

## ABSTRACT

O'DOHERTY, CORMAC SEAMUS. An Assessment of Soil Carbon Dioxide Respiration and Environmental Influences for Undisturbed, Drained and Restored Wetlands. (Under the direction of Ryan Emanuel).

A topic of debate surrounding wetland restoration is whether other ecological processes, including the carbon cycle, are restored as a result of restoring the wetland. Soil CO<sub>2</sub> respiration, a part of the carbon cycle, has many known environmental influences, including soil temperature, soil moisture and water table. We assessed differences in these environmental influences and soil CO<sub>2</sub> respiration in an agricultural field, fallow field, a restored non-riverine wetland, and undisturbed pocosin in the same wetland complex. We also assessed effects of artificial drainage or storage on these environmental state factors and found that artificial water storage by plugged ditches can raise the water table, significantly. Our results show the restored wetland and pocosin were similar in all but one measured variable, and that these landscapes had significantly higher soil CO<sub>2</sub> respiration than the agricultural and fallow fields. Our results contradict previous reports of wetlands having lower or equal soil CO<sub>2</sub> respiration than agricultural associated landscapes. Our results indicate that restored and undisturbed wetlands are similar in more ways than just jurisdictional definition.

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An Assessment of Soil Carbon Dioxide Respiration and Environmental Influences for  
Undisturbed, Drained and Restored Wetlands

by  
Cormac Seamus O'Doherty

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## **BIOGRAPHY**

Cormac Seamus O’Doherty, born to an Irish mother and American father of Irish decent, was raised just outside of Winston-Salem, North Carolina. As a boy he was an active member of the Boy Scouts of America where he received the Eagle Scout Award and was a Brotherhood Member of the Order of the Arrow. He spent the summers of his youth either at Raven Knob Scout Reservation or on his mother’s family farm in the Southwestern Ireland. At both locales he took an interest in his surroundings and came to appreciate and question the physical world, always yearning to learn about relationships in nature. O’Doherty received his BS in Forest Management from North Carolina State University, where he studied abroad three times; going to Chile, Northern Sweden and Southern Sweden. O’Doherty worked on the Hofmann Forest, NC for a short time after graduating with his BS before taking the Atlantis Dual Degree Fellowship for graduate studies. As an Atlantis Fellow at North Carolina State University and Swedish University of Agricultural Sciences, O’Doherty continued his international experience studying at the University of Helsinki and the Swedish University of Agricultural Science Umea. O’Doherty married the love of his life shortly after returning from Sweden in 2012.

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## 1.0 Overview

This study addresses questions relevant to soil carbon dioxide respiration in peat lands and to the environmental factors that influence respiration. The following introductory sections review literature concerning the effect of landscape change, the effect of environmental site factors on soil respiration, and topographic effects on drivers of soil respiration. This review leads to four specific questions addressed by the study conducted on a site in eastern North Carolina's Hofmann Forest, where monitoring extended from May 2011 through August 2012. These questions ask how do environmental site factors vary across the landscape, how well do they explain soil CO<sub>2</sub> respiration, how does artificial drainage affect them and how does soil CO<sub>2</sub> respiration behave in a restored wetland?

The practice of wetland restoration has increased since its inception in the 1980s. At that time, nearly two-thirds of the approximately 900,000 hectares of all freshwater peatlands had been drained in North Carolina (Bridgham and Richardson, 1992; Richardson, 2003), with much of that land having been converted into agriculture or forestry (Cashin et al., 1992). This conversion has had a variety of effects on the landscape (Bruland et al., 2003), including reducing forest floor carbon (C) by 13%-16% for 90 to 120 years after disturbance (Compton and Boone, 2000), accelerating decomposition (Compton and Boone, 2000), reducing litter inputs (Compton and Boone, 2000), increasing soil erosion (Tiessen and Stewart, 1983), reducing microbial biomass and soil organic matter by 50%-75% (Cambardella and Elliot, 1994; Collins et al., 1992), reducing labile nitrogen (N) by tillage (Campbell and Souster, 1982), and elevating net nitrification rates (Schimel, 1986). The conversion of wetlands to agricultural and forestry lands also has had implications for climate change by tipping the ecosystem from a net sink of carbon from the atmosphere to a net source of carbon to the atmosphere (Hirano et al., 2012). Policymakers have realized the importance of wetlands for

ecosystem services and have developed regulations regarding restored wetlands (Hilderbrand et al., 2005). In North Carolina, to qualify as a restored wetland under current regulations, a site must be a former wetland with hydric soils. In addition, a shallow ground water table with regular hydroperiods, and an assemblage of natural wetland plant species must be restored, monitored, and maintained for five years before wetland mitigation credits are released (NCNRF, 2009).

An emerging body of literature, however, questions the wetland restoration regulations put in place by policymakers (Bruland et al., 2003; Hilderbrand et al., 2005; Morse et al., 2012). Specifically questions exist regarding both the length of required monitoring and the attributes for obtaining the status of ‘restored wetland’ (Hilderbrand et al., 2005). Critics claim that restored sites are not functionally equivalent to their previous states (Hilderbrand et al., 2005) and that not all aspects of the sites are restored; they also assert that the time of observation is insufficient (Bruland et al., 2003; Morse et al., 2012). One basis for their criticism is that the regulations say nothing of ecological functions. According to these critics, nutrient cycling, soil physical and chemical properties, and other important factors are ignored in this “Field of Dreams” hypothesis (Hilderbrand et al., 2005; Violin et al., 2011), which operates on the principle that if the shallow ground water table and periods of inundation are the most important factors controlling wetland processes and ecological functions (Bridgham and Richardson, 1992; Bruland et al., 2003), then restoring them will restore associated processes and functions (Hilderbrand et al., 2005), including the carbon cycle. To understand the carbon cycle and craft effective policies, therefore, it is crucial to understand the effects of landscape change on variables affecting these processes and functions.

### **1.1 Effect of Landscape Change**

An integral part of the carbon cycle is soil respiration. Soil respiration comprises both the production of carbon dioxide (CO<sub>2</sub>) in the soil by plants and microorganisms through aerobic

respiration and the efflux of CO<sub>2</sub> from the soil to the atmosphere through diffusion (Riveros-Iregui et al., 2007). CO<sub>2</sub> is produced by the decomposition of organic matter under aerobic conditions by soil microorganisms (heterotrophic respiration), from plant roots (autotrophic respiration), and also from the chemical oxidation of organic compounds (Lloyd and Taylor, 1994; Bridgham and Richardson, 1992; Pacific et al., 2008).

The transformation of wetlands to agricultural and forestry lands through drainage and other management practices has increased rates of decomposition and soil respiration (Bruland et al., 2003) from lands that were characterized previously by relatively low rates of soil CO<sub>2</sub> production and efflux (Raich and Potter, 1995). This phenomenon is exacerbated by the drainage of peatlands, wetlands containing relatively high concentrations of soil organic matter (Bridgham and Richardson, 1992). Although soil respiration is relatively high in drained peatlands (Bridgham et al., 1991; Updegraff et al., 1998), it may only persist for a few years before declining below pre-drainage rates (Hirano et al., 2012). Reestablishment of native vegetation on agricultural land is accompanied by high rates of carbon sequestration (Schlesinger and Andrews, 2000), although they may be preceded by an initial, short-lived release of carbon to the atmosphere (Emanuel et al., 2006). Peatland restoration may enhance the pace of C sequestration because planting and management of native vegetation may reduce the amount of time until the system becomes a net C sink. Through this same process, peatland restoration may contribute to rebuilding the soil carbon pool.

The call for more research in “warm climate peatlands” by Bridgham and Richardson (1992) has generated some insights into nutrient cycling and growth limitation, with most of the research focusing on warming experiments of northern latitudinal peatlands (e.g., Updegraff et al., 1998; Updegraff et al., 2001; Bridgham et al., 2008) or mechanistic processes related to warm climate peatlands (e.g., Bridgham and Richardson, 2003; Bruland et al., 2003; Ardon et al., 2010). Recently,

focus has turned to comparative landscape studies of peatlands and associated landscapes at lower latitudes (e.g., Hirano et al., 2012; Morse et al., 2012; and this study). Hirano et al. (2012) found that tropical peatlands are sensitive to disturbance and climatic variation, signaling a transition from carbon accruing landscapes to carbon emitting landscapes under the influence of humans through direct manipulation, anthropogenic climate change, and climate variation, which is in line with the aforementioned warming and manipulation experiments.

## **1.2 Effect of Environmental State Variables on Soil Respiration**

Many factors affect soil respiration rates, such as soil temperature (Lloyd and Taylor, 1994; Bridgham and Richardson, 1992), soil moisture (Skopp et al., 1990; Lloyd and Taylor, 1994; Emanuel et al., 2006), soil organic matter (Chatterjee and Jenerette, 2011), vegetation structure and composition (Raich and Tufekcioglu, 2000; Updegraff et al., 2001), and soil chemical properties (Raich and Tufekcioglu, 2000). Soil physical properties also affect soil respiration because of the influence they have on soil water retention characteristics and gas diffusion (Skopp et al., 1990). These factors vary temporally and spatially (Riveros-Iregui et al., 2011); therefore, determining a dominant, respiration-influencing variable can be difficult (Raich and Tufekcioglu, 2000; Pacific et al., 2008). Due to their complexity, the interactions between variables must be closely observed so that we recognize when a change in one variable counters an opposite change in another, leading to consistent soil respiration, either in space or in time, which is known as non-identifiability or equifinality (Raich and Tufekcioglu, 2000; Beven, 2002; Pacific et al., 2008).

### ***1.2.1 Temperature and Soil Respiration***

Soil temperature is widely considered to be the most influential variable affecting soil respiration (Bridgham and Richardson, 1992; Lloyd and Taylor, 1994; Raich and Potter, 1995; Raich and Tufekcioglu, 2000), strongly correlating with soil respiration across multiple spatial and temporal

scales (Riveros-Iregui et al., 2011). Soil temperature can explain up to 69% of soil respiration in North Carolina peatlands (Bridgham and Richardson, 1992).

The correlation between soil respiration and soil temperature is not always positive (Pacific et al., 2008). Above a certain threshold, heat begins to suppress respiration (Raich and Potter, 1995). Although no general consensus exists on where temperature suppression begins, Raich and Potter (1995) found evidence that it begins above 33<sup>0</sup>C. The uncertainty regarding the temperature suppression threshold likely arises from the fact that there are many organisms responsible for the production of CO<sub>2</sub>, and each has an individual metabolic response to temperature (Lloyd and Taylor, 1994). Similarly, the relatively weak correlation of temperature with spatial variability of respiration (e.g., Pacific et al., 2008) may be due to the spatial variability of microorganisms. Microorganisms respond more to soil temperature than air temperature, and soil temperature fluctuates less temporally, but more spatially, than air temperature (Raich and Potter, 1995).

### ***1.2.2 Soil Moisture and Soil Respiration***

Soil moisture can explain a significant portion of the temporal and spatial variability in soil respiration in many cases (Schlesinger, 1977; Bridgham and Richardson, 1992; Lloyd and Taylor, 1994). In fact, in some environments landscape position may predict patterns of soil respiration due the influence of topography on the spatial distribution of soil moisture (Pacific et al., 2008; Riveros-Iregui et al., 2011). Like soil temperature, soil moisture may correlate positively or negatively with soil respiration (Skopp et al., 1990; Raich and Potter, 1995; Pacific et al., 2008; Riveros-Iregui et al., 2012). Suppression of soil respiration by soil moisture results from limitations on soil gas diffusion (i.e. CO<sub>2</sub> efflux) caused by the occupation of soil pores by moisture (Skopp et al., 1990). Suppression of soil respiration by soil moisture also results from the formation of anaerobic conditions and associated reduction of aerobic metabolism at high levels of soil moisture (Segers, 1998). The optimum soil moisture for microbial and metabolic activity occurs between 50% and 80% saturation,



which is the ratio of filled to total soil pore space (Skopp et al., 1990; Raich and Potter, 1995; Riveros-Iregui et al., 2012). Although the underlying mechanisms and the general pattern of maximum soil respiration at intermediate soil moisture are well understood (Skopp et al., 1990; Raich and Potter, 1995; Pacific et al., 2008), we are just beginning to understand the influence of heterogeneous landscapes on the soil CO<sub>2</sub> respiration response to soil moisture (Pacific et al., 2011; Riveros-Iregui et al., 2012; Section 1.3 below).

Soil moisture correlates well with precipitation on a global scale and is a better predictor of soil respiration than other climate variables. Therefore, precipitation can be used as a proxy for soil moisture at the global scale ( $P < 0.001$ ; Raich and Potter, 1995). Seasonality of soil respiration has been observed due to the switching point from soil temperature controlled respiration to soil moisture controlled respiration; however, these observations are limited to a few sites where intensive datasets exist (e.g. Riveros-Iregui et al., 2007; Pacific et al., 2008).

### ***1.2.3 Organic Matter's Effect on Soil Respiration***

Organic matter plays a crucial role in soil respiration because it is the substrate that microorganisms metabolize to produce CO<sub>2</sub>. The global pool of C in soil organic matter is estimated to be twice as large as the global pool of C in atmospheric CO<sub>2</sub> (Schlesinger, 1997; Raich and Potter, 1995), and the C flux from soils is one of the largest in the carbon cycle (Schlesinger, 1977; Schlesinger and Andrews, 2000). Moreover, the addition of organic matter causes an increase in soil respiration, suggesting limitation of soil respiration by organic carbon (Schlesinger and Andrews, 2000). Meta-analysis has determined that many differences in respiration behavior among ecosystems can be attributed to soil organic matter (Lloyd and Taylor, 1994). Furthermore, reports suggest that soil respiration varies between and among major forest biomes (Singh and Gupta, 1977; Schlesinger, 1977). This variation, though, can be explained by climatic factors such as temperature and precipitation (Raich and Potter, 1995). Indeed, temperature and precipitation explain so much of

soil CO<sub>2</sub> respiration that in step-wise linear regression, organic matter quantity and quality fail to correlate significantly at the global scale (Raich and Potter, 1995).

### **1.3 Topographic Effects on Environmental Drivers of Respiration**

Topography influences the amount of radiation reaching the soil surface (insolation). In the northern hemisphere, north and east facing slopes receive less heat than south and west facing slopes due to topographic shading associated with solar geometry (Dubayah, 1994). The solar geometry effect on insolation is exacerbated at higher latitudes. Topography can also cause eco-tones, or transitions between ecosystems. Along eco-tones, the soil temperature can vary with the changing vegetation, such that the soil temperature along a hard eco-tone can be higher than in the interior of the ecosystem.

Topography also influences respiration by controlling the distribution of soil moisture across the landscape. Natural drainage patterns affect soil physical properties, soil moisture and water table depth. Daniels et al. (1971) found topographic effects on soil and water table properties within 160m to 300m of natural drainages in extremely flat landscapes. In peatland headwaters, the organic soil mantle may be found within 50m of most streams (Daniels et al., 1977), resulting in a gradient of soil moisture from stream to the mantle. Manipulation of natural drainage by humans, in the form of ditching, also has the ability to change water table depth (Skaggs, 1974), which has the potential to alter patterns of soil moisture across a landscape. Furthermore, micro-topography (e.g. natural hummocks, artificial planting beds) can cause water to pool at low spots on the soil surface, extending the effects of precipitation by storing water above the soil instead of that water becoming runoff. Even for landscapes that are considered “extremely flat” (e.g. the Atlantic Coastal Plain), microtopography may cause such pooling (Skaggs, 1974). Both of these factors, landscape-scale drainage patterns and microtopography, may influence soil respiration by altering the availability of soil moisture across the landscape.

Organic matter may be spatially heterogeneous due to topography and landscape position, with the highest amounts in wetter landscape positions (e.g. near streams) and the lowest amount in drier positions (e.g. on hillslopes) in a topographically heterogeneous landscape (Pacific et al., 2008; Chatterjee and Jenerette, 2011). In extremely flat landscapes, organic matter can accumulate where precipitation exceeds infiltration properties of the soil (Daniels et al., 1977). Organic soils can change substantially after cultivation, with the possibility of organic matter depletion through decomposition. It is also possible that the underlying mineral soil becomes mixed with organic soil as a result of plowing (Bruland et al., 2003). Such alteration of soil structural and physical properties can influence the diffusion of gas from the soil (Skopp et al., 1990).

## **2. Research Questions**

Given the effects of landscape change, environmental state variables, and topography on soil respiration or the factors affecting soil respiration, this study addresses four key questions related to soil CO<sub>2</sub> respiration in peatlands and the environmental state variables that influence respiration. First, how do soil temperature, soil moisture, and depth to water table vary across landscapes? Second, how well do these environmental state factors explain observed variations in soil CO<sub>2</sub> respiration? Third, how are these environmental state factor affected by the presence of artificial drainage? Fourth, in a restored wetland, does soil CO<sub>2</sub> respiration behave more similarly to either an undisturbed reference wetland or to a wetland that has been drained and cultivated for crops?

## **3. Methods**

### ***Field Site***

This study was conducted in North Carolina State University's Hofmann Forest, which is located north of Jacksonville, North Carolina (Figure 1) in the low relief Outer Coastal Plain of the

southeastern United States of America. Hofmann Forest lies on what historically has been known as the White Oak pocosin (Daniels et al., 1977); “pocosin” is the Carolina Algonquian word used to describe the type of non-riparian peatland found exclusively on the Coastal Plain of the southeastern United States (Tooker 1899). Daniels et al. (1977) found that rainfall exceeds evapotranspiration and that excess water reaches streams by overland flow in the Hofmann Forest. Over the 1981 to 2004 period, Hofmann Forest received an average precipitation of 1470 mm yr<sup>-1</sup> (Personal communication with Hofmann Forest staff; unpublished data). Sixty to seventy percent of excess water is lost through evapotranspiration in the summer from pocosins, but most excess water is lost through runoff in the winter and spring (Richardson, 1983).

