FINAL REPORT TO:

THE ILLINOIS DEPARTMENT OF NATURAL RESOURCES

CONTRACT #RC09l17W:

“ECOLOGICAL IMPACTS OF LONG-TERM, LOW-INTENSITY PRESCRIBED FIRE IN A MIDWESTERN OAK FOREST”

06/25/10

IL DNR Sponsor:

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

For the last 23 years, low-intensity prescribed fire has been used with the intent of decreasing shade and fire tolerant tree species and increasing herbaceous plant diversity in the East Woods of The Morton Arboretum, Lisle, Illinois, USA. The impacts of these fires on the belowground ecosystem were yet to be measured. Soil (0 to 10 cm) and litter samples were collected on 40 plots in burned and un-burned control areas over a two-year period. Invertebrates, microbial activity and biomass, available nutrients, and organic matter pools were measured and compared with vegetation composition and structure from these same plots. We found few differences comparing the effects of periodic (once every three to four years) and annual prescribed fire. Compared to un-burned controls, burn plots had greater canopy openness, greater herbaceous richness, and a lower spring/summer herbaceous ratio.

Thirteen and seventeen taxa were found within the soil and litter samples, respectively, with Orders Acari and Collembola predominately found in both. Taxa count data were used to calculate invertebrate richness, abundance, and alpha diversity. Results showed no effect of soil type, but soil samples had significantly lower invertebrate richness, abundance, and diversity in the spring compared with fall sampling times, across all burn treatments. Litter invertebrate richness was similarly lowest in the spring, though litter invertebrate diversity was unaffected by season. Although the burn treatments did not lead to significantly different measures of invertebrate populations, trends were observed in which certain taxa showed a 50% higher abundance in annually or periodically burned plots compared with controls, while other taxa where found to have double abundance in control plots. Litter invertebrates from control plots showed the lowest richness and abundance values compared with annually-burned and periodically-burned. The results suggest that prescribed burning may enhance soil and litter invertebrate biodiversity, however, pronounced differences between spring and fall samples indicate sampling over multiple seasons is needed.

Burned plots had higher soil pH, electrical conductivity, Ca^{2+}, Mg^{2+}, K^+, Na^+, NO_3^- total N, particulate organic matter (POM), total organic C, silt, and lower clay. Principal components were positively correlated with soil biochemical properties (C, N, Ca^{2+}, K^+, POM, invertebrate indices) and confirmed differences observed with ANOVA analyses between burned and un-

burned plots. Three stepwise least squares models predicted woody richness, herbaceous richness, and spring/summer herbs with site (aspect), vegetation (canopy openness and herb richness), forest floor (invertebrate richness), and soil factors (pH, potential N mineralization, C/N ratio, Mg^{2+}, Bray P, and soil invertebrate Simpson index).

Our results confirm others showing prescribed fire to increase soil organic matter decomposition, nutrient mineralization and nutrient availability. Forest structural changes with fire appear correlated with resource availability for light and soil nutrients. The observed increases in available soil nutrients with fire likely increase growth of trees and herbaceous plants growing in more open canopies as a result of these prescribed fires. Our results suggest that low-intensity prescribed fire may benefit primary productivity of oak woodlands by increasing nutrient availability and light availability. This benefit may be more acute in low-fertility sites where nutrient limitation outweighs light availability as a most-limiting resource. Prescribed fire has the potential to oxidize soil and litter C, so concern may exist for forest managers wanting to maximize the C sequestration of their forests while using prescribed burning as a management tool. We found total and particulate organic C to be greater in our burned plots, suggesting low-intensity prescribed fire increases soil C storage in these forests.

Two important considerations pertaining to stimulated nutrient availability with fire are potential nutrient losses and the effects on exotic species. We suspect some oak forests in the Chicagoland region may be susceptible to nutrient loss and increases in exotic species with prescribed fire given the relatively high degree of anthropogenic disturbance and forest fragmentation, high atmospheric nitrogen inputs from urban activities, and strong presence of exotic species in these woodlands. We recommend careful consideration of prescription fire in those oak forests that are susceptible to nutrient loss and exotic invasions.

We observed very few differences comparing periodic and annual prescribed fires, thus surmise the ecological impacts of annual and periodic are quite similar in these oak forests. Periodic fire may be a preferred method for managing these oak forests with the defined goals of decreasing shade and fire tolerant tree species and increasing herbaceous plant diversity. Continued monitoring of these forests is imperative because they represent some of the more longer-term, low-intensity fire plots in the Great Lakes region. Additional sampling should be performed across a wider range of forests to relate ecological impacts associated with differences in fire-intensity, fuel-loading, and fire return intervals.

The remainder of this document contains three appendices. Appendix 1 is a draft of a manuscript that was submitted on 06/25/10 to the scientific, peer-reviewed journal: Forest Ecology and Management. A copy of the printed manuscript will be submitted to the Illinois Department of Natural Resources as a pdf. Appendix 2 is a draft of Brenda Boelter's Master's Thesis, which she will defend in the fall, 2010, through the Department of Biological Sciences at Chicago State University. A final copy of Ms. Boelter's thesis will be submitted as a pdf to the Illinois Department of Natural Resources. Appendix 3 contains various images relevant to the research. These documents and information of the project are also provided on The Morton Arboretum Soil Science laboratory website at www.masslaboratory.org.

BUDGET SUMMARY

According to contract #RC09L17W, the Illinois Department of Natural Resources shall compensate the Contractor a total of $13,475 for this project. On 11/30/09, an invoice was submitted for $10,865 for expenditures from 01/2009 to 12/2009. The remaining $2,610 for expenses for the period 01/2010 to 06/210 is yet to be paid to the contractor. Total hours spent on the project were 1,748.50. The total cost-share match on the project was $15,666 as salaries of Bryant Scharenbroch, MASS Principal Investigator and Doug Johnston, MASS Research Assistant. A summary of expenditures for this project is presented below.

Table 1. Budget Summary for #RC09L17W.

Person	Title	Hours	Cost-share	IL DNR
Bryant Scharenbroch	Principal Investigator	225.00	9,450	-
Brenda Boelter	Graduate Student	363.75	-	4,292
Doug Johnston	Research Assistant	350.00	6,216	-
Michelle Catania	Research Assistant	148.00	-	2,454
Joyce Tanzosh	Research Assistant	19.25	-	344
Ryan Hulet	Research Intern	336.50	-	3,171
David Kizior	Research Intern	306.00	-	3,214
Totals		1748.50	$15,666	$13,475

Expenses invoiced for the period 01/2009 to 12/2009……………..……………$10,865

Expenses yet to be invoiced for the period 01/2010 to 06/2010……...………....**$2,610**

ACKNOWLEDGEMENTS

This research was supported by the Illinois Department of Natural Resources, Illinois Wildlife Preservation Fund, sponsored by Maggie Cole. We also thank The Morton Arboretum and Chicago State University for financial and institutional support. Special thanks for assistance with data collection and analysis are given to: Brenda Boelter (Chicago State University), Marlin Bowles (Morton Arboretum), Ray Brand (Morton Arboretum), Michelle Catania (Morton Arboretum Soil Science, MASS laboratory), Jenny McBride (Morton Arboretum), Karel Jacobs (Chicago State University), Doug Johnston (University of Illinois – Chicago), Eric Peters (Chicago State University), Joyce Tanzosh (MASS laboratory), and the many volunteers in MASS laboratory.

APPENDIX 1. DRAFT OF MANUSCRIPT ENTITLED: THE IMPACTS OF 23 YEARS OF LOW-INTENSITY PRESCRIBED FIRE ON VEGETATION, FOREST FLOOR, AND SOIL PROPERTIES IN A MIDWESTERN, USA OAK FOREST. SUBMITTED TO FOREST ECOLOGY AND MANANGEMENT ON 06/25/10.

Title

The impacts of 23 years of low-intensity prescribed fire on vegetation, forest floor, and soil properties in a Midwestern, USA oak forest

Authors

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Abstract

For the last 23 years, low-intensity prescribed fire has been used with the intent of decreasing shade and fire tolerant tree species and increasing herbaceous plant diversity in the East Woods of The Morton Arboretum, Lisle, Illinois, USA. The impacts of these fires on the belowground ecosystem have yet to be measured. Soil (0 to 10 cm) and litter samples were collected on 40 plots in burned and un-burned control areas over a two-year period. Invertebrates, microbial activity and biomass, available nutrients, and organic matter pools were measured and compared with vegetation composition and structure from these same plots. We found few differences comparing the effects of periodic (once every three to four years) and annual prescribed fire. Compared to un-burned controls, burn plots had greater canopy openness, greater herbaceous richness, and a lower spring/summer herbaceous ratio. Indices of litter and soil invertebrate diversity were not significantly impacted by prescribed fire. Burned plots had higher soil pH, electrical conductivity, Ca^{2+}, Mg^{2+}, K^+, Na^+, NO_3^-, total N, particulate organic matter (POM), total organic C, silt, and lower clay. Principal components were positively correlated with soil biochemical properties (C, N, Ca^{2+}, K^+, POM, invertebrate indices) and confirmed differences observed with ANOVA analyses between burned and un-burned plots. Three stepwise least squares models predicted woody richness, herbaceous richness, and spring/summer herbs with site (aspect), vegetation (canopy openness and herb richness), forest floor (invertebrate richness), and soil factors (pH, potential N mineralization, C/N ratio, Mg^{2+}, Bray P, and soil invertebrate Simpson index). Our results confirm others showing prescribed fire to increase soil organic matter decomposition, nutrient mineralization and nutrient availability. Forest structural changes with fire appear correlated with resource availability for light and soil nutrients. The observed increases in available soil nutrients with fire likely increase growth of trees and herbaceous plants growing in more open canopies as a result of these prescribed fires. Our data show that low-intensity prescribed fires do not decrease soil C storage, nutrient retention, or negatively impact invertebrate diversity in these oak forests.

Keywords

Fire impacts soil; invertebrate diversity; soil carbon; soil nitrogen

Abbreviations

Aspect (Asp), slope (Slp), elevation (Elev), canopy openness (Can), basal area (BA), woody richness (Wric), herbaceous richness (Hric), spring/summer herb ratio (Sp/Su), alien/native (Al/Nt), litter mass (Lit), litter richness (Lric), litter abundance (Labu), litter evenness (Leve), litter Shannon index (Lsha), litter Simpson index (Lsim), litter Acarina (Laca), litter Collembola (Lcol), soil richness (Sric), soil abundance (Sabu), soil evenness (Seve), soil Shannon index (Ssha), soil Simpson index (Ssim), soil Acarina (Saca), soil Collembola (Scol), earthworm numbers (Wnum), earthworm biomass (Wbio), potential N mineralization (Nmin), microbial biomass N (MBN), gravimetric soil moisture (GSM), electrical conductivity (EC), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), ammonium (NH_4^+), nitrate (NO_3^-), dissolved organic N (DON), total soil N (N), particulate organic matter (POM), total organic C (C), soil carbon/nitrogen ration (C/N)

1. Introduction

Midwestern oak (*Quercus* spp.) forests are thought to be maintained by fire (e.g., Kilburn 1959; Leitner et al. 1991; Bowles et al. 1994), and fire suppression following European settlement has resulted in the replacement of oaks by shade-tolerant mesophytic tree species such as sugar maple (*Acer saccharum* L.) (e.g., McIntosh 1957; Schlesinger 1976; Abrams 1992). Ground layer vegetation comprises most of the plant species in oak forests (Roberts 2004, Whigham 2004), and fire has been reported to help maintain its diversity (Wilhelm 1991, Bowles et al. 2000). Altered fire regimes have facilitated the invasion of oak forests by alien plants, such as common buckthorn (*Rhamnus cathartica* L.) and the herb garlic mustard (*Alliaria petiolata* M. Bieb, Cavara and Grande), with potential for control of these plants with prescribed fires (Anderson et al. 1996, Schwartz and Heim 1996).

Prescribing fire is a valuable tool for restoration and management of Midwestern oak forests producing beneficial effects for shade intolerant species, such as, vegetation removal, mineral soil exposure, and nutrient release (Abrams 1992; Bowles et al. 2000; Bowles et al. 2007; Hutchinson et al. 2008). Often neglected are the impacts that these fires have on soil physical, chemical, and biological properties and processes. Soil processes are largely responsible for meeting the vegetation demand for water and nutrients. Consequently, fire can potentially alter aboveground ecosystem structure and function through its impacts on biogeochemical cycling (Neary et al. 1999; Certini 2005). The disruption of soil processes from fire may have immediate and long-lasting consequences to the ecosystem (Perry et al. 1989).

Fires usually decrease the total amount of nutrients on-site through oxidation, volatilization, ash transport, leaching, and erosion (Neary et al. 1999). Due to its low temperature of volatilization, N is lost with the consumption of soil organic matter (SOM) at temperatures around 200°C, but P, K, Ca, and Mg loss is usually minor due to higher volatilization temperatures of these elements (e.g., 1240°C for Ca) (Wright and Bailey 1982). When SOM is heated, carbohydrates and proteins are lost and aromatic compounds increase (Almendros et al. 1992). Fire appears to increase the amount and biodegradation rate of labile C (i.e., readily decomposable C) while increasing resistance of more stable or recalcitrant soil C (Fernandez et al. 1999). Although total nutrient pool size may decrease with fire, nutrient availability often increases due to nutrients added in ash, heating of SOM, increased pH, and increased mineralization (Wright and Bailey 1982; Schoch and Binkley 1986; Wan et al. 2001). Biologically-mediated processes, such as SOM decomposition and nutrient mineralization, tend to increase with fire through increased soil temperature from vegetation and forest floor removal and blackening of soil surface, and increased soil moisture contents from decreased evapotranspiration (Swift et al. 1993). Soil pH has been found to increase with fire from production of K- and Na-oxides, hydroxides, and carbonates (Ulery et al. 1993).

Soil organisms are important for conservation and management of biological diversity and they have impacts on ecosystem processes (e.g., decomposition and nutrient cycling), which are linked to plant health, ecosystem stability, and environmental quality (Coleman et al. 2004). Short-lived bacteria blooms have been observed following fire (Baath et al. 1995). Responses of soil fungi following fire are mixed with some reports of decreases (Baar et al. 1999; Grogan et al. 2000), increases (Klopatek et al. 1988), and no response (Jonsson et al. 1999). In some instances, reported decreases in abundance of microbes following fire coincide with the remaining microbes having greater levels of activity (e.g., Poth et al. 1995). The response of soil microbes is dependent to a large extent upon fire intensity. High-intensity fires can directly kill microorganisms (DeBano et al. 1988), and fire can indirectly impacts these organisms via alterations in soil physical properties (Neary et al. 1999). Soil invertebrates are mobile, thus have capacity to escape heating by burrowing deep into the soil, minimizing the effects of heat and smoke. However, litter loss and microclimatic changes associated with fire indirectly decrease total mass and species numbers of soil and litter dwelling invertebrates (e.g., Kalisz and Powell 2000; Dress and Boerner 2004). This is not always the case, as Seastedt (1984) found macroarthropod biomass, particularly scarab beetles (*Phyllophaga* spp.), increased in burned relative to un-burned sites. Ferrenberg et al. (2006) found prescribed burning to increase arthropod diversity, but decrease their abundance in mixed conifer forests in the Sierra Nevada region. Studies have reported increases (James 1982) and decreases in earthworms with fire (Collett et al. 1983; Bhadauria et al. 2000; Callaham et al. 2003). Evidence suggests that the impact of fire on soil invertebrates is linked to vegetation reestablishment, the presence of un-burned refugee micro-sites, and differences in fuel loadings with landscape heterogeneity (Paquin and Coderre 1997; Ferrenberg et al. 2006; Brand 2002).

Fires have been found to have detrimental impacts on soil physical properties by consuming SOM, thus reducing aggregation, increasing bulk density, reducing soil porosity, and decreasing water storage capacity (Wells et al. 1979). Soil porosity and water infiltration can be further reduced through the loss of soil invertebrate activity with fire (Kettredge 1938) and the impact of raindrops on exposed burnt soils, dispersing soil aggregates (Ralston and Hatcher 1971). Fires can work to aggregate clay particles into sand-sized particles (Dyrness and Youngberg 1957; Ulery and Graham 1993), making soil texture more coarse and soil more erodible (Chandler et al. 1983). Most of these changes in soil physical properties have been observed with intense fires (>400^{o}C), but less intense fires can also impact soil physical properties. For instance, hydrophobic organic compounds formed at temperatures of 176 to 288^{o}C and destroyed at >288^{o}C coat soil aggregates and minerals creating water repellent layers (Neary et al. 1999) and decreasing water infiltration (DeBano 1969, 1971). Fire-derived charcoal has been found to positively impact soil water status via enhancement of water-retentive soil properties (Moore 1996).

Most fire research on edaphic properties has been performed on wildfires or high-intensity prescribed burns (>700°C). Empirical data are relatively less abundant for the impacts of low-intensity fires (<400°C). Most studies of fire impacts on soils have examined short-term responses of isolated soil properties (e.g., Dyrness and Youngberg 1957; Wells et al. 1979; Schoch and Binkley 1986; Ulery and Graham 1993; Moore 1996) or specific organisms (e.g., Klopatek et al. 1988; Baath et al. 1995; Jonsson et al. 1999; Grogan et al. 2000). Few studies have investigated the long-term impacts of low-intensity fire on soil properties in Midwestern oak forests.

This research addresses three general questions. 1) Are the ecological impacts of periodic, every three or four years for 23 years, low-intensity prescribed fire similar to those of 23 years of annual fires in a Midwestern, USA oak forest? Because fires in these Midwestern oak forests are low-intensity, we predicted minimal differences between periodic and annual prescribed fire. 2) What is the direction and magnitude of the impacts of long-term, low-intensity prescribed fire on vegetation, forest floor, and soil properties in these forests? Our expectations were that fire in these forests would favor shade intolerant species, reduce the forest floor layer, and increase soil nutrient availability. 3) Are the changes in aboveground structural characteristics related to soil properties in these oak forests? Edaphic properties are linked to vegetation, so we expect soil properties and processes to help explain variance in our above-ground measurements.

2. Material and methods

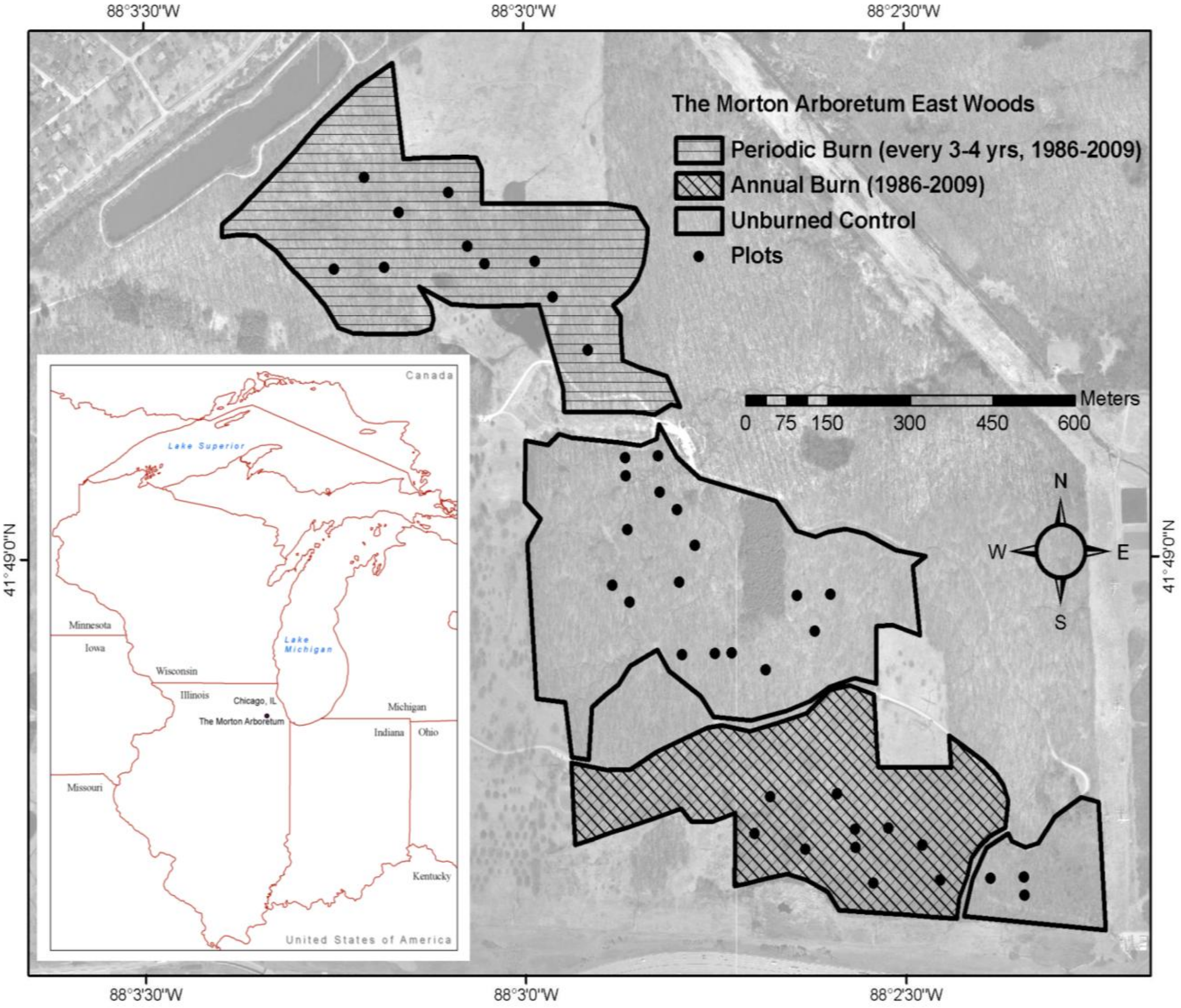
2.1. Site description

The research was conducted in the East Woods of the Morton Arboretum, DuPage County, Illinois, USA (Figure 1). The East Woods comprises a 240 ha former prairie located along the East Branch of the DuPage River, 41°49′0″N latitude and 88°3′0″W longitude. The arboretum lies within the Prairie Peninsula of Eastern North America (Transeau 1935), as well as the Oak-Hickory forest region (Braun 1950). The climate is continental, with average temperatures ranging from -6°C in January to 22°C in July (Mapes 1979). Mean annual precipitation ranges from 800 to 1000 mm (Mapes 1979). The arboretum includes extensive dry-mesic upland forest dominated by white oak (*Quercus alba*), bur oak (*Q. macrocarpa*), and red oak (*Q. rubra),* with more mesic forest dominated by sugar maple (*Acer saccharum*) and basswood (*Tilia americana*). Pre-settlement (early 1800's) vegetation was 80% prairie, with oak-dominated deciduous forest restricted to fire-protected areas of rugged topography along waterways, and vegetation records indicate that bur oak and white oak savanna were present at 37 trees ha^{-1} (Bowles et al. 1994). The Morton Arboretum is located on the Valparasio moraine complex. The soils are deep and moderately-well to poorly drained Alfisols and Mollisols formed in a thin layer of loess underlying glacial till (Kelsey 2000). The major soils in The Morton Arboretum's East Woods are Ashkum series (fine, mixed, superactive, mesic Typic Endoaquolls), Beecher series (fine, illitic, mesic Udollic Epiaqualfs), and Ozaukee series (fine, illitic, mesic Oxyaquic Hapludalfs) (Kelsey 2000).

2.2. Burn treatments

The Morton Arboretum has been conducting dormant season prescribed burns in the East Woods for the past twenty-three years (Figure 1). Burns were usually performed in fall, but weather conditions caused some fires to be delayed until spring. The sites have little topographic relief, and winds are primarily south-westerly, allowing back fires to be set along north burn unit boundaries and head fires along the south boundaries. Our study site is comprised of three burn treatments with three major soil types. Area one has been burned annually (16.6 ha) from 1986 to 2010. The soils in the annual burn area are Ashkum (6 plots) and Beecher (4 plots), which are deep, poorly drained silt loam soils on moraines and till plains. The periodic burn area (19.8 ha) has been burned once every three or four years from 1986 to 2010. Soils in the periodic burn area are Ozaukee series (10 plots), which are moderately-well drained and deep silt loam soils formed in thin loess and underlying loamy dense till on ground moraines. The control block (27.9 ha) has never been burned and is comprised of Ashkum (6 plots), Beecher (4 plots), and Ozaukee (10 plots). In order to account for possible variability due to soil, the number of control plots is equal to the number of treatment plots for each soil type.

