Hydric Soil Properties as Influenced by Land Use in Southeast Virginia Wet Flats

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ABSTRACT

The accuracy of the growing season used by regulators in hydric soil and wetland hydrology and the validity of ignoring land use in these definitions is questionable. This study compared measured air and soil temperature with various growing season dates and indicators, and determined the relationships between the hydrology, air and soil temperature. Water table depths, air temperature at 1-m height, soil temperature at 15-, 30-, and 50-cm depths, and CO_2 efflux were measured at 12 plots representing three land-use treatments (forest, field, and bare ground) at two restored wet flats in the thermic Great Dismal Swamp ecosystem. The forest was driest treatment. The forest air was the warmest in winter and coldest in summer, opposite of the bare ground. The forest soil at 50 cm was the warmest in winter and coolest in summer, opposite of the bare ground. Land use affected hydrology, air, and soil temperatures through the presence of surface litter and differences in shading, albedo, and ET. The regulatory frost-free period fell in between the measured frost-free period and the measured 5 °C soil temperature period. Based on CO_2 efflux and soil temperature at 50 cm, the biological growing season of native plants and microbes should be year-round for forested areas, one week shorter for early-successional fields, and two weeks shorter for active cropland rather than March to November for all land uses. Changing the growing season definition of forested, thermic wet flats to year-round designation must be considered and studied carefully to avoid jeopardizing wetland hydrology qualifications.

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Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

Background Information on Wetlands and Wet flats

<u>Importance of Wetlands</u>

Wetlands are ecotones between terrestrial and aquatic systems (Cowardin et al., 1979). Wetlands are among the most important ecosystems on Earth and are unique because of their hydrologic conditions and role as transitional ecosystems (Mitsch and Gosselink, 2000). Wetlands have recently attained preservation value in our society due to recognition of the ecological functions they perform at the population and ecosystem levels. At the population level, aquatic, avian, mammalian, and wetland vegetative species are important to recreation and conservation interests. Many unique flora and fauna are specifically adapted to seasonally inundated conditions; diminishing wetland habitat may endanger species. At the ecosystem level, wetlands may perform favorable hydrologic and water quality functions including stream-flow augmentation, ground-water recharge, storage, flood attenuation, erosion control, sedimentation, and nutrient sequestration (Mitsch and Gosselink, 2000).

The protection of forested and non-forested wetlands has become a national issue over the last 30 years. Preservation and restoration of forested wetlands are desirable because of increasing alternative land-use pressures and continuing losses (Burke et al., 1988).

<u>Wetland Losses</u>

Currently, wetlands cover less than seven percent of the Earth's land area (Mitsch and Gosselink, 2000). Forested wetlands in the southeastern USA are undergoing rapid changes in composition and reduction in area. There is significant pressure to develop critical wetland ecosystems in the southeastern USA because these areas are highly sought after for agricultural and construction practices (Stanturf et al., 2000). Drained wetlands are among the most productive agricultural and forest soils; the relatively level topographic position of wetlands is desirable for construction practices. Public recognition of wetland importance via water quality concerns has resulted in regulation or protection by various federal and state laws. Attempts have been made to balance the demands for preserving wildlife habitat, protecting water quality, controlling erosion, retaining flood waters, recharging aquifers, supporting commercial forestry operations, and creating recreational areas (Brinson et al., 1981; Abernethy and Turner, 1987; Gosselink and Lee, 1989; Taylor et al., 1990; Sharitz and Mitsch, 1993).

The US Fish and Wildlife Service (FWS) has estimated wetland losses that occurred in the USA over the past 200 years, based on wetland definitions of Cowardin et al. (1979) and on historical records (Dahl, 1990). The contiguous USA had approximately 42 million ha of wetlands in the 1980's, about 53% of the estimated area of original wetlands in the 1780's (Dahl, 1990). The 1982 and 1987, United States Department of Agriculture-Soil Conservation Service (USDA-SCS) Natural Resource Inventory (NRI) data indicate that the forested wetland area in the contiguous USA on nonfederal lands has decreased from 17.4 million ha in 1982 to 17.1 million ha in 1987. About 32,000 ha of wetlands lost from 1982 to 1987 in the South were converted from forested wetland uses to urban uses, about 16,000 ha were lost to rural transportation uses, 30,000 ha were cleared and planted for agronomic use, and 5,400 ha were converted to pastureland. Changes from wetlands to water bodies accounted for 5,000 ha. The largest documented loss or change of nonfederal forested wetlands in the South was to federal purchase. Thus, almost one-half of the reported wetland losses probably remained in wetland, or were lost by flooding due to federal dam projects. Wetland losses in North Carolina and Virginia were higher (3.18% of the total land area) in this survey than losses in the rest of the contiguous USA (Cubbage and Flather, 1993). Hefner and Brown (1984) reported an analysis of wetland development trends from 1950 to the mid 1970's. They indicated that wetland losses in the Southeast occurred at an annual rate of 156,000 ha, and determined losses in the Southeast accounted for a total loss of more than 3 million ha during the study period, or 84% of national losses. Stanturf et al. (2000) reported that 96% of bottomland hardwood systems were lost in the Mississippi Alluvial Valley between 1600 and 1990, and few wetland ecosystems within the USA have suffered such peril as bottomland hardwood wetlands. Current litigation has questioned the basis of wetland jurisdiction. To date, wetland policy has become less protective and suffered setbacks, including loopholes in ditch and draining practice (Tulloch ditching) and the current mandatory connectivity of wetlands to natural waterways (National Research Council, 2001).

Wetland Classification Systems

The Federal Water Pollution Control Act (Public Law 92-500, 33 U.S.C. 1251) of 1972 brought about a change in the way wetlands were regarded. This legislation is also referred to as the Clean Water Act. Prior to the Clean Water Act, little concerted effort was made to inventory or classify wetland resources in the United States. However, in 1974 the FWS began a rigorous wetland inventory to fulfill their internal scientific and management objectives (Mitsch and Gosselink, 2000). Thus, the "Classification of Wetlands and Deep Water Habitats of the United States" was published as the first all-encompassing classification system of wetlands and deepwater ecosystems (Cowardin et al., 1979). The Cowardin system described wetlands as land where saturation with water was the dominant factor determining the nature of soil development and the types of plant and animal communities living in the soil and on its surface.

As wetlands gained prominence in the scientific realm, the limitations of the Cowardin system became evident. The system categorized broad types of wetlands, yet did not provide the user an accurate visualization of the systems classified. Other wetland classification systems have been created to classify and qualify wetland functions and values to society. A recent and widely accepted wetland evaluation technique is the hydrogeomorphic (HGM) classification system (Brinson, 1993). HGM used landscape position and hydrologic parameters to characterize and better describe the dominant processes of the wetland studied, allowing the user to understand the hydrologic ecosystem setting, the dominant processes driving the system, and perhaps their importance to society. The HGM system identified three common types of wetland ecosystems in the Great Dismal Swamp area of southeastern Virginia: Pocosins, bottomland hardwoods, and wet flats. The Cowardin system identified all three of these HGM wetland types as P0F (palustrine - forested) wetlands.

The term pocosin is derived from ancient Algonquin Indian word “Poquosin” meaning “swamp on a hill” (Tooker, 1899). The broadest definition of a pocosin is an area primarily restricted to the southeastern Coastal Plain, occurring in broad shallow basins, drainage basin heads and on broad flat uplands. The depth, duration, frequency, and timing of water table dynamics (hydroperiod) in pocosins indicates consistent shallow water tables throughout most of the year. Pocosins also have temporarily ponded conditions, are influenced by periodic burning, and have subsurface substrates of sandy humus, muck or peat (Wells, 1928; Woodwell, 1958).

Bottomland hardwoods are those areas dominated by woody species where streams or rivers flood at least occasionally beyond their channels. The plants have morphological adaptations, physiological adaptations, and/or reproductive strategies enabling them to achieve maturity in an environment where the soils within the root zone may be inundated or saturated for varying periods of time during the growing season (Huffman and Forsythe, 1981; Sharitz and Mitsch, 1993). The geographic range of the bottomland hardwood community type is as great as or greater than that of most other southeastern forest communities, including the oak-hickory-pine forest and the southeastern mixed hardwood forest (Sharitz and Mitsch, 1993).

Wet flat wetlands are a diverse mixture of non-riverine hardwood and pine dominated systems occurring in the Atlantic to Gulf Coastal Plains. These systems occur on mineral soils on broad, flat interstream divides located between larger drainages, such as broad interstream areas, poorly drained flats, basins, depressions, and drainage ways. Hydrologic inputs are primarily restricted to precipitation and experience ponding due to poor subsurface drainage and low topographic gradients. Wet flats have a hydrologic regime capable of supporting deciduous wetland vegetation in a climax state and are dominated by various water-tolerant and nutrient-demanding pines, oaks, and/or mixed hardwoods, the species assemblages are typically similar to those found in bottomland hardwood (Brinson, 1993; Harms et al. 1998).

Definition of Wetlands

The importance of federal control of wetland habitat and losses came under scrutiny in the early 1970's. Section 404 of the Clean Water Act yields guidance and precedence over wetlands. The US Army Corps of Engineers (ACOE), under the Clean Water Act, is responsible for maintaining the integrity of our nation's waters. Section 404 mandates that anyone dredging or filling in "waters of the United States" must request a permit from the ACOE, which due to the Rivers and Harbors Act of 1899, hold the responsibility to regulate dredge and fill of navigable waters. The ACOE's primary responsibilities include disturbance permitting and mitigation oversight of forested and non-agricultural wetlands. Agricultural wetlands are regulated by the Food Security Act of 1985, and are under the jurisdiction of the USDA-Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service (USDA-SCS, 1985a).

Section 404 of the Clean Water Act indirectly governs wetlands by urging the ACOE to preside over wetlands via wetland connectivity and adjacency to navigable waters.