Field sites in four different landscapes within Hofmann Forest were chosen for this study. The close proximity of sites minimizes differences in climate among sites. Nonetheless, microclimatological differences will persist even with reduced scale (Raich and Tufekcioglu, 2000). The landscapes included in this study are (1) an agricultural field on a drained wetland, (2) a fallow field on a drained wetland slated for restoration, (3) a restored non-riparian wetland, and (4) a pocosin.

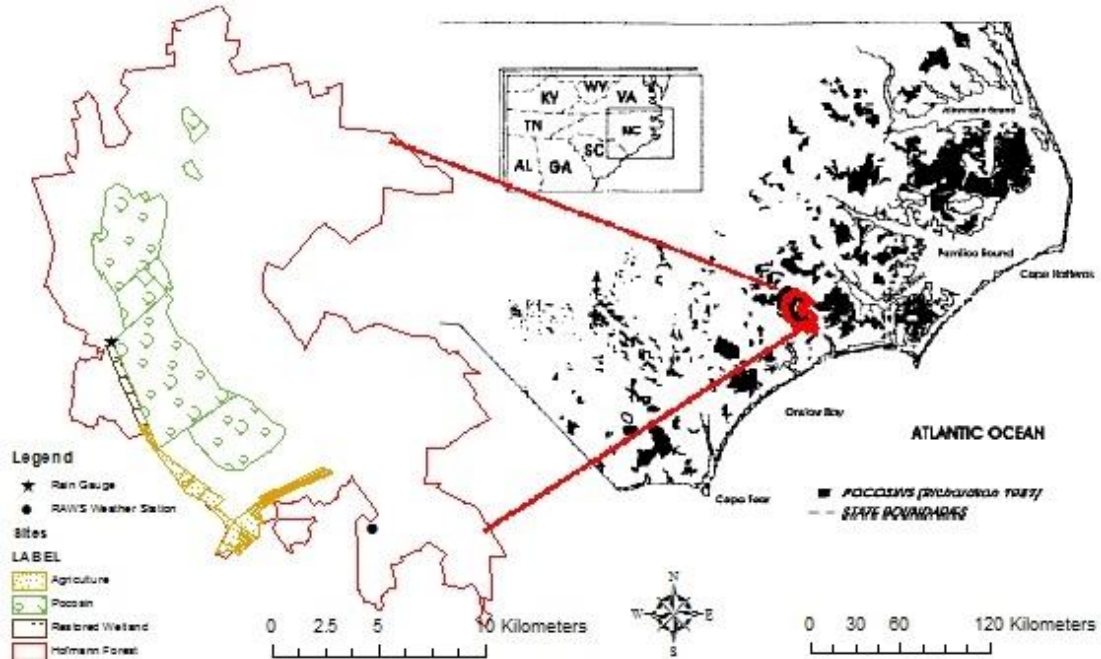


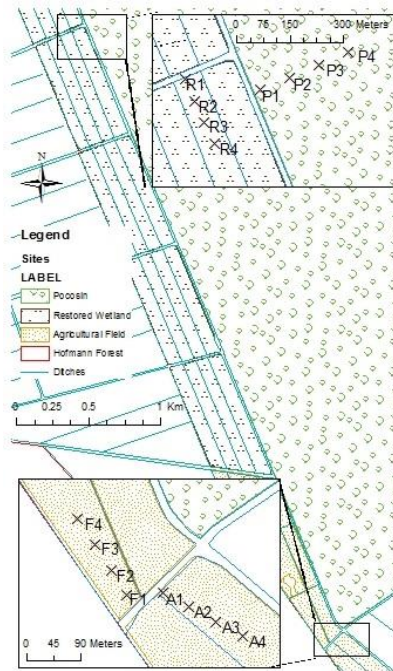
Figure 1: Study sites on Hofmann Forest in North Carolina's coastal plain (Adapted from Richardson, 2003)

Although the pocosin is considered a natural ecosystem, these systems were historically characterized by periodic wildfires (Schafale and Weakley, 1990). Fire has been suppressed at this site, however, since at least the 1950s. As a result, this pocosin ecosystem, though relatively undisturbed, has been managed by fire suppression. Richardson (1983) found that undisturbed pocosins account for 31% of all pocosins in North Carolina, disturbed pocosins represent the largest category of pocosin in North Carolina (36%), and the remaining 33% are totally developed. However, Richardson (1983) failed to specify the fire regime in his categorizations.

The agricultural field was planted in corn (*Zea mays*) in 2011 and in soy beans (*Glycine max*) in 2012 (Figure A1). No crop has grown on the fallow field since 2009. The vegetation in the fallow field was mostly herbaceous including horseweed (*Conyza canadensis*) (Figure A2). The restored

wetland achieved the mandatory five-year of monitoring period in 2010. The restored wetland was planted in a variety of wetland species, including but not limited to longleaf pine (*Pinus palustris*), bald cypress (*Taxodium distichum*), and, the non-native, sawtooth oak (*Quercus acussitima*). The understory of the restored wetland consisted mainly of blueberry (*Vaccinium* sp.), greenbriar (*Smilax* sp.) and grasses (Figure A3). Vegetation in the pocosin corresponds to Schafale and Weakley's (1990) descriptions of a high pocosin, where a dense shrub layer of around a meter and a half or taller is the understory to a sparse over-story of pond pine (*Pinus serotina*)

In each of the four landscapes, four measurement plots for soil respiration, soil temperature and soil moisture were established along a landscape gradient extending from a major ditch toward the interior of the site (Table 1 and Figure 2). The plots are referred to by a letter and number combinations, referring to the landscape (A for agricultural field; F for fallow field; R for restored wetland; and P for pocosin; Table 1) and plot number with varying distances from ditch (1, 2, 3, and 4; Table 1). All plots in the pocosin and restored wetland lie on Croatan muck soil. Plots in the agricultural field are all on Pantego mucky loam. Plots in the fallow field lie half on Pantego mucky loam (Plots F1 and F2), and half on Rains fine sandy loam soil (Plots F3 and F4).



**Figure 2: Location of sampling plots on Hofmann Forest**

Each measurement plot was one meter square. In the plots, three random locations were chosen for replicate measurements and marked with pin flags. At each location soil CO<sub>2</sub> respiration and soil moisture were measured, averaged, and recorded for the plot. Soil moisture was measured as volumetric water content. Soil temperature was taken once per plot, in the center of the three locations. One temperature measurement per plot allowed the temperature probe more time to equilibrate to soil conditions while other measurements, which required less equilibration time, were collected.

Table 1: Distances of sample plots to nearest ditch in meters.

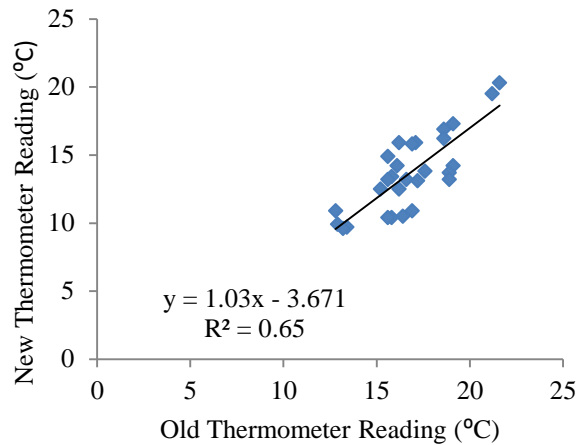
Site	Plot	1	2	3	4
Letter	Site Name	Distance from Ditch (+/- 1.5m)			
A	Agricultural Field	3	13	23	33
F	Fallow Field	16	26	<b>35</b>	37
R	Restored Wetland	11	37	37	37
P	Pocosin	11	99	185	271

*Error unknown for F3.*

Carbon dioxide respiration was measured using an infrared gas analyzer and soil respiration chamber (Models EGM-4, SRC-1, PP Systems International, Inc., Amesbury, Massachusetts, USA). Soil volumetric water content was measured using time domain reflectometry (FieldScout TDR 100 Soil Moisture Meter, Spectrum Technologies, Inc., Plainville, Illinois, USA) integrated vertically for the top 20cm of soil. Non-physical observations (e.g. soil moisture greater than estimated saturation for the sites) were omitted. Soil temperature was measured with a digital soil thermometer inserted in the top 10cm of soil. In February 2012, the digital soil thermometer was replaced with a new model after a period of intercomparison with new and old instruments. Measurements were taken with both instruments, an equation derived, and prior data were converted to the new measurement scale (Figure 3). Shallow ground water wells (1 meter deep) were installed at each plot, allowing for manual monitoring of water table depth using an electric water level indicator. Wells were made of 3.8cm inner-diameter PVC screened over the entire below ground length.



Two continuously monitoring wells were installed prior to this study (Sopp Hollow Reference Well and Block 2 North Well; NCNRF, 2009). These wells correspond to Plot 4 in the pocosin and Plot 4 in the restored wetland, respectively (Figure 2). No manual observation wells were installed at these two plots.



**Figure 3: Thermometer Conversion**

Soils samples were collected from the top 5cm under the O horizon for bulk density analysis using a bulk density soil sampler (Soil Moisture Equipment Corp., CA, USA). One sample was collected from each plot on August 10, 2012. Bulk density was computed by weighing samples after drying them at 105<sup>0</sup>C for at least twenty-four hours and dividing dry soil mass (g) by the volume of the sampling cylinder (141.81cm<sup>3</sup>).

Saturation was found by dividing volumetric soil moisture by one minus the bulk density of soil divided by the density of soil particle, assumed to be 2.65 g cm<sup>-3</sup>. Thus saturation represents the percent of pore space in the soil filled by water, and this fraction was used in the analysis.

A RAWS weather station (MHFMN7), located at N 34.825 ° W 77.322 °, recorded average daily air temperature. Precipitation was recorded by a tipping bucket rain gauge (HOBO, Onset Computer Corp., MA, USA,) located near the measurement sites (Figure 1).

Measurements began in May 2011 and lasted until August 2012. Respiration measurements were taken on all sites from July 2011 to July 2012. Measurements were collected weekly during select portions of the 2011 and 2012 growing seasons (July-August 2011, May-July 2012) and monthly from September 2011 through March 2012. No measurements were taken in December 2011 or April 2012.

Data were analyzed using MATLAB R2012a (The MathWorks, Inc., MA, USA). The Kruskal-Wallis test was used to assess significant differences among sites and plots. Relationships between CO<sub>2</sub> fluxes and environmental state variables were assessed using Spearman's rank correlation test.

Data were fit to two equations, an Arrhenius-based equation (Lloyd and Taylor, 1994; Equation 11) and a Q10 equation (Raich and Potter, 1995; Model B). The Arrhenius-based equation solely models soil respiration based on soil temperature, whereas Q10 equations may better account for the microbial activity contributing to soil respiration by modeling both temperature and moisture. Lloyd and Taylor (1994) modified the Arrhenius equation to describe the relationship as

$$R = R_{10} e^{E_0 \left( \frac{1}{283.15 - T_0} - \frac{1}{T - T_0} \right)} = R_{10} e^{308.56 \left( \frac{1}{56.02} - \frac{1}{T - 227.13} \right)} \quad (\text{Equation 1})$$

where R is soil respiration ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ),  $R_{10}$  is soil respiration at 10°C ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ),  $E_0$  is activation energy (K) at temperature  $T_0$  (K), T is the absolute temperature of respiration (K), and  $T_0$  is

227.13 K, which has a corresponding  $E_0$  of 308.56 K (Lloyd and Taylor, 1994, Equation 11).

Another way to describe this relationship is through the Q10 equation. Across a wide-ranging and variable data set, Q10 may describe soil respiration better than Lloyd and Taylor's modified Arrhenius equation as

$$R = R_0 e^{QT} \frac{P}{K+P} \quad (\text{Equation 2})$$

where soil respiration ( $\text{gC m}^{-2} \text{d}^{-1}$ ) is represented by  $R$ ,  $R_0$  is soil respiration ( $\text{gC m}^{-2} \text{d}^{-1}$ ) at  $0^\circ\text{C}$  when moisture is not limiting, the temperature coefficient ( $^\circ\text{C}$ ) is  $Q$ , the average monthly temperature ( $^\circ\text{C}$ ) is  $T$ , the average monthly precipitation (cm) is  $P$ , and the half-saturation coefficient of the precipitation function ( $\text{cm month}^{-1}$ ) is  $K$  (Raich and Potter, 1995; Model B). The data were fit to the log transformed Equation 1 and log transformed Equation 2.

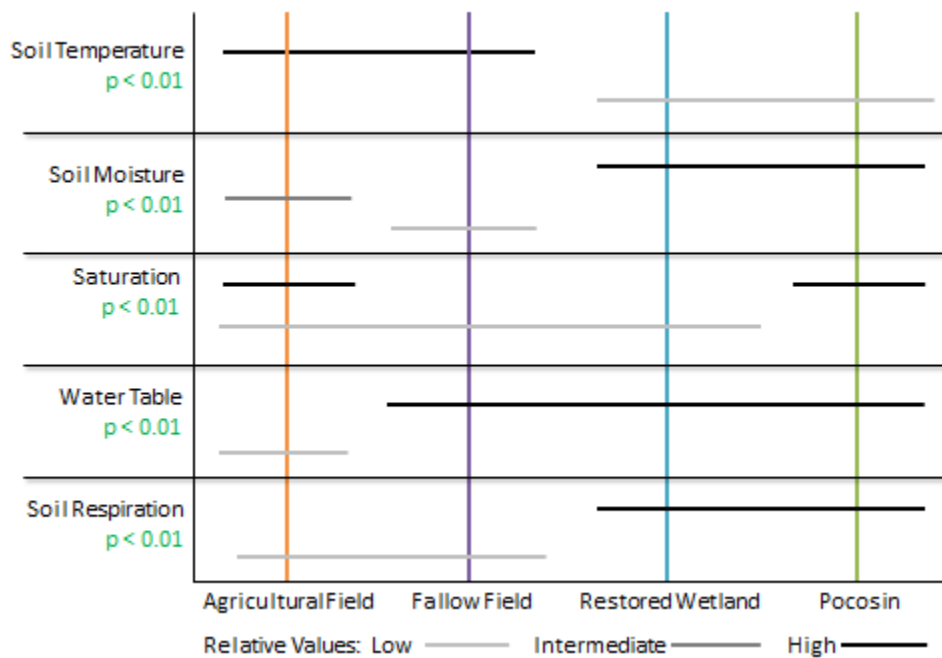
To control for the possibility that landscape is not an important factor, the K means function was done to divide the saturation results into two groups with the least geometric mean. The “Dry” group has the lower average saturation and the “Wet” group has the higher average saturation. Regression and Modeling exercise were also done on these two groups.