Figure 1. Sample plot locations and prescription fire management in the East Woods of The Morton Arboretum, Lisle, IL, USA.



No plots were burned during the sampling period of this study (10/20/08 to 10/01/09). The most recent fire in the burned areas prior to this study was in the fall of 2007, or 12 months prior to our first soil collection. Prescribed burning resumed following the last soil and litter collection on 10/01/09. Measured fire temperatures ranged from 120 to 230°C in past fires in The Morton Arboretum East Woods (Jacobs et al. 2004). Ambient air temperatures during burns ranged between 5 to 16°C with 30 to 60% relative humidity (Bowles et al. 2007). Flame lengths usually reached 1-2 m in height. Depending on the year, pre- and post-burn litter assessments revealed that 30 to 100% of the oven dry litter mass was lost with fire. Woody stems <1 cm were often heavily charred and stems >2.5 cm were less damaged by fires (Bowles et al. 2007).

Fire temperatures in October, 2009 were measured during two dormant season burns (one in the annual burn area and one in a periodic burn area) with a Raytek Raynger ST noncontact infrared thermometer. Fifty measurements were taken 100 cm from the advancing front of the fire. Each measurement reported the temperature integrated over 122.6 cm^2. In 2009, mean fire temperatures in an annual burn area at the advancing front were 184±77°C. Fire temperatures in a periodically burned area in 2009 were similar, 186±78°C. Soil surface temperatures measured immediately after fire and were 16±5°C and 19±6°C, respectively for the periodic and annual fires. Pre- and post-fire litter samples were collected on five plots to assess the amount of litter burned during the fires. On each plot, three replicate 15 cm litter cores were taken 24 hours prior to the fire, with an additional litter sampling performed 24 hours after the fire. Litter samples were returned to the laboratory for dry weight determination, as described below. Litter depth was reduced by 80% and litter mass by 30% in these two monitored fires. Overall, fire intensities in the east woods are light to moderate (Franklin et al. 1997), or cool fires (Roberts 2004).

2.3. Field sampling

Forty plots were randomly located in annually burned, periodically burned, and unburned (control) areas. Plots were purposefully selected to exclude areas that were too close to roads or trails (approximately 10-m), or otherwise disturbed. The slope, aspect, and elevation using a USGS digital elevation model (http://data.geocomm.com/dem/) on ARCVIEW software (http://esri.com) were determined for each plot. Canopy openness was assessed on each plot by photographs taken at 1.5 m above ground level through a 180° fish-eye lens on a tripod-mounted Nikon Coolpix 800 digital camera. Images were processed using Gap Light Analyzer software to calculate percent canopy openness. Vegetation data was collected on these plots in 2007. From tree sub-plots (0.025 ha), species and diameters were recorded for all tree stems ≥10 cm diameter at breast height (dbh) or 1.4 m. Stem densities of woody species (sub-canopy trees, shrubs, and saplings) ≥1 m high and <10 cm dbh were sampled from shrub layer nested sub-plots (0.001 ha). Basal area (BA) was calculated, with r equal to average plot diameter divided by two (Equation 1). Woody richness was tallied per plot. Herbaceous species were sampled in ground layer nested sub-plots (1.0 m^2). Herbaceous richness, the ratio of spring to summer herbs, and the ratio of alien to native plants were recorded per plot.

Equation 1. $BA = \pi * r^2$

On 10/20/08, 05/06/09, and 10/01/09 soil and litter samples were collected from a 5-m radius circular subplots (0.001 ha). On each sub-plot, fifteen 2-cm diameter by 10-cm deep cores were taken at random locations and then composited. Soils were stored in a cooler in the field and then at 5°C until laboratory analyses. Three, 15-cm diameter litter samples were composited per plot. Litter depth was recorded in each of the four cardinal directions for each core. Litter was placed in a paper bag and returned to the laboratory for analyses. Litter samples were dried at 60° C for five days and weighed to determine oven-dry mass (mg).

In the laboratory, soil sub-samples were weighed, dried for 24 h at 105°C, and reweighed to calculate gravimetric soil moisture (%). Sand, silt, and clay (%) were calculated using the modified pipette method of Kettler et al. (2001). Total C and N (%) were determined by automated dry combustion with an Elementar Vario EL III CHNOS analyzer (Elementar, Hanau, Germany). Particulate organic matter (POM) was measured after shaking 50-g subsamples for 15 hr with sodium hexametaphosphate $(NaPO_3)_6$ and then collecting POM on 53 µm sieve (Gregorich and Beare 2008). Loss on ignition at 360°C for 6 hours was used to determine the organic matter content of total soil and POM samples (Nelson and Sommers 1986). Soil sub-samples were extracted with 1 M NH_4OAc (pH 7.0) and mg kg-1 of K^+, Ca^{2+}, Mg^{2+}, and Na^+ were determined with atomic adsorption spectroscopy (Model A5000, Perkin Elmer Inc., Waltham, MA) (Schollenberger and Simon 1945). Soil phosphorus (P) was determined with the Bray P-1 extraction and extracts were analyzed colorimetrically at 882 nm on a spectrophotometer (Model UV mini 1240, Shidmadzu Inc., Kyoto, Japan) (Olsen and Sommers 1982). Soil pH and electrical conductivity (EC) in µs cm^{-1} were measured in 1:1 (soil:deionized) water pastes (Model Orion 5-Star, Thermo Fisher Scientific Inc., Waltham, MA). The soil fumigation-extraction method (Brookes et al. 1982) was used to determine microbial biomass N (MBN) in mg kg^{-1}. Soil sub-samples were fumigated with ethanol-free chloroform for 5 days, extracted with 0.5 M K_2SO_4. Total extractable N was reduced to NH_4^+ with persulfate and Devarda's alloy for NH_4^+ absorbance readings at 650 nm (Model ELx 800, Biotek Instruments Inc., Winooski, VT) (Sims et al. 1995). Microbial biomass N was the difference in N between the fumigated and unfumigated samples, using an extraction efficiency factor of kEN = 0.54 (Joergensen and Mueller 1996). Colorimetric N analyses were also used for determination of dissolved organic N (DON), NO_3^-, and NH_4^+ in mg kg-1 in non-fumigated samples (Sims et al. 1995). Potential N mineralization (Nmin) and microbial respiration (Cres) were measured using 20-day soil incubations in the dark, at 25°C and with soils adjusted to 60% water-filled-pore-space. Carbon dioxide in 0.25 M NaOH traps was precipitated with $BaCl_2$, followed by 0.25 M HCl (standardized) titration to a phenolphthalein endpoint (Parkin et al. 1996). Concentrations of NH_4^+ and NO_3^- in incubated soils and non-incubated soils were determined colorimetrically as previously described. Potential N mineralization was determined by subtracting total inorganic N (NH_4^+ and NO_3^-) in base extracts from the extracts of the incubated soils.

Earthworm sampling was performed from 07/07/09 to 07/24/09 on these plots following methods of Blair et al. (1996). Three 25 by 25 by 25 cm holes were dug on each plot. Soils were hand-sorted to remove all earthworms. A hot mustard powder solution (50 g L^{-1}) was poured in the excavated hole to extract deeper earthworms (Lawrence and Bowers 2002). The number of adult and juvenile earthworms was tallied for each excavation, and reported as individuals m^{-3}. Earthworms were stored in a cooler in petri dishes with damped towels and returned to the laboratory. Earthworms were identified using a dissecting microscope and dichotomous key for the Great Lakes, USA region (Hale 2010). For each subplot, adult earthworm biomass (ash-free dry mass) was determined for each species (Hale et al. 2004).

For invertebrate analyses, litter and soil sub-samples were placed in Berlese-Tullgren funnels (Brower et al. 1998). A 60-watt light source over three days was used to drive invertebrates into the bottom of the funnel, and then captured in a 70% ethanol trap. Invertebrates were classified using Nikon SMZ-2T and Motic SMZ-168 dissecting microscopes and keys for soil and litter invertebrates (Edgar 1992; Meyer 1993). Invertebrates were identified to one of 18 orders or families, i.e. taxa (Coleoptera, Diptera, Esocoptera, Diplura, Gastropoda, Annelida, Protura, Pseudoscorpionida, Araneae, Acarina, Isopoda, Diplopoda, Chilopoda, Hymenoptera, Collembola, Thysanoptera, Hemiptera, and Orthoptera). Acarina subclass (mites) and order Collembola (springtails) were most common and abundances of these taxa were also examined separately. Invertebrate richness (number of taxa present) and abundance (number of individual invertebrates present) were tallied. Richness (S) was used to calculate maximum possible diversity (H_{max}) (Equation 2). Evenness (J) is the relationship between observed and maximum diversity (Equation 3). Maximum diversity denotes that each taxon is equally represented in all treatments and an evenness ratio indicates how evenly the taxa are distributed among all samples (Shannon and Weaver 1949). Diversity was also calculated using the Shannon (H') and Simpson (D) indices (Equations 4 and 5). For these calculations, p_i is the proportion of each taxon found in the overall sample. These diversity indices are preferred to richness because the number of taxa alone may give an inaccurate representation of the diversity of a population as it does not show how many individuals belong to each taxon. In contrast, Shannon and Simpson indices more accurately assess biodiversity using both richness and abundance. Because they are based on proportion of taxa present, they can relate whether a group is rare or widespread.

Equation 2. $H_{max} = \ln S$

Equation 3. $J = H' / H_{max}$

Equation 4. $H' = -\Sigma\, p_i * \ln p_i$

Equation 5. $D = \Sigma\, (p_i)^2$

2.4. Statistical analyses

Statistical analyses were conducted using SAS JMP 7.0 software (SAS Inc., Cary, NC). The design is a randomized incomplete block with a fire main factor, three levels (un-burned control, annually-burned, or periodically-burned). Soil type and sampling dates were treated as blocking variables. Data distributions were checked for normality using the Shapiro-Wilk W test. Transformations of non-normal data were performed with $\log_{10}$, natural log, square root, or exponential functions. The effects of fire, soil, time, and interactions were analyzed using analysis of variance (ANOVA). Mean separations were carried out with Tukey-Kramer HSD tests. Non-parametric Kruskal-Wallis tests were used when data could not be transformed to meet a normal distribution. Pairwise correlations with Pearson product-moment were used to identify significant relationships among variables. Multivariate correlations and principal component analyses (PCA) were used to explore relationships among the measured variables. Significant differences were determined at the 95% confidence level.

3. Results

3.1. Differential impacts of long-term, low-intensity periodic vs. annual prescribed fire

The percent difference relative to unburned control plots for canopy openness was significantly greater in periodic vs. annual prescribed fire plots (Figure 2). The ratio of spring to summer herbaceous plants was greater in annual compared to periodic burn plots (Figure 2). Responses of basal area, woody richness, herbaceous richness and the alien to native plant ratio were similar in both burn types (Figure 2). Neither total litter nor any litter invertebrate measurements (richness, evenness, abundance, Shannon index, Simpson index, Acarina, or Collembola) were significantly different when comparing the effects of annual to periodic prescribed fire (Figure 2). The percent relative difference for soil invertebrate measures (abundance, Shannon index, Simpson index, Acarina, and Collembola) tended to be greater in periodically burned plots compared to the annual burn plots, significantly greater for invertebrate richness (Figure 2). The percent differences changes relative to controls for all other soil properties were not significantly different for periodic compared to annual burn plots (Figure 2). Overall, the impacts of periodic compared to annual fires were minimal. Of the 44 response parameters measured, only soil invertebrate richness was significantly impacted in a differential manner, with a positive response for periodic fire and a negative response for annual fire relative to unburned controls (Figure 2).

Figure 2. Percent differences relative to unburned-controls of vegetation, forest floor, and soil (0-10 cm) properties after 23-years of annual and periodic (once every three to four years) low-intensity prescribed fire in the East Woods of The Morton Arboretum, Lisle, IL, USA. Means with standard error (n = 20). Significant differences evaluated by ANOVA and Tukey's honest significant difference on normalized data. Asterisk showing significant differences at the $p \leq 0.05$ level.

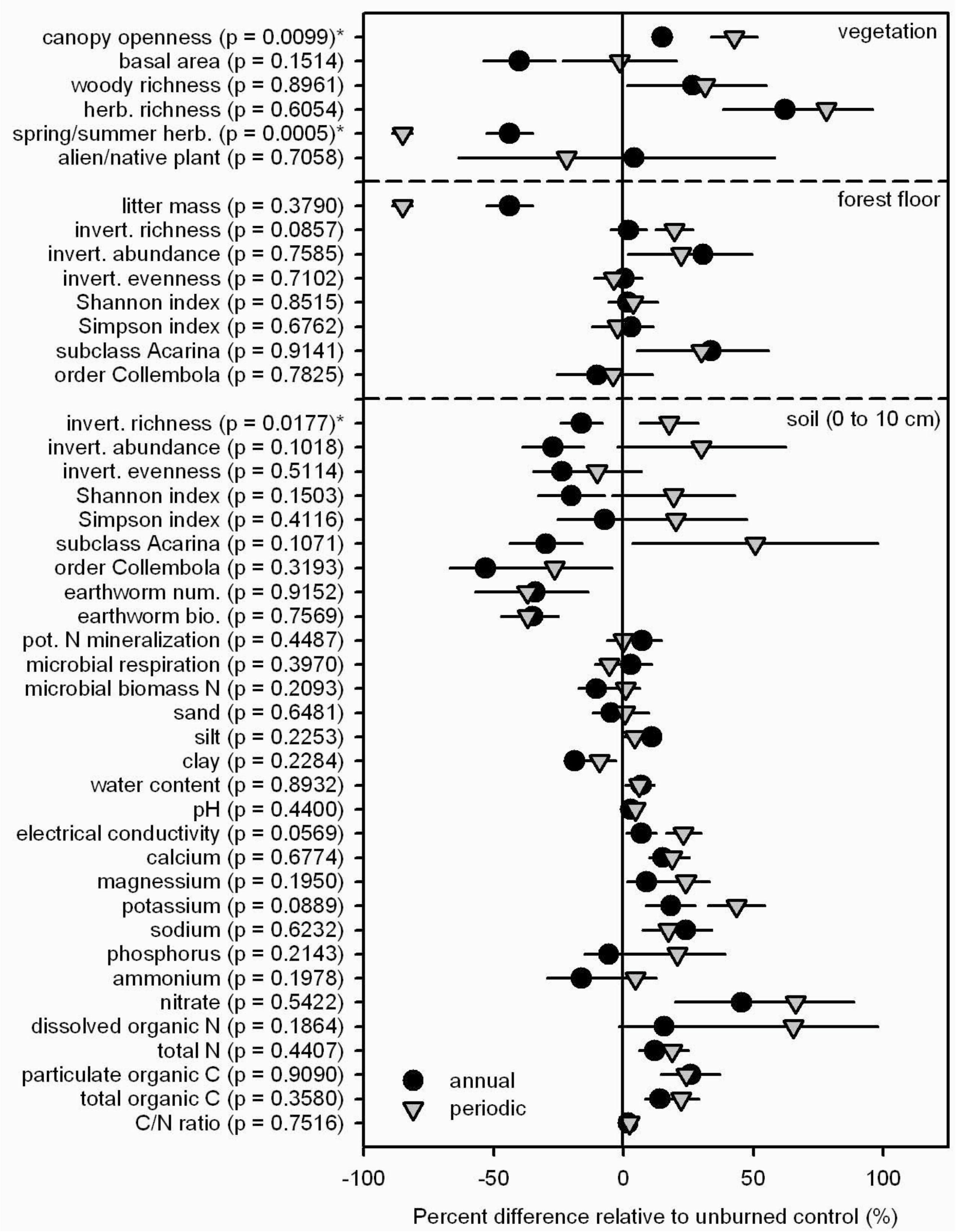

vegetation
canopy openness (p = 0.0099)*
basal area (p = 0.1514)
woody richness (p = 0.8961)
herb. richness (p = 0.6054)
spring/summer herb. (p = 0.0005)*
alien/native plant (p = 0.7058)
forest floor
litter mass (p = 0.3790)
invert. richness (p = 0.0857)
invert. abundance (p = 0.7585)
invert. evenness (p = 0.7102)
Shannon index (p = 0.8515)
Simpson index (p = 0.6762)
subclass Acarina (p = 0.9141)
order Collembola (p = 0.7825)
soil (0 to 10 cm)
invert. richness (p = 0.0177)*
invert. abundance (p = 0.1018)
invert. evenness (p = 0.5114)
Shannon index (p = 0.1503)
Simpson index (p = 0.4116)
subclass Acarina (p = 0.1071)
order Collembola (p = 0.3193)
earthworm num. (p = 0.9152)
earthworm bio. (p = 0.7569)
pot. N mineralization (p = 0.4487)
microbial respiration (p = 0.3970)
microbial biomass N (p = 0.2093)
sand (p = 0.6481)
silt (p = 0.2253)
clay (p = 0.2284)
water content (p = 0.8932)
pH (p = 0.4400)
electrical conductivity (p = 0.0569)
calcium (p = 0.6774)
magnessium (p = 0.1950)
potassium (p = 0.0889)
sodium (p = 0.6232)
phosphorus (p = 0.2143)
ammonium (p = 0.1978)
nitrate (p = 0.5422)
dissolved organic N (p = 0.1864)
total N (p = 0.4407)
particulate organic C (p = 0.9090)
total organic C (p = 0.3580)
C/N ratio (p = 0.7516)
● annual
▽ periodic
-100
-50
0
50
100
Percent difference relative to unburned control (%)

Table 1. Effects of 23 years of low-intensity prescribed fire on vegetation, forest floor, and soil (0-10 cm) properties at The Morton Arboretum, Lisle, IL, USA.

Parameter	Control	Fire	Fire Prob>F	Soil Prob>F	Time Prob>F	Fire x Soil Prob>F	Fire x Time Prob>F
Vegetation							
canopy openness (%)	8.79^a ± 0.31	11.3^b ± 0.31	0.0003*	0.0194*	–	0.1163	–
basal area (m^2 ha^{-1})	23.7 ± 15	17.6 ± 13	0.1693	0.6717	–	0.2806	–
woody richness	1.55 ± 0.27	2.00 ± 0.23	0.2196	0.6795	–	0.8904	–
herbaceous richness	5.15^b ± 0.58	8.75^a ± 0.77	0.0012*	0.9987	–	0.8415	–
spring/summer herb. ratio	1.46^a ± 0.19	0.672^b ± 0.19	0.0051*	0.2309	–	0.2973	–
alien/native plant ratio	0.132 ± 0.058	0.128 ± 0.047	0.9714	0.6089	–	0.7487	–
Forest floor							
litter (kg m^{-2})	5.02 ± 0.20	4.75 ± 0.20	0.4702	0.1478	<0.0001*	0.9763	0.3561
invert. richness	6.95 ± 0.31	7.67 ± 0.35	0.1500	0.6792	0.0095*	0.3070	0.2936
invert. abundance	192 ± 18	231 ± 24	0.4900	0.3325	0.3508	0.9517	0.1499
invert. evenness	0.405 ± 0.017	0.392 ± 0.019	0.5719	0.4437	<0.0001*	0.6909	0.3912
invert. Shannon index	0.744 ± 0.032	0.753 ± 0.039	0.9962	0.2882	0.0002*	0.9482	0.4302
invert. Simpson index	0.383 ± 0.019	0.373 ± 0.021	0.6775	0.1519	<0.0001*	0.5574	0.2612
subclass Acarina (individuals 100 g^{-1})	143 ± 15	179 ± 21	0.3776	0.0029*	<0.0001*	0.8524	0.9682
order Collembola (individuals 100 g^{-1})	38.6 ± 6.5	33.7 ± 4.5	0.6775	0.1519	<0.0001*	0.5574	0.2612
Soil (0-10 cm)							
invert. richness	2.10 ± 0.16	2.10 ± 0.16	1.000	0.1050	<0.0001*	0.1050	0.6842
invert. abundance	8.38 ± 1.2	8.53 ± 0.14	0.9295	0.7908	0.0007*	0.2065	0.7095
invert. evenness	0.565 ± 0.11	0.448 ± 0.050	0.3341	0.1575	0.7160	0.5639	0.6523
invert. Shannon index	0.457 ± 0.055	0.441 ± 0.052	0.8301	0.1590	0.0025*	0.3157	0.9625
invert. Simpson index	0.339 ± 0.043	0.340 ± 0.043	0.9816	0.2647	0.1343	0.6206	0.6293
subclass Acarina (individuals 100 g^{-1})	0.800 ± 0.14	0.667 ± 0.13	0.7962	0.4390	0.0034*	0.1909	0.5937
order Collembola (individuals 100 g^{-1})	6.28 ± 1.0	6.68 ± 1.3	0.4663	0.0192*	0.8535	0.1028	0.7724
earthworm (individuals m^{-3})	321 ± 68	480 ± 161	0.3798	0.5195	–	0.8729	–
earthworm (ash free biomass, mg m^{-3})	27.4 ± 9.1	32.2 ± 9.7	0.7183	0.3020	–	0.2457	–
potential N mineralization (mg kg^{-1} d^{-1})	2.51 ± 0.19	2.77 ± 0.24	0.5423	0.1913	<0.0001*	0.5541	0.0045*
microbial respiration (mg CO_2 kg^{-1} d^{-1})	105 ± 8.9	110 ± 8.9	0.6619	0.1724	<0.0001*	0.5810	0.2120
microbial biomass N (mg kg^{-1})	152 ± 9.2	143 ± 9.1	0.3231	0.2861	<0.0001*	0.4233	0.6921
sand (%)	17.6 ± 0.82	17.3 ± 1.0	0.7868	0.4281	–	0.3931	–
silt (%)	55.5^b ± 1.3	59.7^a ± 1.5	0.0414*	0.3325	–	0.5512	–
clay (%)	26.9^a ± 1.0	23.1^b ± 0.98	0.0113*	0.5438	–	0.9775	–
water (%)	40.2 ± 1.4	42.8 ± 1.7	0.1920	0.0128*	<0.0001*	0.7539	0.3192
pH (1:1)	6.12^b ± 0.084	6.34^a ± 0.080	0.0295*	0.2328	<0.0001*	0.6850	0.2869
electrical conductivity (µs cm^{-1})	102^b ± 5.6	118^a ± 6.2	0.0079*	0.3475	<0.0001*	0.1030	0.0976
Ca^{2+} (mg kg^{-1})	2923^b ± 116	3357^a ± 117	0.0016*	0.0002*	<0.0001*	0.8130	0.1538
Mg^{2+} (mg kg^{-1})	910^b ± 73	976^a ± 67	0.0541*	0.0099*	<0.0001*	0.2735	0.2514
K^+ (mg kg^{-1})	136^b ± 6.5	179^a ± 11	0.0007*	0.0345*	<0.0001*	0.2240	0.2154
Na^+ (mg kg^{-1})	33.3^b ± 1.9	40.8^a ± 2.8	0.0004*	0.5193	<0.0001*	0.9250	0.1054
Bray P (mg kg^{-1})	8.24 ± 0.68	8.67 ± 0.73	0.7030	0.7404	0.0836	0.3784	0.9214
NH_4^+ (mg kg^{-1})	6.32 ± 0.61	5.51 ± 0.42	0.4269	0.5002	0.0551	0.1325	0.0236*
NO_3^- (mg kg^{-1})	13.0^b ± 1.9	17.1^a ± 1.9	0.0043*	0.2919	<0.0001*	0.3949	0.0102*
dissolved organic N (mg kg^{-1})	14.6 ± 2.0	17.4 ± 2.2	0.0976	0.0221*	<0.0001*	0.9364	0.0166*
total N (%)	0.372^b ± 0.013	0.425^a ± 0.016	0.0028*	0.0003*	0.8887	0.8499	0.0155*
particulate organic C (g kg^{-1})	8.73^b ± 0.57	10.7^a ± 0.69	0.0065*	0.0004*	<0.0001*	0.8793	0.3358
total organic C (%)	4.65^b ± 0.15	5.43^a ± 0.19	0.0003*	0.0007*	0.9660	0.9821	0.1151
C/N ratio	12.6 ± 0.12	12.8 ± 0.096	0.0790	0.3906	0.1583	0.8604	0.1357

Values are means ± standard error of the mean. Vegetation (n=20) sampled once in 2007. Litter and soil means (n=60) from collections on 10/20/08, 05/06/09, and 10/01/09. Soil texture (n=20) sampled once, 10/01/09. Earthworms (n=20) sampled once 07/07/09 to 07/24/09. Non-normal variables were transformed with logrithimic, exponential, or square root functions to meet the assumption of normality. Significant differences evaluated by ANOVA and least squares fit model, with letters denoting differences using Student's T-test for the fire treatment compared to the unburned control. Interaction effects are not listed for Soil x Time or Fire x Soil x Time, but were non-significant ($P \geq 0.05$). Significant effects ($P \leq 0.05$) indicated with asterisk.

