ABSTRACT

HAINES, STEPHANIE ANNE. Nitrogen and Phosphorus Fertilizer Effects on Establishment of *Miscanthus ×giganteus* in North Carolina. (Under the direction of Ronald J. Gehl.)

Research efforts have recently been increasing in the United States to evaluate the use of giant miscanthus (*Miscanthus ×giganteus*) as a bioenergy feedstock and to develop recommendations for efficient management practices across various landscapes. The overall goal of this study was to evaluate effects of N and P fertilization on the establishment of giant miscanthus in the Piedmont and Mountain Regions of North Carolina. Specific objectives were to i) measure yield response to increasing rates of N and P fertilizer, ii) identify interactions between N uptake and P uptake, and iii) measure change in inorganic N and extractable P in the soil over multiple years of growth. Research sites were established at Mills River and Oxford, NC in 2008 and 2009, respectively. Treatments were arranged in a split-plot RCBD with main plots of 0, 147, 294, and 441 kg P ha^{-1} incorporated pre-plant and subplots of 0, 45, 90, and 135 kg N ha^{-1} surface broadcast annually. Soil cores were collected each year to a depth of 90 cm in four increments, and analyzed for inorganic N and Mehlich-III P. Yield was determined after senescence and tissue samples were collected at harvest to determine nutrient concentration. Giant miscanthus produced yields of up to 24 Mg ha^{-1} during the 3rd growing season. Nitrogen fertilization of 45 kg N ha^{-1} increased biomass dry yield by 46% in 2010 at Oxford, but did not affect yield at Oxford in 2009 or at Mills River from 2008-2010. Phosphorus fertilization of 147 kg P ha^{-1} increased biomass dry yield by 32% in 2008 at Mills River, but did not affect yield in 2009 or 2010 at Mills River or at Oxford in either year. Yield was not affected by N and P treatment interactions. Soil inorganic N concentration in the upper 20 cm decreased by 5.4 and 5.1 mg N kg^{-1} after the 2^{nd} and 3^{rd} growing seasons, respectively in Mills River and by 4.0 and 2.3 mg N kg^{-1} after the 1^{st} and 2^{nd} growing season at Oxford and did not vary among N treatments. Soil Mehlich-3 P concentration in the upper 20 cm decreased between the 2^{nd} and 4^{th} growing seasons by 37 and 29 mg P kg^{-1} in the 294 and 441 kg P ha^{-1} treatments, respectively at Mills River and decreased between the 2^{nd} and 3^{rd} growing seasons by 34, 68, and 139 mg P kg^{-1} in the 147, 294, and 441 kg P ha^{-1} treatments, respectively at Oxford. Giant miscanthus successfully established at Mills River and Oxford, NC with minimal N and P fertilizer inputs on soils with low initial P concentrations.

Nitrogen and Phosphorus Fertilizer Effects on Establishment of
Miscanthus ×giganteus in North Carolina

by
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BIOGRAPHY

Stephanie has wanted to be a scientist since she was a little girl. Her love and concern for natural resources led her to study Environmental Soil Science at Brigham Young University, where she was first introduced to soil science as a discipline. She spent two summers working/volunteering for the US Department of Agriculture's Natural Resources Conservation Service in Annapolis, MD and Provo, UT, where she met and worked alongside soil scientists. Her experiences in these internships and in classes helped her decide to pursue a career in soils. After graduating with her Bachelor's degree, she served a mission for the Church of Jesus Christ of Latter-day Saints in San Jose, CA for a year and a half before beginning her Master's degree in Soil Science at North Carolina State University.

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1.1 The Need for Renewable Energy

With the ever-increasing demand for energy and the ever-decreasing supply of fossil fuels, researchers around the world are continually searching for and improving upon alternative sources of energy. In 2008, 81% of the world's energy consumption was supplied by fossil fuels (Tanaka, 2010). Fossil Fuels include coal, natural gas, and petroleum, which require thousands to millions of years to form. As global populations increase and nations become more developed, the demand for energy is rapidly increasing. The U.S. Energy Information Administration predicts that from 2007 to 2035, world energy consumption will increase by 49% (Energy Information Administration, 2010). Renewable energy can be provided by wind, solar radiation, geothermal energy, nuclear energy, hydroelectricity, and plant biomass among other sources. These types of energy sources are likely to one day become major providers of energy for the world.

Consumption of fossil fuels is not only using up a limited resource, but is increasing the concentration of CO_2 in the atmosphere. According to the National Oceanic and Atmospheric Association (NOAA), as of 2006, the concentration of atmospheric CO_2 had increased by 36% since the pre-industrial age (Forster et al., 2007). The Environmental Protection Agency reported that in 2009, 95% of man-made C emissions in the United States came from the combustion of fossil fuels (EPA, 2011). These anthropogenic changes are affecting the earth in ways such as climate change and ocean acidification.

In the United States, a dependence on fossil fuels has led to a dependence on foreign nations for petroleum as an energy supply. During 2010, 51% of the petroleum consumed by the United States was imported from foreign countries (EIA, 2011). By utilizing alternative sources of energy, which can be produced locally, the United States could reduce or eliminate dependence on foreign oil.

1.2 Energy Goals for North Carolina

North Carolina has taken action to increase self-sufficiency of energy production. The NC State Senate passed a bill in 2006, mandating a state-wide strategic plan to locally grow and produce fuel from biomass. North Carolina Senate Bill 2051 declares a goal that by 2017, 10% of liquid fuels sold in North Carolina will come from biofuels grown and produced within the state. At the time the bill was passed, all liquid fuel was being imported into the state. To produce 10% of the state's current liquid fuel consumption, 600 million gallons of biofuel must be produced per year (Biofuels Center of North Carolina, 2010). The implementation of this plan is the goal of the Biofuels Center of North Carolina—a private, non-profit corporation headquartered in Oxford, NC.

North Carolina State University, the North Carolina Department of Agriculture, and the Biofuels Center of North Carolina are leading research efforts at sites across the state to study the potential of a variety of different energy crops. Such crops include perennial grasses such as giant miscanthus (*Miscanthus ×giganteus*) and switchgrass (*Panicum virgatum*), trees such as loblolly pine (*Pinus taeda*) and sweetgum (*Liquidambar styraciflua*), various types of sorghums (*Sorghum* spp.), sweet potatoes (*Ipomea batatas*), algae, soybean (*Glycine max*), rapeseed (*Brassica napus L.*), barley (Hordeum vulgare), and others. These can be grown as dedicated energy crops, grown and harvested for the sole purpose of providing fuel—either as a liquid supplement to petroleum products or as a solid to reduce coal usage.

Another step taken by the North Carolina state legislature to increase renewable energy usage was the signing of NC Senate Bill 3 (Session Law 2007-397), passed on 20 August 2007. This bill requires investor-owned utilities to meet up to 12.5% of their energy needs through renewable energy resources or energy efficiency measures. The renewable energy requirement for rural electrical cooperatives and municipal electric suppliers is at least 10% (NC Utilities Commission, 2011). Energy crops like giant miscanthus (which can be converted to fuel in the forms of biodiesel, bioethanol, biobutanol, or bio-coal) can be used to help meet these goals for electricity as well as the liquid fuel goals.

1.3 Introduction to Giant Miscanthus

Giant miscanthus is a perennial warm-season C_4 grass, capable of reaching heights of 3.5 m (Austin, 2010) and yields of 30 Mg ha^{-1} at winter harvest (Heaton et al., 2008). A native of Eastern Asia, giant miscanthus is a sterile hybrid of *Miscanthus sinensis* and *Miscanthus sacchariflorus* (Linde-laursen, 1993). Growth each year originates from the buds on rhizomes. Shoots total approximately 54 to 107 per m^3 in established stands and form stems (which are usually 1.3 to 2 cm in diameter), dark green foliage, and highly infertile flowers (Pyter et al., 2007).

Giant miscanthus has received attention mostly as a bioenergy crop but has several other potential uses as well. These uses include but are not limited to ornamental landscaping, paper production, building materials (such as fiberboards or thatching), and geotextiles (Visser and Pignatelli 2001). Giant miscanthus has been used for centuries as a thatching material in Japan and more recently, has been studied as a source of biochar (Kwapinski et al., 2010).

Previous research has indicated that giant miscanthus requires few fertilizer inputs (Himken et al., 1997), which, along with a high yield, makes giant miscanthus a promising candidate for bioenergy production. By replacing a portion of North Carolina's fuel with renewable bioenergy crops like giant miscanthus, the state can reduce C emissions and dependence on imported fuel. To better understand the nutrient, water, and energy use efficiencies of growing a bioenergy crop such as giant miscanthus, an understanding is needed of each of the processes involved in growing, harvesting, transporting, and converting biomass into a useable fuel form.

1.4 Production Practices

Perennial grasses have become strong biofuel candidate species because of their ability to produce relatively large yields with few inputs compared with food crops (Potter et al., 1995). As a perennial, which will re-grow year after year, giant miscanthus requires fewer energy inputs than most C_4 annual grasses, which require yearly planting (Boehmel et al., 2008). The root systems of perennial crops continue to grow each year, aiding in reduction of water runoff and sediment loss, increasing the organic content of the soil, improving soil structure, and improving water and nutrient holding capacity (Kort et al., 1998). Giant miscanthus rhizomes also have the ability to store nutrients over the winter season and recycle them for the next year's crop (Scurlock, 1999).

Giant miscanthus is a triploid hybrid and is highly infertile, so must be vegetatively propagated. Cutting and planting rhizome pieces is generally considered the most practical method of propagation (Christian and Haase, 2001). The results of various trials have shown that rhizome pieces are most likely to survive if they are greater than 20 cm long and are planted at a depth of 20 cm (Christian and Haase, 2001). Huisman and Kortleve (1994) found a higher survival rate of rhizome pieces planted immediately after harvest (70-95%) than rhizomes stored before planting (50-60%). Other options include micropropagation and stem cutting propagation (Christian and Haase, 2001). Micropropagated plants, produced by in vitro culture, are 10-20 times more expensive to establish than rhizomes (Kim et al., 2010). Recent, unpublished research in Iowa, USA suggests that stem propagation may be more prolific than conventional rhizome propagation (Boersma and Heaton, 2010).

Giant miscanthus is typically planted in spring and planting should be timed according to climate—late enough to prevent frost damage, but early enough to allow time for establishment, growth, and translocation of nutrient reserves before frosts begin in the winter (Christian and Haase, 2001). There are various options available for planting and as demand for biomass grows, specialized equipment is likely to follow. Currently, in the United States, giant miscanthus must be planted using equipment designed for other, similarly planted crops, such as potato planters or machinery normally used for planting vegetable transplants (Pyter et al., 2007). Fertilizers and/or herbicides may be necessary to ensure plant survival—especially during the first few years of growth (Pyter et al., 2007). Effective weed control has been achieved using preplant and preemergence applications of pendimethalin and atrazine and is usually not required after the third year of growth (Heaton et al., 2011).

In North Carolina, spring frost-free date typically occurs in late April to early May in the western mountain region, and late March to April in the central and eastern counties (Perry, 1998), therefore, planting should take place at these locations during their respective months. The plants will reach their peak height during the summer, and go dormant following the first killing frost (Pyter et al., 2007), which typically occurs in Oct. in the mountains and Oct. or Nov. in the central and eastern counties of North Carolina (Perry, 1998). When grown as a bioenergy crop, giant miscanthus is typically harvested late in the year (after killing frost and after plant moisture content decreases). By harvesting in the winter, although some biomass is lost as leaves drop (reported as 2.6 to 6.6 Mg DM ha^{-1} yr^{-1} by Borzecka-Walker et al., 2008), the quality of the biomass as fuel is improved due to a reduction of moisture and nutrient content (Lewandowski et al., 2003). Harvesting can be done with conventional hay mowers and balers to produce bales, or silage choppers to produce chopped material and stored in open air or buildings (El Bassam and Huisman 2001).

1.5 Climate Preferences

Although a native of tropical and subtropical south-east Asia (Greef and Deuter, 1993), giant miscanthus has grown well in Europe and North America, and is well suited to the climate of North Carolina. Using temperature, precipitation and soil depth data, researchers from the Energy Biosciences Institute predicted that the highest yields in the US would be in the eastern half of the country, particularly along the Mississippi river and along the east coast (Somerville et al., 2010). European trials have shown that when water is not a limiting factor, giant miscanthus grows better in warmer locations (Christian and Haase 2001), suggesting that it could thrive in the warm temperatures of southern United States. Trials in Germany found that yields were greatest (greater than 20 Mg ha^{-1} dry matter) when growing season (May to Oct.) average temperature was greater than 16°C and sum of precipitation was greater than 430 mm (Schwarz, 1995). Leaf photosynthesis has been measured to occur between 5 and 38 °C (Naidu et al., 2003). In North Carolina, average monthly minimum and maximum temperatures during the growing season (April to October) are: 6 to 29°C in Asheville (Mountain Region), 8 to 32°C in Raleigh (Piedmont Region), and 11 to 32°C in Wilmington (Coastal Plain Region) (State Climate Office of NC, 2011). Giant miscanthus is best suited to areas with at least 76 cm of annual rainfall and yields improve with increased precipitation (Heaton et al., 2011). However, giant miscanthus will not withstand continuously waterlogged soils (Pyter et al., 2007). Annual precipitation in North Carolina generally varies from 102 to 140 cm in the central and eastern counties. In the mountains of western North Carolina, precipitation can be as high as 229 cm annually, but even at the driest point in North Carolina (the valley of the French Broad River), annual precipitation of 94 cm is more than adequate for giant miscanthus production (State Climate Office of NC, 2011).

1.6 Nutrient Requirements

One of the reasons giant miscanthus has gained popularity as a bioenergy crop is because research has found that giant miscanthus requires relatively few fertilizer inputs to sustain growth, compared with annual C_4 grass crops (Christian and Haase, 2001). Lower fertilizer application rates reduce cost, energy input, and potential for pollution to the environment. Two of the most common limiting and, as a result, over-applied nutrients to agricultural crops are P and N. To better predict the most efficient quantities of P and N fertilizer to apply to giant miscanthus crops, researchers have studied the uptake and remobilization of these nutrients within above-ground and below-ground biomass (Andersohn, 1996; Beale and Long, 1997; Heaton et al., 2009; Strullu et al., 2011).

Inorganic P typically occurs as phosphate in soil. Phosphate binds strongly to soil particles and is most susceptible as a pollutant if carried with surface runoff into bodies of water, however loss due to leaching is very small compared with nitrate leaching loss (Whitson and Walster, 1912). Inorganic fertilizer P, which is initially soluble, will almost entirely be converted to water-insoluble P within a few hours of contact with soil (Schulte and Kelling, 1996). To reduce risk of pollution with surface runoff and to ensure P is available to plant roots, phosphate fertilizer is commonly incorporated into soil with tillage. The plow layer usually retains 98-99% of applied P (Schulte and Kelling, 1996). Since giant miscanthus is a perennial crop, the best time to apply P is prior to planting, when the P can be incorporated. Giant miscanthus stands have been known to survive for at least 10 to 15 years (Jones and Walsh, 2001). Since incorporation of P after the planting year is not feasible, and P is primarily immobile in the soil, appropriate P fertilizer application and incorporation prior to crop establishment is crucial, particularly on very low P-testing soils.

A study conducted in Kansas, USA in 2007 and 2008 compared nutrient removal from annual and perennial biofuel crops (Propheter and Staggenborg, 2010). Phosphorus removal by giant miscanthus was 2 and 4 kg ha^{-1} yr^{-1} (at the 1st and 2nd harvests, respectively), which was similar to other perennial grasses including switchgrass and big bluestem (*Andropogon gerardii*) but less than the removal from annual crops including corn and sorghum, which ranged from 20 to 54 kg of P removed per hectare (Propheter and Staggenborg, 2010). Some of this difference is due to a higher stover yield from the annuals, but P concentration of giant miscanthus plant tissue at harvest was equal to or less than each of the crops researched (Propheter and Staggenborg, 2010). However, this low P concentration at harvest is not consistent throughout the growing season. Studies monitoring giant miscanthus nutrient cycling have found that nutrient concentrations reach their peak at the start of the growing season, become diluted as above-ground biomass increases, and decline further as the plant senesces (Beale and Long, 1997; Himken et al., 1997). According to Himken et al. (1997), 36-50% of P in leaves and stems can be remobilized to the rhizomes. Through this remobilization, giant miscanthus is able to store nutrients during dormancy and recycle the stored nutrient to the growing plant tissue in the next growing season.

Nutrient remobilization in giant miscanthus applies to N as well. Himken et al. (1997) further reported that giant miscanthus remobilized 21 to 46% of N from leaves and stems to roots. By harvesting after senescence, the plants will not only have a store of nutrients for the next growing season, but the biomass will contain a smaller concentration of nutrients that will become atmospheric pollutants during combustion, such as N and S (Heaton et al., 2009). Several studies have been conducted in Europe and the US to determine the effect of N fertilization on giant miscanthus. Miguez et al. (2008) compiled a review of recent European research on N fertilization of giant miscanthus (31 studies) and reported no response to N fertilizer within the first 3 years of growth. They concluded that compared with typical row crops, considerable yields could be obtained with very little N fertilizer.

Some studies have shown a correlation between N fertilization and irrigation/rainfall on biomass yield. An Italian study (Ercoli et al., 1999) found that the effect of irrigation depended on N fertilization rate (irrigation rate was determined by estimated evapotranspiration). When comparing irrigated with rainfed crops, they found that while unfertilized crops showed no response to irrigation, crops with irrigation and fertilized with

100 kg N ha^{-1} yr^{-1} produced 3.7 t ha^{-1} yr^{-1} more biomass. When 200 kg N ha^{-1} yr^{-1} was applied, irrigation improved yields by 9.8 t ha^{-1} yr^{-1}. These results suggest a possibility that the low N response seen in most studies could be the result of inadequate water supply.

Another possible reason giant miscanthus usually has limited response to N fertilizer is an N-fixing bacteria associated with giant miscanthus rhizomes. Eckert et al. (2001) isolated a new group of N-fixing bacteria from giant miscanthus roots and named it *Azospirillum doebereinerae*. These bacteria will fix nitrogen in microaerobic, N-limited conditions (Eckert et al., 2001). A study in Illinois, USA in 2010 confirmed the occurrence of N-fixation in giant miscanthus rhizomes (Davis et al., 2010). Therefore, the bacteria could be supplying unfertilized giant miscanthus crops with an adequate N source, producing similar yields as fertilized crops. However, the actual N contribution of *Azospirillum* in giant miscanthus is not known. Further, studies have shown that when present, fertilizer N is utilized by giant miscanthus. Christian et al. (2006) used ^{15}N-labeled fertilizer to track the uptake and movement of fertilizer N in giant miscanthus. Labeled fertilizer (60 kg N ha^{-1}) was applied to 1, 2, and 3 year old crops and the percentages of labeled N recovered from the different stands at senescence were 38, 55, and 65% respectively, showing that fertilizer N was taken up by giant miscanthus and older crops recovered fertilizer N more effectively than younger plants (Christian et al., 2006). They also found that after applying labeled N to 1-year-old plants, the plants still recovered residual labeled N from the soil 2 and 3 years later, suggesting that as giant miscanthus grows, underground biomass increases and available N in soil is more effectively intercepted and taken up (Christian et al., 2006).

1.7 Sustainability

Giant miscanthus has not been produced commercially in theUnited States—therefore, the possible effects that large-scale production of giant miscanthus may have on the soil and environment must be considered. A review of over 10 years of research data across Europe and North America concluded that warm season-grasses such as giant miscanthus can improve soil qualities and store organic C while still providing biofuel feedstock (Balnco-Canqui, 2010). This contrasts the practice of removing annual crop residue for bioenergy, which has been reported to reduce soil quality and crop yield (Balnco-Canqui, 2010; Lal, 2009; Varvel et al., 2008). Balnco-Canqui (2010) reported that soils in which giant miscanthus were grown had improved structural and hydraulic properties compared with annual row crops grown on the same soils. Balnco-Canqui (2010) also found that giant miscanthus can grow in nutrient-depleted, compacted, poorly drained, acid, and eroded soils. The beneficial impact of growing giant miscanthus is greater on these marginal types of soils than on prime farm land or forest land, therefore Balnco-Canqui (2010) concluded that the most sustainable option for growing giant miscanthus is using marginal, degraded, or abandoned lands. Using land unsuitable for traditional crop production could diminish socio-economic concerns about competition between food and fuel crops (Fike et al., 2007). Stands of giant miscanthus have been shown to sustain with low inputs for at least 14 years (Christian et al., 2008).

1.8 Carbon Sequestration and Greenhouse Gas Reduction

In addition to providing a renewable source of energy to replace fossil fuels, giant miscanthus has the potential to further reduce atmospheric CO_2 by adding C to the soil (Kahle et al., 2001). As giant miscanthus is most commonly harvested post-senescence, many of the leaves have fallen before the stems are harvested. Litter accumulation has been measured at between 2 and 8 Mg ha^{-1} yr^{-1}, adding organic matter to the surface of the soil (Christian et al., 2008). The perennial rooting system of giant miscanthus also contributes to soil C and some researchers have measured storage of up to 2.65 Mg C ha^{-1} yr^{-1} in the top 5 cm of soil by perennial C_4 grasses (Lemus and Lal, 2005). Rhizomes of an established giant miscanthus crop can also penetrate the soil to a depth of at least 2.5 m, with nearly half of the total root mass present below 90 cm (Neukirchen et al., 1999). Deep root penetration can increase C in the subsoil, which has greater long-term storage potential than surface C accumulation. By studying giant miscanthus grown in southern Ireland for 15 years, researchers estimated total C mitigation of 5.2 to 7.2 Mg C ha^{-1} yr^{-1} (Clifton-Brown et al., 2007) and studies in Denmark reported similar results (Olesen, 2001).

Although perennial bioenergy crops may reduce greenhouse gas CO_2, there is concern that energy crop production could contribute to the atmospheric pool of a more potent greenhouse gas, nitrous oxide (N_2O) due to increased use of N fertilizers and conversion of land from native or non-cropped systems. A Danish study measured N_2O flux throughout a giant miscanthus cropping season and found that N_2O emissions were approximately equal to 1.5% of the applied N fertilizer. The researchers concluded that N_2O emissions from a sandy loam cropped with giant miscanthus are a “minor problem” when using energy crops to reduce greenhouse gases (Jorgensen et al., 1997). Therefore, commercial production of giant miscanthus could have a positive impact on greenhouse gas reduction.

1.9 Impact on Biodiversity and the Environment

Bringing a non-native, fast-growing perennial into large-scale production raises concerns about the impact the crop might have on its environment. A study by Bellamy et al. (2008) compared giant miscanthus with winter wheat for number of insects and bird diversity and abundance. Results showed that birds were more abundant and diverse in giant miscanthus, probably due to the presence of more weeds (plant diversity) during establishment years of giant miscanthus, and because the giant miscanthus provided shelter during the winter (prior to harvest). They concluded that giant miscanthus crops would likely benefit bird populations during establishment, but these benefits would diminish over time and croplands would require wildlife management practices to maintain biodiversity (Bellamy et al., 2008). Other studies have shown that giant miscanthus can be successfully used to form buffer strips, which reduce runoff and improve water quality (Balnco-Canqui, 2010).

A prominent concern with most bioenergy crops is invasive potential. However, due to the sterility of giant miscanthus, this concern is greatly diminished when compared with some other potential biofuel crops. For example, Barney and DiTomaso (2008) used a weed risk-assessment based on biogeography, history, biology, and ecology to compare the invasive potential of switchgrass, giant reed (*Arundo donax*), and giant miscanthus. While switchgrass and giant reed have high invasive potentials in California and Florida, respectively, giant miscanthus was found to pose little threat of escape in the United States, and after nearly 3 decades of research across Europe has shown no evidence of escape (Barney and DiTomaso, 2008).

Many invasive species, such as giant reed, fail to produce fertile seeds, but are still able to spread over vast regions and inflict economic and ecological damage (DiTomaso et al., 2007). Mann (2009) studied vegetative propugule regeneration from pieces of giant miscanthus shoots and roots and concluded that the plant's ability to produce shoots and persist in droughty and flooded conditions increases the probability of escaping field boundaries—particularly in waterways or riparian areas. Therefore, any production of giant miscanthus should be monitored by agronomic and ecologic analyses to ensure that the plants do not become invasive (Raghu et al., 2006).

1.10 Energy Production

Energy from giant miscanthus can be generated as both electricity through co-firing in coal burning plants and as liquid fuel by converting biomass to lignocellulosic ethanol, butanol, or biodiesel. Co-firing involves the combination of biomass and coal as energy feedstocks in existing coal power plants. Co-firing has been shown to be a relatively inexpensive option for utilizing biomass for energy production (Baxter, 2005). As electricity generated from coal is already a major source of energy production in North Carolina, biomass co-firing is a viable option for renewable energy production (DOE, 2004). With direct co-firing, biomass is combined in the boiler directly with coal. This process generates electricity in the same manner as a typical coal burning operation.