## 4.0 Results

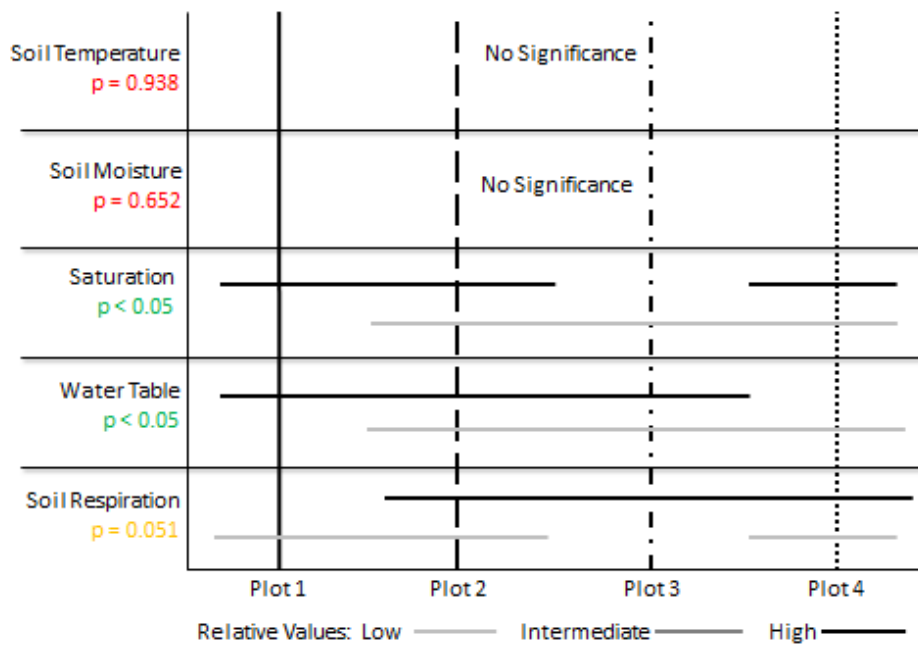
### 4.1 Soil Temperature

Throughout the observation period, soil temperature was significantly higher in the agricultural field and fallow field than in the restored wetland and pocosin (Figure 4). Soil temperature was highest during the growing season and most variable across landscapes in the growing season (Figure 6). In July 2011, the highest observed temperature was  $36^\circ\text{C}$  (F2) and the lowest  $19^\circ\text{C}$  (P4), with an

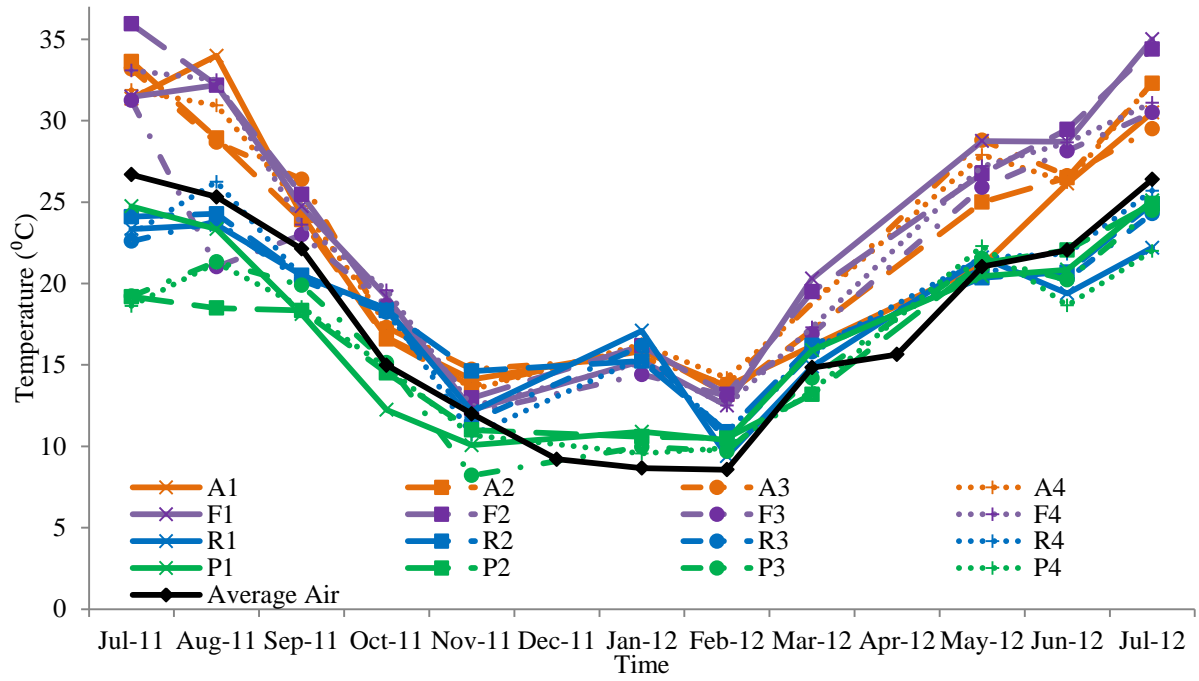
average air temperature of 27<sup>0</sup>C. In the dormant season, soil temperature across landscapes became less variable. February 2012 shows the least variability with the highest observed temperature being 15<sup>0</sup>C (A4) and the lowest 10<sup>0</sup>C (P4), with an average air temperature of 9<sup>0</sup>C. There was a spike in soil temperature during January 2012 that seemed to affect every landscape except the pocosin. Soil temperature was not affected by the plot among all landscapes or within any single landscape (Figure 4 and 6).



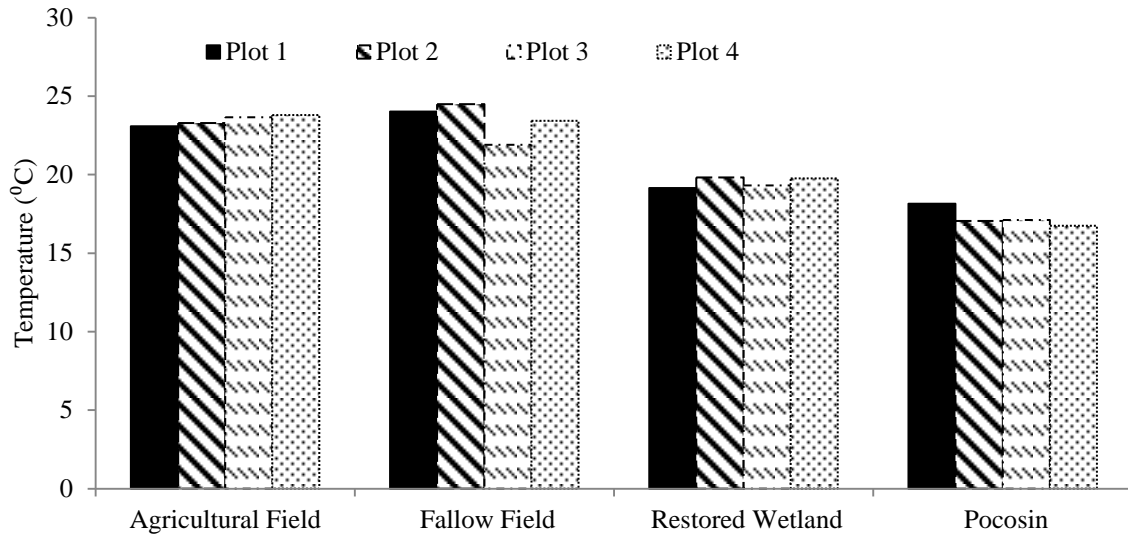
**Figure 4: Visual summary of Kruskal-Wallis test showing significant differences in soil variables among sites. Relative values refer to the ordered observations from lowest to highest used in the Kruskal-Wallis test, so that low relative values correspond to low ranked observations. Landscapes with two relative value denotations are not significantly different from either value.**



**Figure 5: Visual summary of Kruskal-Wallis test showing significant differences in soil variables among plots of all landscapes. Relative values refer to the ordered observations from lowest to highest used in the Kruskal-Wallis test, so that low relative values correspond to low ranked observations. Landscapes with two relative value denotations are not significantly different from either value.**



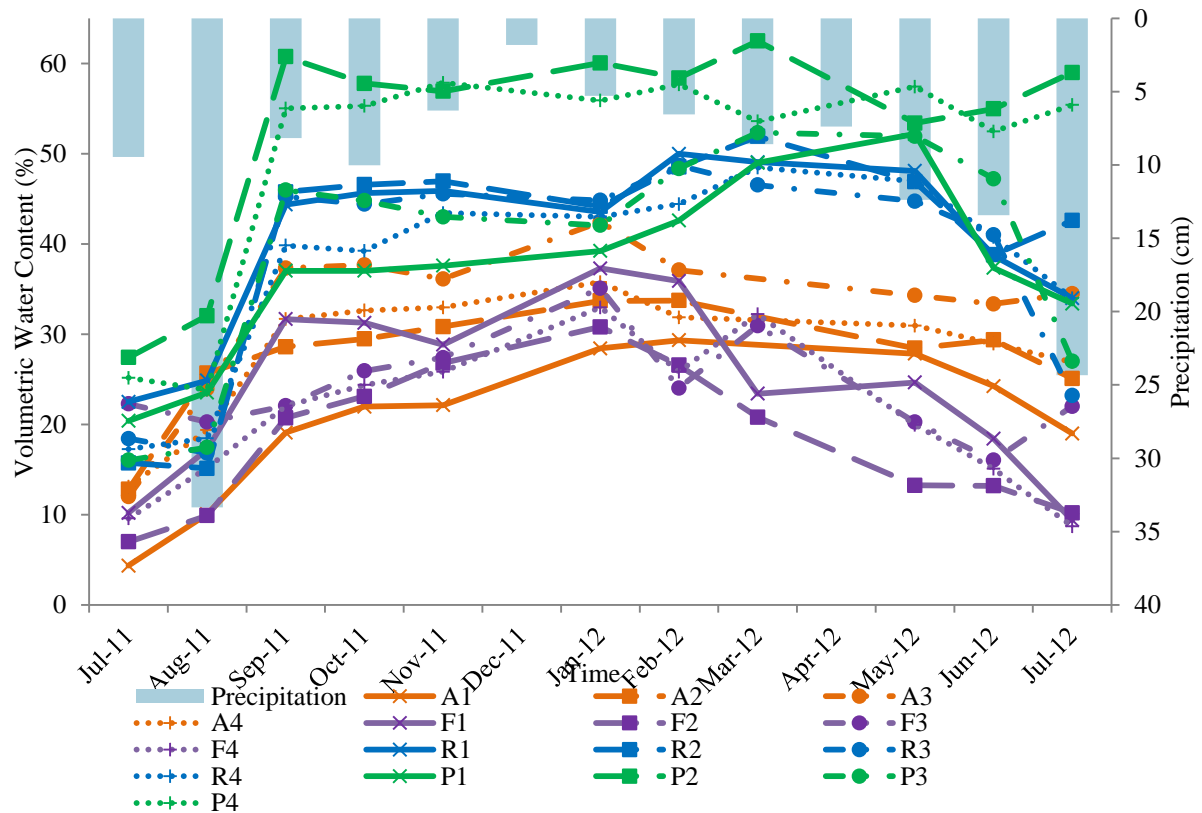
**Figure 6: Monthly average Soil and Air Temperature (°C) from July 2011 to July 2012 in an agricultural field (A), fallow field (F), restored wetland (R), and pocosin (P) by plot number (1-4). For more plot information see Table 1.**



**Figure 7: Soil temperature (°C) averaged by month for each plot. For more plot information see Table 1.**

#### **4.2 Soil Moisture and Saturation**

Volumetric water content was significantly higher in the restored wetland and pocosin than in the agricultural field, which had significantly higher volumetric water content than the fallow field (Figure 4). At the beginning of the study period, volumetric water content was relatively low and less variable than in the later months of observation (Figure 8). After a large amount of precipitation (33cm) in August 2011, volumetric water content increased in all landscapes. In the pocosin and restored wetland, volumetric water content remained high for the rest of the observation period, although it decreased slightly in July 2012. In the fallow field, volumetric water content peaked in January 2012 and declined for the remainder of the observation period. The agricultural field also peaked in volumetric water content in January 2012, but decreased more slowly than the fallow field.

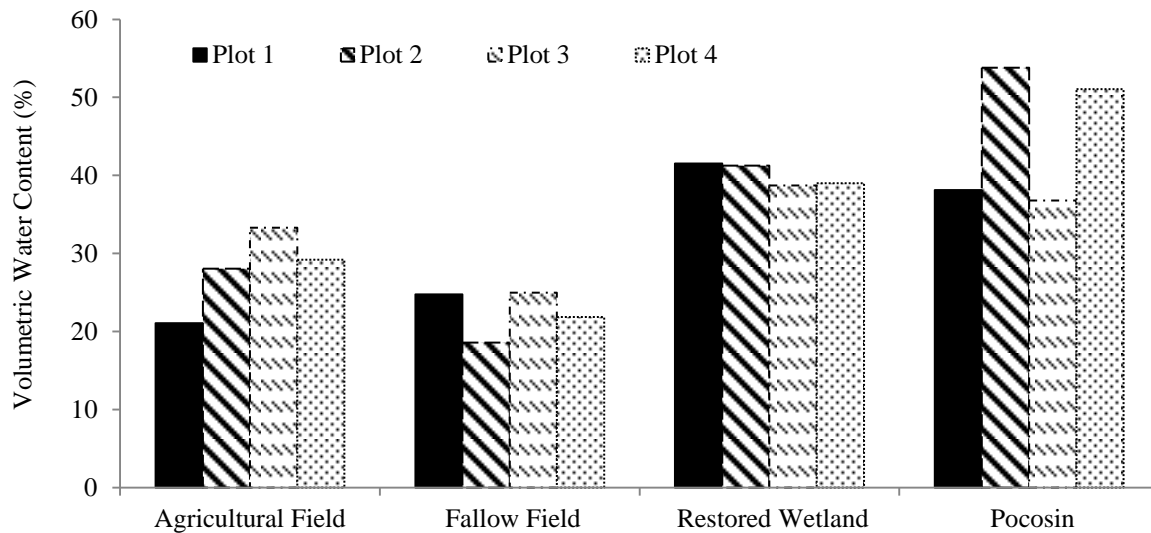


**Figure 8: Monthly average Volumetric Water Content (%) and total monthly precipitation (cm) from July 2011 to July 2012 in an agricultural field (A), fallow field (F), restored wetland (R), and pocosin (P) by plot number (1-4). For more plot information see Table 1.**

We did not detect an effect of distance from ditch on volumetric water content for all sites (Figure 5 and 9), but we did detect variation in volumetric water content for the agricultural field and pocosin. In the agricultural field, Plot 1 had significantly lower volumetric water content than Plot 3 ( $p$ -value  $< 0.01$ ). Neither plot had significantly different volumetric water content from Plots 2 or 4. In the pocosin, Plots 1 and 3 had significantly lower volumetric water content than Plot 2 ( $p$ -value  $< 0.01$ ). Pocosin Plot 4 did not have significantly different volumetric water content from any of



the other plots in the pocosin. The variation in volumetric water content in the agricultural field and pocosin is not clearly due to the presences of the ditch, because the variation is not systematic or changing in the same direction with distance from ditch. The observed variation could be due to microtopographic water storage.

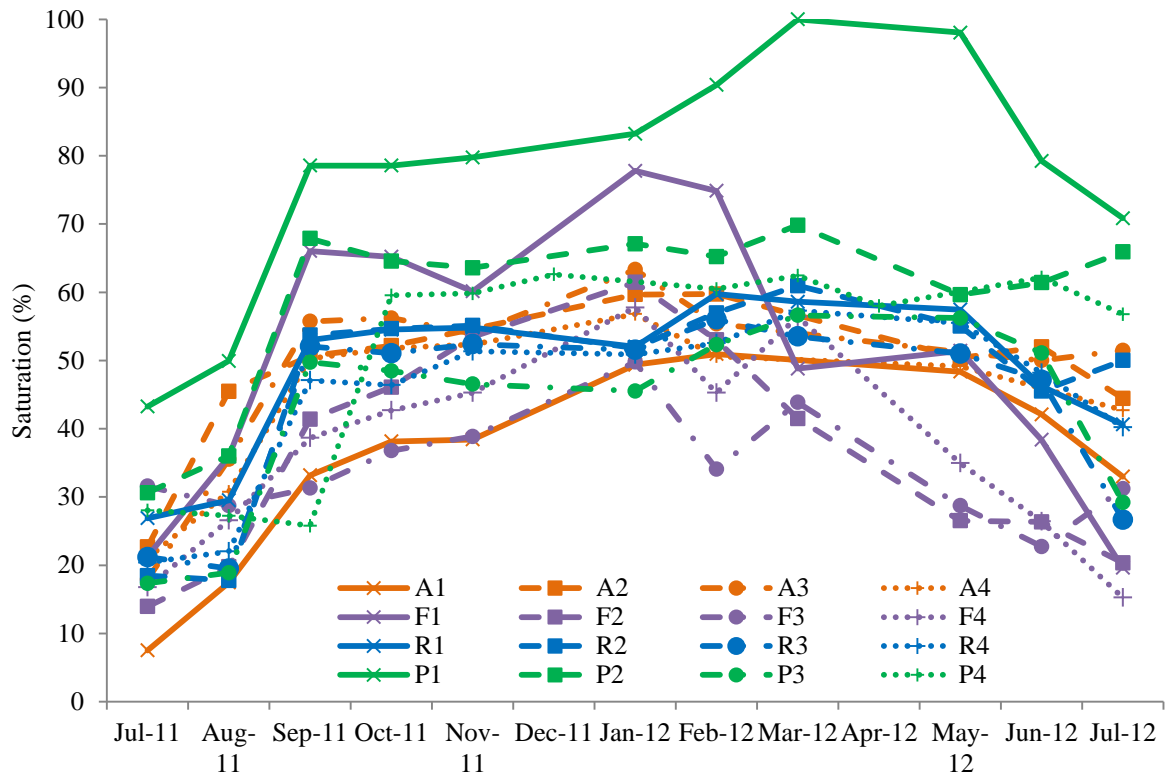


**Figure 9: Volumetric water content (%) averaged by month for each plot. For more plot information see Table 1.**

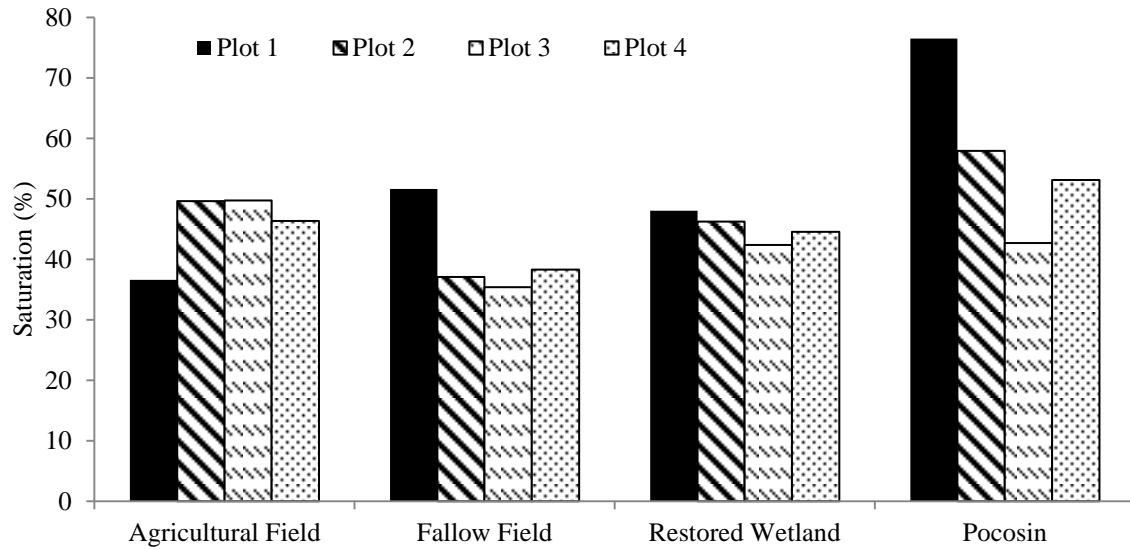
In general, saturation fraction increased through the dormant season and began to decrease with the onset of spring, coming to a low point in July. The pocosin was significantly wetter in terms of saturation fraction than the fallow field and restored wetland, but was not significantly wetter than the agricultural field (Figure 4 and 10). The agricultural field was not significantly wetter than the

restored wetland or fallow field. Pocosin Plot 1 maintained the highest level of saturation fraction throughout the entire observation period, reaching full saturation (100%) in March 2012.