3.2. Impacts of 23 years of low-intensity prescribed fire on vegetation, forest floor, and soil

Because the impacts of periodic compared to annual prescribed fires tended to be minimal, we assessed the overall impact of fire by combining periodic and annual treatments into one fire treatment and compared these 20 plots to the 20 unburned control plots (Table 1). Prescribed fire plots in these oak forests had significantly greater canopy openness and herbaceous richness, and lower spring/summer herb ratio (Table 1). Basal area, woody richness, and the alien/native plant ratio did not differ on these plots (Table 1). No fire by soil interactions were detected for vegetation parameters (Table 1). Significant impacts of fire were not detected for litter mass, litter invertebrate indices, or soil invertebrate indices (Table 1). We only reported one species (*Lumbricus terrestris*) of earthworm, and numbers and biomass did not differ with fire compared to unburned controls (Table 1). Soil silt, pH, EC, Ca^{2+}, Mg^{2+}, K^+, Na^+, NO_3^-, total N, POM, and total organic C were significantly greater, and clay content was less with prescribed fire (Table 1). Soil water content, Bray P, NH_4^+, DON, total C/N, microbial respiration, potential N mineralization, and microbial biomass N were not impacted by fire (Table 1). Significant soil type effects were detected for water, Ca^{2+}, Mg^{2+}, K^+, Na^+, DON, total N, POM, and total organic C, but all fire by soil type interactions were not significant (Table 1). Significant effects of sampling time were detected for most litter and soil properties, except litter invertebrate abundance, soil invertebrate evenness, Simpson's index, Collembola, Bray P, total N, organic C, and C/N (Table 1). Significant fire by time interactions were detected for soil N pools: ammonium, nitrate, dissolved organic N, potential N mineralization, and total N (Table 1). Significantly greater soil nitrate, dissolved organic N, potential N mineralization, and total N were observed in burned soil compared to unburned controls in the spring, but not fall (Figure 3). Differences for soil ammonium and microbial biomass N were not significant for burned vs. unburned plots in either spring or fall (Figure 3).

3.3. Relationships among site, vegetation, forest floor, and soils in these oak forest plots

Woody richness was best correlated with herb richness (r = 0.58), soil C/N ratio (r = 0.45), aspect (r = 0.42), soil ammonium (r = 0.40), alien/native plant (r = -0.39), earthworm numbers (r = -0.36), and litter invertebrate richness (r = 0.34) (Table 2). A step-wise least square model created from 47 parameters (Table 2) explained 64% of the variance in woody richness and included herb richness ($p < 0.0001$), litter invertebrate richness ($p = 0.0057$), soil C/N ($p = 0.0221$), and aspect ($p = 0.0419$) (Figure 4). Single parameters best correlated with herb richness are woody richness (r = 0.58), alien/native plant (r = -0.53), soil pH (r = 0.39), spring/summer herb (r = -0.39), aspect (r = 0.36), and litter Collembola (Table 2). A stepwise model with woody richness ($p < 0.0001$), litter Collembola (p = 0.0044), soil pH (p = 0.0108), and potential N mineralization (p = 0.0323) explained 63% of the herb richness variance (Figure 4). The spring/summer herb ratio was correlated with canopy openness (r = -0.50), herb richness (r = -0.39), K^+ (r = -0.39), electrical conductivity (r = -0.33), and total organic C (r = -0.32) (Table 2). Canopy openness ($p < 0.0001$), potential N mineralization (p = 0.0009), aspect (p = 0.0033), soil invertebrate Simpson index (p = 0.0036), Mg^{2+} (p = 0.0110), and C/N ratio (p = 0.0274) were included in the step-wise model explaining 63% of spring/summer herb ratio (Figure 4).

A principal component analysis with these 47 parameters was performed. The first principal component explained 18% and the second an additional 13% of the total variance in the data set. Soil organic C (r = 0.96), total N (r = 0.95), potassium (r = 0.88), calcium (r = 0.87), moisture (r = 0.85), and particulate organic matter (r = 0.78) had high correlations with the first principal component (Figure 5). Litter invertebrate richness (r = 0.80), abundance (r = 0.68), Collembola (r = 0.66), and Acarina (r = 0.67), as well as soil invertebrate abundance (r = 0.69) and Acarina (r = 0.67) had the strongest correlations with the second principal component (Figure 5). The first principal component was significantly greater on annual and periodic burn plots compared to unburned controls, and significant differences among the treatments for the second principal component were not detected with the ANOVA analyses (Figure 5).

Figure 3. Soil (0 to 10 cm) ammonium (NH4), nitrate (NO3), dissolved organic N (DON), total N, potential N mineralization (Nmin), microbial respiration (Cres), pH and soil moisture (GSM) following 23-years of low-intensity prescribed fire, annual and periodic (once every three to four years) combined (solid bars) compared to un-burned controls (hatched bars) in the East Woods of The Morton Arboretum, Lisle, IL, USA. Spring means with standard error (n = 20) and fall means (n = 40) with standard error shown with bar. Significant differences evaluated by ANOVA and Tukey's honest significant difference test on normalized data. Asterisk showing significant differences at the $p \leq 0.05$ level.

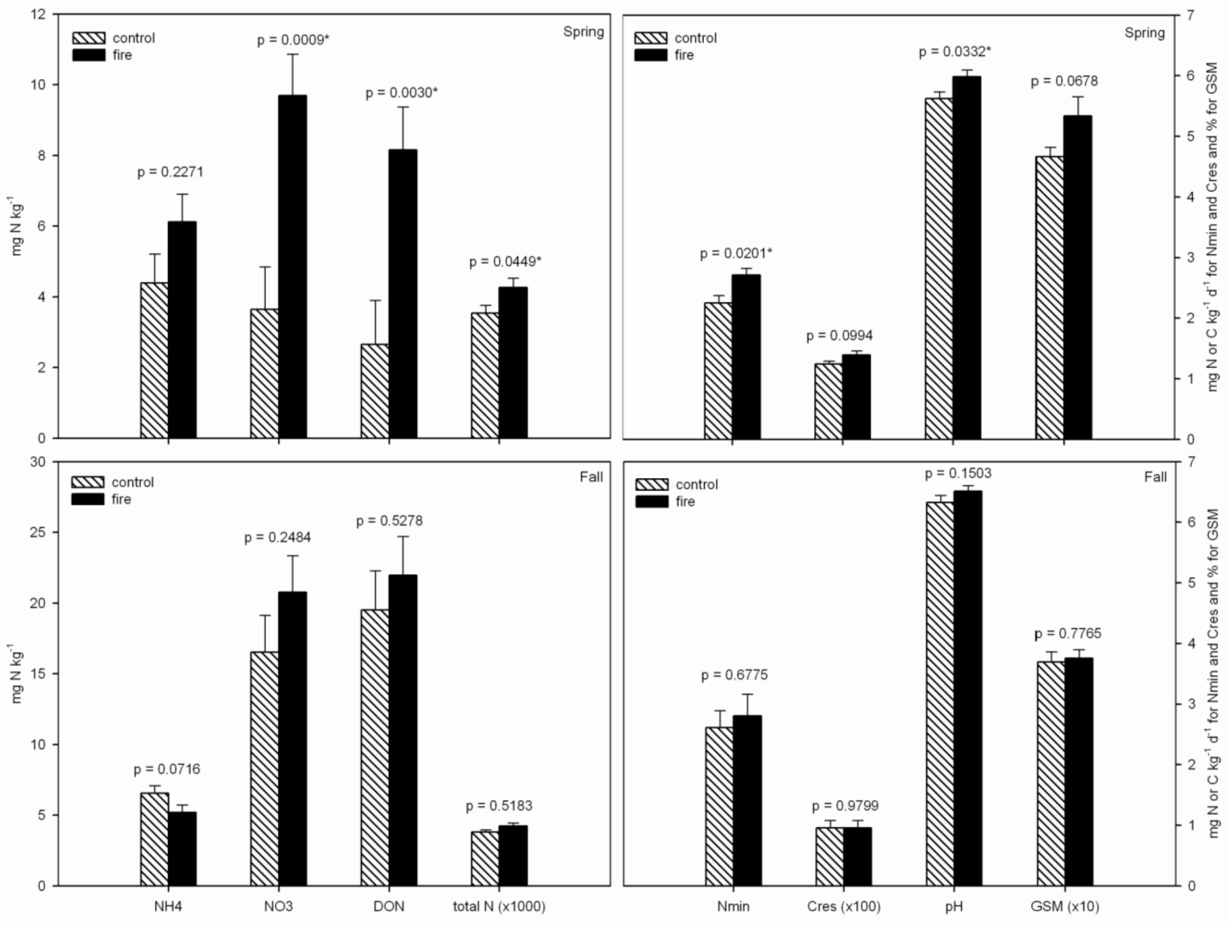
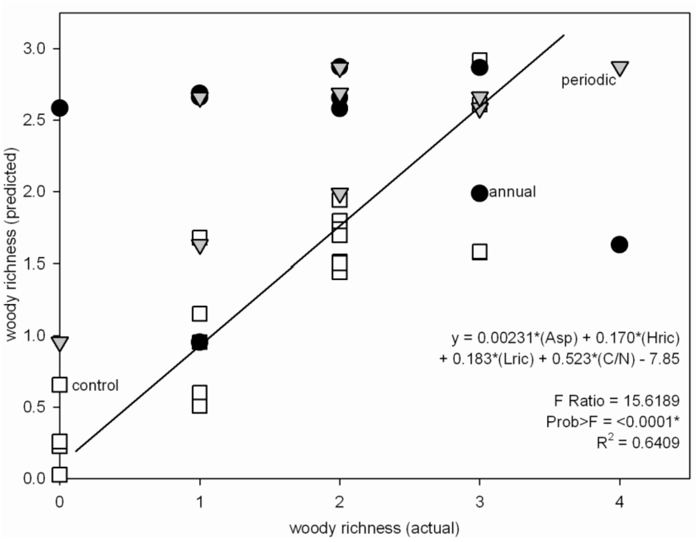
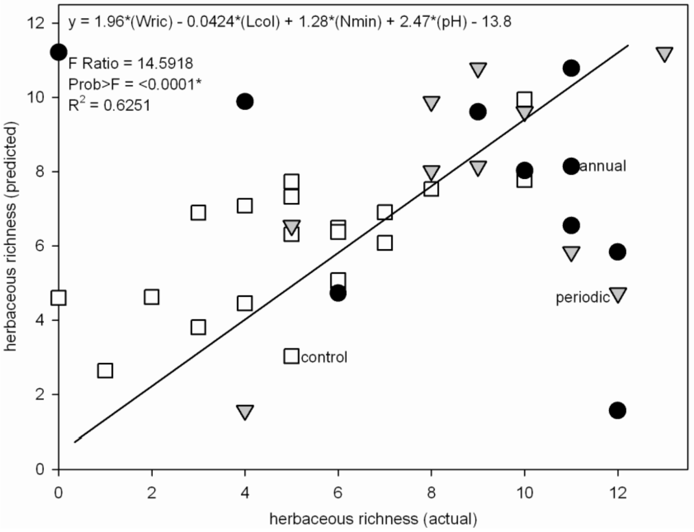


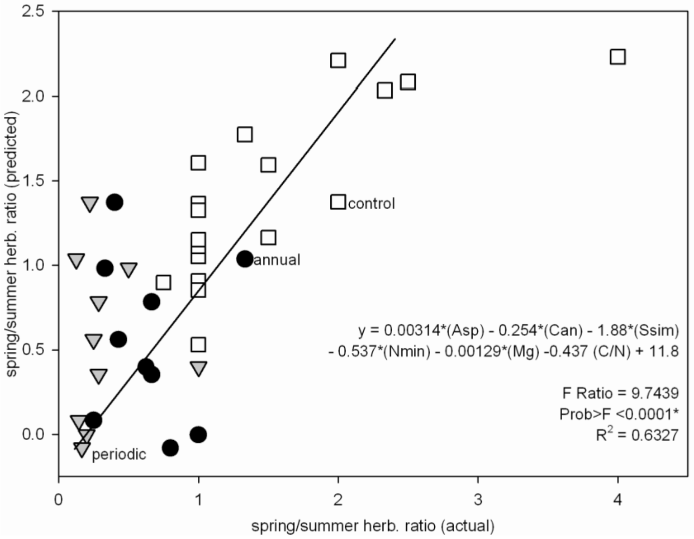
Figure 4. Predicted vs. actual values of woody richness, herbaceous richness, and the alien/native plant ratio using step-wise regression models and 47 site, vegetation, forest floor, and soil (0-10 cm). Data from plots in oak forests following 23-years of low-intensity prescribed fire in the East Woods of The Morton Arboretum, Lisle, IL, USA. Dark circles are annually-burned plots, shaded triangles are periodically-burned plots (once every three to four years), and non-burned controls are open squares. Models, R^2, and p-values are given for each. Asterisk showing significant differences at the $p \leq 0.05$ level.



woody richness (predicted)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
woody richness (actual)
periodic
annual
control
y = 0.00231*(Asp) + 0.170*(Hric)
+ 0.183*(Lric) + 0.523*(C/N) - 7.85
F Ratio = 15.6189
Prob>F = <0.0001*
R2 = 0.6409

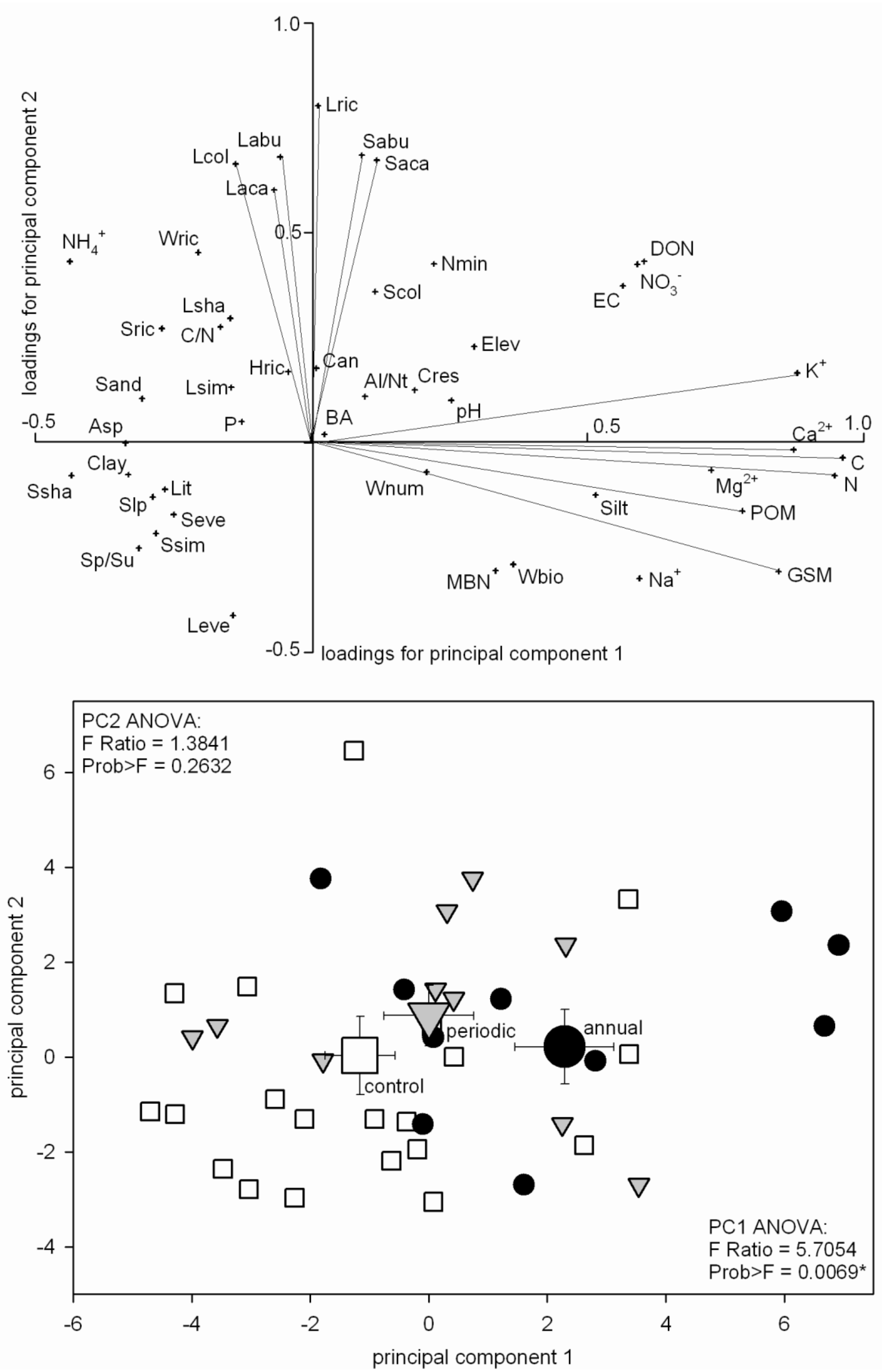


y = 1.96*(Wric) - 0.0424*(Lcol) + 1.28*(Nmin) + 2.47*(pH) - 13.8
F Ratio = 14.5918
Prob>F = <0.0001*
R2 = 0.6251
herbaceous richness (predicted)
12
10
8
6
4
2
0
0
2
4
6
8
10
12
herbaceous richness (actual)
annual
periodic
control



spring/summer herb. ratio (predicted)
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
spring/summer herb. ratio (actual)
control
annual
periodic
y = 0.00314*(Asp) - 0.254*(Can) - 1.88*(Ssim)
- 0.537*(Nmin) - 0.00129*(Mg) -0.437 (C/N) + 11.8
F Ratio = 9.7439
Prob>F <0.0001*
R2 = 0.6327

Figure 5. Principal components and loadings for 47 site, vegetation, forest floor, and soil (0-10 cm) properties following 23-years of low-intensity prescribed fire in the East Woods of The Morton Arboretum, Lisle, IL, USA. Dark circles are annually-burned plots, shaded triangles are periodically-burned plots (once every three to four years), and non-burned controls are open squares. Larger circles, triangles, and squares are means with standard errors of means. Principal components differences evaluated by ANOVA and Tukey's honest significant difference test. Asterisk showing significant differences at the $p \leq 0.05$ level. Abbreviations: aspect (Asp), slope (Slp), elevation (Elev), canopy openness (Can), basal area (BA), woody richness (Wric), herbaceous richness (Hric), spring/summer herb (Sp/Su), alien/native (Al/Nt), litter mass (Lit), litter richness (Lric), litter abundance (Labu), litter evenness (Leve), litter Shannon index (Lsha), litter Simpson index (Lsim), litter Acarina (Laca), litter Collembola (Lcol), soil richness (Sric), soil abundance (Sabu), soil evenness (Seve), soil Shannon index (Ssha), soil Simpson index (Ssim), soil Acarina (Saca), soil Collembola (Scol), earthworm numbers (Wnum), earthworm biomass (Wbio), potential N mineralization (Nmin), microbial biomass N (MBN), gravimetric soil moisture (GSM), electrial conductivity (EC), calcium (Ca), magnessium (Mg), potassium (K), sodium (Na), ammonium (NH4), nitrate (NO3), dissolved organic N (DON), total soil N (N), particulate organic matter (POM), total organic C (C), soil C/N (C/N).



loadings for principal component 2
loadings for principal component 1
1.0
0.5
-0.5
0.5
1.0
-0.5
Lric
Labu
Lcol
Laca
Sabu
Saca
NH4+
Wric
Nmin
DON
NO3-
EC
Scol
Lsha
Sric
C/N
Elev
Hric
Can
K+
Sand
Lsim
Al/Nt
Cres
pH
Asp
P
BA
Ca2+
Clay
C
Ssha
Lit
Wnum
Mg2+
N
Slp
Seve
Silt
POM
Ssim
Sp/Su
MBN
Wbio
Na+
GSM
Leve
PC2 ANOVA:
F Ratio = 1.3841
Prob>F = 0.2632
periodic
annual
control
PC1 ANOVA:
F Ratio = 5.7054
Prob>F = 0.0069*
principal component 2
principal component 1
6
4
2
0
-2
-4
-6
-4
-2
0
2
4
6

Table 2. r-values for pairwise correlations for site, vegetation, forest floor, and soil parameters measured on burned and un-burned control plots at The Morton Arboretum, Lisle, IL, USA.