The net calorific value (lower heating value) of giant miscanthus on a dry basis is around 17 MJ kg^{-1}, with a 2.7% ash content (Visser and Pignatelli, 2001). Wheat straw has a lower heating value of 14-17 MJ kg^{-1} and 2-8.6% ash (Visser and Pignatelli, 2001). Lower heating values for other common combustion materials are 16 MJ kg^{-1} for wood pellets, 18 MJ kg^{-1} for seasoned firewood, 17 MJ kg^{-1} for switchgrass, and 30 MJ kg^{-1} for coal (Forest Products Laboratory, 2004). Ash content in coal can be highly variable, but a typical value is about 7% while wood is about 1% (Demirbas, 2003). Other reported chemical components of giant miscanthus tissue are (on a dry basis) 42% C, 0.5% N, and 0.1% S (Visser and Pignatelli, 2001). The elemental components of coal and wood are also variable. One study reported that coal was composed of 81% C, 1.2 % N, and 3% S while wood contained 50% C and 0.3% N (Demirbas, 2003). Another study reported that coal contained 82% C, 1.4% N, and 0.4% S and wood contained 53% C, 0.1% N, and 0.01 % S (Zhang et al., 2011).

Biomass-coal co-combustion provides a low-risk, low-cost, sustainable alternative to combustion of coal alone, with a reduction in CO_2, SO_x and NO_x emissions (Baxter, 2005). However, a switch to co-firing of biomass is not without concerns. Potential problems include issues with handling and storage of feedstocks, corrosion of machinery, decrease in efficiency, and increase in ash deposition among others (Baxter, 2005). Torrefaction is a method of pyrolysis for pre-treating biomass to improve fuel quality for combustion and gasification (Bergman and Kiel, 2005). Biomass is heated to between 200 and 300 °C in the absence of oxygen, breaking down the fibrous structure of the tissue, increasing the calorific value, and creating a hydrophobic material (Bergman and Kiel, 2005). Combined with pelletisation, torrefaction creates a material similar to coal and can raise the lower heating value of biomass from 17-19 MJ kg^{-1} to 19-23 MJ kg^{-1} (Bergman and Kiel, 2005).

Conversion of lingocellulosic biomass, such as giant miscanthus, to ethanol involves four basic processes: pretreatment, hydrolysis, fermentation, and distillation. Lignocellulosic feedstock is composed of cellulose, hemicellulose and lignin and these components contain fermentable sugars such as glucose, galactose and mannose (Cheng, 2009). Giant miscanthus contains approximately 40% cellulose, 18% hemicellulose, and 25% lignin (Sorenson et al., 2008). Pretreatment is necessary to remove lignin and to loosen and breakdown the structure so that the cellulose and hemicellulose can be accessed by enzymes in the hydrolysis process (Cheng, 2009).

Pretreatment can be thermal, mechanical, chemical, or biological (Lee, 1997). Physical pre-treatment involves mechanical reduction of biomass particle size and steam explosion, while chemical pre-treatment includes acid or base hydrolysis or addition of high-pressure oxygen to the steam explosion process (Sorensen et al., 2008). Biological pre-treatment primarily utilizes fungal enzymes, but also certain actinomycetes, which degrade lignin and liberate cellulose and hemicellulose (Lee, 1997). Hydrolysis uses enzymes specific to cellulose and hemicellulose to break these compounds into the smaller sugars pentoses, and hexoses (Cheng, 2009). Giant miscanthus tissue contains about 26% pentoses (which includes 24% xylose and 2% arabinose) and 39% hexoses (including 38% glucose and 1% galactose) (Visser and Pignatelli, 2001). Fermentation, which uses yeast or bacteria, is the conversion of glucose from to ethanol, CO_2, and energy through a series of enzymatic reactions, which occur when the yeast or bacteria are added and begin to multiply (Cheng, 2009). Giant miscanthus fermentation has been accomplished using thermophilic anaerobic bacteria *Caldicellulosiruptor saccharolyticus* and *Thermotoga neapolitana* (de Vrije et al., 2009).

Ethanol yields for giant miscanthus in the second year of growth have been estimated at 3963 L ha^{-1}, compared with 6899 L ha^{-1} for corn (combining grain and stover), 10184 L ha^{-1} for sweet sorghum (*Sorghum bicolor*), and 2852 L ha^{-1} for switchgrass (Propheter et al., 2010). These values were calculated during the second year of growth with giant miscanthus yields of 12.8 Mg ha^{-1}, however other studies have shown that yields can reach up to 61 Mg ha^{-1} and that the US renewable fuel goal of 35 billion gallons by 2016 could be met by replacing corn with giant miscanthus on land already used to grow corn grain specifically for ethanol (Heaton et al., 2008). Biomass yields of 61 Mg ha^{-1} could produce ethanol yields of 18056 L ha^{-1}, using a conversion of 29.6 L 100 kg^{-1} dry biomass (Singh et al., 2010).

Biobutanol is produced fermentatively in a similar process to ethanol, but unlike ethanol, which is currently blended with gasoline to be used in engines, butanol can be used in conventional combustion engines without modification (Durre, 2007). Although technology for biobutanol production is still developing (Ezeji et al., 2007), butanol has been successfully produced from wheat straw (Qureshi et al., Production, 2006) and corn fiber (Qureshi et al., Butanol, 2006).

Other methods for converting biomass to liquid fuel are thermochemical processes such as pyrolysis and gasification. Pyrolysis involves heating biomass to 400-600 °C in the absence of oxygen to produce oil that can be processed in existing petroleum refineries, while gasification involves heating biomass to over 700 °C, producing a gas which can be converted to liquid transportation fuels (Bahng et al., 2009). Pyrolysis can be performed catalytically or non-catalytically and activated alumina has been shown to be an effective catalyst for pyrolysis of giant miscanthus (Yorgun and Simsek, 2008). Three types of pyrolysis are fast, intermediate, and slow (carbonisation). These processes take place at 500 °C for 1 s, 500 °C for 10-30 s, and 400 °C for several days, producing 75, 50, and 30% liquid, respectively (Bridgwater, 2011). Through fast pyrolysis, it is possible to make diesel from giant miscanthus (Harvey, 2007).

1.11 Summary and Research Objectives

Previous research has shown that giant miscanthus is a promising candidate for biofuel production in the US. Although predictive models have been made to estimate productivity throughout the country (Somerville, 2010), there is a need for regional research to better understand how giant miscanthus will respond to different growing conditions—particularly in states, such as North Carolina, with goals to grow energy crops in the near future (North Carolina General Assembly, 2007).

The goal of this study was to evaluate the effects of N and P fertilization on the establishment of giant miscanthus in North Carolina. Specific objectives were to measure yield response to incremental increases in N and P fertilizer, identify any interactions between N and P uptake, and measure nutrient removal rates from the soil over multiple years of growth and harvest. This research will provide valuable information to future researchers and growers of giant miscanthus in North Carolina and the US Mid-Atlantic/Southeast Regions.

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CHAPTER 2: GIANT MISCANTHUS RESPONSE TO N AND P FERTILIZER

2.1 Introduction

Giant miscanthus (*Miscanthus ×giganteus*) is a perennial warm-season C_4 grass, capable of reaching heights of 3.5 m (Austin, 2010) and yields of 30 Mg ha^{-1} at winter harvest (Heaton et al., 2008). A native of Eastern Asia, giant miscanthus is an infertile hybrid of *Miscanthus sinensis* and *Miscanthus sacchariflorus* (Linde-laursen, 1993). Annual growth each year originates from the buds on rhizomes or from aerial buds. Shoots total approximately 54 to 107 m^{-3} in established stands and form stems, which are usually 1.3 to 2.0 cm in diameter, dark green foliage, and highly infertile flowers (Pyter et al., 2007).

Previous research has indicated that giant miscanthus requires few fertilizer inputs (Himken et al., 1997), which, along with its high annual biomass yield, make it a promising bioenergy crop. Lower fertilizer application rates reduce cost, energy input, and potential for pollution to the environment. Two of the most common limiting nutrients in agricultural lands are nitrogen (N) and phosphorus (P). To better predict the most efficient quantities of P and N fertilizer to apply to giant miscanthus crops, researchers have studied the uptake and remobilization of these nutrients within above- and below-ground biomass (Andersohn, 1996; Beale and Long, 1997; Heaton et al., 2009; Strullu et al., 2011).

The best time to apply P to giant miscanthus is prior to planting, when the P can be incorporated or during planting, when P can be applied by banding. Giant miscanthus stands have been known to survive for at least 10 to 15 years (Jones and Walsh, 2001). Since incorporation of P after the planting year is not feasible, and P is primarily immobile in soil, appropriate P fertilizer application and incorporation or banding prior to crop establishment may be important, particularly on very low P-testing soils. A recent study reported that annual P removal by giant miscanthus ranged from 2 to 5 kg P ha^{-1} yr^{-1}, which was similar to other perennial grasses including switchgrass and big bluestem (*Andropogon gerardii* Vitman) but less than the removal from annual crops including corn and sorghum, which ranged from 20 to 54 kg P ha^{-1} (Propheter and Staggenborg, 2010). Studies monitoring giant miscanthus nutrient cycling have found that nutrient concentrations reach their peak at the start of the growing season, become diluted as above-ground biomass increases, and decline further as the plant senesces (Beale and Long, 1997; Himken et al., 1997). According to Himken et al. (1997), 36-50% of P in leaves and stems can be remobilized to the rhizomes. Through this remobilization, giant miscanthus is able to store nutrients during dormancy and recycle the stored nutrient to the growing plant tissue in the next growing season.

Nitrogen is similarly remobilized in giant miscanthus. Himken et al. (1997) further reported that giant miscanthus remobilized 21 to 46% of N from leaves and stems to roots. By harvesting after senescence, the plants will not only have a store of nutrients for the next growing season, but the biomass will contain a smaller concentration of nutrients that will become atmospheric pollutants during combustion, such as N and S (Heaton et al., 2009). Several studies have been conducted in Europe and the US to determine the effect of N fertilization on giant miscanthus. Miguez et al. (2008) created a model of effect of N fertilization on giant miscanthus yield by compiling recent European research (31 studies) and reported no response to N fertilizer within the first 3 years of growth. They concluded that compared with typical row crops, considerable yields could be obtained with very little N fertilizer.

Another possible reason giant miscanthus usually has shown limited response to N fertilizer is an N-fixing bacteria associated with giant miscanthus rhizomes. Eckert et al. (2001) isolated a new group of N-fixing bacteria from giant miscanthus roots and named it *Azospirillum doebereinerae*. These bacteria will fix N in microaerobic, N-limited conditions (Eckert et al., 2001). A recent study confirmed the occurrence of N-fixation in giant miscanthus rhizomes (Davis et al., 2010). Therefore, the bacteria could be supplying unfertilized giant miscanthus crops with adequate N, producing similar yields as N fertilized crops.

The actual N contribution of *Azospirillum* in giant miscanthus is unclear, as several studies have shown that fertilizer N can be utilized by giant miscanthus. Christian et al. (2006) used ^{15}N-labeled fertilizer to track the uptake and movement of fertilizer N in giant miscanthus. Labeled N (60 kg N ha^{-1}) was applied to one, two, and three year old crops and the % ^{15}N recovered from the different stands at senescence were 38, 55, and 65% respectively, showing that fertilizer N was taken up by giant miscanthus and older crops recovered fertilizer N more effectively than younger plants (Christian et al., 2006). They also found that after applying ^{15}N to one-year-old plants, the plants still recovered residual ^{15}N from the soil two and three years later, suggesting that as giant miscanthus grows, underground biomass increases and available N in soil is more effectively intercepted and taken up (Christian et al., 2006).

Previous research has shown that giant miscanthus is a promising candidate for biofuel production in the US. Although predictive models have been made to estimate productivity throughout the country (Somerville, 2010), there is a need for regional research to better understand how giant miscanthus will respond to different growing conditions—particularly in states, such as North Carolina, with goals to grow energy crops in the near future (North Carolina General Assembly, 2007).

In the US, most research has focused on how giant miscanthus will grow in the Midwest (Heaton et al., Miscanthus, 2004). Soils in the Midwestern US are predominately mollisols or alfisols, while in the Southeastern US, ultisols are most common (NRCS, 2005). Mollisols are rich in organic matter and basic cations and are therefore quite fertile (NRCS, 2011). Alfisols are also productive for most crops while ultisols are more intensely weathered, acidic soils with a moderately low capacity to retain nutrients and basic cations (NRCS, 2011). Ulitisols generally have high P-fixing capacities due to acidity and high concentrations of Fe and Al oxides (Yerima and Van Ranst, 2005). In addition to differences in soil type, giant miscanthus biomass yield is affected by weather, soil moisture, and soil depth (Somerville, 2010). Therefore, research is needed on a regional basis to appropriately determine fertilizer requirements and other agronomic practices.

Researchers who have studied giant miscanthus throughout the world have come to different conclusions about the nutrient requirements of giant miscanthus (Cadoux, 2011).

Yield responses to N have been recorded in some studies (Boehmel et al., 2008; Cosentino et al., 2007; Ercoli et al., 1999; Jacks-Sterrenberg, 1995), while others have reported no response [(Beuch et al., 1998; Bullard, 1996; Jorgensen, 1996; Jorgensen, 1997; Schwarz and Schung, 1993 as cited in Lewandowski et al., 2000); Christian et al., 2008; Clifton-Brown et al., 2007; Danalatos et al., 2007; Heaton et al., Quantitative, 2004; Himken et al., 1997; Strullu et al., 2011]. As of 2010 there had been no published literature reporting giant miscanthus yield response to P fertilizer rates (Defra, 2010).

The goal of this study was to evaluate the effects of N and P fertilization on the establishment of giant miscanthus in western and central North Carolina. Specific objectives were to i) determine the influence of increasing rates of P and N fertilizer on biomass yield, ii) identify interactions between P uptake and N uptake, and iii) measure change in extractable P and inorganic N in the soil over multiple years of growth. This research will provide valuable information to future researchers and growers of giant miscanthus in North Carolina and the US Mid-Atlantic/Southeast Regions.

2.2 Materials and Methods

2.2.1 Site Descriptions

The study was conducted at two North Carolina State University and North Carolina Department of Agriculture & Consumer Services (NCDACS) research farm sites: the Mountain Horticulture and Crops Research Station in Mills River (N 35° 25' 0.5196", W 82° 33' 32.241") and the Tobacco Research Station in Oxford (N 36° 19' 39.5256", W 78° 39'

20.5986"). Soil types were Bradson gravelly loam (clayey, parasesquic, mesic, Typic Hapludult) at Mills River and Cecil sandy loam (fine, kaolinitic, thermic, Typic Kanhapludult) at Oxford. Plot areas at both sites contained fescue hay prior to the experiment. Pre-plant soil characteristics to a depth of 91 cm for each site are listed on Table 2.1.

2.2.2 Treatments

Research plots were established on 16x70 m^2 of land at Mills River and 16x64 m^2 at Oxford (the difference being due to 2 m spacing between replicates in Mills River). Treatments were arranged in a split-plot randomized complete block with main plots of 0, 147, 294, and 441 kg P ha^{-1} and subplots of 0, 45, 90, and 135 kg N ha^{-1} (Fig. 2.1 and 2.2). Individual subplots included 16 plants on 1-m grid spacing (Fig. 2.3). Phosphorus fertilizer was applied as triple superphosphate (0-45-0) and was pre-plant incorporated to about 15 cm soil depth. Nitrogen fertilizer was surface broadcast as ammonium nitrate (33.5-0-0) pre-plant as well as pre-emergence in subsequent years (11 June 2008, 3 April 2009, and 30 March 2010 at Mills River; 22 April 2009 and 25 March 2010 at Oxford). Lime was applied and incorporated (to 15 cm) pre-plant into the entire plot area at Mills River at 3.36 Mg ha^{-1} on 11 June 2008. Herbicide was applied pre-emergence and post-emergence each year at both the Mills River and Oxford sites. Pre-emergence herbicide used was S-metolachlor plus atrazine. Paraquat was direct applied post-emergence where necessary.

2.2.3 Soil Sampling and Analyses

Soil samples were collected before planting and before emergence each year, specifically on 11 June 2008, 19 Mar. 2009, 1 Mar. 2010, and 10 Feb. 2011 at Mills River and 21 Apr. 2009, 22 Feb. 2010, and 17 Feb. 2011 at Oxford. Each subplot was sampled to a depth of 20 cm using a 1.7-cm diameter hand probe, mixing 8-10 cores to form a composite sample from each plot. Each of the plots with 135 kg N ha^{-1} applied N were sampled to a depth of 91 cm at increments of 0-20, 20-41, 41-61 and 61-91 cm using a 5 cm diameter hydraulic probe, mixing 4 cores from each plot. Samples were dried at 38°C and ground to pass through a 2 mm sieve.

Soil samples were sent to the NCDACS Agronomic Division soil testing lab for routine analysis (Hardy et al., 2009). Nutrient analysis was performed by Mehlich-3 extraction using Inductively Coupled Plasma (ICP) (Mehlich, 1984); cation exchange capacity (CEC) was determined by summation of basic cations (excluding Na) and buffer acidity (Mehlich, 1976); soil pH was determined on a 1:1 soil:water volume ratio; and humic matter was determined using NaOH digestion with colorimetric determination (Mehlich, 1984). Inorganic N (NO_3 and NH_4) was measured by KCl extraction using 2.5 g soil with 25 mL of 1 M KCl. Samples were shaken for 1 hour on a reciprocal shaker, filtered with Fisherbrand P4 filter paper, and refrigerated at 2-4°C. Extracts were analyzed colorimetrically using Lachat methods 12-107-04-1-I and 12-107-06-2-A for NO_3 and NH_4, respectively (Lachat, 2010).

2.2.4 Planting and Harvesting

Giant miscanthus plants were obtained from Hoffman Nursery, Inc. (Rougemont, NC). Plants were then propagated by divisions and grown in greenhouse cell flats at the Mountain Horticultural Crops Research Station in Mills River, NC and planted by hand in the Mills River research plots on 17 June 2008 using a 1x1m grid. Rhizome pieces were hand harvested from border plants after a year of growth at Mills River, rinsed, separated, and cut into pieces approximately 7.5-10 cm in length and were not used unless at least 3 buds were visible. The rhizome pieces were then hand-planted on 22 April 2009 to establish the Oxford site. A weed infestation the first year at Oxford resulted in substantial plant loss. As such, 314 giant miscanthus plants of the same age as those in the study were transplanted on 8 March 2010 from a nearby field to replace missing plants. Plants missing from the center 4 of each plot were only replaced with border plants from within the same plot.

Plants were measured and harvested after senescence in winter of each year. Plant heights were taken by measuring the tallest part of the plant (the tallest stem in each cluster) of the center 4 plants in each plot. If a plant was lodged or missing, one of the 12 border plants was measured. Biomass dry yield was determined by hand harvesting and weighing the 4 center plants of each subplot. Harvests at Mills River took place on 6 Feb. 2009, 17 Dec. 2009, and 4 Jan. 2011. Oxford harvest dates were 5 Jan. 2010 and 21 Dec. 2010. In cases where plants were missing, the number of plants harvested was noted, but if more than 2 of the 4 center plants were missing, the border plants were harvested. A subsample of biomass from each subplot was ground through a chipper/shredder on site and collected in paper bags for further preparation and analysis. Biomass samples were weighed, dried at 80°C for 3 days, and re-weighed to determine moisture content. Tissue samples were later ground to pass through a 1 mm mesh screen and sent to the NCDACS tissue testing lab to determine nutrient concentration (Plank, 1992) and thereby calculate plant nutrient uptake and removal.

2.2.5 Statistical Analyses

Statistical analyses of yield, tissue, plant height, and nutrient removal responses to N and P fertilizer treatments were performed separately for each site and year using SAS PROC MIXED (SAS Institute Inc., 2009). Type 3 tests of fixed effects were considered significant at the $P<0.05$ level. Repeated measures analyses were used to determine effects of time and depth on soil N and P concentrations. To compare surface (0-20 cm) N and P concentrations with the initial years at each site (when samples were only taken for each P-treatment block), N and P concentrations were averaged for each block in subsequent years.

2.3 Results and Discussion

2.3.1 Plant Height

Mean plant heights at Mills River in 2008, 2009, and 2010 were 2.06, 3.33, and 3.67 m, respectively. Mean plant height in 2008 was greater for plots receiving P fertilizer compared with the control (Tables 2.2 and 2.3). Unfertilized plots averaged 1.93 m while P fertilized plots averaged 2.10 m, with no height difference among the different N or P application rates. In 2009, average height was greater for plants receiving 0 N (3.42 m) than those receiving any N fertilizer (average of 3.30 m). Similar results occurred in 2010 when plants receiving 0 and 45 kg N ha^{-1} had a higher average height (3.72 m) compared with the average height of plants receiving 135 kg N ha^{-1} (3.57 m). Plants receiving 90 kg N ha^{-1} averaged 3.67 m, which was not significantly different from the other N rates.

Plant height data were not recorded at Oxford in 2009 due to the poor plant stand. The mean plant height across treatments at Oxford in 2010 was 2.65 m. In 2010, there were no differences in plant height among treatments.

The negative N response in plant height in 2009 and 2010 at Mills River may have been caused by increased lodging, particularly since the yield in these same plots did not decrease with N fertilization. Increased lodging of giant miscanthus is related to high N application rates. Kaack and Schwarz (2001) found that giant miscanthus plants fertilized with 0 or 150 kg N ha^{-1} had a significantly higher percentage of lodging than those with 75 kg N ha^{-1}.

Studies of other bioenergy crops such as *Arundo donax* have shown a correlation between plant height and yield (Cosentino et al., 2006). Height data could potentially be a predictor of yield, however studies that have measured height and yield of giant miscanthus have not attempted to determine a relationship between the two factors (Schwarz et al., 1994; Miguez et al., 2009; Danalatos et al., 2007). Clifton-Brown et al. (2001) combined data for 15 *Miscanthus* genotypes and found that yield and height were not significantly correlated. Our data showed a positive correlation between plant height and yield when data from all 3 harvests at Mills River and both harvests at Oxford were combined (Fig. 2.4). However, on an individual site and year basis, the correlation between plant height and biomass yield at harvest was not consistent (data not shown).

2.3.2 Dry Matter Yield

Dry biomass yields during the establishment year (2008) at Mills River averaged 2.97 Mg ha^{-1} across all fertilizer treatments (Table 2.4). Average yields across treatments were 15.01 Mg ha^{-1} in 2009 and 20.74 Mg ha^{-1} in 2010. A positive yield response to P fertilizer (P = 0.0019) was observed in 2008, where control plots receiving 0 P produced less biomass (2.40 Mg ha^{-1}) than P treatment plots (average of 3.16 Mg ha^{-1} across all P rates) (Table 2.2). However, there was no difference in yield among any of the P-fertilized plots, indicating that the yield response observed occurred at or below the lowest P rate (147 kg P ha^{-1}). Biomass harvests from the second (2009) and third (2010) growing seasons at Mills River showed no response to P fertilizer, indicating that plant uptake in year one and residual available soil P was sufficient to achieve maximum yield in the subsequent years of the study. This is further explained by the perennial nature of miscanthus and the ability of the plant to cycle nutrients into rhizomes prior to and during senescence, where the nutrients are stored and used by the plant the next growing season (Himken et al., 1997). No response in dry matter yield to N fertilizer was observed for any of the study years at Mills River.

A significant interaction (P = 0.0276) between N and P fertilizer rate was observed in 2010, which was likely the result of 2 plots (2014 and 3013) with unusually high yields which had both received 0 N and 147 kg P ha^{-1}. These plots were each missing 2 of the 4 center plants harvested for data (see Fig. 2.2), while the other 62 plots contained at least 3 plants that year. The plots with missing plants may have produced higher yield values because surviving plants had less competition for sunlight, water, and/or nutrients than plots containing all 4 center plants. When yield data from the 2-plant plots were removed from statistical analysis, the interaction was no longer significant (P = 0.2494), therefore the averages displayed in Tables 2.2-2.8 exclude data obtained from those plots in 2010 at Mills River.

During the establishment year (2009) at Oxford, severe weed pressure negatively impacted biomass yield. The average dry yield was 0.37 Mg ha^{-1} with no response to N or P fertilizer treatments. A total of 314 missing plants were replaced on 8 March 2010 using plants from a nearby location that had been planted on the same day as the plots. Weed control was improved in 2010, resulting in increased plant survival and average yield across treatments reached 8.56 Mg ha^{-1}. Yield results from 2010 show a significant response (P = 0.0047) to N fertilizer rate with plots receiving 0 N producing less biomass (average of 6.35 Mg ha^{-1}) than plots receiving N fertilizer (average of 9.29 Mg ha^{-1} across N-fertilized plots).

Productivity trials across Europe (15 locations) were initiated in 1993 as part of the European Miscanthus Network (EMN) (Clifton-Brown et al., 2001). First year winter harvest dry matter yields (out of those which survived the winter) ranged from 1.0 to 8.9 Mg ha^{-1} (in Ireland and England, respectively); 2nd year yields ranged from 2.0 to 32.4 Mg ha^{-1} (in Portugal and Sicily, respectively; both sites had received regular irrigation); and 3rd year yields ranged from 3.1 to 26.8 Mg ha^{-1} (at the same sites given in the 2nd year range) (Clifton-Brown et al., 2001). Average yields across all EMN sites were 4.0 Mg ha^{-1} in year 1, 11.1 Mg dm ha^{-1} in year 2, and 15.8 Mg ha^{-1} in year 3 (Clifton-Brown et al., 2001). Compared to the EMN studies, our 1st year yields were below their average, Oxford was below average for the 2nd year, and Mills River was above average for the 2nd and 3rd years. All of the 3rd year yields in the EMN as well as our study were exceeded by 3rd year yields of 37.3 Mg ha^{-1} in southern Illinois (Heaton et al., 2008).