Wetland loss has partially slowed since the establishment of Section 404 wetlands regulations. In 1988, the National Wetland Policy Forum recommended a “No Net Loss” policy on wetland area and function. The federal administration and President George Bush articulated the reform to relevant agencies and adopted the “No Net Loss” policy by 1990. The yearly rate of wetland loss has significantly decreased since 1988, although net wetland losses still incur (National Research Council, 2001).

Based on Executive branch discussion, a list of guidelines was developed in 1987 for the delineation of wetland boundaries to determine whether a landowner must submit a Section 404 permit application. These guidelines are part of a technical manual for the delineation of wetlands. The ACOE Wetland Delineation Manual (1987 Manual) uses the three-parameter approach for wetland identification based on a developed and tested set of definitions and delineation guidelines (Environmental Laboratory, 1987). The 1987 Manual uses site-specific measures of wetland hydrology, hydric soils, and hydrophytic vegetation to determine if land under permit consideration contains wetlands. These criteria were first adopted by the FWS and incorporated by the ACOE as the basis for identification of jurisdictional wetlands by the Clean Water Act (Mausbach and Parker, 2001).

Wetland hydrology is defined as that characteristic of areas periodically inundated, or having soils saturated to the surface by surface or groundwater for some minimum period of time during the growing season. The average annual duration of inundation is characterized during this period. Hydric soils are soils formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part (within 30 cm of the surface). Hydrophytic vegetation are those plants that are competitively selected for under anaerobic soil conditions (Environmental Laboratory, 1987).

Wetlands delineated in accordance with the 1987 Manual are considered jurisdictional wetlands. The 1987 Manual remains the primary delineation tool for most of the contiguous US, although some states have developed a more robust set of delineation guidelines (Mausbach and Parker, 2001). The ACOE, with oversight from the US Environmental Protection Agency (EPA), is authorized to regulate wetland development and to oversee wetland mitigation programs (Kruczynski, 1989). Mitigation is required for all impacts to jurisdictional wetlands under Section 404 provisions. Mitigation is the process of avoiding, minimizing, rectifying, reducing, or compensating for wetland resource loss. On-site restoration is required where impacts are unavoidable. Off-site compensation is usually the last allowable resort from a permitting perspective and generally involves type-for-type replacement in relatively close proximity to the impacted wetland. A compensatory wetland mitigation project is the creation, restoration, enhancement, or preservation of a wetland designed to offset permitted losses of wetland functions in response to special conditions of a permit. Mitigation projects provide a desired set of hydrological, water quality, and/or habitat functions within, or sometimes, outside, the watershed (National Research Council, 1995). Although the ACOE remains the primary governmental enforcement office for the definition and delineation of jurisdictional wetlands in Virginia, site specific permits are also granted and administered by the Virginia Department of Environmental Quality.

Jurisdictional Wetland Parameters and the Growing Season Concept

The growing season concept was introduced to allow wetlands to be classified while eliminating lands that undergo winter saturation with no adverse biotic effects. Soils and vegetation may be products of past and present long-term hydrologic regimes because reduced soil environments that are limiting to non-hydrophytic plant life can occur outside the defined growing season. In wetland regulation, the growing season concept is introduced while defining wetland hydrology and hydric soil. The growing season requirement is often overlooked as part of the definition of hydric soil (Megonigal et al., 1996).

The growing season concept was first introduced as a wetland parameter in Classification of Wetlands and Deepwater Habitats (Cowardin et al., 1979). The report states that a wetland is a landform that is saturated or has shallow water at some time during the growing season of each year. The ACOE adopted this concept and uses the growing season as a standard for wetland hydrology according to the 1987 Manual (Environmental Laboratory, 1987). The hydrology duration threshold is determined on the basis of a sliding scale between 5 to 12.5% in most years (50% probability of recurrence). A wetland is considered irregularly inundated or saturated if inundation or saturation occurs for a continuous period between 5 and 12.5% of the growing season. An area has wetland hydrology if it is inundated or saturated to the surface continuously for at least 5% of the growing season; this 5% determination is referred to as the wetland hydrology threshold. The 5% threshold is used when the area in question is definitely a wetland. The 12.5% threshold is used in marginal wetland systems. The 1987 Manual clearly states that the presence of wetland hydrology may not simply be inferred from the presence of hydric soils and a predominance of hydrophytic vegetation. Instead, the 1987 Manual recommends supporting hydrologic indicators such as verification of water levels via monitoring wells, visual observation of saturated soil, observation of inundation, drift lines, or watermarks on trees (Environmental Laboratory, 1987). The 1987 Manual indicates that secondary indicators could also be used, which include oxidized rhizospheres and water stained leaves, to name a few. Successful mitigation is based on the area having continuous saturation for 5 to 12.5% of the growing season, but the specific amount varies by individual ACOE district. For instance, the Norfolk district ACOE in southeastern Virginia requires wetland hydrology for at least 12.5% of the growing season in mitigated areas.

The current technical definition for a hydric soil states that flooding or soil saturation must occur during a minimum portion of the year when soil temperature is above biological zero (>5 °C) at 50 cm. The definition and criteria for hydric soil and wetland hydrology are both stated in terms of a biological zero growing season concept. The chemistry of soil reduction is biologically driven and therefore, is presumed to be insignificant when soil temperature is below 5 °C because microbial populations and plant activity are assumed to be insignificant and not sufficient to alter biogeochemical processes (Soil Survey Staff, 1999). In March 1992, the ACOE issued guidance to its personnel to clarify the growing season concept and make this concept part of their working regulatory construct. Various alternative indicators of the growing season have been recommended because soil temperatures are impractical to measure on every wetland determination (Lynn et al., 1996). The regulatory guidelines state that this biological zero period can be approximated by the published number of frost-free days. The frost-free period is estimated with starting and ending dates based on an air temperature threshold of –2.2 °C for a frequency of 5 out of 10 years from 30-yr averages. The number of frost-free days is available in climatological tables in NRCS county soil survey reports or from the NRCS Water and Climate Center in Portland, Oregon, for most weather stations in the country. Thus, ACOE has authorized frost-free days as a suitable indicator for accurate biological zero measurements of soil temperature at 50 cm. The NRCS uses the same rule in the third edition of its National Food Security Act Manual, the regulatory guide that governs agricultural wetland regulation (USDA-SCS, 1985a).

The rigorous biological zero definition is extrapolated using air temperature for ease in defining a growing season for each region in Virginia. In the City of Chesapeake, Virginia the accepted growing season encompasses 259 days (March 14 to November 29) while in the City of Suffolk, Virginia, the growing season encompasses 222 days (March 29 to November 7) (unpublished soil survey; Reber et al., 1981).

The ACOE growing season definition used in the classification of jurisdictional wetlands are taken from NRCS air temperature freeze dates. Freeze dates indicated in climatological tables in cooperative soil surveys reports are designed to ensure the proper planting date for farmers. Soil temperature affects seed germination in spring and farmers plant on dates appropriate to the crop grown, somewhere between the minimum and optimum temperature for that specific crop (Mount and Paetzold, 2002). Because the current ACOE growing season definition was adapted from a USDA system intended for agricultural application, their use in wetland identification may be problematic and should be reconsidered prior to use in forested wetland communities commonly found in Southeast Virginia (Day and Megonigal, 1993).

The growing season is defined in Soil Taxonomy as “the portion of the year when soil temperatures are above biological zero in the upper part” (Soil Survey Staff, 1999). The depth of “the upper part” of the soil has not been defined. The 50-cm depth was originally utilized because it is defined to be the middle of the primary root zone for plant growth (Soil Survey Staff, 1975). The ACOE has fully adopted the Soil Taxonomy guidelines (Environmental Laboratory, 1987). However, the National Research Council recommends that the upper part be defined at 30 cm, which is the bottom of the rooting zone in most wetlands (National Research Council, 1995).

Soil temperature is generally described in Soil Taxonomy by soil temperature regimes. Soil temperature regimes are listed in terms of mean annual soil temperature, average seasonal fluctuations from the mean, and the mean warm or cold seasonal soil temperature at a point within the root zone. The thermic temperature regime occurs where the mean annual soil temperature is 15 °C or higher but is lower than 22 °C, and the difference between mean summer and mean winter soil temperatures is > 6 °C either at a depth of 50 cm from the soil surface or at densic, lithic, or paralithic contact, whichever is shallower (Buol, 1977; Soil Survey Staff, 1999). Mean annual soil temperature is most closely related to mean annual air temperature, yet the relationship is dependent on the amount and distribution of rain and snowfall, shading, presence of O horizons, slope aspect, and moisture (Mount and Paetzold, 2002). Soil color, texture, and amount of organic matter can also affect soil temperature (Soil Survey Staff, 1975). Most southeastern bottomland hardwood ecosystems are located within the thermic temperature regime (Soil Survey Staff, 1999). The thermic temperature regime has an official growing season from February to November based on Cooperative Soil Survey definitions. The growing season from February to November is more representative than the frost-free days growing season considered acceptable for delineating wetlands under the ACOE (Megonigal et al., 1996). The National Technical Committee for Hydric Soils recommended growing seasons based on soil temperature regimes according a schedule of inclusive dates, in which the thermic temperature regime covers from February to October (Soil Survey Staff, 1999, p. 100). However, this system for estimating growing season length is impractical for regulatory purposes because it results in sudden discontinuities at regional boundaries (Lynn et al., 1996).

The technical definition of growing season is open to much interpretation in practice (Vepraskas, 1999). The frost-free days growing season is an agricultural term referring to the period for germinating and growing cultivated crops where there is no risk of crop damage due to killing frosts. This concept of the growing season has little relevance to native plants as many are already growing well before this period (Tiner, 1999). Using physiological indicators of native plants may be a more reasonable way to determine biological activity. One study in Massachusetts determined biological activity by observing budburst of specific tree species in a hardwood forest while measuring redox levels in the soil (Whited, unpublished data).