	Asp	Slp	Elev	Can	BA	Wric	Hric	Sp/Su	Al/Nt	Lit	Lric	Labu	Leve	Lsha	Lsim	Laca	Lcol	Sric	Sabu	Seve	Ssha	Ssim	Saca	Scol	Wnum	Wbio	Nmin	Cres	MBN	Sand	Silt	Clay	GSM	pH	EC	Ca	Mg	K	Na	P	NH4	NO3	DON	N	POM	C	C/N
Asp	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Slp	-0.06	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Elev	-0.03	-0.42	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Can	0.23	-0.05	-0.15	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BA	-0.34	0.12	-0.13	-0.33	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Wric	0.42	-0.07	0.24	0.17	-0.14	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hric	0.36	-0.18	0.28	0.26	-0.11	0.58	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sp/Su	0.19	0.29	-0.11	-0.50	-0.03	-0.25	-0.39	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Al/Nt	-0.52	-0.12	0.09	0.06	-0.07	-0.39	-0.53	-0.15	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lit	-0.16	0.16	-0.40	0.04	0.24	-0.21	-0.12	0.11	0.15	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lric	0.00	-0.04	0.06	0.20	0.01	0.34	-0.07	-0.25	0.14	0.05	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Labu	-0.04	0.12	-0.03	0.23	-0.10	0.23	-0.13	-0.09	0.27	0.04	0.71	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Leve	0.23	-0.13	-0.02	-0.07	0.07	-0.25	-0.07	0.16	-0.15	-0.08	-0.35	-0.55	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lsha	0.17	-0.07	0.03	0.08	0.04	0.02	-0.21	-0.03	-0.01	-0.02	0.45	0.04	0.60	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lsim	0.18	-0.04	0.04	-0.02	0.08	-0.10	-0.27	0.15	-0.04	-0.10	0.20	-0.07	0.72	0.92	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Laca	-0.04	0.14	-0.08	0.27	-0.17	0.25	-0.06	-0.11	0.25	0.07	0.61	0.97	-0.62	-0.10	-0.22	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lcol	0.08	0.13	0.01	0.04	0.12	0.11	-0.30	0.09	0.16	-0.05	0.69	0.70	-0.14	0.43	0.41	0.55	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sric	0.26	-0.16	-0.02	-0.10	-0.16	0.14	0.19	-0.04	-0.02	0.05	0.18	0.05	-0.10	0.08	0.01	0.07	0.02	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sabu	-0.07	-0.20	0.14	-0.10	-0.02	0.11	-0.06	-0.04	0.05	-0.15	0.34	0.19	-0.22	0.18	0.15	0.15	0.30	0.45	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Seve	0.25	-0.19	-0.14	-0.14	-0.25	0.13	0.18	0.02	-0.04	0.16	-0.09	-0.13	0.00	-0.04	-0.08	-0.09	-0.18	0.54	-0.02	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ssha	0.33	-0.12	-0.14	-0.08	-0.25	0.05	0.16	-0.05	-0.01	0.12	0.01	-0.09	0.07	0.09	0.01	-0.05	-0.15	0.83	0.08	0.77	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ssim	0.38	-0.04	-0.14	0.01	-0.29	0.09	0.23	-0.07	-0.06	0.07	-0.10	-0.14	0.12	0.03	-0.05	-0.09	-0.24	0.62	-0.06	0.74	0.93	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Saca	-0.08	-0.12	0.10	-0.06	-0.01	0.07	-0.05	-0.02	0.00	-0.14	0.30	0.21	-0.27	0.10	0.09	0.19	0.29	0.37	0.98	-0.11	-0.02	-0.13	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Scol	-0.11	-0.06	0.05	-0.35	0.29	0.02	-0.08	-0.01	-0.06	-0.07	0.37	0.02	0.00	0.27	0.22	-0.09	0.26	0.42	0.42	0.14	0.30	0.17	0.37	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Wnum	-0.30	-0.07	-0.06	-0.18	0.18	-0.36	-0.19	0.11	-0.01	-0.11	-0.08	-0.14	-0.01	-0.04	0.04	-0.17	-0.03	-0.16	0.10	-0.10	-0.25	-0.31	0.13	0.03	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Wbio	0.00	-0.10	-0.16	-0.12	0.26	-0.03	0.17	-0.10	-0.13	-0.07	-0.35	-0.37	0.22	-0.15	-0.07	-0.36	-0.31	-0.17	-0.13	-0.16	-0.16	-0.15	-0.14	0.07	0.17	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nmin	-0.05	-0.41	0.40	-0.07	0.17	0.09	0.13	-0.27	0.07	0.04	0.32	-0.05	0.13	0.34	0.22	-0.14	0.14	0.05	0.30	-0.13	-0.14	-0.21	0.24	0.24	0.18	0.15	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cres	0.21	-0.30	0.30	0.00	-0.21	0.04	0.11	0.27	-0.02	-0.08	0.06	0.01	-0.02	-0.05	-0.04	-0.02	0.13	0.22	0.33	-0.07	0.02	-0.08	0.29	0.07	0.02	0.03	0.13	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MBN	0.05	-0.05	-0.23	-0.03	-0.25	-0.18	-0.15	0.05	-0.16	-0.02	-0.10	-0.13	0.17	0.07	0.07	-0.11	-0.11	-0.06	-0.06	0.18	0.07	0.11	-0.06	0.08	0.13	-0.04	-0.16	0.09	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sand	-0.04	-0.03	-0.04	-0.08	0.15	0.28	0.26	-0.09	-0.13	-0.09	-0.11	0.02	-0.11	-0.16	-0.16	0.05	-0.03	-0.01	-0.01	0.19	0.01	0.03	-0.02	-0.26	0.00	-0.02	-0.10	-0.13	-0.29	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Silt	-0.04	-0.15	0.05	0.14	-0.18	-0.20	0.03	-0.07	0.17	0.03	-0.07	-0.04	0.01	-0.10	-0.12	0.01	-0.23	0.10	0.13	-0.06	0.02	0.00	0.16	0.08	0.09	0.19	0.07	0.17	0.19	-0.68	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Clay	0.08	0.23	-0.03	-0.11	0.11	0.03	-0.27	0.16	-0.13	0.03	0.19	0.03	0.08	0.28	0.30	-0.06	0.34	-0.13	-0.17	-0.08	-0.03	-0.03	-0.20	0.11	-0.12	-0.24	-0.01	-0.11	0.00	0.05	-0.77	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
GSM	-0.14	-0.25	0.04	-0.12	0.02	-0.22	0.03	-0.10	0.04	-0.17	-0.26	-0.17	0.05	-0.21	-0.15	-0.16	-0.24	-0.21	-0.06	-0.03	-0.13	-0.09	-0.06	0.05	0.25	0.53	0.10	0.17	0.51	-0.30	0.44	-0.34	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH	-0.09	0.12	0.20	0.16	-0.28	0.13	0.39	-0.18	-0.15	-0.38	-0.07	0.11	-0.24	-0.31	-0.29	0.15	-0.11	0.02	0.03	-0.06	-0.04	0.00	0.09	-0.01	-0.16	-0.03	-0.31	0.15	0.12	0.15	0.10	-0.27	0.04	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-
EC	-0.17	-0.08	0.13	0.27	-0.13	0.06	0.22	-0.33	-0.03	-0.25	0.17	0.10	-0.25	-0.08	-0.19	0.13	-0.07	-0.05	0.34	-0.17	-0.16	-0.09	0.40	0.05	0.03	0.04	0.23	0.02	0.16	0.09	0.14	-0.26	0.28	0.45	1.00	-	-	-	-	-	-	-	-	-	-	-	-
Ca	-0.30	-0.16	0.23	0.04	-0.15	-0.05	0.12	-0.30	0.08	-0.20	0.03	0.05	-0.26	-0.23	-0.24	0.05	-0.10	-0.08	0.08	-0.09	-0.10	-0.12	0.07	0.22	0.03	0.25	0.10	0.18	0.41	-0.29	0.39	-0.28	0.71	0.51	0.48	1.00	-	-	-	-	-	-	-	-	-	-	-
Mg	-0.21	-0.11	0.12	-0.14	0.09	0.00	0.02	-0.21	-0.01	-0.25	0.02	0.04	-0.18	-0.15	-0.15	0.03	-0.09	-0.07	0.00	0.10	-0.02	-0.04	-0.01	0.32	0.06	0.18	-0.12	0.02	0.51	-0.10	0.26	-0.27	0.63	0.41	0.36	0.74	1.00	-	-	-	-	-	-	-	-	-	-
K	-0.31	-0.10	0.19	0.21	0.06	-0.06	0.11	-0.39	0.18	-0.20	0.17	0.11	-0.19	-0.05	-0.08	0.07	0.05	-0.17	0.22	-0.27	-0.29	-0.31	0.24	0.17	0.20	0.22	0.22	0.09	0.23	-0.21	0.35	-0.29	0.66	0.32	0.63	0.71	0.62	1.00	-	-	-	-	-	-	-	-	-
Na	-0.10	-0.16	0.05	0.14	0.20	-0.06	0.23	-0.29	0.12	0.09	-0.28	-0.26	0.09	-0.18	-0.15	-0.23	-0.35	-0.25	-0.23	-0.11	-0.19	-0.14	-0.21	-0.15	0.07	0.45	0.15	-0.15	0.03	-0.14	0.33	-0.33	0.60	-0.23	0.11	0.26	0.27	0.49	1.00	-	-	-	-	-	-	-	-
P	-0.05	-0.20	-0.09	0.07	0.06	0.14	0.05	-0.15	0.01	0.07	0.06	-0.16	-0.02	-0.03	-0.10	-0.16	-0.23	0.06	0.07	0.14	0.17	0.20	0.03	0.23	0.02	0.11	0.04	0.06	-0.17	-0.02	-0.03	0.05	-0.08	-0.29	-0.12	-0.13	-0.05	-0.12	0.06	1.00	-	-	-	-	-	-	-
NH4	0.38	-0.21	0.14	-0.06	0.25	0.40	0.15	-0.07	-0.23	0.06	0.41	0.04	0.13	0.37	0.26	-0.05	0.34	0.20	0.24	0.15	0.09	0.04	0.19	0.25	-0.04	-0.13	0.43	0.08	-0.18	0.19	-0.38	0.35	-0.44	-0.32	-0.12	-0.50	-0.25	-0.25	-0.25	0.16	1.00	-	-	-	-	-	-
NO3	-0.17	-0.11	0.30	-0.03	0.08	0.12	0.22	-0.20	-0.17	-0.33	0.26	0.17	-0.16	0.05	-0.01	0.13	0.11	-0.13	0.31	-0.24	-0.30	-0.30	0.35	0.23	0.09	0.25	0.33	0.06	0.03	0.06	0.08	-0.17	0.37	0.25	0.69	0.42	0.32	0.56	0.16	-0.16	-0.03	1.00	-	-	-	-	-
DON	-0.18	-0.28	0.42	-0.06	0.07	0.01	0.15	-0.24	0.09	-0.34	0.17	0.04	-0.19	-0.04	-0.06	-0.02	0.06	0.06	0.45	-0.22	-0.14	-0.17	0.47	0.39	0.16	0.20	0.58	0.06	-0.17	-0.09	0.15	-0.13	0.33	0.18	0.60	0.50	0.26	0.56	0.20	-0.01	-0.02	0.57	1.00	-	-	-	-
N	-0.25	-0.22	0.14	0.01	0.04	-0.12	0.04	-0.25	0.14	-0.17	-0.02	-0.03	-0.10	-0.14	-0.15	-0.03	-0.11	-0.13	0.09	-0.10	-0.13	-0.12	0.08	0.21	0.14	0.42	0.18	0.16	0.44	-0.33	0.43	-0.29	0.90	0.19	0.50	0.84	0.71	0.81	0.54	-0.08	-0.40	0.51	0.51	1.00	-	-	-
POM	-0.30	-0.38	0.08	0.01	0.17	-0.17	-0.08	-0.28	0.24	0.07	0.00	-0.03	-0.04	-0.07	-0.06	-0.06	-0.06	-0.16	-0.08	-0.02	-0.10	-0.14	-0.13	0.20	0.21	0.37	0.19	0.04	0.37	-0.32	0.35	-0.20	0.79	-0.11	0.10	0.67	0.63	0.61	0.60	0.15	-0.30	0.16	0.30	0.81	1.00	-	-
C	-0.27	-0.25	0.18	0.06	0.04	-0.04	0.09	-0.32	0.14	-0.18	0.02	-0.01	-0.15	-0.15	-0.17	-0.02	-0.10	-0.17	0.09	-0.13	-0.20	-0.20	0.08	0.17	0.12	0.42	0.20	0.16	0.40	-0.27	0.40	-0.31	0.86	0.25	0.52	0.87	0.73	0.84	0.57	-0.06	-0.38	0.52	0.51	0.98	0.82	1.00	-
C/N	-0.05	-0.13	0.20	0.22	-0.03	0.45	0.25	-0.30	-0.02	-0.03	0.20	0.11	-0.22	-0.02	-0.09	0.11	0.06	-0.10	0.00	-0.05	-0.24	-0.29	0.01	-0.18	-0.12	-0.09	0.04	-0.04	-0.33	0.39	-0.26	0.01	-0.41	0.21	-0.01	-0.09	-0.05	-0.09	0.00	0.14	0.21	-0.03	-0.07	-0.33	-0.15	-0.12	1.00

Abbreviations: aspect (Asp), slope (Slp), elevation (Elev), canopy openness (Can), basal area (BA), woody richness (Wric), herbaceous richness (Hric), spring/summer herb (Sp/Su), alien/native (Al/Nt), litter mass (Lit), litter richness (Lric), litter abundance (Labu), litter evenness (Leve), litter Shannon index (Lsha), litter Simpson index (Lsim), litter Acarina (Laca), litter Collembola (Lcol), soil richness (Sric), soil abundance (Sabu), soil evenness (Seve), soil Shannon index (Ssha), soil Simpson index (Ssim), soil Acarina (Saca), soil Collembola (Scol), earthworm numbers (Wnum), earthworm biomass (Wbio), potential N mineralization (Nmin), microbial biomass N (MBN), gravimetric soil moisture (GSM), electrial conductivity (EC), calcium (Ca), magnessium (Mg), potassium (K), sodium (Na), ammonium (NH4), nitrate (NO3), dissolved organic N (DON), total soil N (N), particulate organic matter (POM), total organic C (C), soil C/N (C/N).

4. Discussion

4.1. Impacts of 23 years of low-intensity prescribed fire on vegetation

Our data indicate that long-term, low-intensity fires increase canopy openness by about 3%, which is less than the 7% increase reported after 17 years of prescribed fire by Bowles et al. (2007). Closed oak canopies have canopy openness values of <6% (Hutchinson et al. 2005) and openness in burned plots was on average 10.1%. Basal area decreased and woody richness increased with fire, but neither response was significant. Herb richness significantly increased 70% with fire. Ground layer vegetation comprises most of the plant species in oak forests (Roberts 2004; Whigham 2004), and our results confirm findings of increased ground layer diversity with fire (Wilhelm and Masters 1994; Franklin et al. 2003), adding support for prescription fire as a conservation tool for maintaining herbaceous richness. Our data support a shift in ground layer vegetation toward more shade tolerant summer herbs with fire (Bowles et al. 2007). More open canopies during the summer full-leaf period with fire likely lead to greater light assimilation by summer herbs (Sparling 1967). Prescribed fires have been proposed to control alien plants, such as, common buckthorn (*Rhammus carthartica* L.) (Schwartz and Heim 1996). Bowles et al. (2007) suggested that alien shrubs in oak forests can be reduced or eliminated by repeated annual burning. Mixed effects have been reported for the impact of fire on another important exotic, garlic mustard (*Alliaria petiolata* M. Bieb, Cavara and Grande) (Anderson et al. 1996). We did not observe a change in the alien/native ratio with fire. Weeding, mowing, and spot herbicide control of alien plants in these oak forests is high (personal communication K. Driesilker, The Morton Arboretum Manager of Natural Areas), perhaps masking any fire-related effects. We did find greater percent relative differences for periodic fire for canopy openness and the spring/summer herb ratio. However, we suspect this is due to inherent canopy differences between the two sites. Historic records, show that during settlement times (prior to 1922), the periodically-burned area had more cattle grazing likely leading to more open canopies compared the annually-burned area (personal communication K. Driesilker, The Morton Arboretum Manager of Natural Areas).

Light is a primary limiting resource for understory trees and herbs (Collins et al. 1985), but Bowles et al. (2007) found percent canopy openness to explain only about a third of the variation in summer herb cover and richness in these oak forests. Our pairwise correlations and stepwise regression models identify site, forest floor, and soil factors as important in explaining variance in woody richness, herb richness and the ratio of spring/summer herbs. Site, litter, and soil factors were included in each of the three aboveground stepwise models, explaining 64, 63, and 63% of the variance in woody richness, herb richness, and spring/summer herb, respectively. A soil nitrogen availability index (nitrate, C/N, or potential N mineralization) was significant in each of the three models. An index of soil or litter invertebrate diversity (litter invertebrate richness or Collembola, and soil invertebrate Simpson index) was also significant in each of these models. Aspect was included in two of the models, positively correlated with woody and herbaceous richness, and negatively correlated with alien to native ratio. In the northern hemisphere, higher aspect values (e.g., 180 to 270°) indicate greater sun exposure and warmer sites. These models and other research indicate that resource availability, both soil nutrients (e.g., Hutchinson et al. 1999) and light appear to be important factors in explaining aboveground structure in these oak forests.

4.2. Impacts of 23 years of low-intensity prescribed fire on litter and invertebrate diversity

One-year following fire, any effects of the 23 years of low-intensity prescribed fire on the litter mass or invertebrate diversity appear to be non-existent (Table 1). Boelter (2010) reported seasonal fluctuations in the Acarina (mites) and Collembola (springtails) taxa groups, but also minimal fire impacts. In these same oak forests, after 12 years of annual spring season prescribed fire, Brand (2002) found litter mass and Collembola diversity to be significantly greater in unburned soils, two and four months removed from most recent fire. Brand (2002) did find that litter mass was greater in burned areas compared to non-burned areas in one sampling year, and explained this inconsistency as a consequence of an incomplete burn. He concluded that fires in these forests rarely consume 100% of the targeted biota and litter (Brand 2002). Our monitoring showed the forest floor mass was reduced by 30% and depth by 80%. The effects of fire on litter invertebrate populations are regulated by burn intensity, fuel loading, microtopography, and moisture content (Bellido 1987). Fluctuations in these factors could be important in explaining our null responses of litter and soil invertebrates to fire. Invertebrate populations are often restricted to microhabitats with high humidity, so it is possible invertebrates could have survived these fires by concentrating populations in moist depressions. The one-year time period between our first sampling and the last prescribed fire on these plots may have been sufficient time for invertebrate populations to expand from these refuge sites.

The quick recovery (1-yr) of the litter mass to un-burned levels suggests the forest floor in these oak forests to be relatively resilient to low-intensity prescribed fire disturbances. The resiliency of the forest floor to annual prescribed fire is an important trait considering it is a key nutrient storage component of these forests (Currie 1999). Litter invertebrates have important ecosystem roles in decomposition and nutrient cycling (Bardgett and Chan 1999). Specifically, they increase the surface area for decay by physically breaking down the litter layer, thereby increasing the release of nutrients into the soil. Invertebrate recovery from fire should be a consideration when evaluating the effects of prescribed fire on ecosystem functioning. Brand (2002) proposed that to maintain richness of forest invertebrates where prescribed burning is used, annual burning should be changed to every two or three years. The results of this study are consistent with the view that fire-return intervals greater than one-year may be preferred for the preservation of invertebrate diversity (Brand 2002).

Not unexpected, all earthworms tallied in this research were the exotic European night-crawler (*Lumbricus terrestris*). Following the last glaciation, hardwood forests in the Great Lakes region developed without native earthworms (James 1995). Invasions of *Lumbricus terrestris* have accelerated during the last few decades with human activity, specifically the widespread use of these earthworms as bait for recreational fishing (Gates 1982; Hale 2008). Our earthworm biomass values (0.027 to 0.032 g m^{-2} to 1 m depth) are low compared to 10 g m^{-2} reported for *Lumbricus terrestris* in invaded forests of northern Minnesota (Hale et al. 2006). A study in a Kansas tall-grass prairie found earthworm abundance increased with repeated burning, and suggested that native earthworms in frequently burned grasslands are adapted to warmer soil conditions (James 1982). More commonly, earthworms are negatively impacted by fire (e.g., Collett et al. 1993; Callaham et al. 2003). We did not observe any impacts on earthworm populations in these oak forests with 23 years of low-intensity prescribed fire. Perhaps the lower fire intensities in these oak forests compared to higher-intensity grassland fires help to explain the null effect of fire on earthworms in this study. Fire temperatures were 184 to 186°C, and soil surface temperatures measured immediately after fire and were 15 to 20°C. Optimum temperatures for *Lumbricus terrestris* are between 10 to 20°C (Lee 1985), and temperatures of 28°C for 48 h have been found to be lethal for earthworms (Reinecke 1974). *Lumbricus terrestris* are deep-soil dwelling and appear adequately protected from these low-intensity fires.

4.3. Impacts of 23 years of low-intensity prescribed fire on soil properties

Our results of increased pH, electrical conductivity, Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, DON (spring only), NO_3^{-}, and potential N mineralization (spring only) confirm findings of others showing increased soil nutrient availability with fire (e.g., Wells et al. 1979; Wright and Bailey 1982; Kennard and Gholz 2001). Substrate, microclimate, and pH are primary controls on microbial activity and nutrient availability (Swift et al. 1979). Prescribed fires typically increase nutrient availability due to increases in nutrients added to the soil as ash, heating of soil organic matter, and increased rates of nutrient mineralization (Wright and Bailey 1982; Pritchett and Fisher 1987). Increased soil temperature from vegetation and forest floor removal and blackening of soil surface, and increased soil moisture contents from decreased evapotranspiration with vegetation removal as a result of fire, may also accelerate decomposition and nutrient mineralization (Swift et al. 1993). Fire tends to increase soil pH from production of K- and Na-oxides, hydroxides, and carbonates (Ulery et al. 1993). These low-intensity fires reduced forest floor depth by 80% and mass by 30%. Litter on the forest floor was not completely charred, but rather shredded to smaller particles sizes, thus facilitating faster decomposition and the observed increase in particulate organic matter with fire. Particulate organic matter is a direct substrate for microbial activity and is correlated with microbial biomass and activity (Scharenbroch and Lloyd 2006; Scharenbroch et al. 2010). Increased POM on our burned plots suggests fire had an effect of accelerating decomposition, labile organic matter inputs to the soil, and nutrient mineralization.

Much research on nutrient availability with fire has focused on soil N pools. Other studies have found increases in available soil NO_3^- and NH_4^+ with fire (Christensen 1973; Dunn and DeBano 1977; Covington and Sackett 1986; Kovacic et al. 1986; Knoepp and Swank 1993; Kaye and Hart 1998). Contrary to these studies and our findings, Vance and Henderson (1984) demonstrated soils under burned oak-hickory forest soils were lower in inorganic N and N mineralization. High C/N ratios and increased aromatic N forms favoring N immobilization following high-intensity burns explain decreases in N mineralization in response to fire (Vance and Henderson 1984). We observed no significant change in the soil C/N ratio with these fires, and our fire intensities were lower than those observed by Vance and Hendersen (1984). Knoepp and Swank (1993) proposed increased inorganic N after fire results from: 1) volatilization of organic N from the soil surface, 2) condensation of N in cooler, deeper soil layers, and 3) increased N mineralization from altered soil temperature and moisture, pH, and microbial activities. Temporal patterns of soil NH_4^+ and NO_3^- we observed are similar to those seen by Covington et al. (1991) and DeBano et al. (1998). One year following fire, soil NH_4^+ on fire plots was equal to non-burned soils. Elevated soil NH_4^+ with fire generally persists for several months following fire (Wilbur and Christensen 1983) then declines to pre-fire levels (Covington et al. 1991; Monleon et al. 1997). Increases in soil NO_3^- tend to be more persistent from longer-term stimulation of nitrification with fire (Christensen 1973; Raison 1979; Kaye and Hart 1998; Kaye et al. 1999). The increases in microbial activity and soil inorganic N with fire were greater in spring compared to fall. Factors impacting microbial activity and nutrient mineralization, such as soil moisture, pH, and dissolved organic N (i.e., microbial substrate) were also greater in the spring with fire. In addition, soil inorganic N may be greater in the spring with fire because these plots had lower spring/summer herbaceous plant richness. This explanation makes the assumption that greater herbaceous richness in the spring on non-burned plots equates to more N uptake by plants and less soil available N.

Low-intensity fires often do not have major effects on soil microbial biomass (Neary et al. 1999). However, soil heating can be lethal to microbes at temperatures as low as 50 to 210°C (Klopatek et al. 1990). We found no significant change in microbial biomass with fire in these oak forests. As previously mentioned, soil surface temperatures measured immediately after fire and were 15 to 20°C and the forest floor remained partially intact. In these same forests, Jacobs (2002) found that *Armillaria* root rot was able to survive and be cultured from partially charred logs. It appears refugee sites in coarse debris, litter and soils provide adequate protection for the microbial populations from these low-intensity fires. Likewise, soil invertebrate diversity indices were not impacted by fire. We did observe that soil rather than litter invertebrate diversity was more impacted by annual compared to periodic fire. We suspect this observation is a consequence of soil invertebrates tending to be less mobile and thus more vulnerable to shorter fire return intervals (DeBano et al. 1998).

Nutrient losses with fire occur through ash convection, oxidation, volatilization, leaching, and erosion (Raison et al. 1985). Losses of nutrients in ash transport tend to be minimal (<4% of mass of burned fuel) in low-intensity fires (Raison et al. 1985). These nutrient losses from litter and soil are a function of fire severity (Neary et al. 1999), and direct loss of nutrients to the atmosphere is temperature dependent. Volatilization of N, K, P, Na, Mg, and Ca occurs at 200, 760, 774, 880, 1107, and 1240°C, respectively (Weast 1988). Fire temperatures in these forests were relatively low, so we expect minimal losses of nutrients from the site via volatilization. The soils are deep and moderately to poorly drained Alfisols and Mollisols (Kelsey 2000) protected by mostly closed tree canopies (18 to 24 m^2 ha^{-1}), so we expect minimal loss of nutrients via leaching and erosion with fire. Increasing decomposition and nutrient mineralization after fire were proposed as important nutrient conservation mechanisms, promoting microbial immobilization and preventing nutrient loss (Woodmansee and Wallach 1981). Perhaps the un-impacted microbial biomass also plays a role via microbial immobilization in decreasing any potential nutrient losses with fire in these forests. One year after prescribed fire we found no significant decreases in key ecosystem nutrient stocks of litter and soil organic matter. In fact, particulate organic matter, total organic C and total soil N were not reduced, but greater with fire compared to the un-burned controls. Increases in soil organic stocks with fire could be a result of: 1) accelerated litter decomposition, 2) increased plant restitution in either leaf-fall or fine-root turnover, or 3) decreased decomposition of the soil organic matter. Regardless of the mechanism, we conclude that soil nutrient loss from these low-intensity prescribed fires in these oak forests is minimal.