Results at Mills River generally correspond to previous research concluding that giant miscanthus requires few fertilizer inputs during establishment years (Himken et. al. 1997; Christian and Haase, 2001). As of 2010 there had been no published literature reporting giant miscanthus yield response to P fertilizer rates (Defra, 2010). The P response observed during the first year at Mills River is likely the result of the relatively low P availability in the soil. Initial soil test P was 29 mg kg^{-1} at 0-20 cm, which converts to a North Carolina soil P index level of 24. Phosphorus index values between 11 and 25 are considered low for crop production in North Carolina (Hardy et al., 2008). Therefore in soils with this P concentration, crops would generally be expected to respond to P fertilizer. As giant miscanthus becomes established, the root system becomes more extensive (with roots able to reach a depth of 250 cm), allowing for better nutrient uptake and survival in soils with low nutrient availability (Neukirchen et al., 1999). This could help explain the lack of P response in subsequent years. Also, P is remobilized in giant miscanthus more than N or K (Cadoux et al., 2011). The percentage of P in above-ground biomass recycled into rhizomes has been measured at 33% (Beale and Long, 1997) and 50% (Himken et al., 1997).

Yield results from the first year at Oxford (2009) are not an accurate representation of potential first year growth in similar soils or climatic conditions due to the high plant mortality resulting from weed pressure. The positive response to N fertilizer found at Oxford in 2010, is contrary to most previously published studies, which have commonly reported no or very limited N response especially during the first few years of growth (Miguez et al., 2008). Soil inorganic N (NO_3^- and NH_4^+) analysis results from samples collected in Feb. 2010 indicate relatively low available N at the beginning of the growing season at Oxford: 6.3 mg kg^{-1} at 0-20 cm depth (Table 2.1). Also, little is known about the soil and climate preferences of the N-fixing bacteria *Azospirillum doebereinerae* associated with giant miscanthus, which has been used to explain a lack of N response in other studies (Eckert, 2001). Rhizomes planted at Oxford originated from Mills River, so any N-fixing bacteria present at Mills River may have been carried with the rhizomes to Oxford. Conditions for N-fixation may not be the same at Mills River and Oxford. Laboratory tests have shown that optimal temperature for *Azospirillum doebereinerae* is 30°C, no growth occurs at 37°C, and optimum growth is observed between pH 6 and 7 (Eckert, 2001). However, this wouldn't explain a stronger prevalence, if any, of N-fixation in Mills River as these ideal temperatures and ranges in pH more closely resemble soils in Oxford than in Mills River (see Table 2.1 and Fig. 2.5).

Although studies reporting no yield response to N fertilizer (Beuch et al., 1998; Bullard, 1996; Christian et al., 2008; Clifton-Brown et al., 2007; Danalatos et al., 2007; Heaton et al., Quantitative, 2004; Himken et al., 1997; Jorgensen, 1996; Jorgensen, 1997; Schwarz and Schung, 1993; Strullu et al., 2011) outnumber the relatively few studies that have found an N response (Boehmel et al., 2008; Cosentino et al., 2007; Ercoli et al., 1999; Jacks-Sterrenberg, 1995), the latter reported research provides evidence that under some conditions, giant miscanthus will indeed respond to N fertilizer. Heaton et al. (Quantitative, 2004) reported a compilation of the results of 21 studies measuring giant miscanthus yield response to N application rate in different parts of the world. The test of fixed effects of N on giant miscanthus yield was significant at $P<0.1$, indicating a positive response to N (Heaton et al., Quantitative, 2004). A study in south Germany compared available N (mineral N plus fertilizer) to yield and using the "boundary line approach" concluded that giant miscanthus responds strongly to low N supply by producing lower yields when available N is less than 50 kg N ha^{-1} yr^{-1} (Lewandowski and Schmidt, 2006). In contrast, Himken et al. (1997) found no yield response to N even with an N supply of only 25 kg ha^{-1} in the upper 30 cm of soil. However Himken et al. (1997) only tested N treatments on an already established, 4-year-old crop. The former studies describing no yield response to N either had: relatively higher soil N concentrations (Schwarz and Schung, 1993) than at Mills River or Oxford, only studied crops after they had at least 3 years of establishment [(Beuch et al., 1998; Bullard, 1996; Jorgensen, 1996; Jorgensen, 1997 as cited in Lewandowski et al., 2000); Strullu et al., 2011], didn’t use a 0 N control (Danalatos et al., 2007; Clifton-Brown et al., 2007), or didn’t provide pre-plant soil N data (Christian et al., 2008).

2.3.3 Nutrient Concentration and Removal

Plant tissue N concentration averaged 8506, 2669, and 1763 mg kg^{-1} at Mills River in 2008, 2009, and 2010 respectively (Table 2.5) The decrease in concentration with time is likely due to the increase in biomass yield, which resulted in dilution of N in the plant tissue. Lower N concentration in older plants may also be related to an improved ability to recycle nutrients into the rhizomes as giant miscanthus becomes more established. For example, Heaton et al. (2009) reported that during the 3rd growing season, tissue N concentration in giant miscanthus decreased from a peak concentration of 1.17% in the spring to 0.33% at senescence in late fall, but in the following year, N concentration decreased by a greater amount (from 1.63% to 0.29% in the same time frame). Nutrient dilution may also account for the higher N concentration in plants given 0 P (9365 mg kg^{-1}) than those with P fertilizer (average of 8219 mg kg^{-1}) in 2008. A corresponding response was seen in the dry yield—plants fertilized with P produced higher yield than the 0 P control. In 2010, N concentration responded to N fertilizer treatment. The plants receiving 135 kg N ha^{-1} had a greater N concentration (1951 mg kg^{-1}) than those with less or no fertilizer (average of 1707 mg kg^{-1}). Because there was no corresponding yield response that year, the increased concentration is likely the result of luxury uptake, which is the accumulation of nutrients in excess of those needed for maximal growth (Harada and Leigh, 2006). The differences in N concentration between P treatments in 2010, however were likely a result of sample variability as there was no P response to yield and concentration does not increase or decrease consistently with change in P fertilizer rate.

Tissue N concentration at Oxford averaged 7725 and 2009 mg kg^{-1} in 2009 and 2010, respectively. In 2010, the plants receiving 135 kg N ha^{-1} had a greater N concentration (2297 mg kg^{-1}) than those with less or no fertilizer (average of 1912 mg kg^{-1}). This is also probably the result of luxury uptake, similar to the response observed at Mills River in 2010. Beale and Long (1997) reported a close similarity of N, P and K concentrations between higher- and lower—yielding stands of giant miscanthus, suggesting that there was no luxury uptake of these nutrients. However, Beale and Long (1997) only studied the results of plants receiving 120 kg N ha^{-1} applied N and did not compare with lower N rates or a 0 N control. There is some precedent for luxury uptake with giant miscanthus. For example, Cadoux et al. (2011) concluded that soils high in K may lead to luxury uptake of K by giant miscanthus.

Luxury uptake is also apparent in the analysis of plant tissue P (Table 2.6). Phosphorus concentrations averaged across all treatments were 320, 114, and 183 mg P kg^{-1} in 2008, 2009, and 2010, respectively at Mills River. Plant tissue P concentrations at Oxford averaged 225 and 226 mg P kg^{-1} across all treatments in 2009 and 2010, respectively. Every year except for 2008 at Mills River, average P concentration tended to increase with increasing P application (the differences in Mills River 2009 and Oxford 2009 were not statistically significant). Biomass yield at Mills River in 2008 responded to P fertilizer and, correspondingly, the plants with higher biomass yield had lower P concentrations: an average of 310 mg P kg^{-1} in the plots with P fertilizer (which produced more yield) versus 347 mg P kg^{-1} in the plots with no P fertilizer and a lower yield. Therefore, the difference in P concentration was likely a result of nutrient dilution. In 2010 at Mills River, 0 P control plots resulted in an average P concentration of 107 mg P kg^{-1} which was less than the 230 mg P kg^{-1} found in the 294 kg P ha^{-1} and 441 kg P ha^{-1} treatments. Plants given 147 kg P ha^{-1} contained 165 mg P kg^{-1}, which was not significantly different from those given 0, 294, or 441 kg P ha^{-1}. In 2010 at Mills River, the plants given 0 N had greater tissue P concentrations (275 mg P kg^{-1}) than those receiving N fertilizer (regardless of rate, average of 153 mg P kg^{-1}).

In 2010 at Oxford, P concentration averaged 176 mg kg^{-1} in plots receiving 0 and 147 kg P ha^{-1} which was less than 323 mg P kg^{-1} in plots receiving 441 kg P ha^{-1}. The 294 kg P ha^{-1} treatment resulted in an average plant P concentration of 231 mg P kg^{-1}, which was not significantly different from those in the 0, 147, or 441 kg P ha^{-1} plots. Plants given 0 N had greater tissue P concentrations than those receiving N fertilizer (regardless of rate), which was similar to results at Mills River the same year (2010). At Oxford, the 0 N plants contained 410 mg P kg^{-1} while the N fertilized plants contained an average of 165 mg P kg^{-1}. The P concentration change at Oxford could be accounted for by the difference in biomass yield—plants that produced more biomass had more diluted concentrations of P. However, yield differences do not account for the P concentration differences in Mills River.

Average N removal across treatments at Mills River was 24.72, 39.46, and 36.0 kg N ha^{-1} in 2008, 2009, and 2010, respectively and 2.87 and 16.98 kg N ha^{-1} in 2009 and 2010, respectively at Oxford (Table 2.7). Average P removal across treatments at Mills River was 0.95, 1.67, and 3.64 kg P ha^{-1} in 2008, 2009, and 2010, respectively and 0.09 and 1.7 kg P ha^{-1} in 2009 and 2010, respectively at Oxford (Table 2.8). Differences in N and P removal among fertilizer treatments generally correspond to the treatment responses observed for yield and nutrient concentration.

Yield, N concentration, P concentration, and N removal each responded to P rate in 2008 at Mills River. However, P removal among P fertilizer rates was not significant. Nitrogen removal was greatest in the plots receiving P fertilizer (average of 25.76 kg N ha^{-1}), while N removal in the 0 P plots was 21.6 kg N ha^{-1}. While N removal was not affected by any treatments in 2009 at Mills River, P removal was affected by P rate. Just as P concentration increased with increasing applied P, P removal also increased. Removal was greatest (2.04 kg P ha^{-1}) for the greatest P rate, and other plots averaged removal of 1.55 kg P ha^{-1} (the 147 kg P ha^{-1} treatment resulted in removal of 166 kg P ha^{-1}, which was not significantly different from the 0, 294, and 441 kg P ha^{-1} treatments). Nitrogen removal at Mills River in 2010 varied among P treatments, though observed differences did not follow a consistent trend. Phosphorus application rate also affected P removal in that plants receiving any P fertilizer removed more P (average of 4.14 kg P ha^{-1}) than plots with 0 applied P (2.12 kg P ha^{-1}). Nitrogen fertilizer rate also impacted plant P removal, though an inverse relationship was found and P removal decreased with increasing N rate. Phosphorus removal rates for 0, 45, 90, and 135 kg N ha^{-1} were 5.71, 3.59, 2.82, and 2.42 kg P ha^{-1}, respectively. The 0 N control plots had significantly greater P removal than the other N treatments.

Neither P nor N removal was affected by fertilizer treatments at Oxford in 2009, whereas in 2010, N removal increased with increasing N fertilizer rate. Plots given 0, 45, 90, and 135 kg N ha^{-1} in 2010 at Oxford removed 11.41, 16.45, 18.14, and 21.92 kg N ha^{-1}, respectively. Nitrogen removal rates for 0 N control plots were significantly less than plots receiving 45, 90, or 135 kg N ha^{-1}. Nitrogen removal was less in plots given 45 kg N ha^{-1} than those given 135 kg N ha^{-1} and N removal in the plots given 90 kg N ha^{-1} was not different from plots given 45 or 135 kg N ha^{-1}. Trends in P removal at Oxford in 2010 were similar to P removal at Mills River in 2010. At Oxford in 2010, greater P fertilization rate resulted in greater P removal. Plots given 0, 147, and 294 kg P ha^{-1} removed an average of 2.26 kg P ha^{-1} while plots given441 kg P ha^{-1} removed 2.53 kg P ha^{-1}. Phosphorus removal at Oxford in 2010 also responded to N fertilizer. Phosphorus removal was significantly greater in the 0 N treatments (2.37 kg P ha^{-1}) than the 45, 90, and 135 kg N ha^{-1} treatments (average of 1.47 kg P ha^{-1}).

Plant tissue concentrations of K, Ca, and Mg each showed no response to P fertilizer treatment for any site-year combination, so results are given by N treatments (Table 2.9). Average values for K, Ca, and Mg removal at Mills River were 1923, 4253, and 958 mg kg^{-1} in 2008; 3534, 1942, and 713 mg kg^{-1} in 2009; and 3826, 1388, and 549 mg kg^{-1} in 2010, respectively. Average values for K, Ca, and Mg concentrations at Oxford are 2365, 3700, and 1007 mg kg^{-1} in 2009; and 3133, 1869, and 900 mg kg^{-1} in 2010, respectively. In 2008 and 2009, plots in Mills River showed no response to fertilizer treatment, but in 2010, tissue Mg concentration increased with increasing N fertilizer application. Mg concentration was greatest in plants receiving 90 and 135 kg N ha^{-1} (average of 590 mg Mg kg^{-1}), least in plots receiving 0 N (485 mg Mg kg^{-1}) and plants receiving 45 kg N ha^{-1} did not have significantly different Mg concentration (530 mg Mg kg^{-1}) from the 0, 90, or 135 kg N ha^{-1} treatments.

Magnesium tissue concentration increased with increasing N fertilization rate at Oxford in 2010. Also at Oxford 2010, tissue K concentration increased with N application, which may be a result of the yield response to N treatment. Plants receiving 0 and 45 kg N ha^{-1} contained less K (3002 mg K kg^{-1}) than plants in the 135 kg N ha^{-1} treatment (3389 mg K kg^{-1}). Tissue K also increased each year at both sites, suggesting that tissue K concentrations increased with greater biomass yields.

Previous studies on crops similar to giant miscanthus have shown a relationship between fertilizer treatment and nutrient uptake. Newman et al. (2009) found that perennial warm season forages stargrass (*Cynodon nlemfuensis* Vanderyst), bahiagrass (*Paspalum notatum* Flugge), and limpograss [*Hemarthria altissima* (Poir.) Stapf & Hubb] each increased P removal with increasing N fertilizer application. However, we measured a decrease in P removal with increasing N application in 2010 at both sites and no response the previous years. Hussaini et al. (2008) reported that N fertilizer up to 60 kg N ha^{-1} increased the concentrations of N, P, K, Ca, and Mg in dry season maize grain (*Zea mays* L.), however in corn stover, N fertilizer only increased tissue concentrations of N and Ca. The positive correlation between N applied and tissue N concentration is similar to our results in 2010 at both sites. We also found a positive correlation between N applied and tissue Mg concentration in 2010 at both sites. Hussaini et al. (2008) also reported that P fertilization of

40 kg P ha^{-1} increased N and Ca concentration in maize stover, while reducing K concentration (Hussaini et al., 2008). Also, according to Khan et al. (1980), greater applications of P fertilizer increased N uptake in wheat. Our results did not show an increased N or Ca concentration with P fertilization. However, Khan et al. (1980) found that increasing P fertilizer rates of 34, 67, 101, and 135 kg ha^{-1} resulted in decreasing N concentrations of corn leaves, which is similar to the treatment response we found in tissue N concentrations at Mills River in 2008.

Our study results provide evidence that giant miscanthus is capable of luxury consumption when supplied with more N and P than needed. Also, the data suggest that N fertilization may increase uptake of N and Mg.

2.3.4 Soil Nutrients

Soil samples were collected each spring prior to N fertilizer application for inorganic N (NO_3^- and NH_4^+) analysis. Results of these analyses indicated no significant difference in inorganic N concentration of the surface 20 cm among plots for any year at either location (Fig. 2.6). Since the soil is sampled approximately a year after fertilizer application, inorganic N from fertilizer treatments had likely either been absorbed by plants or lost via denitrification and/or leaching. Soil inorganic N decreased each year of the study at both Mills River and Oxford except between 2008 and 2009 at Mills River when surface inorganic N did not change significantly. Christian et al. (2006) reported that more inorganic N fertilizer was recovered by 3-year-old giant miscanthus than by 2- or 1-year-old plants.

Therefore, more N was probably absorbed by roots and stored in the rhizomes each year as the plants became established, leaving less inorganic N in the soil. Inorganic N moves with rainfall and normally does not accumulate in North Carolina surface soils that are sufficiently drained for crop production (Gilliam, 2011). Therefore, rainfall patterns may help explain changes in soil inorganic N with depth. Movement of inorganic N through the profile with respect to time is shown in the soil N vs. depth graphs in Fig. 2.7. Total rainfall in the 12 months prior to sampling was 90, 83, 166, and 97 cm for 2008, 2009, 2010, and 2011 at Mills River, respectively and 74, 94, and 79 cm for 2009, 2010, and 2011 at Oxford, respectively (Fig. 2.8). Less precipitation and less time between fertilizer application and soil sampling (9 months as opposed to 11 and 10 months in 2010 and 2011, respectively) may account for the higher inorganic N at 41-61 cm in 2009 than in 2008, 2010, and 2011 at Mills River.

Inorganic N at Mills River in the 20-41-cm sample depth increased from 2008 to 2009, but in 2011 was lower than at pre-plant sampling. Inorganic N at 41-61 cm was greater in 2009 than in 2008, 2010 and 2011. During establishment of giant miscanthus, most roots are usually located above 40 cm. Monti and Zatta (2009) measured giant miscanthus root distribution in a 6-year-old stand and found that almost 90% of total roots were located in the top 35 cm of soil. Therefore, soil nutrients below 41 cm were likely unaffected by root uptake. Inorganic N at Oxford in the 20-41-cm sampling depth was greater in 2009 and 2010 than in 2011. In 2010, inorganic N was greater in the 41-61-cm sampling depth than in 2009 or 2011. In 2010 at Oxford, the only response to N fertilization in the study occurred. Average inorganic N concentration in the upper 41 cm in 2010 at

Oxford was 6.6 mg N kg^{-1}, whereas in 2009 N concentration was 8.7 mg N kg^{-1}. Average inorganic N concentration in the upper 41 cm (of plots receiving 135 kg N ha^{-1}) at Mills River was 11.7, 16.2, and 8.4 mg N kg^{-1} in 2008, 2009, and 2010, respectively.

Soil Mehlich-3 P concentrations for each site, year, and P treatment are given in Table 2.10. Soil P concentration in the upper 20 cm changed with time and P fertilizer treatment (Fig. 2.9). Pre-plant soil test P in the upper 20 cm of soil was 29.4 mg P kg^{-1} across all treatments at Mills River. After P fertilizer was incorporated and giant miscanthus plantlets grew in the soil for a year, average soil P concentrations in the upper 20 cm were 66, 118, and 143 mg kg^{-1}, in the 147, 294, and 441 kg P ha^{-1} treatments, respectively (there was no change in soil P in the 0 P control plots). After the third year of growth, soil P concentrations in the upper 20 cm decreased in the 294 and 441 kg P ha^{-1} treatments, which was probably due to a combination of P fixation and uptake and storage in the giant miscanthus rhizomes. Time and P treatment did not significantly affect P concentration at depths below 20 cm except for a few instances, which were likely caused by sample variability (Table 2.10).

Pre-plant soil test P at Oxford averaged across all plots was 9.9 mg P kg^{-1} in the upper 20 cm of soil, which is considered very low by North Carolina crop fertilization standards (Hardy et al., 2008). Therefore, if the first year of growth at Oxford had not been limited by weeds, a yield response to P fertilizer may have been observed.

Soil Mehlich-3 P concentration in the upper 20 cm decreased between the 2nd and 4th growing seasons by 37 and 29 mg P kg^{-1} in the 294 and 441 kg P ha^{-1} treatments, respectively at Mills River and decreased between the 2nd and 3rd growing seasons by 34, 68, and 139 mg P kg^{-1} in the 147, 294, and 441 kg P ha^{-1} treatments, respectively at Oxford. This drop in soil P concentration is not due to leaching deeper into the profile, nor can it be accounted for by P removal alone since P removal rates (approximately 2-4 kg P ha^{-1}) were much lower than fertilization rates (147-441 kg P ha^{-1}). Inorganic P added to soil can by absorbed by plant roots, immobilized by microorganisms, adsorbed to mineral surfaces, and/or precipitated as secondary P compounds (Havlin et al., 1999). A combination of these processes likely accounts for the decreases in Mehlich-3 P measured at Mills River and Oxford.

In acidic soils with pH < 5.5, phosphate reacts with Al, becoming fixed and unavailable to plants (Busman et al., 2002). After incorporating lime into the acidic (pH = 4.9) soils at Mills River, pH remained a consistent 5.2 each year the soil was sampled, which is still low enough to cause P fixation by Al. Soil nutrient concentrations will need to continue to be measured for the next several years to determine the long-term effects of growing and harvesting giant miscanthus in these soils.

2.4 Summary

Giant miscanthus produced yields of up to 24 Mg ha^{-1} during the 3rd growing season. Biomass yield and plant height increased each year and productivity was generally better at Mills River than at Oxford, NC, probably due to poor establishment at Oxford. Phosphorus fertilization only improved biomass yield the first year at Mills River, and yield did not improve beyond the lowest P treatment (147 kg P ha^{-1}). Nitrogen fertilization only improved yield the second year at Oxford, which was likely the result of low soil inorganic N concentration (6.3 mg kg^{-1} at 0-20 cm). Yield did not improve beyond the lowest N treatment (45 kg N ha^{-1}). No interactions occurred between N and P treatments.

Plant tissue N, Ca, and Mg concentrations decreased each year, as yields increased. Plant tissue P concentrations decreased from year 1 to year 2 at both sites, but increased from year 2 to 3 at Mills River. Apparent luxury consumption for N and P occurred in 2010 at both sites. The greatest tissue N concentration was found in plots with the greatest N treatment (135 kg N ha^{-1}), despite the lack of yield increase beyond the lowest N rate (45 kg N ha^{-1}) and although yield did not respond to P fertilizer in 2010, P tissue concentration was greatest in plots with the greatest P treatment (441 kg P ha^{-1}). In 2010 at both sites, plant tissue P decreased with increasing N application, which can only be partially explained by a yield response to N since there was no yield response in Mills River that year. Increasing N fertilization resulted in increased uptake of N and Mg in 2010 at Mills River and Oxford. Plant tissue K concentration increased with increasing biomass production.

After each growing season, soil inorganic N in the upper 20 cm was not dependent on applied N treatment. With the exception of the 1st growing season at Mills River, soil inorganic N in the upper 20 cm decreased each year that giant miscanthus was grown and harvested. An increase in soil Mehlich-3 P was measured after P treatments were applied and the soil test P decreased with time in plots with the greatest P fertilizer rates (294 and 441 kg P ha^{-1}). Soil Mehlich-3 P did not change with time in the 0 P control plots.

Giant miscanthus successfully established at Mills River and Oxford, NC with minimal fertilizer inputs on soils with low initial N and P concentrations. Weed control was crucial during the first year of growth. Generally, the nutrient removed in greatest amounts was K, therefore additional research focusing on K requirements would be beneficial. Further research should also be done to determine long-term effects of growing and harvesting giant miscanthus on soil quality in North Carolina, particularly to provide appropriate P fertilizer recommendations. Studies specifically determining the role of N-fixing bacteria associated with giant miscanthus would improve understanding of N fertilization requirements.

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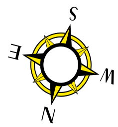
MHCRS, Butler Farm
2008 Miscanthus P and N study
1m x 1m plant spacing
4 P rates x 4 N rates x 4 Reps

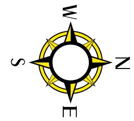


18m																			
1014 0 P 0 N	**1024** 294 P 90 N	**1034** 147 P 135 N	**1044** 441 P 0 N	2m alley	**2014** 147 P 0 N	**2024** 294 P 135 N	**2034** 441 P 45 N	**2044** 0 P 135 N	2m alley	**3014** 147 P 80 N	**3024** 0 P 135 N	**3034** 441 P 45 N	**3044** 294 P 90 N	2m alley	**4014** 441 P 90 N	**4024** 0 P 45 N	**4034** 147 P 135 N	**4044** 294 P 45 N	
1013 0 P 90 N	**1023** 294 P 135 N	**1033** 147 P 45 N	**1043** 441 P 45 N		**2013** 147 P 135 N	**2023** 294 P 90 N	**2033** 441 P 0 N	**2043** 0 P 90 N		**3013** 147 P 0 N	**3023** 0 P 90 N	**3033** 441 P 135 N	**3043** 294 P 0 N		**4013** 441 P 45 N	**4023** 0 P 90 N	**4033** 147 P 0 N	**4043** 294 P 135 N	
1012 0 P 45 N	**1022** 294 P 0 N	**1032** 147 P 90 N	**1042** 441 P 135 N		**2012** 147 P 90 N	**2022** 294 P 45 N	**2032** 441 P 135 N	**2042** 0 P 0 N		**3012** 147 P 40 N	**3022** 0 P 0 N	**3032** 441 P 90 N	**3042** 294 P 45 N		**4012** 441 P 0 N	**4022** 0 P 135 N	**4032** 147 P 90 N	**4042** 294 P 0 N	
1011 0 P 135 N	**1021** 294 P 45 N	**1031** 147 P 0 N	**1041** 441 P 90 N		**2011** 147 P 45 N	**2021** 294 P 0 N	**2031** 441 P 90 N	**2041** 0 P 45 N		**3011** 147 P 135 N	**3021** 0 P 45 N	**3031** 441 P 0 N	**3041** 294 P 135 N		**4011** 441 P 135 N	**4021** 0 P 0 N	**4031** 147 P 45 N	**4041** 294 P 90 N	

72m

Figure 2.1 Plot layout at Mills River, NC, showing N and P fertilizer application rates in kg ha^{-1}.