While defining the growing season based on the concept of biological activity is better than using frost-free days, it still may not be as accurate as indicating microbial activity (Tiner, 1999). Microbial activity has been found to occur in temperatures well below biological zero in some wetlands and certain ecological regions that may have specific adaptations (Flanagan and Bunnell, 1980; Grishkan and Berman, 1993; Zimov et al., 1993; Clark and Ping, 1997). Recent studies have focused on microbial respiration, oxygen consumption and microbial reproduction as indicators of biological activity to assess the proper determination of the growing season (Pickering and Veneman, 1984; Groffman et al., 1992; Megonigal et al., 1996; Lynn et al., 1996).

Soil temperature greatly influences the rates of biological, physical, and chemical processes in the soil. Within a limited range, rates of chemical reactions and biological processes double with every 10 °C increase in temperature, this is referred to as the “Q10” of biological systems (Paul and Clark, 1989). In addition, most soil bacteria are mesophiles, microbes that grow optimally a temperatures ranging from 15 to 35 °C. Biological activity rates are a function of soil temperature and become less expressed as the soil cools during winter months. Applied research indicates that 5 °C is the temperature at which the biological activity of a soil is reduced to 5% of optimum levels. Most measurements relating microbial activity to temperature show growth stopping at 0 °C. Some phychrophilic bacterial are capable of growth below the freezing point, providing that the osmotic concentration of the ambient solution or of the organism’s cytoplasmic constituents is sufficiently high to permit cell structures to remain unfrozen (Paul and Clark, 1989).

Similarly, Clark and Ping (1997) found reducing conditions, indicating regional biological activity at temperatures below 5 °C in an Alaskan study.

Suggestions on growing season terminology have included a characterization of wetlands by a microbial activity season, because wetland creation processes occur outside of the ACOE accepted growing season (Megonigal et al., 1996). Biogeochemical processes are temperature dependent, rates of these processes can be seasonal; however these processes still can occur at appreciable levels during colder periods. Microbes in wetland systems effectively alter the physical processes that create hydric soil conditions, such as a reduction in iron. Soil saturation during any period where microbes are active may effectively cause anaerobic conditions as evidenced by O_2 and CO_2 flux. During winter saturation, if microbes are indeed active, reduction and plant limiting soil environments may be present; those soils may have the capacity to function as hydric soils (Megonigal et al., 1996). Several studies have indicated that the acceptable growing season does not coincide with biological zero and microbial reduction of soils can occur throughout the year (Pickering and Veneman, 1984; Megonigal, et al., 1996). In a study conducted on the Coastal Plain of Texas, windows of highest potential for Fe^{3+} reduction were identified outside of the ACOE defined growing season. The researchers indicated that the growing season inferred from soil temperature regimes and from the air temperature thresholds had no bearing on soil microbial activity. Instead, times of higher potential reduction were correlated to the presence of labile carbon and specific moisture conditions (Griffin et al., 1996).

The ACOE growing season definition is applied to wetlands systems regardless of presence of water, vegetation type, or land use, all of which should influence soil temperature (Cole and Brooks, 2000). Tiner (1999) suggests that more data are needed to determine the wetland hydrology threshold for establishing wetlands, including a de-emphasis of the use of the growing season to define wetland types. The current definition of a jurisdictional wetland is dependent upon agricultural growing season guidelines that are not representative of forested wetland ecology (Day and Megonigal, 1993).

Hydric Soils and Hydric Soil Morphology

Wetland Soils

Hydric soils have traditionally been identified in the field on the basis of the interagency hydric soils definition, hydric soils criteria, or hydric soils field indicators. Rigorous application of the hydric soil definition has generally been limited to research situations, because it requires knowledge of transient periods of oxygen depletion in the soil. Application of hydric soils criteria requires long-term monitoring of water levels above or below the soil surface and thus is useful only when staff gauge or monitoring well data are available. Hydric soil field indicators consist of soil morphological characteristics present in many hydric soils and are frequently used in wetland delineation situations because of their readily observed criteria and ease in field use (Lynn et al., 1996).

The National Technical Committee for Hydric Soils, an interdisciplinary committee of NRCS soil scientists, regulators, and academia, developed the definition and is responsible for assessment procedures and a national operational list of all taxa that could be considered hydric. The committee maintains a database that contains soil property records for all recognized soil series. The database includes soil physical properties, permeability, natural drainage class, water table depths, flooding or ponding frequency and duration, and the time of year for which the data are representative (Mausbach and Parker, 2001).

Evidence that the hydric soil definition has been met include accumulation of organic matter, presence of redoximorphic (redox) features, or use of geochemical measurements such as redox potential (Eh) or chemical detection for Fe^{2+} using α-α dipyridyl dye indicator. Redox potential is used to predict the types of reduced species present in the soil solution. Redox potential is measured using a Pt-tipped electrode and reference electrode that measures voltage differentials within the soil solution. Reduced soils donate electrons to the Pt electrode while oxidized soils tend to accept electrons from the Pt electrode. The voltage measurements are very small and must be corrected along a pH gradient. The α-α dipyridyl dye reacts with Fe^{2+}, creating readily seen color change. However, use in the field is complicated by the sensitivity of the dye (Vepraskas and Faulkner, 2001).

Saturation

Hydromorphology exerts a controlling influence over all wetland processes and functions. Hydromorphology controls the hydroperiod, that is, whether the area is inundated or saturated to the surface and the length of saturation. There are two definitions of saturation. The water content definition indicates that a soil layer is saturated when all pores are filled with water, except those pores containing entrapped air. The water potential definition indicates that a soil layer is saturated when water has a pressure potential that is equal or greater than atmospheric pressure (Richardson et al., 2001). In unconfined conditions, the point at which water is equal to atmospheric is considered the top of the water table; this occurs in auger holes left to equilibrate, open screened monitoring wells, or piezometers installed in unconfined layers. The water content definition is more widely used than the water potential definition. Regulatory interpretation of the water content definition requires the water table to be at or near enough to the surface to wet the soil to the surface via the capillary fringe. The capillary fringe is the region above the apparent water table where soil micropore and surfaces are filled with water via capillary wicking, yet water potential is less than atmospheric (Richardson et al., 2001).

Anaerobic Conditions and Redoximorphic Features

The most significant effect of saturation is isolation of the soil from atmospheric gas exchange and the prevention of O_2 from entering the soil (Day and Megonigal, 1993). Water saturation effects the downward diffusion of O_2; the rate of diffusion is retarded by four orders of magnitude (Ponnamperuma, 1972). Biogeochemical processes change the aerobic soil environment to an anaerobic and reduced state when O_2 is not present in significant quantity. Redox conditions develop sequentially in this anaerobically-reduced soil environment.

Use of redoximorphic features as indicators of anaerbiosis primarily assumes that saturation and biogeochemical reduction lead to the dissolution, mineralization, and precipitation of Fe^{3+} and Mn^{4+} compounds, and that the resultant soil color and mineral forms reflect the long-term average soil moisture state (Genthner et al., 1998). Concentration of organic matter and soil darkening are also implicit assumptions for A horizons. Redoximorphic features form due to oxidation-reduction reactions that begin when organic matter is oxidized during microbial respiration (Vepraskas, 1996). Oxidation is associated with the generation of electrons associated with microbial consumption of organic material, while reduction occurs via the acceptance of transferred electrons. Under normal soil conditions, O_2 is the primary terminal electron acceptor; the end product of this redox reaction is H_2O. As the soil environment becomes more anaerobic, additional elements sequentially function as terminal electron acceptors. The gradient is due to the relative redox equilibria, or redox potential of the following compounds: O_2, NO_3^-, Mn^{4+}, Fe^{3+}, SO_4^{2-}, and CO_2. Due to this gradient, various redoximorphic features are indicative of an environment depleted of O_2, but more significantly, they are indicative of an environment that is reduced with respect to Mn^{4+} and Fe^{3+}. For this reduced condition to occur, the soil must be devoid of all components with higher redox potentials than Mn^{4+} and Fe^{3+} (Vepraskas, 1996).

Manganese will reduce before and separately from Fe^{3+}, and due to inherent heterogeneity of the soil there may be varying degrees of reduction occurring within the soil. As Fe oxides are reduced, the reaction effectively increases pH in acid and circumneutral soils via the following reaction [$Fe\text{-}OH + e^- \rightarrow Fe^{2+}{}_{(aq)} + OH^-$]. Fe^{2+} is typically mobile in the soil solution. Movement of Fe^{2+} is dependent upon the hydroperiod of the system where reduction occurs and local hydraulic gradients. Depending on hydrologic factors within the soil, Fe^{2+} can be leached from the soil horizon, mobilized within the horizon to an area where re-oxidation occurs, or can remain in solution within the horizon. The localized concentration of Fe^{2+} is dependent on temperature, Fe^{3+} availability, organic matter content, and pH. Concentrations of Fe^{2+} will peak after several weeks of reduction then gradually decline (Ponnamperuma, 1972). Absorbed Fe^{2+} can limit the absorptive capacity of clays and release nutrients into the water column due to preferential adsorption onto exchange sites. This can shift the production - respiration balance towards the accumulation of organic material (Ponnamperuma, 1972). In addition, as reduction occurs and pH increases, solubility of phosphorous and silica increases and new minerals tend to form (Ponnamperuma, 1972). Since reduction of Fe^{3+} is a biogeochemical process, reduction tends to occur preferentially in areas of abundant organic material and microbial activity, typically in rhizospheres and areas of root mat. Thus, the soil redox environment is spatially heterogeneous over very short (mm) distances.

