

**FERTILIZER EFFECTS ON SOIL pH, SOIL NUTRIENTS,
AND NUTRIENT UPTAKE IN
SWAMP WHITE AND PIN OAK SEEDLINGS
ON AN ALKALINE MISSOURI RIVER BOTTOMLAND**

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by

MATTHEW J. KRAMER

Dr. John Dwyer

Thesis Supervisors

Dr. Felix Ponder Jr.

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

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AND NUTRIENT UPTAKE IN
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Presented by MATTHEW J. KRAMER

A candidate for the degree of Master of Science

And hereby certify that in their opinion it is worthy of acceptance.

Dr. John P. Dwyer

Dr. Felix Ponder Jr.

Dr. Frieda Eivazi

Dr. Michael A. Gold

DEDICATION

I dedicate this work to my family and to all the good people I have met who were a positive influence on my life.

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CHAPTER I

INTRODUCTION

There is growing interest among forest and wildlife managers in the reforestation of bottomlands in the Lower Missouri River and Mississippi Alluvial valleys (Dey et al., 2003; Shaw et al., 2003; Stanturf et al., 2000, 2001). The emphasis is on reforestation of these lands with mast producing hardwood trees, namely oak species (*Quercus*), hickories (*Carya*), and black walnut (*Juglans nigra* L). As much as 70-90 percent of the floodplain forests in the continental United States have been lost to agriculture, river channelization improvements, and levee systems for flood protection. These alterations in river hydrology have resulted in a higher frequency of intense flooding. This fact was brought to the forefront when the Great Flood of 1993 degraded over 325,000 hectares of cropland along the Lower Missouri River floodplain through scouring and the depositing of sand onto crop fields (Kabrick et al., 2005). It is now desired by both professional natural resource managers and landowners alike that these degraded or abandoned crop lands be reforested by hard mast producing tree species.

LITERATURE REVIEW

Throughout history, bottomland oaks have been an important component of the landscape to both humans and wildlife. Bottomland oak species, of which

there are no less than 15 in the Lower Mississippi Alluvial Valley alone, contribute to the diverse mixture of bottomland flora that flanks our nation's largest watersheds. Many species of birds, mammals, and amphibians depend on oak trees as a source of both food and shelter. Archeological evidence also suggests that acorns were an important part of Native Americans' diet (Gibson, 2001). According to Connaway (1977) and Smith (1986) the first clearing of bottomland forests would have been conducted by early sedentary tribes of Native Americans around 5000 years ago. It is thought that as these settlements expanded, clearings were made and fires were intentionally set to improve the land for plant cultivation and enhance browse for whitetail deer and other game animals. It is suggested by Hamel and Buckner (1998) that much of the bottomland forest types first seen and described by the early European explorers were developed from previously cleared and/or burned lands.

Around 1800, bottomland deforestation began in earnest as European settlers were drawn to the readily available source of quality hardwood timber and began to clear the land in order to farm the fertile soils with row crops. The large Mississippi and Missouri River systems provided a convenient means of transportation for lumber and other resources (Cobb, 1992), and estimates indicate that by the 1930's nearly half of the Mississippi Alluvial Valley land base had been cleared for agriculture (Stanturf et al., 2000).

The completion of mainline levee systems along America's big rivers spurred on the continuing deforestation of bottomland hardwoods as land that had been previously too wet or too frequently flooded was now opened up for

agricultural development. Soaring prices for soybeans (*Glycine max* (L.) Merrill) in the 1960's and 1970's attributed to the last major decline in bottomland hardwood forest acreage (Sternizke, 1976). The majority of the remaining bottomland hardwood forest existed only in fragmented patches of land that was unprotected by levees and too wet for crop production or contained within the boundaries of various conservation areas and wildlife refuges. The deforestation surge declined in the late 1970s with the crash of soybean prices, and Federal and State natural resource managers began implementing practices to restore forest cover for wildlife habitat on former agricultural fields within public holdings (Newling, 1990, Haynes and Moore, 1988). Because these plantings were driven primarily by objectives to develop wildlife habitat, land managers were concerned with the establishment of hard mast producing trees, chiefly the bottomland oaks (King and Keeland, 1999).

Bottomland restoration efforts began to turn around in the 1980s and 1990s. Congressional Farm Bills during this time period funded the Conservation Reserve Program (CRP) and the Wetland Reserve Program (WRP) through which farmers receive cost-share assistance for implementing approved conservation practices, such as bottomland afforestation, on their qualified lands. These programs were established through the U.S. Department of Agriculture to reduce excess grain production by removing highly erosive soils and wetland soils from agriculture (Gardiner and Lockhart, 2007). As a result, many acres of private land with marginal use for farming in addition to the bottomlands of public lands began to be planted back into bottomland hardwoods. Afforestation has

now reclaimed over 200,000 hectares of the Lower Mississippi Alluvial Valley in Louisiana, Arkansas, and Mississippi with more than 75 percent of these lands being privately owned. (Gardiner and Oliver, 2005). It is important to note that while early bottomland restoration plantings usually involved the planting of only one oak species, more recent plantings have been designed to include multiple species of oaks from both the red and white oak groups as well as other non-oak bottomland species such as eastern cottonwood (*Populus deltoides*) in an effort to increase species diversity and obtain additional benefits from the plantings.

BENEFITS OF BOTTOMLAND FORESTS

Bottomland forests are an important part of a riparian ecosystem, which is among the most diverse types of systems (Nilsson et al., 1997). Riparian ecosystems are under severe threat worldwide and considered as key areas for the loss of global biodiversity (Sala et al., 2000). Historically, oaks were significant components of native floodplain forests in the Missouri and Mississippi watersheds. Cottonwood, silver maple, willow, and other flood-tolerant species dominated the low elevation, flood prone areas while oaks, hickories, and walnuts persisted on better drained soils in the bottoms (Dey et al., 2000). These woody species growing in the floodplain increase stream bank stability, protect levees, and reduce negative impacts of flooding by scouring, deposition, and infrastructure damage (Dwyer et al., 1997).

Vegetation buffers along riparian corridors have a broad application throughout the United States, but they are most important in states that are

heavily agricultural (Garrett and Buck, 1997). In the corn belt alone (Illinois, Indiana, Iowa, Missouri, and Ohio), more than 137,000 km of streams and riverbanks are unprotected by trees and shrubs. An additional 129,000 km are unprotected or have only minimal protection in the heavily farmed states of Kansas, Nebraska, North Dakota, and South Dakota (Garrett et al., 1994). Riparian buffer strip management is in need of immediate broad scale adoption for its environmental benefits (Garrett and Buck, 1997). Forested buffer strips 27-46 m in width have proven to be effective in reducing nitrogen (N) in groundwater by 68-100% and in surface runoff by 78-98% (Lowrance, 1992). Recently, buffer strip designs which incorporate trees along the drainage bordered by shrubs and grasses on the outer sides have been proven effective at filtering out potential stream contaminants (Garrett and Buck, 1997).

In addition to trapping excess fertilizers and acting as a storage place for nutrients, bottomland trees in riparian buffers prevent the sedimentation of waterways and help prevent erosion (Garrett and Buck, 1997, Forster et al., 1987). Because a riparian forest has a much lower erosion rate compared with an agro-ecosystem, increasing riparian forest width decreases the mean sediment generation, reducing the amount of sediments to be trapped (Sparovek et al., 2002). Thus, a healthy riparian forest of sufficient width not only decreases the amount of sediments reaching our rivers and lakes but also can catch and retain up to 54% of sediments found in flood water (Sparovek et al., 2002).

It would be difficult to calculate a precise economic or dollar value for the contribution riparian forests make to humans and the health of the environment

as a whole. However, it has been estimated that the cost of cropland sediment in reservoirs run as high as \$200 million annually (Crowder, 1987). In Ohio alone, studies have shown that a 25% reduction in soil erosion would result in a savings of \$2.7 million in water treatment costs each year (Forster et al., 1987)

Bottomland hardwood forests provide a rich habitat for many kinds of valuable wildlife. Hard mast, namely from hickory, walnut, and most importantly, oak, supply a great portion of the year's food for important game species including waterfowl, wild turkey, and deer as well as for many other non-game species (Van Dersel, 1940). Wildlife managers have long recognized the appeal that bottomland oak acorns have to migrating waterfowl. Many waterfowl organizations and hunt clubs, as well as private landowners with bottomland habitat, are very interested in improving the waterfowl attracting and holding ability of their land by afforesting their bottom land with oak trees. Because waterfowl lack teeth and must swallow their food whole, they prefer the smaller acorns of species like pin oak (*Quercus palustris* Muench.), Shumard oak (*Q. shumardii*), Nuttall oak (*Q. texana*), willow oak (*Q. phellos*). In general, waterfowl prefer acorns with smaller top width, thin shell, and greatest meat: shell mass ratio (Van Dersel, 1940).

From a timber production standpoint, the reforestation of bottomlands with valuable species like oak, hickory, and black walnut would greatly improve the potential value of the land. Black walnut's dark, richly grained wood is used for veneer, fine furniture, and is often made into beautiful gunstocks. Wood from some species in the white oak group is used to make staves for whiskey barrels

and all types of oak are made into durable flooring, railroad crossties, and many kinds of furniture. The extremely hard wood of hickories makes durable tool handles and is prized for the flavorful smoke it produces when used for smoking meat (Lazenby, 1916).

Also, by reforesting bottomlands there is a great opportunity to conserve both native bottomland tree and wildlife species for future generations. Because so many different types of plants and animals comprise and depend upon the bottomland hardwood ecosystem, it is important for humans to recognize these lands for their intrinsic value as well as their ability to produce economic gain.

PROBLEMS AND CHALLENGES

The problem with reforesting bottomlands is that attempts at bottomland hardwood plantings commonly have a high failure rate (Kabrick et al., 2005). While working to regenerate oak species on bottomland sites, managers often face problems such as high pH, nutrient leaching, poor drainage, intense vegetative competition, and animal herbivory (Stanturf et al., 2004). For example, a recent survey of WRP plantings in west-central Mississippi revealed that more than 90 percent of the sites failed to meet the criteria of 100 woody stems per acre (247 stems per ha) three years after planting or direct seeding (Stanturf et al., 2004). While planting 1-0 bare root oak seedlings was more successful than direct seeding acorns, only 23 percent of the land planted with bare root seedlings met the criteria (Stanturf et al., 2004). In order for bottomland hardwood plantings to be successfully established, both private and

public land managers must learn to recognize adverse site conditions and implement the right methods and species selection for overcoming site limitations.

SOIL CONSTRAINTS IN HARDWOOD ESTABLISHMENT

Growth of bottomland hardwood species depends on the physical condition of the soil, moisture availability during the growing season, nutrient availability, and aeration (Baker and Broadfoot, 1979). Bottomland oaks, the most frequently planted bottomland hardwood species (King and Keeland, 1999, Schoenholtz et al., 2001); grow best on moist, well drained sites with good fertility and medium textured soils.

Soil chemical properties affect the establishment of bottomland hardwoods. Most oaks grow best in soils with a pH range from 5.5 to 7.0. Unfortunately, recent alluvial deposits may have a pH approaching 8.0 or higher. These soils can be a problem because some oak species, especially cherrybark, and water (pin) oaks experience low vigor and increased mortality, largely due to a lack of Fe availability at this pH level, (Kennedy, 1993). Shumard oak (*Q. shumardii*), however has been planted successfully on high pH soils where other oaks are unsuitable (Kennedy and Krinard, 1985). In three separate plantings, Shumard oak survived and grew well on soils with pH from 7.8 to 8.0. Some other hardwoods, such as green ash and sycamore, are also tolerant of slightly alkaline conditions (Baker and Broadfoot, 1979).

Managers may try to ameliorate the soil around planted seedlings in soil with a high pH by adding elemental sulfur (S) alone and/or in combination with soil nutrients (Velarde et al., 2005). Trace elements such as Fe, manganese (Mn), zinc (Zn), copper (Cu), and phosphorus (P) have limited availability with pH values above 8.0. The highest availability of 12 essential nutrients occurs in soils with a pH range of 6.5 to 7.0 (Lucas and Davis, 1961). Although nutrients such as Fe, Cu, and P could be added to the soil, they would be rapidly converted into insoluble unavailable forms at pH values greater than 8.0. However, the addition of elemental S, which is oxidized by soil bacteria to sulfuric acid, causes a permanent change in the pH and should make micronutrients and P more available thus leading to more rapid growth (Velarde et al., 2005). According to Velarde et al. (2005), elemental S is an inexpensive way to lower soil pH and has an advantage over phosphoric acid as an acidifying agent because increased growth is due to a change in soil pH and increased nutrient availability alone instead of increased soil P concentrations resulting from the use of phosphoric acid.

A study conducted on 3-year-old *Prosopis alba* trees in pH 8.5 soils in Argentina found that treatment with elemental S alone decreased the pH of the soil by 0.3 in the first year. In the same study, a treatment containing S + P + micronutrients also lowered soil pH and had a 42% increase in biomass production over the control group (Velarde et al., 2005).

In another study conducted on soils with a pH of 8.3 in Arkansas, it was found that various commercial formulations of elemental S varied greatly in their

efficiency at decreasing pH (Slaton et al., 2001). The authors found that S oxidation rates were primarily due to S particle size, not concentration. Sixty percent of the smallest particle size S was dissolved in 10 days and decreased the soil pH from 8.3 to 7.5 whereas the largest particle size S had only 10% oxidation in 90 days and had very little effect on pH (Slaton et al., 2001).

Calcareous soils typically occur in arid or semi-arid regions but are also found in alluvial soil deposits having a limestone parent material (Havlin et al., 2005). These soils typically have a pH > 7.2 due to the high amounts of calcium carbonate (CaCO₃). In these high pH/high calcium (Ca) soils the availability of many micronutrients such as Mn, Fe, Cu, Zn, and boron (B) tend to decrease as the pH level increases. The exact mechanisms responsible for reducing availability differ for each nutrient, but can include formation of low solubility compounds, greater retention by soil colloids (clays and organic matter), and conversion of soluble forms to ions that plants cannot absorb (Mc Kenzie, 2003).

Iron is a classic example of an essential micronutrient that is adversely affected by high soil pH. Iron is available to plants in 2 forms: Fe⁺² and Fe⁺³. For each pH unit increase, Fe⁺³ concentration in the soil decreases a thousand fold and Fe⁺² decreases a hundredfold (McKenzie, 2003). Iron needs natural organic chelates, which are products of microorganisms and the breakdown of organic matter and plant residues, to be made available in sufficient amounts to a plant's roots. Other factors adversely affecting Fe availability are poor soil aeration, low organic matter, and excessive bicarbonate in the soil (McKenzie, 2003).

Excessive bicarbonate (HCO_3^-) is often a result of poorly drained or over-irrigated calcareous soils which can in turn lead to Fe chlorosis (Zuo et al., 2007). Increasing soil water content not only directly reacts with CaCO_3 and CO_2 to produce increasing bicarbonate, but also decreases gas exchange (Lucena, 2000). Since the solubility of Fe-oxides is pH dependent, under alkaline and calcareous soils inorganic Fe availability is far below that required to satisfy plant demand, so a major role of Fe nutrition in trees is likely played by the Fe chelated by microbial siderophores, chelated by phytosiderophores, and complexed by organic matter (Tagliavini and Rombola, 2001). Poor soil aeration is listed as a cause of Fe chlorosis in orchard trees and woody vines because the lack of soil oxygen causes poor root development and hinders the activity of important soil microbes such as those mentioned above (Tagliavini and Rombola, 2001).

Low levels of soil organic matter and the resulting poor biological fertility of soils is another factor adversely affecting the uptake of micronutrients such as Fe (Tagliavini and Rombola, 2001). It is accepted that enhancing soil organic matter content greatly reduces the risk of Fe chlorosis. The beneficial effect of soil organic matter on Fe chlorosis prevention does not depend solely on the direct Fe chelating ability of the humic and fulvic substances, but it is also related to the stimulation exerted by the organic components on soil microbial activities (Tagliavini and Rombola, 2001). In addition, organic matter improves soil aeration and may prevent the re-crystallization of ferrihydrite to more crystalline oxides under alkaline conditions (Schwertmann, 1966).

Calcium carbonate is classified as widespread on 30% of the total land area of the world (Chen and Barak, 1982) and plays a major role in soil properties, such as buffering in the rhizosphere, which impair Fe nutrition (Loeppert et al., 1994). Bicarbonate (HCO_3^-) levels resulting from CaCO_3 and carbon dioxide (CO_2) in wet soil may rise during wet periods, such as spring, and cause Fe chlorosis in plants during this period of intense Fe demand (Boxoma, 1982). Total lime, however, is not particularly useful for predicting the development of Fe chlorosis, while the fine, clay-sized fraction of CaCO_3 , active carbonate, or active lime (Drouineau, 1942), is more reactive and, therefore, able to build and maintain high levels of HCO_3^- in the soil solution (Inskeep and Bloom, 1986), and is, therefore, often a more reliable indicator (Tagliavini and Rombola, 2001).

As a result of one or more of the above conditions, many Fe sensitive plants, such as pin oak, experience difficulty in the uptake of available Fe. Iron deficiency can inhibit chlorophyll production and adversely affect oxidation-reduction reactions in respiration and photosynthesis leading to Fe chlorosis in the leaves and ultimately stunted growth and even death of the plant (Havlin et al., 2005).

Poor drainage and nutrient leaching are both problems which occur in many bottomland soils. Clayey soils often hold water in low spots at their surface which causes a ponding effect. These soils can also stay highly saturated for long periods of time which leads to anaerobic conditions in which some trees cannot survive. Furthermore, some alluvial soil deposits are very

sandy and therefore quickly leach out much of the nutrients and water (Stanturf et al., 2004, Kabrick et al., 2005).

Soil bedding is method managers use to manipulate soil in an effort to increase aeration and drainage, lower bulk density, and concentrate soil organic matter and nutrients (Page-Dumroese et al., 1997; Lakel et al., 1999; Fisher and Binkley, 2000; Smolander et al., 2000). Bedding can be beneficial when establishing bottomland oaks because they are generally less tolerant of poorly drained soils than other bottomland tree species (Kabrick et al., 2005). Bedding increased the height of Nuttall oak (*Q. texana* Palmer) seedlings as much as 35% on poorly drained and frequently flooded soils in the Coastal Plain of Louisiana, U.S.A. (Patterson and Adams, 2003). However, soil bedding is not always beneficial. A summary of six soil bedding studies in the Louisiana Coastal Plain found only minor increases in seedling survival and growth (Derr and Mann, 1977).

A soil bedding study done on two Missouri river bottomland sites (Smoky Waters and Plowboy Bend) in Missouri found few significant effects of bedding on organic carbon and basic cations. This was because neither organic carbon nor base cation concentrations in the alluvial soil changed appreciably with depth (Kabrick et al., 2005). Soil bedding did significantly decrease bulk density after three years in bedded rows versus non-bedded rows. This would suggest that total porosity and potential rooting volume was greater in bedded soil (Morris and Lowery, 1988). It is important to note, however, that even though the sandy soils of the Plowboy Bend site had a relatively high bulk density, it did not exceed the

growth limiting density thresholds identified by Morris and Lowery (1988) (Kabrick et al., 2005). Bedding also increased soil temperature and soil drainage on the study sites, which should help the growth and movement of fine roots in the soil (Kabrick et al., 2005).

VEGETATIVE COMPETITION

The same humid, temperate climate and fertile alluvial soils that enable bottomland oaks to flourish also create favorable conditions for many forms of competing vegetation that can ultimately out-compete oak seedlings for light and nutrients (Stanturf et al., 2004). There are several methods that land managers use in order to overcome the problems of competing vegetation on these productive sites including cultivation, chemical site preparation, and herbicides (Stanturf et al., 2004).

A common practice in bottomland hardwood afforestation programs has been to plant without any site preparation immediately after the agricultural crop has been harvested, or simply to disc once on fallowed sites (Stanturf et al., 1998). Kennedy (1981a, 1981b) compared mowing or shallow disking to no vegetation competition control and found that mowing was as ineffective as the no control treatment. Disking, on the other hand, can significantly improve the survival and growth of bottomland hardwood seedlings (Houston and Bucknor, 1989, Kennedy, 1981a, 1981b), although access on wet sites can limit use of cultivation as a weed control technique.

Another method of vegetation control is chemical site preparation before hardwood seedlings are planted. There are many herbicides which can be either broadcast in a granular form or applied with a boom-type spray applicator in a liquid form. Although there are several herbicides which produce excellent results when used for chemical site preparation, sufficient time must be given between application and the planting of seedlings for the herbicide to be effective without harming the planted seedlings (Stanturf et al., 2004). Weed mats, made from tightly woven plastic material, may be placed around seedlings after planting. These barriers allow water and fertilizer nutrients to seep through into the soil while hindering the growth of competing weeds.

Herbicide application is one of the few practical methods of controlling weeds and woody vines after the establishment of hardwood seedlings. Depending on the herbicide used, this may be done as a spot spray around the seedlings or sprayed over the seedlings themselves before bud break in the spring. In old fields with a “normal” weed complex, herbicides consistently increase the survival of oak by as much as 25 percent (Stanturf et al., 2001). In fields with problem species, such as woody vines like Japanese honeysuckle (*Lonicera japonica*) and trumpet creeper (*Campsis radicans*), it is common to see seedling mortality of 60 percent or more even when herbaceous competition has been controlled (Stanturf et al., 2004). If problem species or non-native plants are present, effective competition control prior to planting will likely determine the success or failure of a restoration effort (Stanturf et al., 2004).

ANIMAL HERBIVORY

Herbivory can dramatically affect the survival and growth of bottomland hardwood seedlings. Major herbivores are beaver (*Castor canadensis*) and white-tail deer (*Odocoileus virginianus*) along with small mammals like the hispid cotton rat (*Sigmodon hispidus*) and the eastern cottontail rabbit (*Sylvilagus floridanus*). There are three basic measures that foresters and restorationists use to overcome the effects of herbivorous animals. These measures are fencing, tree shelters, and reducing the amount of plant cover (Stanturf et al., 2004).

Fencing has been used to increase the survival of natural and planted seedlings by excluding large herbivores, such as deer, from regeneration areas. Cattle-wire fence (2.4 m tall) has proven most effective at excluding deer in the northeastern United States (Marquis and Brenneman, 1981). For the most part, fencing, while an effective method of protecting trees, is too expensive and labor intensive to install on any sizeable plot of land. Furthermore, bottomlands by their very nature are often subjected to frequent flooding which often carries with it large quantities of debris that would break down the fencing and render it ineffective. Although electric fencing has proven effective in the northern hardwoods (Marquis and Brenneman, 1981), flooding makes this impractical in most bottomlands.

Tree shelters are another means by which foresters may increase the growth and, more importantly, the survival of hardwood tree seedlings. The shelters are tubes made of plastic material that surrounds the seedling, which

protects it from browsing and also creates a greenhouse-like microenvironment around the tree to encourage growth. The benefits of tree shelters—decreased herbivory, stimulated seedling growth, and increased seedling survival --- have been documented in cutover natural stands in the northeastern United States and in the central hardwood forest region (Frearson and Weiss, 1987; Lantagne et al., 1990; Ponder, 1995; Gillespie et al., 1996). While tree shelters can be very effective at curbing herbivory, they do add considerable cost in material and labor and are probably best reserved for use in small areas of very intense browsing pressure.

Reducing the weedy cover in bottomland plantings is helpful in deterring small prey species such as rabbits and mice which may clip seedling tops, girdle stems, and cache acorns that were direct seeded. A thick growth of vegetation serves as a safe corridor through which small mammals may freely travel without the threat of being preyed upon by both avian and terrestrial predators (Dey et al., 2003).

Natural resource managers face a great challenge in establishing bottomland hardwood plantings. As previously illustrated, bottomland hardwood forests are an ecotype with a rich history and it is encouraging that there is an increasing interest in their revival. It is also abundantly clear that there are as many pitfalls to reforesting a given bottomland with oak trees as there are benefits to doing so. Although there has been a lot of hard work and helpful research information gained from numerous bottomland studies, a need for more understanding on the subject of bottomland hardwood reforestation remains.

CASE IN POINT: PLOWBOY BEND CONSERVATION AREA

Plowboy Bend Conservation Area is an area of 1083.8 ha (2,677 acres) located in the Lower Missouri River floodplain near Jamestown, Missouri. The site, which is owned and managed by the Missouri Department of Conservation, consists of many former agricultural fields on which farmers once grew row crops like corn and soybeans. The floods of 1993 and 1995 rendered the crop fields marginally profitable for farming because much of the topsoil was scoured away and a layer of fine sand around six inches deep was deposited over the area. Like many other abandoned crop field areas along the Mississippi and Missouri rivers, oak tree seedlings were planted in some of the fields as a reforestation effort for wildlife habitat. The tree species chosen were swamp white oak (*Quercus bicolor*) and pin oak (*Quercus palustris*). These two species were chosen because they were bottomland species, one from the red oak group and one from the white oak group, with acorns that are highly palatable for wildlife and in the right size range for waterfowl to utilize them.

Since they were planted, the oak seedlings at the Plowboy Bend site have suffered the same types of hardships as many of the aforementioned bottomland tree plantings. The fields were disked prior to the tree planting but now much of the area is covered with a rank growth of vegetation including Johnson grass (*Sorghum halepense*), goldenrod (*Solidago spp.*), cocklebur (*Xanthium strumarium*), and tick trefoil (*Desmodium spp.*). Although 1.3 m² woven fabric mats were installed around each of the planted seedlings, some vegetative growth such as foxtail (*Setria spp.*) has managed to grow through this barrier.

The sandy soils on this site tend to be droughty during prolonged dry periods but hold water well in low spots during wet periods.

A major problem on tree growth at the site is continuous browsing by white-tail deer during the growing season and damage to the stems of the trees in the dormant season from buck rubs and eastern cottontail rabbits (*Sylvilagus floridanus*) that either girdle or chew off the stems.

Perhaps the biggest challenge on this site is the high soil pH, which is in the vicinity of 8.3. This high pH has caused many of the trees, especially the pin oak, to become seriously chlorotic due to the unavailability of essential micronutrients. Also, many of the young trees are stunted and look poorly. A number of the trees have been subjected to five different fertilizer treatments containing mixtures of Fe, S, and N annually since March of 2004 in an effort to ameliorate the soil pH and increase nutrient availability for tree uptake.

Except for the 1.3 m² plastic mats around the trees, there has been no vegetation control and as a result there is considerable competition between the tree seedlings and herbaceous vegetation throughout the growing season. While these conditions are far from what would be considered ideal conditions for maximum tree growth, they are consistent with many other bottomland plantings which were installed under the “plant and walk away” method.

We wanted to further study the effects fertilization has had on the soil and on the tree seedlings by evaluating the changes in total soil nutrients and foliar nutrient concentration monthly over a growing season. It will also be useful to know the duration of the fertilizers in this sandy textured soil and to monitor the

effects Fe sulfate and water degradable S treatments have on the pH of the soil surrounding the seedlings. Lastly, we wanted to see whether the soil bedding has had any effect on seedling nutrition and the soil's ability to increase nutrient content. Except for differences in foliar nutrient levels between tree species, the influence of tree seedlings on the rooting environment was not investigated.

There are few guidelines available as to the fertilization of bottomland hardwood trees besides cottonwood (Stanturf et al., 2004). It is our hope that this project will further the understanding of fertilization on bottomland oak and help natural resource managers and their efforts in developing healthy mast producing forests in bottomlands having similar soil conditions.

The null hypothesis is that the addition of Fe, S, and N containing fertilizers will not reduce pH, increase the soil nutrient supply, nor increase nutrient uptake in pin oak and swamp white oak seedlings. Soil bedding has no significant effect on soil nutrient supply or plant uptake.

STUDY OBJECTIVES

1. To evaluate the effect of the various fertilizer treatments on the foliar nutrient content of oak seedlings throughout the growing season (June-October). Foliar samples will be taken for the five fertilizer treatments plus a control four times during the growing season after fertilization for one year.
2. To evaluate changes in pH and nutrient concentrations in the soil at two different depths during the growing season. It will be valuable to know the movement of fertilizers in the sandy bottomland soil. Looking at the changes in soil pH for each treatment at two depths should give an idea of the movement patterns of the applied nutrients through the soil over the growing season and how the change in pH may influence seedling nutrient uptake. However, it was not the intention of this study to evaluate the effects of the tree species on the soil.
3. To evaluate whether soil bedding has had any effect on the soil's overall ability to retain S and Fe and its influence on the foliar nutrient concentrations of N, S, and Fe in pin and swamp white oak seedlings when fertilized with fertilizers containing N, S, and Fe.

CHAPTER II

MATERIALS AND METHODS

STUDY SITE

The study site is located on lands owned and managed by the Missouri Department of Conservation. Plowboy Bend Conservation Area is 1083.8 hectares (2,677 acres) located at latitude 38 48' 5"N; longitude 92 24'17" W in Moniteau County, MO (Figure 1).

The area is a mixture of abandoned crop fields and forest remnants consisting of light seeded hardwoods such as cottonwood (*Platanus occidentalis*), silver maple (*Acer saccharinum*), and box elder (*Acer negundo*). The soils at Plowboy Bend Conservation Area are classified as Sarpy Fine Sand (mixed, mesic, Typic, Udipsamments). Sarpy soils are classified as hydric, which means that they are periodically saturated, ponded, or flooded during the growing season.

In 2001, a plot containing a mixture of 336 swamp white (*Quercus bicolor*) and pin oak (*Q. palustris*) seedlings was planted in eight rows with forty-two trees in each row. The seedlings were planted in a randomized block design, with 12 swamp white and 12 pin oak seedlings per block, at a spacing of 12 m x 12 m. Half of the rows were bedded in hopes of improving soil properties and drainage. Both bare root and RPM[®] seedlings were planted on bedded and non-bedded soils.

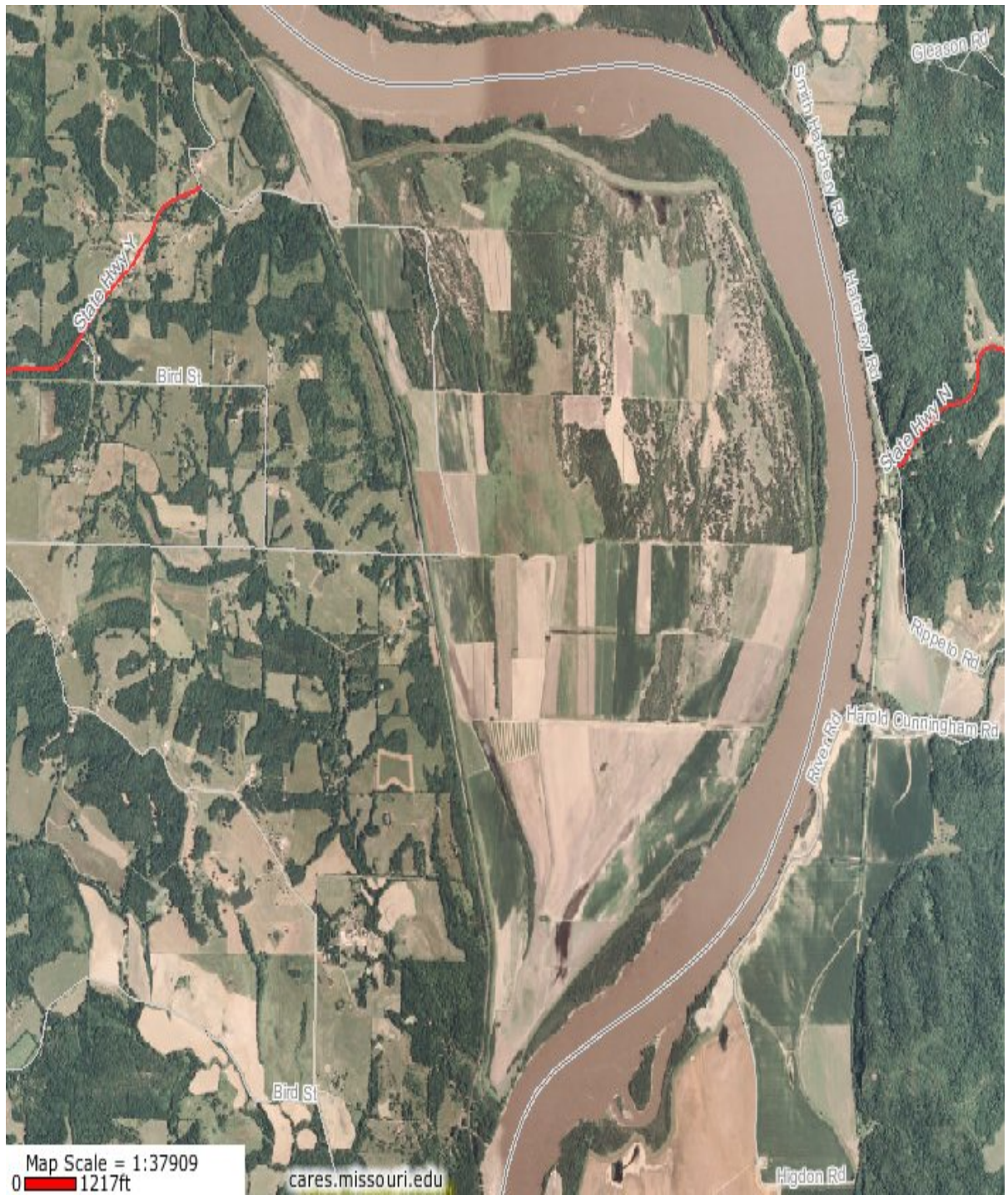


Figure 1. Plowboy Bend Conservation Area, 1083.8 ha (2,677 acres), Moniteau County, MO. Aerial picture courtesy of University of Missouri-Columbia Center for Research and Environmental Systems (CARES).