Oxford, Biofuels Center
2009 Miscanthus P and N study
1m x 1m plant spacing
4 P rates x 4 N rates x 4 Reps



16m

5014 0 P 0 N	**5024** 294 P 90 N	**5034** 147 P 135 N	**5044** 441 P 0 N	**6014** 147 P 0 N	**6024** 294 P 135 N	**6034** 441 P 45 N	**6044** 0 P 135 N	**7014** 147 P 80 N	**7024** 0 P 135 N	**7034** 441 P 45 N	**7044** 294 P 90 N	**8014** 441 P 90 N	**8024** 0 P 45 N	**8034** 147 P 135 N	**8044** 294 P 45 N
5013 0 P 90 N	**5023** 294 P 135 N	**5033** 147 P 45 N	**5043** 441 P 45 N	**6013** 147 P 135 N	**6023** 294 P 90 N	**6033** 441 P 0 N	**6043** 0 P 90 N	**7013** 147 P 0 N	**7023** 0 P 90 N	**7033** 441 P 135 N	**7043** 294 P 0 N	**8013** 441 P 45 N	**8023** 0 P 90 N	**8033** 147 P 0 N	**8043** 294 P 135 N
5012 0 P 45 N	**5022** 294 P 0 N	**5032** 147 P 90 N	**5042** 441 P 135 N	**6012** 147 P 90 N	**6022** 294 P 45 N	**6032** 441 P 135 N	**6042** 0 P 0 N	**7012** 147 P 40 N	**7022** 0 P 0 N	**7032** 441 P 90 N	**7042** 294 P 45 N	**8012** 441 P 0 N	**8022** 0 P 135 N	**8032** 147 P 90 N	**8042** 294 P 0 N
5011 0 P 135 N	**5021** 294 P 45 N	**5031** 147 P 0 N	**5041** 441 P 90 N	**6011** 147 P 45 N	**6021** 294 P 0 N	**6031** 441 P 90 N	**6041** 0 P 45 N	**7011** 147 P 135 N	**7021** 0 P 45 N	**7031** 441 P 0 N	**7041** 294 P 135 N	**8011** 441 P 135 N	**8021** 0 P 0 N	**8031** 147 P 45 N	**8041** 294 P 90 N

64m

Figure 2.2 Plot layout at Oxford, NC, showing N and P fertilizer application rates in kg ha^{-1}.

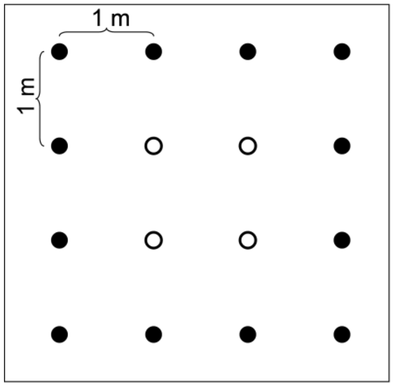


Figure 2.3 Individual subplots containing 16 giant miscanthus plants. The center 4 plants were harvested for yield and tissue data.

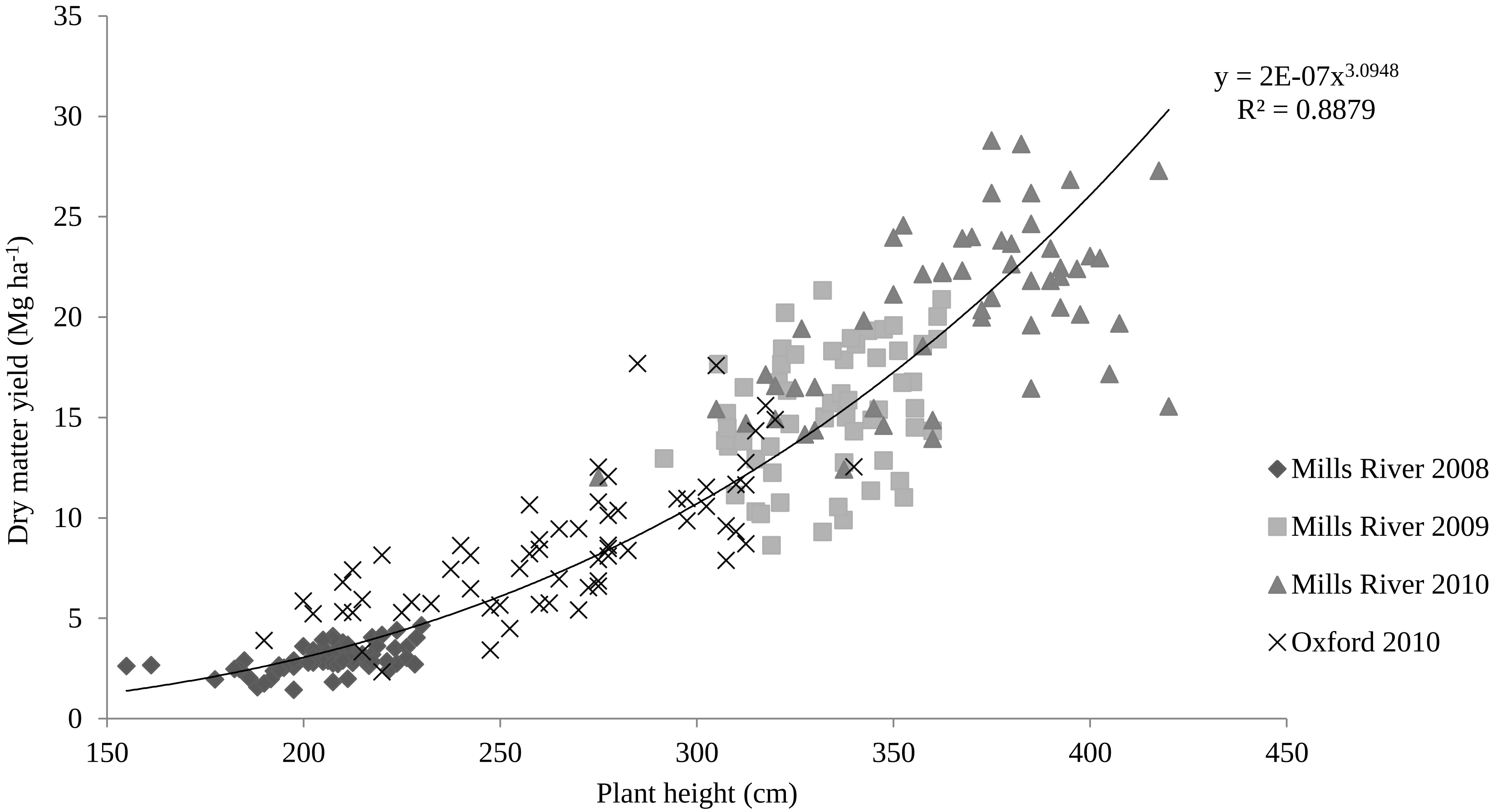
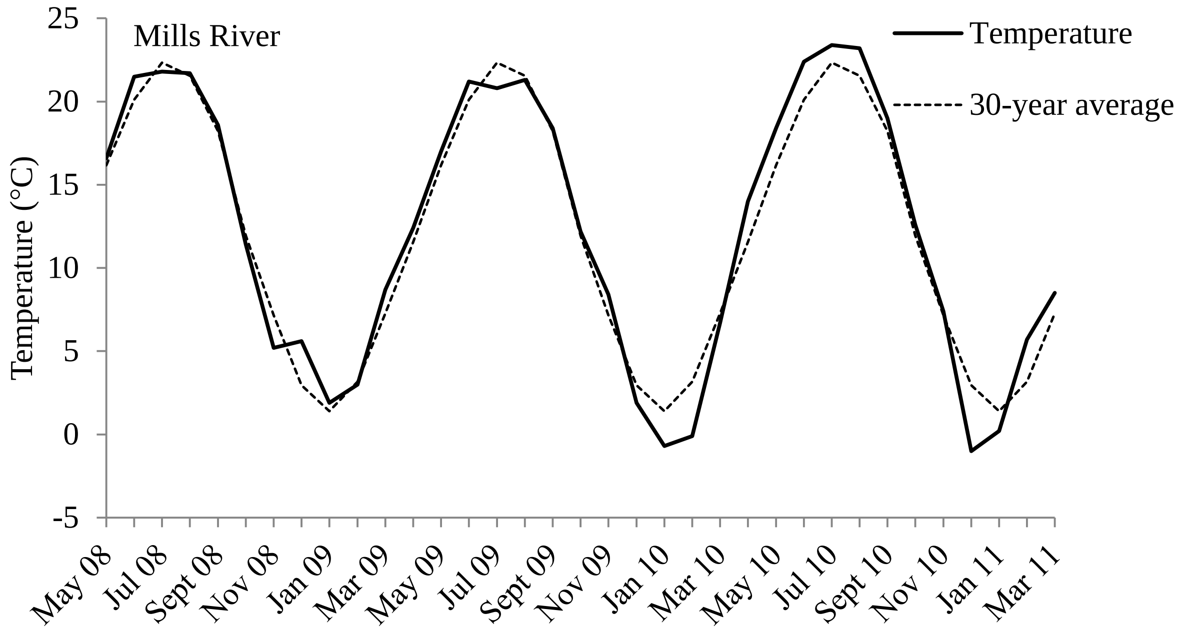


Figure 2.4 Plant height versus dry biomass yield in 2008, 2009, and 2010 at Mills River and 2010 at Oxford, NC. Data points represent individual subplots.



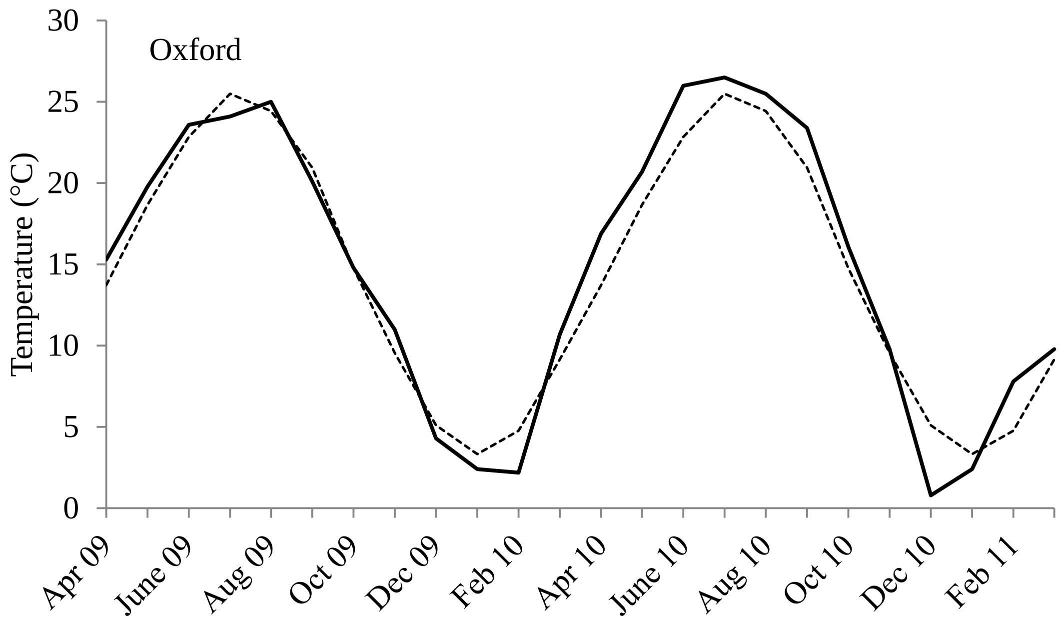


Figure 2.5 Average monthly temperatures and 30-year average (1971-2000) from May 2008 to March 2011 at Mills River and April 2009 to March 2011 at Oxford, NC.

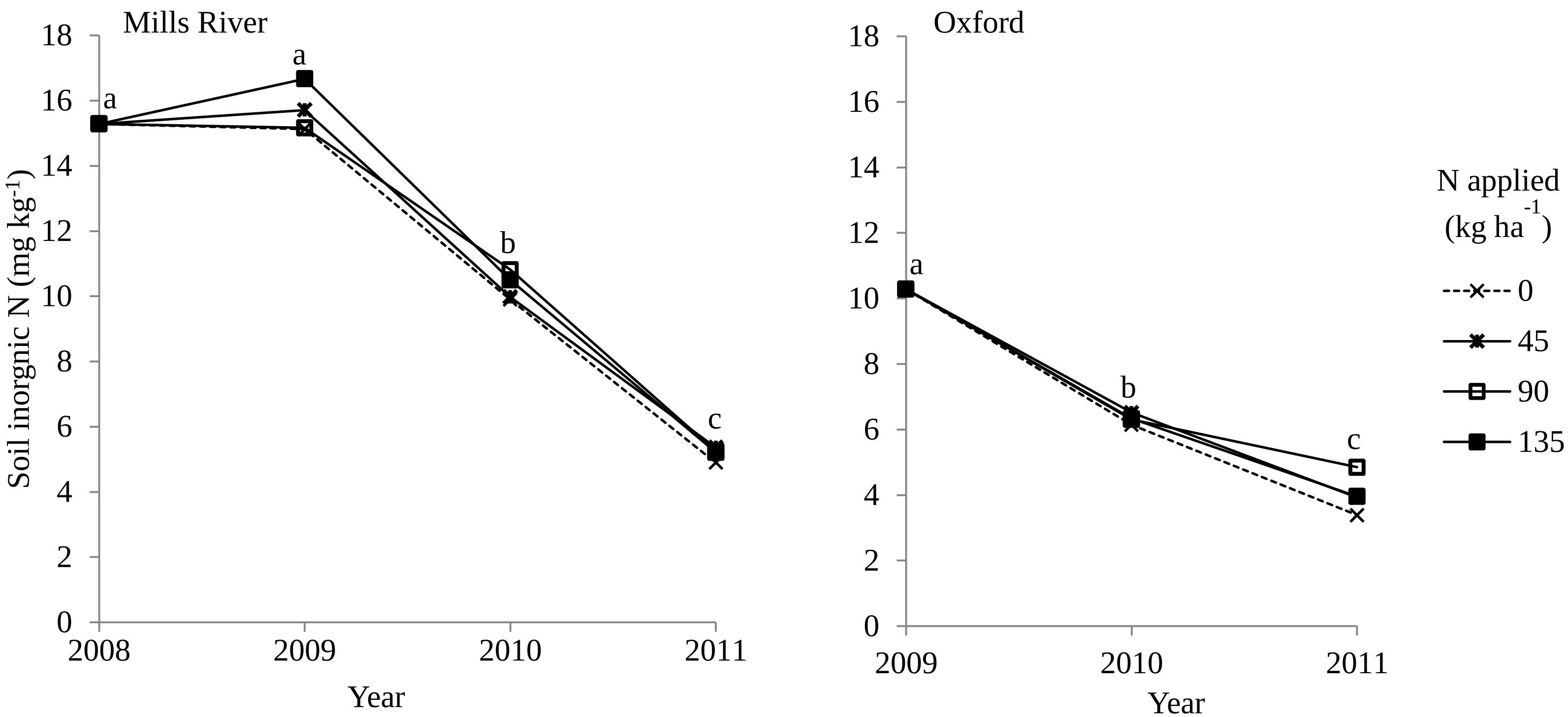


Figure 2.6 Soil inorganic N (NO_3 and NH_4) concentration in the 0-20 cm depth for multiple N fertilizer rates from 2008 to 2011 at Mills River and 2009 to 2011 at Oxford, NC. Means with the same letter at individual sites do not differ by year at *P*<0.05.

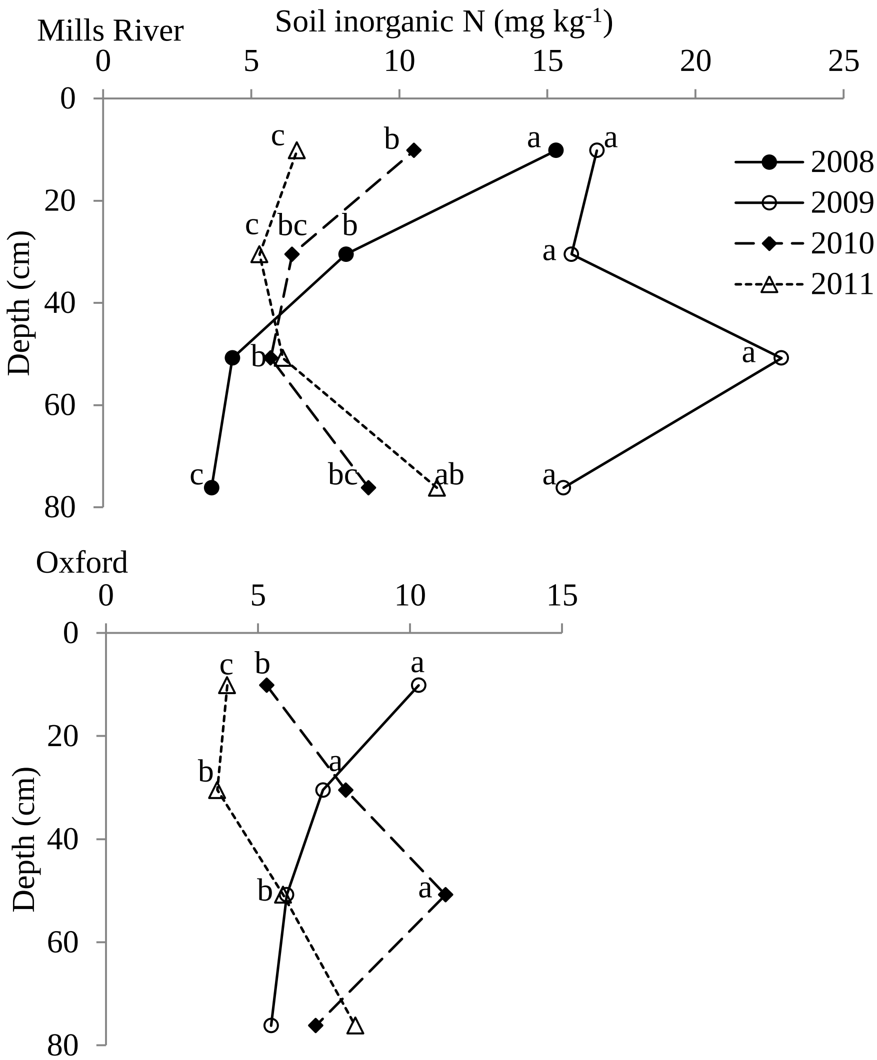


Figure 2.7 Inorganic N (NO_3 and NH_4) concentration with depth for plots with 135 kg ha^{-1} applied N from 2008 to 2011 at Mills River and 2009 to 2011 at Oxford, NC. Means with the same letter at individual sites and depths do not differ by year at P<0.05. Soil inorganic N changed with depth in years 2008, 2009 and 2010 at Mills River and in 2009, 2010 and 2011 at Oxford.

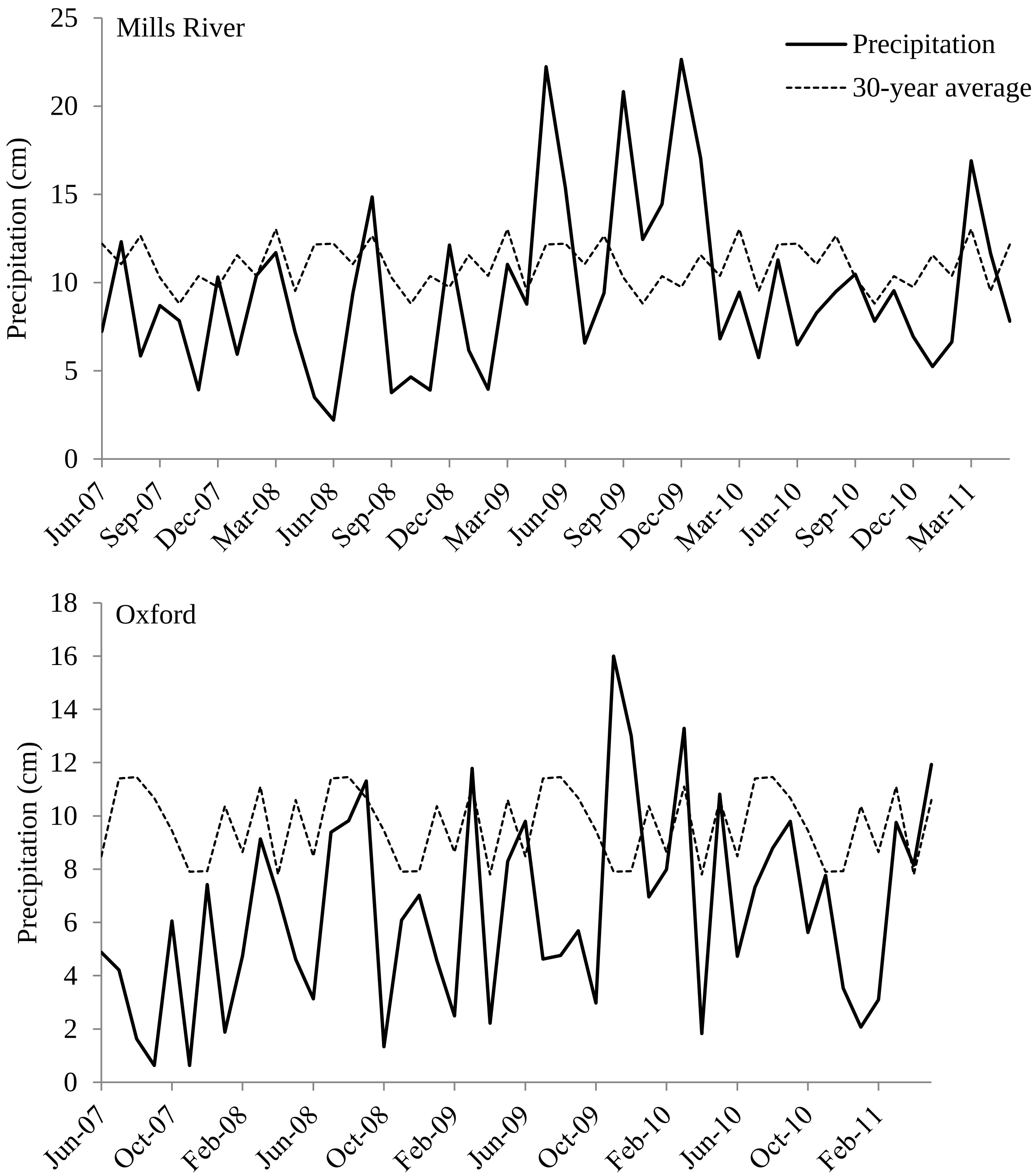


Figure 2.8 Monthly sum of daily precipitation and 30-year averages (1971-2000) from June 2007 to March 2011 at Mills River and Oxford, NC. Source: NC CRONOS Database, State Climate Office of North Carolina, 2011.

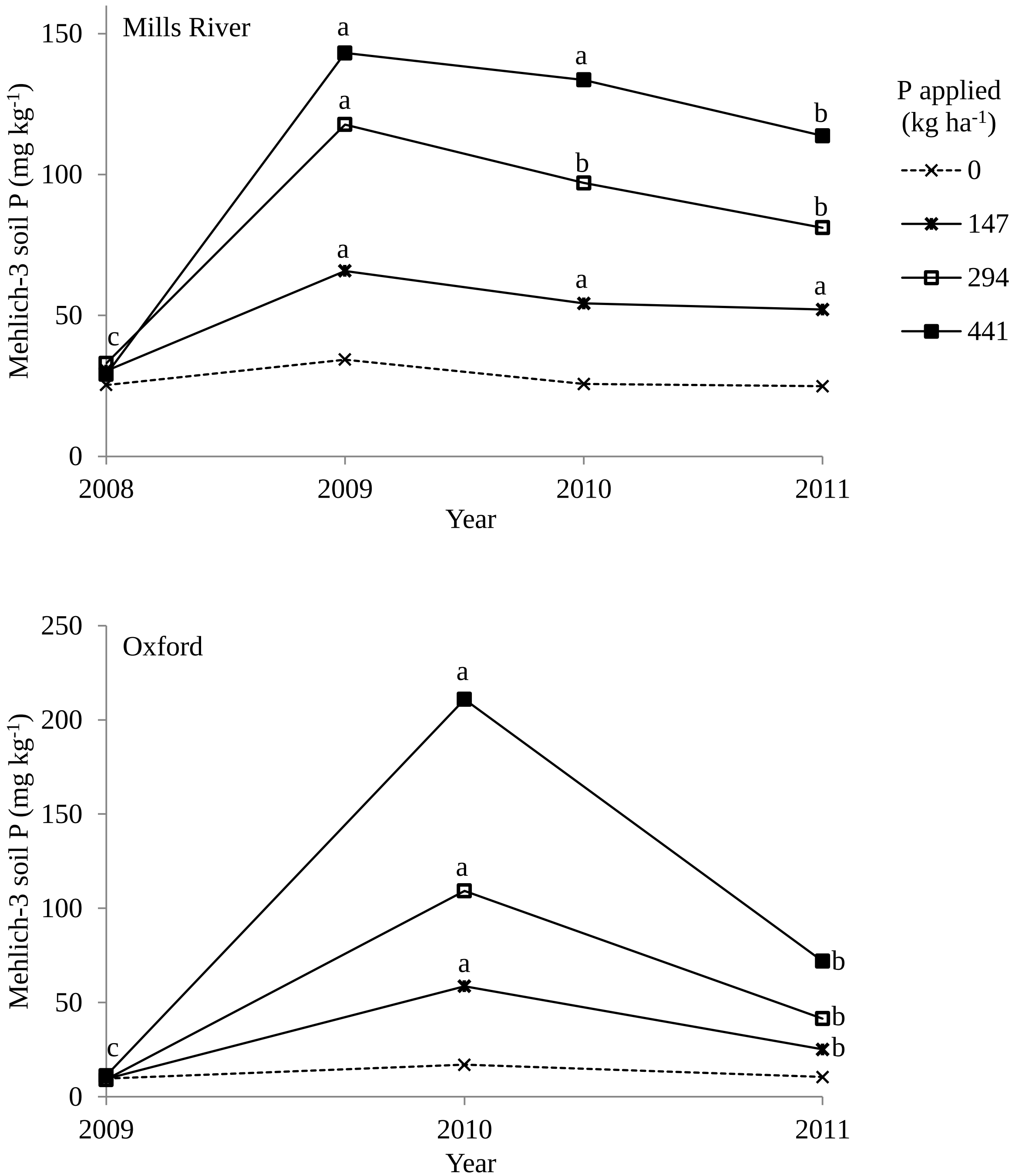


Figure 2.9 Mehlich-3 P concentration in the 0-20 cm depth of soil from 2008 to 2011 at Mills River and from 2009 to 2011 at Oxford, NC by amount of P applied. Means with the same letter are not different by year at P<0.05 for a given site and P treatment.