Soil colors have been routinely used to infer soil saturation and biogeochemical redox processes. These indicative color patterns were previously referred to as mottles or low chroma colors, but since 1996 the term “redoximorphic features” has been mandated by Soil Taxonomy (Vepraskas, 1996). Redoximorphic features include i) redox concentrations, ii) redox depletions and iii) reduced matrices. Redox concentrations are defined as bodies of apparent accumulation of

Fe-Mn oxides (Vepraskas, 1996). Concentrations include nodules, masses, and pore linings. Nodules are not considered truly indicative of active redox concentrations, whereas some masses and pore linings are considered indicative of active redox concentrations. These concentrations are zones of oxidized reddish coatings that indicate Fe^{3+} accumulation. Redox depletions are defined as bodies of low chroma (≤ 2) having values of ≥ 4, where Fe-Mn oxides and/or clays have been stripped (Vepraskas, 1996). These areas have low chroma colors due to the reduction of Fe^{3+} into aqueous Fe^{2+}. Fe^{2+} does not color soil particles. The low chroma (neutral or gray) colors are the natural colors of uncoated soil particles. Reduced matrices are defined as low chroma color, attributed to Fe^{2+} in solution or lack of Fe^{2+} in the soil horizon (Vepraskas, 1996). Reduced matrices are similar to redox depletions; but are more extensive areas of depletion that constitute the dominant color of the soil horizon. Redoximorphic features are highly correlated to the long-term presence of a water table. In some regions concentrations may be more indicative of a seasonal high water table than depletions (Genthner et al., 1998).

The kinetics of redoximorphic features remain poorly understood. The ACOE have indicated that that features may not develop for hundreds of years in constructed systems (Environmental Laboratory, 1987). However, current research indicates that under certain conditions, redoximorphic features, and hydric soils develop much faster than originally assumed. Research on beaver impoundments in northern Minnesota indicates that former upland conversions had developed prominent redox features after 14 years of inundation and subsequent drainage (Johnston and Naiman, 1987). Atkinson et al. (1998) reported that accidental wetlands on mining sites in southwestern Virginia developed strong redoximorphic features within 10 years. Their study also showed that in a significantly reduced soil environment, wetlands created three years prior had dull features including lower chroma, but those features did not yet qualify as redox depletions (Atkinson et al., 1998). Vepraskas et al. (1999) indicated that redoximorphic features have developed in the upper 15 cm within 10 years of wetland construction in North Carolina. The constructed wetland was saturated 60% of the year for 7 of the 10 years studied. These studies indicate that once reducing conditions are established for a significant annual frequency and duration, redoximorphic features may develop in several years.

The formation of redoximorphic features is a biogeochemical reaction that is dependent upon the frequency and duration of a reduced environment, available carbon source, temperature, and microbial activity. Microbial activity is directly dependent upon temperature. Metabolic activity, although retarded, can still occur at an appreciable level during colder periods such that respiration and O_2-consumption rates cause significant anoxia and reduction of the soil environment in low temperatures (Megonigal et al., 1996).

Temperature and Land-use Effects on Coastal Plain Soils

Effects of Soil Temperature

Soil temperature has an important influence on biological, chemical, and physical processes in the soil (Scott, 2000). Solar radiation is the primary source of radiant heat entering the soil. Radiant heat is either absorbed into or re-radiated from the soil surface. Solar radiation is absorbed and transformed into thermal energy and transmitted from the surface to the subsurface horizons. When heat radiates from the soil, expenditure of heat exceeds intake, cooling the surface and eventually cooling the subsurface horizons. Warming or cooling of the soil depends on many factors including temperature differences between soil layers, and soil heat capacity. The temperature difference between layers in the soil effects heat transfer, the greater the temperature differences between the surface and the subsoil layers, the greater the amount of heat entering or leaving the soil. Thermal conductivity is the heat transfer ability in the soil that is dependent on physical properties of the soil such as the content of solids, air, water, and porosity. Thermal conductivity of soil solids is greater than air by a factor of 100, the conductivity of water exceeds air by a factor of 24, and the conductivity of soil solids exceeds water by a factor of 4. Increased soil solids positively effects thermal conductivity, while increased porosity and aeration decreases conductivity (Mount and Paetzold, 2002; Shul'gin, 1965). Cultivation typically increases soil porosity and decreases thermal conductivity (Mount and Paetzold, 2002). Additionally, as soil moisture increases, conductivity increases as air is replaced by pore water. This relationship is dependent on humidity; when soil atmospheric humidity is low and the soil is moist, conductivity increases. When humidity is low, the difference between the thermal conductivity of water and that of soil particles is great. As the soil moisture increases; its conductivity gradually approaches that of water (Mount and Paetzold, 2002).

Warming and cooling events in the soil are contingent upon heat capacity. Gravimetric heat capacity or specific heat is the amount of heat in calories necessary to warm 1 g soil by 1 °C. Heat capacity in the soil is dependent on humidity, porosity, air content, and mineralogical composition. Heat capacity of water is twice that of the solid mineral soil. Heat capacity increases with humidity and porosity, but high air contents reduce heat capacity. Soil mineralogy may affect the heat capacity of a soil; soils high in humus can have a specific heat of 1.8 kJ kg^{-1} K^{-1} while quartz can be 0.96 kJ kg^{-1} K^{-1} (Mount and Paetzold, 2002).

Diurnal oscillations of temperature in a moist soil are less than those in a dry soil due to heat buffering. Also, there are smaller differences in temperature between soil horizons in a moist soil than that of a dry soil. Moist soils are more buffered against temperature changes because water has a higher heat capacity than air. Texture is also a modifier of heat capacity, clayey soils with limited soil moisture content will warm less in daylight and cool less at night than a sandier soil (Mount and Paetzold, 2002). Changes in soil temperature in time and with depth are determined by conductivity and thermal gradient. Mount and Paetzold (2002) indicated that sandy textures are warmer at 25 and 50 cm than finer textured soils in a similar landscape position.

Most temperature studies have focused on well-drained or dry soils (Hillel, 1982; Taylor and Jackson, 1986; Mount et al., 1992). However, the presence of soil water may impact soil temperature. Chang (1958) has shown that the presence of water can reduce seasonal fluctuations of soil temperature. In wetland settings, the heat capacity of waterlogged soils is increased over that of surrounding non-saturated soils, and soil temperature tends to be cooler in the spring and warmer in the fall (Boul and Rebertus, 1988). Mount and Paetzold (2002) measured soil temperature in poorly drained and well drained soils from 1998 to 1999, and reported conflicting results from the two study areas. The poorly drained soils in northeastern North Carolina had warmer mean annual soil temperatures than the well drained soils, but the poorly drained soils in southeastern Virginia had colder mean annual soil temperatures. Discrepancies, although significant, were not explained and may vary because of location or current land use

Smith et al. (1964) indicated that soil temperature is one of the soil's most important properties, because within limits it controls the possibilities of plant growth and soil formation. Vegetative cover can have a significant influence on seasonal fluctuations of soil temperature. Smith et al. (1964) reported that the soil temperature differences between grass, crops, and trees shading or insulating the soil were minor if O horizons were transient or absent and concluded that tree cover seemed to have little effect on soil temperature or direct insulating ability. However, a study in Nigeria found that land use exerts an effect on soil temperature in well drained soils where gravimetric moisture content was similar; differences in forest verses farmland cover had a profound effect on soil temperature (Ogunkungle and Eghaghara, 1992). The study indicated that the densely vegetated forest plots had coolest soil temperatures and soil temperature was increasingly warmer with decreasing vegetative cover. Additionally, soil physics has documented the effect of vegetation on soil temperature (Scott, 2000; Hillel, 1982; Yaalon, 1983; Mount and Paetzold, 2002). Transpiration of water, canopy reflection of incident radiation, and uptake of radiant energy used for photosynthesis by plants tend to decrease the temperature of the microclimate and indirectly, of the soil. Plant cover serves as insulation and consequently tends to reduce soil temperature fluctuations. Most energy that reaches the earth in the daytime is used as energy for evapotranspiration (ET) or is radiated back to the atmosphere. Only a small portion (perhaps 10%) enters and heats the soil.

Soil color and the amount and type of litter layer affect soil temperature (Scott, 2000). Light-colored soils reflect more radiation and absorb less heat than dark-colored soils. Although dark-colored soils absorb heat more readily, these soils also often have higher organic matter contents and thus higher soil water holding capacity than light-colored soils. Soils with high levels of moisture at the surface do not warm as quickly in the spring nor cool as quickly in the fall, and so soil moisture content is the dominant buffering process against temperature change in the soil (Scott, 2000).

Litter layers of woody evergreen species have a negative effect of soil temperature, retarding soil temperature dynamics at the surface (Eckstein, 2000). Litter layer and the effects of soil temperature were monitored in subalpine abandoned and mowed fields (Rosset et al., 2001). Initially, the litter layer in the abandoned field exhibited minor influences on radiation, but the influences became more dominant with increased litter accumulation. The decreased heat flux and net radiation reduced ET losses and resulted in higher soil water content. Over time there was a marked negative effect on heat flux in the abandoned field. Soil temperature changes were delayed up to 1 mo in the abandoned field as compared to the mowed treatment. Soil temperature flux declined with advancing succession and generally increased as a consequence of clearing (Rosset et al., 2001; Van Cleve et al., 1993).

Heat flux occurs from the surface downward or in the opposite direction, depending on thermal gradients. During a 24 hr period, heat flux is normally greater during the day than at night because of the input of solar radiation. The magnitude of heat exchange is dependent upon the presence, height, and character of plant cover (Mount and Paetzold, 2002). Plant cover generally slows down soil surface heat intake and therefore it's warming (Shul'gin, 1965). Plant cover also affects the amplitude of temperature flux; a bare soil is warmer at mid-day than the soil under natural cover. Dense vegetation shades the soil surface from radiation and the soil experiences less heating and cooling. In summer, plant cover increases reflection, evaporation, and heat losses by reradiation; however the highest temperatures occur on soils that are sparingly vegetated with grassy cover. In the northern hemisphere, the greatest positive heat flux occurs in spring and the first half of summer, while the greatest negative heat flux occurs in early winter (Mount and Paetzold, 2002).