SEEDLING STOCK AND FERTILIZER TREATMENTS

Bare root 1-0 seedlings (Figure 3) were acquired from the George O. White State nursery located in Licking, Missouri. Root Production Method™ (RPM®) seedlings were developed at Forrest Keeling Nursery located in Elsberry, Missouri. “The RPM® (root production method) system is a multi-step system of producing container tree seedlings that places primary emphasis on the root system – which ultimately determines the tree’s survival and performance in the environment it is transplanted into.” (Lovelace, 1998). The RPM® process for oak includes selecting seed by weight, stratification, and grading the germinated seedlings in order to keep only the best 50% of the seedlings. The seedlings are grown in shallow, bottomless flats in order to let the roots self prune when they meet the air. This air pruning is the crucial component in the RPM® system as it forces the seedlings to develop many branching lateral roots high on the root collar. The shallow, fibrous root system of the RPM® seedlings support a large, strong stem that may be up to 2.5 m tall which allows the seedling to compete well for soil nutrients (Lovelace, 1998) (Figure 2).



Figure 2. The massive, fibrous root system of a one year old RPM[®] tree seedling. (Image courtesy of Forrest Keeling Nursery www.fknursery.com)



Figure 3. Tap root systems of ordinary bare root tree seedlings. (Image courtesy of www.forestryimages.org)

Trees established in the soils belonging to the Sarpy series often become chlorotic due to the high pH levels (up to 8.2). To amend soil pH and augment nutrient uptake, five fertilizer treatments were applied to the trees on the site. Combinations of Fe, S, and N were applied in the following treatments: FeSO_4 + S, Chelated Fe, Chelated Fe + N, N alone, and N + FeSO_4 . Except for the N alone treatment, treatments were applied according to the rates recommended by the manufacturer (Table 1). Ferrous sulfate was applied at 2240 kg ha^{-1} or 336 g/tree , ammonium nitrate 112 kg ha^{-1} actual N or 49.4 g/tree , Fe chelate (Sprint 330) was applied at a rate of 454 g/93 m^2 or 8 g/tree , and water degradable sulfur at 2240 kg ha^{-1} or 336 g/tree (Table 1). These treatments were

applied randomly to 20 swamp white and pin oak seedlings in the 1.3 m² weed mat area surrounding the base of the trees. These treatments have been applied annually since the early spring (March) of 2004.

The overall purpose of the initial study in 2004 was to determine if oak seedlings nutrient uptake and growth could be improved through amending soil pH, thereby increasing the availability of essential soil nutrients. In the present study, the effect of the aforementioned fertilizer treatments on soil chemical properties and foliar nutrient content will be evaluated.

Table 1. Fertilizer treatments and rates applied to study site.

Treatment	Fertilizer Rate
Iron Sulfate + Sulfur (water degradable S)	FeSO ₄ (2240 kg ha ⁻¹ or 336 g/tree) + S (2240 kg ha ⁻¹ or 336 g/tree)
Iron Chelate	Fe chelate (Sprint 330) (454 g/ 93 m ² or 8 g/tree)
Iron Chelate + Ammonium Nitrate	Fe chelate (Sprint 330) (454g/ 93 m ² or 8 g/tree) + NH ₄ NO ₃ (112 kg ha ⁻¹ actual N or 49.4 g/tree)
Ammonium Nitrate	NH ₄ NO ₃ (112 kg ha ⁻¹ actual N or 49.4 g/tree)
Iron Sulfate + Ammonium Nitrate	FeSO ₄ (2240 kg ha ⁻¹ or 336 g/tree) + NH ₄ NO ₃ (112 kg ha ⁻¹ actual N or 49.4 g/tree)
Control	0

SAMPLING AND ANALYSIS: FOLIAGE AND SOIL

Sampling began in mid-June and ended in mid-October, 2007. Because the goal of this study was to study the treatment effects over the growing season, samples were taken in June, July, August, and October. During the planning of the four sampling periods, it was decided to forego sampling in the month of September in order to obtain data closest to the end of the growing season and leaf senescence in October. Samples were taken from the two species of trees, swamp white and pin oak, with five repetitions per treatment and six treatments (2 species * 6 treatments * 5 replicates = 60). Foliar samples of 15-20 leaves per tree were consistently taken from upper, most recently mature leaves of five trees for each species and treatment (Mills and Jones, 1996). The foliar samples from all 60 trees were placed in a cooler and transported for drying in the laboratory in labeled paper bags. A total of 120 soil samples (60 * 2 depths) were taken per sampling period at two depths, 0-10 and 10-20 cm, in each of the cardinal directions at the edge of the weed mat area. For each individual tree, the four soil samples per depth were combined into a composite sample bag to negate potentially high or low readings due to fertilizer granules moving off to one side of the weed mat area during a heavy rain event. A composite soil sample collected from the control was sent to the University of Missouri Soil Test Laboratory, Columbia, MO for basic analysis (Table 2). Both the soil and leaf samples were labeled by tree number, species, and treatment code in the field. The coordinates of each sampling point was collected using a Global Positioning System. (Figure 4.)

Table 2. Soil chemical properties for soil sample taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

Soil Location	pH	Organic Matter	Bray 1 P	Ca	Mg	K	CEC**
Plowboy Bend CA		%	kg/ha	kg/ha	kg/ha	kg/ha	cmol _c /kg
	8.29	0.6	13.41	514.9	51.1	36.37	8.4

* Soil tests performed by University of Missouri-Columbia Soil Testing Laboratory, 23 Mumford Hall, Columbia, MO 65211.

**CEC = Cation Exchange Capacity



Figure 4. Aerial map of plot and study trees at Plowboy Bend Conservation Area. Swamp white oaks are represented in blue and pin oaks are represented in green. Aerial picture courtesy of University of Missouri-Columbia Center for Research and Environmental Systems (CARES).

Leaves were oven-dried at 65 degrees Celsius for 72 hours and ground into a fine powder using a Wiley mill at the Lincoln University laboratory. The ground foliar samples were then stored in properly labeled zip-lock style polyethylene bags. Soil samples were allowed to air dry in the laboratory and were then ground with a mortar and pestle and sieved through a 2 mm sieve to remove any pebbles, fine roots, and plant debris. The ground and sieved soil samples were also stored in labeled polyethylene bags.

A total of four sampling periods, each approximately one month apart, was conducted during the 2007 growing season. In total, 240 (60 * 4 months) foliar samples and 480 (120 * 4 months) soil samples were collected, prepared, processed, and analyzed.

Prior to analysis, all vessels and glassware to be used were washed with metal free soap, rinsed, soaked in a 30% nitric acid for 24 hours, and finally rinsed in deionized water. Deionized water was used for sample dilutions, rinses, and preparation of diluted standards. The reagents used were trace metal grade concentrated nitric and hydrofluoric acid from Fisher Scientific (St. Louis, Missouri, USA), and ICP tune and calibration solutions were from SPEX Certiprep, Inc. (Metuchen, NJ, USA). Standard reference material (SRM 1640 trace elements in natural water) for method validation was purchased from the National Institute of Standards and Testing (NIST) Gaithersburg, MD 20899, USA.

Total soil digestion for the presence of macronutrients (soil N was not determined) and micronutrients was obtained through an acid microwave

digestion process. The methodology followed for the preparation and digestion of soil and leaf samples was taken from Ikem et al. (2007). Soil samples were tested for pH using a 2:1 water to soil ratio by mixing 10 g of sieved soil into 20 ml of deionized water and testing the mixture with an Accument^R AB15 pH meter.

Soil samples of 0.2 - 0.3 g were weighed accurately (within 0.002 g) into Teflon vessels and mixed with 9 ml nitric acid (HNO₃) and 3 ml hydrofluoric acid (HF). The vessel was sealed with a torque wrench and digested at 180^o C for 30 minutes in an Ethos EZ Microwave Digestion Lab-station (Milestone Inc., Shelton, CT 06484 USA).

Ground foliar material of 0.2 - 0.3 g in weight was accurately weighed and digested using the same process as used for the soil except that 15 ml of concentrated nitric acid was used as the digesting agent in the microwave acid digestion process. After cooling, the vessels were opened with a torque wrench and the digest was carefully filtered into a 25 ml flask. The sample digest volume was brought up to the 25 ml mark with deionized water – 0.22 micro (Milli-Q Millipore S.A-67120 Molsheim, France). All of the digested samples were then stored at 4^o C until analyzed using an Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) (Varian Inc., Walnut Creek, CA 94598, USA) to obtain the total concentration of macro and micronutrients contained within the samples.

Reagent blanks and sample duplicates were prepared for analysis in the ICP along with the samples. The inductively coupled plasma-optical emission

spectrometer (ICP-OES) was calibrated using multi-element Standard Reference Material 1640 from the National Institute of Standards and Technology (NIST) containing K, Ca, Fe, Mg, Mn, Al, As, Ba, Be, Cd, Co, Cr, Cu, Mo, Ni, Na, Ag, Pb, Sb, Se, Zn, and V. The reference material for elements P and S were obtained from individual Certified Reference Material (CRM) solutions (1000 mg/L) also purchased from SPEX Certiprep. The ICP-OES was automatically recalibrated after every 10 analytical samples run with a known standard analyzed as part of the quality check (Table 3).

Table 3. Certified SRM 1640 values compared with laboratory value: laboratory values are the average of seven complete runs.

Element	Certified Value**	Our Value	Recovery (%)
Phosphorus	np	0.00935	
Silver	7.62 ± 0.25	7.91	100.5
Sulfur	np	4081.9	
Aluminum	52.0 ± 1.5	53.01	99.8
Arsenic	26.67 ± 0.41	26.59	99.7
Barium	148 ± 2.2	144.91	97.9
Beryllium	34.94 ± 0.41	34.18	97.8
Calcium*	7.045 ± 0.089	6.38	90.5
Cadmium	22.79 ± 0.96	21.61	94.07
Cobalt	20.28 ± 0.31	18.72	92.3
Chromium	38.6	36.5	94.5
Copper	85.2 ± 1.2	84.1	98.7
Iron	34.3± 1.6	35.7	104
Potassium	994 ± 27	1151.11	115
Magnesium*	5.819 ± .056	5.1	87.6
Manganese	121.5± 1.1	116.95	96.2
Molybdenum	46.75 ± 0.26	43.9	93.9
Sodium*	29.35 ± 0.31	20.63	70.2
Nickel	27.4 ± 0.8	26.51	96.7
Lead	27.89 ± 0.14	25	89.6
Selenium	21.96 ± 0.51	20.1	91.5
Vanadium	12.99 ± 0.37	10.61	81.6
Zinc	53.2 ± 1.1	51.8	97.3

* Values are shown in mg/kg. The remaining is given in µg/kg as appears in NIST (± standard deviation).

**Certified SRM 1640 values from National Institute of Standards and Testing. np values are not provided

Foliar N content for the pin and swamp white oak leaves was measured using the Kjeldahl Digestion method for N determination as described in Mills and Jones (1996). A Foss Tecator™ Digester and a Foss Kjeltac™ 2300 analyzer were used in the digestion and analysis process. Previously dried and ground oak leaf samples were weighed out to between 1 and 1.3 grams and placed into 250 ml tubes. Catalyst tablets containing 0.15 g cupric sulfate (CuSO_4) and 1.5 g K sulfate (K_2SO_4) were added to the samples in the test tube along with 12 ml of sulfuric acid (H_2SO_4) as a reagent. The samples were then heated to 115.5°C for one hour. The samples were allowed to cool before determining the percent N.

STATISTICAL ANALYSIS

Statistical analysis was conducted on the data using analysis of variance (ANOVA). Foliar data were analyzed for effects of treatment, sampling date, oak species and interactions between treatments and other study parameters. Soil data were also analyzed for effects of treatment, sampling date, soil depth on treatment and interactions between them. The statistical software package SAS (version 9.1, SAS institute, Inc., NC, USA) was used to complete all statistical analyses. The GLM procedure with $\alpha = 0.05$ was used in SAS assuming a split – split plot treatment design. Least significant differences were used to separate means at the 5% probability level. A Duncan’s statement was used for the separation of means on main effects in the ANOVA. Table 4 shows ANOVA models used for foliage and soil analysis.

Table 4. Analysis of variance (ANOVA) models.

ANOVA Model I		Model I*	ANOVA Model II**	
Source	df		Source	df
Species (S)	1		Depth (Dp)	1
Treatment (T)	5		Treatment (T)	5
S * T	5		D * T	5
Error A ~ T * Rep (S)	48		Error A ~ T * Rep (Dp)	48
Date (D)	3		Date (D)	3
S * D	3		Dp * D	3
T * D	15		T * D	15
S * T * D	15		T * D * Dp	15
Residual Error	144		Residual Error	144
Total	239		Total	239

*ANOVA for analysis of treatments for pin oak and swamp white oak foliage.

**ANOVA for analysis of soil nutrients by depth assuming no species effect.

CHAPTER III

RESULTS AND DISCUSSION

SOIL pH

Many of the soils on floodplain bottomlands have high pH, high nutrient leaching, intense vegetation competition, and poor drainage; all of which reduce tree performance (Stanturf et al., 2004). When these sites are planted to hardwoods, including oaks, they may exhibit leaf symptoms of Fe deficiency usually induced by poor drainage or by soils with a high Ca content and pH levels above 7.5 (Courchesne et al., 2005). These bottomland soils contain adequate amounts of mineral Fe, but as soil pH rises above 7.0, Fe changes to an insoluble form that many plants have difficulty taking up. Affected leaves turn to a yellowish color while leaf veins remain a dark green. When not corrected, Fe deficiency can cause poor root development, severe stunting, and plant death. Mineral deficiencies other than Fe such as N, P, Mg, Mn, Cu, Zn, or B may also result in chlorosis symptoms. Symptoms of Mg deficiency, in particular, may be similar to those of Fe deficiency. The two can be distinguished by broad bands of normal green color that remain next to the major vein if Mg is lacking. Also, leaves on the ends of the branches of Mg deficient trees are generally not affected until late summer after growth has stopped (Ponder et al., 2008).

Just as pH has an effect on the form and plant availability of many essential soil nutrients, it also has an effect on soil clay mineral edge charge (Havlin et al., 2005). The edge charge is a pH-dependent charge because the

quantity of positive (+) or negative (-) charge depends on the soil solution pH. Soil pH also influences the charge of soil organic matter. Together the total quantity of negative surface charge on minerals and organic matter which attract and hold cations in soil solution is referred to as the soil cation exchange capacity (CEC) (Havlin et al., 2005). The cation exchange capacity (CEC) is one of the most important properties influencing nutrient availability and retention in the soil (Havlin et al., 2005).

In this experiment, there was a significant ($p = 0.0008$) soil depth * treatment * date interaction for soil pH. Treatments containing elemental S and Fe sulfate as acidifying agents caused a drop in soil pH levels throughout the growing season of 2007 (Figure 5). The $\text{FeSO}_4 + \text{S}$ treatment reduced the pH by the greatest margin in the surface layer (0 – 10 cm) of the soil. Soil pH readings were 6.05, 6.42, 6.6, and 6.43 respectively for the sampling dates in the months of June, July, August, and October as compared to an average control treatment pH of 8.29. The addition of S treatments to the soil was intended to lower the soil pH, rather than to supply S in order to correct a deficiency.

Elemental S added to the soil is oxidized by soil bacteria into sulfuric acid, causing a permanent change in pH resulting in greater availability of micronutrients and phosphorus (Velarde et al., 2005). The majority (12) of essential nutrients have their highest availability at a pH range of 6.5 – 7.0 (Lucas and Davis, 1961). Micronutrients such as Fe, Mn, Zn, and Cu as well as the macronutrient phosphorus have limited availability with pH values above 8

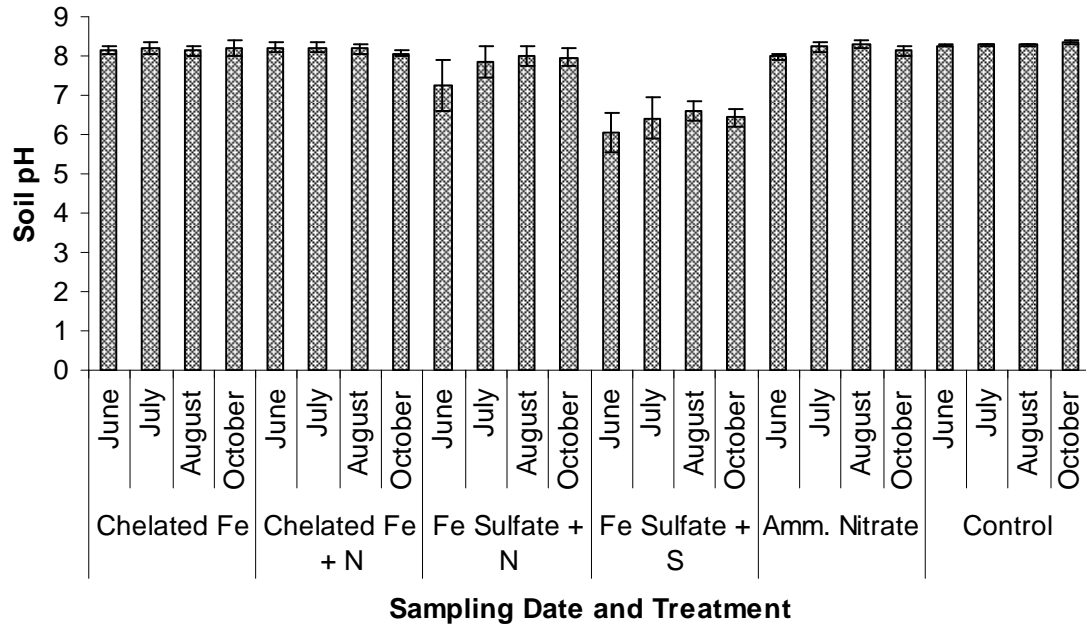
(Velarde et al., 2005). The availability of 12 essential plant nutrients at a broad pH range (4 –10) can be seen in Figure 6 (Miller and Donahue, 1995).

Some of the differences in pH between depth 1 (0 – 10 cm) and depth 2 (10 – 20 cm) and the sampling dates can be explained by the amount of precipitation received during the summer of 2007 (Table 5). Both treatments containing S, FeSO₄ + S and FeSO₄ + N, caused a significant drop in pH during June, which received just slightly above average rainfall. The oxidation of elemental S (S⁰) to sulfate (SO₄⁻²), which in turn lowers soil pH, depends on soil microbial activity, the S source, and soil environmental conditions, namely soil moisture or in this case rainfall (Havlin et al., 2005). Furthermore, large seasonal and year-to-year fluctuations in sulfate can occur due to the influence of environmental conditions on organic S mineralization, downward or upward movement of sulfate in soil water, and sulfate uptake by plants (Havlin et al., 2005). The months of July, August, and September were dry with July and August receiving about one inch (2.54 cm) less rain than normal and September receiving nearly two inches (5.08 cm) less rain than in an average year. This may have influenced pH results for July and August as there was a slight rise in pH followed by stabilization for these months. The final sampling month, October, received nearly average rainfall amounts and also indicated a slight drop in pH in soil depth 1 and in the FeSO₄ + N treatment for soil depth 2.

The addition of nitrogen fertilizer in the form of ammonium nitrate (NH₄NO₃) can also have an effect on soil pH and the chemical form of N taken up by a plant can distinctly influence the rhizosphere pH (Nye, 1981; Gijsman, 1990;

Tang and Rengel, 2003). Nitrogen can be absorbed by plant roots as NH_4^+ or NO_3^- . When plants take up NH_4^+ , they take up more cations than anions into the root cells. Consequently, H^+ is exuded to regulate cytosolic pH and charge balance, and the rhizosphere pH decreases. In contrast, uptake of NO_3^- can cause H^+ influx (or OH^- efflux) with a rhizosphere pH increase (Nye, 1981; Haynes, 1990; Mengel and Kirkby, 2001; Hinsinger et al., 2003). These processes are likely reasons explaining why the ammonium nitrate treatment caused a decrease in soil pH during the wet months of June and October followed by an increase in pH during the dryer months of July and August.

A.



B.

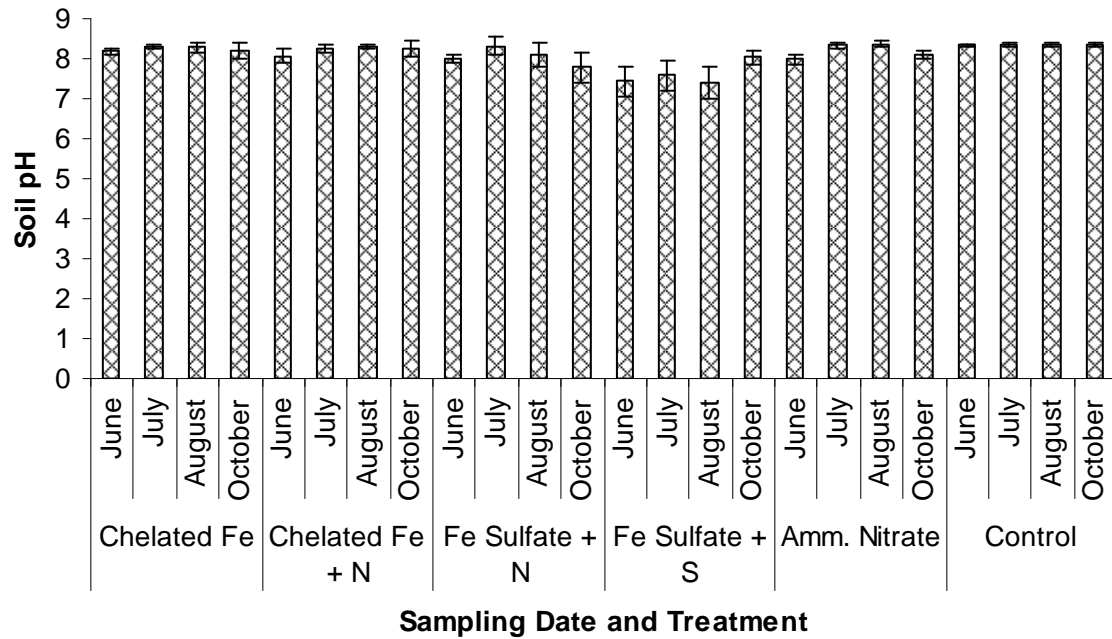


Figure 5. Soil pH (\pm SE) for soil depth 1 (A) and depth 2 (B), * treatment * sampling date during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

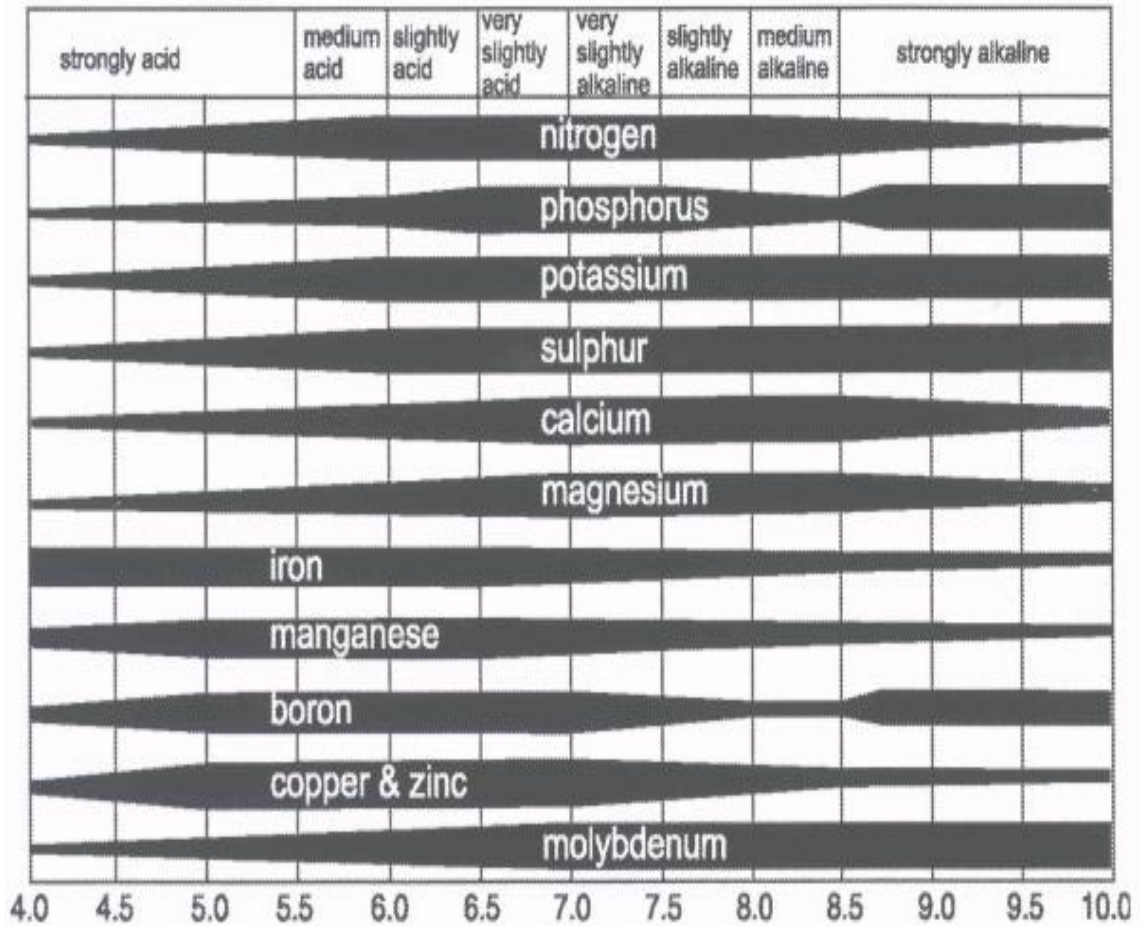


Figure 6. Nutrient availability at pH ranging from strongly acid to strongly alkaline. Adopted from Mengel and Kirkby (2001).

Table 5. Precipitation received June – October 2007 and average precipitation for the central Missouri region (Boone county) approximately 10 miles from Plowboy Bend Conservation Area near Jamestown, MO. (Information courtesy of University of Missouri Extension).

Month	Total Inches	Total Centimeters	Avg. Precip. (Inches)
June	4.23	10.743	4.02
July	2.12	5.385	3.8
August	2.49	6.324	3.75
September	1.62	4.115	3.42
October	2.96	7.519	3.18

FOLIAR AND SOIL MACRONUTRIENTS

Nitrogen

Nitrogen is often the most limiting nutrient in plant growth and it can be utilized by plants as the ammonium cation or the nitrate anion (Miller and Donahue, 1995). It is an important constituent of chlorophyll, plant proteins, and nucleic acids (Havlin et al., 2005). There can be many different forms of N in the soil, but not all forms are available to plant uptake. Atmospheric dinitrogen (N_2) is abundant but is not available to plants until a process called N fixation takes place. Microorganisms in symbiosis with leguminous plants fix gaseous N into organic form in the soil, which in turn can become available to plants (Miller and Donahue, 1995). Organic matter in the soil is broken down or mineralized into ammonium ions available for plant uptake. The breakdown of soil organic matter is the major source of N for non-fertilized soils as it contains approximately 5% by weight of N (Miller and Donahue, 1995).

Nitrogen can also be lost from the soil through leaching and volatilization as a gas. Because NO_3^- is very soluble in water, it can easily be carried away from the rooting zone of soil as rain or irrigation water percolates into the groundwater (Havlin et al., 2005). Usually, the most extensive gaseous N loss is from denitrification, a process occurring in poorly aerated soils in which certain bacteria are forced to use the nitrogen in NO_3^- as an electron acceptor instead of oxygen (O_2) (Miller and Donahue, 1995; Havlin et al., 2005). When this condition occurs, the end products are dinitrogen gas and/or nitrous oxide (N_2O), which volatilize from the soil and into the atmosphere (Miller and Donahue, 1995). The

greatest N loss due to ammonia volatilization occurs when urea or ammonium fertilizers are broadcast applied to the surface of high pH, calcareous soils (Miller and Donahue, 1995). In basic soils, ammonium reacts with calcium hydroxide to form ammonium hydroxide which easily decomposes into ammonia (NH₃) gas (Havlin et al., 2005).

In this study, there were three treatments (chelated iron + ammonium nitrate, iron sulfate + ammonium nitrate, and ammonium nitrate alone) which contained nitrogen fertilizer. Among species, foliar N was significantly different between the control and other treatments except for chelated Fe + N for pin oak and between control and all other treatments for swamp white oak (Table 6). Sampling date * treatment interaction was significant ($p = 0.0321$). The mean foliar nitrogen concentrations for pin oak were 1.93, 1.86, 1.79, and 1.93 percent respectively, for mid-month in June, July, August, and October. Swamp white oak foliar nitrogen concentrations were 1.93, 1.84, 1.79, and 1.61 percent, following the same pattern as pin oak until the October sampling period, where the foliar N concentration in swamp white oak was significantly less than for pin oak (Figure 7). The N concentrations for pin oak and swamp white oak in this study (Figure 7) are below the sufficiency range for healthy pin oak and swamp white oak described by Mills and Jones (1996) in Table 8. Treatment was significant ($p = 0.004$), as the control for both species was significantly lower in foliar N concentration than for all other treatments.

Table 6. Mean separations for treatment effects on foliar macronutrients in pin oak and swamp white oak.

Treatment	N	P	K	S	Mg	Ca
.....%.....						
Pin Oak						
Chelated Fe	1.85ab	.13614a	.66795a	.107913c	.128737d	.306093ab
Chelated Fe + N	1.79abc	.126316abc	.62361ab	.110338c	.156824c	.308387ab
Fe Sulfate + N	1.88ab	.122621bc	.59443bc	.122677ab	.175551b	.321552a
Fe Sulfate + S	1.88a	.136917a	.52754d	.129653a	.199178a	.314613ab
Amm. Nitrate	1.83ab	.119402c	.54867cd	.117808b	.166269bc	.318209a
Control	1.72c	.132226ab	.50021d	.104726c	.140186d	.300681b
Swamp White Oak						
Chelated Fe	1.87a	.174442a	.67587a	.1161a	.15155d	.314214a
Chelated Fe + N	1.84ab	.147384bc	.59932b	.116512a	.18584c	.316141a
Fe Sulfate + N	1.85ab	.15619b	.60112b	.116537a	.19473bc	.322909a
Fe Sulfate + S	1.78b	.140775c	.53837c	.121114a	.2241ab	.326139a
Amm. Nitrate	1.80ab	.135106c	.5582bc	.118633a	.21825b	.313296a
Control	1.58c	.15434b	.59238b	.105454b	.23217a	.312779a
S x T*	0.0734	0.1934	0.2411	0.0126	0.7836	0.2473

*p-values at species x treatment interaction

Different letters denote significant ($p < 0.05$) differences between treatments. Mean separations are results from separate ANOVA by individual species.

Table 7. Mean separations for treatment effects on selected foliar micronutrients/heavy metals in pin oak and swamp white oak.

Treatments	Fe	Mn	Mo	Cu	Zn	Na	Al
.....ppm.....							
Pin Oak							
Chelated Fe	63.65b	22.12d	.53b	6.12ab	51.31b	61.17c	60.49ab
Chelated Fe + N	55.93b	36.73cd	.76ab	4.99c	54.94b	111.93ab	54.81b
Fe Sulfate + N	88.61a	77.25b	.95a	6.76a	59.99b	101.28ab	69.26a
Fe Sulfate + S	63.15b	144.22a	.80ab	6.73a	74.6a	123.93a	64.32ab
Amm. Nitrate	66.74b	50.27c	.83ab	5.74bc	52.22b	89.73abc	62.35ab
Control	95.67a	53.68bc	.79ab	4.96c	52.8b	86.59bc	67.41a
Swamp White Oak							
Chelated Fe	101.05a	15.82d	0.93a	7.08b	33.59ab	89.39b	75.092b
Chelated Fe + N	66.98c	28.32c	0.98a	5.72c	29b	163.22a	66.331bc
Fe Sulfate + N	90.76ab	41.08b	1.02a	7.01b	31.41ab	59.05c	90.403a
Fe Sulfate+ S	72.88bc	54.16a	1.21a	6.41bc	36.93a	132.59a	63.695c
Amm. Nitrate	78.3bc	41.85b	0.92a	6.15c	35.45ab	157.55a	62.25c
Control	76.08bc	39.89b	1.12a	8.03a	29.39ab	136.35a	71.794bc
S x T*	0.2768	0.0126	0.456	0.1663	0.3932	0.7101	0.5221

*p-values at species x treatment interaction

Different letters denote significant ($p < 0.05$) differences between treatments.

Mean separations are results from separate ANOVA by individual species.