Saturation fraction varied significantly by plot among all landscapes with Plot 1 having the highest saturation fraction and Plot 3 having the lowest saturation fraction (Figure 5 and 11). Plot 1 has the highest saturation fraction among plots for all sites except the agricultural field, where Plot 1 was the driest. Like soil moisture, saturation fraction also varied significantly among plots in the agricultural field and pocosin. Saturation did not vary significantly by plot within the fallow field or restored wetland. In the agricultural field, Plot 1 had significantly lower saturation than Plots 2 and 3 ( $p$ -value  $< 0.05$ ). No plot within the agricultural field had significantly different saturation from Plot 4. In the pocosin, Plot 3 had significantly lower volumetric water content than Plots 1 and 2 ( $p$ -value  $< 0.01$ ), but no plot was significantly different from Plot 4.



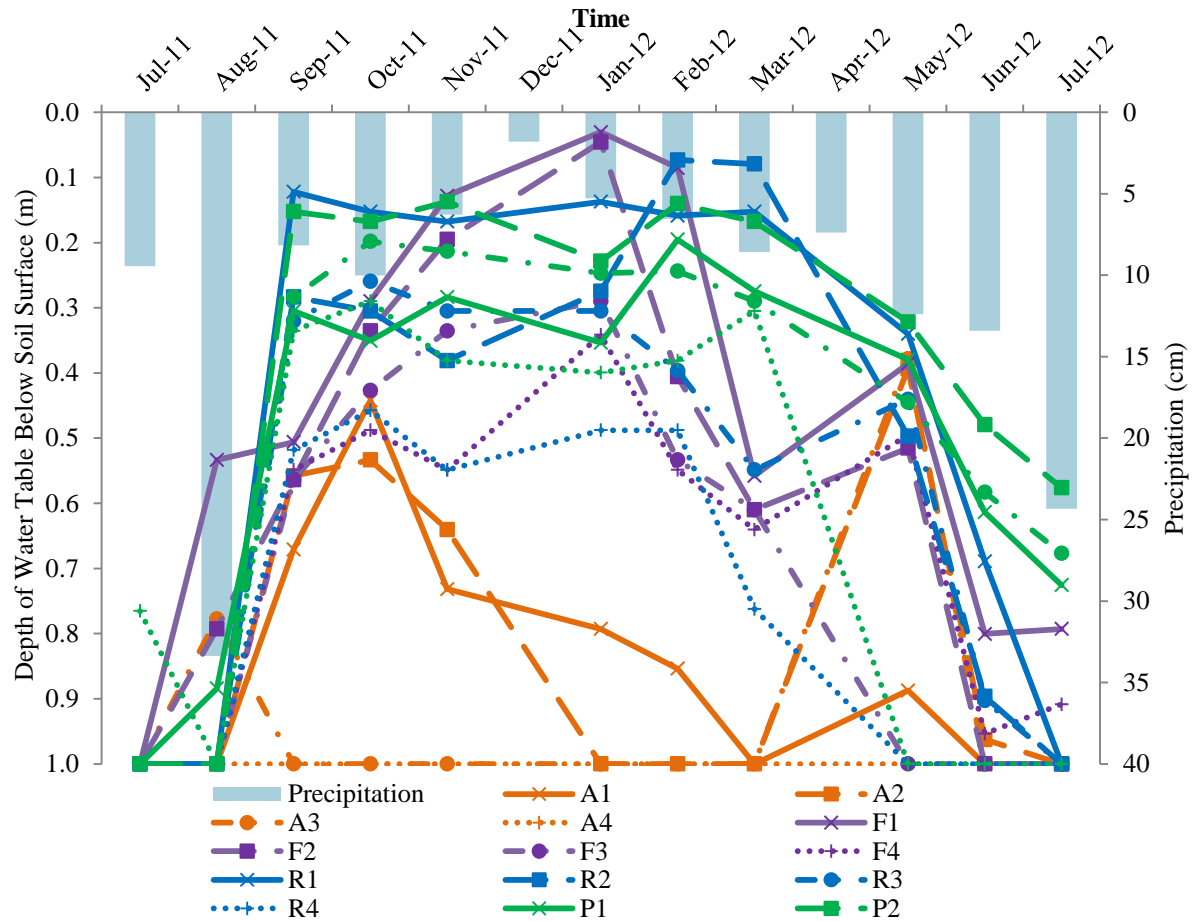
**Figure 10: Monthly average saturation (%) from July 2011 to July 2012 in an agricultural field (A), fallow field (F), restored wetland (R), and pocosin (P) by plot number (1-4). For more plot information see Table 1.**



**Figure 11: Saturation fraction (%) averaged by month for each plot.**

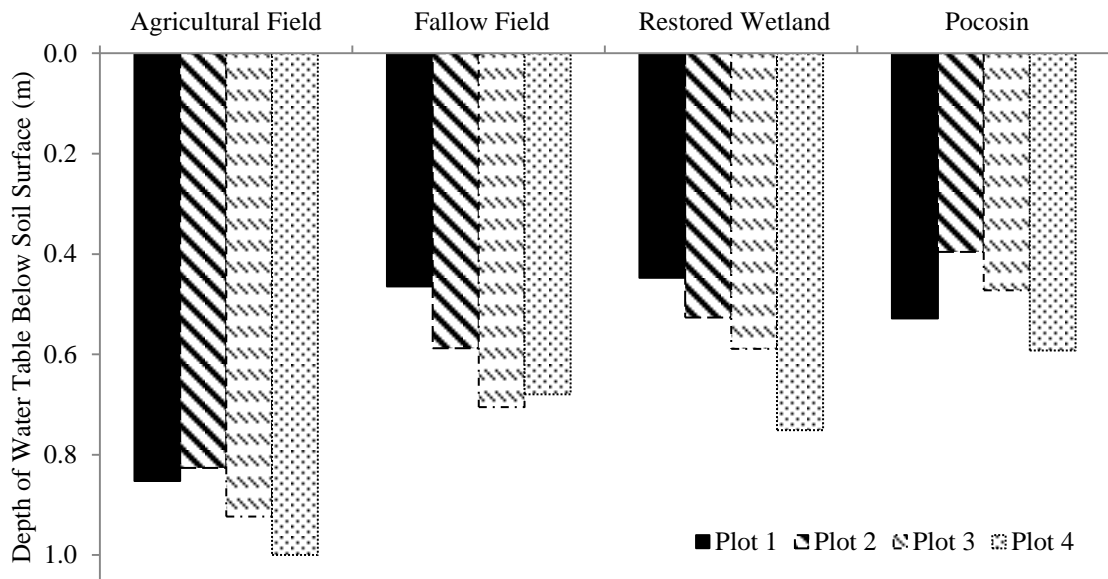
### 4.3 Water Table

The agricultural field had a significantly lower water table than the other three landscapes (Figure 4). In general, the water table rose in late summer 2011 and fell during late spring 2012 (Figure 12). With the 33cm of precipitation in August 2011, all plots except Agricultural Plots 3 and 4 rose. Agricultural Plot 3 actually fell. In May 2012, all plot decreased, except for Agricultural Plot 4. The water table in Agricultural Plot 4 never exceeded the bottom of the well in any measurement.



**Figure 12: Monthly average depth of water table below soil surface (m) and total monthly precipitation (cm) from July 2011 to July 2012 in an agricultural field (A), fallow field (F), restored wetland (R), and pocosin (P) by plot number (1-4). For more plot information see Table 1.**

Water table was significantly affected by plot among all landscapes ( $p$  value  $< 0.05$ ; Figure 5 and 13). Across all landscapes, Plot 1 had a higher water table than Plot 4. Yet, the only landscape in which Plot 1 had the highest water table and Plot 4 the lowest was the restored wetland, in which the ditches were plugged. When assessed within single landscapes, there was no observable response of water table to plot, unlike when assessed across landscapes.



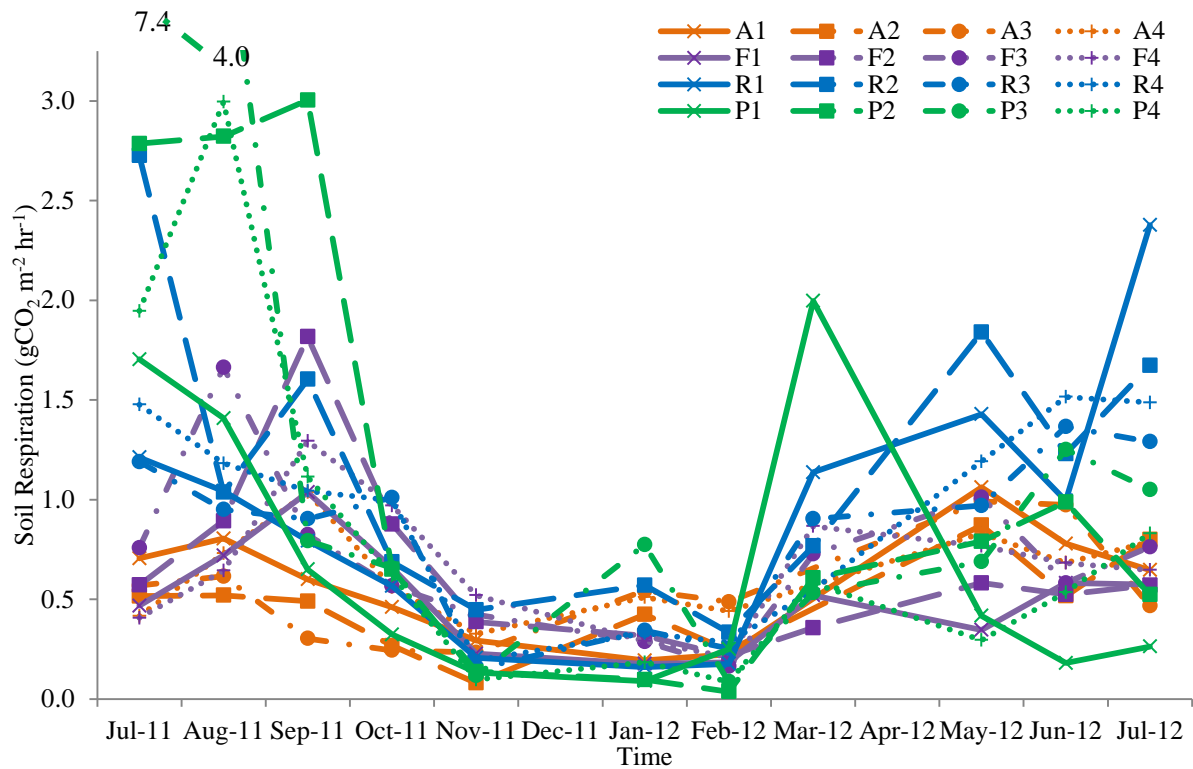
**Figure 13: Depth of water table below soil surface (m) averaged by month for each plot.**

#### **4.4 Soil CO<sub>2</sub> respiration**

Soil CO<sub>2</sub> respiration was significantly higher in the restored wetland and pocosin than the agricultural field and fallow field (Figure 4 and 14). Relatively high rates of soil CO<sub>2</sub> respiration were observed from July through October 2011, but with the onset of winter respiration rates fell considerably. During the following spring (2012), soil CO<sub>2</sub> respiration rates in all landscapes increased compared to the previous dormant season. In the pocosin and restored wetland, respiration rates during summer 2012 did not exceed respiration rates during summer 2011, but in the agricultural field and fallow field, the spring 2012 rates were higher than the summer 2011 rates (Figure 14).

## Data Quality Assurance

The June 27, 2011 Pocasin Plot 3 replicate 2 of soil CO<sub>2</sub> respiration (20.24 gCO<sub>2</sub> m<sup>-2</sup> hr<sup>-1</sup>) failed to pass the Dixon Q-test for outliers and was omitted from the average of that data point. The July 6, 2011 Pocasin Plot 3 replicate 2 (28.45 gCO<sub>2</sub> m<sup>-2</sup> hr<sup>-1</sup>) failed to pass the Dixon Q-test for outliers and was omitted from the average for that data point. The July 27, 2011 Restored Wetland Plot 2 (R2) Respiration replicates 2 (11.8 gCO<sub>2</sub> m<sup>-2</sup> hr<sup>-1</sup>) and replicate 3 (10.4 gCO<sub>2</sub> m<sup>-2</sup> hr<sup>-1</sup>) failed to pass the Dixon Q-test for outliers and thus were not used in analysis. Replicate 1 constitutes the datum for July 27, 2011 R2.



**Figure 14: Monthly average soil CO<sub>2</sub> respiration (gCO<sub>2</sub> m<sup>-2</sup> hr<sup>-1</sup>) from July 2011 to July 2012 in an agricultural field (A), fallow field (F), restored wetland (R), and pocasin (P) by plot number (1-4). For more plot information see Table 1.**

Soil respiration differed slightly by plot among all sites ( $p$  value = 0.051), with Plot 1 having lower respiration than Plot 3 overall (Figure 5 and 15). This pattern is most evident in the pocosin. Soil CO<sub>2</sub> respiration showed a response to plot within the pocosin, where Plot 1 had significantly lower soil CO<sub>2</sub> respiration rates than Plots 2 and 3 ( $p$ -value<0.01). No plot in the pocosin was significantly different from Plot 4. Within any other single landscape there was no effect on soil CO<sub>2</sub> respiration by plot.

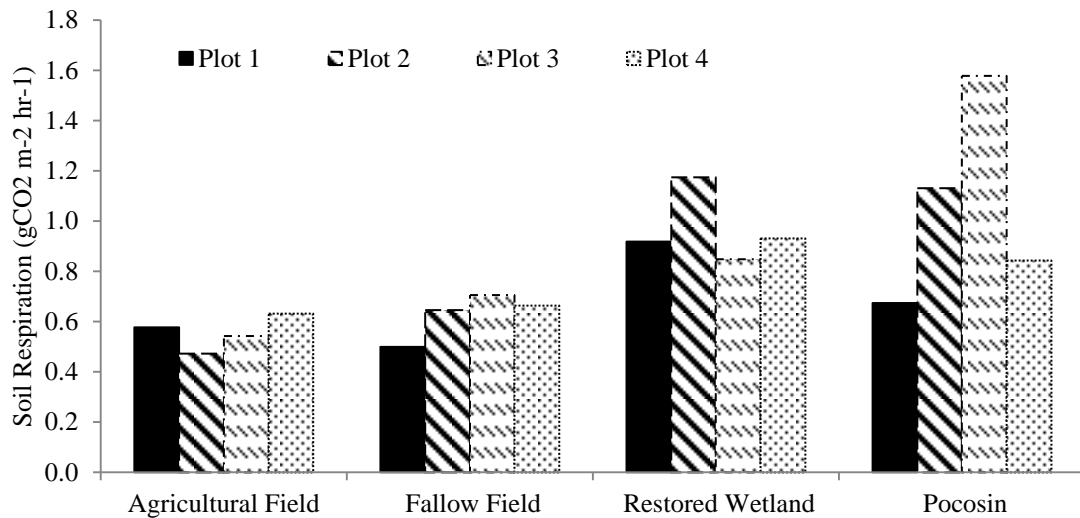


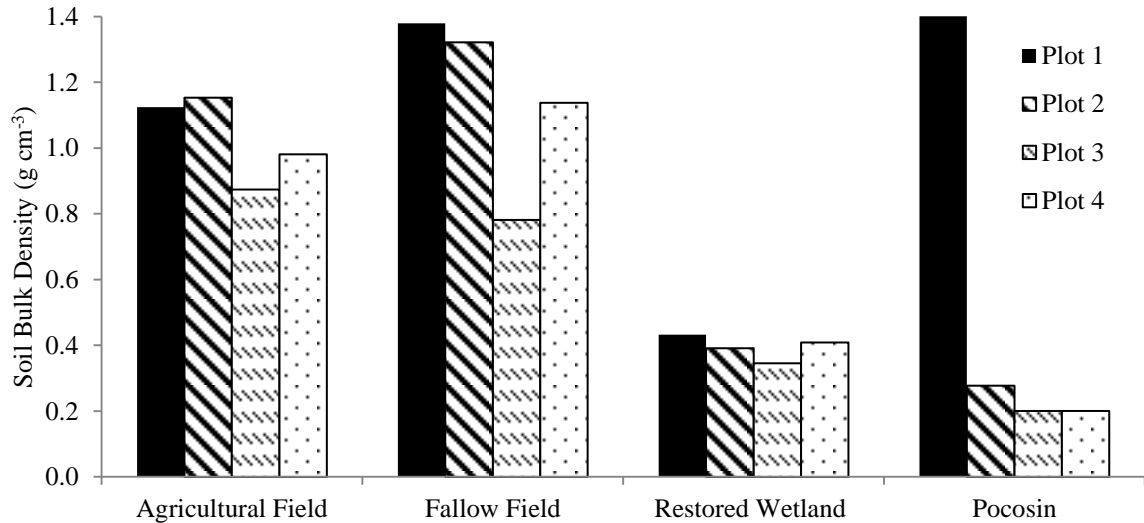
Figure 15: Saturation (%) averaged by month and then by plot.