Kang et al. (2000) developed a hybrid soil temperature model using air temperature data to predict daily spatial patterns of soil temperature in forested landscapes that incorporated topography, canopy, and surface litter effects in South Korea. The model accurately assessed soil temperature values in three hardwood forests and a bare ground area based on field checked methods. The model quantified the relationship between air and soil temperatures under all four landscapes. Increases in leaf area index values and litter layer thickness negatively impacted the air and soil temperature values.

The daily temperature variation at the soil surface is generally characterized by a minimum around sunrise and a maximum at approximately 1300 hrs. The largest daily temperature flux occurs at the surface of the soil then decreases with depth. Damping of diurnal temperature flux occurs at a depth of 35 to 100 cm where the diurnal temperature remains constant. However, gradual changes in soil temperature may occur at those depths on a weekly basis. The gradient of soil temperature change decreases with depth because the upper layers absorb and dissipate most of the heat and downward heat flow is buffered. In sandier substrates, heat is more readily transferred and diurnal amplitude of temperature flux is greater than in any other texture (Jury et al., 1991; Mount and Paetzold, 2002).

Soil temperature has been characterized in temperature latitudes in the northern hemisphere. Annual soil temperatures reach a maximum in July or August and a minimum in January or February. The depth of annual fluctuation exceeds the depth of diurnal fluctuation and annual soil temperature oscillations have been recorded from 15 m to 20 m deep (Mount and Paetzold, 2002).

Soils also exhibit seasonal temperature dynamics. In the northern hemisphere, summer soil temperature decreases with depth, while in winter soil temperature increases with depth. In the transitional seasons peculiarities occur in the distribution of soil temperature. In fall, temperature is highest in subsoil layers and decreases both upward and downward. Conversely, in spring, temperature is lowest at a subsoil layer and increase both upward and downward (Mount and Paetzold, 2002). Mean annual air temperature is lower than mean annual soil temperature, and soil temperature differs by 1 > 5 °C due to vegetative and soil buffering as discussed earlier.

Below the freezing point, there is little biological activity because water no longer moves in liquid or vapor form between temperatures of 0 and 5 °C in most plants, so root growth and seed germination are rare (Mount and Paetzold, 2002). Yet, a recent study in a constructed wastewater wetland Germany found biologically driven N_2O release at soil temperature < 0 °C and N_2O emissions spiked after freeze events (Fey et al., 1999).

Effects of Forest Conversion on Southeastern Wetland Soils

For more than two centuries, foresters in many parts of the globe have attempted to improve the productivity of certain types of wetland forest ecosystems through drainage (Heikurainen, 1983). Drainage ditches may have immediate effects on hydrology after construction. Changes in the soil and vegetation that are caused by natural processes or silvicultural practices following drainage result in additional hydrologic changes (Gregory, 1988). The most visible hydrologic change that occurs after drainage is an increase in average depth to the water table (Gregory, 1988). Water table height is influenced by ditch depth and spacing, soil hydraulic conductivity (vertically and horizontally), thickness of capillary fringe, ET rates, and precipitation patterns (Vepraskas, 1999; Gregory, 1988). The water table is usually nearest the surface at the midpoint between ditches and the deepest where it intersects the ditch (Hauser, 1992). A study indicated that ditching in poorly drained Coastal Plain soils had little impact on the water table for distances 40 m or greater (Hauser, 1992). The increase in soil water storage capacity that occurs due to lower water table depths depends on soil properties and has a major influence on the runoff regime of the site (Lundin, 1972). Drainage canals, ditches and their accompanying spoil banks have changed surface water levels and flow patterns. Logging practices and roads built on spoil banks have provided high ground and sunlit areas and such changes and have altered the native flora and fauna.

Poorly drained mineral soils in the southeastern USA are some of the most intensively managed forest sites in the world. Many non-productive or marginally productive sites have been converted into productive forest land in the region through site-specific application of silvicultural treatments such as drainage, bedding, phosphorous fertilization, liming, and vegetation control (Allen and Campbell, 1988; Barnes, 1981; Gilliam and Skaggs, 1981). Other disturbance includes agriculture. Areas abandoned after unsuccessful attempts at cotton and other agricultural commodities support a variety of forest cover on southern soils (Wharton et al., 1982).

Objectives

The current ACOE concept of the growing season may not be accurate in predicting soil temperature at 50 cm below biological zero and underestimates the period of activity for microbes or native vegetation. Under the current growing season many wetlands, especially marginal wetlands such as wet flats are lost because regulation does not take into account the winter high hydromorphology of these systems. Further, wet flats in the Great Dismal Swamp ecosystem of Southeast Virginia have undergone drastic changes in land use over the last two hundred years that have resulted in the present mosaic of altered and degraded natural plant community types and hydrologic conditions. Plant community type and land use affects hydrology and air temperature and thus soil properties and temperature in wet flat ecosystems. The growing season should be reflective of these specific properties. The interaction between land use, hydrology, soil temperature, and the growing seasons in wetlands is under reported in current literature, especially for wet flats.

The objectives of this study were

(i) to compare measured air temperature with the frost-free days growing season dates used by the US ACOE and measured soil temperature at 50 cm with various growing season dates and indicators on three different land-use types on two wet flat study areas in the Great Dismal Swamp ecosystem of Southeast Virginia, and

(ii) to determine the relationships between the hydrology, air temperature at 1-m height, and soil temperature at 15-, 30-, and 50-cm depths on three different land-use types on two wet flat study areas in the Great Dismal Swamp ecosystem of Southeast Virginia.

Chapter 2. The Great Dismal Swamp Study Areas

Coastal Plain Wetlands

The thermic soil temperature regime encompasses a large extent of the Atlantic Coastal Plain, from northern Florida to Virginia (Figure 2-1) (Walker and Coleman, 1987; Soil Survey Staff, 1999). Within this region a great diversity of aquatic, terrestrial, and transitional biotic communities exist. Vegetation community types vary tremendously across a hydrology-soils-fire continuum (Harms et al., 1998; Stout and Marion, 1993). The Atlantic Coastal Plain was naturally forested with hardwoods, mixed conifers, and forested wetlands. Thus, uplands and wetlands were juxtaposed over short longitudinal distances by slight differences in elevation (Stout and Marion, 1993).

Fifteen percent of the Atlantic Coastal Plain is composed of wetlands, with some coastal states, such as Florida being nearly one-third wetlands. In the mid 1970's, 47% (18.8 million ha) of the 40 million ha of wetlands in the contiguous USA were found in the Atlantic Coastal Plain (Hefner and Brown, 1984). One of the largest wetland areas in the Atlantic Coastal Plain is the Great Dismal Swamp (Dismal Swamp) ecosystem of southeastern Virginia and northeastern North Carolina (Figure 2-1).

Distribution of the Great Dismal Swamp

The Dismal Swamp is one of the northernmost "southern" swamps on the Atlantic Coastal Plain and is arguably the most studied and romanticized wetland in the USA (Mitsch and Gosselink, 2000). The Dismal Swamp is one of the few remaining large areas of wet wilderness in the eastern USA. The Great Dismal Swamp National Wildlife Refuge (GDSNWR) is located in the cities of Chesapeake and Suffolk, Virginia, and Camden, Pasquotank and Gates counties in North Carolina. The GDSNWR is mainly forested wetlands with Lake Drummond at the center.

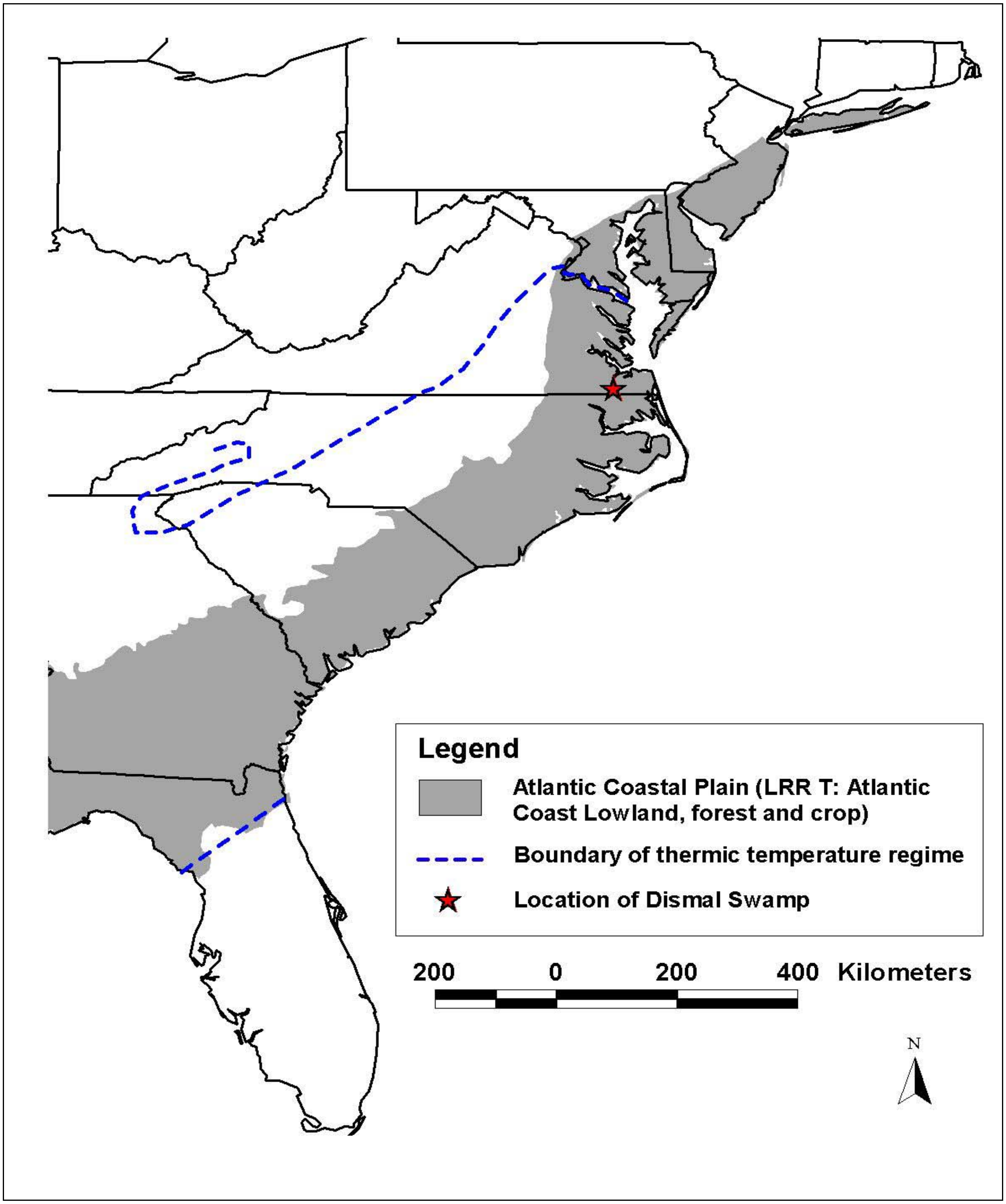


Figure 2-1. The Atlantic Coastal Plain Province (darkened) with the thermic temperature regime boundary outlined within the Coastal Plain (Soil Survey Staff, 1999). General location of Dismal Swamp is indicated by the star.

