phosphate mg/g dry soil* | 0.05 (0.01) | 0.06 (0.01) | 0.07 (0.03) | 0.09, (F 2,32 = 2.61 ) |
| *Magnesium mg/g dry soil* | 1.58 (0.34) | 0.99 (0.74) | 0.77 (0.61) | 0.21, (F 2,32 = 1.64 ) |
| ***Calcium mg/g dry soil*** | **0.59 (0.14)a** | **0.38 (0.34)ab** | **0.19 (0.2)b** | **0.05, (F 2,32 = 3.29 )** |
| ***Gravimetric moisture content*** | **0.09 (0.02)a** | **0.16 (0.02)b** | **0.2 (0.03)c** | **<0.001, (F 2,8 = 25.64)** |
|  |  |  |  |  |
| Clarity | | | | |
|  | Time one | Time two | Time three |  |
|  | mean (sd) | mean (sd) | mean (sd) | p-value (F) |
| ***Nitrate mg/g dry soil*** | **0.29 (0.26)a** | **0.15 (0.1)ab** | **0.06 (0.04)b** | **0.03, (F 2,32** **= 3.76 )** |
| ***Ammonium mg/g dry soil*** | **0 (0)a** | **0 (0)b** | **0 (0)b** | **<0.001, (F 2,32** **= 8.35 )** |
| ***Total inorganic N*** | **0.29 (0.26)a** | **0.15 (0.107)ab** | **0.07 (0.04)b** | **0.03, (F 2,32** **= 3.83 )** |
| ***Phosphate mg/g dry soil*** | **0.04 (0.01)a** | **0.04 (0.01)a** | **0.06 (0.02)b** | **0.01, (F 2,32** **= 6.06 )** |
| ***Magnesium mg/g dry soil*** | **1.46 (0.26)a** | **1.19 (0.66)ab** | **0.77 (0.6)b** | **0.01, (F 2,32** **= 5.84 )** |
| ***Calcium mg/g dry soil*** | **0.52 (0.09)a** | **0.5 (0.33)a** | **0.19 (0.2)b** | **0.01, (F 2,32** **= 5.91 )** |
| ***Gravimetric moisture content*** | **0.1 (0.02)a** | **0.17 (0.02)b** | **0.2 (0.02)c** | **<0.001, (F 2,32** **= 41.16)** |
|  |  |  |  |  |
| Roundup Powermax | | | | |
|  | Time one | Time two | Time three |  |
|  | mean (sd) | mean (sd) | mean (sd) | p-value (F) |
| *Nitrite mg/g dry soil* | 0.01(0.05) | 0 (0) | 0 (0) | 0.21, (F 2,30= 1.65 ) |
| ***Nitrate mg/g dry soil*** | **0.42 (0.47)** | **0.28 (0.19)** | **0.12 (0.13)** | **0.02, (F 2,31= 4.27 )** |
| *Ammonium mg/g dry soil* | 0.01 (0.03) | 0 (0) | 0 (0) | 0.19, (F 2,31= 1.77 ) |
| ***Total inorganic N*** | **0.483 (0.552)a** | **0.28 (0.19)ab** | **0.12 (0.13)b** | **0.03, (F 2,30 = 4.07 )** |
| ***Phosphate mg/g dry soil*** | **0.04 (0.01)a** | **0.06 (0.02)ab** | **0.06 (0.02)b** | **0.05, (F 2,31 = 3.25 )** |
| ***Magnesium mg/g dry soil*** | **1.46 (0.24)a** | **1.2 (0.76)ab** | **0.76 (0.66)b** | **0.03, (F 2,31 = 3.78 )** |
| ***Calcium mg/g dry soil*** | **0.47 (0.11)a** | **0.49 (0.36)a** | **0.17 (0.19)b** | **<0.001, (F 2,31 = 7.78 )** |
| ***Gravimetric moisture content*** | **0.09 (0.02)a** | **0.18 (0.03)b** | **0.19 (0.02)b** | **<0.001, (F 2,8 = 38.3)** |