#### 4.5 Bulk Density

Based on the small sample size of 4 observations per landscape, there is no significant differences between landscapes in terms of bulk density ( $p > 0.05$ ). There was no significant difference in plots among all landscapes ( $p > 0.20$ ). Bulk density appears higher in the agricultural field and



fallow field than the pocosin and restored wetland. Restored wetland had the least variation in bulk density (0.35-0.43 g cm<sup>-3</sup>). Pocosin had the most variation in bulk density (0.20-1.40 g cm<sup>-3</sup>). Plot 1 in the pocosin had the greatest overall bulk density (1.4 g cm<sup>-3</sup>; See Discussion), but the three other plots in the pocosin were the lowest (0.28, 0.20, and 0.20 g cm<sup>-3</sup> for Plots 2, 3, and 4, respectively; Figure 16).

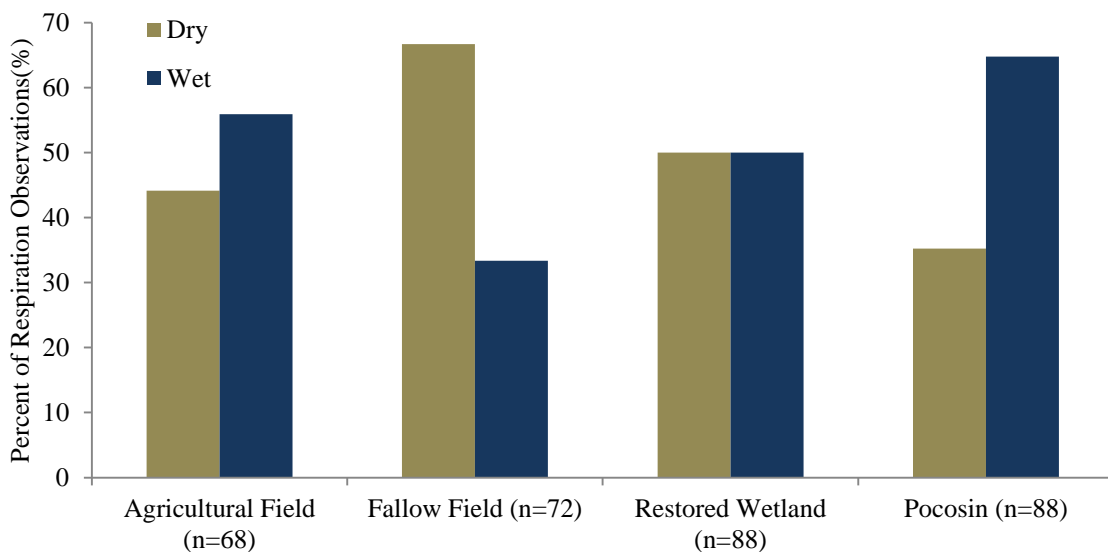


**Figure 16: Soil bulk density (g cm<sup>-3</sup>) of each plot in each landscape.**

#### 4.6 Results of K-means categorization

The K-means function divided the observations into two groups based on saturation. This function determines two means with the lowest residuals. The mean for group 1 was 26.4% (n = 153) and the mean for group 2 was 57.0% (n = 163); as such, group 1 is defined as “Dry” and group 2 as “Wet” for this study. Using the Wilcoxon Rank Sum test, the dry and the wet groups are significantly

different in terms of saturation, and water table depth ( $p < 0.01$ ), but not in terms of soil temperature, or soil CO<sub>2</sub> respiration. Sixty-seven percent of the observations in the fallow field were dry, which was the most of any landscape; the fallow field was the only landscape with more dry observations than wet (Figure 17). Observations in the restored wetland were evenly split, with 50% being dry and 50% being wet. The pocosin and agricultural field had more wet observations — 65% and 56%, respectively — than dry observations. The period from July to August 2011 included mostly dry observation with a few interspersed wet observations (Figure 18). From September 2011 until early May 2012, the observations were mainly categorized as wet. Thereafter, there was a mixture of wet and dry observations.



**Figure 17: Percent of observations that fall into the MATLAB K-means denoted categories of Dry (n=153) and Wet (n=163) based on saturation.**

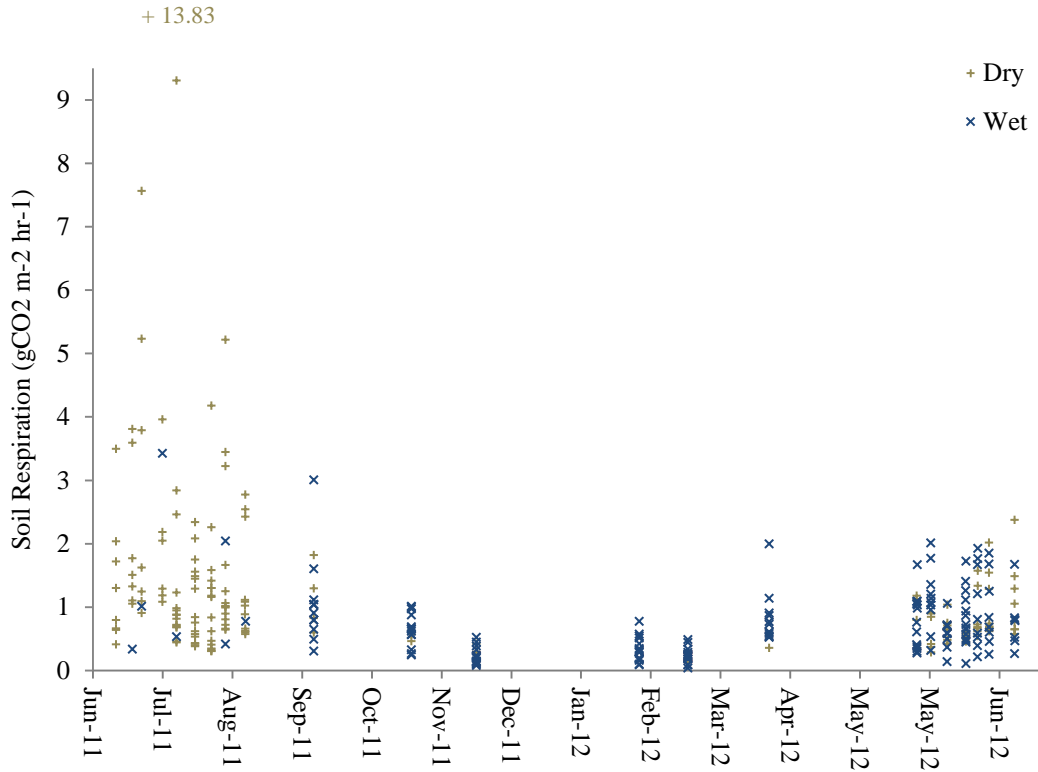


Figure 18: Time series of soil CO<sub>2</sub> respiration categorized by MATLAB K-means denoted categories of Dry (n=153) and Wet (n=163) based on saturation.

#### 4.7 Results of Spearman Regression Analysis

##### *Correlations by Landscape*

Among all landscapes, average air temperature correlates most strongly with soil CO<sub>2</sub> respiration, with a Spearman’s  $\rho$  of 0.50 (Table 2). In the agricultural field, average air temperature and soil temperature were the only variables to correlate significantly with soil CO<sub>2</sub> respiration, with Spearman’s  $\rho$ ’s of 0.32 and 0.30, respectively. In the fallow field, soil CO<sub>2</sub> respiration was correlated

significantly with water table, average air temperature, and soil bulk density, with Spearman's  $\rho$ 's of -0.31, 0.43 and -0.27, respectively. In the restored wetland, soil CO<sub>2</sub> respiration was correlated significantly with all but two variables, precipitation and soil bulk density. Two sets of variables had the strongest correlation in the restored wetland: soil temperature and soil CO<sub>2</sub> respiration on the one hand and average air temperature and soil CO<sub>2</sub> respiration on the other hand, at Spearman's  $\rho=0.58$ . In the pocosin, saturation was correlated most strongly with soil CO<sub>2</sub> respiration, with Spearman's  $\rho$  of -0.71. In dry observations, bulk density was correlated most strongly with soil CO<sub>2</sub> respiration, with Spearman's  $\rho$  of -0.74.

Table 2: Spearman's correlation of Soil CO<sub>2</sub> respiration

	All	Agricultural Field	Fallow Field	Restored Wetland	Pocosin	Dry	Wet
Variables which vary over time and space							
Soil Temperature	0.16	0.30	0.22	0.58	0.21	-0.60	0.50
Volumetric Water Content	-0.15	-0.14	-0.12	-0.26	-0.57	0.46	0.02
Water Table	-0.36	-0.11	-0.31	-0.53	-0.55	-0.20	-0.23
Saturation	-0.36	-0.19	-0.16	-0.26	-0.71	0.08	-0.28
Variables which only vary over time							
Precipitation	0.09	-0.04	0.10	-0.02	0.17	0.09	-0.10
Average Air Temperature	0.50	0.32	0.43	0.58	0.62	0.20	0.56
Variable which only vary over space							
Bulk Density	-0.39	-0.14	-0.27	0.13	-0.22	-0.74	-0.16
	+ $\rho$ & $p < 0.05$				- $\rho$ & $p < 0.05$		

Overall, soil CO<sub>2</sub> respiration was correlated significantly with every variable except for precipitation, which did not correlate significantly with soil CO<sub>2</sub> respiration under any conditions. In the agricultural field, soil CO<sub>2</sub> respiration was only correlated significantly with soil temperature,  $\rho = 0.30$ .

### *Correlations by Variable*

Soil temperature was correlated significantly with soil CO<sub>2</sub> respiration overall ( $\rho = 0.16$ ), in the agricultural field ( $\rho = 0.30$ ), restored wetland ( $\rho = 0.58$ ), dry ( $\rho = -0.60$ ) and wet observations ( $\rho = 0.50$ ), but not in the fallow field or in the pocosin. Dry observations had a negative correlation with soil CO<sub>2</sub> respiration, but all others were positive.

Volumetric soil content was correlated significantly with soil CO<sub>2</sub> respiration overall ( $\rho = -0.15$ ), in the restored wetland ( $\rho = -0.26$ ), pocosin ( $\rho = -0.57$ ), and in dry observations ( $\rho = 0.46$ ). Dry observations were the only variable that was correlated significantly with soil CO<sub>2</sub> respiration to have a positive  $\rho$  value.

Water table was correlated significantly with soil CO<sub>2</sub> respiration overall ( $\rho = -0.36$ ), in the fallow field ( $\rho = -0.31$ ), restored wetland ( $\rho = -0.53$ ), pocosin ( $\rho = -0.71$ ), and wet observations ( $\rho = -0.28$ ), but not in the agricultural field or in dry observations. These negative correlations signify that when the water table rises, or nears the soil surface, soil CO<sub>2</sub> respiration goes down.

Certain variables, namely precipitation and air temperature, varied only among sampling dates, not sampling locations within a landscape. As such, the same value was used for all plots in a landscape on a specific sampling date. Precipitation was not correlated significantly with any landscape and air temperature was correlated significantly with all landscapes.

As bulk density only varied over space, and not time, the same value at each plot was used for every sample for that plot. Bulk density was correlated significantly with soil CO<sub>2</sub> respiration overall ( $\rho=-0.39$ ), in the fallow field ( $\rho=-0.27$ ), pocosin ( $\rho=-0.22$ ), and dry ( $\rho=-0.74$ ) and wet observations ( $\rho=-0.16$ ).

#### 4.8 Results of Modeling

The results of the modeling exercise show that the highest  $r^2$  was attained by fitting Equation 1 to the restored wetland observations ( $r^2=0.61$ ; Table 3). The highest  $r^2$  for Equation 2 was also attained by fitting the restored wetland observations ( $r^2=0.55$ ; Table 4).

Table 3: Data fit to natural logarithm transformed modified-Arrhenius (Equation 1).  $T_0 = 227.13\text{K}$ . Coefficients with  $\pm 95\%$  confidence interval.

	$R_{10}$	$E_0$	Adjusted $r^2$
All	2.9 $\pm 0.6$	146.7 $\pm 64.1$	0.06
Agricultural field	1.9 $\pm 0.6$	168.5 $\pm 77.4$	0.21
Fallow Field	2.1 $\pm 0.6$	132.3 $\pm 74.4$	0.15
Restored Wetland	1.5 $\pm 0.4$	485.8 $\pm 82.5$	0.61
Pocosin	2.1 $\pm 1.1$	428.0 $\pm 210.3$	0.15
Dry	21.3 $\pm 7.1$	-327.3 $\pm 85.6$	0.27
Wet	1.5 $\pm 0.3$	347.0 $\pm 84.0$	0.29

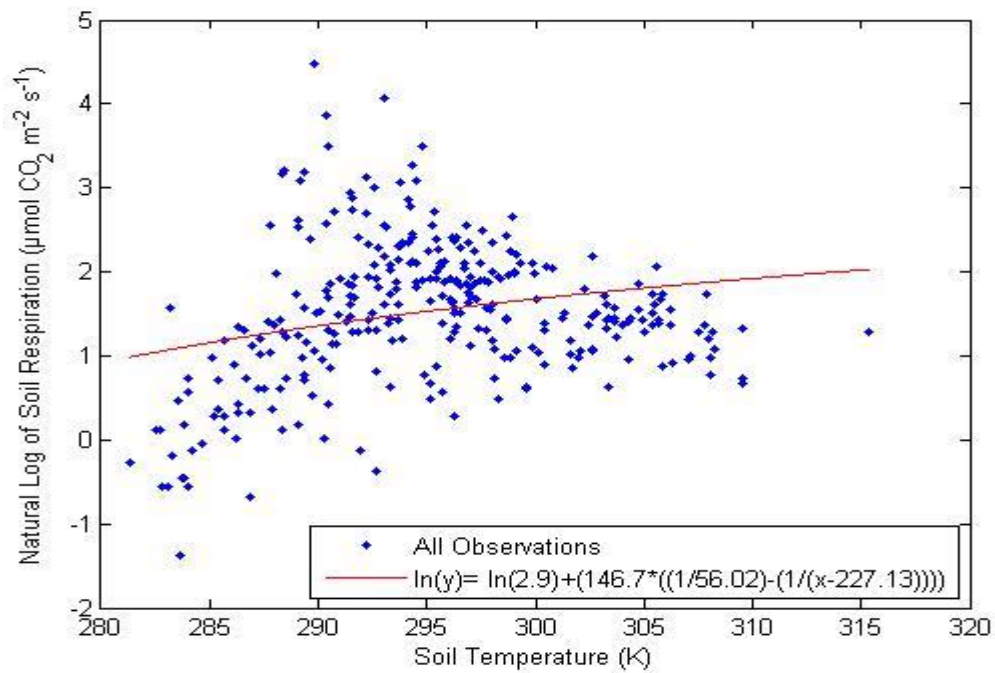
Table 4: Data fit to natural logarithm transformed Q10 (Equation 2). Coefficients with  $\pm 95\%$  confidence interval.

	$R_0$		Q		K		Adjusted $r^2$
All	0.71	$\pm 0.59$	0.09	$\pm 0.02$	-0.77	$\pm 5.71$	0.35
Agricultural field	0.93	$\pm 0.98$	0.05	$\pm 0.03$	-3.09	$\pm 5.06$	0.23
Fallow Field	0.81	$\pm 0.76$	0.06	$\pm 0.03$	-3.76	$\pm 4.15$	0.27
Restored Wetland	0.72	$\pm 0.63$	0.09	$\pm 0.02$	-2.90	$\pm 4.46$	0.55
Pocosin	526.90	$\pm 6.9E+05$	0.12	$\pm 0.05$	15210	$\pm 2.0E+07$	0.51
Dry	400.50	$\pm 2.9E+05$	0.13	$\pm 0.07$	11600	$\pm 8.5E+06$	0.00
Wet	1.03	$\pm 1.15$	0.08	$\pm 0.02$	2.24	$\pm 11.57$	0.34

*Fit by Landscape*

*Overall*

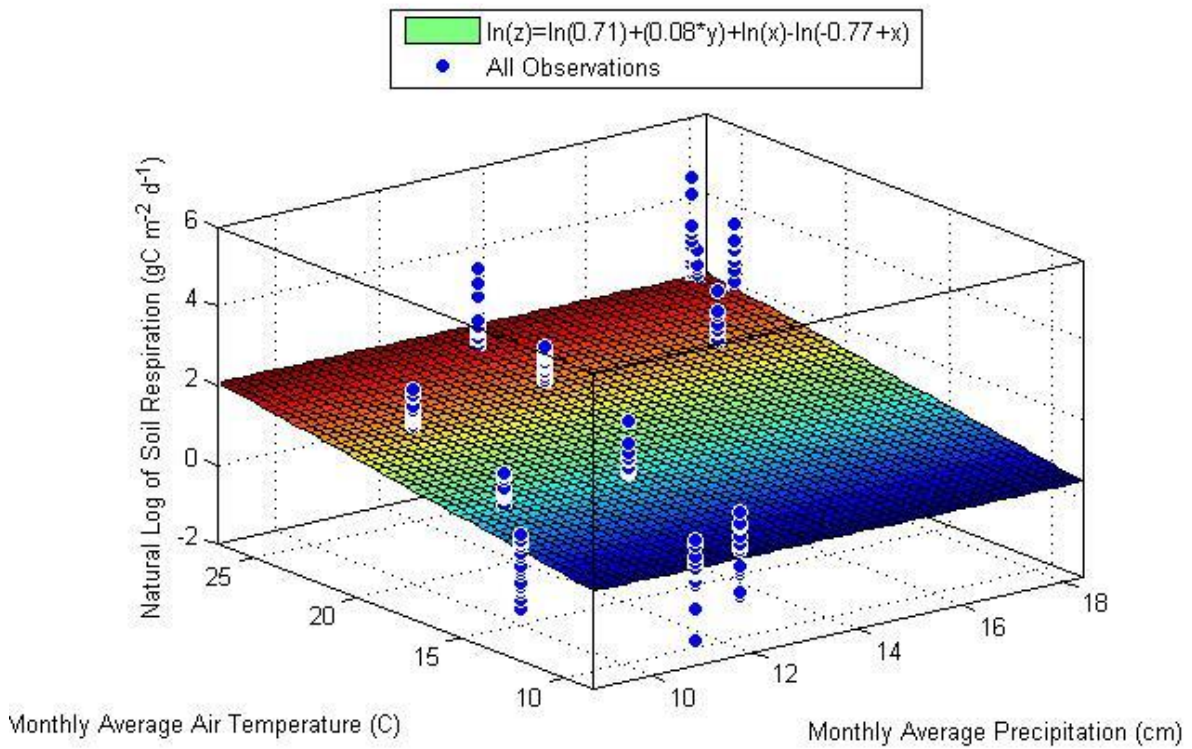
Equation 1 overestimates soil CO<sub>2</sub> respiration at relatively low temperatures and relatively high temperatures when fit to all observations and thus has a low  $r^2$  of 0.06 (Figure 19).