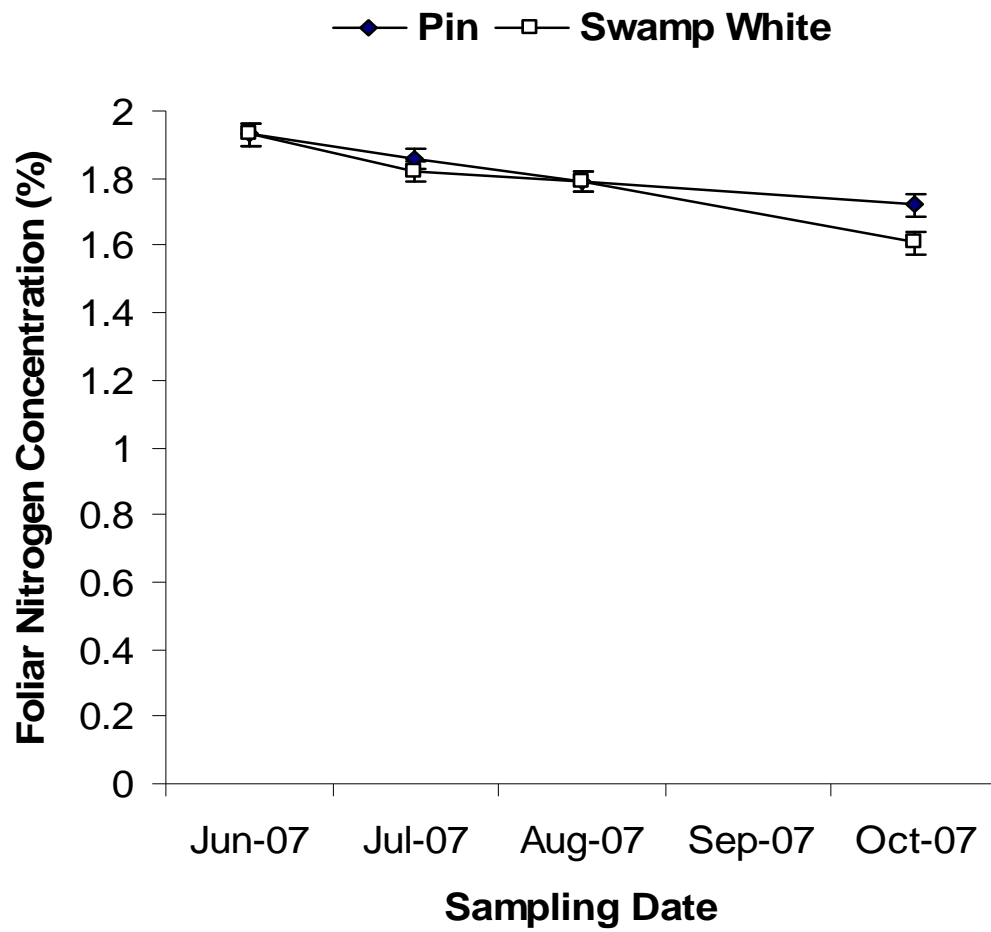


Figure 7. Mean foliar nitrogen concentration across treatments (\pm SE) for pin oak and swamp white oak during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

Specific information on desirable soil nutrient levels for pin oak and swamp white oak was not located from literature searches. One explanation for the relatively low foliar N content in both species is likely associated with the Sarpy Fine Sand soils at Plowboy Bend. The sandy nature of this soil could allow nitrate from the fertilizers to leach out of the rooting zone of the seedlings as rain water percolates downward into the water table. Furthermore, the hydric nature of these soils has the potential to create an anaerobic environment in which N would be lost from denitrification and volatilization. In addition, the ammonium fertilizer in this study was broadcast applied onto a weed mat and at the surface of a high pH (8.29), calcareous soil. The fertilizer treatments were therefore exposed to elements responsible for causing atmospheric losses at the soil's surface and were totally dependent on precipitation to dissolve and incorporate them into the soil. A combination of the factors above could have reduced the ability of the N fertilizer treatments to have a great effect on the swamp white and pin oak seedlings.

Regardless of concentration, foliar N decreased throughout the 2007 growing season. The earliest foliar sample reading (1.93), which was taken in June, was the highest. This could be expected as these leaves were just newly matured at the end of May and would likely contain the higher amounts of N common to new foliar flush tissue (Scherzer et al., 2003). Because most of the elements essential to plant growth, including N, are assimilated through root absorption of ions from the soil solution (Jungk, 1996), the unusually dry months of July and August, 2007 would not have been very conducive to the uptake and

assimilation of nutrients. Gradually decreasing mean foliar N content for July and August reflect this point. The lowest mean foliar N reading (1.61%) for swamp white oak could have been a combination of continued dry weather during September and an effect of sampling date. Since concentrations can vary considerably throughout a growing season, the timing of sampling is critical. Deciduous foliage should be sampled after full leaf expansion but before appreciable redistribution of nutrients in late summer or autumn (Walker, 1991). The translocation of about 50 to 90% (Aerts, 1996, Tagliavini et al., 1998) of foliar nutrients to stems occurs 3 to 4 weeks prior to leaf abscission (van den Driessch, 1984). Although only green leaves were sampled from the trees during the October sampling period, as had been done in previous months, the translocation of mobile nutrients (N, P, K, Mg) was most likely occurring, resulting in lower foliar nutrient concentrations for swamp white oak leaves (Scherzer et al., 2003).

Inherent differences among a species play an important role in the absorption and utilization of mineral nutrients from the soil (Goddard and Hollis, 1984) which can result in differences in foliar nutrient concentrations and in the allocation of minerals within a tree (Scherzer et al., 2003). Perhaps swamp white oak begins the translocation of foliar nutrients earlier than pin oak.

Table 8. Foliar sufficiency ranges of macro and micronutrients from healthy swamp white oak (A) and pin oak (B) trees grown in a field research plot setting. (Nutrient values taken from Mills and Jones, 1996.)

A) Swamp White Oak

Macronutrients	percent (%)
Nitrogen	2.02 - 2.29
Phosphorus	0.15 - 0.26
Potassium	1.15 - 1.20
Calcium	0.33 - 1.07
Magnesium	0.13 - 0.31
Sulfur	0.13 - 0.16
Micronutrients	parts per million (ppm or mg/kg)
Iron	47 - 149
Manganese	121 - 323
Boron	23 - 52
Copper	8.0 - 10
Zinc	16 - 26
Molybdenum	0.05 - 0.12
Nonessential Elements	parts per million (ppm or mg/kg)
Sodium	39
Aluminum	55

B) Pin Oak

Macronutrients	percent (%)
Nitrogen	2.79 - 2.85*
Phosphorus	0.16 - 0.39
Potassium	0.76 - 1.25
Calcium	0.40 - 1.36
Magnesium	0.14 - 0.28
Sulfur	0.16
Micronutrients	parts per million (ppm or mg/kg)
Iron	45 - 180
Manganese	218 - 633
Boron	19 - 122
Copper	7.0 - 38
Zinc	29 - 88
Molybdenum	0.02 - 1.58
Nonessential Elements	parts per million (ppm or mg/kg)
Sodium	29 - 34*
Aluminum	15 - 51*

* indicates values were obtained from nursery/arboretum trees.

Phosphorus

Phosphorus is second only to nitrogen as the most often deficient nutrient in plant growth (Miller and Donahue, 1995). The most important function of P within a plant is energy storage and transfer in adenosine di- and triphosphates, and also plays a major role in the construction of DNA and proteins (Havlin et al., 2005). Because of its role in proteins and nucleotides, adequate P is associated with increased root growth, strong stem development, and proper development of reproductive parts (Havlin et al., 2005).

The major problem with getting soil P into plant tissue is that the supply of phosphorus in most soils is low and that the phosphates within the soil are often held in forms that are unavailable to plants (Miller and Donahue, 1995). Plants are able to absorb orthophosphate, an ion which quickly reacts in the soil, depending on pH, to form insoluble phosphates. In acid soils, phosphate ions bind to Fe and Al ions or adsorb to the surfaces of insoluble Fe, Al, and Mn hydroxides to form insoluble phosphates (Miller and Donahue, 1995). Alkaline and calcareous soils, like the soil encountered in this study, cause soluble phosphate ions to form low solubility calcium triphosphate or be adsorbed onto solid calcium carbonate surfaces (Miller and Donahue, 1995). Phosphorus is most available in mineral soils at a pH of around 6.5 (Havlin et al., 2005).

It is believed that many of the natural P used by plants comes from organic phosphates released by the break down of soil organic matter because there is no efficient mechanism by which the soil is able to retain sufficient

quantities of exchangeable (H_2PO_4^- or HPO_4^{2-}) phosphate ions (Miller and Donahue, 1995).

In main treatment effects, foliar P in pin oak leaves was significantly higher with the $\text{FeSO}_4 + \text{S}$ and chelated Fe treatments than for all other treatments. Swamp white oak foliar P was highest for the chelated Fe treatment and lowest for the $\text{FeSO}_4 + \text{S}$ and (N) ammonium nitrate treatments (Table 6).

There was a significant ($p = 0.0044$) interaction at the species * date * treatment level for mean foliar P concentration during the 2007 growing season. Foliar phosphorus concentration for swamp white oak ranged from 0.116 to 0.216% which was higher throughout the season than that of the pin oak which ranged from 0.103 to 0.191% (Figure 8). The majority of the mean foliar P values for both pin oak and swamp white oak are low or below the sufficiency ranges given for these species (Table 8).

According to Mills and Jones (1996), both the addition of ammonium nitrate fertilizers and changes in the soil pH can increase P uptake and the P concentration in the foliage of plants. In this study, the pH was reduced by treatments containing S, while N was added to the soil in other treatments containing ammonium nitrate. While lowering soil pH does improve the availability of soil P for plant uptake, it can also increase the risk of P absorption by Fe/Al oxides (Havlin et al., 2005). Conversely, as soil pH increases above 7.0, Ca^{+2} precipitates with P and decreases the P availability to plants (Havlin et al., 2005). The soil environment is constantly changing due to factors such as pH, soil moisture/temperature, and organic matter content and consequently the

availability of nutrients held in the soil are dynamic in their availability. Adding fertilizers containing various mineral nutrients, as was done in this study, further complicates the interactions among nutrients in the soil. One would hypothesize that in this study trees fertilized with N and S containing fertilizers that lowered pH would have consistently higher foliar P concentrations. This was not the case, however, as high levels of foliar P were present in both tree species for the treatments of chelated Fe and control, both of which had no effect on soil pH.

Because foliar P is a mobile nutrient, one might expect that its levels in fall oak tree foliage would be tapering off, as is the pattern in black walnut foliage, Ponder et al. (1979), due to translocation before leaf senescence. As the sampling season progressed, factors such as moisture stress, nutrient deficiency, and leaf age could also have had an impact on leaf quality and nutrient content (Mills and Jones, 1996). Regardless, it is apparent that the study trees had not yet begun to translocate foliar phosphorus out of the leaves and into other tree parts by sampling time in October of 2007.

The total soil P concentration was significant by depth ($p = 0.0001$) and by treatment ($p = 0.0031$). Total soil phosphorus concentration means were 0.0425% for soil depth 1 (0 – 10 cm) and 0.0405% for soil depth 2 (10 – 20 cm) during the 2007 growing season (Figure 9). It is common for soil P levels to be higher in the first 10 cm of the soil surface because it is relatively immobile and that is where the majority of the soil organic matter can be found (Miller and Donahue, 1995). Organic P represents about 50% of total soil P in soils and typically varies between 15 to 80%. Like organic matter, soil organic P

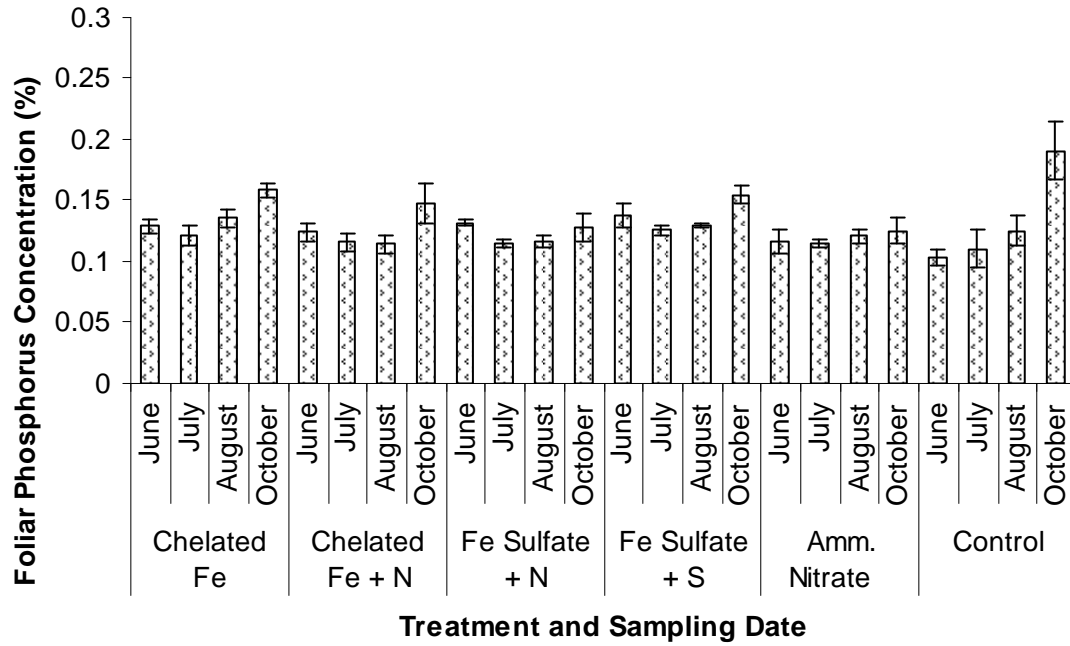
decreases with depth and its distribution varies in the soil, with organic matter P content ranging from 1 to 3% (Havlin et al., 2005). Organic phosphates are broken down by soil microorganisms into other organic compounds which are then mineralized into plant available inorganic P (Havlin et al., 2005).

Total soil P concentration varied by treatment from a range of 0.0403% to 0.0434% across soil depths (Figure 10). The treatments containing chelated iron had the highest total soil phosphorus concentrations. These findings are consistent with the literature as Fe is believed to interfere with the absorption, translocation, and assimilation of phosphorus by forming iron phosphates (Mills and Jones, 1996). Treatments containing Fe sulfate, elemental S, and ammonium nitrate recorded the three lowest total soil P concentrations.

According to Mills and Jones (1996), in alkaline soils ammonium-based fertilizers increase P availability because of their acidifying effect. Iron sulfate and the sulfate resulting from oxidation of elemental S by soil microbes also contribute to increased P availability by the acidifying effect they have on the soil (Havlin et al., 2005). The control treatment had a mean soil P concentration of 0.0415% which is roughly in the middle of the range given above for P.

Apparently, treatments containing Fe reacted with soil P, perhaps forming Fe phosphates, making it unavailable to the trees and thereby increasing its total concentration in the soil. By contrast the S and N treatments, whose effect on soil properties such as pH should have made more of the total soil P available for the tree's roots to absorb, were neither absorbed in greater amounts by the trees nor held in the soil.

A.



B.

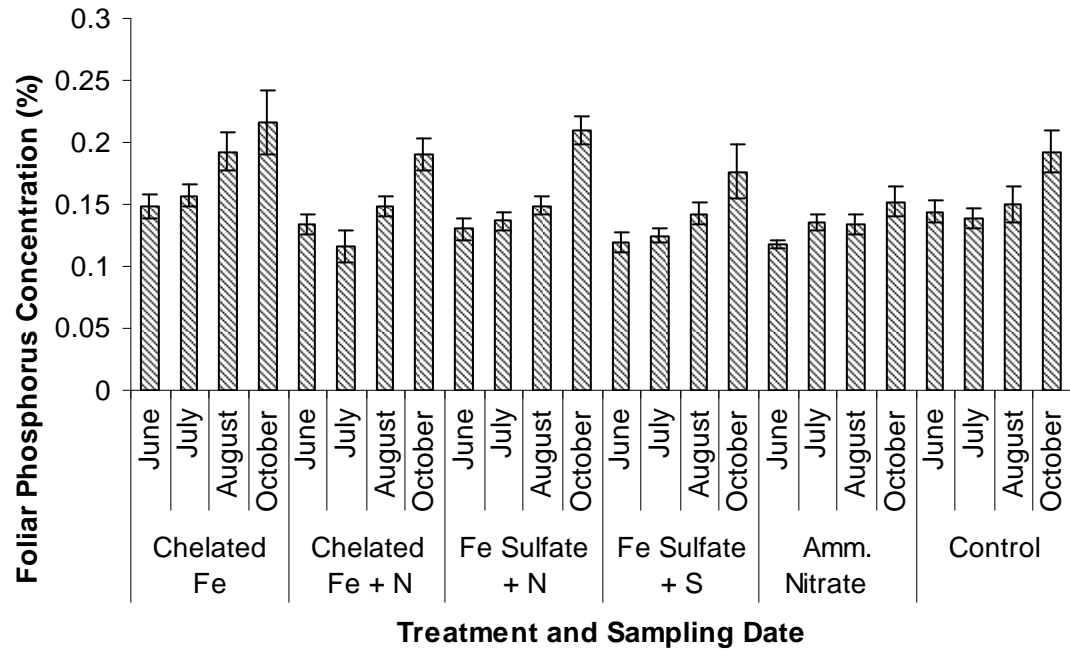


Figure 8. Mean foliar phosphorus concentration (\pm SE) by species * treatment * sampling date for pin oak (A) and swamp white oak (B) during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

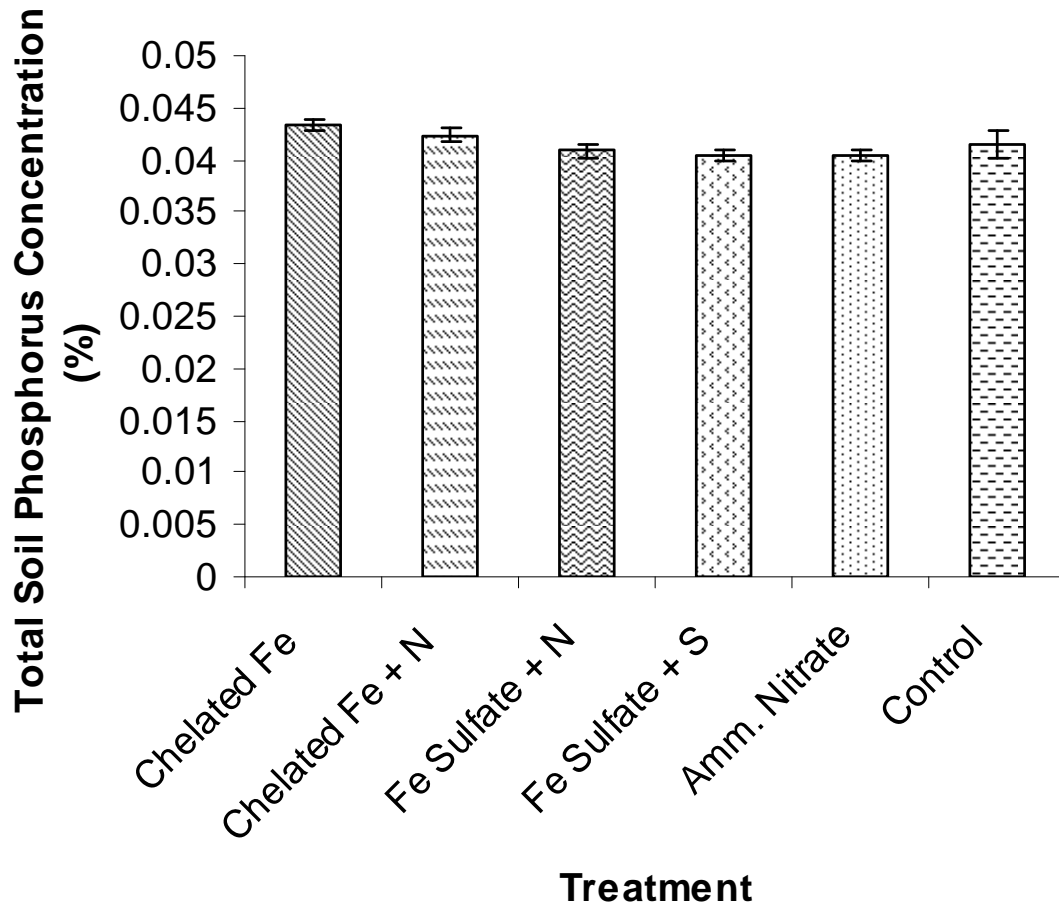


Figure 9. Total soil phosphorus concentration (\pm SE) by treatment across both species during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

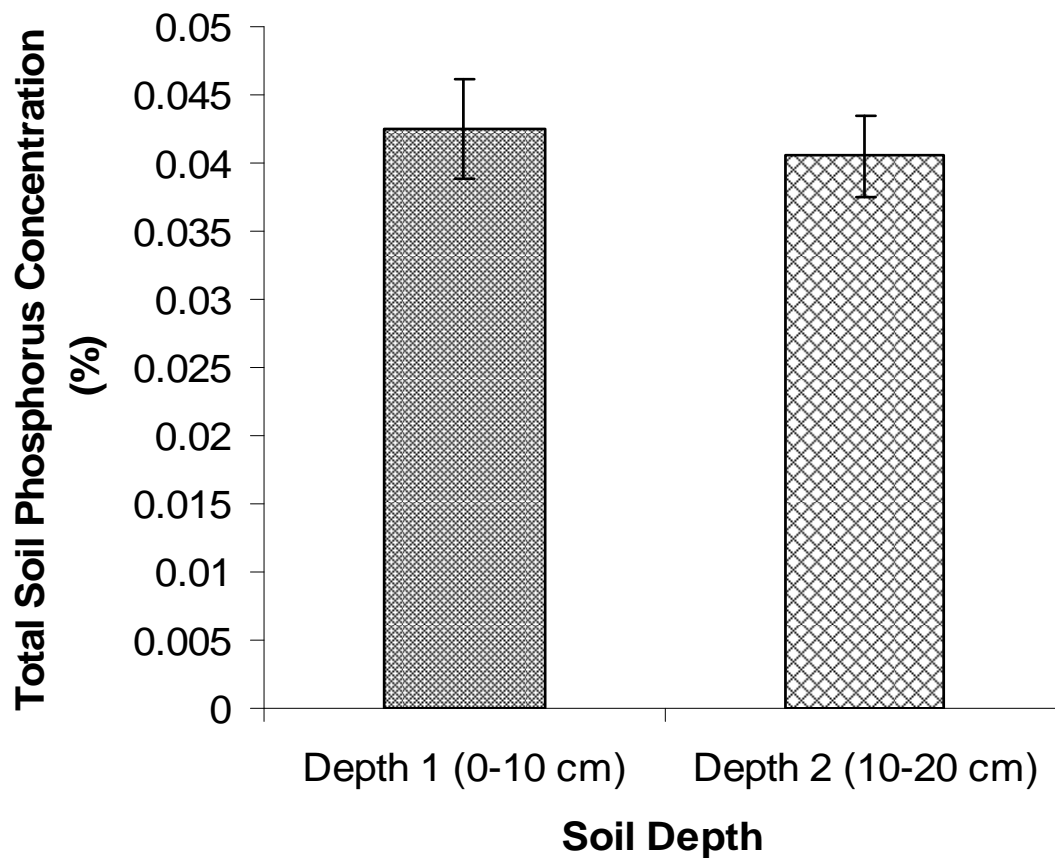


Figure 10. Total soil phosphorus concentration across treatments (\pm SE) at depth 1 (0 – 10 cm) and depth 2 (10 – 20 cm) during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

Potassium

Potassium is an essential element absorbed by plants in amounts second only to nitrogen (Havlin et al., 2005). Potassium has many essential roles within higher plants such as oak trees. Potassium is involved in maintaining plant water status, cell turgor pressure, and controlling the opening and closing of stomata. Since the opening of stomata affects the availability of carbon dioxide, K has an indirect control over photosynthetic activity (Mills and Jones, 1996). Other important functions of K include the activation of enzymes, the translocation of photosynthates, and the synthesis of cellulose, a key building block of every plant cell wall (Havlin et al., 2005).

Potassium is absorbed by a plant's roots in the ionic form of K^+ , mainly through diffusion (Mills and Jones, 1996). The total amount of K found in most soils is sufficient to last several decades, even centuries, yet the low solubility of soil micas and feldspars (the soil minerals that contain K) supply only very small amounts of it during a growing season (Miller and Donahue, 1995). Soil organic matter contributes only a minute fraction of the plant available potassium (Miller and Donahue, 1995). The problem with soluble K^+ is that it is quickly captured on exchange sites on clay particles and humus after leaching into the soil solution from decaying organic matter (Havlin et al., 2005).

Several environmental factors affect the availability and movement of K including soil moisture, soil aeration, and soil pH. Because K moves from the soil to the roots mainly by diffusion, higher soil moisture reduces tortuosity and improves the rate of K^+ diffusion (Havlin et al., 2005). According to Mills and

Jones (1996), K uptake is affected by the oxygen level in the soil, more so than most other elements. High soil moisture and/or compacted soils restrict root growth and reduce soil oxygen supply, therefore reducing K absorption (Havlin et al., 2005). Maintaining a soil pH of 6 - 6.5 helps prevent K losses (Miller and Donahue, 1996). Soils which are too acidic contain toxic amounts of exchangeable Al^{+3} and Mn^{+2} , creating an unfavorable root environment for nutrient (namely K^{+}) uptake (Havlin et al., 2005). Conversely, alkaline or calcareous soils contain large quantities of Ca^{+2} and Mg^{+2} , both of which compete directly with K for uptake (Mills and Jones, 1996). Thus, the availability of K^{+} is somewhat more dependent on its concentration relative to that of Ca^{+2} and Mg^{+2} than on the total quantity of K^{+} present in the soil (Havlin et al., 2005).

Main treatment effects for both pin oak and swamp white oak foliar K were highest in the chelated Fe treatment. Pin oak was lowest in foliar K for the control treatment while the lowest reading in swamp white oak was for the FeSO_4 + S and ammonium nitrate treatments (Table 6). The foliar K concentration was significant ($p = 0.0079$) for the species * date interaction. In the study, swamp white oak had a foliar K concentration range of 0.519% in October to 0.672% in July of 2007 (Figure 11). These amounts are nearly two times below the normal foliar K concentration range of 1.15 – 1.2 (Table 8) for healthy swamp white oak. Pin oak foliage was also deficient in K with a range of 0.536% in October to 0.617 in August (Figure 11). Healthy pin oak foliar K ranges from 0.76% to 1.25% (Table 8). The uptake of K was similar for both species, with pin oak responding slower and absorbing less K than swamp white oak during the first

few months of the sampling period. The only significant difference in the two species came in the month of July as swamp white oak foliage peaked in its foliar K concentration. The spike in K concentration likely arose from an increased rate of diffusion from June rains and perhaps the influence of lowered pH in some of the treatments.

Total soil K concentration was significant ($p = 0.0001$) for the treatment * date interaction (Figure 12). In both treatments containing S, total K concentration was lower in the dry months of July and August than they were for the months of June and October which received normal amounts of precipitation. Treatments containing chelated Fe followed the same trend in total soil K concentration levels as the treatments with S. As mentioned before, S applications lower soil pH which in turn causes K to become more available for plant uptake, perhaps explaining the lower amounts of soil K in July and August of the sampling periods.

Also, the source of N has an influence on the accumulation of K. Mills and Jones (1996) reported that N sources which caused an increase in nitrate-N levels promoted K accumulation, while ammonium-N tended to depress K concentration, especially in soil-grown plants. These authors also reported that when applying N in the combination form of ammonium nitrate, the resulting interaction with K and how it affects K availability is highly variable (Mills and Jones, 1996). This variability can be seen in the treatments of chelated Fe + nitrogen and ammonium nitrate only (Figure 12).

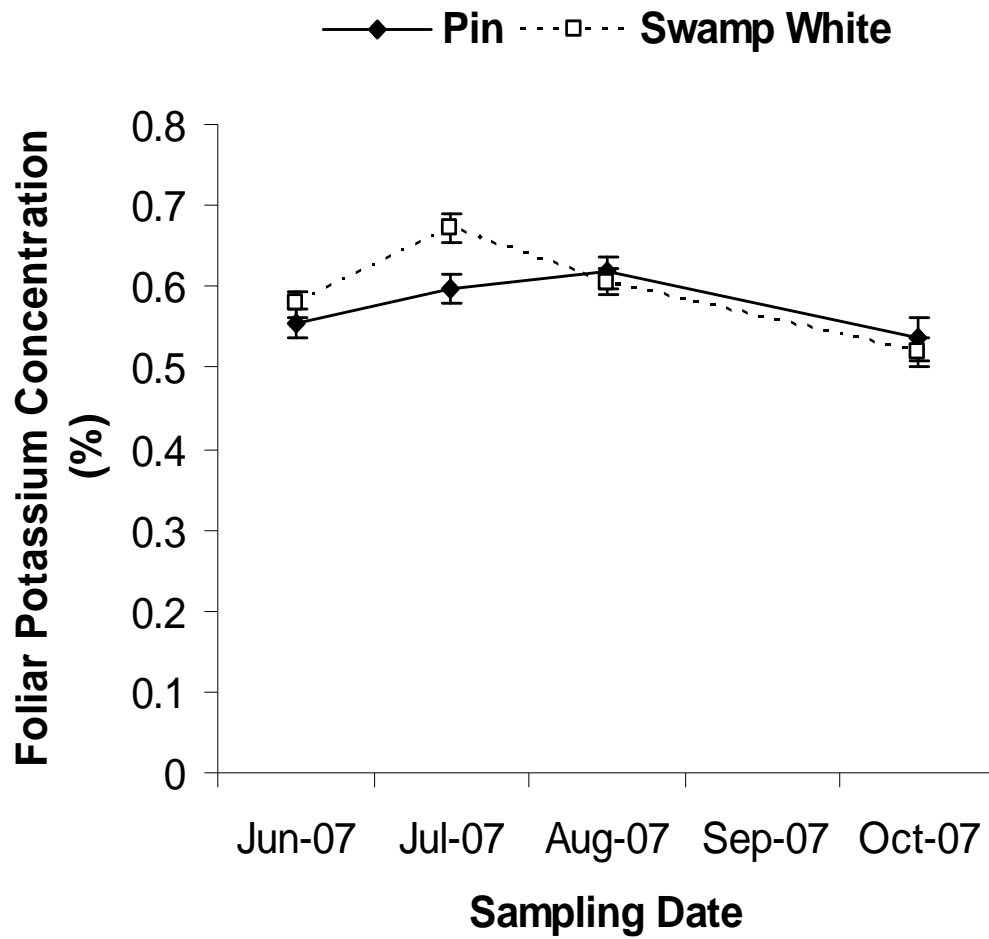


Figure 11. Mean foliar potassium concentration across treatments (\pm SE) by sampling date for pin oak and swamp white oak during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

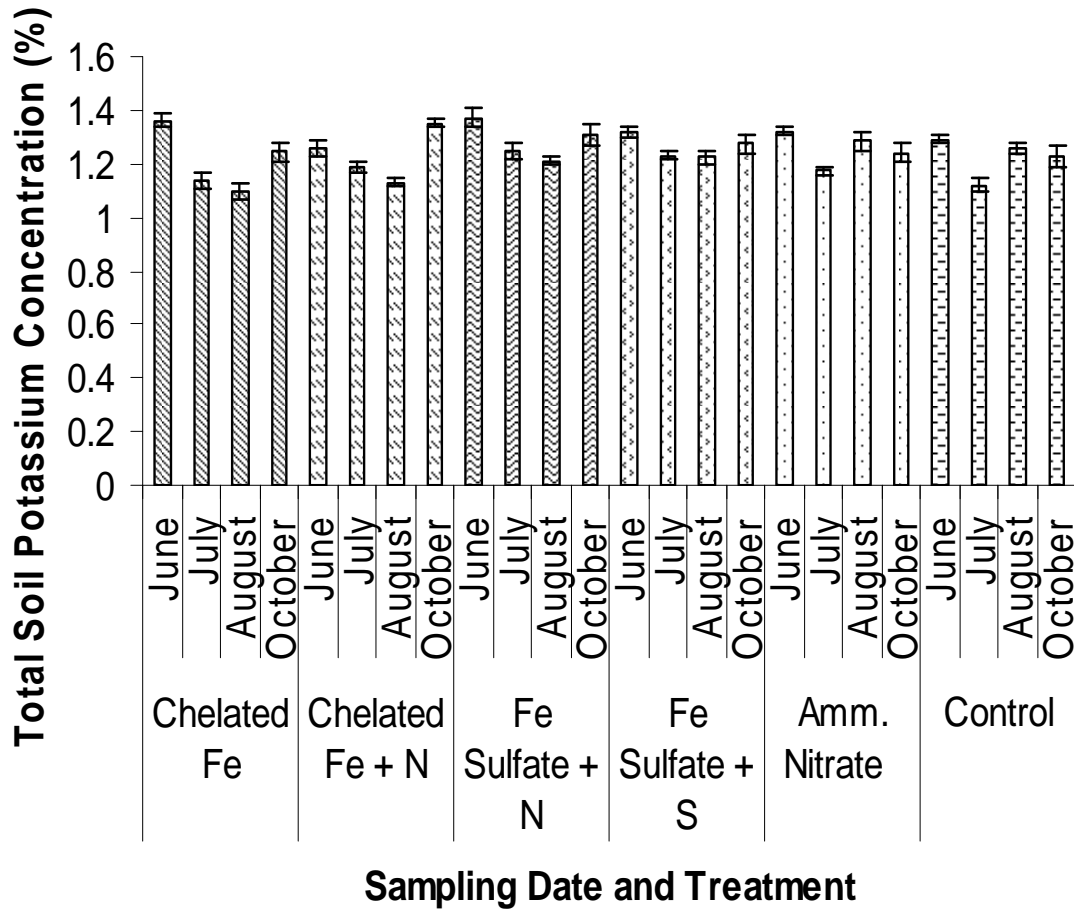


Figure 12. Total soil potassium concentration (\pm SE) by treatment * sampling date across both species during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

Sulfur

Sulfur reactions in the soil are similar to those of N and are dominated by organic and/or microbial fractions in the soil (Havlin et al., 2005). Sulfur is required in plants for the synthesis of amino acids and fatty acids as well as disulfide bonds between polypeptide chains (Miller and Donahue, 1995). Sulfur containing amino acids like cystine and methionine are essential components of protein and comprise about 90% of S found in plants (Havlin et al., 1996).