Table 4.Summary statistics of enzymatic activities across treatment types at each sampling time. Values are represented as mean (standard deviation). Significant global ANOVA models for the effect of herbicide treatment are indicated in bold. Letters indicate significant pairwise differences among treatments.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | | | | | | | |
| Sampling Time One | | | | | | | |
|  | | Nontreated | Handweeded | Aatrex | Clarity | Roundup Powermax | p-value (F) |
| *BG* | | 180.72 (105.95) | 168.02 (23.65) | 214.36 (21.49) | 195.24 (51.84) | 200.81 (46.43) | 0.73, (F 4,14 = 0.51 ) |
| *BX* | | 37.44 (24.62) | 16.19 (1.62) | 33.81 (13.16) | 22.87 (10.41) | 35.86 (14.21) | 0.08, (F 4,14 = 2.64 ) |
| *CBH* | | 26.15 (18.69) | 15.24 (4.83) | 23.07 (10.4) | 18.28 (7.03) | 28.08 (10.13) | 0.27, (F 4,14 = 1.45 ) |
| *AG* | | 29.58 (21.06) | 11.09 (2.53) | 27 (15.73) | 17.36 (9.86) | 27.96 (12.82) | 0.13, (F 4,14 = 2.14 ) |
| *NAG* | | 23.2 (19.27) | 7.5 (1.78) | 13.11 (7.66) | 10.26 (6.71) | 16.46 (7.57) | 0.29, (F 4,14 = 1.38 ) |
| *LAP* | | 229.86 (41.22) | 225.26 (49) | 292.63 (63.93) | 220.1 (33.98) | 239.74 (34.7) | 0.27, (F 4,13 = 1.45 ) |
| ***PHOS*** | | **152.77 (14.05)a** | **95.58 (17.06)b** | **130.1 (23.25)ab** | **106.62 (21.6)ab** | **117.08 (21.4)ab** | **0.02, (F 4,14 = 3.99 )** |
| *C.N\_enz* | | 1.01 (0.51) | 0.93 (0.24) | 0.98 (0.06) | 1.09 (0.14) | 1.15 (0.26) | 0.72, (F 4,13 = 0.53 ) |
| *C.P\_enz* | 1.74 (1.02) | 2.3 (0.74) | 2.29 (0.12) | 2.37 (0.4) | 2.49 (0.29) | 0.66, (F 4,14 = 0.62 ) |
| ***N.P enz*** | **1.64 (0.24)a** | **2.45 (0.44)b** | **2.34 (0.22)ab** | **2.18 (0.20)ab** | **2.21 (0.25)ab** | **0.02, (F 4, 13 = 3.85)** |
|  | |  |  |  |  |  |  |
|  | |  |  |  |  |  |  |
| Sampling Time Two | | | | | | | |
|  | | Nontreated | Handweeded | Aatrex | Clarity | Roundup Powermax | p-value (F) |
| ***BG*** | | **239.69 (98.72)a** | **328.07 (67.9)a** | **235.01 (94)a** | **199 (60.5)a** | **237.49 (52.16)a** | **0.03, (F 4,14 = 3.72 )** |
| *BX* | | 40.75 (26.77) | 49.8 (13.24) | 44.87 (24.07) | 41.37 (23.02) | 39.86 (14.09) | 0.57, (F 4,14 = 0.75 ) |
| *CBH* | | 29.05 (13.46) | 33.42 (7.61) | 23.52 (14.55) | 28.23 (14.04) | 32.93 (8.11) | 0.36, (F 4,14 = 1.19 ) |
| *AG* | | 32.96 (19.72) | 38.08 (9.4) | 30.19 (22.54) | 30.8 (19.05) | 36.79 (13.85) | 0.68, (F 4,14 = 0.59 ) |
| *NAG* | | 19.74 (14.79) | 22.42 (7.36) | 14.49 (8.7) | 15.65 (12.56) | 17.39 (5.65) | 0.58, (F 4,14 = 0.74 ) |
| *LAP* | | 250.96 (49.15) | 256.6 (24.21) | 214.08 (43.38) | 233.48 (60.33) | 251.63 (28.92) | 0.1, (F 4,14 = 2.38 ) |
| ***PHOS*** | | **114.92 (24.89)a** | **155.57 (18.2)a** | **110.36 (25.6)a** | **128.09 (29.0)a** | **137.8 (7.22)a** | **0.04, (F 4,14 = 3.46 )** |
| *C.N\_enz* | | 1.24 (0.34) | 1.63 (0.27) | 1.41 (0.4) | 1.18 (0.19) | 1.31 (0.32) | 0.27, (F 4,14 = 1.46 ) |
| *C.P\_enz* | | 2.91 (0.86) | 2.89 (0.13) | 2.92 (0.8) | 2.28 (0.37) | 2.53 (0.56) | 0.13, (F 4,14 = 2.15 ) |
| *N.P enz* | | 2.41 (0.60) | 1.82 (0.33) | 2.10 (0.45) | 1.93 (0.16) | 1.96 (0.19) | 0.71, (F 4, 14 = 0.54) |
|  | |  |  |  |  |  |  |
| Sampling Time Three | | | | | | | |
|  | | Nontreated | Handweeded | Aatrex | Clarity | Roundup Powermax | p-value (F) |
| *BG* | | 307.85 (100.03) | 236.65 (55.2) | 219.77 (24.81) | 206.02 (52.38) | 207.13 (26.13) | 0.95, (F 4,13 = 0.16 ) |
| *BX* | | 42.53 (30.81) | 35.77 (21.9) | 31.74 (16.92) | 44.34 (37.15) | 26.91 (8.89) | 0.92, (F 4,13 = 0.23 ) |
| *CBH* | | 33.56 (21.58) | 27.63 (15.46) | 25.62 (12.98) | 21.68 (11.9) | 16.5 (4.78) | 0.92, (F 4,13 = 0.22 ) |
| *AG* | | 32.53 (30.87) | 30.84 (22.5) | 32.84 (27.01) | 25.23 (16.13) | 23.4 (11.7) | 0.98, (F 4,13 = 0.11 ) |
| *NAG* | | 20.14 (12.64) | 24.06 (11.58) | 14.7 (8) | 12.36 (6.74) | 11.1 (5.77) | 0.51, (F 4,13 = 0.86 ) |
| *LAP* | | 290.93 (80.75) | 256.49 (26.45) | 254.4 (18.14) | 238.96 (53.68) | 214.94 (4.55) | 0.61, (F 4,12 = 0.7 ) |
| *PHOS* | | 144.77 (54.28) | 128.97 (18.95) | 114.11 (19.35) | 120.37 (24.19) | 105.19 (5.17) | 0.91, (F 4,13 = 0.23 ) |
| *C.N\_enz* | | 1.32 (0.09) | 1.16 (0.28) | 1.15 (0.2) | 1.17 (0.29) | 1.21 (0.1) | 0.98, (F 4,12 = 0.11 ) |
| *C.P\_enz* | | 2.9 (0.32) | 2.51 (0.52) | 2.71 (0.32) | 2.41 (0.49) | 2.61 (0.28) | 0.87, (F 4,13 = 0.31 ) |
| *N.P enz* | | 2.20 (0.27) | 2.19 (0.13) | 2.39 (0.30) | 2.08 (0.15) | 2.15 (0.10) | 0.36, (F 4, 12 = 1.19) |