**Figure 19: Equation 1 fit to all observations.  $r^2=0.06$**

Equation 2, when fit to all observations, has an  $r^2$  of 0.35 (Figure 20). Equation 2 shows that soil CO<sub>2</sub> respiration responds more to average monthly air temperature than average monthly precipitation. An increase in average monthly precipitation actually decreases soil CO<sub>2</sub> respiration.





**Figure 20: Equation 2 fit to all observations.  $r^2=0.35$**

***Agricultural Field***

In the agricultural field, Equation 1 fits the data with an  $r^2 = 0.21$  (Figure 21). As temperature increases in the agricultural field, soil CO<sub>2</sub> respiration tends to increase. Figure 22 shows that the data from the agricultural field are described by Equation 2 with an  $r^2 = 0.23$ . Monthly average precipitation slightly decreases soil CO<sub>2</sub> respiration in the agricultural field, whereas monthly average air temperature increases soil CO<sub>2</sub> respiration (Figure 22).

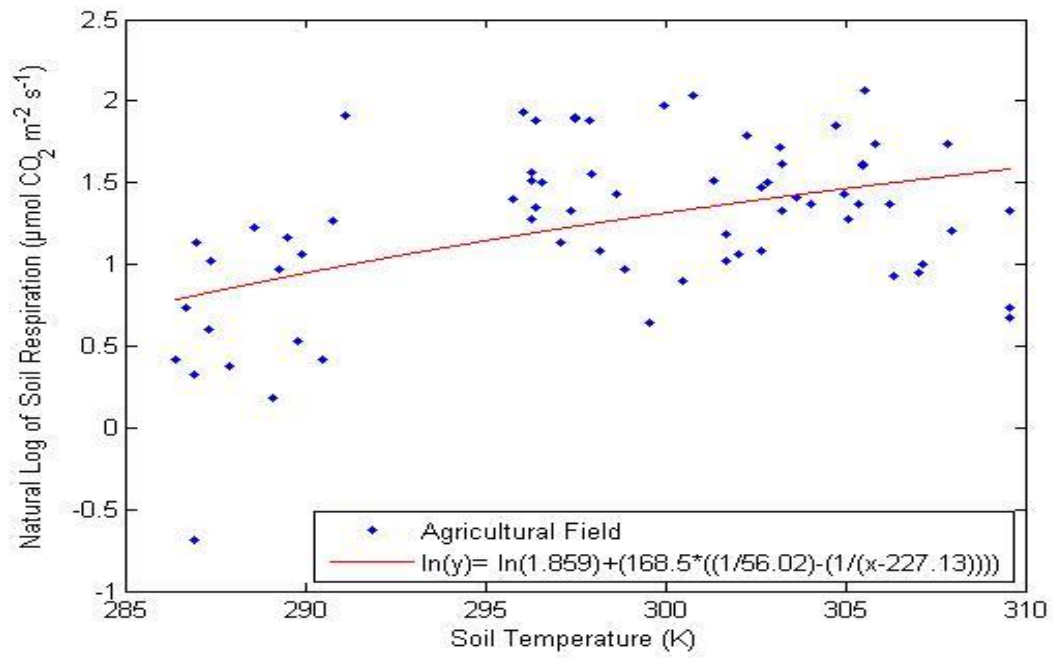
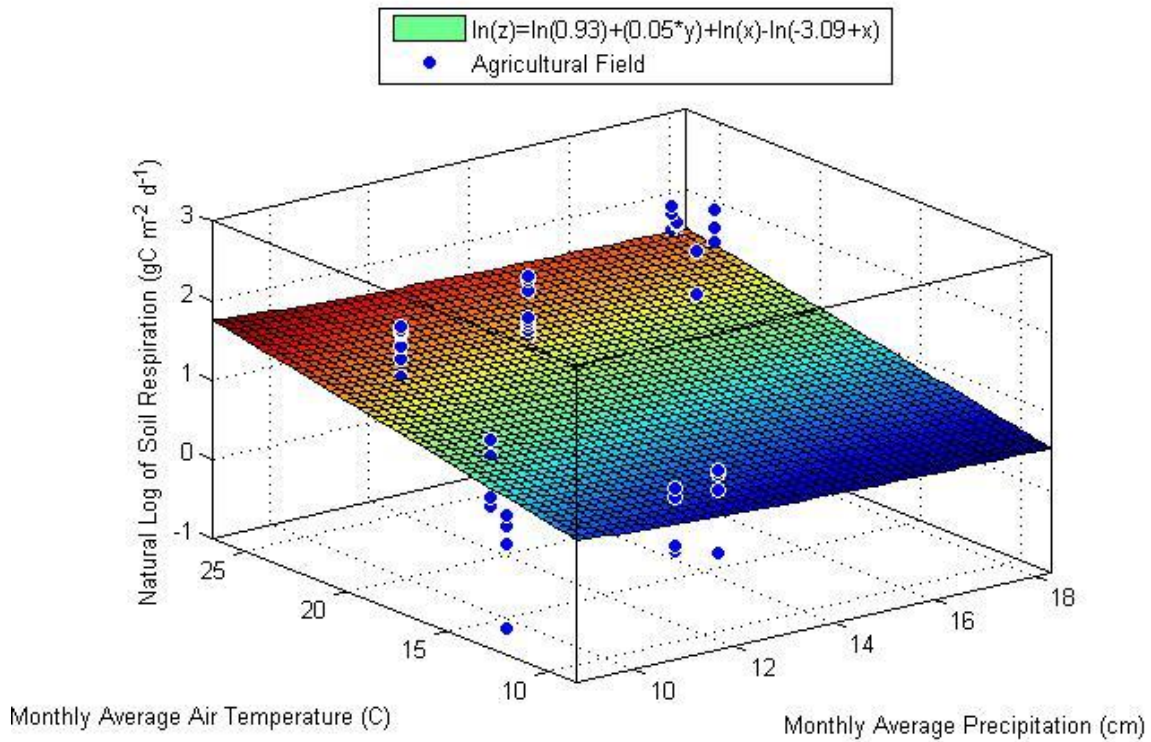


Figure 21: Equation 1 fit to observations in the agricultural field.  $R^2=0.21$



**Figure 22: Equation 2 fit to observations in the agricultural field.  $R^2=0.23$**

### ***Fallow Field***

The relationship for the fallow field, when described by Equation 1, has an  $r^2$  of 0.15 and, when described by Equation 2, has an  $r^2$  of 0.27. There is a large spread of soil respirations at intermediate temperature ranges, which may reduce the quality of fit (Figure 23). In general, though, increasing soil and monthly average air temperature increases soil CO<sub>2</sub> respiration (Figure 23 and 24). Increasing average monthly precipitation decreases soil respiration in the fallow field (Figure 24).

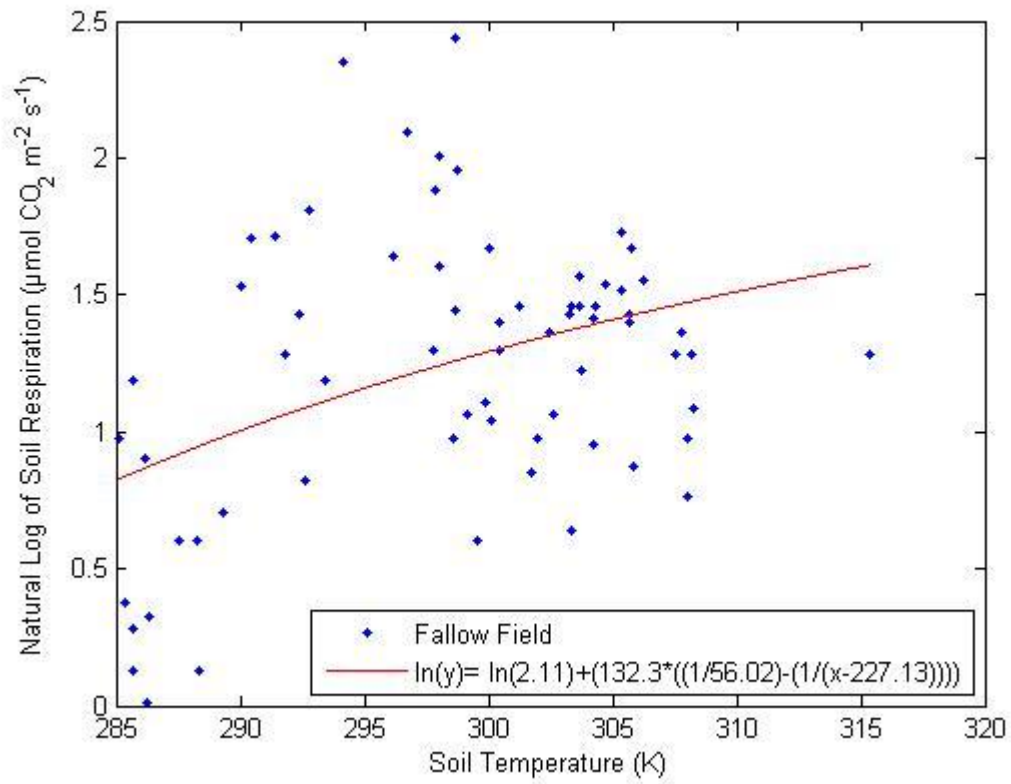
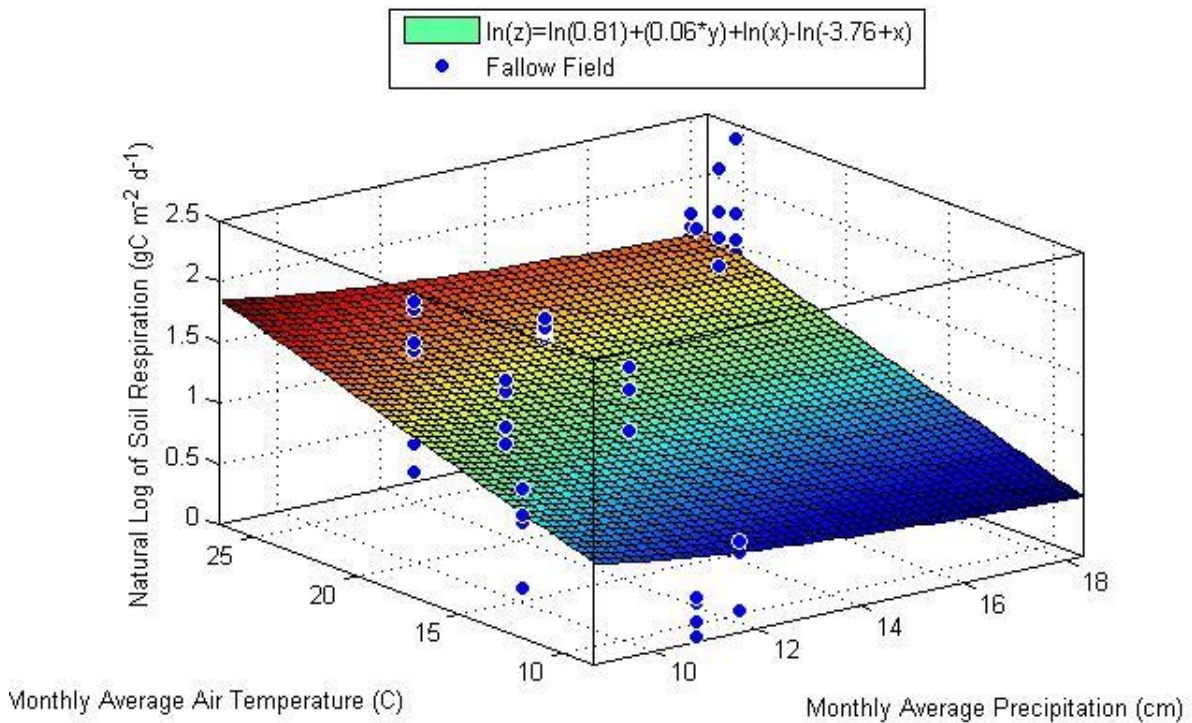


Figure 23: Equation 1 fit to observations in the fallow field.  $R^2=0.15$



**Figure 24: Equation 2 fit to observations in the fallow field.  $R^2=0.27$**

### ***Restored Wetland***

Equation 1 describes the restored wetland data very well with an  $r^2$  of 0.61 (Table 3). Out of all the landscapes, there is the steepest slope in Equation 1 in the restored wetland, indicating that the greatest response of soil  $\text{CO}_2$  respiration to soil temperature occurs in the restored wetland (Figure 25). Equation 2 describes the data from the restored wetland better than it does any other landscape ( $r^2=0.55$ ; Table 4). In the restored wetland, increasing average monthly precipitation slightly

decreases soil CO<sub>2</sub> respiration, whereas increasing monthly average air temperature dramatically increases soil CO<sub>2</sub> respiration (Figure 26).

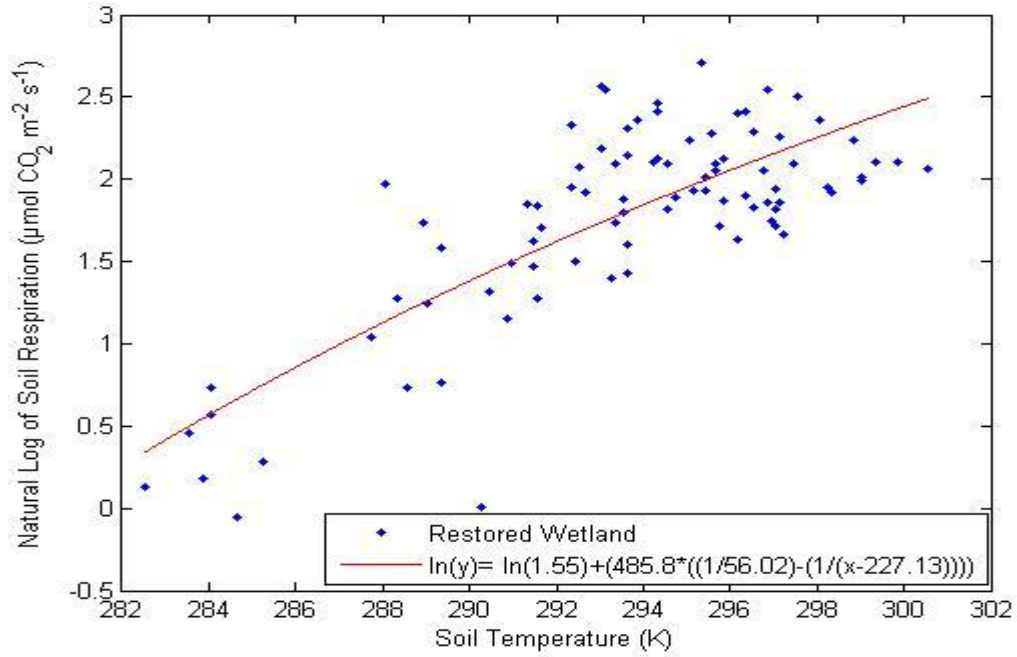
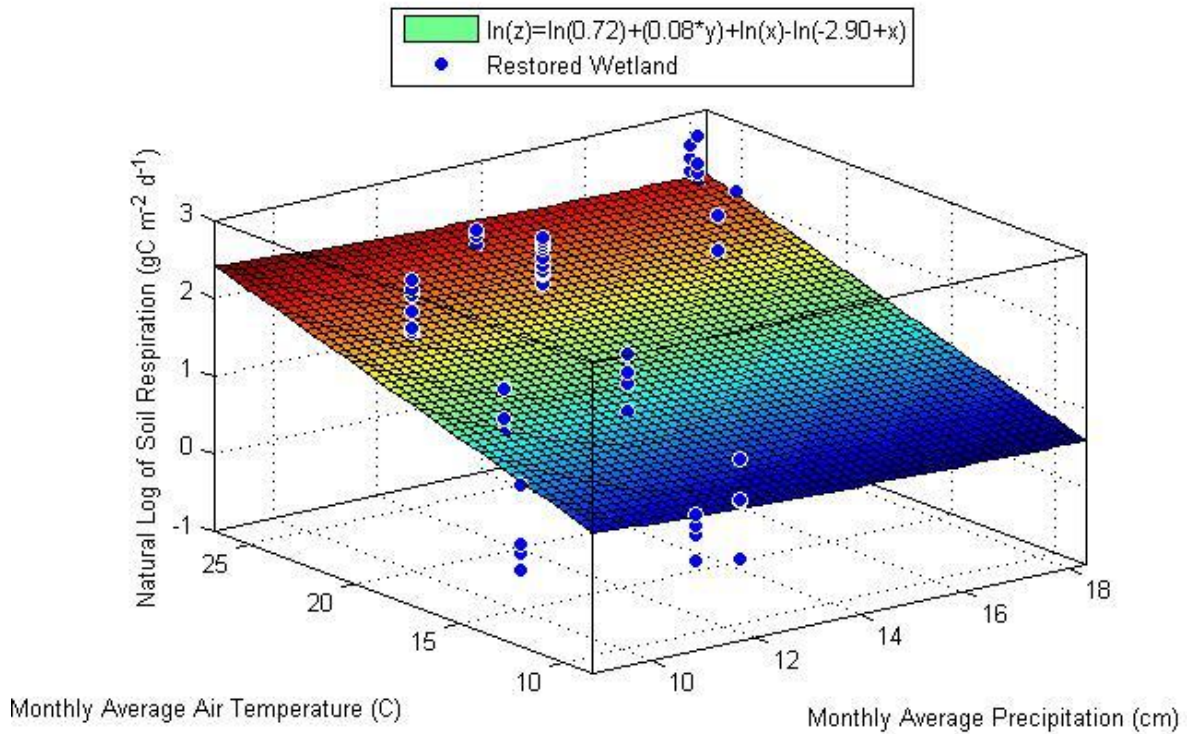