Soil hydrophobic properties and reduced water infiltration have been reported with higher-intensity fires (Wells et al. 1979). During our field sampling we did not observe any changes in soil aggregation to suggest a loss of structure. Our soil moisture contents were not impacted by prescribed fire, so we do not believe soil hydrophobicity is created by these low-intensity fires. We did observe a decrease in soil clay and an increase in the silt fraction. Others have reported fires to aggregate clay particles into larger-sized particles (Dyrness and Youngberg 1957; Ulery and Graham 1993). One potential impact of this change in soil texture is that soil may be more erodible (Chandler et al. 1983).

4.4. Management implications

Our ANOVA results show soil C and N pools increase with low-intensity prescribed fire. Furthermore, total C and N explain most variance in the first principal component separating these burned and unburned plots. It is apparent that fire imparts significant change on soil C and N. According to a model by DeBano et al. (1998), the greatest impacts of C and N occur in low site productivity forests and with large fire-induced changes in nutrient capital. Relatively high soil fertility (Kelsey 2000) and floristic quality (Bowles et al. 2007) suggests these oak forests are on productive sites. The case for increasing soil nutrient availability with long-term low-intensity prescription fire is strengthened considering that our sites were rather fertile and one year removed from fire. Our results suggest that low-intensity prescribed fire may benefit primary productivity of oak woodlands by increasing nutrient availability and light availability. This benefit may be more acute in low-fertility sites where nutrient limitation outweighs light availability as a most-limiting resource.

Globally, soils contain twice as much C ($1580*10^{15}$ g) as the atmosphere ($750*10^{15}$ g) or terrestrial vegetation ($610*10^{15}$ g) (Schimel 1995). Consequently, soil C storage and sequestration has a direct impact on atmospheric CO_2 levels, which are directly linked to climate change (IPCC 2007). Prescribed fire has the potential to oxidize soil and litter C, so concern may exist for forest managers wanting to maximize the C sequestration of their forests while using prescribed burning as a management tool. We found total and particulate organic C to be greater in our burned plots, suggesting low-intensity prescribed fire increases soil C storage in these forests. Others have found fires to increase soil C storage through increased presence of recalcitrant SOM (e.g., charcoal, lipids, waxes), thus slowing SOM decomposition (Bird et al. 1999; Guinto et al. 1999; Preston and Schmidt 2006).

Two important considerations pertaining to stimulated nutrient availability with fire are potential nutrient losses and the effects on exotic species. As soil nutrient availability increases, its potential loss from the system also increases (Schlesinger 1997). Nutrient losses in the form of leaching, runoff, erosion, and volatilization tend to increase with the degree of disturbance (Likens and Bormann 1995). Further, nutrient retention tends to decrease with greater nutrient inputs, such as atmospheric nitrogen deposition (Aber et al. 1989). Consequently, an increase in soil nutrient availability via prescribed fire may be viewed as an environmental threat in a highly-disturbed forest with high nutrient inputs and a low-nutrient retention capacity. Secondly, an exotic understory shrub, European buckthorn (*Rhamnus cathartica* L.), is a prevalent invader in these forests. One mechanism for the increased buckthorn is via increased soil nitrogen availability, stimulated by increased nitrogen mineralization and leaf litter decomposition associated with the invasion of *Lumbricus terrestris* earthworms (Heneghan et al. 2007). We suspect some oak forests in the Chicagoland region may be susceptible to nutrient loss and increases in exotic species with prescribed fire given the relatively high degree of anthropogenic disturbance and forest fragmentation (Pearson 2006), high atmospheric nitrogen inputs from urban activities (Egerton-Warburton and Allen 2000), and strong presence of exotic species in these woodlands (Heneghan et al. 2004). We recommend careful consideration of prescription fire in those oak forests that are susceptible to nutrient loss and exotic invasions.

Both the annual and periodic (once every three to four years) prescribed fire-return intervals we studied are lower than the historic fire return interval for these forests. Guyette and

Day (1995) estimated fire return intervals based on fire scarred stumps for oak forests in the Great Lakes region to be 13 years, with a range of 5 to 72 years. Differences in fire intensity are linked to the fire return interval and increased fuel loading (Neary et al. 1999). Cleland et al. (2004) propose high-intensity fires to occur in the Great Lakes region with fire return intervals exceeding 9 to 69 years and low-intensity fires occurring at one to 37 year fire return intervals. We observed very few differences comparing periodic and annual prescribed fires (Figure 2), thus surmise the ecological impacts of annual and periodic are quite similar in these oak forests. Periodic fire may be a preferred method for managing these oak forests with the defined goals of decreasing shade and fire tolerant tree species and increasing herbaceous plant diversity. Canopy openness, spring/summer herb ratio, and soil invertebrate diversity (richness) responses were more favorable in periodic compared to annual burned plots. Jacobs et al. (2004) found increased *Armillaria* root rot and canker incidence in these annually-burned oak forests. Time and labor savings in burning once every three or four years compared to annually may also be a benefit for management. An important consideration that requires more research is whether fuel loading increases with periodic burning to the point that fire intensity would prohibit prescription fires. Due to proximity to human habitation, high-intensity prescribed fires are not practical throughout in many Midwestern forests. We did not observe differences in fire intensity between a monitored annual and periodic fire, but that could be a consequence of environmental conditions and limited sample size.

5. Conclusions

This research demonstrates that the ecological impacts of periodic (every three of four years for 23 years) low-intensity prescribed fires are mostly similar to those of 23 years of annual fires in a Midwestern, USA oak forest. The significant changes we observed from 23 years of low-intensity prescribed fire in these oak forests were: increased canopy openness, increased herb richness, decreased spring/summer herbaceous plants, and increased soil silt, pH, electrical conductivity, Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, NO_3^{-}, total N, organic C, and particulate organic matter, and lower clay. Statistical models show that changes in aboveground structural characteristics are related to edaphic, vegetation, and site factors. We conclude that long-term, low-intensity prescribed fire increases both light and soil nutrient resource availability in these oak forests. Continued monitoring of these forests is imperative because they represent longer-term, low-intensity fire plots in the Great Lakes region. Additional sampling should be performed across a wider range of forests to relate ecological impacts associated with differences in fire-intensity, fuel-loading, and fire return intervals. In the context of the pre-defined management goals of decreasing shade and fire tolerant species and maximizing biological diversity, it appears a periodic fire return interval may be preferred to annual fires in these forests, but more research in other oak forests is required to confirm this hypothesis.

6. Acknowledgements

This research was supported by the Illinois Department of Natural Resources, Illinois Wildlife Preservation Fund, sponsored by Maggie Cole. We thank The Morton Arboretum and Chicago State University for financial and institutional support. Special thanks for assistance with data collection and analysis are given to Ray Brand, Michelle Catania, Jenny McBride, Doug Johnston, Joyce Tanzosh, and volunteers in The Morton Arboretum Soil Science laboratory.

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APPENDIX 2. DRAFT OF BRENDA BOELTER THESIS, DEPARTMENT OF BIOLOGICAL SCIENCE, CHICAGO STATE UNIVERSITY, ENTITLED: IMPACTS OF PRESCRIBED BURNING ON SOIL AND LITTER INVERTEBRATE DIVERSITY IN A NORTHEASTERN IL OAK WOODLAND. IN PREPARATION WITH DEFENSE SCHEDULED FOR FALL OF 2010.

CHICAGO STATE UNIVERSITY

IMPACTS OF PRESCRIBED BURNING ON SOIL AND LITTER INVERTEBRATE DIVERSITY IN A NORTHEASTERN IL OAK WOODLAND

A Thesis Presented to the Faculty of the

Department of Biological Science

in Partial Fulfillment of the Requirements of the Degree of

Master of Science in Biological Sciences

By

Brenda Boelter

Abstract

The effects of low-intensity, prescribed burning on soil and litter-dwelling invertebrates were studied in an oak-dominated woodland in northeastern Illinois. Soil and litter samples were collected from 40 plots during Spring (2009) and Fall (2008 and 2009) that were randomly distributed among three treatment areas (annually-burned for 20 years, periodically-burned, or never burned (control). and blocked for three soil types. Invertebrates were extracted using Burlese-Tullgren funnels and specimens were identified to Order, and stored in 70% ethanol. Thirteen and seventeen taxa were found within the soil and litter samples, respectively, with Orders Acari and Collembola predominately found in both. Taxa count data were used to calculate invertebrate richness, abundance, and alpha diversity. Results showed no effect of soil type, but soil samples had significantly lower invertebrate richness, abundance, and diversity (All $P < 0.001$) in the spring compared with fall sampling times, across all burn treatments. Litter invertebrate richness was similarly lowest in the spring ($P < 0.005$), though litter invertebrate diversity was unaffected by season. Although the burn treatments did not lead to significantly different measures of invertebrate populations, trends were observed in which certain taxa showed a 50% higher abundance in annually or periodically burned plots compared with controls, while other taxa where found to have double abundance in control plots. Litter invertebrates from control plots showed the lowest richness and abundance values compared with annually-burned and periodically-burned. The results suggest that both prescribed burning may enhance soil and litter invertebrate biodiversity, however, pronounced differences between spring and fall samples indicate sampling over multiple seasons is needed.

Introduction

Low-intensity prescribed burning (123°C to 230°C) is an important ecological tool used to regenerate and improve vegetative diversity of woodland ecosystems (Bowels & Jacobs, 2007). In Midwestern oak woodlands, fire is crucial in maintaining native oak (*Quercus spp.*) canopy dominance, as well as the overall diversity of the ecosystem (Abrams, 1992). Fires regenerate native, shade-intolerant trees, such as oaks, by opening tree canopies, exposing mineral soil and releasing nutrients (Kennard & Gholz, 2001). It also removes litter, making the soil surface more accessible for seeds of native plants to reach the ground and grow (Abrams, 1992).

European settlement of Midwestern lands led to fire suppression of these forests, increasing the survival of invading shade-tolerant mesophytes, like sugar maples (*Acer sacchurm).* When fire is suppressed, native, shade-intolerant under-story species are overtaken by dense packing of non-native, shade-tolerant trees, resulting in a decrease of species richness (Allen et al., 2002). As diversity of native plant species decrease, there is more room for shade-tolerant non-native species to invade (Baron, 2002). As a result, canopy densities increase while native oak trees and vegetation decline, leaving room for harmful invasive, like buckthorn (*Rhamnus cathartic* L.) and garlic mustard (*Alliaria petiolata*) (Abrams, 1992).

Importance of soil invertebrates

Less is known on how these fires affect the belowground ecosystem, especially soil invertebrates. Soil invertebrates are essential components of the soil and their diversity is vital in maintaining invaluable ecological services, including decomposition, nutrient cycling, soil engineering, and food web dynamics. For this reason, it is important to understand how burning may affect these organisms and the roles they play in the woodland ecosystem (Coleman et al., 2004; Lavelle et al., 2006; Moldenke et al., 2000).

These ecosystem services are the result of various interactions between soil fauna, soil flora, and abiotic components of soil. Because soil invertebrates are a key part of ecosystem functions, their biodiversity provides a good indicator of soil function and quality (Arroyo et al., 2006; Knoepp, et al., 2000; Lavelle et al., 2006). For example, Callaham et al., (2003) found that a decrease in soil invertebrate density and biomass in tallgrass prairies directly correlates with a loss in nitrogen, while other studies show that a loss of soil invertebrates leads to a decrease in the decomposition rates of forest litter (Knoepp et al., 2000).

Soil invertebrates contribute to 65-78% of leaf litter decomposition of oak forests (Coleman et al., 2004). Decomposition of litter and soil organic matter is an important step in various nutrient cycles, and is facilitated by interactions between soil invertebrates and soil microbes (Coleman et al., 2004; Lavelle et al., 2006; Moldenke et al., 2000). Soil invertebrates directly breakdown organic material, such as leaf litter, releasing nutrients into soil that can then be taken up by plants or microbes (Moldenke et al., 2000). Feeding on organic matter, as well as fungal hyphae and soil bacteria, is the mechanism by which soil invertebrates help to increase rates of nutrient release and cycling (Knoepp et al., 2000).

Soil fauna have been shown to enhance nutrient cycling by increasing mineralization by 20-50% (Coleman et al., 2004). Carbon becomes available through invertebrate decomposition of plant cellulose and other organic material and is then released through microbial respiration. Decomposition of litter enhances nitrogen mineralization and immobilization by microbes, increasing the presence of nitrogen in the litter. Sulfur, phosphorus, sodium, potassium, calcium, and magnesium levels of litter and soil are also highly affected by decomposition caused by soil invertebrates and microbes (Coleman et. al, 2004).

Soil invertebrates play an important part in the food web of the woodland ecosystem. Many invertebrates, such as beetles and mites, are detritivores that feed on dead organic material and release nutrients into the soil that can be taken up by microbes (Moldenke et al., 2000). Soil microbes are fed on by soil microfauna, which are, in turn, fed on by soil invertebrates. Many of these invertebrates are an important food source for several secondary and higher-order consumers such as predatory mites, centipedes, and pseudoscorpions (Coleman et al., 2004).

Another valuable ecosystem service provided by soil invertebrates is soil formation, in which soil organic matter, such as leaf litter, is converted into soil. Invertebrates, including earthworms, millipedes, and ants, create soil aggregates and porosity through burrowing, and this significantly improves soil structure, aeration, water movement and water holding capabilities (Lavelle et al., 2006; Neary et al., 2005). Invertebrates also transport nutrients vertically from deeper to shallower soils through the mixing of soil horizons (Knoepp et al., 2000)

Because soil invertebrates provide essential ecosystem services, their overall biodiversity is vital to maintaining a healthy, well-functioning ecosystem (York, 1996). Biodiversity is a measure of the number of species in a given habitat (species richness), with consideration to how many individuals of each species are present (species abundance) and how evenly these individuals are distributed (species evenness) (Stiling, 2002). A loss of species richness or abundance in a soil habitat may negatively alter ecosystem services, such as nutrient cycling, decomposition, and soil formation, resulting in decreased soil quality (York, 1996). Detrimental effects on vegetation and the ecosystem as a whole can be expected once soil quality is diminished. Determining how the practice of prescribed burning in Midwestern oak woodlands affects soil invertebrate diversity will help understand how fire impacts the ecosystem as a whole.

Fire and soil invertebrates

Although soil organisms are a critical part of the larger forest ecosystem, effects of prescribed burning on soil, including soil invertebrates are not well understood. Neary et al. (1999) performed a review and synthesis of fire effects on forest and grassland soils and found that prescribed burning can have harmful effects on physical and chemical properties of forest's soils, as well as nutrient cycles of the habitat. Deleterious effects result because fire consumes soil organic matter, releasing nutrients, such as nitrogen, that are then lost from the ecosystem through volatilization and mineralization. Burning may also lead to a change in the microclimate of the soil and forest floor, which can alter root growth and microbial activity (Boerner, 2000). Loss of litter and vegetation through fire can subsequently decrease soil structure and its ability to infiltrate and retain water, creating hydrophobic conditions of the soil. This can lead to a loss of nutrients through run-off, leaching, and erosion (Neary et al., 2005, 1999). When soils cannot take-in water or store nutrients easily, plant growth can be impaired and the ecosystem as a whole can be negatively affected (Kennard & Gholz, 2001).

Neary (2005) suggests that the effects of fire on soil and litter invertebrates are dependent on both fire severity and fire frequency. These two factors influence the amount of litter and organic matter consumed by the fire, which will affect invertebrate survival either directly (mortality of individuals living in litter) or indirectly (reduction of invertebrate food source). Similarly, Bezkorovainaya et al. (2006), found that density of soil invertebrates depends on the moisture and thickness of the organic (O) horizon (Coleman, 2004). Low-intensity fire tends to consume leaf litter (L horizon), fine stems, and twigs, but not humus (O horizon) or upper mineral soil layers (A horizon). Thus, prescribed burning at low intensity should have a greater impact on litter fauna than soil. However, heat transfer to upper-soil layers can occur which can kill fungi, bacteria, and invertebrates of the soil, as well (Boerner, 2000).

Siemann et al. (1997) tested the effects of burn frequency on litter arthropods of oak savanna woodlands and found that frequencies ranging from never burned to burned nearly every year over a 30-year period did not significantly alter litter arthropod abundance. However, fire frequency did significantly affect composition of taxonomic orders. Order Hemiptera (true bugs) was favored by fires at high frequencies of burning 9 out of every 10 years, while orders Diptera (flies) and Homoptera (cicadas, aphids, & leaf hoppers) decreased with more frequent burning.

Fire may cause more mobile species, such as spiders and flies, to emigrate elsewhere (Neary, 2005). Also, high temperature and low humidity from fires limit soil-forming invertebrate activity (Bezkorovainaya et al., 2006). Fire may also cause habitat modification of litter and soil, altering the microclimate, foraging sites, and rates of predation of the fauna present. These negative consequences imply a reduction of soil invertebrate density directly following a burn, though long-term effects are uncertain (Neary 2005).

Several studies, though only a few in oak woodlands have tested the effects that prescribed burning has on soil and litter invertebrate diversity parameters with varying results. Some studies found no effect of fire (Lussenhop, 1976; Vasconcelos et al., 2009), while others showed that soil and litter invertebrate diversity, richness, and abundance increased with fire (Ferrenberg et al., 2006; York, 1999). Most studies have documented a decrease of invertebrate diversity parameters immediately after burning (Dawes-Gromadzki, 2007; Ferrenberg et al., 2006; York, 1999), but found a return to pre-burn levels over time, usually one to five years (Antony, 1997; Bezkorovainaya et al., 2006; Siemann et al., 1997, Vasconcelos et al., 2009). The differing results of these articles may be due to varying habitats, fire-intensity, fire frequency, and types of invertebrates studied.

Many studies have found that fire leads to the immediate decline of soil and litter fauna with varying amounts of recovery time. Antony (1997) compared soil arthropods density in a Central Amazon forest plot in Brazil by collecting soil samples just prior to burning, and then 1-week through 5-years after burning. Some groups, such as immature beetles and flies, increased with fire, possibly due to an increased release of nutrients by the consumption of organic matter. For most taxa, however, a drastic decrease in diversity was immediately observed. For these groups, population densities reached that of the pre-burn soil after one year and group diversity returned to pre-burn numbers after five years.

In the Scotch pine forests of the Yenisey Region of Siberia, Bezkorovainaya et al. (2006) tested the effect of low, medium, and high fire intensities on soil invertebrate diversity. They found an immediate decrease of microarthropods in all but the lowest intensity plot. One year after burning all invertebrate abundance was still low, but was completely restored four to five years after fire. Overall, fire had negative impacts on soil biota, but the invertebrates of low-intensity plots showed higher recovery rates than those of high-intensity plots.

Siemann et al. (1997) sampled arthropods from an oak savanna and woodland in Minnesota to determine the long and short-term effects of prescribed burning on arthropod diversity. Samples were collected during a two-year period from plots that had been burned with moderate-intensity at varying frequencies throughout the past 30 years. Within a year after burning, overall arthropod richness and abundance decreased. After a year, however, these numbers were restored to those of the control plots.

Prescribed burning can have various effects on soil and litter invertebrates, even within the same habitat. York (1999) studied the effects of low-intensity, periodic burning on litter invertebrates of an Australian sclerophyll forest. Two years after fire, he found some taxa had increased compared to controls, while other taxa decreased. Four taxa were found in unburned areas that had been lost in areas where prescribed burning had taken place; however, overall diversity in burned areas was not significantly different from control. This study focused on aboveground arthropods, which are more mobile than soil arthropods and are thus more likely to escape the negative impacts of burning and increase their chances of a faster recovery. The frequency of prescribed burning may have a higher impact on less mobile soil invertebrates.

Ferrenberg et al. (2006) also found mixed results when studying litter arthropod populations of a Sierra Nevada mixed-conifer forest. One and a half to two years after a low to moderate-intensity burn, they found arthropod abundance decreased, while arthropod diversity increased. This may have been due to fire favoring more unique taxa while eliminating taxa with higher abundance thus, creating a more evenly distributed and diverse population. Dawes-

Gromadzki (2007) also found that soil invertebrate abundance decreased two weeks after low-intensity burning in an Australian savanna.

Lussenhop (1976) looked how biennially prescribed burning of a restored prairie in Wisconsin affects soil invertebrates and found no effect on invertebrate abundance or diversity one month to six months after fire. Similarly, Vasconcelos et al. (2009) found that litter arthropod composition was unaffected three to twenty-two months after prescribed burning in a woodland savanna of Central Brazil. However, this study did find that arthropod richness and abundance decreased immediately after fire, but returned to pre-burn numbers after the 22-month sampling period.

Fire and Acari and Collembola

Acari (mites) and Collembola (springtails) are, by far, the most abundant Orders of soil invertebrates of almost every type of soil on earth (Nardi, 2007). In temperate forests, soil mites may represent up to 80% of all soil fauna (Osler & Beattie, 2001). Oribatid mites (Suborder: Oribatida) with hard, usually brown or tan exoskeletons are the most dominant mite in these ecosystems, with 40-70 different species typical (Arroyo & Iturrondobeitia, 2006; Olser & Beattie, 2001). Mites influence decomposition rates of forests directly by feeding on decaying leaves and plant debris and indirectly by feeding on soil microbes. Mites of suborders Mesostigmata (gamasid) can also be found in the soil and are largely predatory (Olser & Beattie, 2001).

Camann et al. (2008) studied the effect of low-intensity prescribed burning on California Acari populations in a pine forest. They found that populations overall declined after fire, but some species, such as *Aphelacarus acarinus* and *Nortonella gildersleeveae* survived better than others. Species richness and diversity of oribatid mites were found to be lower one year after fire. Bezkorovainaya et al. (2006) found a similar result of lowered oribatid mite density after burning, but two to three years post-burn, oribatid populations were restored to pre-burn densities.

Springtails often rival the abundance of mites in soil and are similarly important litter decomposers, as well as fungi grazers (Coleman et al., 2004; Nardi, 2007). Few studies have documented for effects of fire on this group compared to mites.

Brand (2002) collected litter springtails from low-intensity, annually burned and unburned plots in spring, summer, and autumn from the East Woods of the Morton Arboretum in Lisle, Illinois. He identified 30 different springtail taxa and found that while fire caused increases in some species, such as *Entomobrya assuta* and *Sminthurinus elegans*, overall species richness was significantly lower in annually burned sites compared to unburned controls. He also found that springtail richness was highest in the spring, compared to summer or autumn.

The objective of this study is to discover what effects, if any, prescribed annual and periodic burning of an urban oak woodland has on the richness, abundance, and overall diversity of soil and litter-dwelling invertebrates. Based on previous literature, annual burning may be too frequent to maximize diversity of soil invertebrates, as it may not leave enough time for populations to recover. Instead, periodic burning may be a favorable alternative that benefits native vegetation without diminishing invertebrate diversity.

Specific Aims

I. My first aim is to quantify soil and litter invertebrate populations of a Northeastern Illinois urban oak woodland using the measurements of diversity, richness, abundance, density and evenness. Portions of the woodland have been annually burned, periodically burned (about once every three to four years), and never burned (control). I will sample the leaf litter, known as the organic layer (O horizon) found directly above mineral soil and the upper A soil horizon (0-10 cm) where most soil fauna are found (Nardi, 2007).

II. My second aim is to look in detail at Orders Acari (mites) and Collembola (springtail) by examining abundance and diversity of sub-order groupings of both taxa. I focus on Acari and Collembola because they are the most abundant taxa in oak woodland litter and soil (Nardi, 2007).

I hypothesize that both annual and periodic burning will decrease soil and litter invertebrate diversity and associated parameters of richness, abundance, and evenness compared to no burning (control). Orders Acari and Collembola are expected to drive the decrease due to their dominant presence in the soil and litter. Annual burning is expected to result in the lowest soil and litter invertebrate diversity because of the lack of recovery time between burns. Since fire has been shown to mostly affect soil invertebrate abundance, a decrease in soil invertebrate diversity will most likely be due to lowered invertebrate abundance rather than richness (Antony, 1997; Bezkorovainaya et al., 2006; Siemann et al., 1997).

Significance

The results of this study will present needed information on how prescribed burning in urban woodlands, which is commonly low-intensity, affects soil invertebrates. I anticipate that the results will further increase the understanding of how fire affects belowground aspects of woodland ecosystems. Ecologists and land managers can use the information to better determine how frequently prescribed burning should be applied, in order to sustain native oak woodlands, while maintaining healthy rates of decomposition, carbon and nitrogen cycling, and related soil formation processes.