Plants take up S in the form of sulfate (SO_4^{-2}) with over 90% of the available S being found in association with organic matter (Mills and Jones, 1996). Other sources of S are acid rain, Fe and Al oxides, and clay minerals containing S compounds (Miller and Donahue, 1995). Large seasonal and year to year fluctuations in SO_4^{-2} can occur due to the influence of environmental conditions on organic S mineralization, downward or upward movement of SO_4^{-2} in soil water, and SO_4^{-2} uptake by plants (Havlin et al., 2005). Sulfur is mobile in the soil and can therefore be readily taken up by plants or leached. Increases in soil acidity reduce sulfate leaching while sulfate absorption decreases with increasing pH and is negligible above a pH of 6.5 (Mills and Jones, 1996).

Elemental S is a water-insoluble solid which is oxidized to sulfate by microorganisms when finely ground and mixed with the soil (Havlin et al., 2005). Chemical reactions in the soil from elemental S and sulfate oxidation liberate diluted sulfuric acid and lowers soil pH (Mills and Jones, 1996). Studies conducted by Messenger (1990) on pin oaks in calcareous, alkaline soils suggested that adding sulfur treatments to acidify the surface rooting zone and/or

the planting hole could stimulate height and diameter growth due to the prevention of leaf chlorosis. Sulfur fertilizers were also found to decrease soil pH and increase the availability and uptake of several micronutrients by Argentine mesquite (*Prosopis alba*) in calcareous soils in Argentina (Velarde et al., 2005).

Among species, foliar S was lowest in the control and significantly different than all other treatments in swamp white oak. Furthermore, both species had the highest foliar sulfur concentration when treated with $\text{FeSO}_4 + \text{S}$ (Table 6). Foliar S concentration was significant ($p = 0.0442$) for species * treatment * sampling date (Figure 13). In general, swamp white oak was slightly higher in foliar S than pin oak in June, July, and August of the 2007 growing season. Across all treatments, swamp white oak began to drop off in foliar S concentration by October. Pin oak mainly followed the same trends as swamp white oak except for the treatments of $\text{FeSO}_4 + \text{S}$ and control where foliar S increased through the mid-October sampling date. Pin oak was significantly higher in foliar S concentration than swamp white oak for the month of October when treated with $\text{FeSO}_4 + \text{S}$ and in June when treated with $\text{FeSO}_4 + \text{N}$.

The effect $\text{FeSO}_4 + \text{S}$ on foliar S concentration in the study was more apparent at the date * species interaction ($p = 0.0066$) (Figure 14). Both swamp white oak and pin oak followed similar patterns in foliar S concentration from June to August, but while the S level in pin oak leaves continued to increase through the October sampling date, swamp white oak foliar S level dropped significantly from 0.118 to .0109% from August to October. Two factors likely influencing the downward trend of S in swamp white oak leaves were the

combination of moisture stress and earlier nutrient resorption of nutrients before leaf senescence. Because sulfate moves into a plant via diffusion and mass flow, soil moisture content plays a key role in its uptake (Miller and Donahue, 1995). Several months of the 2007 growing season were exceedingly dry, especially August and September. This alone, however, does not explain why pin oak continued to assimilate foliar S while swamp white oak did not. It is widely known that pin oaks will “hold on” to their leaves significantly longer than many other species of oak trees, including swamp white oak. In addition, moisture and nutrient stress has a bearing on tree physiology and may magnify the resorption process of foliar nutrients (Aerts, 1996; Tagliavini et al., 1998). Water stressed plants were found to coincide with higher levels of N resorption in northern red oak (*Quercus rubra*), suggesting that the resorption process may have evolved as a mechanism for N conservation at low soil fertility (Salifu and Jacobs, 2006). Therefore the combination of moisture stress and early resorption of the stressed swamp white oak is believed to have caused the sharp drop in foliar S concentration.

It is important to note that all mean foliar S values for both pin oak and swamp white oak are below sufficiency values given for the two species (Table 8).

The total soil S concentration had a significant ($p = 0.0001$) interaction for the depth * treatment level (Figure 15). The treatment containing sulfate and elemental S significantly raised the S concentration at both depths. Iron sulfate + elemental S raised soil S levels higher than any treatment at soil depths 1 and 2.

Furthermore, soil treated with Fe sulfate + S recorded significantly higher soil S concentrations in the top 10 cm of soil than at sampling depth 2. The treatment Fe sulfate + elemental S at depth 1 (0 – 10 cm) recorded the only mean soil S value (0.07%) that is within the average normal soil S range (0.06% – 0.1%) (Havlin et al., 2005). Fertilizer treatments which did not contain S recorded values ranging from 0.017% to 0.02%, well below the average soil S range. Clearly, the S containing fertilizer treatments had a positive impact on total soil S concentration and, as expected, were more pronounced in depth 1 of the soil due to surface application.

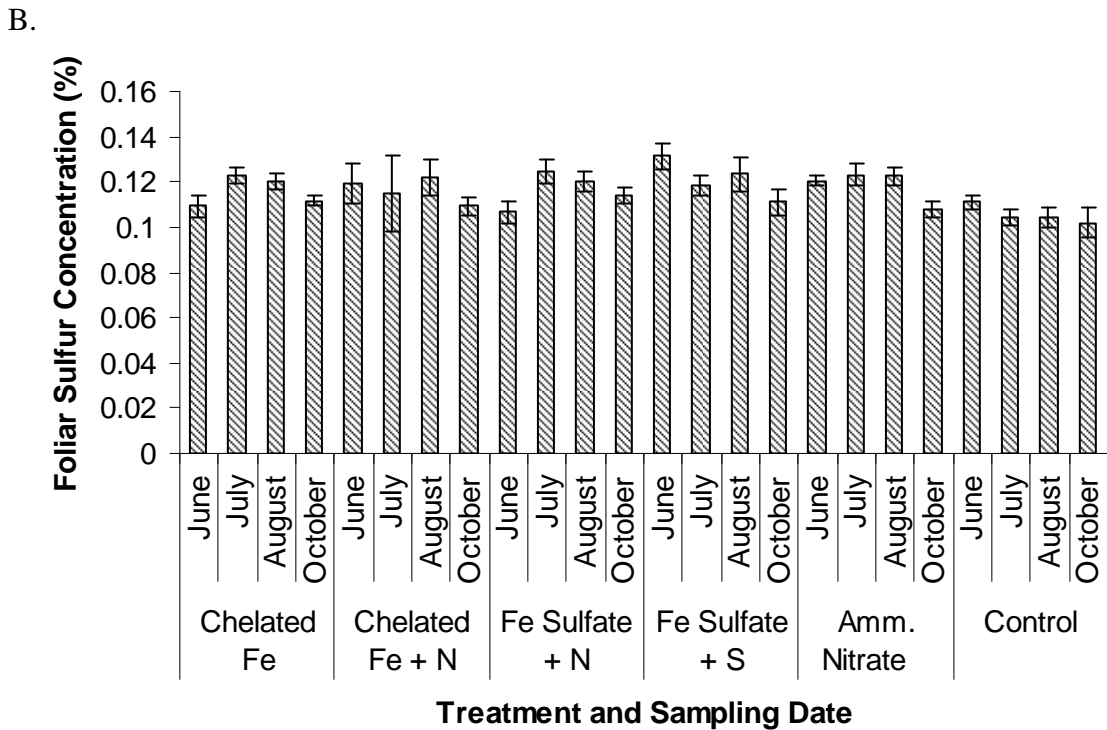
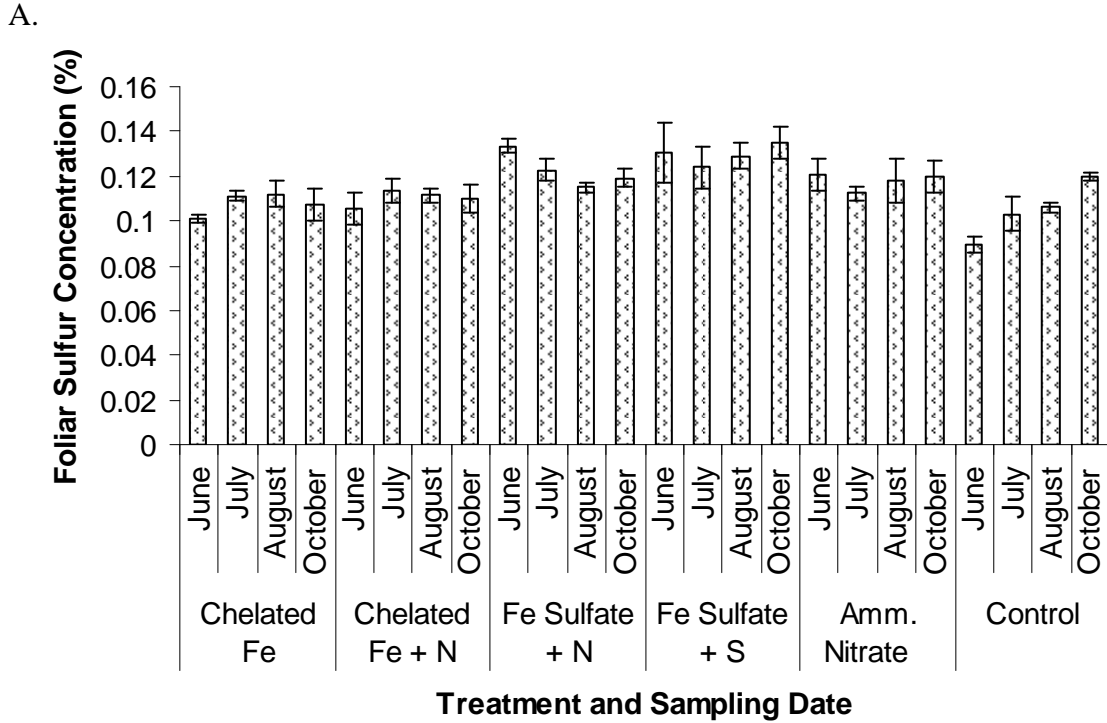


Figure 13. Foliar sulfur concentration (\pm SE) by species * treatment * sampling date for pin oak (A.) and swamp white oak (B.) during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

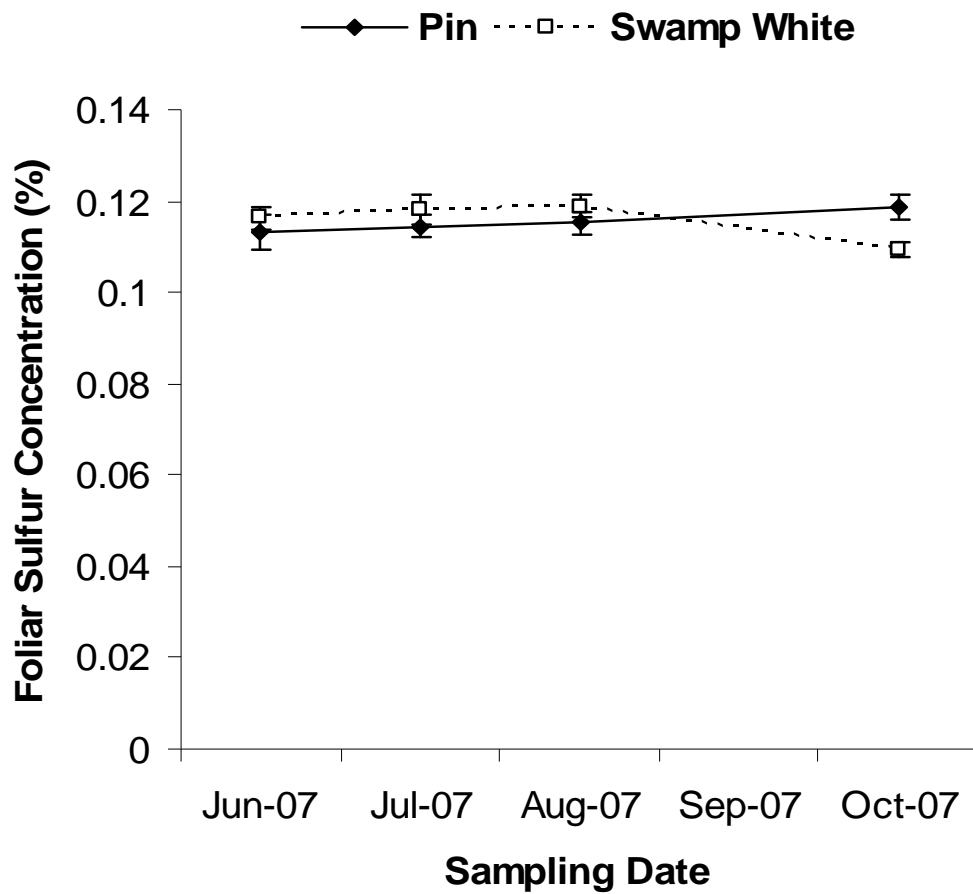


Figure 14. Mean foliar sulfur concentration across treatments (\pm SE) for pin oak and swamp white oak during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

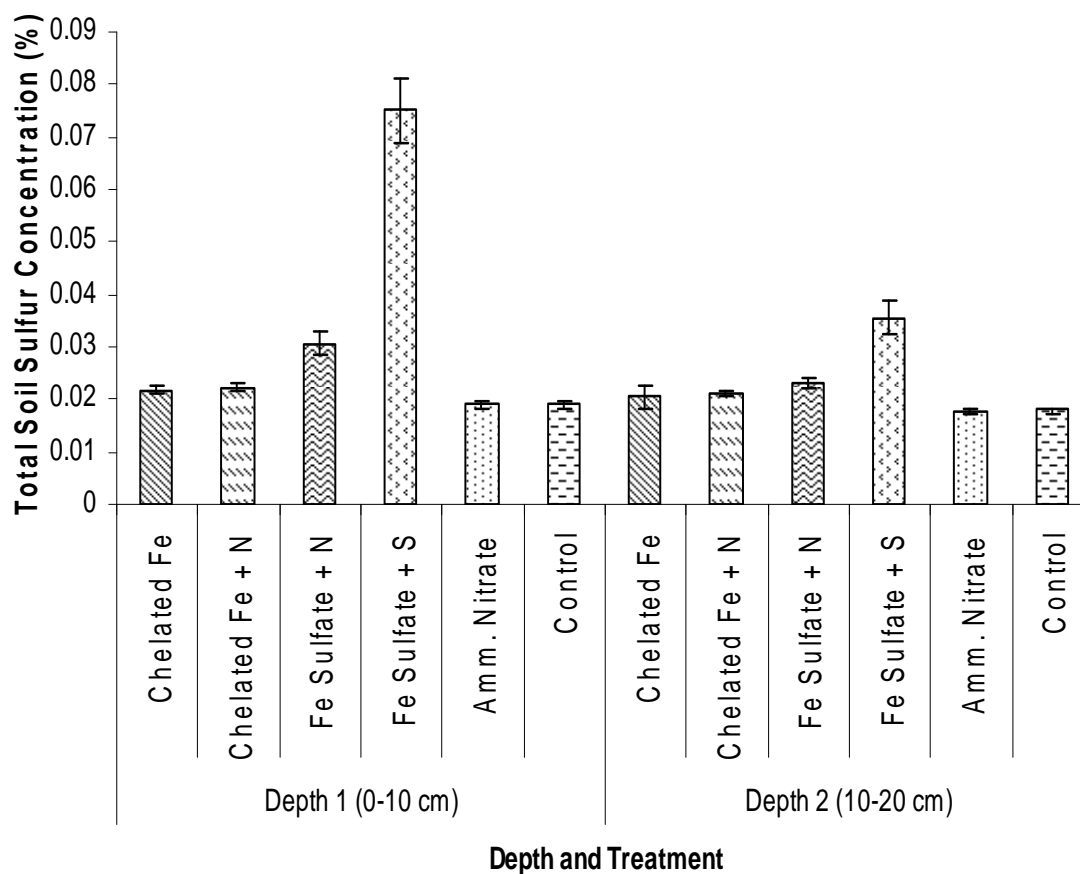


Figure 15. Total soil sulfur concentration (\pm SE) by treatment * depth across both species for the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

Magnesium

Magnesium occurs predominantly as exchangeable and solution Mg^{+2} and its absorption by plants depends on the amount of solution Mg^{+2} , soil pH, % Mg saturation on the CEC, quantity of other exchangeable ions, and the type of clay (Havlin et al., 2005). Magnesium is very mobile both in the soil and in plant tissue (Miller and Donahue, 1995).

In the soil, Mg moves mainly by mass flow mediated by ionophores down an electrochemical gradient. The involvement of ionophores may explain the effect cation competition from ammonium, K, Ca, and Na on Mg uptake (Mills and Jones, 1996). This means that when other cations, especially K, ammonium, and Ca are much more abundant in the soil, they compete directly with Mg for uptake into the plant. Magnesium uptake is strongly influenced by pH and its availability to plants strongly declined with a pH of 5.5 or lower (Mills and Jones, 1996). Although Mg constitutes 1.93% of the earth's crust, the total soil Mg content ranges from 0.1% to 4% (Havlin et al., 2005).

In the plant, Mg is a mobile nutrient with deficiency first showing in the older leaves and then moving on to younger growth. Magnesium is an important part of the chlorophyll molecule, is associated with the anions malate and citrate, and acts as a stabilizing agent for phosphoryl groups in ADP and ATP (Mills and Jones, 1996).

Swamp white oak foliar Mg main treatment effects were significant between chelated Fe and all other treatments. The $FeSO_4 + S$ treatment was significantly different than all other treatments for pin oak. In general, both

species had the lowest foliar Mg levels when treated with chelated Fe and the highest foliar Mg concentrations when treated with $\text{FeSO}_4 + \text{S}$ (Table 6). Foliar Mg concentrations were significant ($p = 0.0003$) for the sampling date * treatment interaction (Figure 16). Foliar Mg concentration for both species was higher in June than in October when treated with chelated Fe. Foliar Mg followed similar trends when treated with $\text{FeSO}_4 + \text{N}$ and $\text{FeSO}_4 + \text{S}$, as foliar Mg concentration rose steadily from June to August and then began to decrease by the October sampling date. Foliar Mg concentration was significantly lower in June when treated with ammonium nitrate than for all other treatments. The Mg levels in the foliage increased throughout the growing season and gradually declined in October at the onset of autumn. Perhaps the most important response from the treatments was that the increase in foliar Mg concentration was greatest in the treatments of $\text{FeSO}_4 + \text{N}$ and $\text{FeSO}_4 + \text{S}$. These treatments lowered soil pH significantly more than the other treatments and thereby improved the absorption of Mg.

Pin oak had a significantly ($p = 0.0001$) higher foliar Mg level than swamp white oak for the species level interaction (Figure 17). Swamp white oak may have had lower levels of Mg, a highly mobile element dependant on soil moisture and mass flow, for the same reasons it experienced low levels of S later in the year. Swamp white oak under moisture stress and undergoing earlier nutrient resorption would be expected to have lower mean Mg levels than pin oak for the growing season.

Normal foliar Mg ranges for swamp white oak is 0.13% to 0.31% and 0.14% to 0.28% for pin oak (Table 8). Foliar Mg levels for both pin oak (0.2011%) and swamp white oak (0.1611%) in this study fell within the sufficiency range for healthy trees of those species.

Total soil Mg concentration was significant ($p = 0.0096$) for sampling date. Mean soil Mg was significantly higher in June (0.0056%) than during the rest of the growing season (Figure 18). Magnesium can be lost from the soil through leaching and erosion. Magnesium leaching losses depend on soil Mg content, rate of weathering, intensity of leaching, and plant uptake (Havlin et al., 2005). Leaching is often a severe problem in sandy soils or in calcareous soils with inherently low Mg levels (Mills and Jones, 1996; Havlin et al., 2005). Ample rains in the month of June would have caused Mg in the soil to become available for uptake by the study trees and soil Mg levels to drop for the rest of the growing season due to leaching. Total Mg levels in the soil at Plowboy Bend range from 0.0037% to 0.0056%. These levels are very low considering that total Mg content normally ranges from 0.1% to 4% in most soils (Havlin et al., 2005). The soil at Plowboy Bend is both calcareous and sandy, which magnifies the effects of leaching on already low soil Mg levels.

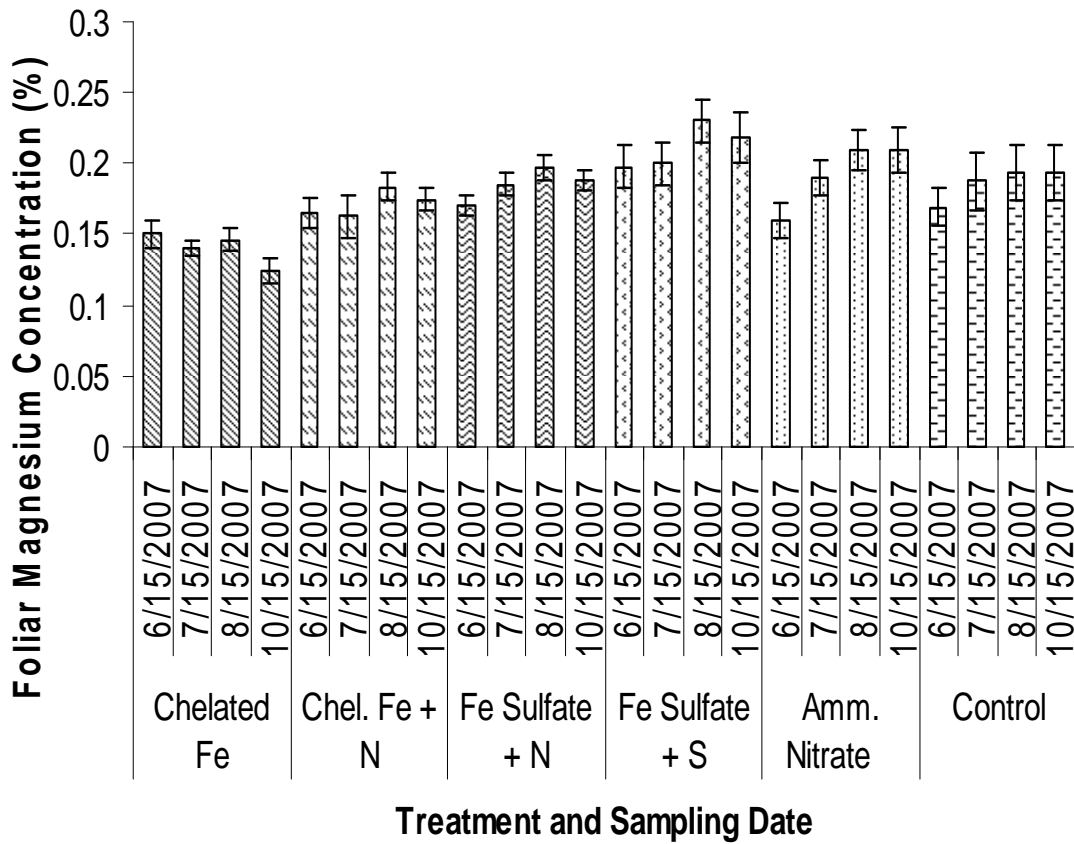


Figure 16. Mean foliar magnesium concentration (\pm SE) by treatment * sampling date across both species for the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

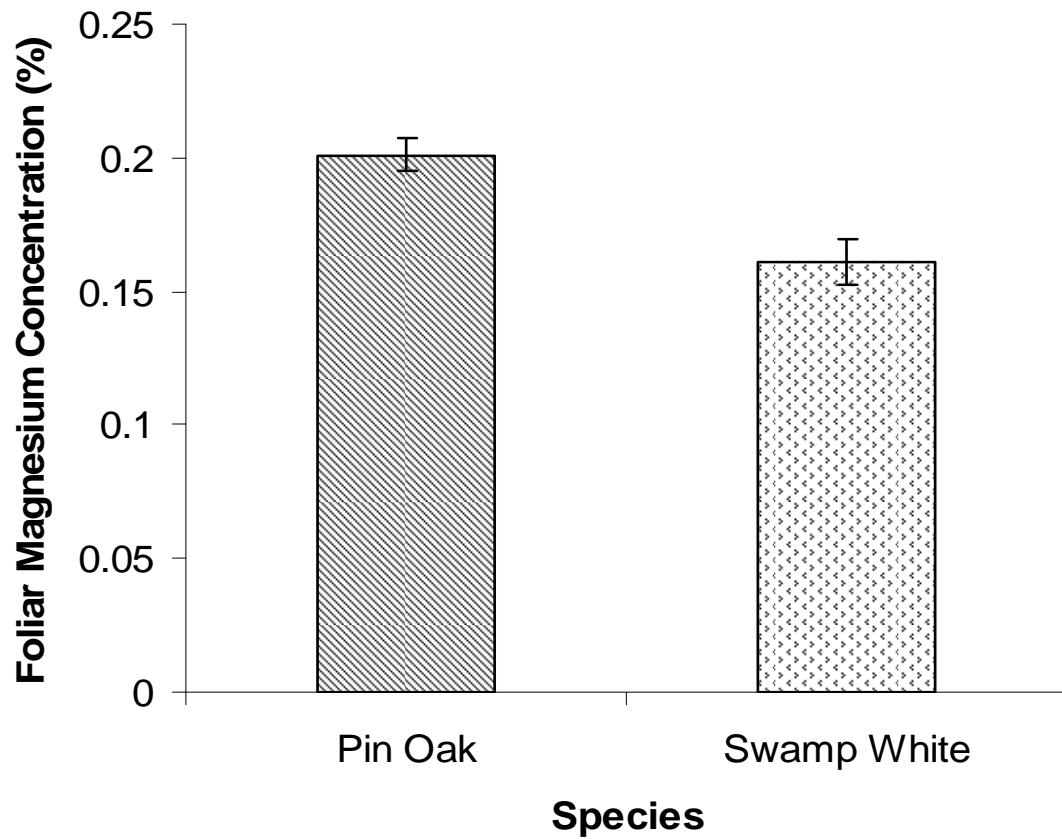


Figure 17. Mean foliar magnesium concentration across treatments (\pm SE) for pin oak and swamp white oak during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

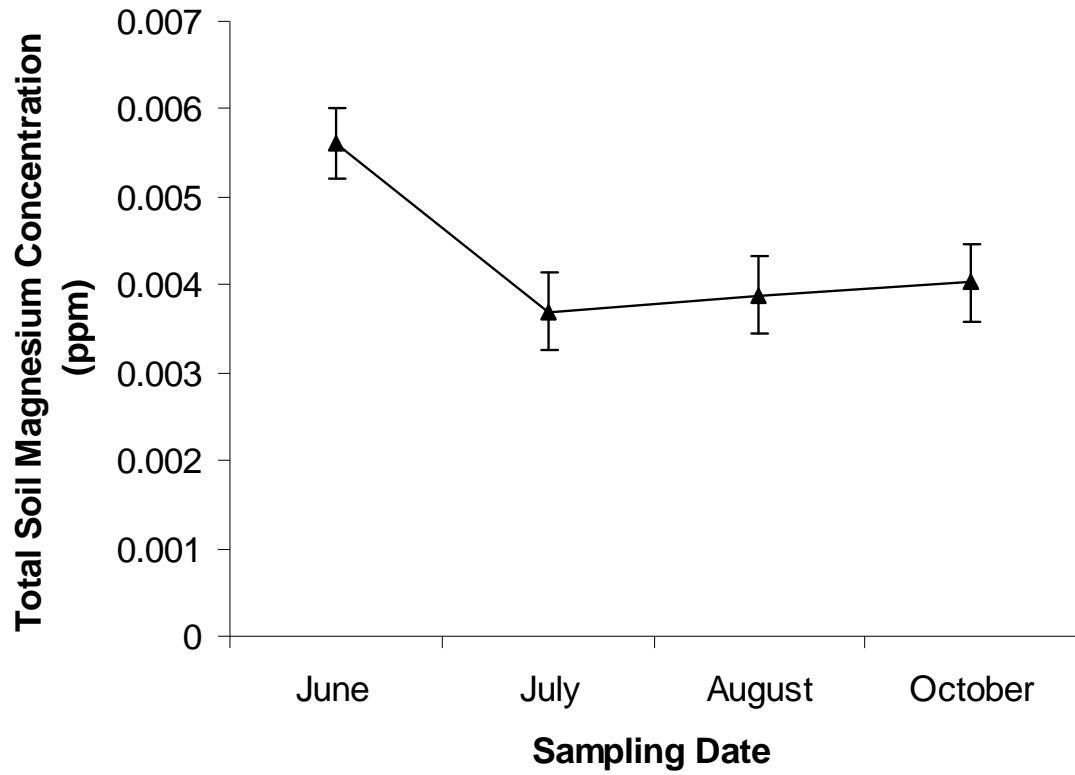


Figure 18. Total soil magnesium concentration (\pm SE) by sampling date across both species during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

Calcium

Calcium is an essential macronutrient similar to Mg in that it moves into plants mainly by mass flow and is easily leached from soils if not adsorbed to the soil (Havlin et al., 2005). The carbonates and carbonic acid in liming materials such as calcite and dolomite increase soil pH (Mills and Jones, 1996). Calcium is taken up by plants in the form of Ca^{+2} . It is important to note that Ca uptake is passive and restricted to the unsubsized portion of young root tips, thus limiting the capacity of Ca^{+2} sorption (Mills and Jones, 1996; Havlin et al., 2005).

Calcium plays many essential roles in plant tissue with the most notable being its role in cell division and elongation in the meristematic portions of a plant's stem, leaves, and root/shoot tips (Mills and Jones, 1996). Calcium is also a structural component in the middle lamella, acting as a cement between adjacent cell walls in the plant (Mills and Jones, 1996). Lastly, Ca^{+2} is essential to cell wall membrane structure and permeability. Low Ca^{+2} weakens cell membranes, resulting in increased permeability, loss of cell contents, and failure of nutrient uptake mechanisms (Havlin et al., 2005).

Total soil Ca concentration can be widely variable, depending on a number of factors including parent material, precipitation, and soil texture. In general, humid regions with coarse textured soils and high rainfall contain lower amounts of Ca in the soil than fine textured soils in more arid regions in which the soil is less susceptible to the effects of leaching (Havlin et al., 2005). However, even calcareous soils where total Ca content may range from 1% to 30% express low Ca concentration in the surface layers due to the ease at which Ca

and other cations are removed by excessive leaching (Havlin et al., 2005; Mills and Jones, 1996; Miller and Donahue, 1995).

The main effects of treatments among species showed no significant difference in foliar Ca concentrations for swamp white oak. Pin oak had its lowest foliar Ca concentration when left untreated (Table 6). Foliar Ca concentration was significant ($p = 0.0197$) at the species * sampling date interaction for the month of August, 2007. While pin oak steadily decreased in foliar Ca throughout the growing season, swamp white oak fluctuated widely with the highest foliar Ca value coming from the August sampling date (Figure 19). Such a spike in foliar Ca content could be expected in samples from newly formed leaves or meristematic tissues, but in this study only fully mature leaves were used in foliar sampling. The literature does not explain why foliar Ca in the swamp white oak, the range of which fluctuated from 0.33%, 0.311%, 0.331%, and 0.29% for the months of June, July, August, and October respectively, experienced such variation while foliar Ca in pin oak from the same site fluctuated very little.

Normal foliar Ca ranges from 0.33% to 1.07% in swamp white oak and 0.4% to 1.36% in pin oak (Table 8). According to these levels, all of the trees sampled were low in foliar Ca except for the swamp white oak in June and August.

Total soil Ca concentration was significant ($p = 0.0147$) for the treatment level alone (Figure 20). The treatment containing the most S, iron sulfate + elemental S, had considerably less soil Ca (0.067%) than the control (0.09%).

The iron sulfate + elemental S treatment decreased the soil pH, thus favoring high levels of Al^{+3} and H^{+} ions, which impede Ca^{+2} adsorption and uptake, perhaps leaving the Ca in the soil more vulnerable to leaching (Havlin et al., 2005).

All values for soil Ca concentration were lower than 1% which is below the normal soil Ca concentration which ranges from 1 to 30 percent for calcareous soils. The soils at Plowboy Bend Conservation Area have a layer of fine sand, approximately six inches deep deposited over them as a result of the Great Flood of 1993. This layer of sand contributes to the site's very low organic matter content (0.6%, Table 2) and also allows mobile soil nutrients to be easily leached out of the uppermost layers of the soil surface. Thus the sandy quality and low organic matter would cause at least the upper layer of the study site's calcareous, high pH soil to be low in soil Ca that would be available for plant uptake.