Figure 25: Equation 1 fit to observations in the restored wetland.  $R^2=0.61$



**Figure 26: Equation 2 fit to observations in the restored wetland.  $R^2=0.55$**

### *Pocosin*

Equation 1 over-predicts soil CO<sub>2</sub> respiration at lower soil temperatures in the pocosin (Figure 27). In the pocosin, there was a large spread of soil CO<sub>2</sub> respiration rates at intermediate soil temperatures, resulting in an  $r^2 = 0.15$  for Equation 1 (Table 3). For Equation 2, the  $r^2$  is equal to 0.51 for the pocosin (Table 4). This is the only landscape where the Equation 2 predicts an increase of soil CO<sub>2</sub> respiration with an increase in monthly average precipitation (Figure 28).

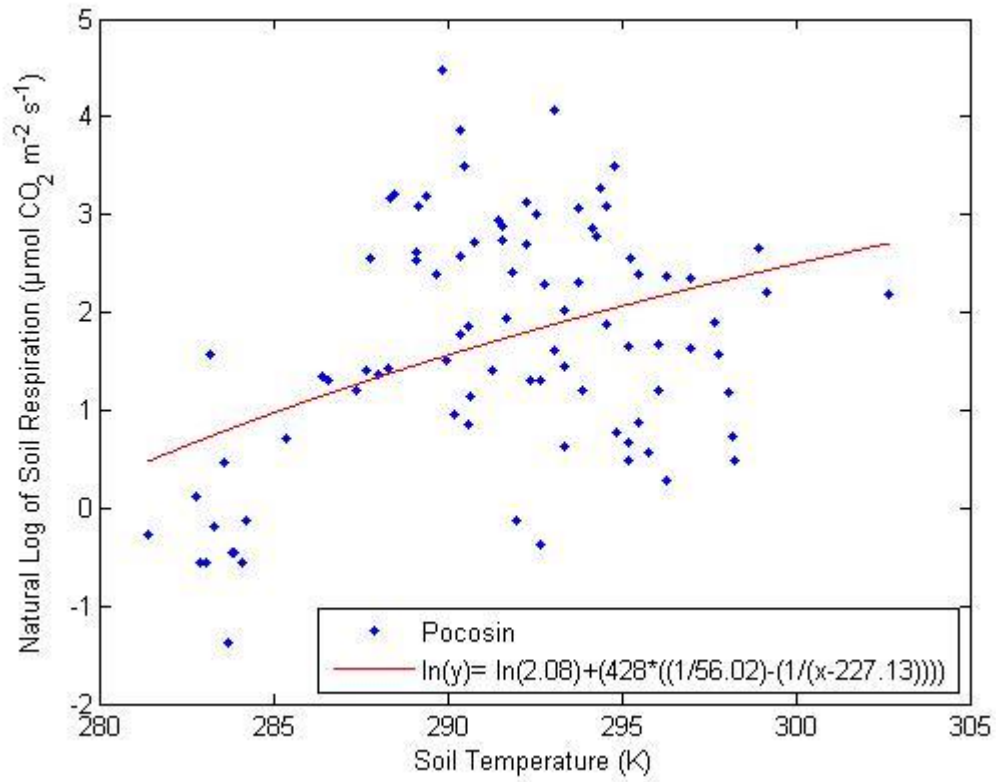
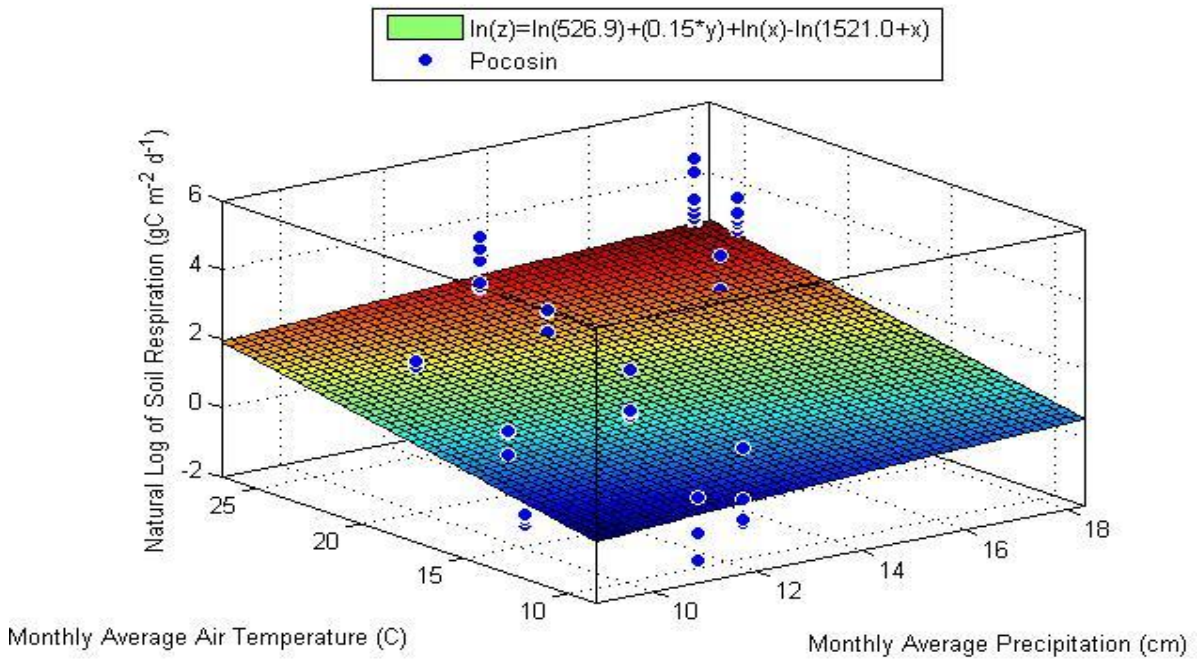


Figure 27: Equation 1 fit to observations in the pocosin.  $r^2=0.15$





**Figure 28: Equation 2 fit to observations in the pocosin.  $r^2=0.51$**

### *Dry Observations*

The dry observations show that when soil temperature increases, soil  $\text{CO}_2$  respiration decreases (Figure 29). With an  $r^2$  of 0.27, Equation 1 predicts soil  $\text{CO}_2$  respiration in dry observations at higher temperatures better than at lower temperatures (Figure 29). Equation 2 fails to meaningfully predict soil  $\text{CO}_2$  respiration in dry observations, with an  $r^2=0.00$  (Figure 30).

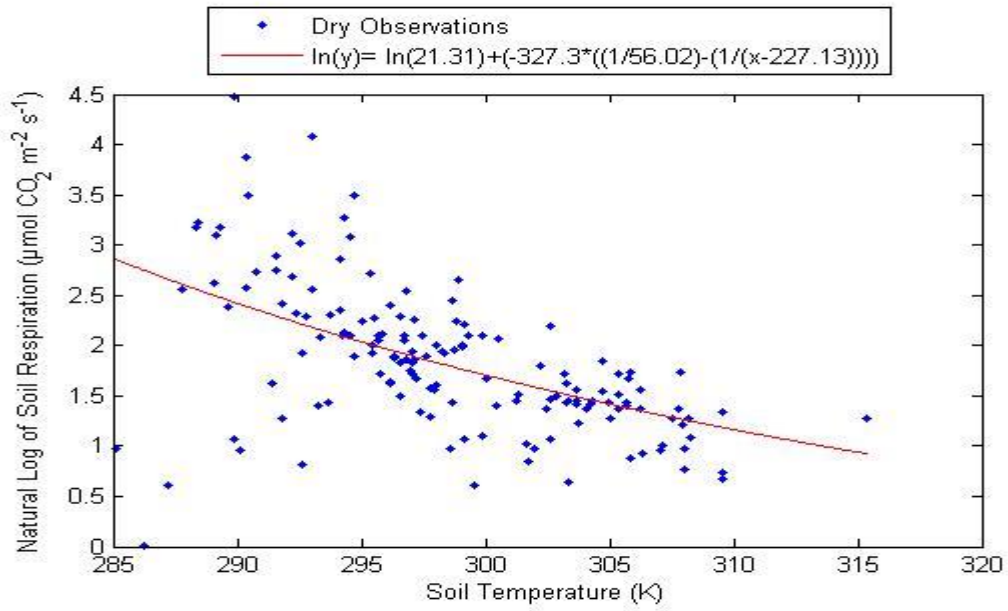
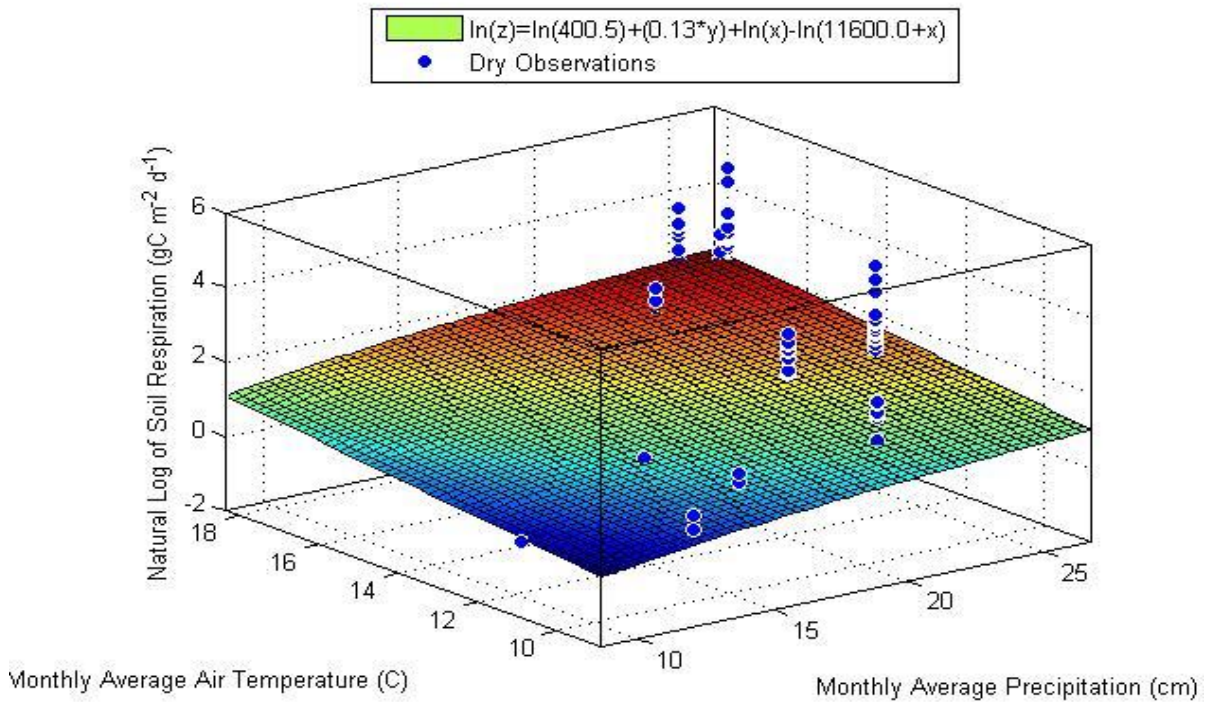


Figure 29: Equation 1 fit to dry observations.  $r^2=0.27$



**Figure 30: Equation 2 fit to dry observations.  $r^2=0.00$**

### *Wet Observations*

For wet observations, Equation 1 may slightly over-predict soil CO<sub>2</sub> respiration at lower and higher temperatures, with an  $r^2 = 0.29$  (Figure 31). Equation 2 does a slightly better job of predicting soil CO<sub>2</sub> respiration in wet observations, with an  $r^2 = 0.34$  (Table 4). Monthly average precipitation increases soil CO<sub>2</sub> respiration only slightly, whereas monthly average air temperature has a significant effect on soil CO<sub>2</sub> respiration (Figure 32).

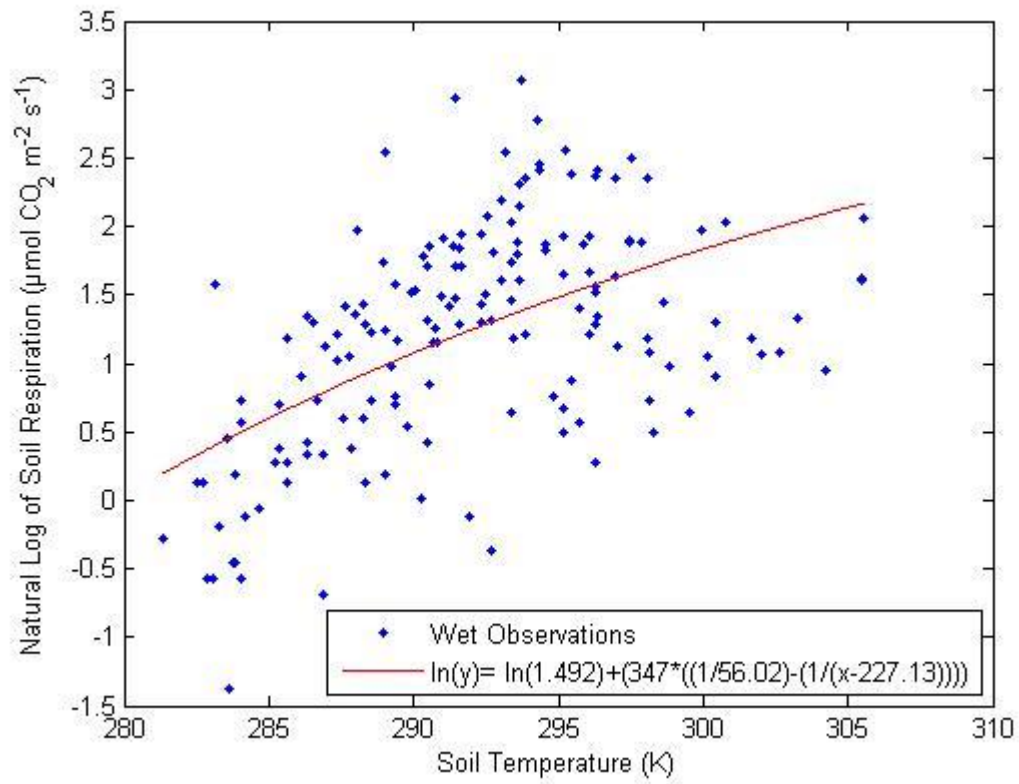
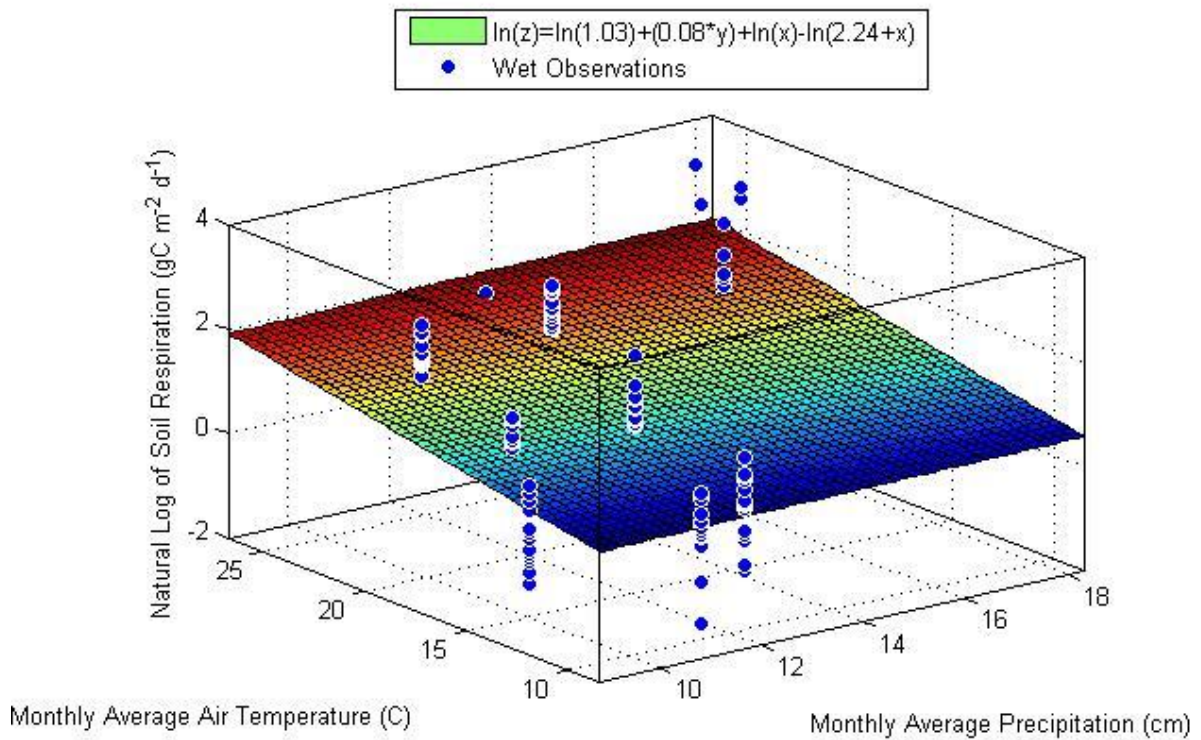


Figure 31: Equation 1 fit to wet observations.  $r^2=0.29$



**Figure 32: Equation 2 fit to wet observations.  $r^2=0.34$**

The results of the model fitting exercise demonstrate that overall the Q10 describes soil  $\text{CO}_2$  respiration better than the modified-Arrhenius (Tables 3 and 4). The only landscape that Equation 1 describes better than Equation 2 is the restored wetland. As between dry and wet observations, Equation 1 describes dry observations better and Equation 2 describes wet observations better.