Table 2.1 Preplant soil characteristics by depth in 2008 at Mills River and 2009 at Oxford, NC.

Location	Depth	HM†	pH	CEC	Ca	Mg	K	P	N
	cm	g kg^{-1}		-----meq 100 g^{-1}-----			--------mg kg^{-1}--------		
Mills River‡	0-20	0.47	4.9	6.4	2.4	1.0	208	29.4	15.3
	20-41	0.14	5.0	5.1	2.1	0.8	134	5.5	8.2
	41-61	0.04	5.2	4.0	2.1	0.7	104	0.7	4.4
	61-91	0.04	5.3	2.5	1.3	0.4	72	0.6	3.7
Oxford§	0-20	0.28	5.4	5.7	2.6	1.4	101	9.9	10.3
	20-41	0.08	5.2	6.2	2.6	1.8	66	1.5	7.1
	41-61	0.05	5.0	6.2	2.1	1.6	40	0.8	5.9
	61-91	0.06	4.9	5.5	1.4	1.1	35	1.1	5.4

†Humic Matter
‡Bradson gravelly loam (clayey, parasesquic, mesic, Typic Hapludult)
§Cecil sandy loam (fine, kaolinitic, thermic, Typic Kanhapludult)

Table 2.2 Type 3 tests of fixed effects† for yield, height, plant tissue, and nutrient removal data at Mills River and Oxford, NC in 2008, 2009, and 2010.

Location	Year	Effect	Dry Yield	Plant Height	Tissue N	Tissue P	Tissue K	Tissue Ca	Tissue Mg	N Removed	P Removed
Mills River	2008	P rate (P)	0.0019*‡	0.0002*	0.0136*	0.0491*	0.7864	0.3249	0.1548	0.0358*	0.0652
		N rate (N)	0.9039	0.3908	0.2334	0.2136	0.3687	0.7651	0.8381	0.8327	0.5285
		P x N	0.9252	0.0526	0.7592	0.9334	0.4434	0.8223	0.9466	0.9035	0.6823
	2009	P	0.7902	0.5294	0.9404	0.1754	0.3732	0.8912	0.7519	0.7932	0.0351*
		N	0.2848	0.0075*	0.0834	0.5535	0.4916	0.4391	0.6536	0.0837	0.0505
		P x N	0.5563	0.8856	0.7421	0.3993	0.5780	0.3930	0.6253	0.5879	0.5575
	2010	P	0.1151	0.6120	0.0369*	0.0154*	0.4664	0.5350	0.5164	0.0087*	0.0062*
		N	0.7192	0.0230*	0.0079*	0.0002*	0.2942	0.4124	0.0368*	0.8945	0.0004*
		P x N	0.2494	0.9098	0.3487	0.1575	0.9036	0.2874	0.3780	0.0677	0.4444
Oxford	2009	P	0.8321	nd§	0.3081	0.0806	0.8594	0.7913	0.7980	0.6068	0.2675
		N	0.1555	nd	0.2298	0.4670	0.7312	0.3120	0.0082*	0.2799	0.1122
		P x N	0.1662	nd	0.0190*	0.5407	0.1099	0.7192	0.1528	0.0977	0.1165
	2010	P	0.2314	0.5693	0.4502	0.0209*	0.1573	0.3846	0.9911	0.2772	0.0087*
		N	0.0047*	0.3948	0.0003*	<.0001*	0.0174*	0.9159	<.0001*	0.0002*	0.0002*
		P x N	0.1224	0.0661	0.9591	0.1810	0.9769	0.9877	0.5100	0.1620	0.0401*

†Evaluated in PROC MIXED (SAS Institute Inc., 2009)
‡Values denoted with an asterisk are significant to P > 0.05
§ nd, no height data collected at Oxford, 2009

Table 2.3 Mean plant heights at Mills River in 2008, 2009, and 2010 and at Oxford, NC in 2010 in response to N and P fertilizer rate. Means for a given site and year with the same lowercase letter are not different by P rate and means with the same upper case letter are not different by N rate at P<0.05.

			N rate (kg ha^{-1})				
Location	Year	P rate	0	45	90	135	Mean
		(kg ha^{-1})	----------------------------------	m	-------------------------------		
Mills River	2008	0	1.86	1.93	2.06	1.88	1.93b
		147	2.15	2.13	1.90	2.11	2.07a
		294	2.21	2.11	2.05	2.17	2.13a
		441	2.08	2.12	2.04	2.13	2.09a
		Mean	2.07	2.07	2.01	2.07	2.06
	2009	0	3.35	3.33	3.30	3.27	3.31
		147	3.47	3.34	3.36	3.29	3.36
		294	3.46	3.35	3.23	3.36	3.35
		441	3.41	3.31	3.23	3.24	3.30
		Mean	3.42A	3.33B	3.28B	3.29B	3.33
	2010	0	3.70	3.70	3.59	3.54	3.63
		147	3.70	3.73	3.74	3.55	3.68
		294	3.73	3.62	3.58	3.58	3.63
		441	3.81	3.66	3.77	3.61	3.71
		Mean	3.73A	3.68A	3.67AB	3.57B	3.66
Oxford	2010	0	2.49	2.49	2.69	2.52	2.55
		147	2.63	2.89	2.74	2.59	2.71
		294	2.71	3.04	2.29	2.67	2.68
		441	2.50	2.57	2.71	2.93	2.68
		Mean	2.58	2.75	2.61	2.68	2.65

Table 2.4 Mean biomass dry yield at Mills River in 2008, 2009, and 2010 and Oxford, NC in 2009 and 2010 in response to N and P fertilizer rate. Means for a given site and year with the same lowercase letter are not different by P rate and means with the same upper case letter are not different by N rate at *P*<0.05.

			N rate (kg ha^{-1})				
Location	Year	P rate	0	45	90	135	Mean
		(kg ha^{-1})	------------------------------Mg ha^{-1}---------------------------				
Mills River	2008	0	2.61	2.36	2.36	2.27	2.40b
		147	3.15	3.48	2.94	3.02	3.15a
		294	2.99	2.99	3.31	2.96	3.06a
		441	3.27	3.38	2.98	3.48	3.28a
		Mean	3.01	3.05	2.90	2.93	2.97
	2009	0	15.78	13.77	12.51	14.08	14.04
		147	17.49	13.86	14.44	15.26	15.26
		294	16.11	14.62	15.56	13.57	14.96
		441	15.18	16.68	16.35	14.97	15.79
		Mean	16.14	14.73	14.71	14.47	15.01
	2010	0	22.75	20.60	19.67	17.51	20.13
		147	23.68	19.43	20.96	20.50	21.14
		294	17.15	17.66	20.69	18.81	18.58
		441	19.00	23.97	22.85	22.32	22.03
		Mean	20.65	20.41	21.04	19.79	20.47
Oxford	2009	0	0.35	0.41	0.34	0.42	0.38
		147	0.27	0.30	0.41	0.44	0.35
		294	0.35	0.32	0.27	0.43	0.34
		441	0.36	0.27	0.53	0.41	0.39
		Mean	0.33	0.33	0.39	0.43	0.37
	2010	0	6.72	7.01	8.26	8.60	7.65
		147	5.45	9.74	9.60	9.48	8.57
		294	7.43	10.35	6.47	8.86	8.28
		441	5.79	7.95	11.68	13.46	9.72
		Mean	6.35B	8.77A	9.01A	10.10A	8.56

Table 2.5 Mean plant tissue N concentration at Mills River in 2008, 2009, and 2010 and Oxford, NC in 2009 and 2010 in response to N and P fertilizer rate. Means for a given site and year with the same lowercase letter are not different by P rate and means with the same upper case letter are not different by N rate at $P<0.05$.

			N rate (kg ha^{-1})				
Location	Year	P rate	0	45	90	135	Mean
		(kg ha^{-1})	-------------------------------	mg kg^{-1}	----------------------------		
Mills River	2008	0	9787	9487	9422	8765	9365a
		147	8641	7931	8628	8299	8375b
		294	7763	8066	8692	8085	8152b
		441	7988	7137	9192	8209	8131b
		Mean	8545	8155	8983	8339	8506
	2009	0	2764	2160	3238	2215	2594
		147	2758	2126	3204	2456	2636
		294	2636	2746	2797	3018	2799
		441	2496	2514	2857	2714	2645
		Mean	2664	2386	3024	2601	2669
	2010	0	1497	1652	1656	1870	1669b
		147	1812	1869	1788	2110	1895a
		294	1605	1482	1896	1750	1683b
		441	1582	1927	1717	2075	1826ab
		Mean	1624B	1732B	1764B	1951A	1763
Oxford	2009	0	7091	7049	7020	6415	6894
		147	8766	7947	8358	6508	7894
		294	8129	8762	8108	7768	8192
		441	6599	8135	8275	8663	7918
		Mean	7646	7973	7940	7338	7725
	2010	0	2006	1946	2165	2506	2156
		147	1750	2037	2043	2342	2043
		294	1679	1653	1895	2113	1835
		441	1881	1955	1939	2230	2001
		Mean	1829B	1898B	2010B	2297A	2009

Table 2.6 Mean plant tissue P concentration at Mills River in 2008, 2009, and 2010 and Oxford, NC in 2009 and 2010 in response to N and P fertilizer rate. Means for a given site and year with the same lowercase letter are not different by P rate and means with the same upper case letter are not different by N rate at P<0.05.

			N rate (kg ha^{-1})				
Location	Year	P rate	0	45	90	135	Mean
		(kg ha^{-1})	------------------------------mg kg^{-1}--------------------------				
Mills River	2008	0	366	347	352	324	347a
		147	332	288	305	305	307b
		294	310	291	337	306	311b
		441	315	288	330	317	313b
		Mean	331	303	331	313	320
	2009	0	102	82	111	111	101
		147	116	120	118	88	110
		294	108	126	101	107	111
		441	175	138	99	126	135
		Mean	125	117	107	108	114
	2010	0	119	111	94	106	107b
		147	230	137	150	143	165ab
		294	361	237	198	117	228a
		441	391	252	150	136	232a
		Mean	275A	184B	148B	126B	183
Oxford	2009	0	212	248	224	226	227
		147	252	271	272	231	256
		294	251	286	260	248	261
		441	265	268	255	310	275
		Mean	245	268	253	254	255
	2010	0	173	125	124	132	139b
		147	408	161	139	146	213b
		294	447	138	209	129	231ab
		441	612	301	226	154	323a
		Mean	410A	181B	175B	140B	226

Table 2.7 Mean N removal at Mills River in 2008, 2009, and 2010 and at Oxford, NC in 2009 and 2010 in response to N and P fertilizer rate. Means for a given site and year with the same lowercase letter are not different by P rate and means with the same upper case letter are not different by N rate at P<0.05.

			N rate (kg ha^{-1})				
Location	Year	P rate	0	45	90	135	Mean
		(kg ha^{-1})	--------kg ha^{-1}--------				
Mills River	2008	0	24.44	21.16	21.22	19.57	21.60b
		147	26.99	27.44	25.92	24.96	26.33a
		294	22.95	24.42	27.20	23.50	24.52ab
		441	26.66	24.57	26.97	27.58	26.44a
		Mean	25.26	24.40	25.33	23.90	24.72
	2009	0	43.64	31.22	39.71	31.27	36.46
		147	48.15	26.49	42.88	35.79	38.33
		294	43.10	39.74	43.23	39.63	41.43
		441	37.12	42.12	46.98	40.35	41.64
		Mean	43.00	34.89	43.20	36.76	39.46
	2010	0	32.52	33.71	34.24	34.25	33.68bc
		147	38.25	32.84	42.96	43.49	43.49a
		294	29.22	25.69	38.73	34.78	32.10c
		441	30.28	46.57	37.73	40.67	38.81ab
		Mean	32.57	34.70	38.41	38.30	36.00
Oxford	2009	0	2.44	2.90	2.39	2.84	2.64
		147	2.38	2.31	3.36	2.74	2.70
		294	2.82	3.68	2.19	3.40	3.02
		441	2.39	2.20	4.48	3.47	3.14
		Mean	2.51	2.77	3.10	3.11	2.87
	2010	0	13.59	13.83	16.79	18.23	15.61
		147	9.20	19.99	19.54	22.05	17.70
		294	12.45	17.26	12.27	17.99	14.99
		441	10.38	14.72	23.97	29.41	19.62
		Mean	11.41C	16.45B	18.14AB	21.92A	16.98

Table 2.8 Mean P removal at Mills River in 2008, 2009, and 2010 and at Oxford, NC in 2009 and 2010 in response to N and P fertilizer rate. Means for a given site and year with the same lowercase letter are not different by P rate and means with the same upper case letter are not different by N rate at P<0.05.

			N rate (kg ha^{-1})				
Location	Year	P rate	0	45	90	135	Mean
		(kg ha^{-1})	---------------------------------kg ha^{-1}------------------------------				
Mills River	2008	0	0.91	0.78	0.80	1.04	0.89
		147	1.04	0.98	0.90	0.92	0.96
		294	0.92	0.87	1.09	0.90	0.94
		441	1.04	0.98	0.97	1.05	1.01
		Mean	0.98	0.90	0.94	0.98	0.95
	2009	0	1.58	1.10	1.37	1.57	1.41b
		147	2.00	1.56	1.77	1.29	1.66ab
		294	1.82	1.62	1.55	1.35	1.59b
		441	2.49	2.22	1.61	1.84	2.04a
		Mean	1.97	1.62	1.58	1.51	1.67
	2010	0	2.42	2.04	1.94	2.06	2.12b
		147	5.78	2.54	3.27	2.66	3.56a
		294	7.16	3.88	2.97	2.30	4.08a
		441	7.50	5.88	3.11	2.66	4.79a
		Mean	5.71A	3.59B	2.82BC	2.42C	3.64
Oxford	2009	0	0.07	0.10	0.07	0.10	0.09
		147	0.07	0.08	0.11	0.10	0.09
		294	0.09	0.12	0.07	0.11	0.09
		441	0.09	0.07	0.14	0.13	0.11
		Mean	0.08	0.09	0.10	0.11	0.09
	2010	0	1.14	0.83	1.01	1.13	1.03b
		147	1.65	1.51	1.33	1.35	1.46b
		294	3.28	1.46	1.26	1.07	1.77b
		441	3.39	2.52	2.20	2.00	2.53a
		Mean	2.37A	1.58B	1.45B	1.39B	1.70

Table 2.9 Mean plant tissue K, Ca, and Mg concentration in response to applied N at Mills River in 2008, 2009, and 2010 and at Oxford, NC in 2009 and 2010. Means with the same letter are not different by N rate at *P*<0.05 for a given nutrient, site, and year.

			N rate (kg ha^{-1})				
Location	Year	Nutrient	0	45	90	135	Mean
			mg kg^{-1}				
Mills River	2008	K	1971	1842	1890	1988	1923
		Ca	4306	4163	4320	4223	4253
		Mg	959	948	951	973	958
	2009	K	3253	3758	3358	3766	3534
		Ca	2026	1772	2000	1969	1942
		Mg	677	693	723	760	713
	2010	K	3860	3582	3783	4078	3826
		Ca	1389	1326	1462	1373	1388
		Mg	485b	530ab	578a	601a	549
Oxford	2009	K	2323	2333	2438	2367	2365
		Ca	3793	3571	3731	3704	3700
		Mg	1046ab	950c	1051a	981bc	1007
	2010	K	3022b	2981b	3161ab	3389a	3133
		Ca	1891	1854	1837	1895	1869
		Mg	803b	865b	960a	973a	900

Table 2.10 Mean soil Mehlich-3 P for each P treatment at Mills River in 2008, 2009, 2010, and 2011 and at Oxford, NC in 2009, 2010, and 2011. Means with the same letter are not different by year at *P*<0.05 for a given site, depth, and P treatment.

			P (kg ha^{-1}) ‡			
Location	Depth† (cm)	Year	0	147	294	441
			----------------------mg kg^{-1}---------------------			
Mills River	0-20	2008	25.33	30.36b	33.02c	29.08c
		2009	34.31	65.78a	117.78a	143.15a
		2010	25.65	54.25a	97.04b	133.58a
		2011	24.86	52.07a	81.16b	113.75b
	20-41	2008	4.99	6.17	4.27	6.71
		2009	6.84	8.41	3.42	5.99
		2010	4.49	2.68	4.20	7.93
		2011	3.95	6.28	5.11	6.91
	41-61	2008	0.55	0.71	0.82	0.62
		2009	0.55	1.01	1.08	0.86
		2010	0.80	0.75	1.13	1.17
		2011	0.83	0.94	0.89	0.95
	61-91	2008	0.64	0.70	0.70	0.56c
		2009	0.71	0.86	0.74	0.72bc
		2010	0.91	0.97	0.78	1.58a
		2011	0.66	0.96	0.88	1.08b
Oxford	0-20	2009	9.61	9.56c	9.16c	11.20c
		2010	16.97	58.64a	109.30a	210.93a
		2011	10.52	25.11b	41.49b	72.00b
	20-41	2009	1.03	1.82a	0.98	2.05
		2010	1.26	1.51a	1.67	0.75
		2011	1.44	1.04b	2.37	1.10
	41-61	2009	0.89	0.74	0.80ab	0.93
		2010	0.51	0.60	0.52b	0.53
		2011	0.94	0.77	1.09a	0.59
	61-91	2009	1.23	0.85	0.89	1.58a
		2010	0.43	0.50	0.44	0.43b
		2011	0.61	0.67	0.72	0.59b

†Depth effect was significant between 0-20 and 20-41 cm for each site and year, between 20-41 and 41-61 each year at Mills River, and between each depth at Oxford in 2010.
‡Data listed for Mills River 2008 and Oxford 2009 are for samples taken before P was applied to plots.

APPENDIX

Table A.1 Site, year, plot, P fertilizer treatment, N fertilizer treatment, dry matter yield, plant height, plant tissue nutrient concentrations, and nutrient removal rates for Mills River in 2008, 2009, and 2010 and Oxford in 2009 and 2010.

Site	**Year**	**Plot**	**P rate**	**N rate**	**DM**	**Height**	**Plant tissue concentrations** mg kg^{-1}					**Removal rates** kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
MR	2008	1011	0	135	1.95	178	10619	417	2004	5342	985	20.72	0.81	3.91	10.42	1.92
MR	2008	1012	0	45	3.51	205	6903	289	1714	4372	919	24.23	1.01	6.02	15.35	3.23
MR	2008	1013	0	90	2.87	206	6622	274	1757	4251	909	19.02	0.79	5.05	12.21	2.61
MR	2008	1014	0	0	2.88	185	6792	286	1640	4748	1067	19.58	0.82	4.73	13.69	3.08
MR	2008	1021	294	45	2.37	193	7595	316	1662	4685	979	18.02	0.75	3.94	11.12	2.32
MR	2008	1022	294	0	3.50	223	5635	232	2270	4069	859	19.72	0.81	7.94	14.24	3.00
MR	2008	1023	294	135	3.55	226	6053	310	2150	4550	1071	21.47	1.10	7.63	16.14	3.80
MR	2008	1024	294	90	4.40	224	5232	294	2748	4083	1059	23.01	1.29	12.09	17.96	4.66
MR	2008	1031	147	0	3.32	213	6258	305	1879	4600	1115	20.77	1.01	6.24	15.27	3.70
MR	2008	1032	147	90	2.59	198	6279	306	2142	4001	868	16.24	0.79	5.54	10.35	2.24
MR	2008	1033	147	45	2.78	213	7073	310	1992	4397	884	19.65	0.86	5.53	12.22	2.46
MR	2008	1034	147	135	3.16	208	6729	279	2167	4501	964	21.25	0.88	6.84	14.21	3.04
MR	2008	1041	441	90	3.79	210	7570	281	1806	4160	816	28.66	1.06	6.84	15.75	3.09
MR	2008	1042	441	135	3.56	211	6825	234	1680	3998	889	24.28	0.83	5.98	14.22	3.16
MR	2008	1043	441	45	2.92	210	4348	230	2083	4008	1003	12.68	0.67	6.07	11.68	2.92
MR	2008	1044	441	0	2.37	193	6165	305	2358	4850	1224	14.61	0.72	5.59	11.49	2.90
MR	2008	2011	147	45	4.10	208	7293	230	1587	4138	1056	29.88	0.94	6.50	16.95	4.33
MR	2008	2012	147	90	4.01	208	10030	296	1655	4654	971	40.19	1.19	6.63	18.65	3.89
MR	2008	2013	147	135	2.41	222	8944	325	2028	4802	992	21.57	0.78	4.89	11.58	2.39
MR	2008	2014	147	0	3.23	210	9424	334	2259	4501	1020	30.48	1.08	7.31	14.56	3.30
MR	2008	2021	294	0	2.63	217	7539	302	1949	3939	1140	19.85	0.80	5.13	10.37	3.00
MR	2008	2022	294	45	2.74	224	7830	291	1164	4229	1078	21.45	0.80	3.19	11.59	2.95
MR	2008	2023	294	90	3.60	200	8488	304	1691	4373	1058	30.59	1.10	6.10	15.76	3.81
MR	2008	2024	294	135	2.84	205	8680	279	1943	4603	1072	24.61	0.79	5.51	13.05	3.04

Site	Year	Plot	P rate	N rate	DM	Height	Plant tissue concentrations mg kg^{-1}					Removal rates kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
MR	2008	2031	441	90	2.65	194	9655	320	1434	4531	1151	25.57	0.85	3.80	12.00	3.05
MR	2008	2032	441	135	3.92	205	8241	333	2006	5260	1223	32.30	1.30	7.86	20.62	4.79
MR	2008	2033	441	0	4.05	218	7568	325	2246	4006	1034	30.63	1.32	9.09	16.22	4.19
MR	2008	2034	441	45	3.40	203	7772	312	1738	4644	1169	26.39	1.06	5.90	15.77	3.97
MR	2008	2041	0	45	2.01	186	10256	378	1754	4440	954	20.66	0.76	3.53	8.95	1.92
MR	2008	2042	0	0	2.97	213	8686	298	1851	4069	967	25.84	0.89	5.50	12.10	2.88
MR	2008	2043	0	90	2.84	216	8538	337	1637	4717	1046	24.21	0.96	4.64	13.38	2.97
MR	2008	2044	0	135	3.11	203	7874	275	1514	3944	1034	24.49	0.86	4.71	12.27	3.22
MR	2008	3011	147	135	2.89	198	8618	296	1643	4088	977	24.90	0.85	4.75	11.81	2.82
MR	2008	3012	147	45	4.16	220	7941	264	2153	3643	958	33.04	1.10	8.96	15.16	3.99
MR	2008	3013	147	0	3.19	215	8709	289	1843	4149	880	27.79	0.92	5.88	13.24	2.81
MR	2008	3014	147	90	2.52	195	8079	256	1594	4600	1038	20.39	0.65	4.02	11.61	2.62
MR	2008	3021	0	45	2.47	184	9650	314	2049	4099	952	23.87	0.78	5.07	10.14	2.35
MR	2008	3022	0	0	2.61	155	9127	334	1973	4274	937	23.83	0.87	5.15	11.16	2.45
MR	2008	3023	0	90	1.98	211	10133	377	2182	4171	938	20.05	0.75	4.32	8.25	1.86
MR	2008	3024	0	135	1.56	188	8616	296	1968	4126	941	13.44	0.46	3.07	6.44	1.47
MR	2008	3031	441	0	3.07	211	7991	290	1646	4160	857	24.53	0.89	5.05	12.77	2.63
MR	2008	3032	441	90	2.79	203	8168	336	2085	4159	993	22.80	0.94	5.82	11.61	2.77
MR	2008	3033	441	135	4.64	230	7591	281	2086	3605	938	35.20	1.30	9.67	16.71	4.35
MR	2008	3034	441	45	3.20	208	8384	308	1859	4517	962	26.82	0.99	5.95	14.45	3.08
MR	2008	3041	294	135	2.75	208	9022	300	2186	3807	960	24.78	0.82	6.00	10.45	2.64
MR	2008	3042	294	45	3.20	218	7495	258	2039	3649	916	23.96	0.83	6.52	11.66	2.93
MR	2008	3043	294	0	3.02	226	8789	325	2240	3962	871	26.52	0.98	6.76	11.95	2.63
MR	2008	3044	294	90	2.43	194	9731	322	1686	4865	946	23.69	0.78	4.10	11.84	2.30
MR	2008	4011	441	135	1.82	208	10180	421	2281	4282	1042	18.56	0.77	4.16	7.80	1.90
MR	2008	4012	441	0	3.61	210	10230	341	1889	3901	832	36.88	1.23	6.81	14.06	3.00