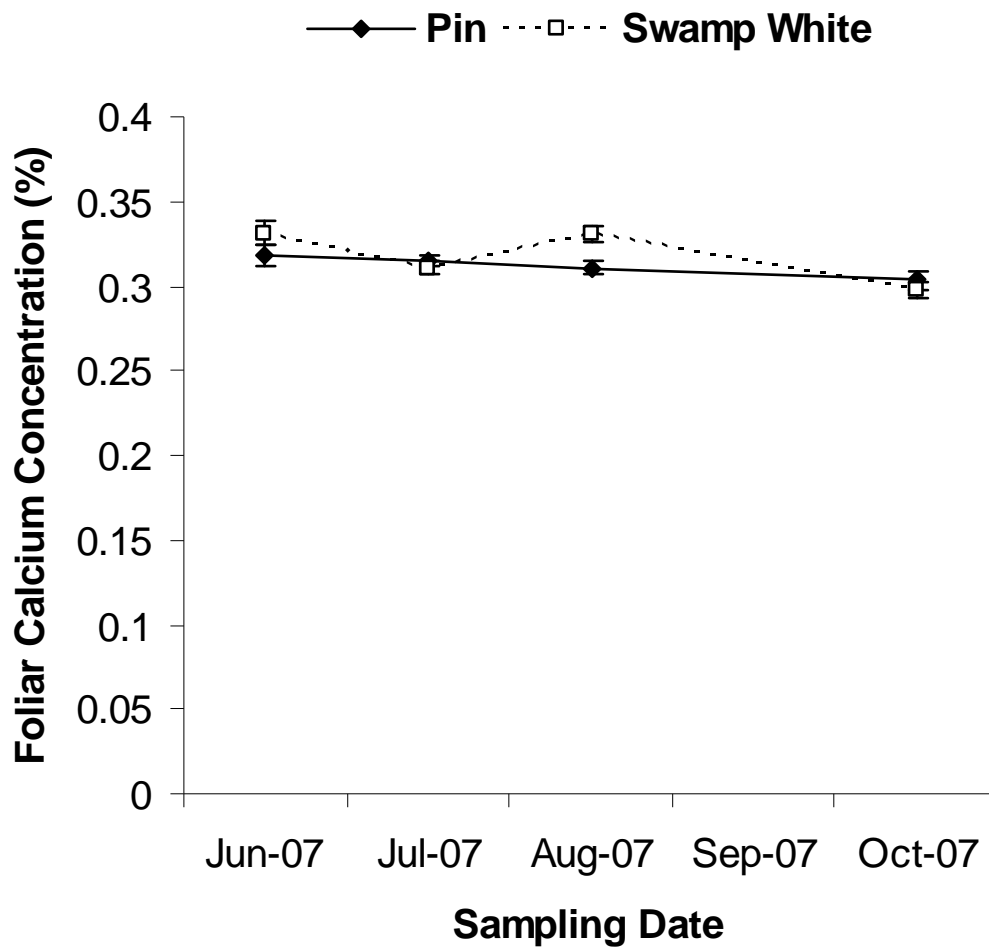


Figure 19. Mean foliar calcium concentration across treatments (\pm SE) by species * sampling date for pin oak and swamp white oak during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

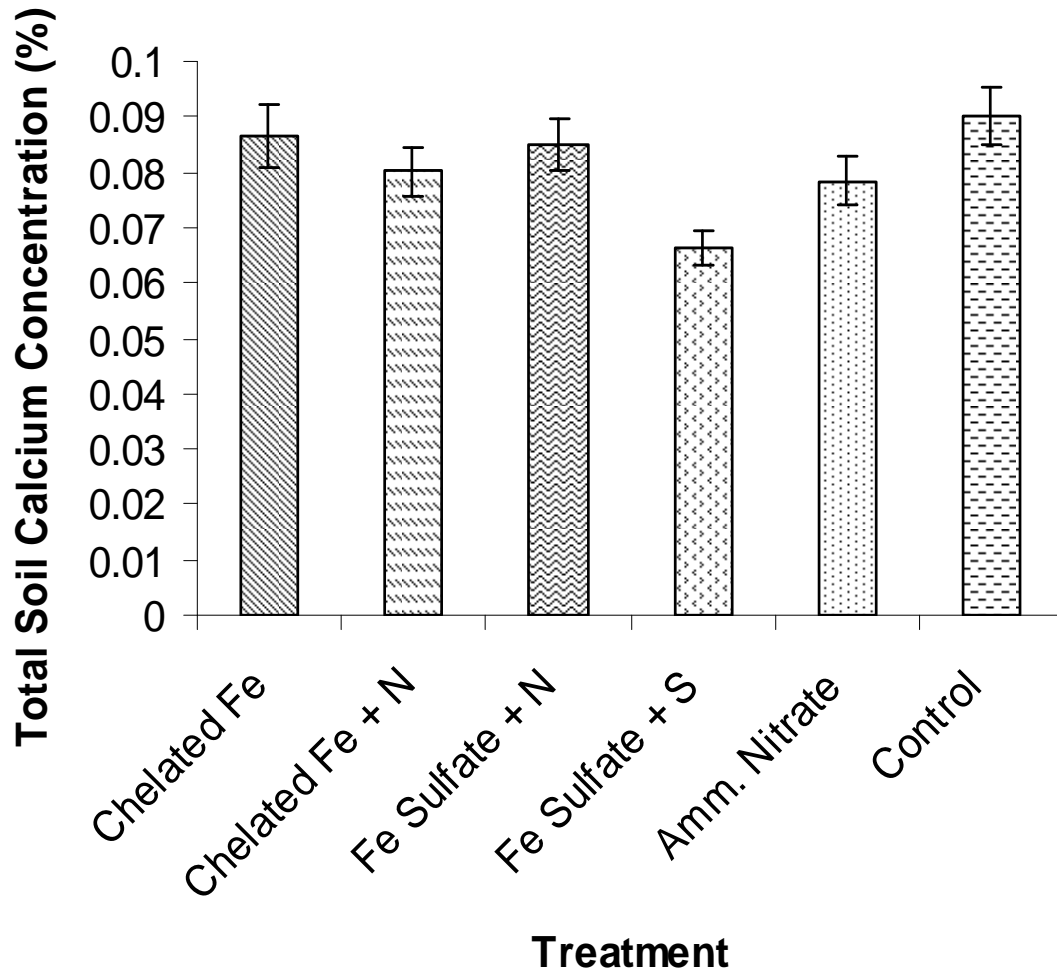


Figure 20. Total soil calcium concentration (\pm SE) by treatment across both species during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

FOLIAR AND SOIL MICRONUTRIENTS

Iron

Iron is a micronutrient essential to the health of plants. It plays a key role in oxidation-reduction reactions and is a structural component of cytochromes, hemes, and numerous other electron transfer systems (Miller and Donahue, 1995). About 80% of the Fe in leaves is localized in the chloroplasts (Terry and Abadia, 1986). With Fe deficiency, therefore, there is a decrease in the concentration of chlorophyll and other light-harvesting pigments (carotene and xanthophylls), as well as in the activities of electron carriers of both photosystems – thus, a sharp decline in photosynthetic activity takes place (Mortvedt et al., 1991). This is why broadleaved plants that are Fe deficient exhibit the typical interveinal chlorosis-light-colored areas between the darker veins on young leaves (Miller and Donahue, 1995).

Iron deficiencies are most common in calcareous soils, arid soils, and soils cropped to high-Fe demand plants (corn, soybeans, sorghum) (Miller and Donahue, 1995). Pin oak (*Quercus palustris*) often develops chlorosis, becomes necrotic, and dies when planted in calcareous, alkaline soil (Messenger, 1983). Iron deficiency symptoms are similar to those of Mg deficiency except that because Fe is immobile in the plant, deficiency shows first in young leaves and new growth (Mills and Jones, 1996). Plants are classified as either Fe-efficient or Fe-inefficient, as some plants (Fe-efficient) are able to acidify the rhizosphere and/or release siderophores which enhance the uptake of Fe (Mills and Jones,

1996). The ability of plants to influence Fe availability makes it unique among the micronutrients.

Iron availability depends to a large extent on soil pH range and redox potential (Mortvedt et al., 1991). Fe has low mobility in the soil, but most deficiencies are due to reduced availability because of unfavorable pH range, not low Fe levels (Mills and Jones, 1996). The Fe^{+3} (ferric) forms of Fe is the dominant form in the soil, but Fe^{+2} (ferrous) is the physiologically active form (Mills and Jones, 1996). The solubility of inorganic Fe in well aerated soils is controlled by the dissolution and precipitation of Fe^{+3} oxides. The concentration of Fe^{+3} is related to pH, declining from 10^{-8} to 10^{-20} as pH increased from 4 to 8 (Romheld and Marschner, 1986). High levels of bicarbonate and phosphates lower iron availability to plants because of the formation of relatively insoluble Fe salts, and, all Fe salts are less soluble in basic media (Miller and Donahue, 1995).

Managers often try to alleviate the Fe availability problem by acidifying the soil and/or adding Fe, as Mortvedt and Kelsoe (1988) did to improve grain sorghum forage yields and Fe uptake by applying Fe sulfate fertilizer. Another method of supplying more available Fe is to bond it with a synthetic chelating agent which forms ligand bonds to Fe^{+2} and “holds” the metal longer in the soil making it available longer for uptake by the plant (Mortvedt et al., 1991). Soil organic matter forms soluble Fe complexes by naturally occurring chelating ligands and enhances the solubility of Fe, even in high pH soils (Olomu et al., 1973). As mentioned above, some Fe-efficient plants are able to produce

substances which chelate soil Fe under unfavorable (deficient) Fe conditions and thus survive better in high pH soils (Miller and Donahue, 1995).

The oak trees (especially pin oak) at Plowboy Bend Conservation Area show symptoms of Fe chlorosis and the soil has an average pH of 8.29. As a result, combinations of chelated Fe and Fe sulfate fertilizers were used in hopes of addressing both low Fe availability and the high soil pH.

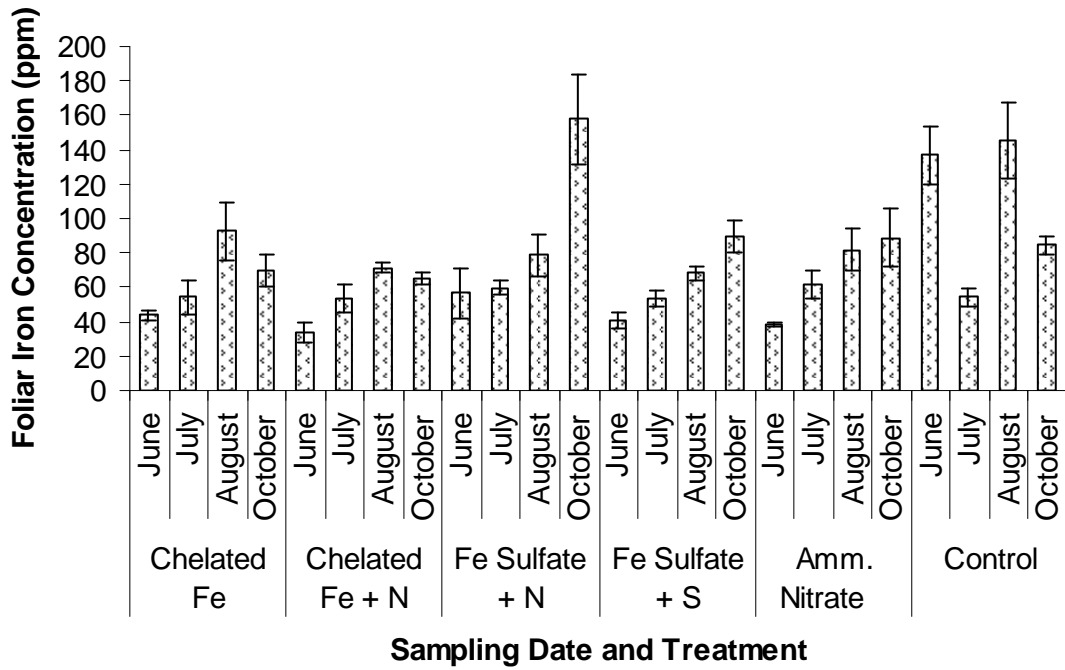
Foliar Fe concentration was lowest for the chelated Fe + N treatment for both species. Foliar Fe concentration was highest for pin oak in the control treatment and highest for swamp white oak in the chelated Fe treatment (Table 7). Foliar Fe concentration had a significant ($p = 0.0003$) interaction for species * treatment * sampling date during the 2007 growing season (Figure 21). Foliar Fe content was generally higher in swamp white oak than pin oak for all months except October (treatment: Fe sulfate + N) where iron was added to the soil but the pH was not greatly reduced. This difference between the species may reflect the ability of swamp white oak to acidify its rhizosphere or release siderophores into the soil to enhance Fe uptake. The foliar Fe concentration for the Fe sulfate + elemental S treatment follows the same pattern for both species. Pin oak, a pH sensitive species with a tendency toward Fe chlorosis, mirrored swamp white, which had significantly higher foliar Fe in most treatments. This indicates the ability of iron sulfate + elemental S to lower soil pH and improve the availability of Fe for uptake to the trees of both species. The nitrogen and control treatments did not show any consistent trends in foliar Fe levels. Swamp white oak had the

higher foliar Fe content except for a couple of spikes in June and August for the pin oak control.

Healthy swamp white oak foliage ranges from 47 to 149 ppm in Fe concentration and pin oak foliar Fe normally ranges from 45 to 180 ppm in healthy trees (Table 8). At Plowboy Bend, swamp white oak ranged from 41.88 to 128.63 ppm and pin oak ranged from 33.59 to 157.7 ppm across all treatments for the growing season of 2007. Though foliar Fe concentration varied widely for both species, only two values were below sufficiency for swamp white oak and just four values were below sufficiency for pin oak.

Total soil Fe concentration was significant ($p = 0.0001$) at the treatment level only. Total soil Fe content ranged from a low for the N (ammonium nitrate) treatment of 6,170.2 ppm to a high for the chelated Fe treatment at 7,082.4 ppm (Figure 22). All treatments where Fe was added had the highest soil Fe levels, and as would be expected, treatments containing Fe chelates had the two highest values. The ammonium nitrate treatment recorded the lowest soil Fe value as Fe became available from favorable rhizosphere pH changes due to ammonium reactions in the plant's roots. The control, Fe sulfate + N, and Fe sulfate + S treatments had similar soil Fe concentrations, which is noteworthy given that two treatments added Fe, S, and lowered soil pH while the control added nothing. These interactions further illustrate the ability of chelated Fe to resist leaching at differing soil pH.

A.



B.

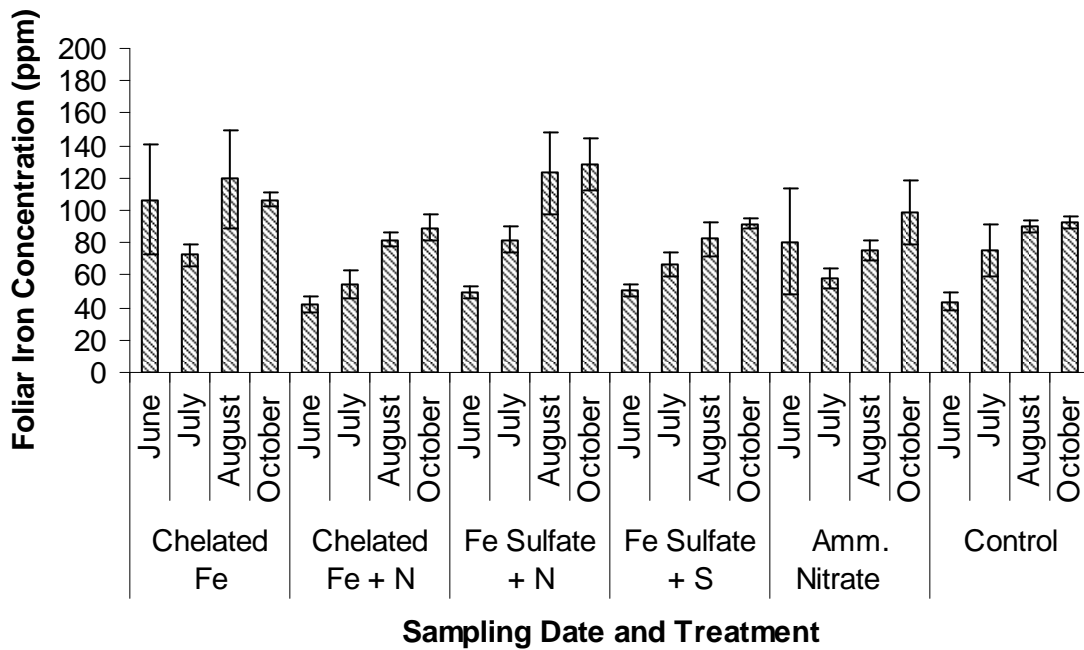


Figure 21. Mean foliar iron concentration (\pm SE) by species * treatment *sampling date for pin oak (A.) and swamp white oak (B.) during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

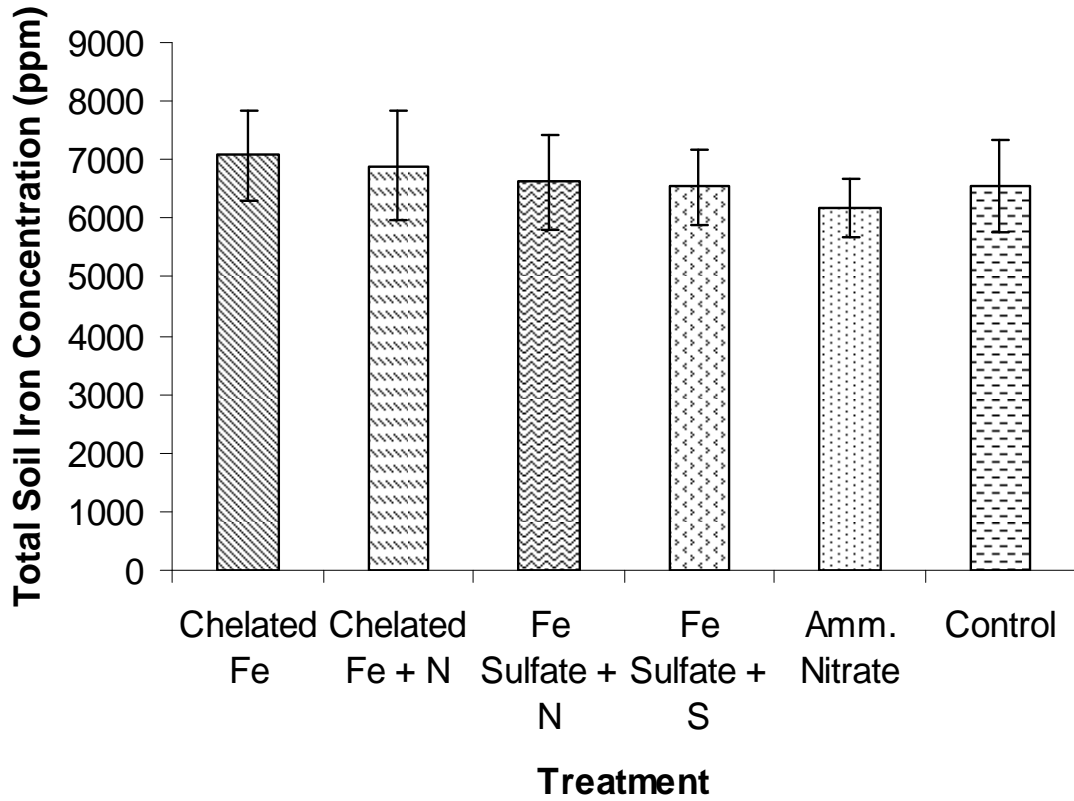


Figure 22. Total soil iron concentration (\pm SE) by treatment across both species during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

Manganese

Manganese is an essential soil micronutrient that behaves similarly to Fe in that soil pH and redox potential greatly influence its availability (Mortvedt et al., 1991). Most of the soil Mn is derived from parent materials of basalt, limestone, shale or sandstone (Glinski and Thai, 1971) with the greatest amounts coming from limestone (Krauskopf, 1972). Plants mainly use the divalent (Mn^{+2}) form of Mn, which tends to oxidize to insoluble oxide forms at high pH and redox potential. Lower pH (5.0 – 6.5) and redox potential favors the divalent, water soluble form of Mn (Sparrow and Uren, 1987). As a rule, the same plants that are Fe-efficient and have the ability to acidify their rhizosphere by releasing H^+ and reducing/complexing compounds also may enhance the availability of soluble Mn in high pH soils (Moraghan, 1979; Marschner, 1986).

Organic matter in the soil provides an energy source for microbes which release organic compounds that complex Mn into available form (Mortvedt et al., 1991). The positive effect of organic matter on Mn availability is also dependent on soil pH. McBride (1982) reported that exchangeability of Mn from organic solids was strongly dependent upon pH, with high pH causing some forms of organic matter, like humic acid, to fix Mn into unavailable forms (Pavanasasivam, 1973).

Influenced by soil saturation and temperature, soil redox status has a great bearing on Mn availability in soils (Mortvedt et al., 1991). Gotoh and Patrick (1972) found that the conversion of insoluble soil Mn to the water soluble and extractable forms was dependent on a pH between 6 and 8, as the critical

potential for Mn reduction occurred at a much lower redox potential as pH increased. Increases in soil saturation and temperature were shown to increase microbial activity and decrease the electrical potential between oxidation or reduction reactions and the H electrode, resulting in increased plant availability of soil Mn (Sonar and Ghurgare, 1982).

The most well known function of Mn in the plant is its involvement in photosynthetic O₂ evolution in the chloroplasts, known as the Hill Reaction (Motrvedt et al., 1991). Due to this key function in the water-splitting reaction, Mn deficiency primarily affects photosynthesis. Manganese also protects plant cells from superoxide-free radicals formed from water-splitting during the Hill Reaction (Mills and Jones, 1996). Lastly, Mn is a key component in various enzymes and is vital to cell elongation in the growing parts of plants (Neumann and Stewart, 1968).

As with the other essential divalent cations, such as Ca and Mg, Mn uptake is competitive and metabolically mediated (Mills and Jones, 1996). Symptoms of Mn deficiency consists of interveinal chlorosis of younger and middle aged leaves, but is usually not uniformly distributed over the entire leaf blade as in iron chlorosis (Mortvedt et al., 1991).

Foliar Mn was highest for the FeSO₄ + S treatment and lowest in the chelated Fe treatment for both species (Table 7). Manganese was significant (p = 0.0051) for sampling date * treatment and for species * treatment interaction (p = 0.0028). Foliar Mn increased significantly for all treatments throughout the growing season (Figure 23). The treatments containing sulfate and elemental S

had the highest foliar Mn concentrations, with Mn values in October significantly higher than Mn values in June. Treatments containing chelated Fe were noticeably lower in foliar Mn concentration throughout the growing season.

Other than greater availability of Mn^{+2} due to favorable changes in soil pH, the literature does offer an explanation as to why mean foliar Mn would increase steadily, regardless of rainfall, throughout the growing season. Clark and Smith (1990) reported that foliar Mn in persimmon (*Diospyros virginiana* var. kaki) increased steadily throughout the growing season. The findings of Bubb et al. (1998) also demonstrated varying degrees of net N, Ca, and Mn accumulation in hoop pine (*Araucaria cunninghamii*) foliage. Regardless of these foliar trends, the range of foliar Mn is well below the normal Mn ranges for pin oak and swamp white oak (Table 8). As for the species * treatment interaction, the positive influence of lowering soil pH can be readily seen as treatments containing S had the highest Mn values regardless of tree species (Figure 24). Pin oak treated with iron sulfate + elemental S showed the highest foliar Mn concentration value at 144.22 ppm. Between species, pin oak recorded a significantly higher foliar Mn value (144.22 ppm) than swamp white oak (54.16 ppm) for the Fe sulfate + elemental S treatment.

Fertilization with Fe fertilizers affects a plant's ability to take up and assimilate Mn properly. Romero (1988) concluded that the effect of Fe fertilization on plant Mn response may involve the following phenomena: (i) Fe applications that increase plant growth may decrease Mn concentrations in tops to deficient levels by dilution; (ii) Fe applications that correct Fe deficiency may

also lower root to shoot ratios; and (iii) Fe applications may decrease Mn uptake, and the resultant low-yielding, Mn deficient plants may contain toxic concentrations of Fe. Each of these three effects of either Fe or Mn on plant growth may lead to symptoms attributed to Mn deficiency.

Normal healthy swamp white oak has a foliar Mn range of 121 ppm to 323 ppm and pin oak should contain 218 ppm to 633 ppm of foliar Mn (Table 7). While applications of S fertilizers did significantly increase foliar Mn, both species of trees contain foliar Mn levels well below their respective sufficiency ranges.

Total soil Mn was significant for sampling date ($p = 0.0001$) and treatment ($p = 0.0001$) independently. Mean soil Mn concentration followed a trend consistent with the rainfall pattern for the 2007 growing season (Figure 25). Ample rainfall fell during the months of June and October while July, August, and September received well below average rainfall amounts (Table 3). Manganese as the Mn^{+2} ion is easily leached from the soil (Mills and Jones, 1996). As a result, soil Mn was 15 to 20 ppm lower in the wetter months of June and October.

Soil Mn concentration was highest in chelated iron, chelated Fe + N, and Fe sulfate + N treatments (Figure 26). These three treatments added significant amounts of Fe to the soil without significantly changing the pH. Manganese, like Fe, is greatly affected by soil pH and the availability of both nutrients is best in the slightly acid 6.0 to 6.5 range (Figure 6). Observers have noted that an excess of Mn can result in Fe deficiencies and vice versa. According to Mills and Jones (1996), hydroponic studies have shown by means of plant analyses that high levels of solution Mn reduce Fe plant content, while high levels of solution

Fe reduce Mn plant content. Perhaps this interaction between Fe and Mn explains higher soil Mn for the above treatments. The remaining treatment containing Fe, Fe sulfate + elemental S, lowered pH enough to make Mn available for uptake by the trees despite the addition of iron in iron sulfate. Nitrogen and control treatments show the lowest amounts of total Mn in soil. The ammonium in the N treatment only slightly acidified the soil and the control treatment had no effect on soil pH. These treatments did not increase Mn uptake by the trees.

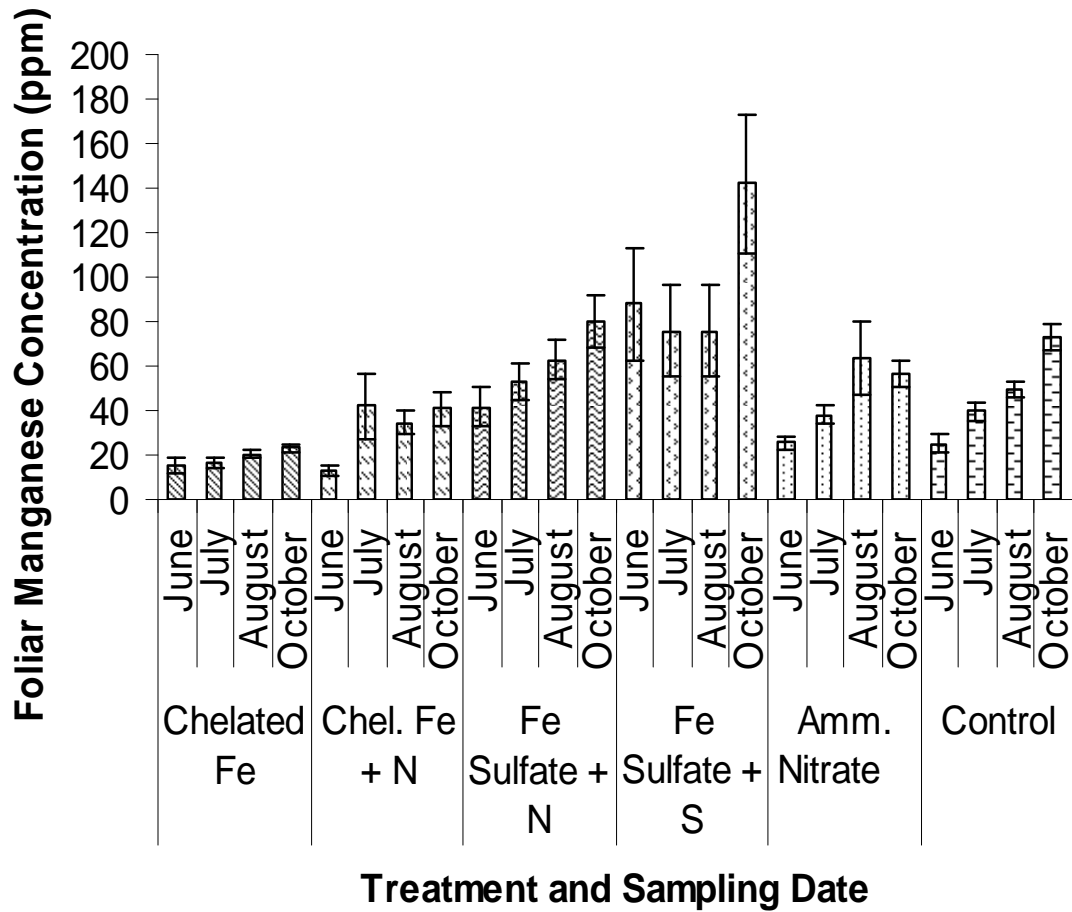


Figure 23. Mean foliar manganese concentration (\pm SE) by treatment * sampling date across both species during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

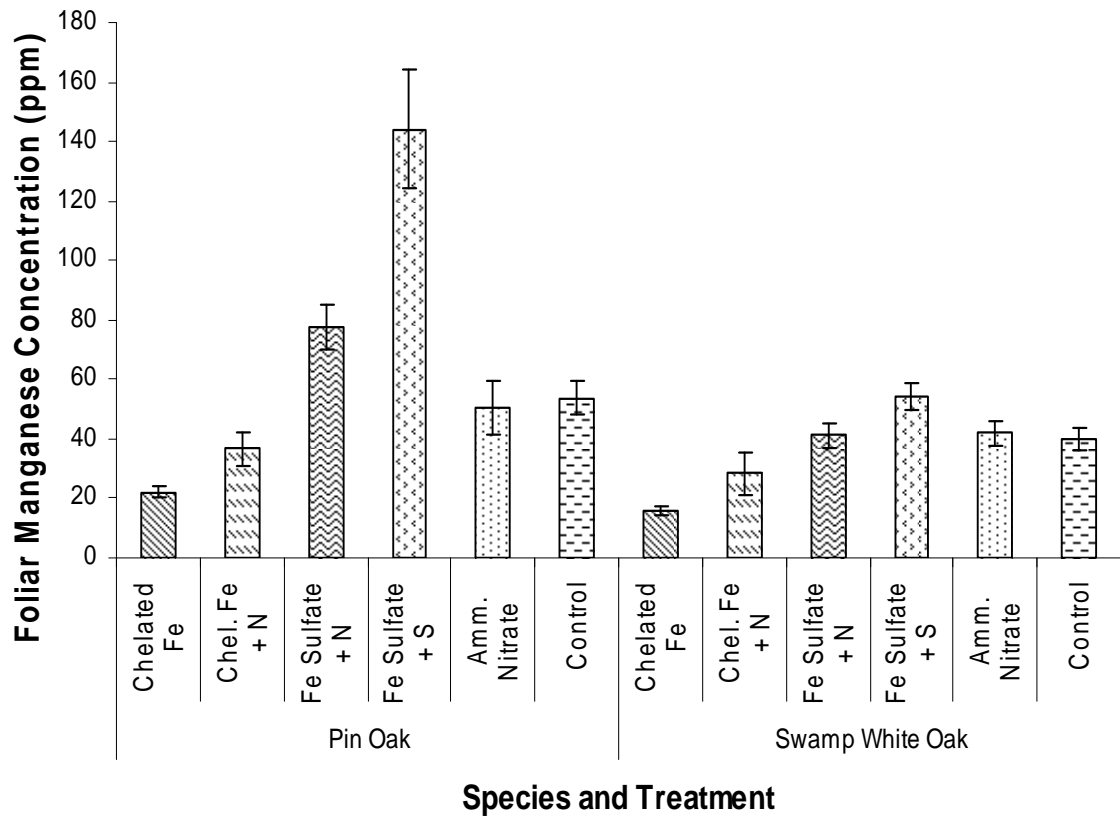


Figure 24. Mean foliar manganese concentration (\pm SE) by species * treatment across both species during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

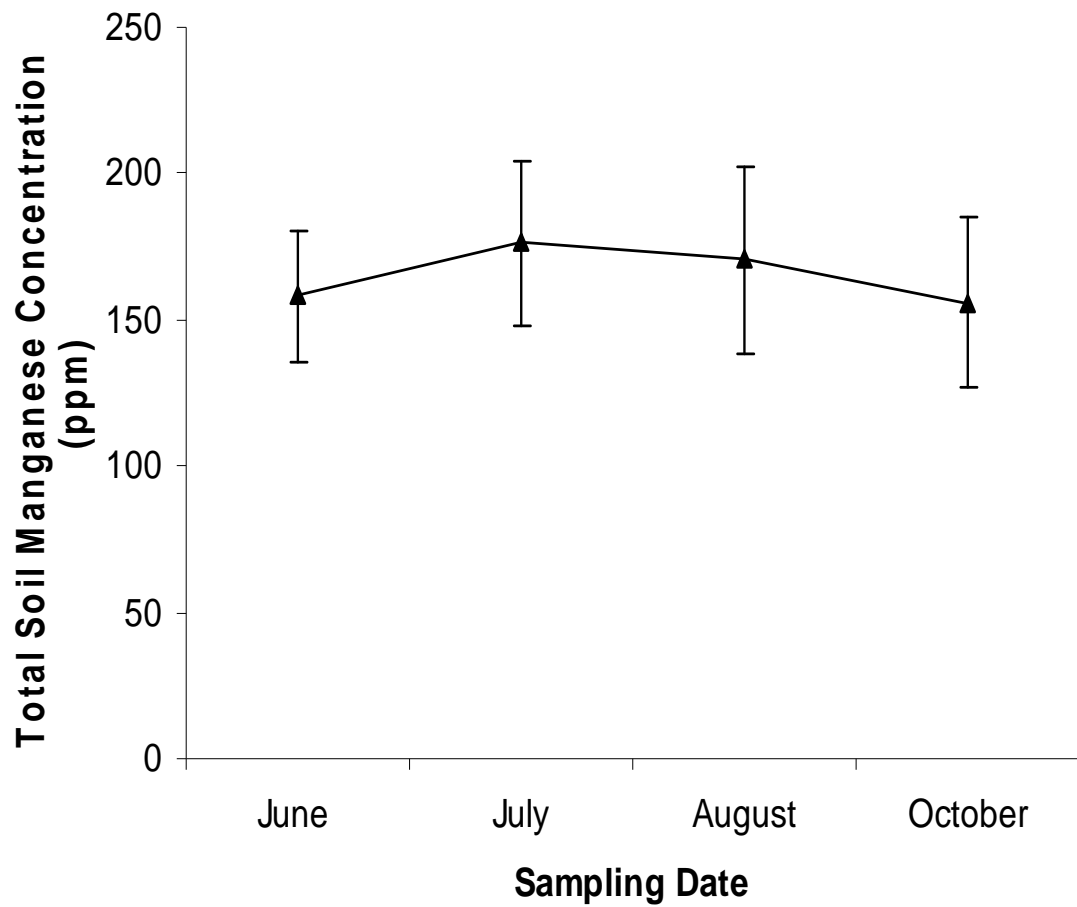


Figure 25. Total soil manganese concentration across treatments (\pm SE) by sampling date across both species during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

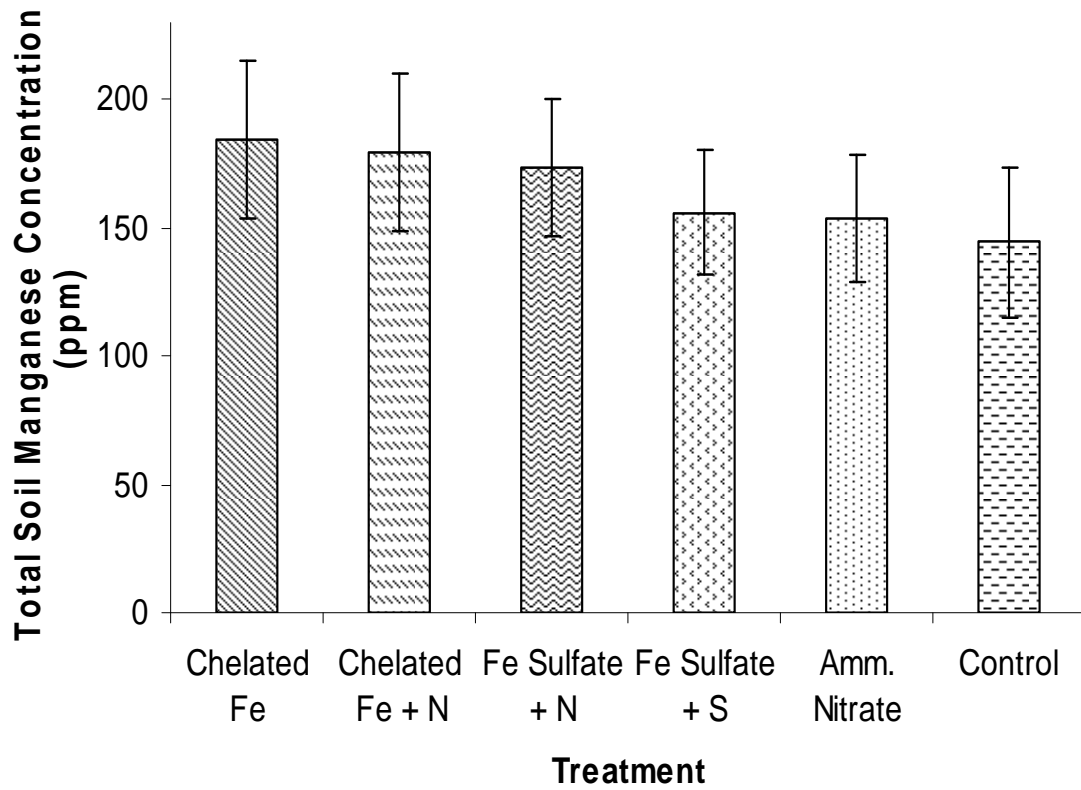


Figure 26. Total soil manganese concentration (\pm SE) by treatment across both species during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

Molybdenum

Molybdenum is the only micronutrient in which availability normally increases with an increase in pH (Mortvedt et al., 1991). Molybdenum is taken up as the molybdate anion (MoO_4^-) and translocated preferentially to the leaves (Mills and Jones, 1996). Soil properties affect the availability of Mo primarily through adsorption of MoO_4 onto inorganic soil components, especially under acid conditions (Mortvedt et al., 1991). Molybdenum is found as a relatively insoluble salt in association with Pb, Ca, or Fe, and in association with organic matter. The weathering of these materials and the decomposition of organic matter release MoO_4 into the soil solution (Mills and Jones, 1996). In acid soil conditions Mo is strongly adsorbed to Fe and aluminum oxide surfaces, becoming unavailable to the plant (Havlin et al., 2005).