Table 5.Summary statistics of enzymatic parameters across sampling times and split by treatment types. Values are represented as mean (standard deviation). Significant global ANOVA models for the effect of time since treatment are indicated in bold. Letters indicate significant pairwise differences among sampling times.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Nontreated | | | | |
|  | T1 | T2 | T3 |  |
|  | mean (sd) | mean (sd) | mean (sd) | p-value (F) |
| BG | 214.36 (21.49) | 235.01 (94) | 219.77 (24.81) | 0.32, (F 2,8 = 1.33 ) |
| BX | 33.81 (13.16) | 44.87 (24.07) | 31.74 (16.92) | 0.43, (F 2,8 = 0.95 ) |
| CBH | 23.07 (10.4) | 23.52 (14.55) | 25.62 (12.98) | 0.57, (F 2,8 = 0.6 ) |
| AG | 27 (15.73) | 30.19 (22.54) | 32.84 (27.01) | 0.53, (F 2,8 = 0.68 ) |
| NAG | 13.11 (7.66) | 14.49 (8.7) | 14.7 (8) | 0.44, (F 2,8 = 0.91 ) |
| LAP | 292.63 (63.93) | 214.08 (43.38) | 254.4 (18.14) | 0.44, (F 2,8 = 0.94 ) |
| PHOS | 130.1 (23.25) | 110.36 (25.61) | 114.11 (19.35) | 0.30, (F 2,8 = 1.39 ) |
| C.N\_enz | 0.98 (0.06) | 1.41 (0.4) | 1.15 (0.2) | 0.44, (F 2,8 = 0.95 ) |
| C.P\_enz | 2.29 (0.12) | 2.92 (0.8) | 2.71 (0.32) | 0.81, (F 2,8 = 0.22 ) |
| *N.P enz* | 1.64 (0.24) | 2.40 (0.60) | 2.20 (0.27) | 0.59, (F 2,8 = 0.74 ) |
|  |  |  |  |  |
| Handweeded | | | | |
|  | T1 | T2 | T3 |  |
|  | mean (sd) | mean (sd) | mean (sd) | p-value (F) |
| **BG** | **168.02 (23.65)a** | **328.07 (67.9)b** | **236.65 (55.2)ab** | **0.01, (F 2,8 = 8.87 )** |
| **BX** | **16.19 (1.62)a** | **49.8 (13.24)b** | **35.77 (21.9)ab** | **0.02, (F 2,8 = 6.99 )** |
| CBH | 15.24 (4.83) | 33.42 (7.61) | 27.63 (15.46) | 0.1, (F 2,8 = 3.2 ) |
| **AG** | **11.09 (2.53)a** | **38.08 (9.4)b** | **30.84 (22.5)ab** | **0.03, (F 2,8 = 5.55 )** |
| **NAG** | **7.5 (1.78)a** | **22.42 (7.36)ab** | **24.06 (11.58)b** | **0.03, (F 2,8 = 5.79 )** |
| LAP | 225.26 (49) | 256.6 (24.21) | 256.49 (26.45) | 0.5, (F 2,8 = 0.77 ) |
| **PHOS** | **95.58 (17.06)a** | **155.57 (18.17)b** | **128.97 (18.95)ab** | **0.01, (F 2,8 = 8.95 )** |
| **C.N\_enz** | **0.93 (0.24)a** | **1.63 (0.27)b** | **1.16 (0.28)ab** | **0.01, (F 2,8 = 8.56 )** |
| C.P\_enz | 2.3 (0.74) | 2.89 (0.13) | 2.51 (0.52) | 0.16, (F 2,8 = 2.3 ) |
| *N.P enz* | 2.45 (0.43) | 1.81 (0.33) | 2.18 (0.13) | 0.059, (F 2,8 = 4.11 ) |
|  |  |  |  |  |
| Aatrex | | | | |
|  | T1 | T2 | T3 |  |
|  | mean (sd) | mean (sd) | mean (sd) | p-value (F) |
| BG | 214.36 (21.49) | 235.01 (94) | 219.77 (24.81) | 0.35, (F 2,8 = 1.2 ) |