Historical estimates of the original size vary widely. Estimates range from one million to a few tens of ha; the Dismal Swamp ecosystem is commonly estimated at 500,000 ha. The larger estimates are based on physical and biological features associated with the Dismal Swamp that once dominated much of the low-lying landscape in southeastern Virginia and northeastern North Carolina; while smaller estimates were taken from early exploration journals or are based on specific waterways and landmarks that are quantifiable (Lichtler and Walker, 1974; Culp, 1998). Human activities before the earliest topographic mapping in the area impacted the Dismal Swamp such that the original size may never be known (Oaks and Whitehead, 1979). The area presently considered the Dismal Swamp is 85,000 ha; the current acreage probably represents the "heart" of the original Dismal Swamp ecosystem since it is logical to assume that the developed acreage was more easily drained than that remaining.

The surrounding area east of the Suffolk Scarp is characterized by low altitude and low relief; only a few localities have elevations above 7.5 m. The Dismal Swamp is bounded by the Suffolk Scarp on the western boarder and the Deep Creek Swale on the eastern border. The surface of the Dismal Swamp slopes gently eastward at about 0.2 m km^{-1} from an altitude of 7.6 m near the toe of the Suffolk Scarp to 4.6 m near the Deep Creek Swale. In the west, the edge of the Dismal Swamp is distinct. In other directions the boundaries of the Dismal Swamp are irregular and indistinct, commonly merging with headwater swamps that extend down tributary systems and into low areas along interfluves (Oaks and Whitehead, 1979).

Land-use History

The Dismal Swamp has been in a state of dynamic equilibrium for the last several thousand years, with natural disturbance and subsequent successional stages. Natural and man-made disturbance processes were active over centuries, but the current rate of disturbance is to an unprecedented degree. These changes are indicated by shrinkage in surface area, the loss of characteristic trees, and increased frequency of fires (Whitehead and Oaks, 1979). Studies have indicated that prehistoric man used the Dismal Swamp as a vast hunting and fishing range (Stewart, 1979). Whitehead and Oaks (1979) indicated that pollen distributions had been truncated with depth, suggesting that considerable amounts of peat have oxidized due to human manipulations.

Much of southeastern Virginia and northeastern North Carolina was settled by the 1700's, most rural areas were more densely populated that even today (Kirby, 1995; Lane, 1998). Agriculture was characterized by slash and burn clearing and cultivation, then abandonment (Kirby, 1995). Livestock was open-range, roaming freely within the remaining forested lands until the late 1800's (Kirby, 1995).

The Dismal Swamp has been the focus of many development schemes since settlement times. Drainage occurred in the Dismal Swamp as early as 1763 when the Dismal Swamp Land Company, co-owned by George Washington, built a canal from the western edge of the Dismal Swamp to Lake Drummond to establish farms in the basin. In general, that effort and many of those to follow failed.

The Dismal Swamp Canal and subsequent projects, opened about 1836, interfered with eastward drainage in the Dismal Swamp and thereby permitted much of the acreage to be "improved" to the east (Shaler, 1890; Henry et al., 1959). By the late 1800's access to the interior of the Dismal Swamp was relatively easy since many ditches radiated from Lake Drummond with an extensive ship canal system. These ditches were created for fire control and navigation. The resulting changes in water budget may have accounted for the oxidation of peat layers. Drainage projects continued to become more widespread until the Civil War, when the land was abandoned (Sharitz and Gresham, 1998).

In 1901 William Camp, of Union Camp Company, purchased the land from the Dismal Swamp Land Company (Stutts, 1998). Multiple timber companies and private citizens illegally harvested the Dismal Swamp bald cypress (*Taxodium distichum* L.) and Atlantic white cedar (*Chamaecyparis thyoides* L.) populations for shipbuilding, shingles, and other uses (Mitsch and Gosselink, 2000; Stewart, 1979). Union Camp Corporation let a portion of their forestry practices lapse in the Dismal Swamp region after World War II (Stutts, 1998).

Before 1973, the land was threatened by fires, low water levels, land clearing in the region, and illegal activities, such as timber theft and dumping (Ashley, 1998). Developers were considering building an international airport, a large racetrack, planned communities, and draining areas for soybean production. Yet by 1972, public interest in conservation led to a federal agency study authorized by federal law (Public Law 92-478). The federal agency study found that the Dismal Swamp was a unique and important ecological system and a repository that could not be recreated if destroyed, especially due to the close proximity of Hampton Roads metropolitan area. After the study, the Nature Conservancy worked with Union Camp Corporation to protect a portion of sensitive lands within their holdings by creating a National Wildlife Refuge (Stutts, 1998). In 1973, the Union Camp Corporation gave almost 25,000 ha of the Dismal Swamp to the federal government to be maintained as a National Wildlife Refuge (Dabel and Day 1977; Stutts 1998). The refuge was officially established through the Dismal Swamp Act of 1974 (Public Law 93-402).

Today, the Great Dismal Swamp National Wildlife Refuge and the Great Dismal Swamp State Natural Area in North Carolina encompass 55,000 ha of contiguous permanently protected land. A primary mission of the Dismal Swamp Refuge is to preserve the unique ecosystem and to provide for the diversity and abundance of native animals and plants. The Dismal Swamp Refuge is a severely impacted ecosystem, about 240 km of logging roads disrupt natural hydrology, ditches excavated to provide soil for the road beds lowered the water table and the roads block natural flow of water across the Dismal Swamp, affecting plant community structure and wetland function (Fish and Wildlife Service, 2002).

Dismal Swamp is situated near the urban sprawl of the Norfolk-Newport News-Virginia Beach metropolitan area, one of the fastest growing areas in the country (Lichtler and Walker, 1974; Mitsch and Gosselink, 2000). Census and planning agencies indicate that rapid growth in the area is not a “spurt” but a long-term trend (Hampton Roads Planning District Commission, 1996). Development of the adjacent former swampland undoubtedly affects present hydrology of the Dismal Swamp, but modification of surface drainage into the Dismal Swamp via drainage ditches had greater impact (Lichtler and Walker, 1979). Wells located along the Suffolk Scarp draw water for domestic, stock, and irrigation uses from the Norfolk aquifer that underlies the Dismal Swamp, reversing the potentiometric gradient and hence the direction of ground-water movement. These modern modifications and water loss through the Dismal Swamp Canal have probably resulted in a generally drier Dismal Swamp as indicated by changes in vegetation (Lichtler and Walker, 1979; Levy and Walker, 1979).

The Ramsar Convention, a Convention on Wetlands of International Importance Especially as Waterfowl Habitat, named for its place of origin in Ramsar, Iran, identified the Dismal Swamp as a wetland of international importance in 1971. Ramsar defined the Dismal Swamp Refuge as an ecosystem that is highly representative of wetlands throughout the southeastern and central USA (Navid, 1988).

Geology

The Atlantic Coastal Plain Province has a long history of sea level fluctuation events which have periodically altered landscape wetness regimes. During the last glaciation (~10,000 B.P.), the emerged portion of the province was much greater due to sea-level lowering (Stout and Marion, 1993). Most of the province has been above sea level since the Cretaceous, with numerous marine transgressive-recessive sequences (Walker and Coleman, 1987). The present level of the Atlantic Ocean has marked the seaward limits of woody vegetation over the last 5000 years. Local relief is modest with more than half of the region under 30 m; the more extreme topography in the range of 30-90 m. Because of modest relief and historic subsidence, the slight relief of the Coastal Plain supports extensive riverine and non-riverine wetlands (Stout and Marion, 1993; Wharton et al., 1982).

The former sea bottom that formed at the trailing edge of the North American Plate during Mesozoic and Cenozoic Eras now extends inland from 160 to 320 km (Hunt, 1974; Walker and Coleman, 1987). Cretaceous, Tertiary, Quaternary, and Holocene geologic formations underlie the Coastal Plain and represent seaward deposition of sediments. The underlying bedrock is Precambrian and Paleozoic in age and includes metamorphic, igneous, and sedimentary rock dating from the Triassic and Precambrian (Stout and Marion, 1993; Hunt, 1974; Walker and Coleman, 1987). The Coastal Plain province is divided into the Upper, Middle, and Lower Coastal Plain based on major seaward deposition and relative age of sediments. The division between the Upper and Middle Coastal Plain is demarcated by the Surry Scarp, while the Middle and Lower Coastal Plain is separated by the Suffolk Scarp (Oaks and Whitehead, 1979). The Suffolk Scarp is a continuous 340 km boundary from the Potomac River in northern Virginia to the Neuse River in North Carolina. It was formed as a shoreline feature during the Pleistocene Epoch, when sea level was approximately 14 m higher than at present (Lichtler and Walker, 1974). The Deep Creek Swale trends north-south, and is a depressional feature with a slight topographic rise both westward and eastward from the center. Deep Creek Swale is topographically lower than the Dismal Swamp, yet is not part of the Dismal Swamp due to the geologic age and energy of deposition at the time of development.