In the plant, Mo is an essential component of nitrate reductase, an enzyme in chloroplasts which catalyzes the conversion of NO_3^- to NO_2^- . Molybdenum also is a structural component of nitrogenase, the enzyme essential to N_2 fixation (Havlin et al., 2005). Further, Mo is believed to play an essential role in iron absorption and translocation in plants, explaining why Mo-deficiency symptoms are similar to the interveinal symptoms of iron chlorosis (Havlin et al., 2005).

Main treatment effect foliar Mo concentration for pin oak was highest for $\text{FeSO}_4 + \text{N}$ and lowest in the chelated Fe treatment. Treatments were not significantly different for the main effects in swamp white oak foliage (Table 7).

Mean foliar Mo concentration was significant ($p = 0.0003$) for treatment * species * sampling date interaction (Figure 27). Swamp white oak had significantly higher foliar Mo than pin oak in the months of June, July, and August when treated with chelated Fe + N; in July when treated with Fe sulfate + N; in July and October when treated with Fe sulfate + elemental S; in August when treated with N only; and in June and July for the control treatment respectively. Pin oak was significantly higher in foliar Mo than swamp white oak in October when treated with Fe sulfate + N and again in October when treated with N. Everything in the literature suggests that the foliar Mo should be lower in treatments containing S because it would lower the soil pH and decrease Mo availability to the trees. Ammonium in ammonium nitrate fertilizer also can lower soil pH. Regardless of pH, swamp white oak was able to absorb more Mo than pin oak during the majority of the growing season for all treatments containing S and N. Soil pH was significantly lowered by the Fe sulfate + elemental S treatment in this study, while all other treatments were not lowered sufficiently to expect interference with Mo uptake.

Regardless of treatment, sampling date, and species, all trees at this study site contain sufficient levels of foliar Mo, with healthy pin oak ranging from 0.02 to 1.58 ppm and swamp white oak ranging from 0.05 to 0.12 ppm foliar Mo (Table 8).

Mean soil Mo showed a significant ($p = 0.0001$) reaction at the treatment * date interaction (Figure 28). For the month of July, the treatment Fe sulfate + N had significantly lower total soil Mo than all other treatments. The month of

August showed a significantly higher value (1.97 ppm) than other treatments while August control treatment showed a significantly lower value (0.55) for soil Mo concentration. Iron sulfate + elemental S also had a significantly high soil Mo value for the final sampling month of October. Reactions and nutrient availability can vary widely in soils (Mortvedt et al., 1991), but soil Mo did show a trend during the 2007 growing season. Soil Mo concentration was higher in soils treated with S, N, and Fe, especially during dryer months of the growing season. Lower pH (due to S and ammonium) and/or soil reactions with Fe would reduce the amount of Mo available to the plants, thus leaving more of the element in the soil. Dry soil reduces the movement of elements in the soil, uptake by plants, and the potential for microbes and soil organic matter to influence soil nutrient concentrations in oxidation-reduction reactions.

Mean soil Mo was significantly ($p = 0.0001$) higher in soil depth 1 (0 to 10 cm) than at soil depth 2 (10 to 20 cm) (Figure 29). This difference is likely due to soil organic matter, which is higher at the soil surface, where its decomposition releases soil Mo. Therefore the distribution of Mo in the surface layer of the soil profile is influenced by the distribution of soil organic matter (Aubert and Pinta, 1977).

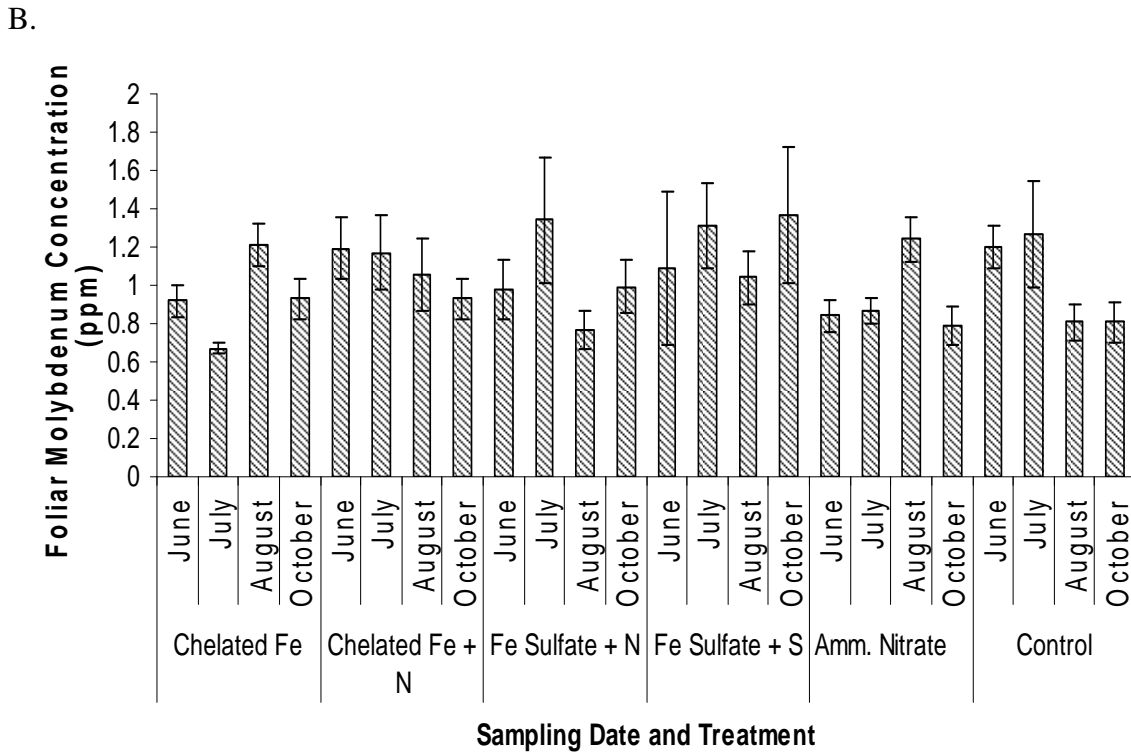
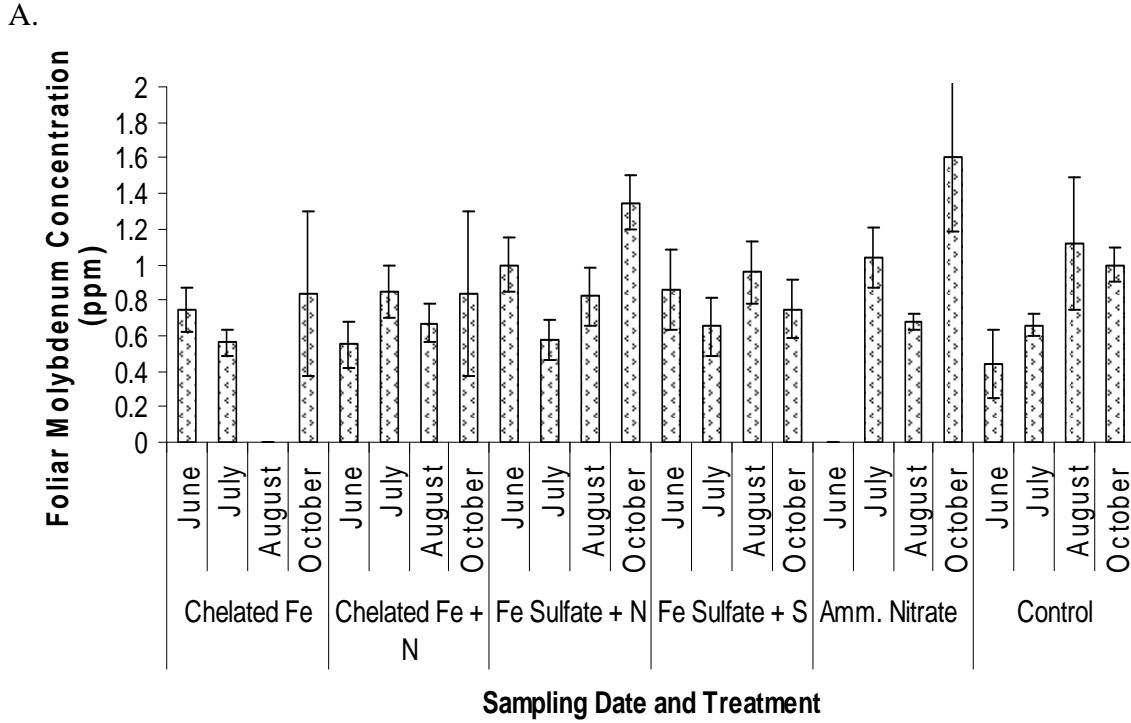


Figure 27. Mean foliar molybdenum concentration (\pm SE) by species * treatment * sampling date for pin oak (A.) and swamp white oak (B.) during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

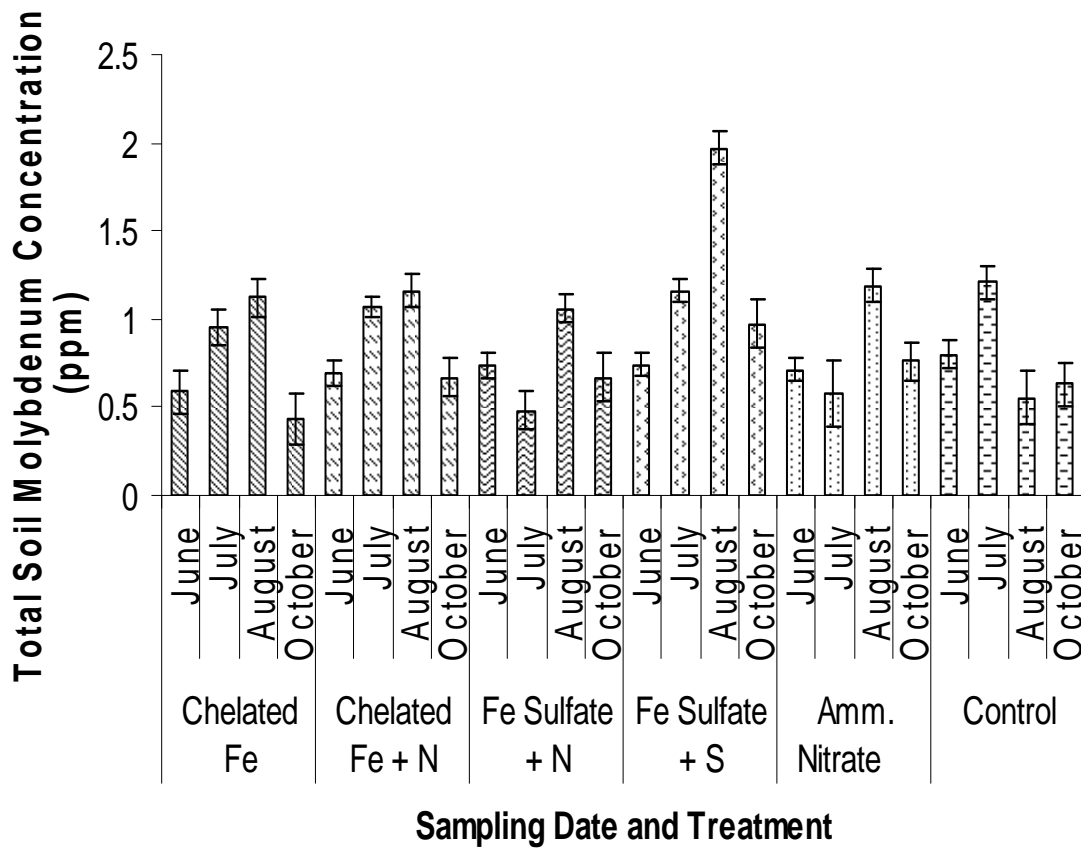


Figure 28. Total soil molybdenum concentration (\pm SE) by sampling date * treatment across both species during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

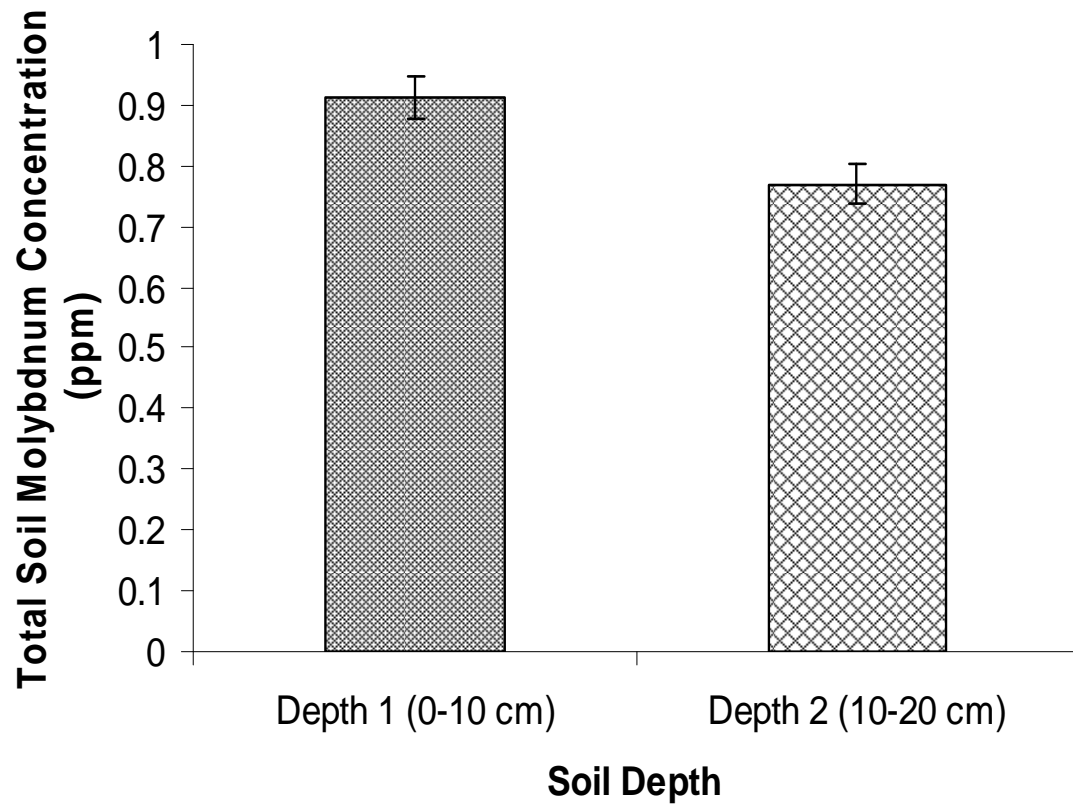


Figure 29. Total soil molybdenum concentration across treatments (\pm SE) by soil depth across both species during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

Copper

Copper is an essential micronutrient, existing in soils mainly as cupric (Cu^{2+}) and less as cuprous (Cu^+) ions (Miller and Donahue, 1995). Plants absorb Cu in the cupric form but it may be present in the soil in exchangeable forms as well as the stable organic complexes and chelates (Mortvedt et al., 1991). Copper uptake is active and metabolically controlled by the plant but it is not mobile within plant tissue. As a result, deficiency symptoms are first noticed in the young leaves and other plant organs. Copper deficiency results in stunted growth, distortion of young leaves, and necrosis of the apical meristem (Mills and Jones, 1996).

Copper is important in the plant as part of various Cu proteins important in processes such as photosynthesis, respiration, detoxification of superoxide radicals, and lignification (Mortvedt et al., 1991). Copper is part of several enzyme complexes that influence carbohydrate and N metabolism of plants. Over half of the foliar Cu is associated with plastocyanin, an enzyme involved in the electron transport chain of Photosystem I (Mills and Jones, 1996).

Copper is one of the most immobile nutrients in the soil, relying on root exploitation for movement into the plant (Jarvis and Whitehead, 1981). Adsorption of Cu increased as soil pH increased from 4 to 7 in studies done by Cavallaro and McBride (1984), and Loneragan (1975) concluded that the formation of soluble Cu-organic complexes explain why plants grown in calcareous soils are insensitive to Cu deficiency. Soils high in organic matter may reduce the availability of Cu to plants because of the complexing of Cu to

insoluble organic forms (Goodman and Cheshire, 1976). However, Cu can become more available to plants in calcareous soils if it complexes with soluble organic ligands to form Cu chelates, which are highly available to plants (Stevenson and Fitch, 1981). Copper has an important reaction with Zn, as it significantly inhibits the uptake of Zn, and vice versa, as Zn is believed to interfere with Cu at the absorption site (Mills and Jones, 1996).

Among species, foliar Cu concentration did not follow any patterns among treatments (Table 7). Foliar Cu concentration was significant ($p = 0.0021$) for date * species interaction (Figure 30). Both pin oak and swamp white oak followed similar trend of foliar Cu concentrations throughout the growing season. The two species did differ significantly during the growing season for the months of July through October, with swamp white oak foliage containing significantly higher amounts of Cu than pin oak. Healthy swamp white oak normally contains 8 to 10 ppm in the foliage while pin oak has foliar Cu concentration ranging from 7 to 38 ppm (Table 8). However, on the Plowboy Bend site, swamp white oak contains more foliar Cu than pin oak on this alkaline site. Though both species in this study are deficient in most of the essential nutrients, including Cu, swamp white oak is frequently less deficient than pin oak due to its higher tolerance of high pH, thus affording it more growth/activity than pin oak to take up Cu (Gilman, 1997).

Foliar Cu concentration was significant ($p = 0.0083$) for treatment. The foliar Cu concentration for the trees treated with ammonium nitrate was significantly lower than all other treatments except chelated Fe + N, which was

significantly lower than the ammonium nitrate treatment. According to Havlin et al. (2005), high Fe, Zn, and P concentrations in the soil can depress Cu absorption. Also, increasing N in plants can dilute foliar Cu concentrations and impede Cu translocation from older to newer leaves.

Total soil Cu was significant ($p = 0.0169$) at the treatment * depth * sampling date interaction (Figure 31). All total soil Cu concentrations were significantly higher during the month of August at depth 1 (1-10 cm) regardless of treatment. Treatments containing N recorded higher soil Cu levels at soil depth 2 (10-20 cm) for every month except August in the ammonium nitrate treatment. In general, total soil Cu concentration at both sampling depths was higher in the months of July and August. These two months were exceptionally dry during the growing season of 2007, while June and October received ample precipitation. Because Cu is immobile in the soil, leaching is not a likely reason for loss as it is for most other soil nutrients. Rainfall would affect the Cu content of soils by enabling the roots to take up soil Cu in greater quantities, as reflected by the lower values in the wetter months of June and October. Moist soils in the months of June and October enhanced the ability of tree roots to explore and come in contact with soil colloids containing Cu (Jarvis and Whitehead, 1981). Furthermore, soil moisture and the resulting microbial activity/organic matter breakdown may have increased the availability of Cu by the formation of soluble Cu chelates, (Stevenson and Fitch, 1981). Moist soil conditions favor greater Cu availability and uptake by the trees more than dry soil conditions, therefore resulting in lower soil Cu concentrations in moist soil months.

Copper concentration ranges from 1 to 40 ppm and averages about 9 ppm in most soils. Deficient soils have only 1 to 2 ppm Cu content (Havlin et al. 2005). While the soils at Plowboy Bend Conservation Area are not deficient, both species of oak trees are Cu deficient. High Zn, Fe, and P concentrations in soil solution can depress Cu absorption by roots and intensify Cu deficiency. Also, increased growth response to N or other nutrients may be proportionally greater than Cu uptake, which dilutes Cu concentration in plants (Havlin et al., 2005).

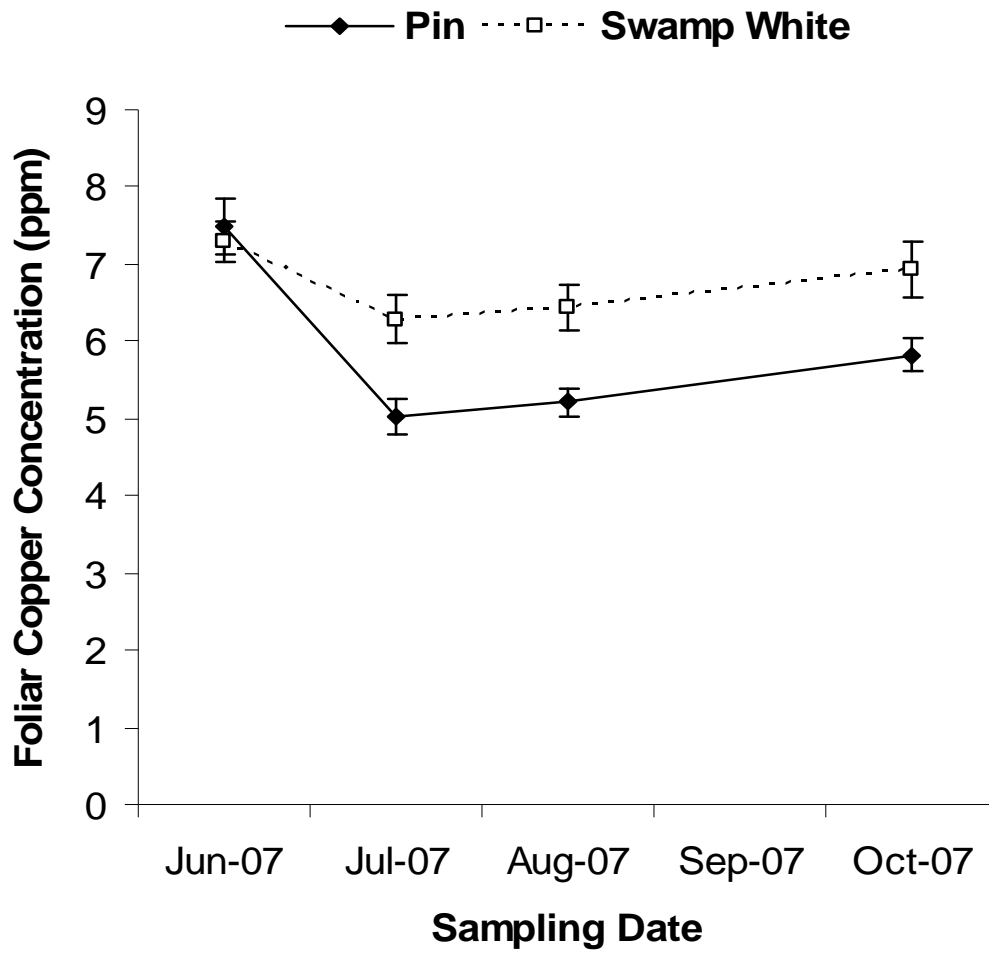


Figure 30. Mean foliar copper concentration across treatments (\pm SE) by species * sampling date for pin oak and swamp white oak during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

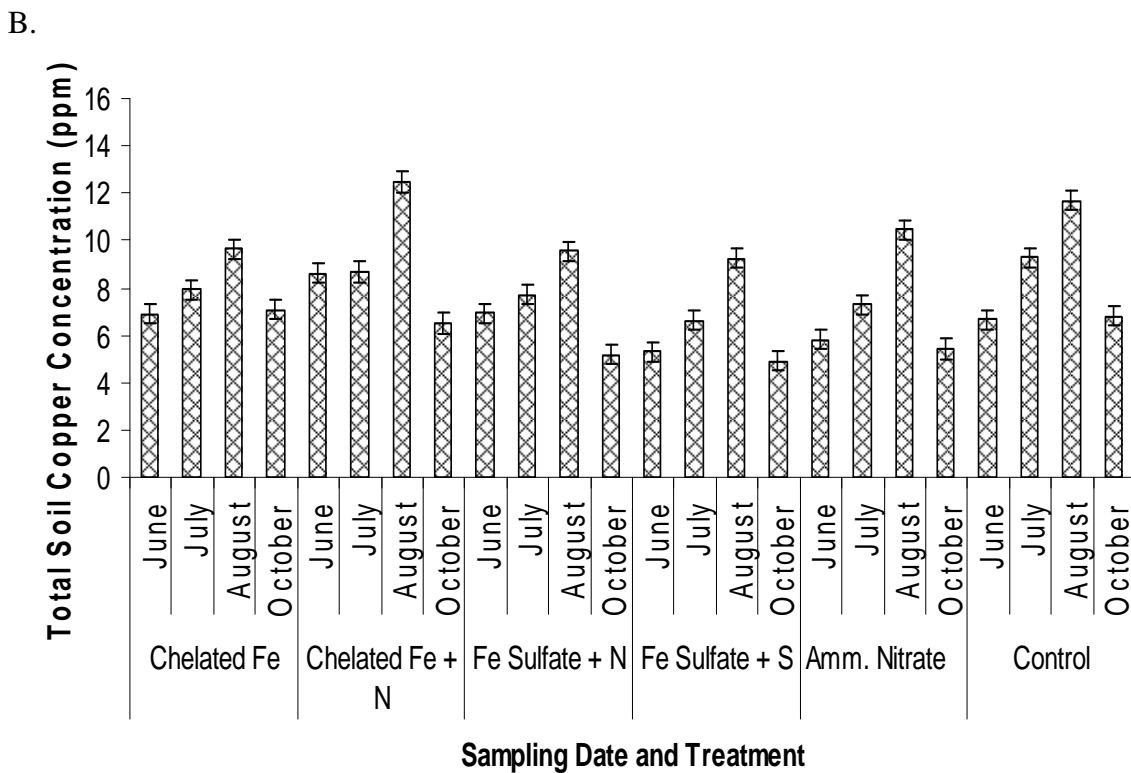
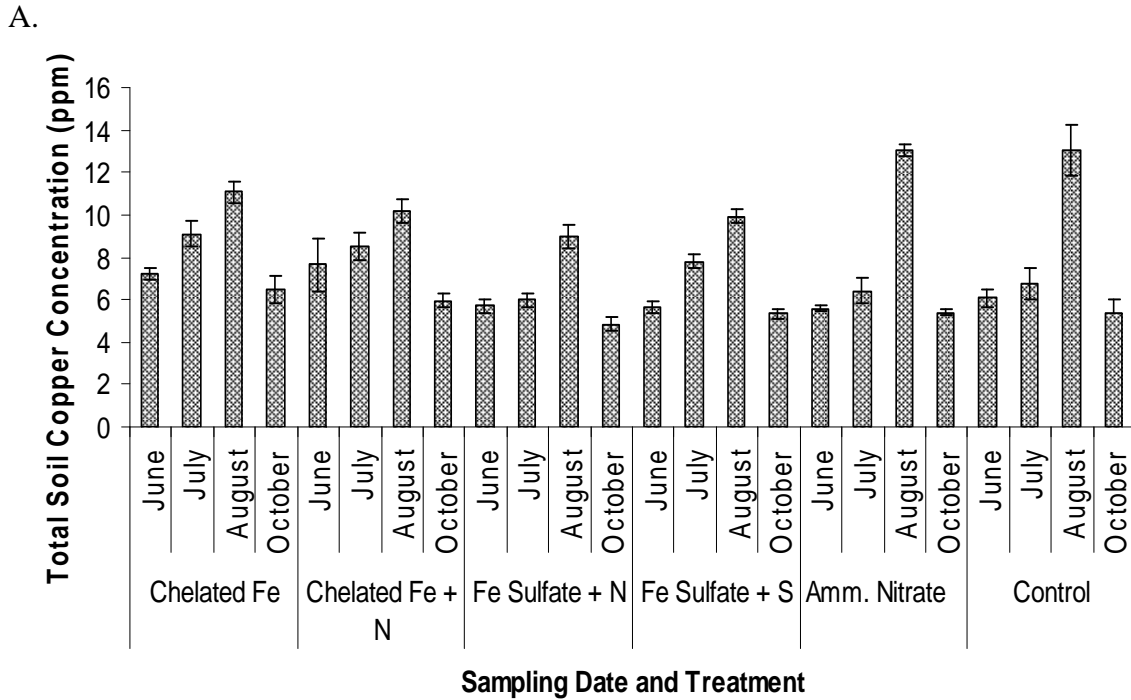


Figure 31. Total soil copper concentration (\pm SE) for soil depth 1 (1-10 cm) (A.) and soil depth 2 (10-20 cm) (B.) * treatment * sampling date during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

Zinc

Zinc is an essential micronutrient with a role similar to Mn and Mg, binding substrate and enzyme in several enzyme systems (Mills and Jones, 1996). Zinc occurs in soil solution as the positive ion Zn^{2+} and is very immobile in the soil, with up to 95% of its movement in the soil being by diffusion (Miller and Donahue, 1995). In general, Zn does not form strongly insoluble inorganic compounds but does form a sulfide (sphalerite) which is the primary Zn containing mineral (Mills and Jones, 1996; Miller and Donahue, 1995).

Besides involvement in enzyme activities, Zn is important in the synthesis of tryptophane, a component of some proteins and a compound needed for the production of growth hormones (auxins) such as indoleacetic acid (Havlin et al., 2005). Zn deficiency symptoms include interveinal chlorosis in both younger and older leaves; stunted, twisted, or rosetted leaves and leaf necrosis followed by premature foliage loss (Havlin et al., 2005).