Also, this study will give a broad picture of the soil and litter invertebrate taxa present in this woodland of the Morton Arboretum, which have never before been investigated at this scale. This information can serve as a base for the development of future studies on soil and litter invertebrates of this woodland, the results of which can be compared to this study to gauge potential changes over time. Finally, the invertebrate specimens collected for this study will be submitted to the Illinois Natural History Survey to be cataloged in their archives, making them accessible to help others conducting similar studies.

Methods and Materials

Site Description

The study was conducted in the 500-acre oak-hickory woodlands of the Morton Arboretum, located in DuPage County, in northeastern Illinois (41°48’N, 88°05’W). Average temperature of this area ranges from -4.06°C in the winter to 22.22°C in the summer with a mean annual precipitation of 93.01 cm (Calsyn, 1997). Soils of the woodland are mollisols and alfisols and the dominant soil types include Ashkum silt loam (Typic Endoaquolls), Beecher silt loam (Udollic Epiaqualf), and Ozaukee silt loam series (Oxyaquic Hapludalf) (Kelsey 2000).

Portions of these woods have been annually or periodically burned in order to emulate lightning fires that naturally occur in this type of woodland, helping to maintain the native biodiversity and decrease presence of invasive species. The prescribed burns are typically low-intensity fires occurring primarily in late fall, but sometimes in early spring, ranging from 123°C to 230°C (Bowels & Jacobs, 2007). The annually burned portions have been burned once a year (with a few exceptions in which 18-month interruptions of burning occurred due to poor weather conditions) since 1986. These areas were burned in Fall 2007, but were unable to be burned again during this study due to poor weather conditions, so sampling of these areas began approximately one year after the last burn. Periodically burned areas have also been burned since 1986, but at a frequency of approximately once every three to four years. These areas were not burned during the course of this study and the last burn occurred in the fall and spring of 2006. Thus, sampling of this area began approximately 2-2.5 years after the most recent burn.

Experimental Design

Forty plots of 5-m radius each were located using a Randomized Incomplete Block Design in annually burned, periodically burned, and unburned (control) areas of the woodlands. Plots were purposefully selected to exclude areas that were too close to roads or trails (approximately 10-m) or otherwise disturbed. The main factor (treatment) was the burn treatment with three levels (control- not burned, annually burned, or periodically burned). Soil type was treated as a blocking variable, but was represented incompletely across the main treatment levels: annually burned treatment consisted of Ashkum and Beecher silt loam series, periodically burned treatment contained Ozaukee silt loam series and control treatment consisted of all three soil types. The number of control plots is equal to the number of treatment plots for each soil type, in order to account for possible variability due to soil series: 6 Ashkum annual, 6 Ashkum control; 4 Beecher annual, 4 Beecher control; 10 Ozaukee periodic, 10 Ozaukee control.

Sample Collection

Sampling took place in October 2008, 2009 and May 2009 within a one-week time frame to minimize variation in soil moisture and temperature. Invertebrates were collected from both soil and litter. A composite of three litter samples was collected from each plot by hammering a 15-cm diameter cylinder into the ground, measuring the depth of litter, and collecting all the litter within the cylinder. These steps were performed first at a random azimuth then repeated at 120° increments from first collection point around the plot center. Litter was placed in a paper bag and stored at room temperature for up to one week. Composite soil samples of fifteen 2-cm diameter soil cores (0-10 cm deep) were collected at random azimuths and distances within the 5-m radius of each plot while encircling plot center. Soils were placed in plastic bags, labeled, and stored at 5°C until for up to three weeks.

Soil and Litter Invertebrate Extraction and Identification

Invertebrate extractions were performed on litter samples within one week and soil samples within three weeks of collection using modified Tullgren funnels. Litter invertebrates were extracted by placing the entire litter sample was placed on a screen, layered with cheesecloth inside of a modified Tullgren funnel under which a collection jar of 70% ethanol was placed. A 40-watt bulb at the top of the funnel created a light and temperature gradient that drove the invertebrates downward into the ethanol (Brand & Dunn, 1998). The air-dried litter was then weighed and volume of litter calculated. The modified Tullgren funnel procedure was also used to extract soil invertebrates using 100 grams of soil per composite sample from each plot. The collection jars were left underneath the funnels for 3 days, after which the samples were transferred to vials and stored at room temperature.

Each vial of extracted invertebrates was transferred to Petri dishes and specimens were counted and identified using Nikon SMZ-2T and Motic SMZ-168 dissecting microscopes with up to 6.3x magnification. Specimens were identified to the approximate taxonomic level of Order using the “Kwik-Key to Soil-Dwelling Invertebrates” (Meyer, 1993) and “How to Know the Insects” (Bland, 1978), as well personal communication with collembola specialist Dr. Ray Brand and entomologist Dr. Fredric Miller of the Morton Arboretum. Digital images of most extracted specimens were taken using either the Nikon Coolpix 950 or the Moticam 2000 digital cameras and archived using Adobe Bridge CS3.

Richness (number of taxa present), abundance (number of individual invertebrates present) and density (invertebrates per gram of litter/soil) were calculated once all soil and litter invertebrates were identified and counted. Richness *(S)* is used to ascertain the maximum possible diversity (H_{max}), which is then used to calculate Evenness *(J)* to establish the relationship between observed and maximum diversity. Maximum diversity denotes that each taxon is equally represented in all treatments and an evenness ratio indicates how evenly the taxa are distributed among all samples (Shannon and Weaver, 1949; Stiling, 2002). Diversity was calculated using the Shannon *(H')* and Simpson (*D)* indices, where p_i is the proportion of each taxon found in the overall sample. The Simpson Index for soil and litter diversity was less amenable to normalization than the Shannon Index, so the latter was used for further analysis. Richness is important, but accounting for the number of taxa alone may give an inaccurate representation of the diversity of a population, as it does not show how many individuals belong to each taxon. The Shannon Index, in contrast, more accurately assesses biodiversity as it accounts for richness as well as abundance. It can determine whether a group is rare or widespread, because it is based on proportion of taxa present.

$$H_{max} = \ln S$$

$$J = H' / H_{max}$$

$$H' = -\Sigma p_i * \ln p_i$$

$$D = \Sigma(p_i)^2$$

Earthworm Sampling

Earthworm abundance was determined from a one-time sample in July 2009 by digging three randomly selected 25x25x20-cm pits with a straight-edged shovel at each plot. Soil and litter from the three pits were collected and at stored 5°C. Samples were hand-sorted with-in 1 week of collection and abundance of adults and juveniles counted. Adult earthworms were stored in Petri dishes with wet paper towels at 5°C, weighed after 2-3 days and biomass calculated.

Statistical Analysis

Samples were analyzed by treatment and soil series to determine if soil and litter invertebrate diversity is significantly different across the three treatments, as well as the three soil types. All analyses were performed using JMP 8.0 SAS software. All litter data was normalized using square root and natural log transformations. ANOVA, Least Squares Fit Models, Tukey-Kramer HSD mean separation tests were used to evaluate burn treatment, soil type, and sampling time effects on litter invertebrate diversity, richness, abundance, density, and evenness. Soil data could not be successfully normalized, so non-parametric analyses were performed to assess diversity parameters of soil, including Kruskal-Wallis test and Chi-Square analysis. Statistical significance was determined at the 95% or greater confidence level.

Results

A total of 26,416 individual invertebrates and 18 invertebrate taxa were identified through the modified Tullgren funnel method. All 18 taxa were found in litter, but only 15 found in soil (Table 1). All taxa found in the soil were also observed in litter, with orders Isopoda, Orthoptera, and Gastropoda found only in litter. An order of magnitude more invertebrates were found in litter (25,401individuals) than soil (1,015 individuals). An average density of 2.41 invertebrates per gram of litter and 0.85 per gram of soil were recorded. Orders Acari (mites) and Collembola (springtails) were by far the most abundant groups with Acari representing 76% (19,291 individuals (litter); 778 individuals (soil)) and Collembola 17% (4,339 individuals (litter); 88 individuals (soil)) of all invertebrates collected. There was an average of 1.83 mites and 0.41 springtails per gram of litter and 0.65 mites and 0.07 springtails per gram of soil. Hymenoptera were the third most abundant taxa with 639 individuals, comprising 2% of all invertebrates collected. The remaining 15 taxa represented only 5% of total invertebrate abundance.

Fifteen of all eighteen taxa are represented at least once in each treatment and for all 3 sampling dates, including mites, springtails, and Hymenoptera. Orthoptera (grasshoppers) and Gastropoda (slugs) were both unique taxa, with only 1 Orthoptera individual (annually burned treatment) and 2 Gastropoda individuals identified (both control treatment). Order Dipluran was represented by only 7 individuals (in both periodically burned and control treatments).

ANOVA and non-parametric Kruskal-Wallis analyses showed that soil type had no significant impact on diversity parameters of litter or soil. Thus, soil type was removed as a blocking variable and data were combined across all soil types for the remainder of the data analyses.

No significant differences ($p \leq .05$) were found due to the burn treatments for invertebrate diversity, richness, abundance, density, or evenness (Figure 1; Appendix 1 & 2). However, some trends were observed in which specific taxa were found to be 50% more abundant in one treatment over another (Table 2). Hymenoptera, Thysanoptera (thrips), and Psocoptera (book lice) were 50% more abundant in annually burned plots compared to either periodically burned or control plots. Similarly, periodic burning appeared to favor Chilopoda (centipede), Diplopoda (millipede), and Hemiptera (true bugs). In contrast, Annelida (worms) and Protura were found to be 50% more abundant in control plots than either burn treatment.

Kruskal-Wallis and Chi-Square analyses of soil data identified a significant sampling date and season effect (Figure 2; Appendix 1). Sampling date impacted richness, abundance, and density ($p < .0001$), diversity ($p < .0012$), and evenness ($p < .0277$). Fall 2008 and Fall 2009 data were combined to observe differences between spring and fall regardless of year. Season of sampling significantly affected richness, abundance, and density ($p < .0001$), diversity ($p < .0003$), and evenness ($p < .0062$) as well, with parameters lower in spring compared to fall.

ANOVA of litter revealed significant differences in richness ($p < .0098$), diversity ($p < .0002$), and evenness ($p < .0001$) across sampling date (Appendix 2). Seasonal differences can explain these variations for richness and evenness, but not for diversity, which decreased as sampling time progressed. When fall data were combined, richness was significantly lower in spring than fall ($p < .0050$), while evenness ($p < .0005$) was significantly higher in spring. Diversity did not show significant differences between spring and fall (Figure 2).

Acari and Collembola abundance were not significantly affected by burn treatment. Sampling date and season had significant effects on Acari and Collembola abundance and Acari diversity ($p < .0001$) of soil. Collembola abundance was significantly higher in spring compared to fall ($p < .0001$), while Acari abundance was significantly lower in spring ($p < .0001$). Acari diversity of soil was also significantly lower in spring than fall ($p < .0001$). Collembola ($p < .0001$) and Acari ($p < .0458$) abundance of litter were significantly different across sampling date. Collembola abundance ($p < .0001$) of litter was significantly higher in spring compared with fall; however, seasonal difference had no significant effect on Acari abundance. Acari diversity of litter was significantly affected by burn treatment ($p < .0005$) with significantly more diversity in control treatments than annually burned treatments (Figure 3; Appendix 3).

Earthworm abundance totaled 751, with 528 juveniles and 223 adults (average mass of 0.313 grams). A total of 69.853 grams of adult biomass was calculated with a density of 4.66×10^{-5} g/cm^3. Earthworm data were normalized using natural log transformations. ANOVA of total adults, juveniles, earthworms, biomass, and density indicated there were no significant influences of burn treatment or soil type on abundance or density (Table 3).

Table 1. Total number and densities (individuals per gram) of litter and soil invertebrates found in three separate sampling times between October 2008 and 2009.

Parameter	Richness	Abundance	Avg Density
Litter	18	25401	2.41
Soil	15	1015	0.85
Total	18	26416	2.25

A total of 120 samples of soil and litter were collected during three sampling times: Fall 2008, 2009 and Spring 2009; 40 per sampling time

Table 2. Average abundance (number of individuals) of **l**itter and soil invertebrate taxa found by treatment

Taxa	Annual	Periodic	Control
Acari[1]	167.17	203.53	149.13
Oribatid	85.77	119.23	80.90
Gamasid	8.57	15.53	13.37
Other	72.83	68.77	54.87
Collembola[2]	30.2	38.53	39.35
Entomobryomorpha	3.3	10.9	6.2
Podomorpha	5	5.7	4.5
Symphypleona	0.3	1.1	0.35
Other	5.2	10	8.95
Hymenoptera	11.03	3.63	3.15
Coleoptera	1.8	1.83	1.32
Diptera	1.9	0.97	1.42
Thysanoptera	2.77	0.63	0.75
Isopoda	1.67	1.27	0.75
Araneae	1.43	1.4	0.78
Psuedoscorpian	0.53	0.97	0.93
Annelida	0.63	0.37	1
Diplopoda	0.37	1.33	0.3
Chilopoda	0.23	1	0.45
Psocoptera	0.37	0.07	0.07
Protura	0.03	0.1	0.2
Hemiptera	0.03	0.27	0.08
Diplura	-	0.07	0.08
Orthoptera	0.03	-	-
Gastropoda	-	-	0.03

Annual, Periodic (n=30), Control (n=60); [1]Most common sub-orders of soil Acari included. [2]Most common sub-orders of Collembola included (for Fall 2009 only; periodic, annual (n=10), control (n=20))

Table 3. Comparison of Earthworm abundance, biomass and density in three burn treatments.

	Means			Burn Treatment	
Parameters	Annual	Periodic	Control	F Ratio	Prob > F
# Juveniles	12.2	5.3	17.65	0.79	0.46 ns
# Adults	4.9	7.1	5.15	0.08	0.93 ns
Total # Earthworms	17.1	12.4	22.8	0.52	0.60 ns
Average Adult Biomass (g)	1.84	1.92	1.61	0.45	0.64 ns
Density (g/cm^3)	4.89×10^{-5}	5.13×10^{-5}	4.30×10^{-5}	0.12	0.89 ns

Annual, Periodic (n=10); Control (n=20); double controls to account for differences in soil types in burn treatments; ns indicates variances were not significantly different across burn treatments at p = .05 level

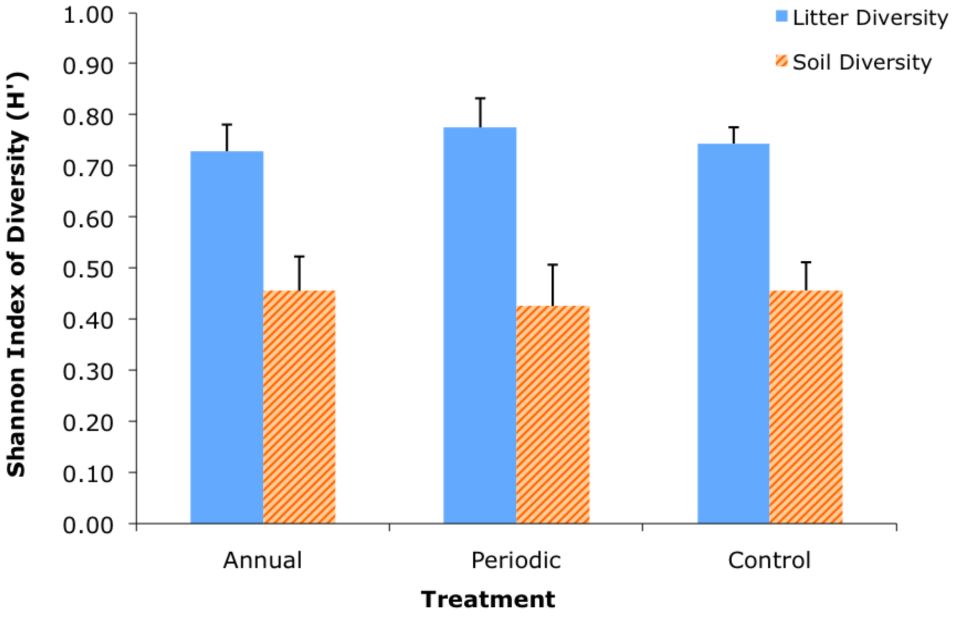

Figure 1. Soil and litter invertebrate diversity in three burn treatments

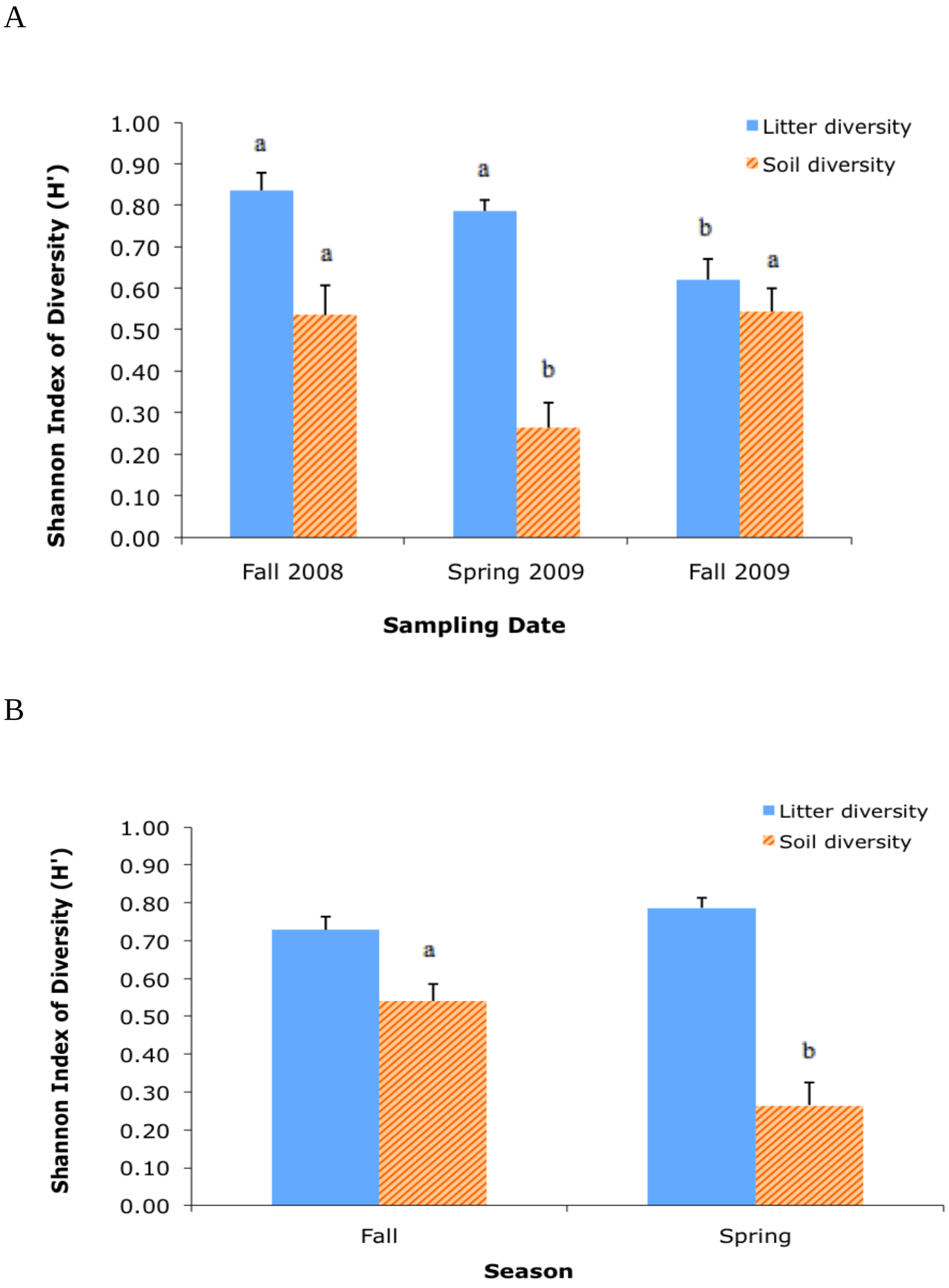

Figure 2. Litter and soil invertebrate diversity of different sampling dates (A) and seasons (B); lowercase letters indicates significant differences ($p < .05$) between sampling date and season for litter and soil invertebrate diversity)

Discussion

Effect of burn treatment on soil and litter invertebrates

Prescribed annual and periodic burning of an urban oak woodland did not alter significantly soil and litter invertebrate diversity or related parameters of richness, abundance, density, and evenness compared with unburned areas. The findings were somewhat surprising as several other studies found prescribed burning significantly lowers soil and litter invertebrate diversity and associated parameters (Antony, 1997; Bezkorovainaya et al., 2006; Dawes-Gromadzki, 2007; Ferrenberg et al., 2006; Siemann et al., 1997, Vasconcelos et al., 2009; York, 1999). However, some of these studies found mixed results. For instance, York (1999) found that some taxa decreased with fire, while others increased. Ferrenberg et al. (2006) observed that arthropod abundance decreased one and a half to two years after burning, but arthropod diversity increased. Still, some studies found differences due to burning only within a short time interval after burning, and after one year invertebrate diversity returned to pre-burn levels (Antony, 1997; Bezkorovainaya et al., 2006; Siemann et al., 1997, Vasconcelos et al., 2009). In my study, soil and litter samples were collected from annually burned plots between 1 and 2 years post-burn, and no additional burning took place during the course of the study. Similarly, the last periodic burn was done in Fall and Spring 2006, 2-3.5 years prior to sampling. Again, no additional burning was done in periodic treatment plots for the duration of the study. The relatively long interval between burning and sampling in annual and prescribed burn plots may explain much of the lack of difference I detected between burn and control plots. Recolonization of litter and soil fauna post-burn is often swift (Boerner, 2000; York, 1999) so one to three years may have been sufficient time for soil and litter invertebrate diversity, richness, abundance, density, and evenness to return to pre-burn levels.

Still, some authors, including Lussenhop (1976) found no effect of burning on soil invertebrate density in prairies one and six months after fire. The author suggested the lack of impact was due possibly to favorable moisture conditions. Thus, prescribed burning in my study may not have decreased or otherwise affected invertebrate populations at all on a gross taxonomic scale. I must reject my original hypothesis that annual and periodic prescribed burning would significantly lower soil and litter invertebrate diversity parameters.

Importance of taxonomic level of soil and litter invertebrate diversity

It is estimated that only 10% of soil arthropod species have been described (Coleman, 2004), most likely because it is often laborious and cost-inefficient to identify the multitude of soil and litter invertebrates to species, genera, or even family level (Osler & Beattie, 2001). The intent of this study was to examine the possible impact of fire on the soil fauna community as a whole. Due to the large number of organisms included, I focused on approximate taxonomic level of Order. Broadly speaking, taxa richness was found to be 18 orders in litter and 15 orders in soil.

Each taxa found provides valuable ecosystem services for the soil and are important parts of the soil food web. Diplurans, Psuedoscorpians, Chilopoda, Araneae, along with some Acari and Hymenoptera are predaceous taxa that feed on smaller arthropods, such as Collembola and Protura. Some Orthoptera, Thysanoptera, Hemiptera, Coleoptera, Diptera, and Gastropoda can also be predaceous, but mostly feed on various types of organic matter contributing to decomposition and nutrient cycling. Other important decomposers include Acari, Collembola, Isopoda, Psocoptera, Hymenoptera, Diplopoda and Annelida. The latter three taxa also contribute to soil formation and structure by burrowing through the soil, circulating organic and mineral material and debris (Coleman, 2004; Nardi, 2007).

Average diversity based on order in both soil and litter was less than one. A diversity value less than one is considerably low compared to other studies of soil and litter invertebrate using the Shannon index (Arroyo & Iturrondobeitia, 2006; Lussenhop, 1976). The low diversity index measured in this study is due to the overwhelming dominance of Acari and Collembola. They comprised over 76% and 17% of all invertebrates identified, respectively. This result is expected as mites often account for over 80% of all arthropods in soil, with often 100,000 to 400,000 mites in a square meter of forest soil, while springtails range from 10,000 to 100,000 per square meter of soil (Brand, 2001; Nardi, 2007; Osler & Beattie, 2001). Similar studies that obtained higher values of invertebrate diversity (using Shannon index) evaluated species diversity as opposed to diversity of taxonomic Order.