Extensive geologic investigation has demonstrated that the near-surface history of the Dismal Swamp is quite complex. Numerous borings east of the Suffolk Scarp (Oaks and Coch, 1973; Oaks et al., 1974) have established the geologic configuration within 15 m of the Dismal Swamp mineral surface, comprised of Miocene aged Yorktown Formation and five formations of Pleistocene age. The Yorktown Formation is chiefly composed of compact, gradually sloping (0.2 m km^{-1}), impermeable, fossiliferous silt and clay. The overlying post-Yorktown deposits control the Dismal Swamp ground-water hydrology. The Great Bridge Formation is the oldest formation overlying the Yorktown Formation and is present locally beneath the eastern edge of the Dismal Swamp. The four younger units are composed of highly permeable, sandy shoreline deposits, and moderately permeable to impermeable lagoonal deposits. These are the Norfolk, Kempsville, Londonbridge, and Sand Bridge Formations in upward sequence (Figure 2-2) (Oaks and Coch 1973).

The Norfolk Formation unconformably overlies the Yorktown beneath most of the Dismal Swamp (Oaks and Whitehead, 1979). The Norfolk formation probably plays the most significant role in the hydrology of the Dismal Swamp (Lichtler and Walker, 1979). The Norfolk Formation is dominated by permeable coarse sand facies near the Suffolk Scarp, grading eastward into facies that are much less permeable. These facies act as a barrier to eastward movement of water through the Norfolk Formation, thus backing up water and creating artesian pressure within the Dismal

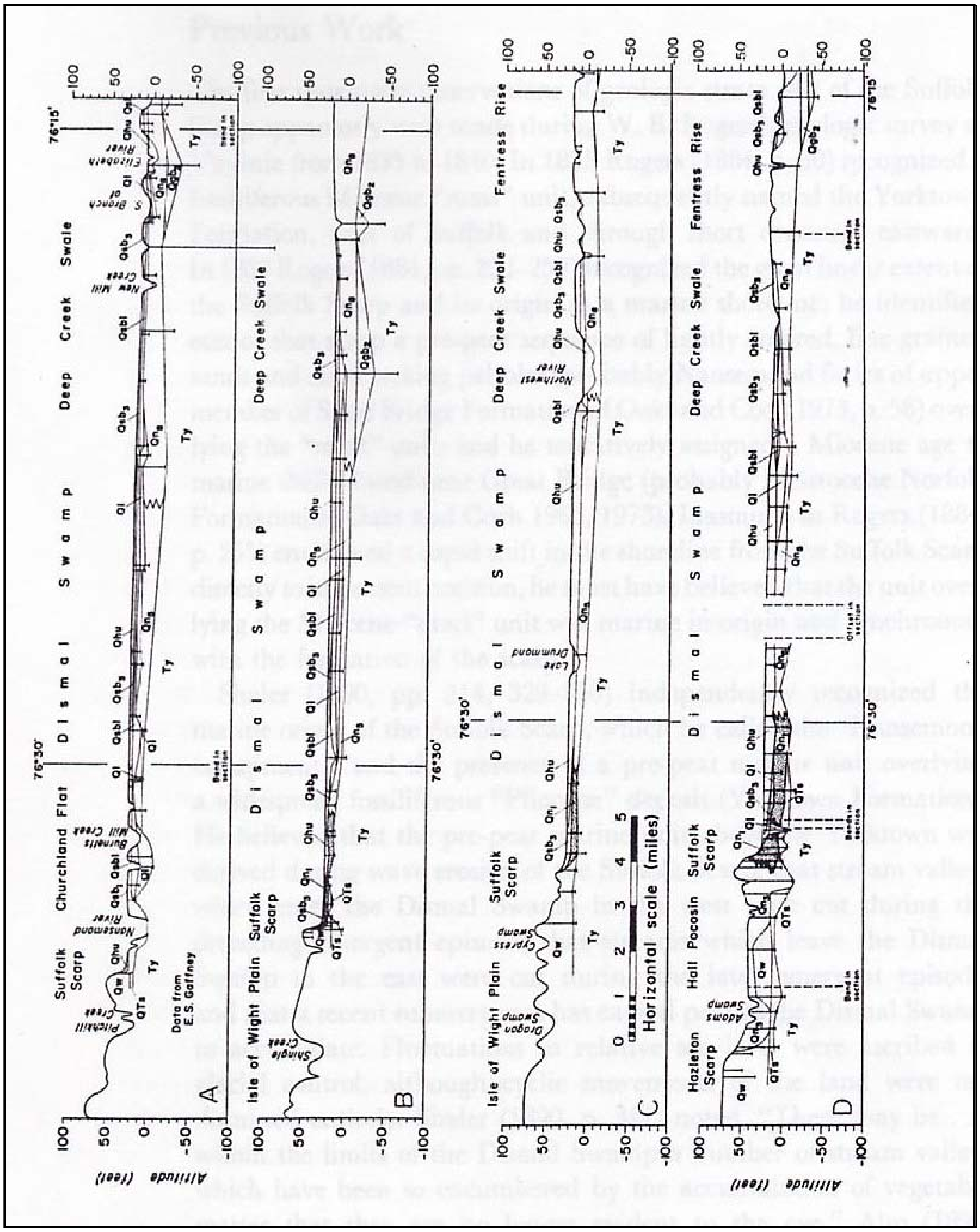


Figure 2-2. Geologic sections through Dismal Swamp. Locations of sections throughout Dismal Swamp. *Qhu* = Dismal Swamp Peat; *Qsb₁* = Sand Bridge Formation (Fm), upper member, clayey-sand facies; *Qsb₃* = silty-clay facies; *Qsbl* = lower member; *Ql* = Londonbridge Fm.; *Qn₁* = Norfolk Fm., coarse-sand facies; *Qn₃* = silty-clay facies; *Qn₅* = medium-sand facies; Qn8 = fine-sand facies; Qgb2 = Great Bridge Fm., silty-clay facies; Qw = Windsor Fm.; QTs = Sedley Fm.; Ty = Yorktown Fm. From Oaks, R.Q., Jr., and N.K. Coch. 1973. Post-Miocene stratigraphy, and morphology, southeastern Virginia. VA. Div. Miner. Res., Bull. 82 (plate 2). Courtesy of Virginia Division of Mineral Resources.

Swamp proper (Oaks and Whitehead, 1979). The Norfolk sediments are unconformably overlain by the sand facies of the Kempsville and Londonbridge Formation in very small areas of the Dismal Swamp and by the Sand Bridge Formation in the westernmost Dismal Swamp. During the Sand Bridge deposition, impermeable clayey silts accumulated westward in a lagoon laying both east and west of the high-standing remnants of the Norfolk Formation and in the present location of the Dismal Swamp (Oaks and Whitehead, 1979). Sandy deposits apparently blocked northward drainage from the area of the Dismal Swamp. These impermeable Sand Bridge lagoonal sediments extended entirely to the Suffolk Scarp and are widely interspersed in the Dismal Swamp (Oaks and Whitehead, 1979).

Before development of the drainage pattern in the surface of the Sand Bridge Formation, water in the Norfolk Formation was under artesian pressure caused by recharge above the Suffolk Scarp, and was confined by the finer facies of the Sand Bridge. As downcutting of the broad shallow valleys of the present drainage system proceeded, the silty clay confining layer of the Sand Bridge was removed, thereby allowing upwelling of water from the medium sand facies of the Norfolk Formation. The addition of this artesian water into a level, low-lying area of poor surface drainage, combined with abundant precipitation, may have been sufficient to trigger the morphology of the Dismal Swamp about 9,000 years ago (Lichtler and Walker, 1979). Pollen evidence and radiocarbon dating estimate that the Dismal Swamp surficial formation was probably initiated as an open freshwater marsh in the late-Pleistocene, about 11,000 to 12,000 B.P.

Hydrology

Precipitation is the primary source of water inputs to the ecosystem in wet flats, though groundwater flow and runoff are also contributing sources (Harms et al., 1998). Groundwater and surface water are more closely interrelated in the Dismal Swamp than in most environments and the dividing line is not always clearly defined (Lichtler and Walker, 1979). Seepage from the Norfolk formation has probably continued in modified form to the present day. Ditches designed to remove surface water and lower the water table often intersect underlying aquifers and may deplete ground-water resources. Precipitation falling on and near the Dismal Swamp may stand on the surface before running off as sheet flow or soaking into the underlying formations. As shallow groundwater, it may move laterally toward areas of discharge, such as canals or ditches and become surface water again (Lichtler and Walker, 1979).

The 29,000 ha upland area surrounding the western edge of the Dismal Swamp is responsible for most surface inflow via numerous small streams and sloughs that enter from Suffolk Scarp. Two main areas of inflow to the Dismal Swamp are Cypress Swamp and Hamburg Ditch. Cypress Swamp is a low area directly west of the Dismal Swamp above the Suffolk Scarp. Hamburg Ditch runs through the Dismal Swamp and drains an unknown amount of water into the Pasquotank River. Little runoff from Hamburg Ditch is retained in the Dismal Swamp. There is a seasonally varied flow rate into and through the Dismal Swamp. Most streams and sloughs do not last through the dry season. The principal modern outlet is the Dismal Swamp Canal (Figure 2-3). Other outlets are Jericho, Portsmouth, and Hamburg ditches. However, there is a network of secondary draining ditches throughout the Dismal Swamp that vary considerably in discharge during the mid and late parts of the growing season. During summer, average surface inflow to the Dismal Swamp from uplands west of the Suffolk Scarp is typically small, while average winter inflow to the Dismal Swamp may be three or four times greater (Lichtler and Walker, 1979).