As stated earlier, Zn, like Mn and Fe, moves to the plant roots primarily by diffusion. As a result, soil properties that affect diffusion and the movement of Zn obviously will affect its availability to plants (Mortvedt et al., 1991). Zn^{2+} availability decreases with increasing pH, therefore most pH induced Zn deficiencies occur in neutral or calcareous soils, although not all of these soils exhibit Zn deficiency due to increased availability of Zn through chelation (Havlin et al., 2005). Zinc can form complexes with organic compounds such as lignin and humic/fulvic acids in organic matter, resulting in either soluble Zn chelate

compounds or insoluble complexes like ZnSiO_4 (Miller and Donahue, 1995; Havlin et al., 2005).

Plants vary by species and cultivar in their susceptibility to Zn deficiency (Havlin et al., 2005), as some species are able to exude H^+ and/or complexing agents into the rhizosphere to overcome the effects of high pH on Zn availability. Bar-Yosef et al. (1980) concluded that excretion of H^+ and probably other means of reducing the pH near the root were more effective in enhancing Zn uptake than excretion of complexing agents.

Pin oak foliar Zn concentration was significantly higher for the $\text{FeSO}_4 + \text{S}$ treatment than for any other treatment. Swamp white oak foliar Zn concentration was also highest when treated with $\text{FeSO}_4 + \text{S}$ and lowest in the chelated Fe + N treatment (Table 7).

Foliar Zn concentration showed a significant ($p = 0.0002$) interaction for species * sampling date (Figure 32). Pin oak was significantly higher in foliar Zn concentration than swamp white oak throughout the 2007 growing season. Pin oak foliar Zn concentration ranged from 48.9 to 73.9 ppm, with much higher values for August and October than for the months of June and July. Swamp white oak foliage ranged from 30.1 to 36.6 ppm with the highest reading in October. Foliar Zn concentrations in swamp white oak were above the sufficiency range 16 – 26 ppm (Table 8). Also, pin oak was well within the normal sufficiency range of 29 – 88 ppm (Table 8). Pin oak foliar Zn concentration followed the same trend at the species * treatment level ($p = 0.0252$), as trees treated with $\text{FeSO}_4 + \text{S}$ were significantly higher in pin oak than

for any other treatment (Figure 33). Pin oak also had higher foliar Zn levels than swamp white oak throughout the growing season.

For both species, treatments containing S had the highest levels of foliar Zn, a result of lowered pH and improved Zn availability to the trees. The significantly higher foliar Zn levels in pin oak treated with FeSO_4 + S indicate that the species is responding most favorably to this treatment. However, neither species was deficient in foliar Zn for any treatment. Perhaps these species, despite the alkaline soil they are planted in, have the ability to influence the rhizosphere pH and/or take advantage of Zn chelates in their uptake of Zn.

Total soil Zn concentration was significant ($p = 0.0001$) for treatment and sampling date independently during the growing season of 2007. Total soil Zn concentration was high in June (Figure 34), afterward tapering off in the dry months of July and August (Table 4). Soil Zn concentration was up again by sampling time in October. Likely, adequate rainfall in June allowed microbial and root activity to increase Zn uptake, leaving it in lower quantities in the soil during the relatively inactive dry months of July and August. Most likely, greater quantities of precipitation in October once again began to allow more soil microbe and root activity and thus greater amounts of soil Zn were taken up.

Total soil Zn levels were significantly lower for the treatments of Fe sulfate + N, Fe sulfate + elemental S, and ammonium nitrate than for the remaining fertilizer treatments (Figure 35). Zinc becomes more available to plant uptake in acidic pH soils. Due to the lowering effect these treatments had on high pH soil of the study site, Zn was more available to the trees and uptake was increased.

Consequently, the soil which received these treatments became lower in total Zn concentration than soil in which treatments did not significantly affect pH.

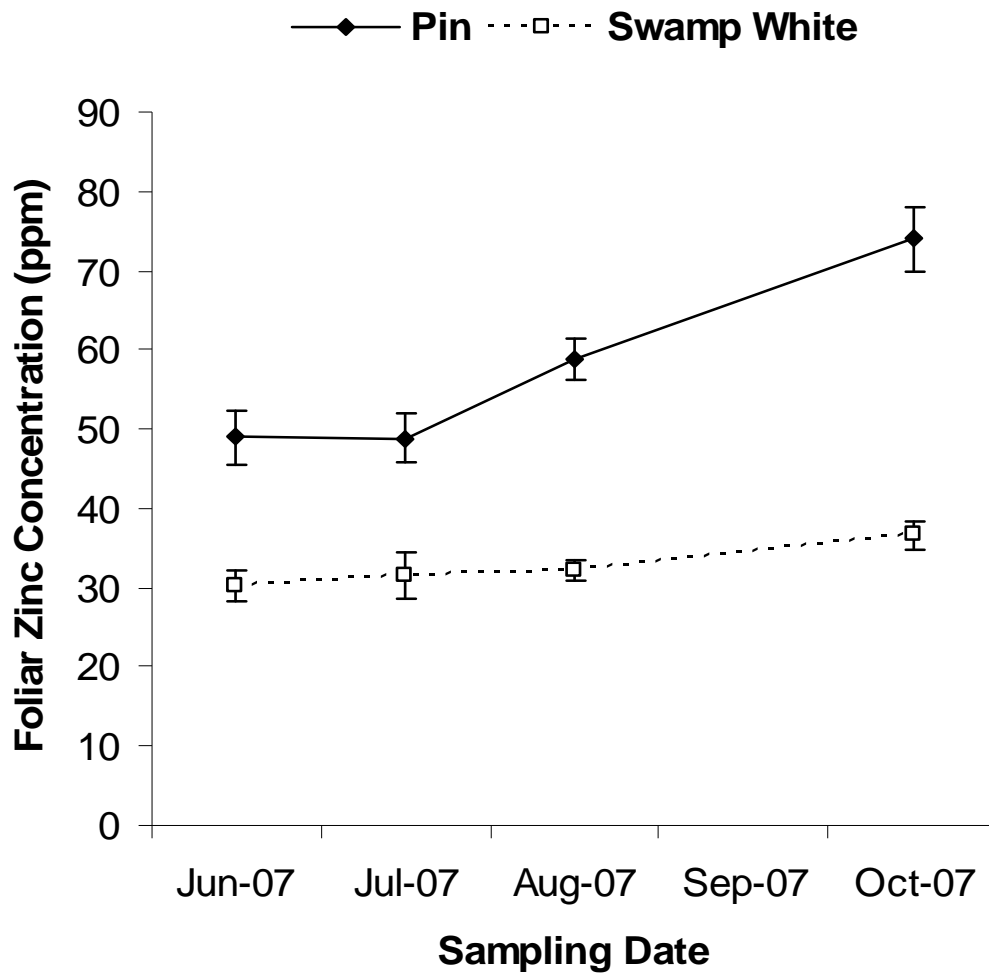


Figure 32. Mean foliar zinc concentration across treatments (\pm SE) by sampling date for pin oak and swamp white oak during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

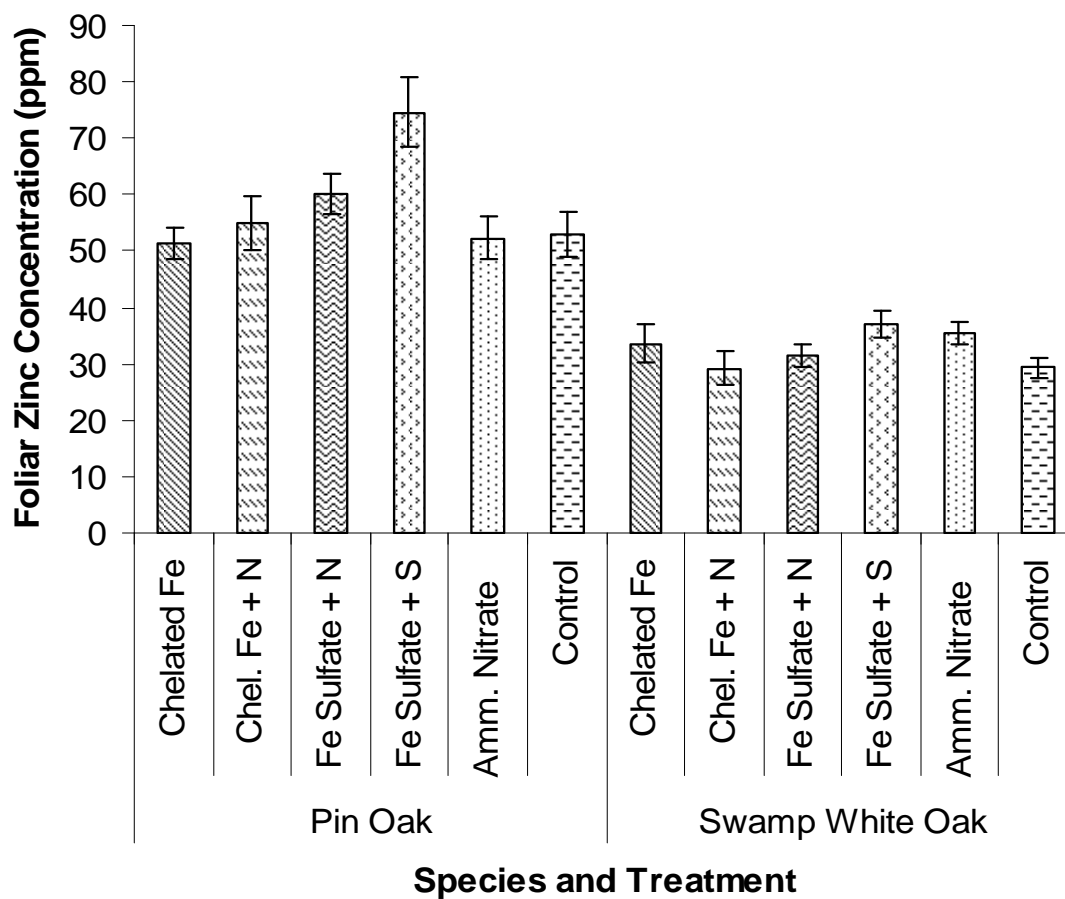


Figure 33. Mean foliar zinc concentration (\pm SE) by treatment across both species during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

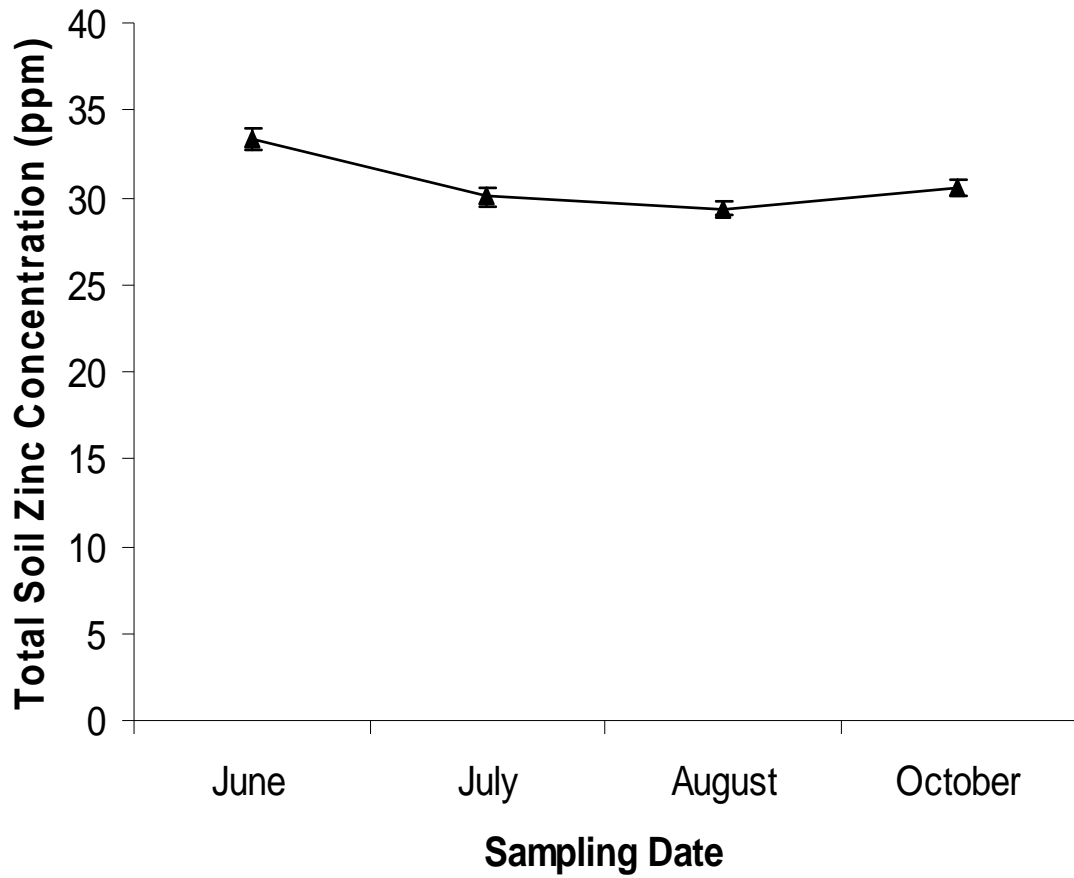


Figure 34. Total soil zinc concentration across treatments (\pm SE) by sampling date during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

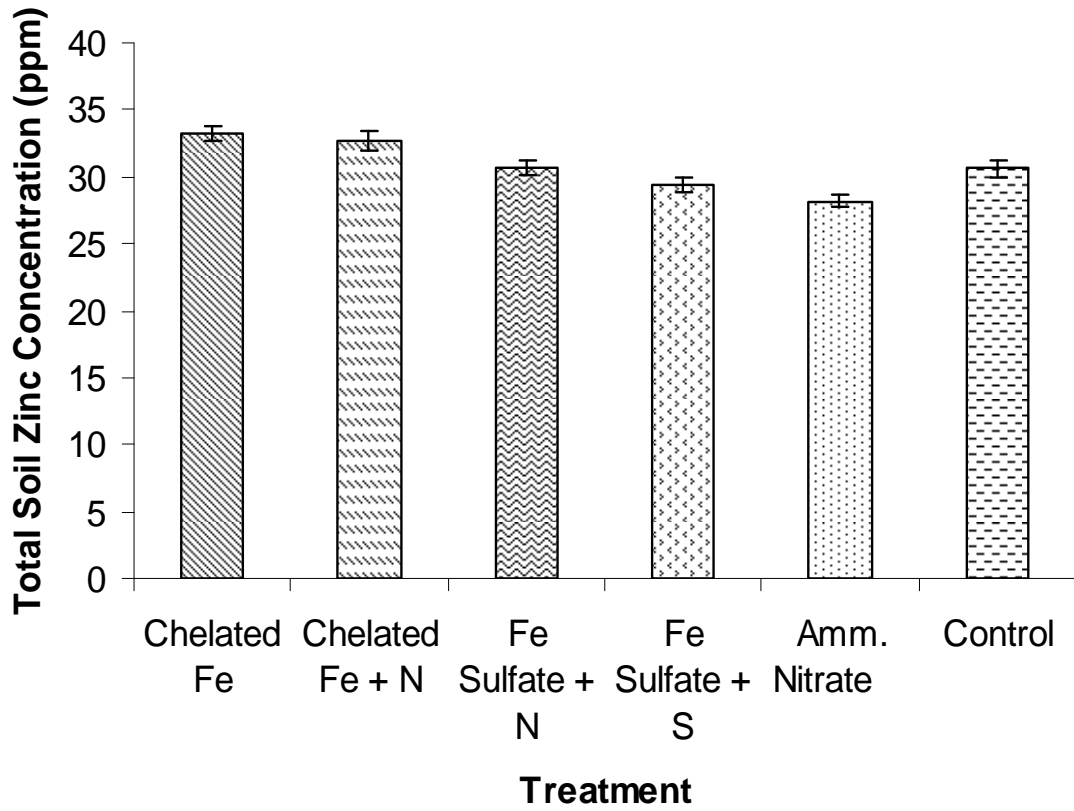


Figure 35. Total soil zinc concentration (\pm SE) by treatment during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

Sodium

Sodium is an abundant element which in excessive amounts is responsible for impeding agriculture over large areas of the earth (Mortvedt et al., 1991). Sodium is considered a beneficial element and has a wide variety of effects on individual plant species, therefore making generalizations about these effects difficult (Brownell, 1979).

Plants absorb Na⁺, and concentration in leaf tissue varies from 0.01 to 10% (Havlin et al., 2005). Sodium is especially important to C₄ plants, which occur in arid, semi-arid, and tropical environments. In these growing conditions, Na plays an important role in turgor pressure and the opening and closing of stomates (Havlin et al., 2005; Mortvedt et al., 1991). The beneficial effects of Na in plant growth are often observed in low-K soils, because Na can partially replace K (Havlin et al., 2005). The precise nature of the partial substitution of Na for K in plants is not well understood, and it is possible that different mechanisms may be in operation in different species (Mortvedt et al., 1991).

In cotton (*Gossypium spp.*) partial substitution of Na for Ca has been reported for the growth of excised roots (Johansen and Johan, 1971), and Na has been found to overcome the impairment of carbohydrate transport with Cu deficiency (Johan and Johansen, 1973).

Among species, foliar Na did not follow any patterns due to treatment main effects (Table 7). Foliar Na concentration was significant ($p = 0.0001$) for treatment * species * sampling date interaction (Figure 36). Both pin oak and swamp white oak foliar Na was highest in June for all treatments except for pin

oak control. Swamp white oak generally had higher foliar Na values than pin oak and was significantly higher in June for all treatments except for Fe sulfate + N. Sodium normally ranges from 29-34 ppm in pin oak foliage and around 39 ppm in swamp white oak foliage (Table 8). Foliar Na concentrations in the study trees range from 39.3 to 344 ppm in swamp white oak and 29.1-301.7 in pin oak.

The foliar K content of the trees on the Plowboy Bend site is very low due to the unavailability of K to plants in high pH soils. As a result, Na is apparently being used as a partial substitute for K as stated in the literature above by Havlin et al. (2005). Therefore, it is likely that the high levels of Na in the study trees are due to substitution of Na for K in these K deficient plants.

Total soil Na concentration was significant ($p = 0.0001$) at the treatment * sampling date interaction (Figure 37). Total soil Na concentration was significantly lower in the month of August for the treatments of chelated Fe and chelated Fe + N as compared to the same month for all other treatments. Soil Na concentration in the treatments of Fe sulfate + N and Fe sulfate + S followed opposing trends to the soil K concentration for the same treatments and sampling dates. When soil Na went up in concentration, soil K concentration was down and vice versa, suggesting that there was indeed substitution of Na for K in the trees.

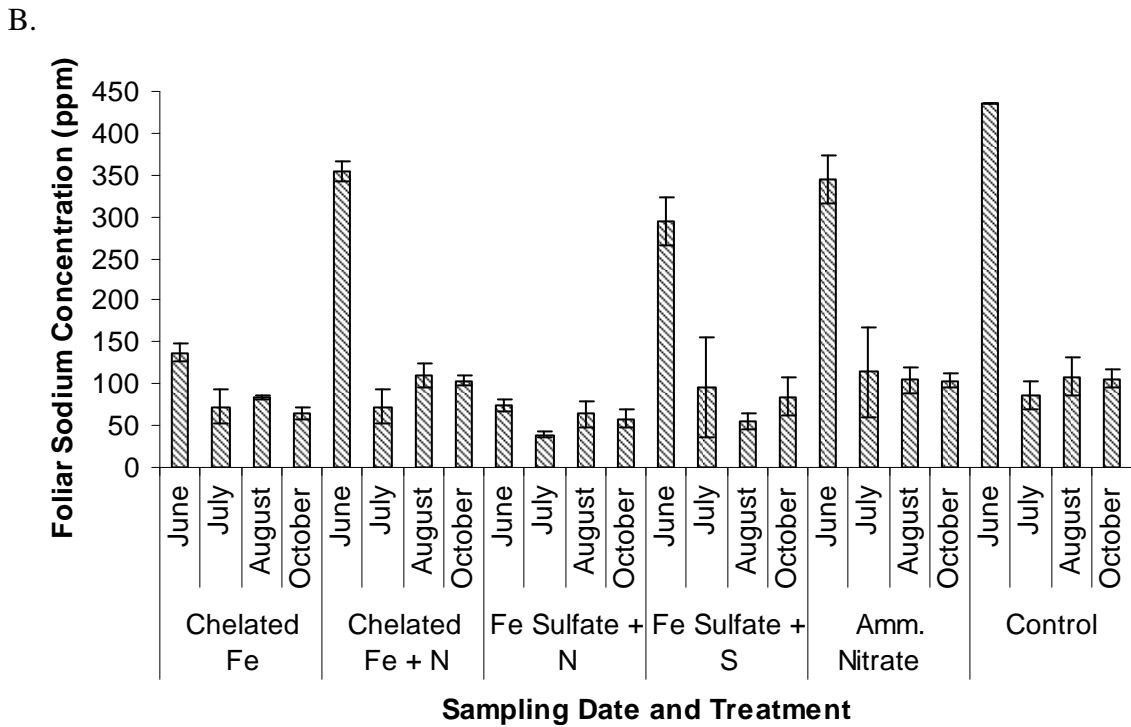
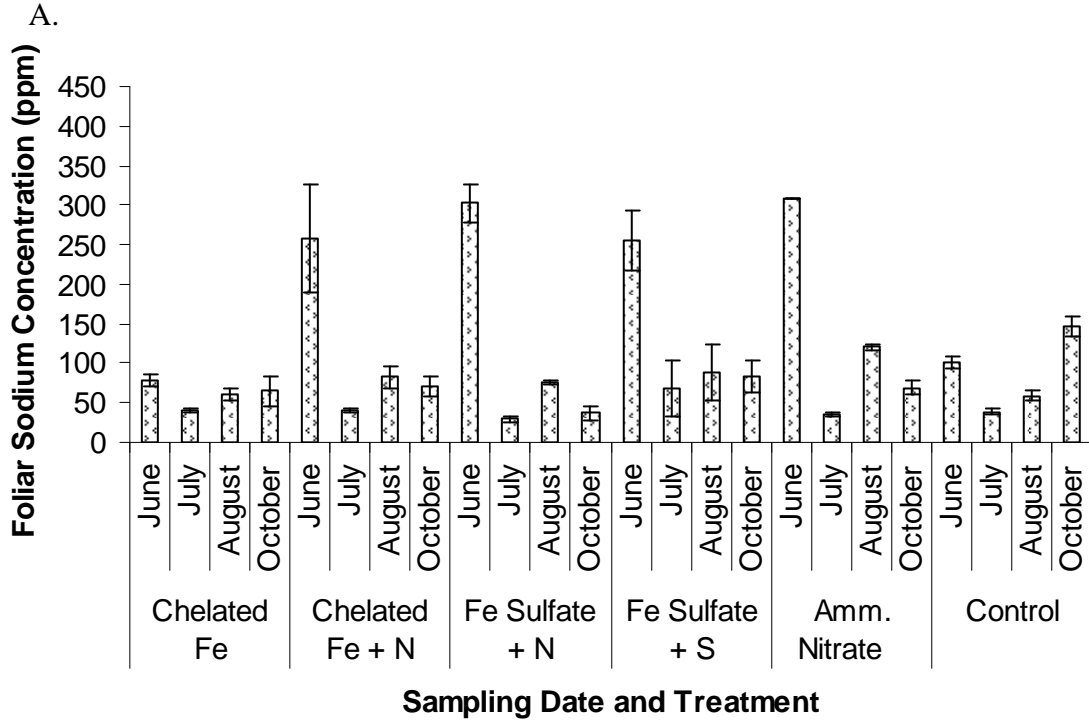


Figure 36. Foliar sodium concentration (\pm SE) by species * treatment * sampling date for pin oak (A.) and swamp white oak (B.) during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

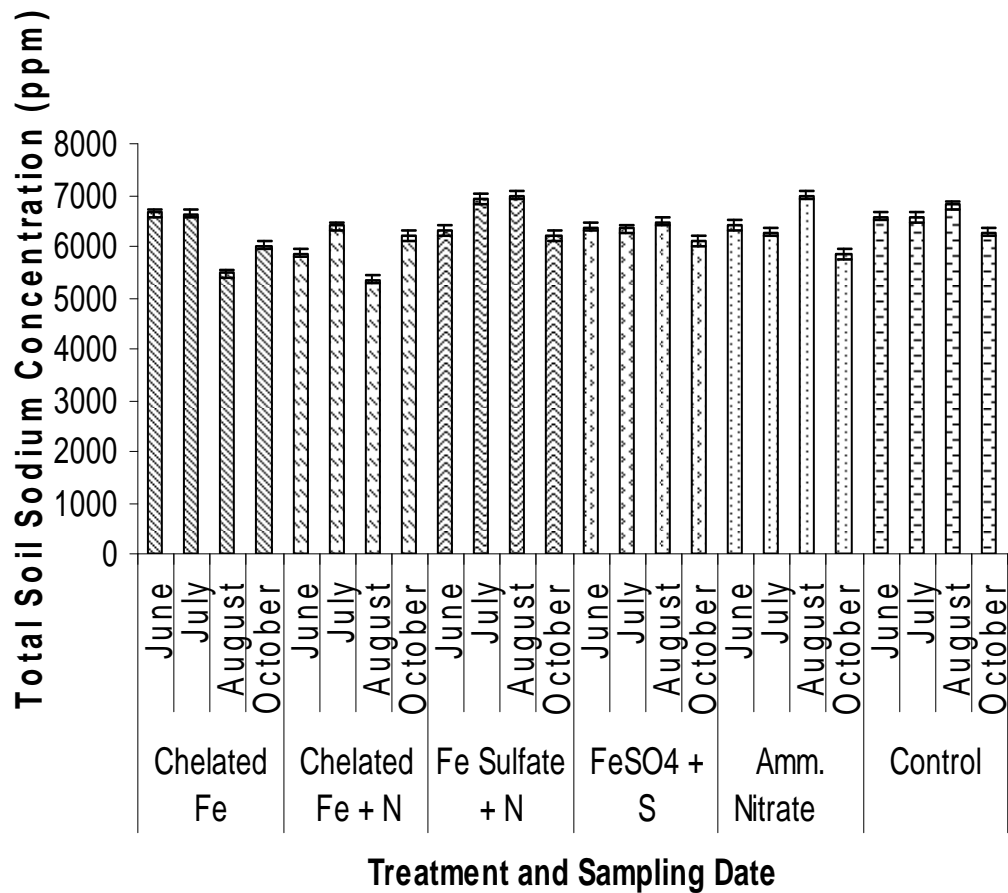


Figure 37. Total soil sodium concentration (\pm SE) by treatment * sampling date during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

Aluminum

Aluminum is also considered a non-essential or beneficial element, which means that it is beneficial to some plants but not considered necessary for the completion of a plant's life cycle (Havlin et al., 2005). Main interest in this element has been observed with (i) the ability of some plant species (accumulators) to tolerate very high Al concentrations (up to several percent) in their tissues; and (ii) the toxic effects on plant growth of free Al ions in the soil solutions of acid soils (Bell and Edwards, 1987). In the latter case, both direct toxic effects and Al-induced deficiencies of essential elements may be involved (Mortvedt et al., 1991). In some cases, reported beneficial effects of Al may be related to a reduction, by Al, in the uptake of a second element, such as Cu, present in the root environment at potentially toxic concentrations (Mortvedt et al., 1991).

Both species had the highest foliar Al concentration when treated with $\text{FeSO}_4 + \text{N}$ but otherwise did not follow any treatment main effect patterns (Table 7). Foliar Al concentration was significant ($p = 0.0049$) for species. Swamp white oak foliage was significantly higher in Al during the months of July and October than pin oak foliage (Figure 38). Pin oak foliage in healthy trees range from 15-51 ppm and healthy swamp white oak foliar Al averages 55 ppm. Both species of oak trees were near or below the sufficiency range (Table 8) in June but was well above sufficiency level for the remainder of the growing season. Swamp white oak is more tolerant of alkaline soils and as demonstrated by foliar nutrient levels was able to take up more nutrients, which is further shown again

by higher Al concentration. Foliar Al concentration was also significant ($p = 0.0001$) in the treatment * sampling date interaction (Figure 39). Foliar Al concentration was significantly higher in October than for the rest of the growing season when treated with $\text{FeSO}_4 + \text{N}$, $\text{FeSO}_4 + \text{S}$, and control. In general, foliar Al was low in June and increased, regardless of treatment, throughout the growing season with the highest levels in October.

According to Mills and Jones, (1996), at a pH near 8 and reaching a maximum concentration near pH 10, two new soluble Al species, described simply as $\text{Al}(\text{H}_2\text{O})_2(\text{OH})_4^-$ and $\text{Al}(\text{H}_2\text{O})(\text{OH})_5^{-2}$ occur. These may cause toxicity in excessively basic soils. As soils are leached, some basic cations are exchanged and the exchange sites are increasingly occupied by aluminum species.

A decrease in Al toxicity with increasing Ca concentration in solution has been widely reported, although the concentration of soluble Ca at which this effect becomes evident varies depending on the plant species and the amount of Al present (Alva et al., 1986; Noble et al., 1988). Because of interaction between these parameters, the limits of Al toxicity vary greatly among different species and environmental conditions, making it difficult to establish a reference Al level for evaluating toxicity (Alvarez et al., 2005).

Total soil Al was significant ($p = 0.0023$) for treatment * sampling date interaction (Figure 40). Total soil Al was significantly lower in the months of June and August for all treatments than it was in July and October. Low soil Al concentrations in June coincide with uptake of soluble Al species by the seedlings. High soil Al in the dry month of July is likely a result of low soil

moisture resulting in no apparent losses to leaching and diminished root activity/plant uptake. Literature search, however, does not explain the low soil Al levels in August followed by high readings in the October soil samples.