| BX | 33.81 (13.16) | 44.87 (24.07) | 31.74 (16.92) | 0.58, (F 2,8 = 0.57 ) |
| CBH | 23.07 (10.4) | 23.52 (14.55) | 25.62 (12.98) | 0.59, (F 2,8 = 0.57 ) |
| AG | 27 (15.73) | 30.19 (22.54) | 32.84 (27.01) | 0.95, (F 2,8 = 0.05 ) |
| NAG | 13.11 (7.66) | 14.49 (8.7) | 14.7 (8) | 0.86, (F 2,8 = 0.16 ) |
| LAP | 292.63 (63.93) | 214.08 (43.38) | 254.4 (18.14) | 0.91, (F 2,8 = 0.1 ) |
| PHOS | 130.1 (23.25) | 110.36 (25.61) | 114.11 (19.35) | 0.94, (F 2,8 = 0.06 ) |
| C.N\_enz | 0.98 (0.06) | 1.41 (0.4) | 1.15 (0.2) | 0.21, (F 2,8 = 1.87 ) |
| C.P\_enz | 2.29 (0.12) | 2.92 (0.8) | 2.71 (0.32) | 0.16, (F 2,8 = 2.33 ) |
| *N.P enz* | 2.34 (0.22) | 2.10 (0.45) | 2.38 (0.29) | 0.69, (F 2,8 = 0.37 ) |
|  |  |  |  |  |
| Clarity | | | | |
|  | T1 | T2 | T3 |  |
|  | mean (sd) | mean (sd) | mean (sd) | p-value (F) |
| BG | 195.24 (51.84) | 199 (60.5) | 206.02 (52.38) | 0.76, (F 2,8 = 0.28 ) |
| BX | 22.87 (10.41) | 41.37 (23.02) | 44.34 (37.15) | 0.47, (F 2,8 = 0.83 ) |
| CBH | 18.28 (7.03) | 28.23 (14.04) | 21.68 (11.9) | 0.42, (F 2,8 = 0.97 ) |
| AG | 17.36 (9.86) | 30.8 (19.05) | 25.23 (16.13) | 0.51, (F 2,8 = 0.74 ) |
| NAG | 10.26 (6.71) | 15.65 (12.56) | 12.36 (6.74) | 0.59, (F 2,8 = 0.57 ) |
| LAP | 220.1 (33.98) | 233.48 (60.33) | 238.96 (53.68) | 0.60, (F 2,8 = 0.55 ) |
| PHOS | 106.62 (21.59) | 128.09 (29.01) | 120.37 (24.19) | 0.43, (F 2,8 = 0.95 ) |
| C.N\_enz | 1.09 (0.14) | 1.18 (0.19) | 1.17 (0.29) | 0.82, (F 2,8 = 0.20 ) |
| C.P\_enz | 2.37 (0.4) | 2.28 (0.37) | 2.41 (0.49) | 0.82, (F 2,8 = 0.20 ) |
| *N.P enz* | 2.17 (0.20) | 1.93 (0.16) | 2.08 (0.09) | 0.19, (F 2,8 = 1.99) |
|  |  |  |  |  |
| Roundup Powermax | | | | |
|  | T1 | T2 | T3 |  |
|  | mean (sd) | mean (sd) | mean (sd) | p-value (F) |
| BG | 200.81 (46.43) | 237.49 (52.16) | 207.13 (26.13) | 0.76, (F 2,7 = 0.28 ) |
| BX | 35.86 (14.21) | 39.86 (14.09) | 26.91 (8.89) | 0.46, (F 2,7 = 0.88 ) |
| CBH | 28.08 (10.13) | 32.93 (8.11) | 16.5 (4.78) | 0.09, (F 2,7 = 3.42 ) |
| AG | 27.96 (12.82) | 36.79 (13.85) | 23.4 (11.7) | 0.43, (F 2,7 = 0.96 ) |
| NAG | 16.46 (7.57) | 17.39 (5.65) | 11.1 (5.77) | 0.50, (F 2,7 = 0.76 ) |
| LAP | 239.74 (34.7) | 251.63 (28.92) | 214.94 (4.55) | 0.06, (F 2,7 = 4.15 ) |
| **PHOS** | **117.08 (21.42)ab** | **137.8 (7.22)a** | **105.19 (5.17)b** | **0.02, (F 2,7 = 6.57 )** |
| C.N\_enz | 1.15 (0.26) | 1.31 (0.32) | 1.21 (0.1) | 0.96, (F 2,7 = 0.04 ) |
| C.P\_enz | 2.49 (0.29) | 2.53 (0.56) | 2.61 (0.28) | 0.85, (F 2,7 = 0.16 ) |
| *N.P enz* | 2.21 (0.25) | 1.95 (0.19)) | 2.15 (0.09) | 0.39, (F 2,7 = 1.06 ) |