Site	Year	Plot	P rate	N rate	DM	Height	Plant tissue concentrations					Removal rates				
							mg kg^{-1}					kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	N	P	K	Ca	Mg	N	P	K	Ca	Mg
MR	2008	4013	441	45	4.03	229	8042	301	2318	3775	843	32.37	1.21	9.33	15.20	3.39
MR	2008	4014	441	90	2.71	209	11374	384	1570	4673	847	30.83	1.04	4.26	12.67	2.30
MR	2008	4021	0	0	1.96	192	14541	547	1618	6204	893	28.50	1.07	3.17	12.16	1.75
MR	2008	4022	0	135	2.47	183	7950	310	2212	3550	807	19.62	0.76	5.46	8.76	1.99
MR	2008	4023	0	90	1.74	190	12393	419	2126	4369	810	21.62	0.73	3.71	7.62	1.41
MR	2008	4024	0	45	1.43	198	11140	407	1870	4610	798	15.88	0.58	2.67	6.57	1.14
MR	2008	4031	147	45	2.89	210	9416	346	1724	3483	798	27.18	1.00	4.98	10.06	2.30
MR	2008	4032	147	90	2.65	161	10123	360	2066	3536	851	26.86	0.96	5.48	9.38	2.26
MR	2008	4033	147	0	2.84	221	10174	401	2113	3609	769	28.93	1.14	6.01	10.26	2.19
MR	2008	4034	147	135	3.61	219	8904	320	1950	3593	805	32.12	1.15	7.04	12.96	2.90
MR	2008	4041	294	90	2.78	201	11318	428	2053	3975	916	31.50	1.19	5.71	11.06	2.55
MR	2008	4042	294	0	2.83	218	9090	382	1766	3853	880	25.70	1.08	4.99	10.89	2.49
MR	2008	4043	294	135	2.70	228	8585	334	1992	3513	861	23.14	0.90	5.37	9.47	2.32
MR	2008	4044	294	45	3.67	211	9344	298	1767	3924	903	34.25	1.09	6.48	14.39	3.31
MR	2009	1011	0	135	13.57	308	827	173	4093	2548	924	11.22	2.35	55.53	34.56	12.53
MR	2009	1012	0	45	10.75	321	813	110	2489	1381	521	8.74	1.18	26.76	14.85	5.60
MR	2009	1013	0	90	12.24	319	3304	118	3199	2285	955	40.45	1.44	39.16	27.97	11.69
MR	2009	1014	0	0	13.81	312	2824	140	2874	2016	732	39.00	1.94	39.69	27.84	10.11
MR	2009	1021	294	45	10.31	315	2896	106	3316	1730	708	29.85	1.10	34.19	17.84	7.30
MR	2009	1022	294	0	11.35	344	2380	114	3634	1907	620	27.02	1.29	41.26	21.65	7.04
MR	2009	1023	294	135	8.62	319	3814	162	4014	2781	1109	32.89	1.40	34.62	23.98	9.56
MR	2009	1024	294	90	13.85	307	3023	111	3171	1825	644	41.86	1.54	43.92	25.27	8.91
MR	2009	1031	147	0	15.03	333	2556	145	2873	1619	620	38.42	2.17	43.19	24.33	9.32
MR	2009	1032	147	90	11.48	-	5047	-	-	-	-	57.96	-	-	-	-
MR	2009	1033	147	45	9.30	332	3304	142	3663	2236	750	30.72	1.32	34.06	20.78	6.98
MR	2009	1034	147	135	11.13	310	2960	97	3085	2059	749	32.94	1.08	34.34	22.91	8.34

Site	Year	Plot	P rate	N rate	DM	Height	Plant tissue concentrations mg kg^{-1}					Removal rates kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
MR	2009	1041	441	90	17.65	306	3167	140	2976	2269	699	55.88	2.47	52.52	40.05	12.34
MR	2009	1042	441	135	12.95	292	2545	124	1927	2255	848	32.96	1.60	24.96	29.21	10.99
MR	2009	1043	441	45	12.92	315	2702	201	2012	1903	869	34.91	2.59	26.00	24.59	11.22
MR	2009	1044	441	0	9.88	337	2682	200	2346	1542	529	26.52	1.98	23.19	15.24	5.23
MR	2009	2011	147	45	20.21	323	707	94	2406	1141	644	14.29	1.90	48.63	23.06	13.01
MR	2009	2012	147	90	18.42	322	1404	96	3795	1177	546	25.86	1.77	69.89	21.68	10.06
MR	2009	2013	147	135	11.83	352	3398	103	5394	1711	678	40.20	1.22	63.83	20.24	8.02
MR	2009	2014	147	0	19.31	344	2558	84	3333	1831	529	49.41	1.63	64.38	35.37	10.21
MR	2009	2021	294	0	13.55	319	2574	-	2468	4599	1643	34.88	-	33.43	62.31	22.26
MR	2009	2022	294	45	10.19	316	2787	248	3391	2148	1291	28.39	2.53	34.55	21.89	13.15
MR	2009	2023	294	90	15.20	308	2903	102	2796	2166	875	44.13	1.55	42.51	32.92	13.30
MR	2009	2024	294	135	14.96	333	2568	80	3810	1883	664	38.42	1.20	57.00	28.18	9.93
MR	2009	2031	441	90	14.47	308	2637	87	2520	1623	788	38.17	1.25	36.47	23.49	11.40
MR	2009	2032	441	135	13.34	-	3767	180	6066	2881	1227	50.25	2.40	80.92	38.44	16.37
MR	2009	2033	441	0	14.67	324	3350	290	4477	2415	947	49.14	4.25	65.67	35.42	13.89
MR	2009	2034	441	45	17.87	338	2575	106	2368	1936	644	46.02	1.89	42.32	34.59	11.50
MR	2009	2041	0	45	15.71	334	2461	68	3042	1755	622	38.66	1.07	47.79	27.57	9.77
MR	2009	2042	0	0	18.64	341	2582	81	2963	2183	618	48.13	1.52	55.25	40.69	11.52
MR	2009	2043	0	90	16.50	312	3163	119	4950	2393	785	52.19	1.97	81.67	39.49	12.95
MR	2009	2044	0	135	17.66	322	2785	90	3228	1931	864	49.17	1.59	57.00	34.09	15.25
MR	2009	3011	147	135	16.74	321	851	77	2549	1696	617	14.25	1.29	42.67	28.39	10.33
MR	2009	3012	147	45	10.53	336	1687	149	6615	1642	627	17.77	1.57	69.68	17.30	6.61
MR	2009	3013	147	0	18.90	361	2655	123	3077	1871	557	50.17	2.33	58.15	35.35	10.52
MR	2009	3014	147	90	15.01	338	2720	104	3648	2427	940	40.83	1.56	54.76	36.43	14.11
MR	2009	3021	0	45	12.75	338	2444	73	3423	1651	513	31.16	0.93	43.64	21.05	6.54
MR	2009	3022	0	0	12.37	-	2697	89	5137	1947	608	33.35	1.10	63.52	24.08	7.52

Site	Year	Plot	P rate	N rate	DM	Height	Plant tissue concentrations mg kg^{-1}					Removal rates kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
MR	2009	3023	0	90	6.99	-	3642	123	5191	3009	1032	25.45	0.86	36.28	21.03	7.21
MR	2009	3024	0	135	11.01	353	3034	70	4619	1528	630	33.40	0.77	50.86	16.82	6.94
MR	2009	3031	441	0	19.40	348	2495	83	3454	1528	453	48.38	1.61	67.00	29.63	8.78
MR	2009	3032	441	90	14.31	340	2734	100	4586	1828	606	39.13	1.43	65.62	26.16	8.68
MR	2009	3033	441	135	18.14	325	2967	88	2323	1757	523	53.82	1.60	42.13	31.87	9.49
MR	2009	3034	441	45	16.34	323	1845	132	5961	1939	709	30.15	2.16	97.40	31.68	11.58
MR	2009	3041	294	135	16.20	337	2776	85	3642	1268	541	44.97	1.38	58.98	20.53	8.76
MR	2009	3042	294	45	20.02	361	2676	69	2827	1368	457	53.58	1.39	56.60	27.38	9.15
MR	2009	3043	294	0	20.87	362	2794	110	2480	1807	517	58.32	2.31	51.76	37.72	10.80
MR	2009	3044	294	90	18.31	335	2511	78	1807	1676	656	45.97	1.43	33.09	30.68	12.01
MR	2009	4011	441	135	15.45	356	1577	113	4156	1695	687	24.37	1.75	64.23	26.20	10.61
MR	2009	4012	441	0	16.78	355	1457	127	3568	1736	561	24.44	2.13	59.86	29.12	9.41
MR	2009	4013	441	45	19.57	350	2933	114	3790	1707	491	57.41	2.23	74.19	33.41	9.61
MR	2009	4014	441	90	18.95	339	2889	68	2538	1658	516	54.74	1.29	48.08	31.41	9.78
MR	2009	4021	0	0	18.32	351	2953	96	4297	1738	644	54.08	1.76	78.70	31.83	11.79
MR	2009	4022	0	135	-	-	-	-	3153	1789	528	-	-	45.17	25.63	7.56
MR	2009	4023	0	90	14.33	360	2845	85	2804	1581	519	40.76	1.21	44.47	25.07	8.23
MR	2009	4024	0	45	15.86	339	2921	77	4205	1547	701	46.32	1.22	64.69	23.80	10.78
MR	2009	4031	147	45	15.39	346	2807	95	6854	2494	849	43.19	1.46	88.08	32.04	10.91
MR	2009	4032	147	90	12.85	348	3646	155	3286	2139	589	46.85	1.99	54.98	35.78	9.86
MR	2009	4033	147	0	16.73	352	3263	111	2230	1791	583	54.59	1.86	47.56	38.21	12.43
MR	2009	4034	147	135	21.33	332	2614	74	4505	1826	902	55.75	1.57	67.04	27.17	13.42
MR	2009	4041	294	90	14.88	345	2752	113	3107	1950	697	40.95	1.69	57.96	36.39	13.01
MR	2009	4042	294	0	18.66	358	2798	100	2835	1889	668	52.20	1.87	41.10	27.38	9.68
MR	2009	4043	294	135	14.50	356	2913	99	3695	1892	665	42.23	1.43	66.39	33.98	11.95
MR	2009	4044	294	45	17.97	346	2625	82	-	-	-	47.15	1.47	-	-	-

Site	Year	Plot	P rate	N rate	DM	Height	Plant tissue concentrations mg kg^{-1}					Removal rates kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
MR	2010	1011	0	135	16.46	325	2231	146	3548	1307	644	36.72	2.40	58.40	21.52	10.60
MR	2010	1012	0	45	16.57	320	1738	156	3498	1307	613	28.80	2.59	57.98	21.66	10.16
MR	2010	1013	0	90	15.41	305	1743	125	2799	1601	709	26.87	1.93	43.15	24.68	10.93
MR	2010	1014	0	0	14.15	328	1501	202	4037	1302	452	21.24	2.86	57.13	18.42	6.40
MR	2010	1021	294	45	12.40	338	1723	219	3652	920	576	21.37	2.71	45.29	11.40	7.15
MR	2010	1022	294	0	14.59	348	1560	256	3372	1114	397	22.77	3.74	49.20	16.26	5.80
MR	2010	1023	294	135	17.14	318	1905	98	3019	1154	756	32.65	1.69	51.75	19.78	12.96
MR	2010	1024	294	90	14.71	313	2061	165	3126	1635	643	30.31	2.42	45.98	24.04	9.45
MR	2010	1031	147	0	23.95	350	1627	353	3150	1433	512	38.98	8.45	75.46	34.31	12.26
MR	2010	1032	147	90	-	333	1528	122	3281	1392	487	-	-	-	-	-
MR	2010	1033	147	45	19.42	327	1599	129	3366	987	416	31.05	2.50	65.37	19.17	8.08
MR	2010	1034	147	135	12.02	275	2345	193	4664	1692	666	28.17	2.32	56.04	20.33	8.01
MR	2010	1041	441	90	21.13	350	1783	173	4259	1324	457	37.68	3.66	90.00	27.97	9.65
MR	2010	1042	441	135	-	-	2779	194	5324	1784	745	-	-	-	-	-
MR	2010	1043	441	45	14.92	320	1742	320	3171	1400	649	26.00	4.77	47.31	20.88	9.69
MR	2010	1044	441	0	16.51	330	1732	540	4898	1296	590	28.60	8.92	80.86	21.40	9.74
MR	2010	2011	147	45	19.82	343	2059	204	3491	1683	847	40.81	4.04	69.20	33.35	16.79
MR	2010	2012	147	90	21.80	390	2357	201	4851	2018	800	51.38	4.37	105.75	43.99	17.45
MR	2010	2013	147	135	22.40	397	2460	151	4181	1349	653	55.09	3.39	93.64	30.21	14.62
MR	2010	2014	147	0	-	-	-	-	-	-	-	-	-	-	-	-
MR	2010	2021	294	0	14.87	360	1657	694	2361	1669	818	24.63	10.32	35.09	24.81	12.17
MR	2010	2022	294	45	15.46	345	1396	462	2293	1185	713	21.57	7.14	35.43	18.31	11.02
MR	2010	2023	294	90	22.27	363	2159	169	3733	1680	802	48.09	3.77	83.15	37.41	17.86
MR	2010	2024	294	135	18.55	358	2191	167	4540	1552	611	40.64	3.10	84.21	28.78	11.34
MR	2010	2031	441	90	-	415	1942	193	3006	1332	688	-	-	-	-	-
MR	2010	2032	441	135	14.36	330	2020	112	4388	1179	709	29.01	1.61	63.02	16.93	10.19

Site	Year	Plot	P rate	N rate	DM	Height	Plant tissue concentrations mg kg^{-1}					Removal rates kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
MR	2010	2033	441	0	22.63	380	1894	450	3451	1751	630	42.87	10.19	78.09	39.63	14.25
MR	2010	2034	441	45	28.61	383	1715	299	3751	1545	528	49.06	8.54	107.34	44.21	15.11
MR	2010	2041	0	45	22.31	368	1924	112	3866	1706	602	42.93	2.50	86.25	38.05	13.44
MR	2010	2042	0	0	-	340	1665	110	4234	1338	434	-	-	-	-	-
MR	2010	2043	0	90	22.19	363	1911	132	4899	1742	684	42.42	2.92	108.72	38.65	15.19
MR	2010	2044	0	135	22.13	358	2006	124	3475	1476	700	44.41	2.75	76.91	32.68	15.48
MR	2010	3011	147	135	23.66	380	1814	101	3431	1340	525	42.93	2.39	81.19	31.71	12.42
MR	2010	3012	147	45	15.55	420	1701	97	3941	1426	515	26.45	1.51	61.27	22.18	8.00
MR	2010	3013	147	0	-	-	-	-	-	-	-	-	-	-	-	-
MR	2010	3014	147	90	20.96	375	1665	144	3358	1598	711	34.90	3.01	70.37	33.49	14.90
MR	2010	3021	0	45	23.04	400	1503	83	4405	1264	407	34.63	1.90	101.47	29.13	9.38
MR	2010	3022	0	0	27.28	418	1449	88	3106	1576	467	39.53	2.40	84.72	42.98	12.75
MR	2010	3023	0	90	16.44	385	1578	61	3096	1271	531	25.95	1.01	50.91	20.90	8.73
MR	2010	3024	0	135	13.94	360	1550	75	4680	1020	460	21.61	1.05	65.23	14.22	6.42
MR	2010	3031	441	0	19.68	408	1295	414	4791	1262	410	25.49	8.14	94.28	24.84	8.06
MR	2010	3032	441	90	-	390	1605	131	4449	1330	441	-	-	-	-	-
MR	2010	3033	441	135	28.78	375	1936	139	3966	1646	600	55.72	4.00	114.16	47.39	17.28
MR	2010	3034	441	45	26.16	375	2138	194	2863	1093	571	55.94	5.07	74.90	28.60	14.94
MR	2010	3041	294	135	19.59	385	1628	110	4296	1244	567	31.89	2.15	84.13	24.36	11.11
MR	2010	3042	294	45	22.45	393	1507	167	4082	1388	407	33.84	3.74	91.65	31.17	9.14
MR	2010	3043	294	0	-	390	1503	381	4802	1340	409	-	-	-	-	-
MR	2010	3044	294	90	23.99	370	1535	122	2700	1328	468	36.83	2.93	64.77	31.85	11.24
MR	2010	4011	441	135	23.81	378	1566	100	3760	1221	484	37.29	2.38	89.51	29.07	11.52
MR	2010	4012	441	0	17.17	405	1408	160	4116	1180	298	24.16	2.75	70.64	20.25	5.11
MR	2010	4013	441	45	26.17	385	2113	197	3778	2067	560	55.30	5.15	98.85	54.08	14.65
MR	2010	4014	441	90	24.57	353	1538	104	3696	1187	343	37.77	2.56	90.80	29.15	8.43

Site	Year	Plot	P rate	N rate	DM	Height	Plant tissue concentrations mg kg^{-1}					Removal rates kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
MR	2010	4021	0	0	26.83	395	1372	75	3682	1287	398	36.80	2.00	98.79	34.54	10.67
MR	2010	4022	0	135	-	375	1693	77	-	-	-	-	-	-	-	-
MR	2010	4023	0	90	24.64	385	1391	58	4003	1236	380	34.27	1.42	98.64	30.46	9.37
MR	2010	4024	0	45	20.47	393	1441	92	3542	1113	306	29.49	1.88	72.51	22.77	6.26
MR	2010	4031	147	45	22.93	403	2117	121	3746	1174	489	48.56	2.77	85.90	26.94	11.21
MR	2010	4032	147	90	20.12	398	1603	133	5077	1492	560	32.26	2.67	102.15	30.02	11.28
MR	2010	4033	147	0	23.40	390	1997	107	4191	1179	359	46.74	2.50	98.08	27.60	8.41
MR	2010	4034	147	135	23.92	368	1820	126	4176	1547	470	43.54	3.02	99.89	37.00	11.24
MR	2010	4041	294	90	21.80	385	1830	337	4193	1229	544	39.90	7.35	91.42	26.80	11.87
MR	2010	4042	294	0	22.00	393	1698	113	3853	1721	621	37.36	2.49	84.78	37.87	13.66
MR	2010	4043	294	135	19.98	373	1277	94	3727	1089	428	25.52	1.89	74.45	21.75	8.55
MR	2010	4044	294	45	20.34	373	1300	100	3868	954	277	26.44	2.03	78.67	19.41	5.62
OX	2009	5011	0	135	0.33	-	4837	208	2456	3811	949	1.58	0.07	0.80	1.24	0.31
OX	2009	5012	0	45	0.34	-	7098	233	2221	3690	872	2.43	0.08	0.76	1.26	0.30
OX	2009	5013	0	90	0.38	-	5985	184	2500	3322	1154	2.26	0.07	0.94	1.26	0.44
OX	2009	5014	0	0	0.16	-	7498	230	2215	3394	924	1.16	0.04	0.34	0.53	0.14
OX	2009	5021	294	45	-	-	-	-	2654	2996	784	-	-	1.08	1.22	0.32
OX	2009	5022	294	0	0.41	-	8151	233	2589	3673	1132	3.31	0.09	0.76	1.08	0.33
OX	2009	5023	294	135	0.29	-	7296	272	2875	3338	1019	2.14	0.08	0.59	0.68	0.21
OX	2009	5024	294	90	0.20	-	6412	245	2194	4189	1083	1.31	0.05	0.85	1.63	0.42
OX	2009	5031	147	0	0.39	-	9574	255	2350	4318	1188	3.72	0.10	0.87	1.61	0.44
OX	2009	5032	147	90	0.37	-	9120	253	2013	3833	1018	3.39	0.09	0.37	0.71	0.19
OX	2009	5033	147	45	0.19	-	9364	285	2288	3472	1019	1.74	0.05	0.51	0.78	0.23
OX	2009	5034	147	135	0.22	-	7257	239	2289	3794	1071	1.63	0.05	1.62	2.68	0.76
OX	2009	5041	441	90	0.71	-	8104	233	2094	4174	1275	5.72	0.16	0.84	1.68	0.51
OX	2009	5042	441	135	0.40	-	9672	288	1847	3218	870	3.90	0.12	0.57	1.00	0.27

Site	Year	Plot	P rate	N rate	DM	Height	Plant tissue concentrations mg kg^{-1}					Removal rates kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
OX	2009	5043	441	45	0.31	-	7384	218	2829	3426	902	2.29	0.07	0.42	0.51	0.13
OX	2009	5044	441	0	0.15	-	6958	328	1834	3798	1068	1.03	0.05	0.74	1.53	0.43
OX	2009	6011	147	45	0.40	-	7141	248	2009	3421	1077	2.87	0.10	1.00	1.70	0.53
OX	2009	6012	147	90	0.50	-	7583	337	2363	3520	1104	3.76	0.17	0.65	0.96	0.30
OX	2009	6013	147	135	0.27	-	7278	236	2473	3202	770	1.99	0.06	0.41	0.53	0.13
OX	2009	6014	147	0	0.16	-	7838	225	2692	3800	999	1.29	0.04	0.73	1.02	0.27
OX	2009	6021	294	0	0.27	-	6877	253	1920	4328	1195	1.85	0.07	0.82	1.84	0.51
OX	2009	6022	294	45	0.43	-	9180	270	2605	3620	1000	3.91	0.11	0.74	1.03	0.28
OX	2009	6023	294	90	0.28	-	8631	223	2096	3251	1002	2.45	0.06	0.41	0.64	0.20
OX	2009	6024	294	135	0.20	-	7567	222	1884	3604	988	1.49	0.04	0.91	1.74	0.48
OX	2009	6031	441	90	0.48	-	8103	270	2013	3837	1214	3.91	0.13	0.72	1.36	0.43
OX	2009	6032	441	135	0.36	-	8048	280	2468	4320	956	2.86	0.10	0.74	1.30	0.29
OX	2009	6033	441	0	0.30	-	5810	171	2462	3362	1010	1.75	0.05	0.45	0.61	0.18
OX	2009	6034	441	45	0.18	-	8012	265	2239	3171	784	1.45	0.05	0.85	1.21	0.30
OX	2009	6041	0	45	0.38	-	7562	281	2451	3990	1040	2.87	0.11	0.82	1.34	0.35
OX	2009	6042	0	0	0.34	-	8187	260	2243	3738	1043	2.75	0.09	0.41	0.69	0.19
OX	2009	6043	0	90	0.18	-	7423	274	2499	3770	1094	1.37	0.05	0.68	1.03	0.30
OX	2009	6044	0	135	0.27	-	5668	237	2394	3825	978	1.55	0.06	1.56	2.49	0.64
OX	2009	7011	147	135	0.65	-	4946	234	1954	3627	1036	3.22	0.15	0.42	0.77	0.22
OX	2009	7012	147	45	0.21	-	8001	315	2375	3602	966	1.71	0.07	0.69	1.05	0.28
OX	2009	7013	147	0	0.29	-	9151	257	2261	3999	970	2.67	0.08	0.63	1.12	0.27
OX	2009	7014	147	90	0.28	-	8490	242	2879	3659	1008	2.38	0.07	1.54	1.95	0.54
OX	2009	7021	0	45	0.53	-	7157	214	1945	3603	855	3.82	0.11	0.99	1.83	0.43
OX	2009	7022	0	0	0.51	-	7835	214	1962	3731	933	3.99	0.11	0.77	1.47	0.37
OX	2009	7023	0	90	0.39	-	8631	243	2952	3809	1059	3.40	0.10	1.62	2.10	0.58
OX	2009	7024	0	135	0.55	-	7411	247	2786	3819	1062	4.08	0.14	1.46	2.01	0.56