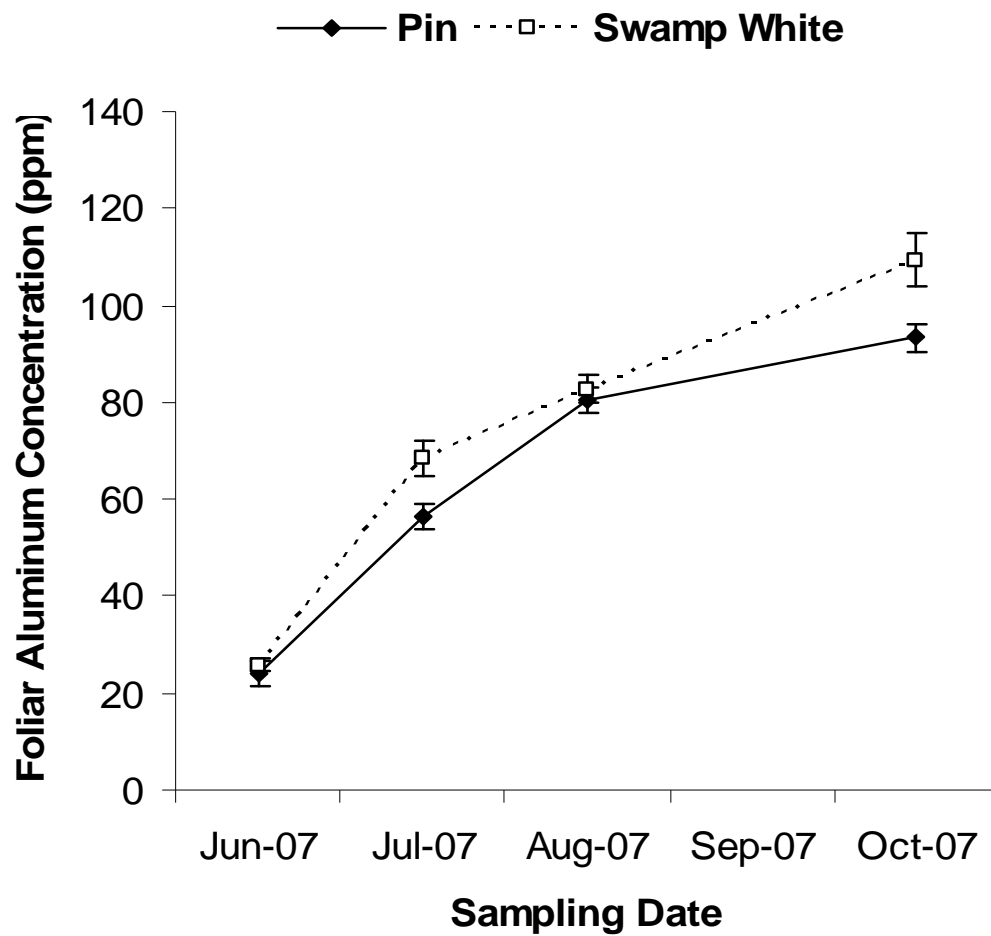


Figure 38. Mean foliar aluminum concentration across treatments (\pm SE) for pin oak and swamp white oak during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

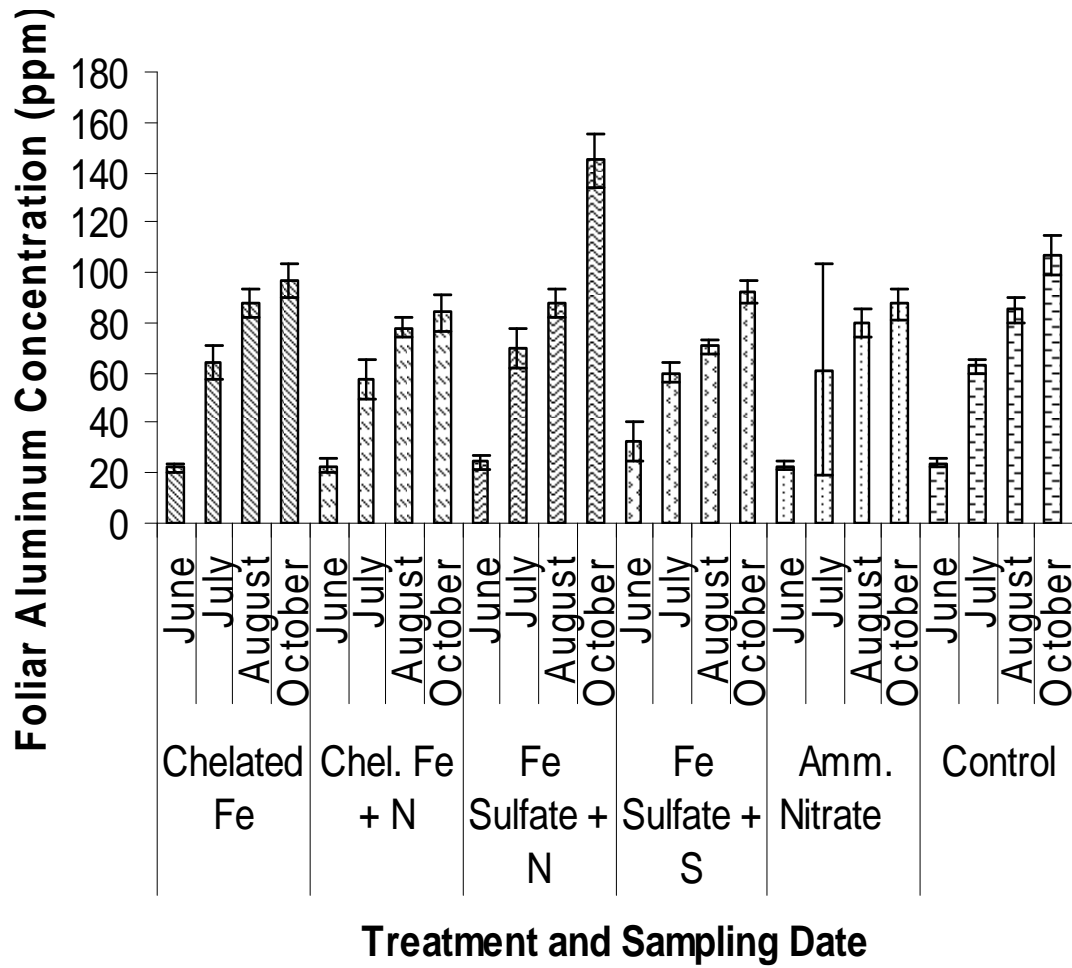


Figure 39. Mean foliar aluminum concentration (\pm SE) by treatment * sampling date across both species the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

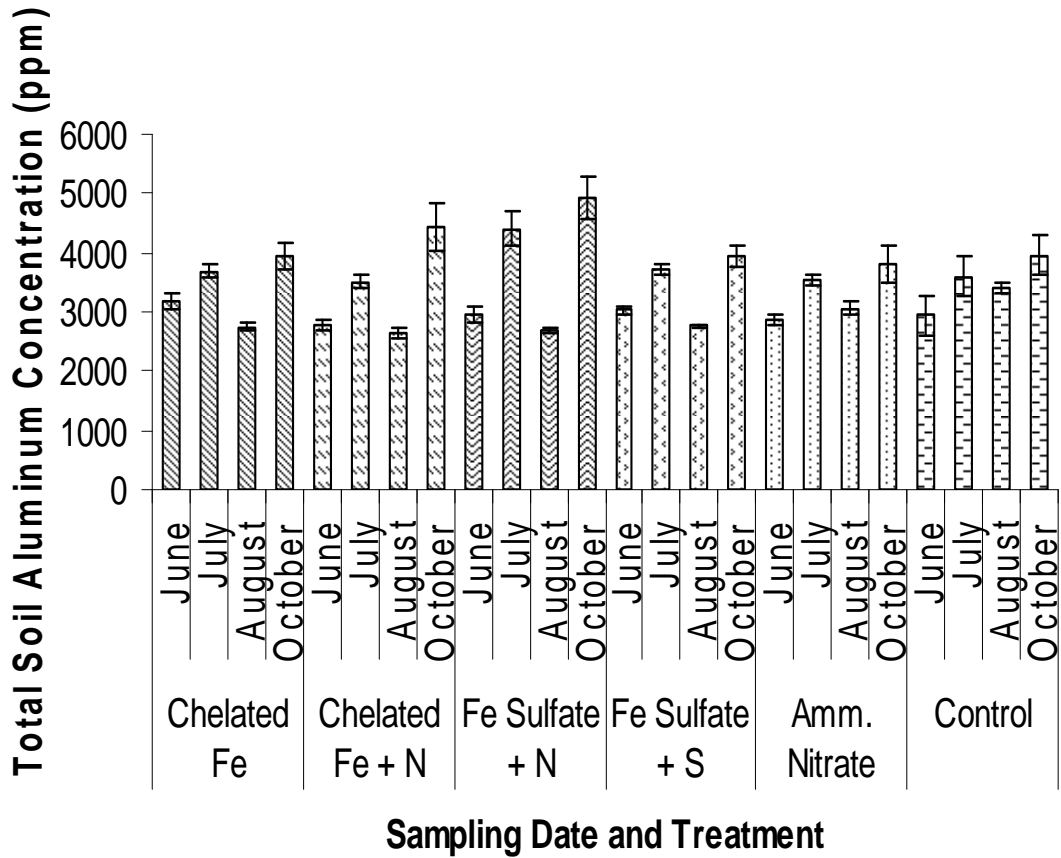


Figure 40. Total soil aluminum concentration (\pm SE) by treatment * sampling date during the 2007 growing season taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO.

SOIL BEDDING

The effect of soil bedding on the concentrations of N, S, and Fe in foliage and on concentrations of S and Fe in the soil after the application of fertilizers containing combinations of Fe chelate, Fe sulfate, ammonium nitrate, and elemental S was analyzed. No significant interaction was found between bedded and non-bedded soil for foliar or soil nutrient concentrations, regardless of the treatment applied (Table 9). Treatment effects, however, were significant as the addition of N, S, and Fe to the soil raised foliar levels N and S, but not Fe significantly. Sulfur fertilizer treatments did significantly raise Fe concentrations in the soil.

Soil bedding can improve soil aeration and drainage (Page-Dumroese et al., 1997, Lakel et al., 1999, Fisher and Binkley, 2000, and Smolander et al., 2000) and also concentrate soil organic matter and nutrients. Soil bedding has not always proven beneficial to seedling survival and growth. Kabrick et al. (2005) reported that the growth of swamp white oak and pin oak planted in bedded soils on two conservation areas along the Missouri River did not improve from soil bedding. However, soil bedding did improve organic carbon content, soil drainage, and reduced bulk density.

According to Kabrick et al. (2005), alluvial soils, such as the soil at Plowboy Bend, often do not change appreciably in organic carbon and base cation concentration with depth. Bedding likely has a greater effect in soils where the properties differ consistently with soil depth, such as in uplands (Kabrick et al., 2005). Furthermore, because the Sarpy Fine Sand at Plowboy

Bend Conservation Area is a sandy alluvium and the water table is generally more than 1.5 m below the soil surface, this soil is excessively drained. The combinations of the above soil conditions contribute to the fact that soil bedding had no significant effect on the soil and foliar nutrient concentrations.

Table 9. Mean foliar and soil nutrient concentrations for two oak species (*Quercus palustris* and *Q. bicolor*) planted in an alkaline Missouri River bottomland soil. Treatments were bedded or non-bedded and with or without fertilizer treatments containing N, S, and Fe

Treatment	Foliar					
	Nitrogen		Sulfur		Iron	
	Bedded	Non-bedded	Bedded	Non-bedded	Bedded	Non-bedded
With N	1.84a	1.85a	1157.06a	1187.74a	70.11a	77.33a
Without N	1.68b	1.8a	1053.91b	1144.73a	78.07a	78.2a
With S	1.87a	1.85a	1166.2a	1235.67a	85.5a	77.6a
Without S	1.75b	1.8a	1108.9b	1120.8a	66.6a	78.01a
With Fe	1.83a	1.86a	1139.97a	1192.86a	77.22a	77.8a
Without Fe	1.70b	1.75a	1096.65b	1103.77a	61.24a	81.34a
	Soil					
With S	-----	-----	7.11a	6.27a	0.1a	0.07a
Without S	-----	-----	7.63b	7.99a	0.1a	0.09a
With Fe	-----	-----	7.8a	7.14a	0.11a	0.09a
Without Fe	-----	-----	6.69a	7.96a	0.1a	0.08a

* Different letters denote significant differences ($p < 0.05$) between the two treatments for a nutrient.

HEIGHT AND DIAMETER GROWTH

Height and diameter at breast height (dbh) was recorded for trees at Plowboy Bend Conservation Area. In 2007, the mean height of swamp white oak was 2.47, 3.41, 2.3, 2.05, 2.28, and 2.74 m respectively for the treatments of chelated Fe, chelated Fe + N, FeSO₄ + N, FeSO₄ + S, ammonium nitrate, and control. The mean dbh of swamp white oak was 2.65, 4.74, 2.49, 4.39, 2.01, and 3.18 cm respectively for the same treatments above. Pin oak mean heights were 2.23, 2.13, 1.55, 1.7, 1.26, and 1.75 m respectively for the treatments of chelated Fe, chelated Fe + N, FeSO₄ + N, FeSO₄ + S, ammonium nitrate, and control. The mean dbh of pin oak was 2.13, 2.45, 1.08, 1.73, 0.55, and 1.68 respectively for the treatments above.

Appendix A-3 shows mean height and dbh growth by treatment over a two year period from 2005 through 2007. Regardless of treatment, swamp white oak out performed pin oak on this bottomland site. This further confirms the belief that swamp white oak is superior to pin oak at coping with the high soil pH at Plowboy Bend. Height and dbh growth patterns for both tree species were the same for treatments chelated Fe, chelated Fe + N, FeSO₄ + N, and control. These treatments caused little or no change in the soil environment that affected nutrient uptake. The study showed that FeSO₄ + S and ammonium nitrate treatments did change the soil environment by acidification, which was associated with the trees taking up more nutrients and becoming healthier than trees without these treatments. These treatments, however, resulted in negative pin oak height and reduced dbh.

White-tailed deer and eastern cottontail rabbits are abundant on Plowboy Bend Conservation Area. These herbivores have done considerable damage to both species of oak tree seedlings. Deer mainly damage trees during the growing season by browsing the foliage. Also, bucks rub the bark from saplings with their antlers during the fall mating season. Cottontail rabbits girdle trees by eating the bark during the winter months.

Deer are selective feeders and according to the optimal forage theory, they select foods that maximize their net range or energy gain (Renaud et al., 2003). In order to do this, deer will always select browse which is more palatable, choosing to eat vegetation which is highest in nutrient content (Hanley, 1997). By fertilizing tree seedlings, as was done in this study, one may actually increase the chances that the tree's foliage will be browsed by deer in preference to unfertilized trees. A nitrogen fertilizer study conducted by Bouchard and O'Leary (2008) confirmed that plants higher in nitrogen are more nutritious and palatable to deer, and are thus preferred as browse over plants with less nitrogen.

As shown in appendix A-3, trees that were treated with $\text{FeSO}_4 + \text{N}$, $\text{FeSO}_4 + \text{S}$, and ammonium nitrate showed the lowest height and dbh increases, except for swamp white oak (dbh) when treated with $\text{FeSO}_4 + \text{S}$. These three treatments, especially $\text{FeSO}_4 + \text{S}$ and ammonium nitrate, changed soil pH and increased overall foliar nutrition more than the remaining treatments. As a result, seedlings treated with $\text{FeSO}_4 + \text{N}$, $\text{FeSO}_4 + \text{S}$, and ammonium nitrate were browsed more heavily by deer and rabbits at Plowboy Bend Conservation Area.

It is also notable that swamp white oak was significantly larger than pin oak in height and dbh gains, regardless of treatment. It is our belief that the thinner, more tender leaves of the pin oak are preferred to the thicker, tough leaves of the swamp white oak. Though not quantified in this study, seedling height would also have a bearing on its susceptibility to browsing by deer. Renaud et al. (2003) found that deer prefer to browse at or below their shoulder height. Adult white-tailed deer stand 0.86 to 0.99 m tall at the shoulder (Rue, 1962), suggesting that foliage on seedlings at or below this height would be most likely to be browsed by deer. Therefore, the smaller bare root seedlings and stump sprouts from rabbit-girdled RPM[®] seedlings are subject to repeated browsing by deer, keeping them shorter and in the deer's preferred browsing zone longer. This suggests that RPM[®] trees which can quickly attain heights out of the deer's preferred browsing zone gain an advantage over their shorter companions of the same species and treatment regime.

While the effects of fertilizers on pH and nutrient availability is the main focus of this study, it is important to recognize the potential impacts that wildlife such as white-tailed deer and cottontail rabbits have had on the growth and survival of the study trees. Ungulates like white-tailed deer can profoundly alter the structure and composition of forest communities (Rooney and Walker, 2003). Benner (2006) found that young white and red oaks were the 4th and 7th most preferred browse by white-tailed deer in forests. Clearly, the full growth potential and influence of fertilizers on oak growth at Plowboy Bend Conservation Area could be better realized if trees were free from herbivory.

CHAPTER IV

CONCLUSIONS

Efforts to reforest the Missouri River Floodplain at Plowboy Bend Conservation Area with swamp white oak and pin oak has met with many challenges including high soil pH, calcareous soil, vegetative competition, and herbivory damage. Five fertilizer treatment combinations including chelated Fe, Fe sulfate, elemental S, and ammonium nitrate have been applied since 2004 in an effort to ameliorate soil pH and improve the nutrient availability to the planted oak seedlings.

Soil pH is one of the most important soil properties that affect the availability of soil nutrients. The soil at Plowboy Bend has an alkaline pH of 8.29. The S in treatments $\text{FeSO}_4 + \text{N}$ and $\text{FeSO}_4 + \text{S}$ acidified the soil and lowered the pH to more favorable levels for nutrient availability, especially in the upper 10 cm of the soil. Soil reactions with ammonium in the ammonium nitrate treatment also caused a slight but insignificant drop in pH. $\text{FeSO}_4 + \text{S}$ lowered soil pH significantly from an average of 8.29 to 6.4. This is very important because the majority (12) of the essential nutrients have their highest availability at a pH range of 6.5 to 7.0.

Concentrations of nine elements: P, S, Mg, Fe, Mn, Mo, Cu, Zn, and Na were increased as a result of decreased pH from treatments containing S. However, with these increases, foliar nutrient levels were still below sufficiency levels for N, P, K, S, Ca, Mn, and Cu.

In this study, the buffering capacity of the soil was not taken into account. The soil environment is constantly changing. The availability and movement of soil nutrients is dynamic due to factors such as soil pH, soil moisture and temperature, and organic matter content. The addition of fertilizers containing various mineral nutrients, as was done in this study, further complicates the interactions among nutrients in the soil. For example, foliar K concentration was very low in both species of trees but foliar Na levels were high. This data coupled with the fact that soil K and Na levels were inversely related confirms the literature's indication that Na is likely being utilized as a substitute for K in the trees for processes such as maintaining turgor pressure.

Even with the addition of S to acidify the soil, we have not yet reached the optimal pH (below 6.0) preferred by these tree species (Gilman, 1997). The high soil pH and resulting problems make it difficult to get correlations between soil nutrient availability and plant uptake. As stated earlier, the addition of S and sulfate in the treatments $\text{FeSO}_4 + \text{N}$ and $\text{FeSO}_4 + \text{S}$ caused the most significant drop in pH which generally favored greater uptake of soil nutrients.

Fertilizers in this study were broadcast applied onto a weed mat over the surface of a high pH, calcareous soil. Broadcast fertilization without soil incorporation leaves treatments exposed to the elements and totally dependant upon precipitation to move them into the soil, leaving them vulnerable to atmospheric losses. Although precipitation was not part of the data collected in this study, the effects of area monthly rainfall totals were considered in the study results. Aside from soil moisture being necessary for the movement of nutrients

into the root zone of plants, it supports the growth and activity of soil microbes which break down soil organic matter and form chemical bonds, such as chelates, which result in soil nutrients becoming available for plant uptake.

Total soil nutrient concentration was often higher in the first 10 cm (depth 1) than in the second 10 cm (depth 2, 10 to 20 cm) at Plowboy Bend. Because the fertilizer treatments containing Fe, S, and N were broadcast applied, as expected, these nutrients were higher at the soil's surface. Also, the somewhat higher organic matter in the top 10 cm of soil at Plowboy Bend Conservation Area helps to retain and release soil nutrients.

The Great Flood of 1993 scoured away top soil taking with it much of the organic matter and both it and subsequent floods deposited a layer of sand onto Plowboy Bend Conservation Area which has undoubtedly limited the ability of the top layer of the soil to hold nutrients. During soil sampling we noticed that approximately the top 14 to 16 cm of the samples were almost pure sand while the bottom 4 cm was darker in color and contained more silt and clay. Many of the soil nutrients, including Ca, were higher in the top sampling depth, but nutrients were generally deficient in the entire top 20 cm of soil tested. It is plausible that many of the soil nutrients are not held in the top 20 cm of the soil but are instead subjected to leaching into the soil below.

In conclusion, the availability of nutrients in general was improved, resulting in increased uptake by pin oak and swamp white oak. The lowering of soil pH to more favorable levels with the application of fertilizers containing sulfate and elemental S was responsible for much of these increases. However,

many of the essential nutrients remain below sufficiency levels in the foliage. Iron chlorosis was not alleviated by adding chelated Fe, but foliar Fe levels improved when pH was lowered. This illustrates that the application of fertilizers will do little to improve nutrient availability if the soil pH is not correct for plant species and optimum soil nutrient availability. The sandy soil at Plowboy Bend did not benefit significantly from soil bedding. Overall, the growth of the trees at Plowboy Bend Conservation Area in response to fertilizers could not be accurately measured because of herbivory by rabbits and white-tailed deer. It appeared that because of herbivory damage, trees in treatments that had higher P, S, Mg, Fe, Mn, Mo, Cu, Zn, and Na levels tended to have less growth than trees with less of these nutrients.

TAKE HOME MESSAGE FOR MANAGERS

There are some important points to be gleaned from this research for land managers, both public and private, who wish to reforest bottomlands with hardwood trees. It is imperative to match the intended tree species to the soil in which it will be planted. Pin oak and swamp white oak are bottomland tree species that produce small acorns which are highly palatable to waterfowl, making them desirable oak species for bottomland hardwood restoration. These tree species, however, prefer soil with an acidic pH while the soils at Plowboy Bend Conservation Area are alkaline. The resulting situation is oak seedlings which are unhealthy due to various nutrient deficiencies. Many problems can be avoided by matching species to planting site.

While conducting research at Plowboy Bend, we noticed that a few of the RPM[®] pin oaks which had received no treatment appeared to be growing well. Wayne Lovelace (Personal communication, Forest Keeling Nursery, Elsberry, MO) revealed that some of the unexplainably healthy looking “pin oak” at Plowboy Bend are likely Nuttall oak (*Quercus texana*) that were mistakenly mixed in with the pin oak during planting. While this species was not intentionally planted, many of them look healthy and are growing well because of their inherent tolerance to higher soil pH than pin oak. Perhaps Nuttall oak should be further investigated for recommendation in bottomland hardwood plantings in alkaline soils.

If it is determined that the soil which is to be planted with trees requires amendment, it may be easier to apply these soil amendments before the trees

are planted. Soil amendments with lasting effects, such as elemental S, could be broadcast with a tractor drawn spreader and then incorporated into the soil with a tractor and harrow or some other implement before trees are planted in order to better prepare a greater volume of the soil for root exploration. Broadcast application of fertilizers to individual trees leaves fertilizer nutrients vulnerable to great losses at the soil's surface. Broadcast application and fertilizer application in general may not be either feasible or economical for large scale bottomland hardwood restoration.

Finally, the majority of surviving seedlings on our study plot at Plowboy Bend are of RPM[®] origin. Because of their greater height and well developed root system, RPM[®] tree seedlings can more quickly grow out of the preferred browsing zone of white-tailed deer, a clear advantage over bare root seedlings. It is our belief that these trees, if grown in the correct soil pH and given protection from herbivory, would perform in a manner worthy of their greater cost.

RECOMMENDATIONS FOR PLANTING HARDWOODS IN ALKALINE BOTTOMLAND SOILS

There are thousands of hectares of alkaline soils along the Missouri River Alluvial Valley, with about 7211 ha of Sarpy soils like those found at Plowboy Bend in the state of Missouri alone (Kabrick et al., 2005). Managers from many different entities including the USDA Forest Service (federal), Missouri Department of Conservation (state), Ducks Unlimited (private), and individual landowners will need to apply a set of guidelines in order to be successful at restoring these alkaline bottomlands such as these to valuable, mast producing hardwoods to be enjoyed by people and wildlife alike.

Bearing in mind information learned from our study, we would like to make the following recommendations for successfully reforesting alkaline bottomlands with hardwoods. We would recommend that managers follow the principals set forth in Recognizing and Overcoming Difficult Site Conditions for Afforestation of Bottomland Hardwoods by Stanturf et al. (2004). Most importantly, one should choose a tree species which has a natural tolerance for alkaline soils. In the red oak group, Nuttall oak and Shumard oak are two species which can tolerate a higher pH and produce acorns small enough to be utilized by waterfowl. Swamp white oak can tolerate a higher pH than pin oak but is naturally an acid soil species. However, according to Wayne Lovelace, (Personal communication, Forest Keeling Nursery, Elsberry, MO) swamp white oak will readily hybridize with many different white oak species which are more tolerant of high pH. Mr. Lovelace spoke of a swamp white oak * burr oak hybrid that does well in alkaline

soils, although acorn size for this hybrid may be too large for utilization by waterfowl.

Once tree species are selected, we would recommend planting larger seedlings, such as RPM[®] at a wide spacing. Protective devices such as tree shelters, tree wraps, or cages should be installed around each tree to protect them from herbivory and stem damage from deer and rabbits. This approach would result in fewer trees with higher cost per tree, but we feel that ultimately it would be more successful than planting many small, cheaper trees without protection from wildlife damage. One could also plant hardy, fast growing bottomland softwood trees such as cottonwood, silver maple, and box elder between the hardwoods to act as trainer trees and to add organic matter to the soil from leaf litter. Managers would always have the option of later harvesting the softwood trees for pulpwood or lumber in order to allow for canopy expansion of the hardwoods.

Vegetation control would benefit the hardwood seedlings early in the project, especially an application of herbicides before bud break in early spring. While effective, the application of herbicides is time consuming and costly. We would recommend killing existing vegetation with herbicide if needed and preparing the area to be planted with redtop grass (*Agrostis gigantea*) before tree seedlings are planted. Dey et al. (2003) found that planting a cover crop of redtop grass not only kept out more competitive vegetation but also created an environment less favorable to cottontail rabbits and other rodent pests.

By following these recommendations, managers should be able to develop a successful plan for reforesting bottomland forests in alkaline soils.

CHAPTER V

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University of Missouri-Columbia Center for Applied Research and Environmental Systems (CARES) 130 Mumford Hall, Columbia, MO 65211
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APPENDIX

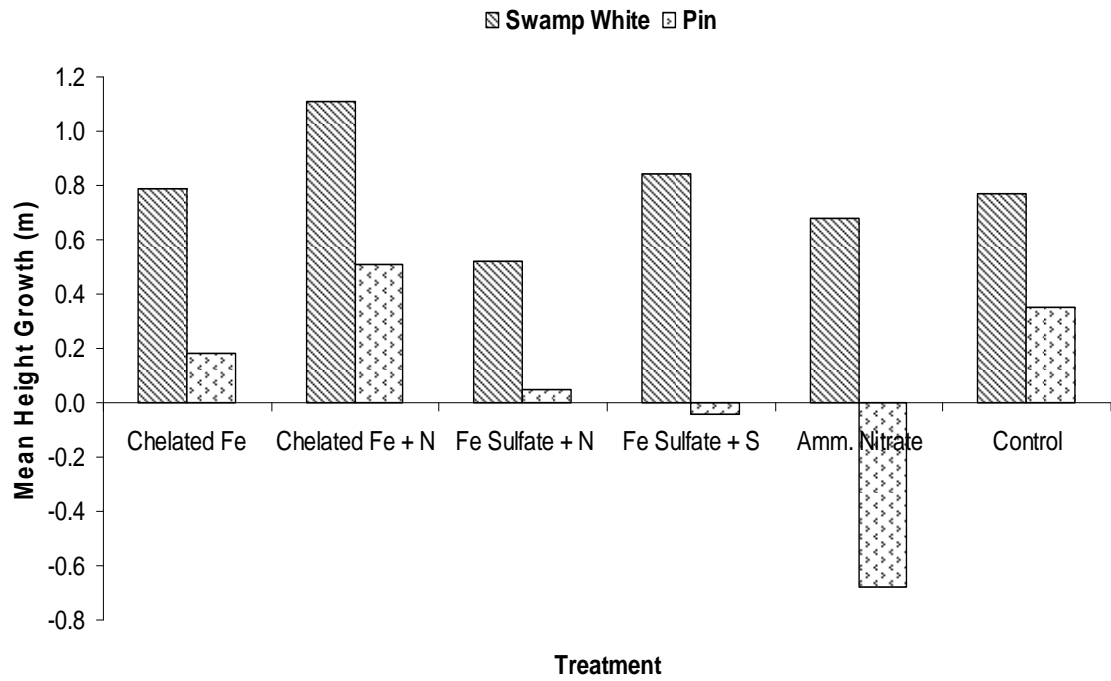
Appendix A-1. Foliar error mean squares for all sources of variation across two oak species, six fertilizer treatments, and four sampling dates.

Macronutrients										
Source	df	N	P	K	S	Mg	Ca			
Species (S)	1	0.0807	3305602.5	1843277.3	46.36	9559849.53	234103.77			
Treatment (T)	5	0.2527	411535.09	10819867	200584	2297892.56	141010.57			
S x T	5	0.0515	204805.45	1471927.1	44226	781836.59	44870.08			
Error A	48	0.0628	121934.25	1217303.3	32689.9	363438.38	70435.21			
Date (D)	3	0.7284	2455207.4	13646498	10983.4	660578.39	638724.79			
S x D	3	0.045	314028.75	2626578.8	55952.1	50956.11	238389.05			
T x D	15	0.0197	83693.58	1323667.1	18715.6	120880.76	65520.55			
S x T x D	15	0.0152	73973.87	1426750.8	23360.6	127361.3	117164.56			
Error B	144	0.0149	31111.3	64059	13184.2	39822.9	70219.07			
R-Square		0.776	0.829	0.698534	0.657	0.891	0.502			
Coefficient of Var.		6.76	12.61	13.67	9.93	11.01	8.42			
Mean		1.807	1398.63	5854.79	1155.85	1812.18	3146.28			
Micronutrients and Selected Heavy Metals										
Source	df	Fe	Mn	Mo	Cu	Zn	Na	Al		
Species (S)	1	2559.91	44356.5	3.31	42.93	37542.99	3827.34	3497.37		
Treatment (T)	5	5835.89	30370.7	0.33	12.48	1188.21	4193.85	2146.22		
S x T	5	3747.55	10709.01	0.19	13.76	595.47	1461.06	660.82		
Error A	48	1061.91	2514.04	0.16	3.52	209.67	2869.03	401.18		
Date (D)	3	22226.8	13127.66	0.49	36.33	3168.66	259003.06	63504.71		
S x D	3	273.95	808.59	0.77	7.57	1258.19	4982.39	650.8		
T x D	15	2069.24	1457.68	0.24	2.32	272.93	13584.03	1025.99		
S x T x D	15	2119.75	569.05	0.61	1.52	279.71	10918.18	321.97		
Error B	144	692.84	623.79	0.196	1.43	179.06	2490.19	231.17		
R-Square		0.707	0.831	0.551	0.721	0.752	0.789	0.884		
Coefficient of Var.		34.53	49.51	48.74	18.95	29.64	45.74	22.57		
Mean		76.11	50.49	0.907	6.31	45.14	109.09	67.36		

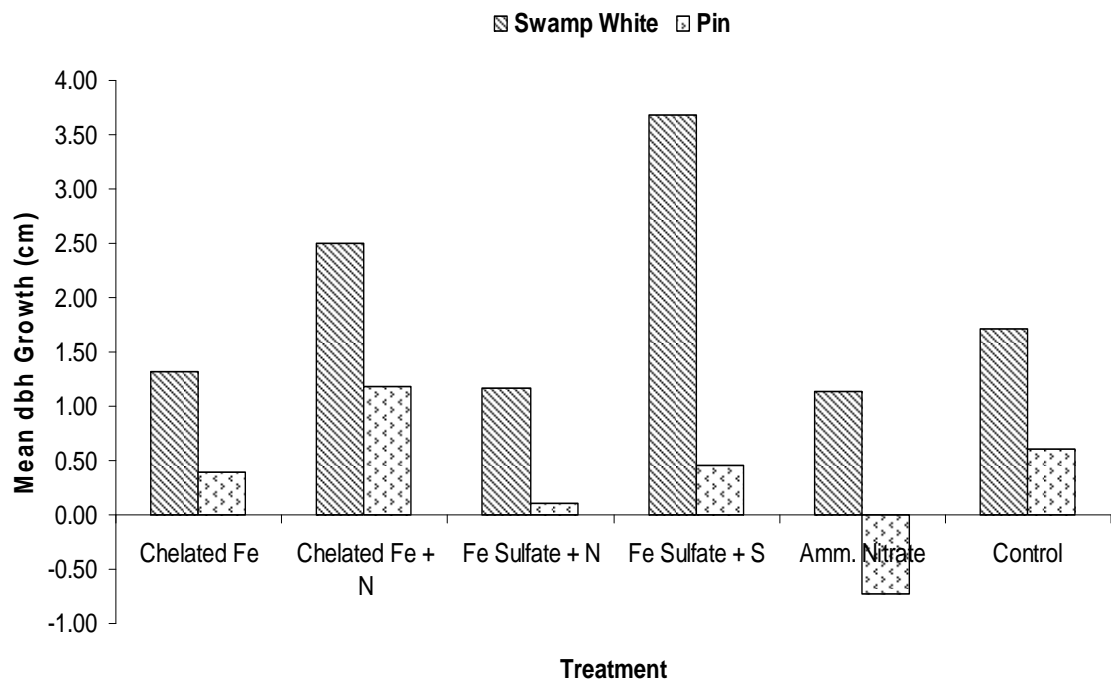
Appendix A-2. Soil error mean squares for all sources of variation across two soil depths, six fertilizer treatments, and four sampling dates.

Macronutrients										
Source	df	pH	P	K	S	Mg	Ca			
Depth (DP)	1	5.31	9347.77	9347.77	445174	1764.57	187860.76			
Treatment (T)	5	9.66	5715.15	2951813	810352	1078.53	278270.58			
DP x T	5	2.22	1957.22	554010.71	234170	716.14	134127.19			
Error A	48	0.78	1363.19	850647.8	14625.7	1064.42	87524.35			
Date (D)	3	0.71	34516.41	24620700	7943.22	4583.36	128300.08			
DP x D	3	0.09	2015.69	960148.82	1451.83	1230.63	122739.18			
T x D	15	0.11	744.36	2983864.6	3215.07	828.46	69509.79			
DP x T x D	15	0.127	737.56	506488.07	17337	1094.61	57204.073			
Error B	144	0.046	824.05	802848.5	9645.06	1159.53	85744.52			
R-Square		0.92	0.687	0.62	0.829	0.39	0.42			
Coefficient of Var.		2.68	6.92	6.92	36.41	79.12	36.09			
Mean		7.96	414.87	414.87	269.77	43.03	811.31			
Micronutrients and Selected Heavy Metals										
Source	df	Fe	Mn	Mo	Cu	Zn	Na	Al		
Depth (DP)	1	669828	3572.64	1.2	6.104	20.33	1206354	219947.6		
Treatment (T)	5	3963653	10386.56	0.31	24.15	148.06	1694306.9	983645.5		
DP x T	5	1257356	1049.03	0.09	5.64	40.36	423523.03	125819.5		
Error A	48	618629	1514.34	0.07	3.28	20.11	597367.88	335405.8		
Date (D)	3	1.8E+07	5706.24	1.49	268.2	183.56	1828545.2	23153947		
DP x D	3	103323	166.87	0.05	0.99	9.37	274110.81	222756.9		
T x D	15	408314	642.06	0.53	3.26	17.24	1591944.7	1012908		
DP x T x D	15	269362	383.41	0.04	2.24	9.71	402315.74	219703		
Error B	144	253199	608.9	0.119	1.101	11.84	408673	400386.5		
R-Square		0.77	0.65	0.53	0.88	0.63	0.57	0.651		
Coefficient of Var.		7.57	14.94	41.02	13.78	11.17	10.142	18.404		
Mean		6649.49	165.15	0.84	7.61	30.81	6302.77	3438.24		

A.



B.



Appendix A-3. Mean height (A) and dbh (B) growth by treatment for swamp white oak and pin oak averaged over the year 2005 through 2007 taken from Plowboy Bend Conservation Area experimental plots near Jamestown, MO. (Data courtesy of Dan Dey, US Forest Service).