Assessing litter and soil invertebrate diversity on a more specific taxonomic level may yield different diversity results and provide a better explanation of how prescribed burning impacts soil and litter invertebrate diversity parameters. As an example, calculations of diversity of Acari sub-orders: Oribata and Mesostigmata, the two most common groups found in soil and litter (Osler & Beattie, 2001), showed litter mite diversity was significantly lower in annually burned plots compared to control.

Coleman (2004; 2005) has suggested an alternative method to categorize soil invertebrates by considering functional groups based on the ecosystem function they provide. Examples include decomposition, nutrient cycling, and soil formation. Further, examining soil fauna based on their functional grouping is beneficial toward understanding their contribution to the ecosystem and better gauges of the overall health of the ecosystem. If functional group diversity is low, it may be a more alarming signal than taxa biodiversity that burning is affecting ecosystem services, and in turn, putting the ecosystem at risk. Thus, functional group diversity is an important indicator of ecosystem health and would be beneficial in understanding the impact of prescribed burning on soil and litter invertebrates (Coleman, 2005). Future studies may consider accounting for soil and litter invertebrate groups on a more narrow taxonomic scale.

Relationship of litter and soil abiotic characteristics and invertebrates

Another important factor in understanding the effects of prescribed burning on soil and litter invertebrates is fire intensity. Low-intensity burning is typical in hardwood forests and intensity can be dependent on many factors, such as weather, litter depth, and slope of forest floor (Boerner, 2000). Changes in amount of litter can estimate the intensity of burning. I measured litter depth and weight for each sample collected. ANOVA showed surprisingly, that the burn treatment did not significantly reduce litter depth or weight. This corroborates my finding that soil and litter invertebrates were unaffected by the burn treatment since litter is the habitat and food source of the invertebrates I collected. Prior studies of the Morton Arboretum’s East Woods have found fires to be of low-intensity and spotty, which may lead to a low consumption of leaf litter and negligible impact on litter and soil invertebrate diversity.

Soil invertebrates are an integral part of the underground ecosystem, therefore it is important to understand how prescribe burning is affecting key soil characteristics. Soil cores collected for invertebrate extraction for this study were used in a concurrent study to determine effects of annual and periodic burning on various soil parameters of the woodland. The results of this study showed burn treatment had no significant effect on litter weight, soil moisture, pH, electric conductivity, or C: N ratio, which may also be explained by the low-intensity of the burns (Scharenbroch, 2010). However, particulate organic matter (POM) was found to be significantly higher in annually burned plots compared to control. Prescribed burning significantly altered very few soil parameters, which may help explain lack of burn treatment effect on soil invertebrate diversity. Fire had only a small effect on the overall soil environment, thus soil invertebrates were affected little, as well.

Benda (2006) collected soil from annually burned and unburned areas of the same woodland and found that annual burning significantly lowered C: N ratios and significantly increased bulk density and soil moisture. However, the soil samples were purposefully collected within a 50-cm radius of European buckthorns (*Rhamnus cathartica* L.) trunks to determine the effect of this invasive species on the soil, so these results may not be representative of all soil of the woodland.

Seasonal and sampling date effect

The timing of sample collection had a significant effect on all soil invertebrate diversity parameters and on diversity, richness, and evenness of litter invertebrates. This effect may be explained by variation in temperature and precipitation with season and time of sampling, which can have varying affects on the life stages of soil and litter invertebrate taxa. Differences in soil and litter diversity parameters can mostly be explained by a seasonal effect, as spring resulted in significantly lower diversity parameters compared to fall samples. A seasonal trend in soil and litter invertebrates has been noted in other studies (Arroyo & Iturrondobeitia, 2006; Lussenhop, 1976). Seasonal fluctuations are expected as temperature and precipitation vary with different seasons. These variations can influence the developmental stages of soil invertebrates, which differ by taxa and can determine their presence in the litter or soil. Litter and soil invertebrates differ greatly in development, function, and life history strategy; some are k-selected species, while others are r-selected. (Coleman, 2004; Stiling, 2002). Variation in climate may have affected the various taxa groups differently resulting in an alteration in diversity.

There are different categories of soil invertebrates defined by the stages of life spent in the soil: transient invertebrates only hibernate in the soil; temporary invertebrates spend larval and juvenile stages in soil and emerge aboveground as adults; periodic invertebrates reside belowground throughout all life stages, but migrate out of soil periodically as adults; and permanent soil invertebrates spend their entire lives in the soil (Coleman, 2004). These stages may be affected by variation in temperature and precipitation, leading to a significant difference in soil invertebrate diversity parameters based on season.

Seasonal effects can also explain sampling date effect of invertebrate litter richness and evenness, with litter invertebrate richness being significantly lower in spring and evenness significantly lower in fall. However, spring litter diversity was not significantly different from the two fall samples combined, but was significantly lowest in Fall 2009. Neither litter invertebrate richness nor abundance experienced this trend, so the drop in diversity cannot be explained by a reduction in taxa number or individual numbers alone. Instead, the decrease in litter invertebrate diversity may have been due to lower than average precipitation during Fall 2009, while Spring 2009 saw above average precipitation and Fall 2008 was one of the wettest seasons on record (Weather Underground, 2010).

Significance

Other studies conducted in the same woodland show that prescribed burning affects vegetation structure and composition, tree canopy density, and fungi rhizomorphs (Benda, 2006; Bowles & Jacobs, 2007; Jacobs et al., 2004). Jacobs et al. (2004) found annual prescribed burning increased native summer flowering plants, but reduced presence of native woody species due to increased tree mortality. Bowles & Jacobs (2007) found that annual burning significantly reduced the density of shrubs and small saplings, leading to an increase in canopy openness and abundance of spring herbs. Benda (2006) found that annual burning leads to a significant increase in invasive buckthorn infection rates and mortality. He suggested this might be due to fungal pathogens such as *Armillaria* infiltrating the trees through cracks or bark loss of trees brought on by fire, infesting the tree and feeding on dead branches.

These studies show the importance of prescribed burning on the vegetation of the East Woods of the Morton Arboretum. It is also important to understand how fire affects the rest of the ecosystem, including soil biota. The results of this study show that there has not been a measurable long-term impact of annual or periodic burning on the soil and litter invertebrate populations of the East Woods of the Morton Arboretum. This is an important implication for land managers and ecologists so that they are aware that annual and periodic low-intensity burning is not harming the diversity of important soil biota and they can continue to perform burns at these frequencies in order to benefit native vegetation.

Future studies involving fire effects of soil and litter invertebrates should collect samples within one year of the burn, as well as after one year as this is appears to be an important threshold of soil and litter invertebrate recovery after fire.

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APPENDIX 1. Detailed statistical analyses of soil invertebrates

Table 1. Kruskal-Wallis results and means showing the effect of prescribed burning on soil invertebrates

Parameter	Annual	Periodic	Control	Chi Square	Prob>ChiSq
Richness	2.10	2.10	2.10	0.01	1.00 ns
Abundance	7.23	9.83	8.38	0.13	0.51 ns
Density (per g)	0.07	0.10	0.08	1.34	0.51 ns
Diversity	0.46	0.43	0.46	0.25	0.88 ns
Evenness	0.50	0.40	0.57	1.03	0.60 ns

Control (n=60); Annual, Periodic (n=30); double controls to account for differences in soil types in burn treatments

Table 2. Kruskal-Wallis results and means showing effects of sampling date on soil invertebrates

Parameter	Fall 2008	Spring 2009	Fall 2009	Chi Square	Prob>ChiSq
Richness	2.40	1.43	2.48	22.35	.0001**
Abundance	9.65	3.90	11.83	36.16	.0001**
Density (per g)	0.10	0.04	0.12	36.16	.0001**
Diversity	0.54	0.27	0.54	13.38	.0012**
Evenness	0.54	0.44	0.54	7.17	.0277*

All means (n=40); * $p < .05$, ** $p < 0.01$

Table 3. Kruskal-Wallis results and means showing effects of season on soil invertebrates

Parameter	Fall	Spring	Chi Square	Prob>ChiSq
Richness	2.44	1.43	21.47	.0001**
Abundance	10.74	3.90	28.07	.0001**
Density (per g)	0.11	0.04	28.07	.0001**
Diversity	0.54	0.27	12.94	.0003**
Evenness	0.54	0.30	7.48	.0062**

Fall (n=80), Spring (n=40) ** $p < 0.01$

APPENDIX 2. Detailed statistical analysis of litter invertebrates

Table 1. ANOVA results and means of effects of prescribed burning on litter invertebrates

Parameter	Annual	Periodic	Control	F Ratio	Prob>F
Richness	7.57	7.83	6.95	1.07	0.35 ns
Abundance	214.10	247.83	192.38	0.50	0.61 ns
Density (per g)	2.51	2.67	2.35	0.01	0.99 ns
Diversity	0.73	0.78	0.74	0.22	0.80 ns
Evenness	0.39	0.40	0.40	0.16	0.85 ns

Annual, Periodic (n=30); Control (n=60); ns indicates variances were not significantly different across burn treatments at p = .05 level

Table 2. ANOVA results and means of effects of sampling date on litter invertebrates

Parameter	Fall 2008	Spring 2009	Fall 2009	F Ratio	Prob>F
Richness	8.10	6.48	7.40	4.82	0.0098**
Abundance	209.85	206.58	218.60	1.05	0.35 ns
Density (per g)	2.93	2.38	2.10	0.92	0.40 ns
Diversity	0.84	0.79	0.62	9.38	0.0002**
Evenness	0.42	0.46	0.32	13.25	.0001**

Fall 2008, 2009; Spring 2009 (n=40); ns indicates variances were not significantly different across burn treatments at p = .05 level; ** p < .001

Table 3. ANOVA results and means of effects of season on litter invertebrates

Parameter	Fall	Spring	F Ratio	Prob>F
Richness	7.75	6.48	8.17	0.0050**
Abundance	214.23	206.58	0.55	0.46 ns
Density (per g)	2.51	2.38	0.59	0.43 ns
Diversity	0.73	0.79	2.25	0.14 ns
Evenness	0.37	0.46	12.87	0.0005**

Fall (n=80), Spring (n=40); ns indicates variances were not significantly different across burn treatments at $p = .05$ level; ** $p < .001$

APPENDIX 3. Detailed statistical analysis of Acari and Collembola

Table 1. ANOVA results and means of effects of prescribed burning, sampling date, and season on Collembola abundance

Parameter	Annual	Periodic	Control	F Ratio/Chi Square	Prob>F/Chi Square
Litter	29.47	37.93	38.55	1.92	0.15
Soil	1.29	0.90	1.23	1.12	0.57
	Fall 2008	Spring 2009	Fall 2009	F Ratio/Chi Square	Prob>F/Chi Square
Litter	29.85	58.83	19.70	14.6	.0001**
Soil	0.74	1.68	1.50	19.36	.0001**
	Fall	Spring		F Ratio/Chi Square	Prob>F/Chi Square
Litter	24.78	58.83		25.71	.0001**
Soil	0.98	1.68		10.32	.0013**

Annual, Periodic (n=30); Control (n=60)

Table 2. ANOVA results and means of effects of prescribed burning, sampling date, and season on Acari abundance

Parameter	Annual	Periodic	Control	F Ratio/Chi Square	Prob>F/Chi Square
Litter	162.10	195.23	142.85	0.37	0.69
Soil	5.07	8.30	6.28	1.77	0.41
	Fall 2008	Spring 2009	Fall 2009	F Ratio	Prob>F
Litter	159.60	136.50	186.18	3.17	.046**
Soil	7.50	2.83	9.13	34.56	.0001**
	Fall	Spring		F Ratio	Prob>F
Litter	172.89	136.50		0.93	0.40
Soil	8.31	2.83		28.04	.0001**

Annual, Periodic (n=30); Control (n=60)

Table 3. ANOVA results and means of effects of prescribed burning, sampling date, and season on Acari diversity

Parameter	Annual	Periodic	Control	F Ratio	Prob>F
Litter	0.72	0.79	0.85	8.09	.0005**
Soil	0.23	0.29	0.26	0.75	0.69

	Fall 2008	Spring 2009	Fall 2009	F Ratio	Prob>F
Litter	0.83	0.76	0.82	2.02	0.14
Soil	0.29	0.09	0.39	32.25	.0001**

	Fall	Spring		F Ratio	Prob>F
Litter	0.83	0.76		3.9	0.051
Soil	0.34	0.09		28.51	.0001**

Annual, Periodic (n=30); Control (n=60)

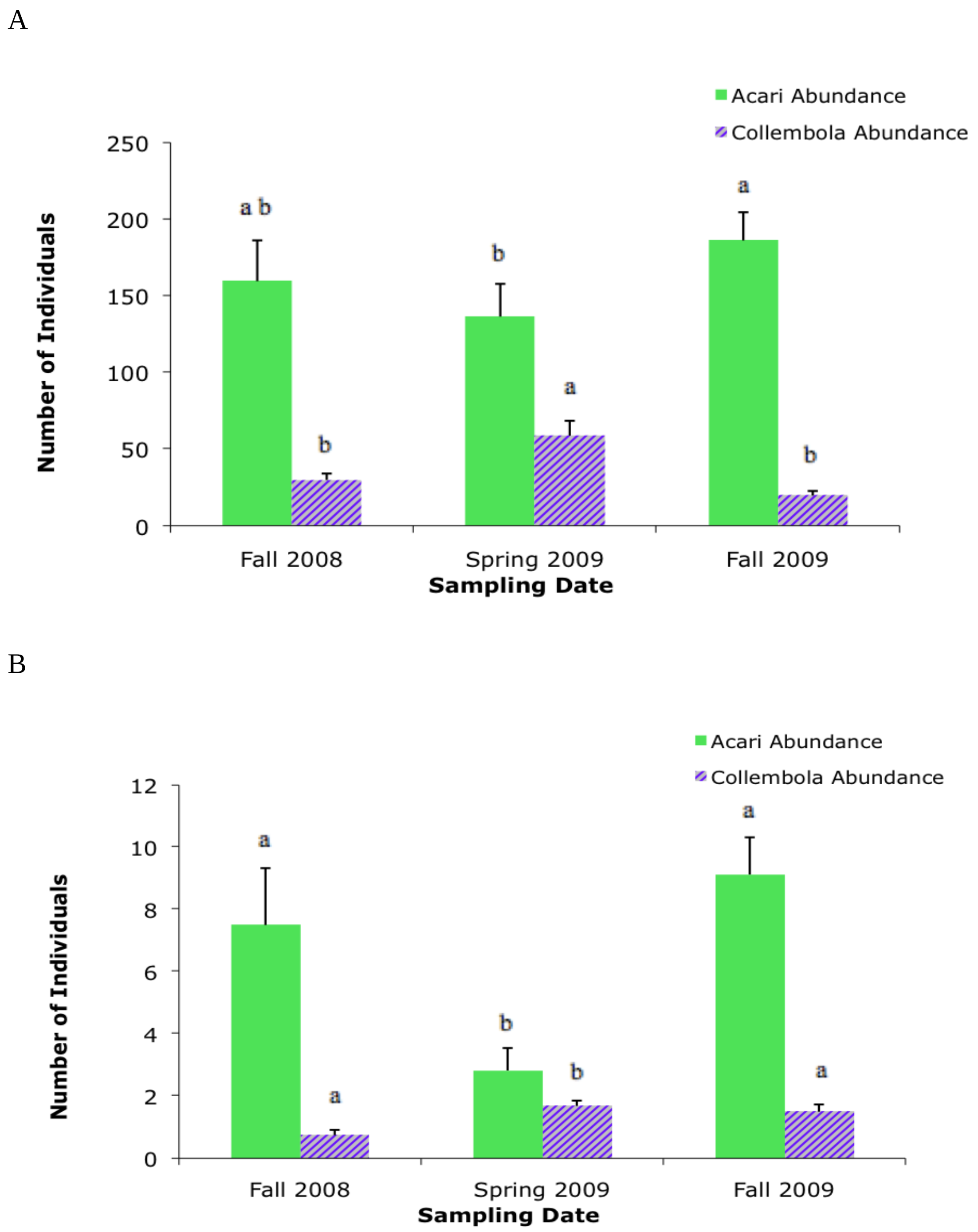


Figure 1. Change in litter (A) and soil (B) Acari and Collembola abundance over time (lowercase letter indicates significant differences (p < .05) between sampling dates for each taxonomic group)

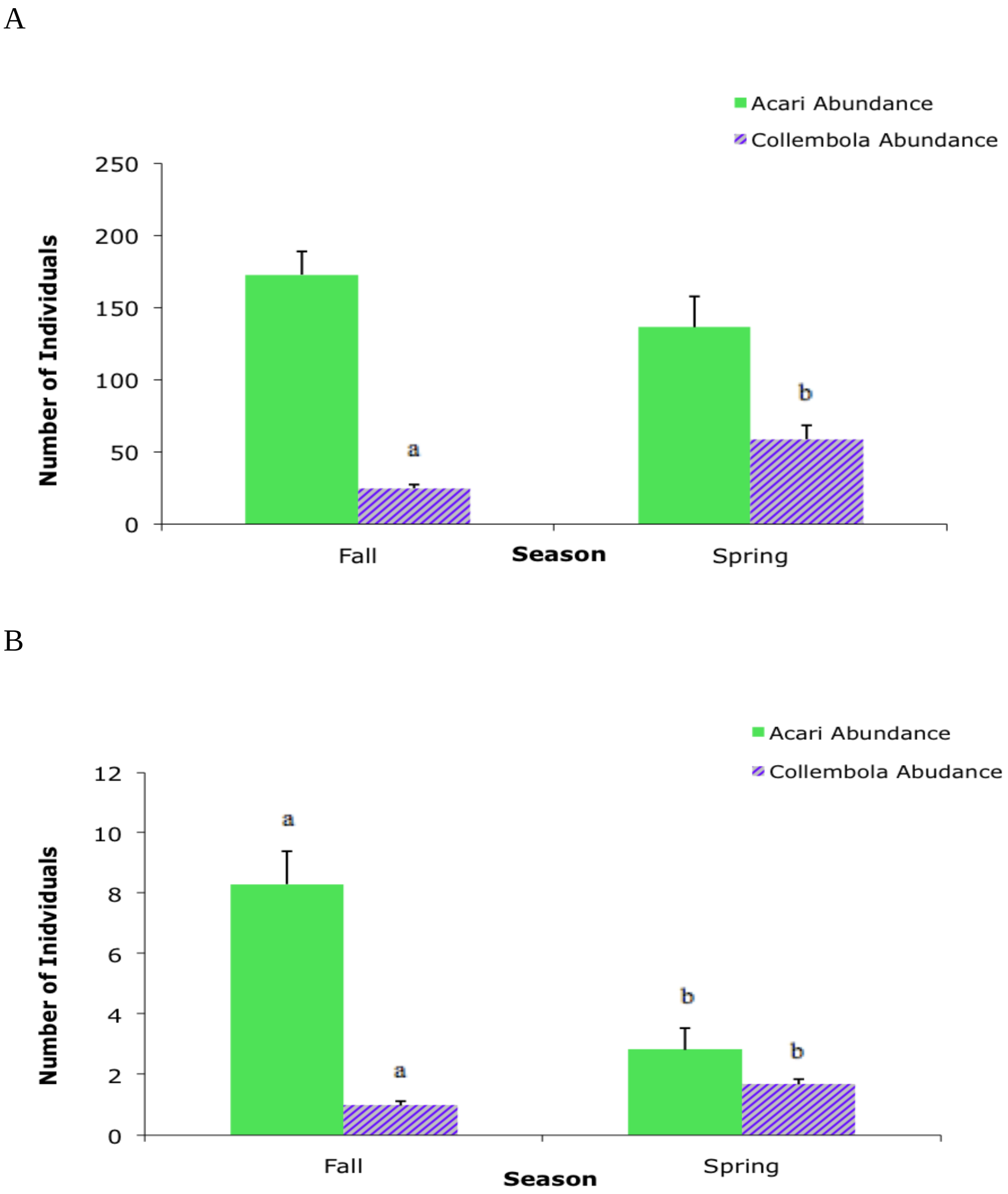


Figure 2. Seasonal change in litter (A) and soil (B) Acari and Collembola abundance (lowercase letter indicates significant differences ($p < .05$) between seasons for each taxonomic group)

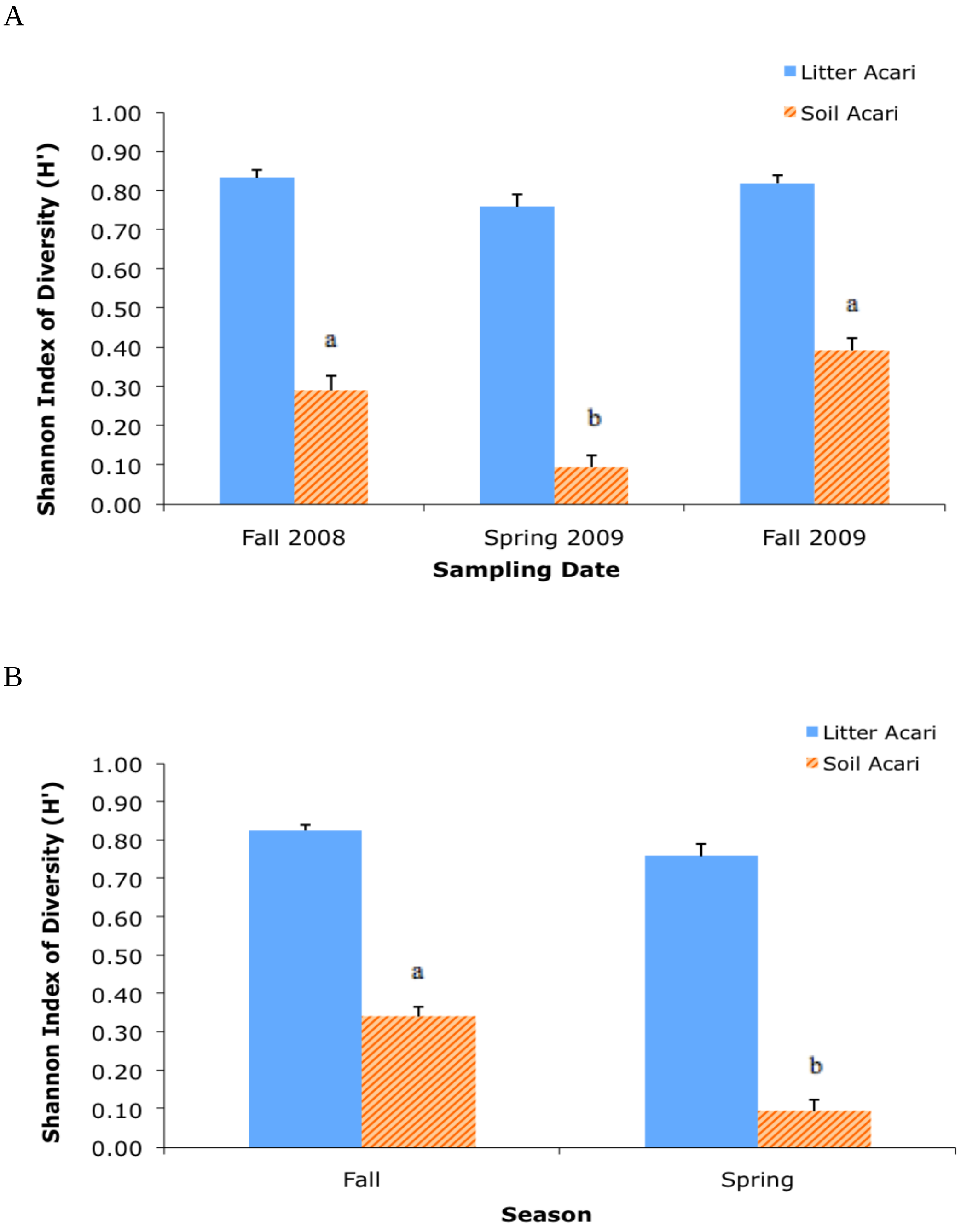


Figure 3. Sampling date (A) and seasonal (B) effect on litter and soil Acari sub-order diversity (lowercase letter indicates significant differences ($p < .05$) between sampling date or season for litter or soil Acari diversity)