Site	Year	Plot	P rate	N rate	DM	Height	Plant tissue concentrations					Removal rates				
							mg kg^{-1}					kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	N	P	K	Ca	Mg	N	P	K	Ca	Mg
OX	2009	7031	441	0	0.53	-	8863	273	2517	4098	1169	4.65	0.14	1.42	2.31	0.66
OX	2009	7032	441	90	0.56	-	10773	291	3081	4167	1205	6.07	0.16	1.07	1.45	0.42
OX	2009	7033	441	135	0.35	-	10714	376	2960	3800	1012	3.72	0.13	0.80	1.03	0.27
OX	2009	7034	441	45	0.27	-	10180	355	2507	3769	1101	2.77	0.10	1.63	2.44	0.71
OX	2009	7041	294	135	0.65	-	8507	261	2790	3490	1025	5.52	0.17	1.51	1.89	0.55
OX	2009	7042	294	45	0.54	-	7162	222	2332	4056	946	3.88	0.12	0.65	1.13	0.26
OX	2009	7043	294	0	0.28	-	9311	288	2223	3683	1003	2.59	0.08	0.27	0.45	0.12
OX	2009	7044	294	90	0.12	-	9172	330	2060	3570	955	1.13	0.04	1.13	1.96	0.52
OX	2009	8011	441	135	0.55	-	6216	294	2416	3560	885	3.41	0.16	1.09	1.60	0.40
OX	2009	8012	441	0	0.45	-	4766	290	2636	3209	871	2.14	0.13	0.87	1.06	0.29
OX	2009	8013	441	45	0.33	-	6964	234	2175	3300	813	2.29	0.08	0.79	1.19	0.29
OX	2009	8014	441	90	0.36	-	6119	225	2684	2748	888	2.22	0.08	1.02	1.05	0.34
OX	2009	8021	0	0	0.38	-	4845	143	1988	3585	1079	1.85	0.05	1.06	1.92	0.58
OX	2009	8022	0	135	0.53	-	7746	213	2082	3509	929	4.14	0.11	0.87	1.46	0.39
OX	2009	8023	0	90	0.42	-	6043	195	2668	3796	884	2.51	0.08	1.04	1.48	0.34
OX	2009	8024	0	45	0.39	-	6380	263	2172	3622	1016	2.49	0.10	0.88	1.46	0.41
OX	2009	8031	147	45	0.40	-	7280	237	2194	3823	1076	2.94	0.10	1.04	1.82	0.51
OX	2009	8032	147	90	0.48	-	8237	257	2674	4112	1006	3.91	0.12	0.58	0.89	0.22
OX	2009	8033	147	0	0.22	-	8500	269	2661	4156	1091	1.84	0.06	1.68	2.62	0.69
OX	2009	8034	147	135	0.63	-	6549	215	1695	4130	1137	4.13	0.14	0.79	1.94	0.53
OX	2009	8041	294	90	0.47	-	8217	241	2246	3941	870	3.85	0.11	0.97	1.70	0.37
OX	2009	8042	294	0	0.43	-	8178	231	2611	3823	1062	3.52	0.10	1.52	2.22	0.62
OX	2009	8043	294	135	0.58	-	7701	239	2503	4213	1012	4.47	0.14	0.82	1.38	0.33
OX	2009	8044	294	45	0.33	-	9943	366	-	-	-	3.25	0.12	-	-	-
OX	2010	5011	0	135	5.22	203	3227	139	2990	2645	964	16.83	0.72	15.59	13.80	5.03
OX	2010	5012	0	45	5.32	210	2129	163	3476	2270	815	11.33	0.87	18.50	12.08	4.34

Site	Year	Plot	P rate	N rate	DM	Height	Plant tissue concentrations					Removal rates				
							mg kg^{-1}					kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
OX	2010	5013	0	90	7.43	238	2036	112	3570	1727	916	15.14	0.83	26.54	12.84	6.81
OX	2010	5014	0	0	5.86	200	1831	238	2962	1652	722	10.72	1.39	17.34	9.68	4.23
OX	2010	5021	294	45	9.85	298	1760	101	2633	1515	724	17.34	1.00	25.94	14.92	7.13
OX	2010	5022	294	0	6.85	275	1951	469	3008	2069	869	13.36	3.21	20.61	14.17	5.95
OX	2010	5023	294	135	3.41	248	2740	137	3315	1941	846	9.33	0.47	11.29	6.61	2.88
OX	2010	5024	294	90	8.22	258	1676	127	3091	1333	701	13.77	1.05	25.40	10.95	5.76
OX	2010	5031	147	0	9.60	308	1585	151	2729	1233	664	15.22	1.45	26.20	11.84	6.38
OX	2010	5032	147	90	9.44	265	2019	121	3138	1481	730	19.05	1.14	29.60	13.97	6.89
OX	2010	5033	147	45	7.88	308	1862	217	3252	1466	701	14.68	1.71	25.63	11.56	5.53
OX	2010	5034	147	135	5.27	225	2190	150	3562	1504	841	11.55	0.79	18.78	7.93	4.44
OX	2010	5041	441	90	17.58	305	2582	129	3387	2024	1084	45.40	2.26	59.55	35.58	19.05
OX	2010	5042	441	135	17.68	285	2156	131	2864	1805	1034	38.12	2.32	50.63	31.91	18.28
OX	2010	5043	441	45	5.92	215	2776	229	2469	2380	946	16.43	1.36	14.62	14.09	5.60
OX	2010	5044	441	0	3.33	215	2249	1042	3140	2112	786	7.48	3.47	10.45	7.03	2.62
OX	2010	6011	147	45	11.52	303	2022	100	2446	1775	1025	23.30	1.15	28.19	20.46	11.81
OX	2010	6012	147	90	12.76	313	1981	136	2888	1693	1025	25.27	1.74	36.84	21.59	13.07
OX	2010	6013	147	135	7.40	213	2320	161	3072	1867	1147	17.17	1.19	22.74	13.82	8.49
OX	2010	6014	147	0	2.33	220	2046	791	3437	2044	822	4.76	1.84	8.00	4.76	1.91
OX	2010	6021	294	0	7.92	275	1727	276	2438	1844	948	13.69	2.19	19.31	14.61	7.51
OX	2010	6022	294	45	8.47	278	1429	130	2569	2034	1186	12.10	1.10	21.75	17.23	10.04
OX	2010	6023	294	90	3.88	190	1959	194	2812	2104	1117	7.60	0.75	10.92	8.17	4.34
OX	2010	6024	294	135	6.79	210	1533	166	3132	1933	943	10.41	1.12	21.27	13.13	6.40
OX	2010	6031	441	90	12.06	278	1558	146	3080	2147	1124	18.79	1.76	37.14	25.89	13.55
OX	2010	6032	441	135	8.90	260	2715	181	3177	2387	1202	24.17	1.61	28.29	21.26	10.70
OX	2010	6033	441	0	5.51	248	1895	379	3632	1957	823	10.43	2.09	20.00	10.77	4.53
OX	2010	6034	441	45	5.80	228	1953	215	3305	1956	936	11.33	1.25	19.17	11.34	5.43

Site	Year	Plot	P rate	N rate	DM	Height	Plant tissue concentrations					Removal rates				
							mg kg^{-1}					kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
OX	2010	6041	0	45	8.62	240	2306	101	2905	2447	1043	19.87	0.87	25.03	21.09	8.99
OX	2010	6042	0	0	7.48	255	2509	139	2463	2568	1063	18.76	1.04	18.42	19.20	7.95
OX	2010	6043	0	90	5.28	213	3046	140	2581	2780	1368	16.09	0.74	13.63	14.68	7.23
OX	2010	6044	0	135	5.72	233	2718	123	2964	2039	1101	15.54	0.70	16.96	11.66	6.30
OX	2010	7011	147	135	10.36	280	2835	141	3832	2190	1140	29.37	1.46	39.69	22.68	11.81
OX	2010	7012	147	45	10.11	278	2563	161	3147	2645	1104	25.92	1.63	31.83	26.75	11.17
OX	2010	7013	147	0	5.41	270	1852	234	3228	1964	998	10.02	1.27	17.46	10.62	5.40
OX	2010	7014	147	90	8.13	243	2195	129	3677	1733	1067	17.84	1.04	29.89	14.09	8.68
OX	2010	7021	0	45	8.36	283	1853	81	2601	1632	726	15.50	0.68	21.76	13.65	6.07
OX	2010	7022	0	0	6.59	275	2018	169	2921	1994	701	13.31	1.11	19.26	13.14	4.62
OX	2010	7023	0	90	8.71	313	1949	136	4000	1669	907	16.97	1.18	34.83	14.53	7.89
OX	2010	7024	0	135	10.95	298	2038	141	4344	1932	1182	22.32	1.54	47.58	21.16	12.94
OX	2010	7031	441	0	5.68	260	1882	291	3115	1672	725	10.70	1.65	17.70	9.50	4.12
OX	2010	7032	441	90	10.64	258	2001	169	4038	1782	872	21.28	1.80	42.95	18.95	9.28
OX	2010	7033	441	135	11.66	310	1968	178	4304	1655	847	22.95	2.07	50.19	19.30	9.88
OX	2010	7034	441	45	10.78	275	1583	276	3495	1681	818	17.06	2.98	37.68	18.11	8.82
OX	2010	7041	294	135	10.92	295	2249	104	3220	1290	765	24.57	1.13	35.17	14.09	8.36
OX	2010	7042	294	45	12.53	340	1749	180	3581	1426	803	21.92	2.25	44.87	17.87	10.06
OX	2010	7043	294	0	6.52	273	1501	559	2845	1604	694	9.79	3.65	18.55	10.46	4.52
OX	2010	7044	294	90	5.65	250	1782	372	3053	1701	864	10.07	2.10	17.25	9.61	4.88
OX	2010	8011	441	135	15.58	318	2079	128	3401	1581	998	32.40	1.99	52.99	24.63	15.56
OX	2010	8012	441	0	8.63	278	1498	736	2858	1921	729	12.92	6.35	24.66	16.58	6.29
OX	2010	8013	441	45	9.31	310	1509	484	2708	1571	686	14.05	4.51	25.22	14.63	6.38
OX	2010	8014	441	90	6.46	243	1613	461	2831	1622	761	10.42	2.98	18.28	10.47	4.91
OX	2010	8021	0	0	6.95	265	1664	149	3261	1956	750	11.56	1.03	22.66	13.59	5.21
OX	2010	8022	0	135	12.53	275	2040	125	3272	2126	830	25.55	1.56	40.98	26.63	10.40

Site	**Year**	**Plot**	**P rate**	**N rate**	**DM**	**Height**	**Plant tissue concentrations** mg kg^{-1}					**Removal rates** kg ha^{-1}				
			kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	cm	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
OX	2010	8023	0	90	11.63	313	1629	109	2827	1591	700	18.95	1.27	32.88	18.51	8.14
OX	2010	8024	0	45	5.76	263	1497	153	3149	1596	689	8.62	0.88	18.13	9.19	3.97
OX	2010	8031	147	45	9.45	270	1700	165	3198	1584	882	16.07	1.56	30.24	14.97	8.33
OX	2010	8032	147	90	8.10	278	1976	171	3129	2120	880	16.00	1.39	25.33	17.17	7.13
OX	2010	8033	147	0	4.47	253	1519	454	3265	2035	770	6.80	2.03	14.61	9.10	3.44
OX	2010	8034	147	135	14.89	320	2022	132	3913	1684	776	30.11	1.96	58.26	25.08	11.56
OX	2010	8041	294	90	8.14	220	2165	141	2483	1879	1242	17.62	1.15	20.21	15.29	10.11
OX	2010	8042	294	0	8.43	260	1537	482	3052	1632	784	12.96	4.07	25.74	13.77	6.62
OX	2010	8043	294	135	14.33	315	1929	110	2867	1745	945	27.65	1.57	41.08	25.00	13.54
OX	2010	8044	294	45	10.57	303	1674	143	2755	1687	761	17.70	1.51	29.12	17.83	8.04

Table A.2 Site, year, plot, P fertilizer treatment, N fertilizer treatment, and N and P concentrations at 0-20, 20-41, 41-61, and 61-91 cm depths.

					Hand-sampled		**Giddings probe-sampled**						
Site	**Year**	**Plot**	**P rate**	**N rate**	**N**	**P**	**N**				**P**		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
MR	2008	1011	0	135	16.05	42.04	-	13.34	-	-	15.56	-	-
MR	2008	1023	294	135	17.38	33.16	-	7.17	-	-	8.14	-	-
MR	2008	1034	147	135	15.30	35.14	-	8.55	-	-	10.40	-	-
MR	2008	1042	441	135	20.18	43.07	-	12.75	-	-	20.19	-	-
MR	2008	2013	147	135	11.94	58.49	-	7.41	-	-	8.99	-	-
MR	2008	2024	294	135	11.37	57.31	-	6.43	4.71	5.02	4.31	0.82	0.82
MR	2008	2032	441	135	12.38	45.32	-	4.14	4.52	5.23	1.88	0.22	0.52
MR	2008	2044	0	135	9.96	34.34	-	5.98	3.69	3.95	1.68	0.43	0.11
MR	2008	3011	147	135	14.85	14.76	-	6.56	4.02	2.87	2.32	0.75	0.74

Site	Year	Plot	P rate	N rate	Hand-sampled N	Hand-sampled P	Giddings probe-sampled N				Giddings probe-sampled P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
MR	2008	3024	0	135	12.91	12.42	-	6.59	3.69	2.59	1.00	0.45	0.94
MR	2008	3033	441	135	13.44	14.12	-	6.18	3.82	2.14	1.67	0.78	0.63
MR	2008	3041	294	135	18.11	14.46	-	7.21	4.23	2.64	1.10	0.67	0.42
MR	2008	4011	441	135	18.83	13.81	-	13.03	5.36	3.48	3.09	0.88	0.53
MR	2008	4022	0	135	15.77	12.50	-	8.49	3.67	3.31	1.74	0.78	0.86
MR	2008	4034	147	135	16.96	13.05	-	9.14	5.34	4.65	2.96	0.67	0.66
MR	2008	4043	294	135	19.21	27.13	-	8.29	5.00	4.41	3.52	0.96	0.87
MR	2009	1011	0	135	15.19	45.49	-	15.66	-	-	21.47	-	-
MR	2009	1012	0	45	12.80	44.26	-	-	-	-	-	-	-
MR	2009	1013	0	90	11.84	32.64	-	-	-	-	-	-	-
MR	2009	1014	0	0	12.79	52.48	-	-	-	-	-	-	-
MR	2009	1021	294	45	11.66	184.31	-	-	-	-	-	-	-
MR	2009	1022	294	0	11.18	117.71	-	-	-	-	-	-	-
MR	2009	1023	294	135	14.96	86.83	-	11.60	-	-	7.07	-	-
MR	2009	1024	294	90	15.36	119.44	-	-	-	-	-	-	-
MR	2009	1031	147	0	11.90	60.00	-	-	-	-	-	-	-
MR	2009	1032	147	90	12.48	52.77	-	-	-	-	-	-	-
MR	2009	1033	147	45	11.77	50.00	-	-	-	-	-	-	-
MR	2009	1034	147	135	17.77	51.33	-	10.06	-	-	27.10	-	-
MR	2009	1041	441	90	13.99	119.41	-	-	-	-	-	-	-
MR	2009	1042	441	135	11.58	103.93	-	11.71	-	-	10.46	-	-
MR	2009	1043	441	45	11.82	186.02	-	-	-	-	-	-	-
MR	2009	1044	441	0	13.74	129.52	-	-	-	-	-	-	-
MR	2009	2011	147	45	12.46	92.55	-	-	-	-	-	-	-

					Hand-sampled		Giddings probe-sampled						
Site	**Year**	**Plot**	**P rate**	**N rate**	**N**	**P**	**N**				**P**		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
MR	2009	2012	147	90	13.57	83.50	-	-	-	-	-	-	-
MR	2009	2013	147	135	14.65	97.03	-	17.68	34.03	22.43	3.65	1.85	0.94
MR	2009	2014	147	0	13.19	85.05	-	-	-	-	-	-	-
MR	2009	2021	294	0	11.77	124.44	-	-	-	-	-	-	-
MR	2009	2022	294	45	11.36	130.09	-	-	-	-	-	-	-
MR	2009	2023	294	90	15.06	108.79	-	-	-	-	-	-	-
MR	2009	2024	294	135	17.49	99.33	-	13.58	34.52	23.84	3.44	2.21	1.16
MR	2009	2031	441	90	14.89	165.05	-	-	-	-	-	-	-
MR	2009	2032	441	135	19.57	147.42	-	15.90	18.70	21.39	9.04	0.85	0.72
MR	2009	2033	441	0	24.03	201.10	-	-	-	-	-	-	-
MR	2009	2034	441	45	18.52	212.57	-	-	-	-	-	-	-
MR	2009	2041	0	45	15.81	32.22	-	-	-	-	-	-	-
MR	2009	2042	0	0	18.81	24.90	-	-	-	-	-	-	-
MR	2009	2043	0	90	16.42	77.25	-	-	-	-	-	-	-
MR	2009	2044	0	135	13.94	88.50	-	15.56	14.91	8.51	2.38	0.59	0.51
MR	2009	3011	147	135	11.80	60.20	-	21.70	23.00	7.50	1.08	0.63	0.95
MR	2009	3012	147	45	17.57	81.68	-	-	-	-	-	-	-
MR	2009	3013	147	0	16.91	65.86	-	-	-	-	-	-	-
MR	2009	3014	147	90	16.05	87.90	-	-	-	-	-	-	-
MR	2009	3021	0	45	13.27	24.48	-	-	-	-	-	-	-
MR	2009	3022	0	0	12.64	6.00	-	-	-	-	-	-	-
MR	2009	3023	0	90	12.13	28.73	-	-	-	-	-	-	-
MR	2009	3024	0	135	12.99	28.00	-	18.53	26.08	26.67	1.61	1.09	0.74
MR	2009	3031	441	0	20.31	120.63	-	-	-	-	-	-	-

					Hand-sampled		Giddings probe-sampled						
Site	**Year**	**Plot**	**P rate**	**N rate**	**N**	**P**	**N**				**P**		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
MR	2009	3032	441	90	16.69	102.29	-	-	-	-	-	-	-
MR	2009	3033	441	135	20.58	136.11	-	14.98	18.60	12.27	2.99	0.73	0.62
MR	2009	3034	441	45	26.73	165.83	-	-	-	-	-	-	-
MR	2009	3041	294	135	14.81	166.63	-	19.01	11.14	5.41	0.99	0.44	0.44
MR	2009	3042	294	45	20.60	108.02	-	-	-	-	-	-	-
MR	2009	3043	294	0	21.79	81.96	-	-	-	-	-	-	-
MR	2009	3044	294	90	14.58	83.33	-	-	-	-	-	-	-
MR	2009	4011	441	135	15.45	153.04	-	30.79	35.74	19.88	1.46	0.99	0.83
MR	2009	4012	441	0	12.50	110.43	-	-	-	-	-	-	-
MR	2009	4013	441	45	18.42	132.53	-	-	-	-	-	-	-
MR	2009	4014	441	90	15.77	104.59	-	-	-	-	-	-	-
MR	2009	4021	0	0	12.50	20.79	-	-	-	-	-	-	-
MR	2009	4022	0	135	21.67	12.99	-	13.84	22.00	11.80	1.91	0.69	0.89
MR	2009	4023	0	90	17.34	16.19	-	-	-	-	-	-	-
MR	2009	4024	0	45	17.87	14.06	-	-	-	-	-	-	-
MR	2009	4031	147	45	16.60	62.55	-	-	-	-	-	-	-
MR	2009	4032	147	90	23.23	50.33	-	-	-	-	-	-	-
MR	2009	4033	147	0	14.38	29.18	-	-	-	-	-	-	-
MR	2009	4034	147	135	19.03	42.60	-	11.70	18.44	13.74	1.81	0.54	0.71
MR	2009	4041	294	90	13.23	66.46	-	-	-	-	-	-	-
MR	2009	4042	294	0	13.63	112.32	-	-	-	-	-	-	-
MR	2009	4043	294	135	25.29	117.90	-	10.69	17.64	13.09	2.17	0.59	0.61
MR	2009	4044	294	45	14.13	176.89	-	-	-	-	-	-	-
MR	2010	1011	0	135	9.17	41.46	-	6.37	-	-	12.41	-	-

					Hand-sampled		Giddings probe-sampled						
Site	Year	Plot	P rate	N rate	N	P	N				P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
MR	2010	1012	0	45	8.68	37.56	-	-	-	-	-	-	-
MR	2010	1013	0	90	8.44	41.77	-	-	-	-	-	-	-
MR	2010	1014	0	0	9.70	43.53	-	-	-	-	-	-	-
MR	2010	1021	294	45	9.92	126.67	-	-	-	-	-	-	-
MR	2010	1022	294	0	9.29	84.56	-	-	-	-	-	-	-
MR	2010	1023	294	135	13.05	96.70	-	7.51	-	-	7.43	-	-
MR	2010	1024	294	90	7.95	93.84	-	-	-	-	-	-	-
MR	2010	1031	147	0	7.53	63.81	-	-	-	-	-	-	-
MR	2010	1032	147	90	17.74	45.27	-	-	-	-	-	-	-
MR	2010	1033	147	45	9.09	32.41	-	-	-	-	-	-	-
MR	2010	1034	147	135	8.57	44.13	-	5.22	-	-	4.31	-	-
MR	2010	1041	441	90	8.83	130.00	-	-	-	-	-	-	-
MR	2010	1042	441	135	9.40	132.63	-	7.21	-	-	24.78	-	-
MR	2010	1043	441	45	6.73	117.01	-	-	-	-	-	-	-
MR	2010	1044	441	0	13.23	91.27	-	-	-	-	-	-	-
MR	2010	2011	147	45	12.30	87.57	-	-	-	-	-	-	-
MR	2010	2012	147	90	11.08	71.77	-	-	-	-	-	-	-
MR	2010	2013	147	135	9.07	56.03	-	5.88	5.67	17.35	2.24	0.83	0.95
MR	2010	2014	147	0	10.63	75.04	-	-	-	-	-	-	-
MR	2010	2021	294	0	8.21	98.89	-	-	-	-	-	-	-
MR	2010	2022	294	45	8.99	194.25	-	-	-	-	-	-	-
MR	2010	2023	294	90	10.61	137.05	-	-	-	-	-	-	-
MR	2010	2024	294	135	12.05	62.31	-	5.29	4.61	5.02	3.42	1.10	1.05
MR	2010	2031	441	90	10.08	181.19	-	-	-	-	-	-	-

Site	Year	Plot	P rate	N rate	Hand-sampled N	Hand-sampled P	Giddings probe-sampled N				Giddings probe-sampled P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
MR	2010	2032	441	135	10.32	204.48	-	6.52	4.90	12.67	3.17	1.30	1.67
MR	2010	2033	441	0	12.07	180.00	-	-	-	-	-	-	-
MR	2010	2034	441	45	8.40	196.47	-	-	-	-	-	-	-
MR	2010	2041	0	45	8.66	20.00	-	-	-	-	-	-	-
MR	2010	2042	0	0	8.24	13.02	-	-	-	-	-	-	-
MR	2010	2043	0	90	10.66	30.90	-	-	-	-	-	-	-
MR	2010	2044	0	135	7.70	66.06	-	4.33	3.36	18.63	1.98	0.66	0.57
MR	2010	3011	147	135	9.88	39.91	-	3.95	7.44	6.98	1.75	0.81	0.78
MR	2010	3012	147	45	10.80	33.05	-	-	-	-	-	-	-
MR	2010	3013	147	0	11.93	57.96	-	-	-	-	-	-	-
MR	2010	3014	147	90	11.84	62.17	-	-	-	-	-	-	-
MR	2010	3021	0	45	8.96	18.60	-	-	-	-	-	-	-
MR	2010	3022	0	0	10.33	11.80	-	-	-	-	-	-	-
MR	2010	3023	0	90	9.91	13.87	-	-	-	-	-	-	-
MR	2010	3024	0	135	10.10	24.52	-	7.53	7.05	15.90	1.62	1.01	1.02
MR	2010	3031	441	0	7.83	65.62	-	-	-	-	-	-	-
MR	2010	3032	441	90	12.65	110.94	-	-	-	-	-	-	-
MR	2010	3033	441	135	8.16	80.72	-	5.49	6.16	7.11	1.43	0.92	1.12
MR	2010	3034	441	45	9.40	155.40	-	-	-	-	-	-	-
MR	2010	3041	294	135	9.60	41.27	-	8.77	3.81	4.67	1.55	1.17	0.71
MR	2010	3042	294	45	9.35	48.49	-	-	-	-	-	-	-
MR	2010	3043	294	0	12.22	40.46	-	-	-	-	-	-	-
MR	2010	3044	294	90	12.49	116.52	-	-	-	-	-	-	-
MR	2010	4011	441	135	11.85	242.45	-	6.43	10.41	4.07	2.35	1.29	1.94

					Hand-sampled		Giddings probe-sampled						
Site	**Year**	**Plot**	**P rate**	**N rate**	**N**	**P**	**N**				**P**		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
MR	2010	4012	441	0	8.47	94.95	-	-	-	-	-	-	-
MR	2010	4013	441	45	13.70	89.35	-	-	-	-	-	-	-
MR	2010	4014	441	90	10.36	64.77	-	-	-	-	-	-	-
MR	2010	4021	0	0	9.17	13.63	-	-	-	-	-	-	-
MR	2010	4022	0	135	9.96	14.02	-	11.19	8.28	8.59	1.94	0.73	1.15
MR	2010	4023	0	90	8.96	7.52	-	-	-	-	-	-	-
MR	2010	4024	0	45	12.06	12.10	-	-	-	-	-	-	-
MR	2010	4031	147	45	11.28	81.98	-	-	-	-	-	-	-
MR	2010	4032	147	90	12.50	52.37	-	-	-	-	-	-	-
MR	2010	4033	147	0	10.86	31.16	-	-	-	-	-	-	-
MR	2010	4034	147	135	13.52	33.36	-	5.00	2.62	3.34	2.41	0.61	1.19
MR	2010	4041	294	90	8.90	97.31	-	-	-	-	-	-	-
MR	2010	4042	294	0	8.67	109.91	-	-	-	-	-	-	-
MR	2010	4043	294	135	15.58	96.61	-	5.43	3.60	3.27	4.38	1.12	0.58
MR	2010	4044	294	45	11.29	107.86	-	-	-	-	-	-	-
MR	2011	1011	0	135	10.54	30.69	6.43	4.86	-	-	9.68	-	-
MR	2011	1012	0	45	6.61	38.09	-	-	-	-	-	-	-
MR	2011	1013	0	90	6.93	29.83	-	-	-	-	-	-	-
MR	2011	1014	0	0	8.00	48.48	-	-	-	-	-	-	-
MR	2011	1021	294	45	8.21	98.77	-	-	-	-	-	-	-
MR	2011	1022	294	0	7.02	77.09	-	-	-	-	-	-	-
MR	2011	1023	294	135	7.00	49.74	7.81	6.21	-	-	12.26	-	-
MR	2011	1024	294	90	7.04	65.57	-	-	-	-	-	-	-
MR	2011	1031	147	0	5.01	63.21	-	-	-	-	-	-	-