## 5.0 Discussion

### 5.1 How do soil temperature, soil moisture and water table vary across landscapes?

In general, soil temperature, soil moisture and water table do vary across landscapes, with the wetlands (pocosin and restored wetland) and agriculture related fields (agricultural field and fallow field) having differences in many measured variables.

This difference in temperatures comports with the findings of Morse et al. (2012) that soil temperature was higher in agricultural sites than in wetland sites. The temperature difference may be due to vegetation in the pocosin and restored wetland shading the soil year round. Whereas in the agricultural field vegetation only shaded the soil during the growing season, and in the fallow field vegetation was sparse. Furthermore, the significantly higher water table in the pocosin, restored wetland and fallow field may have shifted the energy balance towards latent heat flux. The sparse vegetation, in the fallow field, exposing the bare Pantego mucky loam and Rains fine sandy loam soils could have allowed for less energy reflectance due to the low albedos of the black and very dark gray colors of the soils, respectively. The heat stored in the soils could have been transferred to latent heat due to the high water table in the fallow field increasing evaporation, and thus decreasing soil moisture explaining the discrepancy in the fallow field having both a relatively high water table and relatively low soil moisture.

The effect of higher soil temperature increasing soil CO<sub>2</sub> respiration was not seen in the agricultural field and fallow field, however, because saturation is below the optimal range of 50%–80% (Skopp et al., 1990; Raich and Potter, 1995; Riveros-Iregui et al., 2012). Saturation is not

significantly different between the agricultural field and the pocosin. This is probably because of land use, as agricultural practices are known to compact soil and destroy soil structure (Bruland et al., 2003).

## **5.2 How well do these environmental state factors explain the variation in soil CO<sub>2</sub> respiration?**

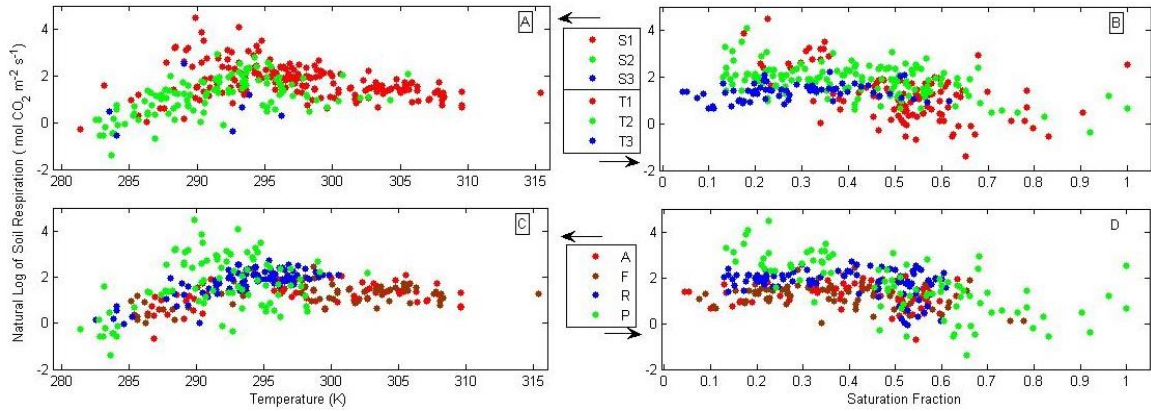
This study set about answering this question using Spearman's correlations, a modified – Arrhenius equation, and a Q10. All of the environmental state factors were significantly correlated among all sites. However, none of them correlated to all landscapes individually. Air temperature was the only variable to correlate significantly with all landscapes (Table 2). Equation 2 described respiration better among all landscapes and in the pocosin (Table 3 and 4). This aligns with Raich and Potter (1995), who found that their equation explained soil CO<sub>2</sub> respiration variation better globally than Lloyd and Taylor's equation 11 (1994). Yet, the modified-Arrhenius explained soil CO<sub>2</sub> respiration better in the restored wetland and dry observations. In the other modeled groups (agricultural field, fallow field, and wet observations) there was not a significant difference in the two equations. The negative slope of the dry observation modified-Arrhenius (Figure 29) suggests that temperature suppression of soil CO<sub>2</sub> respiration changes based on saturation, to be expounded upon below.

Soil CO<sub>2</sub> respiration was not correlated significantly with soil temperature in the pocosin, which is contrary to results of prior research (e.g. Bridgham and Richardson, 1992; Updegraff et al., 2001). It was correlated significantly with average air temperature, however, suggesting that most of the respiration in this pocosin may have come from autotrophic respiration. Nevertheless, saturation was correlated most strongly with soil CO<sub>2</sub> respiration in the pocosin, suggesting that during much of the year respiration is gas diffusion limited.

Among all sites except the fallow field, water table correlated significantly with soil CO<sub>2</sub> respiration (Spearman's  $\rho$  of -.036). By contrast, Updegraff et al. (2001) found that water table is not a significant source of variation for ecosystem respiration. Bridgham et al. (1991) found that water table has no effect on decomposition in natural pocosins, giving credence to the argument that autotrophic respiration dominates in natural pocosins. Water table was correlated strongly with soil CO<sub>2</sub> respiration in the restored wetland and pocosin in this study, and it should be further evaluated for its correlations with net ecosystem exchange in this region (i.e., Hirano et al., 2012). In addition, soil moisture was significantly correlated with soil CO<sub>2</sub> respiration in the pocosin (contra Bridgham and Richardson, 1992), although precipitation did not correlate with soil respiration overall (contra Raich and Potter, 1995).

Among all landscapes, Equation 1 overestimated soil CO<sub>2</sub> respiration at both ends of the temperature spectrum (Figure 19). After the peak in soil respiration observed in Figure 19 maximum respiration rates generally decrease with increasing temperature while minimum respiration rates generally increase. This can be explained by the saturation fraction with optimal saturation (0.50-0.80) continuing to rise with increased temperature, and saturation limited ( $s < 0.50$ ) decreasing with increasing temperature (Figure 33A). Temperature and saturation, among all sites, were correlated with a Spearman's  $\rho$  of -0.48 ( $p < 0.01$ ) explaining why the higher saturation occur at lower temperatures (Figure 33A) and vice versa (Figure 33B). The wide scatter of the soil CO<sub>2</sub> respiration in the pocosin (Figure 27 and Figure 33C), especially at intermediate soil temperatures, exhibit limited saturation, optimal saturation and saturation suppressed soil CO<sub>2</sub> respiration (Figure 33A and 33C).





**Figure 33: Temperature (K) and saturation fraction (s) effects on soil CO<sub>2</sub> respiration. Subplot A shows saturation groups S1 (n=197;  $s < 0.50$ ), S2 (n=123;  $0.50 < s < 0.80$ ), and S3 (n=8;  $s > 0.80$ ). Subplot B shows temperature groups T1 (n=103; mean=288K), T2 (n=155; mean=296K), and T3 (n=69; mean=305K). Subplots C and D show the same observations as subplots A and B, respectively, but when grouped by site; A for agricultural field, F for Fallow Field, R for restored wetland and P for pocosin.**

In terms of explaining variation in soil CO<sub>2</sub> respiration through the Q10 model (Equation 2), the wetland ecosystems had the highest coefficients of variance. Equation 2 takes into account monthly average air temperature and monthly average precipitation, which were strongly correlated to each other with a Spearman's  $\rho$  of 0.84. Increases in monthly average precipitation, and thus monthly average air temperature, result in decreases of soil CO<sub>2</sub> respiration in the agricultural field (Figure 22) and in the fallow field (Figure 24). However, an increase in saturation fraction shows no clear relationship to soil CO<sub>2</sub> respiration in the agricultural field, nor in the fallow field (Figure 33D). When temperature is categorized into relatively low, intermediate and high using the k-means functions in MATLAB, we find that low and intermediate temperature respond negatively or moderately to not at all to increases in saturation (Figure 33B; T1 and T2, respectively). However, in

observations with relatively high soil temperature, increases in saturation result in increases in soil CO<sub>2</sub> respiration (Figure 33B; T3), these observations are primarily in the agricultural (32/69) and fallow fields (35/69) (Figure 33D).

### **5.3 How are these environmental state factors affected by the presence of artificial drainage?**

The only measured variable to be clearly affected by the presence of artificial drainage was water table (Figure 5). Although saturation shows plot-to-plot variation we cannot say this variation is due to the artificial drainage. The unsystematic variation in saturation (Plots 1 and 3 differing, but not plots 2 and 4; Figure 5) shows natural landscape variation and the high spatial heterogeneity of the Hofmann Forest pocosin (Anderson, 2004; unpublished Ph.D. dissertation). The effect of artificial drainage on the water table warrants further investigation.

Water table is slightly higher in Plot 1 than Plot 4 among all sites, which is somewhat counterintuitive (Figures 5 and 13). Interestingly, within any single landscapes there is no significant difference in water table among plots. Yet, when grouped into landscapes with plugged ditches (the fallow field and restored wetland) and landscapes with opened ditches (agricultural field and pocosin), the location of the plot near the artificial drainage significantly increases the water table compared to plots further from the artificial drainage only in the landscapes with plugged ditches ( $p$ -value $<0.05$ ), and not for the landscapes with open ditches ( $p$ -value $>0.10$ ). This suggests that the plugged ditches are acting as micro-topographical features storing water and recharging the water table (e.g., Skaggs, 1974), but that open ditches do not necessarily lower the water table.

The reason a ditch might not lower the water table could be due to the effects of bulk density. In the pocosin, Plot 1 has a bulk density five times higher than Plot 2. This increase of bulk

density could be blocking water from flowing through the soil to the ditch, causing water to be stored on the inward side of Plot 1. Pocosin Plot 1 was located on the side of the ditch where the dirt was placed when excavating. This material along with the compaction by the excavator may be the reason for the higher bulk density. This could be the reason Pocosin Plot 1 ( $1.40 \text{ g cm}^{-3}$ ) has a higher bulk densities than found in the literature for pocosins ( $0.11\text{-}0.23 \text{ g cm}^{-3}$ , Bruland et al., 2003;  $0.08\text{-}0.24 \text{ g cm}^{-3}$ , Bridgham et al., 1991). However, Plot 2 falls above the limits of the same study but only slightly ( $0.28 \text{ g cm}^{-3}$ ) and Pocosin Plots 3 and 4 ( $0.20 \text{ g cm}^{-3}$ ; each) fall among observed bulk densities.

#### **5.4 In a restored wetland, does soil CO<sub>2</sub> respiration behave more like an undisturbed reference wetland or an agricultural field?**

The restored wetland behaves like the undisturbed reference wetland (pocosin) in many ways, including soil temperature, volumetric water content, water table, and soil CO<sub>2</sub> respiration. Soil CO<sub>2</sub> respiration was significantly different in the agricultural field and the restored wetlands, which differs from Morse et al. (2012) who found no significant difference. Saturation is the only variable in which the restored wetland behaves more similarly to an agricultural field than the pocosin (Figure 4).

Although soil CO<sub>2</sub> respiration was not significantly different in the restored wetland and the pocosin, it is worth noting that saturation is significantly lower in the restored wetland than in the pocosin. This is worth noting because saturation was the most strongly correlated variable with soil CO<sub>2</sub> respiration, in the pocosin, and soil temperature did not significantly correlate with soil CO<sub>2</sub> respiration, whereas soil CO<sub>2</sub> respiration in the restored wetland was correlated most strongly with soil temperature. This difference in correlations signals differences in controls on soil CO<sub>2</sub> respiration in the restored wetland and the pocosin and by extension different sources of respiration, whether it is differing microbial assemblages producing the heterotrophic respiration, different plant

assemblages producing the material for decomposition, or in-fact producing the autotrophic respiration, cannot be determined by the assessed variables in this study.

It should be noted that this study did not assess the amount of soil organic carbon (SOC), which could help distinguish among landscapes. Published reports indicate that SOC may be less on a per volume basis in a pocosin ( $91.6 \text{ mgC cm}^{-3}$ ) than in a restored wetland ( $111 \text{ mgC cm}^{-3}$ ) or agricultural field ( $173 \text{ mgC cm}^{-3}$ ; Bruland et al., 2003). However, should these numbers be applied to the bulk densities found in this study, it would appear that agricultural fields would have  $0.15\text{-}0.19 \text{ gC gSoil}^{-1}$ , restored wetlands would have  $0.25\text{-}0.32 \text{ gC gSoil}^{-1}$ , and pocosins would have  $0.33\text{-}0.46 \text{ gC gSoil}^{-1}$  (excluding Plot 1 due to the aforementioned disturbance history). If these numbers were to be actual observation, it would give credibility to wetland restoration efforts as it may be more than thirty years after secondary succession that an increase in SOC can be noticed (Richter et al., 1995), thus warranting further investigation into the SOC balance before during and after wetland restoration. Even so, because the restored wetland and pocosin are not significantly different in three of the four measured influences on soil  $\text{CO}_2$  respiration, and in soil  $\text{CO}_2$  respiration itself, we can say that the restored wetland and pocosin are similar.

## **6. Conclusion**

Due to doubts of prior research on the restoration of ecological processes by the restoration of shallow ground water table, period of inundation, and species composition in restored wetlands, this study was designed to compare soil temperature, soil moisture (including saturation), and ground water table between an agricultural field on a drained wetland, a fallow field on a drained wetland, a restored wetland and an undisturbed pocosin on the Hofmann Forest, NC and their influences on soil  $\text{CO}_2$  respiration in those landscapes.

Soil temperature and volumetric water content follow a wetland non-wetland divide, with water table differing between the fallow field, restored wetland and pocosin, and the agricultural field. All the environmental state variables were correlated significantly with soil CO<sub>2</sub> respiration. However, air temperature was correlated stronger over all landscapes. The Q10 (Equation 2) explained soil CO<sub>2</sub> respiration overall, however, Q10 and the modified-Arrhenius (Equation 1) did not differ that considerably in four of the seven fitted data sets. The modified-Arrhenius only explained soil CO<sub>2</sub> respiration considerably better than the Q10 in the dry observations. However, the correlations since in these landscapes tell us that they are other factors to consider and they should be investigated further. Micro-topological water storage capacity of plugged ditches shifts the water table to be significantly higher towards the ditch. Restored wetland is more similar to the pocosin than the agricultural field. Spatial variation of saturation and soil CO<sub>2</sub> respiration could not be differentiated from effects of artificial drainage or storage. Therefore, our insight into these effects would benefit from further investigation with more than one transect per landscape. Finally, now that we have established similar soil CO<sub>2</sub> respiration in the restored wetland and pocosin, we need to evaluate other pieces of the carbon cycle, including gross primary productivity, above ground respiration, and dissolved organic carbon transport, so that we can have a complete and holistic view of the carbon cycle in restored wetlands.

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## **APPENDIX**

## APPENDIX A – Photographs of Field Locations



Figure A1: Agricultural Field, looking from Plot 1 towards Plot 2, during August 2012, planted with *Glycine max*.



Figure A2: Fallow Field during installation of Plot 1, June 2011.



**Figure A3: Restored Wetland in July 2012, looking from opposite side of ditch towards Plot 1.**



**Figure A4: The Hofmann Forest Pocosin in the vicinity of Plot 3, May 2011**