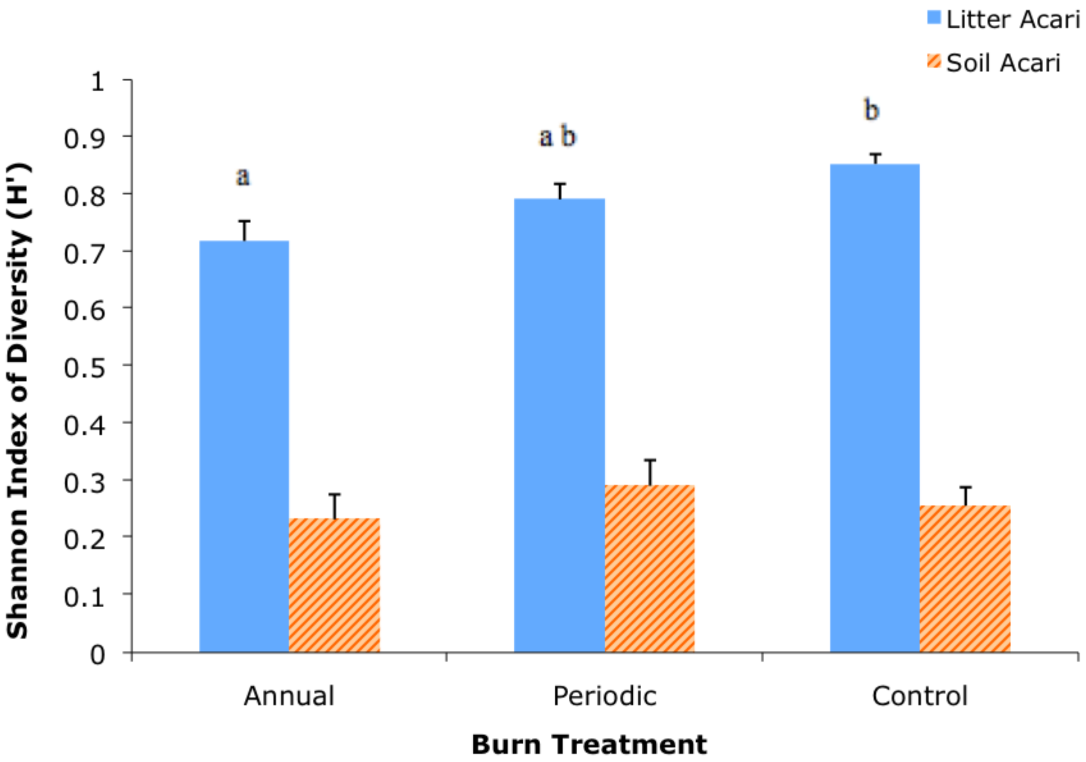
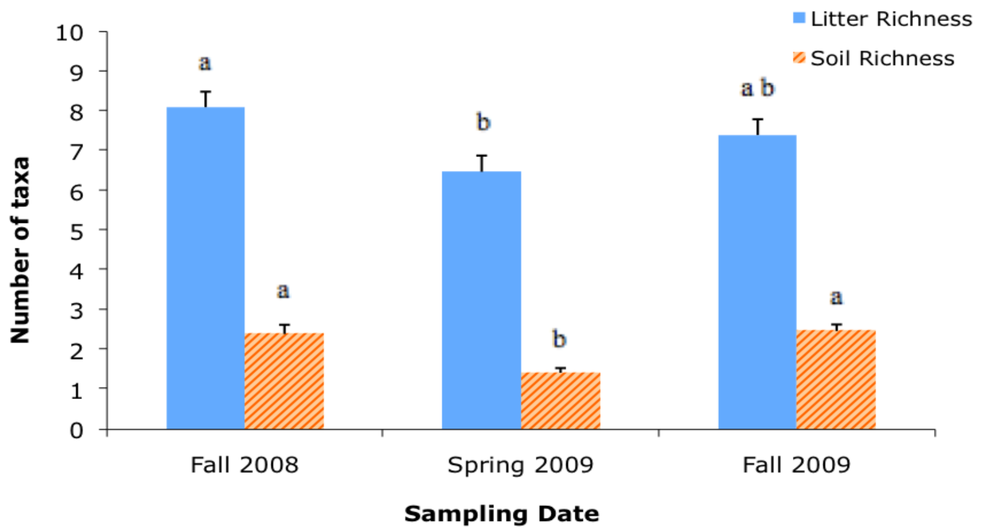


Figure 4. Burn treatment effect on Acari sub-order diversity (lowercase letter indicates significant differences ($p < .05$) between burn treatments for litter or soil Acari diversity)

APPENDIX 4. Sampling date and seasonal effect on soil and litter invertebrates

A



B

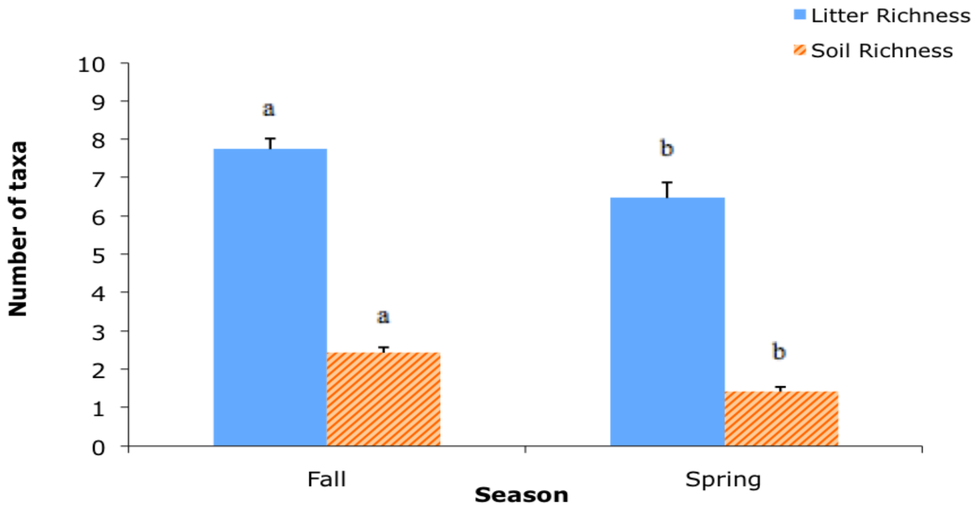


Figure 1. Sampling date (A) and seasonal (B) effect on litter and soil invertebrate richness (lowercase letter indicates significant differences ($p < .05$) between sampling date and season for litter and soil invertebrate richness)

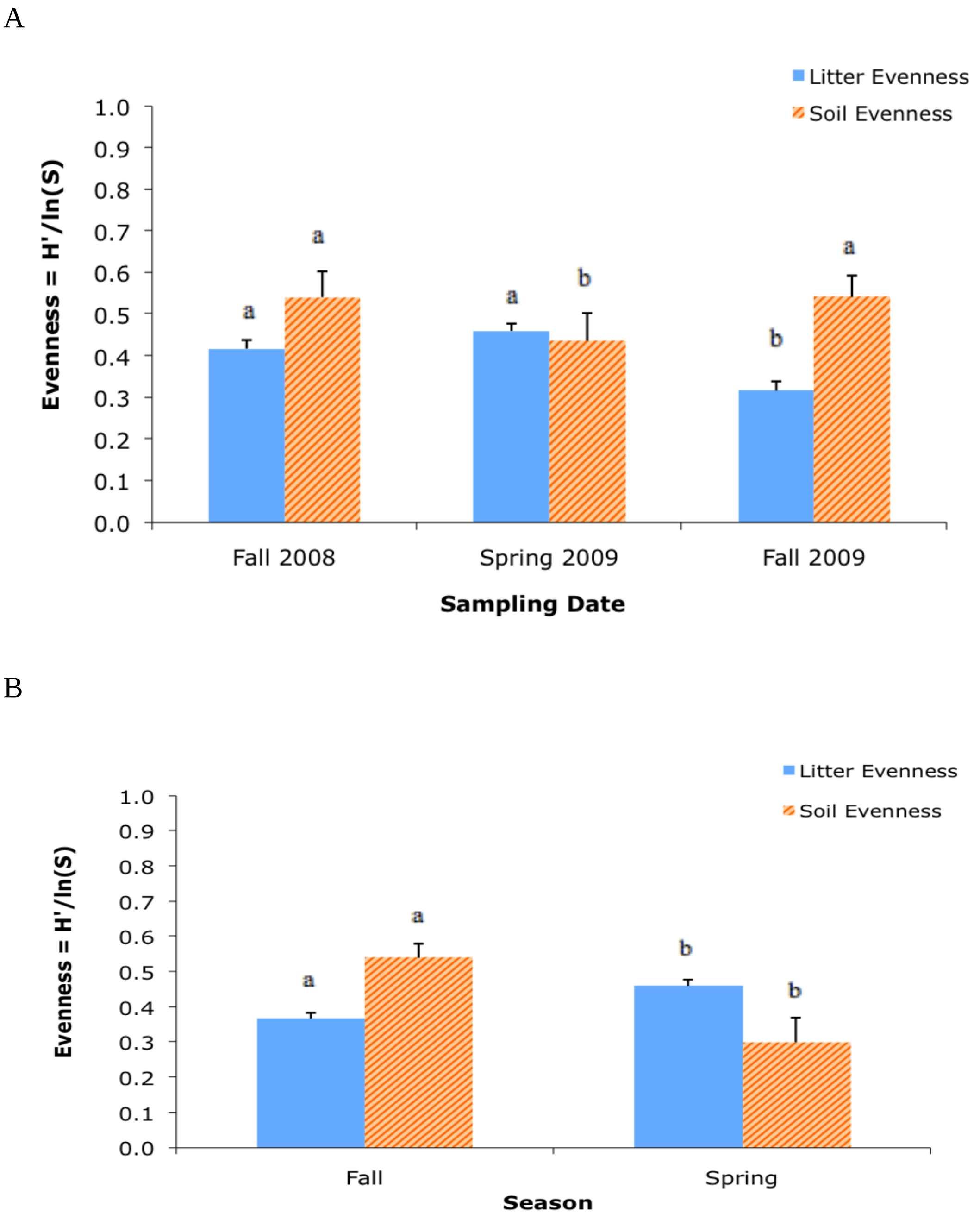


Figure 2. Sampling date (A) and seasonal (B) effect on litter and soil invertebrate evenness (lowercase letter indicates significant differences (p < .05) between sampling date and season for litter and soil invertebrate evenness)

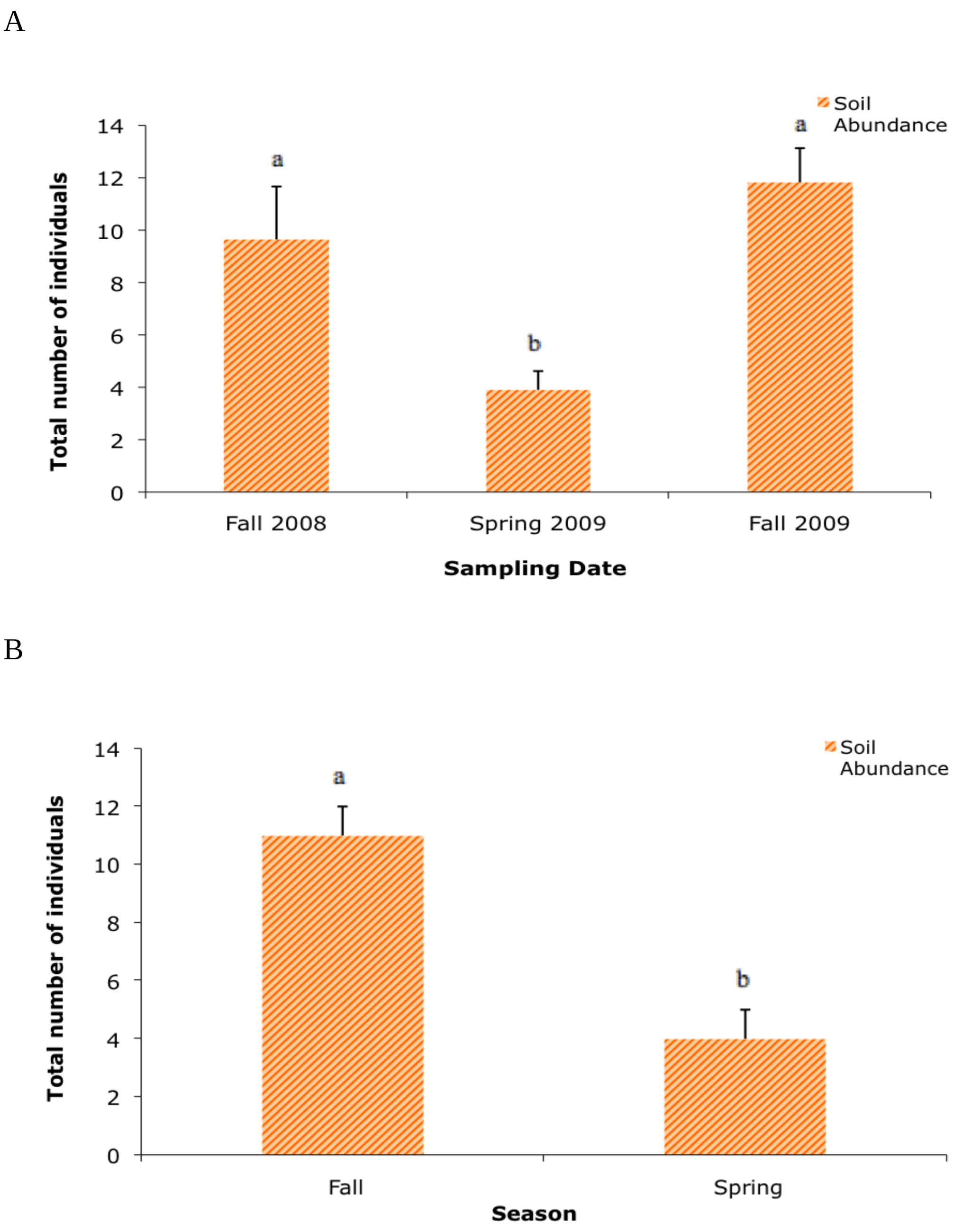


Figure 3. Sampling date (A) and seasonal (B) effect on soil invertebrate abundance (density = abundance/100g of soil; lowercase letter indicates significant differences ($p < .05$) between sampling date and season for soil invertebrate abundance)

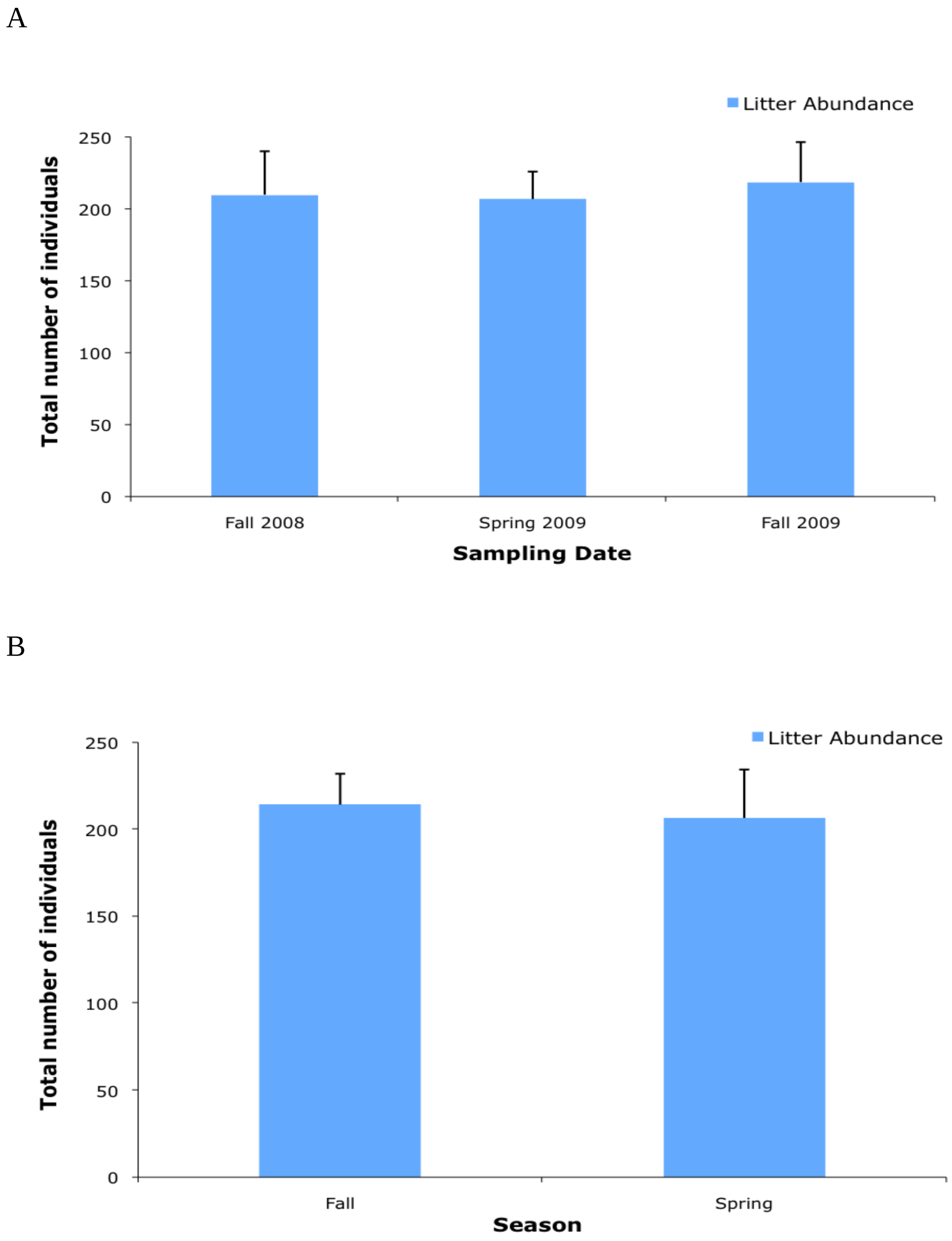


Figure 4. Sampling date (A) and seasonal (B) effect on litter invertebrate abundance

APPENDIX 5. Micrograph images of soil and litter invertebrate taxa found

Figure 1. Symphypleona

Figure 2. Entomobryomorpha

Figure 3. Poduromorpha

Figure 4. Gamasid

Figure 5. Oribatid

Figure 6. Annelida

Figure 7. Araneae

Figure 8. Colepotera

Figure 9. Diptera

Figure 10. Hemiptera

Figure 11. Hymenoptera

Figure 12. Isopoda

Figure 13. Millipede

Figure 14. Psocoptera

Figure 15. Psuedoscorpian

Figure 16. Thysanoptera

APPENDIX 3. VARIOUS IMAGES PERTAINING TO ECOLOGICAL IMPACTS OF LONG-TERM, LOW-INTENSITY PRESCRIBED FIRE IN A MIDWESTERN OAK FOREST.

Image 1. Plot center posts in the East Woods of The Morton Arboretum, Lisle, IL, 09/01/08.

Image 2. Annually burned oak forest at The Morton Arboretum, Lisle, IL, 09/01/08.

Image 3. Periodically burned oak forest at The Morton Arboretum, Lisle, IL, 07/28/09.

Image 4. Un-burned control oak forest at The Morton Arboretum, Lisle, IL, 09/01/08.

Image 5. Ozaukee soil in the periodically burned oak forest at The Morton Arboretum, Lisle, IL, 09/01/08.

Image 6. Ashkum soil in the un-burned control oak forest at The Morton Arboretum, Lisle, IL, 09/01/08.

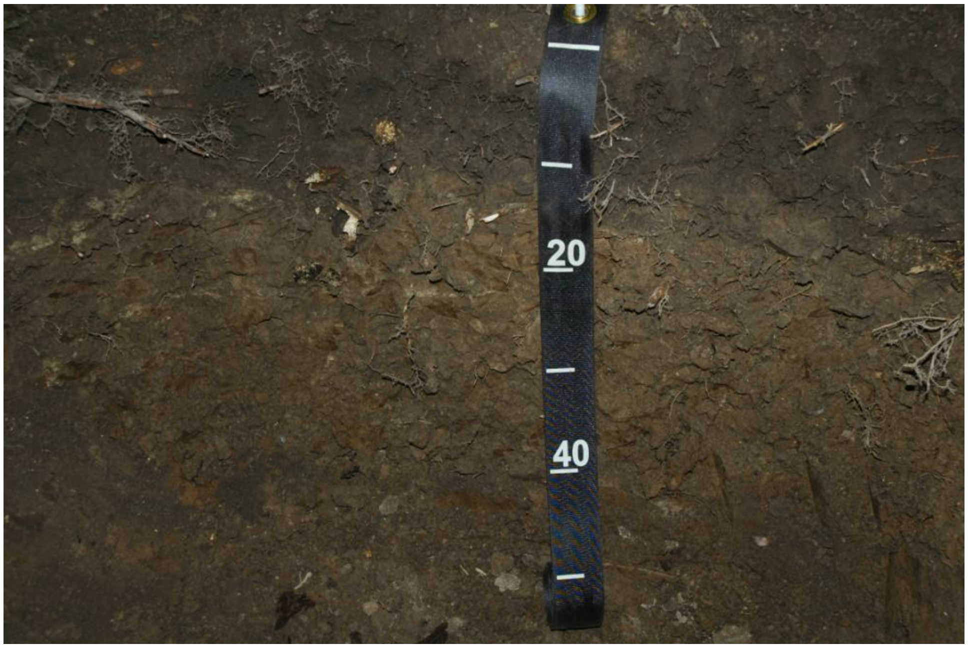


Image 7. Low-intensity prescribed burn in an oak forest at The Morton Arboretum, Lisle, IL, 11/06/09.

Image 8. Low-intensity prescribed burn in an oak forest at The Morton Arboretum, Lisle, IL, 11/06/09.

Image 9. Forest floor following low-intensity prescribed burn in an oak forest at The Morton Arboretum, Lisle, IL, 11/06/09.

Image 10. Bryant Scharenbroch measuring surface temperature with Raytek infrared thermometer, 11/06/09.

Image 11. Brenda Boelter identifying soil invertebrates in the MASS laboratory, 01/18/09.

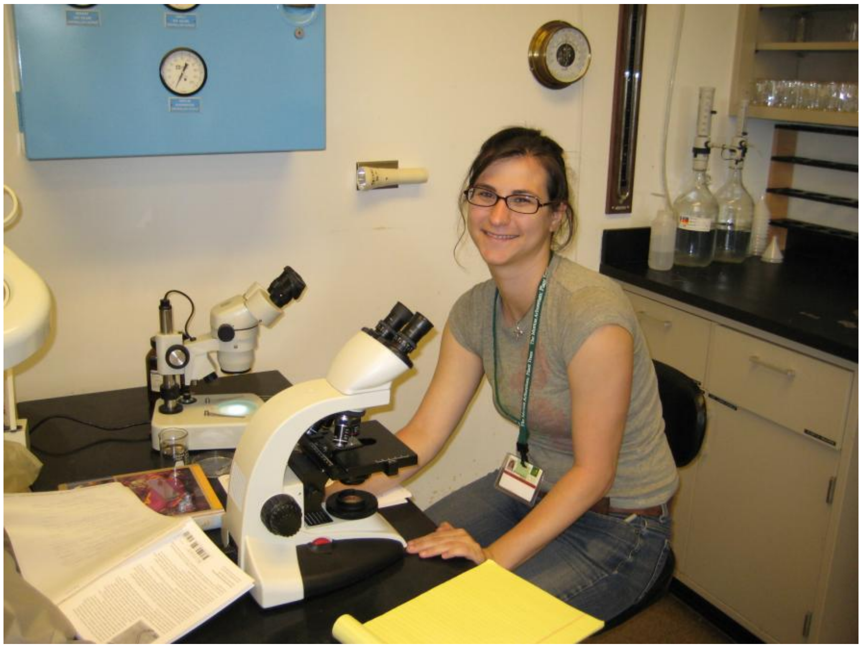


Image 12. Berlese-Tullgren funnels for extracting invertebrates from soil and litter in the MASS laboratory, 01/18/09.