Figures

Figure 1. Soil nitrate concentration by treatment across sampling times. ﻿Thick middle lines in boxes of box and whisker represent the median, with top and bottom of each box representing the 75th and 25th quartiles, respectively. Whiskers represent 1.5 x IQR. Within each panel, letters indicate significant pairwise differences between weed removal treatments at α = 0.05. No letters indicate lack of significant pairwise differences.

Chart, waterfall chart, box and whisker chart

Description automatically generated

Figure 2. Non-metric multi-dimensional scaling (NMDS) of total enzymatic profiles. Treatment type was not a significant predictor as per Adonis testing at any of the three time points. Each panel represents samples collected from a single time point, time one (a), time two (b), and time three (c). Ellipses represent the 95% confidence interval for the mean of each treatment. Points represent individual soil samples and are colored by treatment type.

Diagram

Description automatically generated

Figure 3. a) Phosphatase (PHOS), b) ß-glucosidase (BG), and c) leucine aminopeptidase (LAP) activity by treatment across sampling times. ﻿Thick middle lines in boxes of box and whisker represent the median, with top and bottom of each box representing the 75th and 25th quartiles, respectively. Whiskers represent 1.5 x IQR. Within each panel, letters indicate significant pairwise differences between weed removal treatments at α = 0.05. No letters indicate lack of significant pairwise differences.

Chart

Description automatically generated

Figure 4. Enzyme activities of the a) handweeded and b) Roundup Powermax treatment plots over three sampling times. Enzyme activities were significant as per global models for AG, BG, BX, PHOS, and the ratio of C:N cycling enzymes for the handweeded plots. Only PHOS activity was significant in the Roundup Powermax plots, but the same trend was observed for many enzymes in both treatment types. Thick middle lines in boxes of box and whisker represent the median, with top and bottom of each box representing the 75th and 25th quartiles, respectively. Whiskers represent 1.5 x IQR. Within each panel, letters indicate significant pairwise differences between sampling time points at α = 0.05. No letters indicate lack of significant pairwise differences.

Diagram

Description automatically generated