Site	Year	Plot	P rate	N rate	Hand-sampled		Giddings probe-sampled						
					N	P	N				P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
MR	2011	1032	147	90	4.35	42.12	-	-	-	-	-	-	-
MR	2011	1033	147	45	4.65	29.17	-	-	-	-	-	-	-
MR	2011	1034	147	135	5.20	39.04	5.14	4.97	-	-	11.90	-	-
MR	2011	1041	441	90	3.99	136.35	-	-	-	-	-	-	-
MR	2011	1042	441	135	5.62	132.13	8.29	4.95	-	-	23.04	-	-
MR	2011	1043	441	45	4.17	94.41	-	-	-	-	-	-	-
MR	2011	1044	441	0	3.38	88.48	-	-	-	-	-	-	-
MR	2011	2011	147	45	4.32	88.57	-	-	-	-	-	-	-
MR	2011	2012	147	90	5.66	66.95	-	-	-	-	-	-	-
MR	2011	2013	147	135	6.55	53.25	5.18	4.70	3.78	26.21	4.73	1.49	1.33
MR	2011	2014	147	0	3.36	75.34	-	-	-	-	-	-	-
MR	2011	2021	294	0	2.58	147.79	-	-	-	-	-	-	-
MR	2011	2022	294	45	4.46	111.36	-	-	-	-	-	-	-
MR	2011	2023	294	90	5.78	93.45	-	-	-	-	-	-	-
MR	2011	2024	294	135	2.82	124.48	6.57	4.91	3.26	10.37	2.35	1.00	0.80
MR	2011	2031	441	90	5.58	173.28	-	-	-	-	-	-	-
MR	2011	2032	441	135	8.70	168.02	8.33	10.82	21.78	25.30	1.01	0.71	0.76
MR	2011	2033	441	0	8.67	202.27	-	-	-	-	-	-	-
MR	2011	2034	441	45	2.53	176.78	-	-	-	-	-	-	-
MR	2011	2041	0	45	6.34	14.12	-	-	-	-	-	-	-
MR	2011	2042	0	0	6.11	15.09	-	-	-	-	-	-	-
MR	2011	2043	0	90	3.74	26.40	-	-	-	-	-	-	-
MR	2011	2044	0	135	3.83	107.95	6.16	4.68	3.80	11.52	0.62	-	0.59
MR	2011	3011	147	135	3.87	43.85	4.79	4.55	5.60	8.18	3.13	0.84	0.69

Site	Year	Plot	P rate	N rate	Hand-sampled N	Hand-sampled P	Giddings probe-sampled N				Giddings probe-sampled P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
MR	2011	3012	147	45	14.26	33.81	-	-	-	-	-	-	-
MR	2011	3013	147	0	4.13	52.26	-	-	-	-	-	-	-
MR	2011	3014	147	90	4.86	81.47	-	-	-	-	-	-	-
MR	2011	3021	0	45	6.84	15.14	-	-	-	-	-	-	-
MR	2011	3022	0	0	4.64	7.61	-	-	-	-	-	-	-
MR	2011	3023	0	90	3.95	9.22	-	-	-	-	-	-	-
MR	2011	3024	0	135	4.35	16.00	5.89	3.67	7.84	26.51	1.24	0.91	0.67
MR	2011	3031	441	0	6.21	55.23	-	-	-	-	-	-	-
MR	2011	3032	441	90	5.07	63.39	-	-	-	-	-	-	-
MR	2011	3033	441	135	2.99	93.71	5.34	5.01	4.04	3.61	1.55	0.73	1.21
MR	2011	3034	441	45	2.76	122.78	-	-	-	-	-	-	-
MR	2011	3041	294	135	3.90	60.27	6.51	3.33	4.82	4.87	1.96	0.79	0.76
MR	2011	3042	294	45	4.75	32.55	-	-	-	-	-	-	-
MR	2011	3043	294	0	4.31	33.97	-	-	-	-	-	-	-
MR	2011	3044	294	90	2.96	48.75	-	-	-	-	-	-	-
MR	2011	4011	441	135	3.43	105.49	5.97	4.60	4.22	4.67	2.04	1.40	1.26
MR	2011	4012	441	0	3.92	83.91	-	-	-	-	-	-	-
MR	2011	4013	441	45	3.91	58.97	-	-	-	-	-	-	-
MR	2011	4014	441	90	4.39	64.86	-	-	-	-	-	-	-
MR	2011	4021	0	0	4.25	13.60	-	-	-	-	-	-	-
MR	2011	4022	0	135	6.47	8.62	9.55	4.69	5.67	7.31	4.27	0.76	0.73
MR	2011	4023	0	90	4.80	8.00	-	-	-	-	-	-	-
MR	2011	4024	0	45	3.71	8.88	-	-	-	-	-	-	-
MR	2011	4031	147	45	4.60	56.16	-	-	-	-	-	-	-

Site	Year	Plot	P rate	N rate	Hand-sampled N	Hand-sampled P	Giddings probe-sampled N				Giddings probe-sampled P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
MR	2011	4032	147	90	10.27	45.30	-	-	-	-	-	-	-
MR	2011	4033	147	0	4.21	36.55	-	-	-	-	-	-	-
MR	2011	4034	147	135	4.30	26.09	-	5.75	3.94	1.93	5.36	0.50	0.86
MR	2011	4041	294	90	4.51	70.83	-	-	-	-	-	-	-
MR	2011	4042	294	0	2.56	66.25	-	-	-	-	-	-	-
MR	2011	4043	294	135	3.85	125.23	6.18	6.82	4.11	4.77	3.86	0.87	1.09
MR	2011	4044	294	45	3.71	92.43	-	-	-	-	-	-	-
OX	2009	5011	0	135	9.02	7.52	-	7.04	5.83	5.02	0.80	0.57	0.65
OX	2009	5012	0	45	9.02	-	-	-	-	-	-	-	-
OX	2009	5013	0	90	9.02	-	-	-	-	-	-	-	-
OX	2009	5014	0	0	9.02	-	-	-	-	-	-	-	-
OX	2009	5021	294	45	9.71	-	-	-	-	-	-	-	-
OX	2009	5022	294	0	9.71	-	-	-	-	-	-	-	-
OX	2009	5023	294	135	9.71	10.83	-	7.27	4.81	5.06	0.74	0.93	0.68
OX	2009	5024	294	90	9.71	-	-	-	-	-	-	-	-
OX	2009	5031	147	0	5.40	-	-	-	-	-	-	-	-
OX	2009	5032	147	90	5.40	-	-	-	-	-	-	-	-
OX	2009	5033	147	45	5.40	-	-	-	-	-	-	-	-
OX	2009	5034	147	135	5.40	11.21	-	10.97	6.61	5.91	3.82	0.89	0.91
OX	2009	5041	441	90	10.27	-	-	-	-	-	-	-	-
OX	2009	5042	441	135	10.27	11.44	-	7.61	6.98	7.17	5.14	0.89	0.95
OX	2009	5043	441	45	10.27	-	-	-	-	-	-	-	-
OX	2009	5044	441	0	10.27	-	-	-	-	-	-	-	-
OX	2009	6011	147	45	11.05	-	-	-	-	-	-	-	-

					Hand-sampled		Giddings probe-sampled						
Site	Year	Plot	P rate	N rate	N	P	N				P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
OX	2009	6012	147	90	11.05	-	-	-	-	-	-	-	-
OX	2009	6013	147	135	11.05	8.70	-	5.75	6.21	7.89	1.22	0.79	0.88
OX	2009	6014	147	0	11.05	-	-	-	-	-	-	-	-
OX	2009	6021	294	0	11.85	-	-	-	-	-	-	-	-
OX	2009	6022	294	45	11.85	-	-	-	-	-	-	-	-
OX	2009	6023	294	90	11.85	-	-	-	-	-	-	-	-
OX	2009	6024	294	135	11.85	7.01	-	8.86	6.85	5.89	1.06	0.57	0.68
OX	2009	6031	441	90	11.41	-	-	-	-	-	-	-	-
OX	2009	6032	441	135	11.41	9.36	-	7.48	6.22	5.88	0.76	1.14	0.67
OX	2009	6033	441	0	11.41	-	-	-	-	-	-	-	-
OX	2009	6034	441	45	11.41	-	-	-	-	-	-	-	-
OX	2009	6041	0	45	12.37	-	-	-	-	-	-	-	-
OX	2009	6042	0	0	12.37	-	-	-	-	-	-	-	-
OX	2009	6043	0	90	12.37	-	-	-	-	-	-	-	-
OX	2009	6044	0	135	12.37	9.91	-	8.87	8.63	7.34	1.17	0.77	0.99
OX	2009	7011	147	135	9.45	10.83	-	5.00	5.56	6.21	1.24	0.71	0.81
OX	2009	7012	147	45	9.45	-	-	-	-	-	-	-	-
OX	2009	7013	147	0	9.45	-	-	-	-	-	-	-	-
OX	2009	7014	147	90	9.45	-	-	-	-	-	-	-	-
OX	2009	7021	0	45	9.98	-	-	-	-	-	-	-	-
OX	2009	7022	0	0	9.98	-	-	-	-	-	-	-	-
OX	2009	7023	0	90	9.98	-	-	-	-	-	-	-	-
OX	2009	7024	0	135	9.98	11.47	-	7.67	8.40	5.97	1.15	0.68	0.47
OX	2009	7031	441	0	11.26	-	-	-	-	-	-	-	-

					Hand-sampled		Giddings probe-sampled						
Site	Year	Plot	P rate	N rate	N	P	N				P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
OX	2009	7032	441	90	11.26	-	-	-	-	-	-	-	-
OX	2009	7033	441	135	11.26	13.45	-	5.67	4.93	4.22	1.31	0.80	0.89
OX	2009	7034	441	45	11.26	-	-	-	-	-	-	-	-
OX	2009	7041	294	135	9.67	11.79	-	7.04	7.40	4.32	0.99	0.90	0.90
OX	2009	7042	294	45	9.67	-	-	-	-	-	-	-	-
OX	2009	7043	294	0	9.67	-	-	-	-	-	-	-	-
OX	2009	7044	294	90	9.67	-	-	-	-	-	-	-	-
OX	2009	8011	441	135	11.50	10.55	-	6.47	3.70	2.99	0.99	0.91	3.81
OX	2009	8012	441	0	11.50	-	-	-	-	-	-	-	-
OX	2009	8013	441	45	11.50	-	-	-	-	-	-	-	-
OX	2009	8014	441	90	11.50	-	-	-	-	-	-	-	-
OX	2009	8021	0	0	9.71	-	-	-	-				
OX	2009	8022	0	135	9.71	9.52	-	4.51	3.54	2.87	1.01	1.53	2.82
OX	2009	8023	0	90	9.71	-	-	-	-	-	-	-	-
OX	2009	8024	0	45	9.71	-	-	-	-	-	-	-	-
OX	2009	8031	147	45	11.40	-	-	-	-	-	-	-	-
OX	2009	8032	147	90	11.40	-	-	-	-	-	-	-	-
OX	2009	8033	147	0	11.40	-	-	-	-	-	-	-	-
OX	2009	8034	147	135	11.40	7.50	-	7.44	4.69	5.02	1.01	0.57	0.80
OX	2009	8041	294	90	10.52	-	-	-	-	-	-	-	-
OX	2009	8042	294	0	10.52	-	-	-	-	-	-	-	-
OX	2009	8043	294	135	10.52	6.99	-	6.60	4.81	5.23	1.11	0.80	1.29
OX	2009	8044	294	45	10.52	-	-	-	-	-	-	-	-
OX	2010	5011	0	135	4.73	21.83	5.91	9.84	16.13	8.47	2.08	0.74	0.30

					Hand-sampled		Giddings probe-sampled						
Site	**Year**	**Plot**	**P rate**	**N rate**	**N**	**P**	**N**				**P**		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
OX	2010	5012	0	45	8.89	17.24	-	-	-	-	-	-	-
OX	2010	5013	0	90	6.19	15.46	-	-	-	-	-	-	-
OX	2010	5014	0	0	5.99	20.76	-	-	-	-	-	-	-
OX	2010	5021	294	45	6.51	97.61	-	-	-	-	-	-	-
OX	2010	5022	294	0	6.08	95.59	-	-	-	-	-	-	-
OX	2010	5023	294	135	5.94	100.59	5.49	6.58	16.74	14.68	3.98	0.72	0.41
OX	2010	5024	294	90	8.94	71.53	-	-	-	-	-	-	-
OX	2010	5031	147	0	5.29	83.14	-	-	-	-	-	-	-
OX	2010	5032	147	90	5.98	63.17	-	-	-	-	-	-	-
OX	2010	5033	147	45	5.91	55.58	-	-	-	-	-	-	-
OX	2010	5034	147	135	6.79	45.04	6.77	5.83	11.00	8.80	3.88	0.97	0.60
OX	2010	5041	441	90	6.32	263.54	-	-	-	-	-	-	-
OX	2010	5042	441	135	5.60	197.93	5.09	11.16	16.31	6.09	0.98	0.62	0.42
OX	2010	5043	441	45	7.03	180.25	-	-	-	-	-	-	-
OX	2010	5044	441	0	8.13	170.26	-	-	-	-	-	-	-
OX	2010	6011	147	45	5.10	32.48	-	-	-	-	-	-	-
OX	2010	6012	147	90	5.24	43.10	-	-	-	-	-	-	-
OX	2010	6013	147	135	6.01	58.70	4.95	5.24	6.70	6.20	0.97	0.61	0.50
OX	2010	6014	147	0	8.96	51.29	-	-	-	-	-	-	-
OX	2010	6021	294	0	5.94	65.17	-	-	-	-	-	-	-
OX	2010	6022	294	45	5.69	145.63	-	-	-	-	-	-	-
OX	2010	6023	294	90	5.81	92.27	-	-	-	-	-	-	-
OX	2010	6024	294	135	7.18	175.45	6.19	9.01	9.06	5.40	1.39	0.61	0.41
OX	2010	6031	441	90	4.87	113.04	-	-	-	-	-	-	-

Site	Year	Plot	P rate	N rate	Hand-sampled N	Hand-sampled P	Giddings probe-sampled N				Giddings probe-sampled P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
OX	2010	6032	441	135	4.85	196.43	3.68	7.46	6.99	4.26	0.61	0.41	0.51
OX	2010	6033	441	0	4.84	194.20	-	-	-	-	-	-	-
OX	2010	6034	441	45	6.55	285.22	-	-	-	-	-	-	-
OX	2010	6041	0	45	4.85	9.65	-	-	-	-	-	-	-
OX	2010	6042	0	0	6.04	14.46	-	-	-	-	-	-	-
OX	2010	6043	0	90	5.62	17.74	-	-	-	-	-	-	-
OX	2010	6044	0	135	6.99	16.67	5.69	5.83	9.40	7.23	1.45	0.49	0.40
OX	2010	7011	147	135	6.63	70.43	4.95	9.38	7.65	4.21	0.51	0.41	0.51
OX	2010	7012	147	45	5.74	114.02	-	-	-	-	-	-	-
OX	2010	7013	147	0	5.78	42.44	-	-	-	-	-	-	-
OX	2010	7014	147	90	7.31	58.05	-	-	-	-	-	-	-
OX	2010	7021	0	45	5.99	13.11	-	-	-	-	-	-	-
OX	2010	7022	0	0	5.86	17.69	-	-	-	-	-	-	-
OX	2010	7023	0	90	4.50	20.83	-	-	-	-	-	-	-
OX	2010	7024	0	135	6.48	21.95	3.79	6.64	13.51	7.57	0.94	0.40	0.61
OX	2010	7031	441	0	6.50	165.73	-	-	-	-	-	-	-
OX	2010	7032	441	90	6.01	318.40	-	-	-	-	-	-	-
OX	2010	7033	441	135	5.23	197.40	5.69	6.19	13.71	5.27	0.89	0.67	0.41
OX	2010	7034	441	45	7.33	177.56	-	-	-	-	-	-	-
OX	2010	7041	294	135	5.50	140.61	4.56	11.08	11.98	7.99	0.61	0.32	0.42
OX	2010	7042	294	45	7.01	143.55	-	-	-	-	-	-	-
OX	2010	7043	294	0	5.61	102.08	-	-	-	-	-	-	-
OX	2010	7044	294	90	7.65	88.00	-	-	-	-	-	-	-
OX	2010	8011	441	135	6.36	413.60	5.04	5.85	9.51	6.73	0.53	0.43	0.40

Site	Year	Plot	P rate	N rate	Hand-sampled		Giddings probe-sampled						
					N	P	N				P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
OX	2010	8012	441	0	5.96	157.33	-	-	-	-	-	-	-
OX	2010	8013	441	45	5.57	106.86	-	-	-	-	-	-	-
OX	2010	8014	441	90	7.15	237.08	-	-	-	-	-	-	-
OX	2010	8021	0	0	5.11	12.32	-	-	-	-	-	-	-
OX	2010	8022	0	135	9.72	16.72	5.86	13.46	15.26	7.11	0.55	0.41	0.41
OX	2010	8023	0	90	6.34	17.95	-	-	-	-	-	-	-
OX	2010	8024	0	45	6.18	17.12	-	-	-	-	-	-	-
OX	2010	8031	147	45	7.07	50.97	-	-	-	-	-	-	-
OX	2010	8032	147	90	6.68	51.21	-	-	-	-	-	-	-
OX	2010	8033	147	0	5.45	41.55	-	-	-	-	-	-	-
OX	2010	8034	147	135	7.34	76.99	6.09	6.42	6.88	5.09	0.69	0.40	0.40
OX	2010	8041	294	90	6.36	100.45	-	-	-	-	-	-	-
OX	2010	8042	294	0	6.82	121.65	-	-	-	-	-	-	-
OX	2010	8043	294	135	5.99	102.97	4.83	6.26	7.95	5.39	0.70	0.43	0.50
OX	2010	8044	294	45	8.86	105.57	-	-	-	-	-	-	-
OX	2011	5011	0	135	4.30	10.78	4.64	4.73	9.32	12.26	1.83	0.83	0.94
OX	2011	5012	0	45	4.14	9.30	-	-	-	-	-	-	-
OX	2011	5013	0	90	10.54	9.67	-	-	-	-	-	-	-
OX	2011	5014	0	0	3.45	13.05	-	-	-	-	-	-	-
OX	2011	5021	294	45	3.51	45.00	-	-	-	-	-	-	-
OX	2011	5022	294	0	2.87	39.27	-	-	-	-	-	-	-
OX	2011	5023	294	135	4.44	46.83	9.87	5.22	11.14	26.71	5.22	1.88	0.91
OX	2011	5024	294	90	3.89	38.71	-	-	-	-	-	-	-
OX	2011	5031	147	0	3.04	24.19	-	-	-	-	-	-	-

Site	Year	Plot	P rate	N rate	Hand-sampled N	Hand-sampled P	Giddings probe-sampled N				Giddings probe-sampled P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
OX	2011	5032	147	90	3.00	26.85	-	-	-	-	-	-	-
OX	2011	5033	147	45	4.20	37.17	-	-	-	-	-	-	-
OX	2011	5034	147	135	4.45	33.76	4.58	5.38	6.50	9.07	25.68	0.71	0.61
OX	2011	5041	441	90	3.94	57.10	-	-	-	-	-	-	-
OX	2011	5042	441	135	3.50	79.45	5.11	6.39	8.61	10.45	1.17	0.95	1.03
OX	2011	5043	441	45	3.86	50.41	-	-	-	-	-	-	-
OX	2011	5044	441	0		72.70	-	-	-	-	-	-	-
OX	2011	6011	147	45	3.30	10.43	-	-	-	-	-	-	-
OX	2011	6012	147	90	2.79	13.36	-	-	-	-	-	-	-
OX	2011	6013	147	135	3.04	28.15	6.47	6.43	6.58	8.81	1.71	1.04	1.15
OX	2011	6014	147	0	4.56	29.35	-	-	-	-	-	-	-
OX	2011	6021	294	0	3.04	30.26	-	-	-	-	-	-	-
OX	2011	6022	294	45	4.12	39.52	-	-	-	-	-	-	-
OX	2011	6023	294	90	9.43	52.66	-	-	-	-	-	-	-
OX	2011	6024	294	135	7.28	44.67	6.83	2.48	2.45	3.44	2.67	1.20	0.80
OX	2011	6031	441	90	5.00	65.21	-	-	-	-	-	-	-
OX	2011	6032	441	135	3.92	92.46	2.17	1.69	5.17	6.08	1.15	0.51	0.42
OX	2011	6033	441	0	3.84	55.16	-	-	-	-	-	-	-
OX	2011	6034	441	45	4.54	63.25	-	-	-	-	-	-	-
OX	2011	6041	0	45	6.10	5.00	-	-	-	-	-	-	-
OX	2011	6042	0	0	2.57	9.61	-	-	-	-	-	-	-
OX	2011	6043	0	90	3.11	11.97	-	-	-	-	-	-	-
OX	2011	6044	0	135	4.81	11.05	3.71	3.92	5.54	8.66	2.11	1.83	0.59
OX	2011	7011	147	135	3.45	14.03	3.90	3.20	5.98	5.89	0.42	0.61	0.43

					Hand-sampled		Giddings probe-sampled						
Site	Year	Plot	P rate	N rate	N	P	N				P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
OX	2011	7012	147	45	3.20	22.30	-	-	-	-	-	-	-
OX	2011	7013	147	0	3.79	29.77	-	-	-	-	-	-	-
OX	2011	7014	147	90	4.22	30.31	-	-	-	-	-	-	-
OX	2011	7021	0	45	3.69	9.42	-	-	-	-	-	-	-
OX	2011	7022	0	0	3.59	12.00	-	-	-	-	-	-	-
OX	2011	7023	0	90	8.02	14.76	-	-	-	-	-	-	-
OX	2011	7024	0	135	3.85	14.79	2.07	2.92	2.27	5.59	1.05	0.61	0.51
OX	2011	7031	441	0	4.31	74.66	-	-	-	-	-	-	-
OX	2011	7032	441	90	2.21	73.44	-	-	-	-	-	-	-
OX	2011	7033	441	135	3.34	68.60	1.97	2.65	5.09	7.94	1.28	0.52	0.50
OX	2011	7034	441	45	3.96	107.20	-	-	-	-	-	-	-
OX	2011	7041	294	135	3.06	36.29	3.54	3.51	10.46	9.66	0.59	0.54	0.43
OX	2011	7042	294	45	3.42	50.56	-	-	-	-	-	-	-
OX	2011	7043	294	0	3.74	53.86	-	-	-	-	-	-	-
OX	2011	7044	294	90	5.87	73.75	-	-	-	-	-	-	-
OX	2011	8011	441	135	2.90	29.92	2.86	3.07	3.91	6.83	0.82	0.40	0.40
OX	2011	8012	441	0	3.85	78.98	-	-	-	-	-	-	-
OX	2011	8013	441	45	4.11	87.50	-	-	-	-	-	-	-
OX	2011	8014	441	90	4.24	95.97	-	-	-	-	-	-	-
OX	2011	8021	0	0	3.48	7.39	-	-	-	-	-	-	-
OX	2011	8022	0	135	3.86	9.16	2.95	2.18	3.77	4.04	0.78	0.51	0.40
OX	2011	8023	0	90	4.03	9.59	-	-	-	-	-	-	-
OX	2011	8024	0	45	3.77	10.72	-	-	-	-	-	-	-
OX	2011	8031	147	45	3.86	16.55	-	-	-	-	-	-	-

Site	Year	Plot	P rate	N rate	Hand-sampled N	Hand-sampled P	Giddings probe-sampled N				Giddings probe-sampled P		
					0-20 cm	0-20 cm	0-20 cm	20-41 cm	41-61 cm	61-91 cm	20-41 cm	41-61 cm	61-91 cm
OX	2011	8032	147	90	4.43	39.92	-	-	-	-	-	-	-
OX	2011	8033	147	0	3.16	19.92	-	-	-	-	-	-	-
OX	2011	8034	147	135	3.60	25.67	1.37	2.99	3.27	2.04	0.99	0.73	0.51
OX	2011	8041	294	90	2.91	19.73	-	-	-	-	-	-	-
OX	2011	8042	294	0	4.92	28.12	-	-	-	-	-	-	-
OX	2011	8043	294	135	3.55	45.38	1.76	1.79	3.17	3.78	1.00	0.73	0.74
OX	2011	8044	294	45	3.11	19.17	-	-	-	-	-	-	-