Ground-water inflow to the Dismal Swamp is mostly from the west through the Norfolk aquifer and surficial sands that overlie the Sand Bridge confining layer. Ditches that intersect the

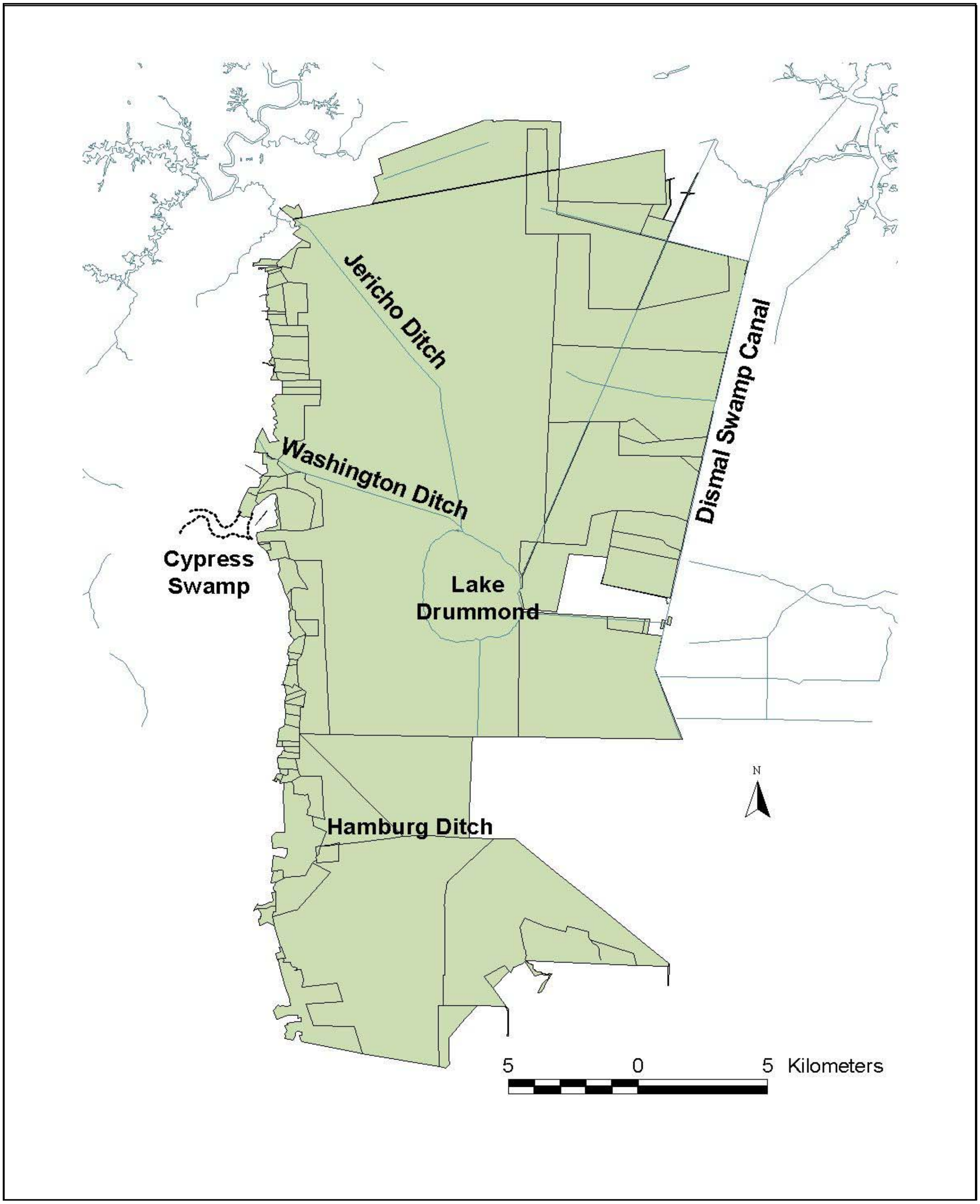


Figure 2-3. Major inlets and ditches in the Great Dismal Swamp Wildlife Refuge.

Norfolk aquifer drain groundwater to Lake Drummond, or out of the Dismal Swamp through the network of ditches.

Ground-water discharge occurs by upward seepage into Lake Drummond through the overlying peat, where the Sand Bridge Formation is permeable or absent, by direct seepage into canals and ditches that intersect the aquifer, or pumping along the Suffolk Scarp (Lichtler and Walker, 1979). Groundwater moves regionally toward the east in the more permeable sand layers, and these aquifers are separated by discontinuous layers of clay that restrict vertical ground-water movement. Near the land surface, local ground-water flow systems are associated with changes in land slope, such as at major scarps and streams (USGS, 2001). Water table wells and deep piezometers placed across the Suffolk scarp indicate a downward component of ground-water flow in the upland and upward component of ground-water flow in the lowland at the edge of the Dismal Swamp. However, in the lowland, the direction of vertical flow changed seasonally (USGS, 2001). Temperature of groundwater fluctuates little throughout the year and remains near the mean annual air temperature. Surface water temperature fluctuates widely during the year tending to be warmer in the summer than groundwater and colder in winter. This connection could yield valuable information about the location and extent of ground-water flow and its relationship to surface water flow (USGS, 2001).

ET is the primary source of hydrologic losses to the ecosystem in wet flats, though runoff and groundwater loss are also contributing sources (Harms et al., 1998). ET losses account for a significant output of wet flat wetlands water budget, typically from 80 to 90% of incoming precipitation (Muller and Grymes, 1998; Harms et al., 1998). Ditching and other management practices may impact ET losses in the water budget, lowering evaporation rates by making soil water less available, but increasing transpiration losses by enhancing the growth of woody plants and biomass increases allowing ET to rise as leaf area and rooting depth increase (Gregory, 1988). Runoff is highest during the winter months and lowest during the summer months. Ground-water losses are less than 1% of precipitation due to underlying impermeable clay strata (Heath, 1975).

Climate

The Dismal Swamp is temperate, characterized by long, humid summers and mild winters. The Dismal Swamp is within the thermic soil temperature regime, characterized by a mean annual temperature between 15 °C and 22 °C (Soil Survey Staff, 1999). The average annual air temperature is 15 °C. The average winter air temperature is 5 °C and the average daily minimum winter air temperature is -1 to 0 °C (Soil Survey Staff, 2002). The lowest air temperature on record in the Dismal Swamp, which occurred on January 21, 1985, was -20 °C (Soil Survey Staff, 2002). In summer, the average air temperature is 25 °C and the average daily maximum air temperature is 30 °C (Soil Survey Staff, 2002). The highest recorded air temperature was 40.6 °C which occurred on June 26, 1952.

The average annual precipitation is 124 cm. Of this, about 77 cm (62%) usually falls in April through October. The wettest months are July, August, and June and the driest months are November, April, and December. The heaviest one-day precipitation during the period of record was 23.4 cm on September 15, 1999. Thunderstorms occurred about 37 to 40 times each year, mostly during June, July, and August. Hurricanes are a common occurrence in the Dismal Swamp study area, influencing weather patterns approximately once every six years. As much as 40% of precipitation during hurricane season (July to October) originates from tropical storms (Hayden and Michaels, 2000). The average seasonal snowfall is 17 cm. The greatest snow depth at any one time during the period of record was 43 cm recorded on February 6, 1980. On average, at least 2.5 cm of snow occurs on the ground three days yr^{-1} (Soil Survey Staff, 2002). The average relative humidity in mid-afternoon is about 57%. Humidity increases at night, and average humidity at dawn is about 79%. The sun shines 64% of the time during the summer months and 56% of the time during the winter months. Prevailing winds are predominantly from the southwest, occasionally prevailing winds from the northeast occur in September and October. The highest average wind speed (~19 km per hour) occurs from February to April (Soil Survey Staff, 2002).

Vegetation

The Dismal Swamp is an extensive fresh deepwater swamp forest, historically containing predominantly bald cypress-tupelo ecosystems (*Nyssa sylvatica* Marsh. var. *biflora*) or extensive stands of Atlantic white cedar in its wetter landscapes (Conner and Buford, 1998). Although remnants of those communities exist today, much of the Dismal Swamp is dominated by red maple (*Acer rubrum* L.) and mixed hardwoods typically found in drier areas (Day, 1982). The region had an intense burning regime, but post-settlement selective harvesting, fire suppression, and drainage have led to an increase in red maple and sweet gum (*Liquidambar styraciflua* L.) (LeGrand, 1998).

In the Dismal Swamp the flora and fauna are predominantly southern, yet a large number of northern plants and animals occur at the extent of their distribution. There are five major forest plant communities which comprise the Dismal Swamp's vegetation including (1) pine, (2) Atlantic white cedar, (3) maple-blackgum, (4) tupelo-bald cypress and (5) sweet gum-oak poplar forests (Levy and Walker, 1979). Currently, red maple is the most abundant and widely distributed plant community, expanding into other communities due to lingering effects of past logging, extensive draining, and forest fire suppression. The canopy of the forest at the Bruff study area, west of the Dismal Swamp is dominated by planted loblolly pine (*Pinus taeda* L.). The gum-oak poplar forests or mixed hardwood mineral flat forests are the third dominant vegetation in the Dismal

Swamp. This mixed hardwood subtype is typical of the Hall study area, to the east of the Dismal Swamp Wildlife Refuge and is a secondary dominant at Bruff property (Levy and Walker, 1979).

The distribution of flora in forested wetlands revolves around the presence and intense selective power of anaerobic conditions generated by the wet hydroperiod and tolerances of plant species to these conditions (Wharton et al., 1982). Although factors such as light intensity, soil pH, and nutrient availability affect plant distributions in other forest communities, they are secondary to anaerobiosis in wetland forest communities. The effects of periodic or permanent flooding are the crucial selective stress on wetland forests and are responsible for sorting of species into broad community types (Huffman and Forsythe, 1981). Plants growing in saturated substrate must respond to multiple rapid physical and chemical changes such as depletion of available oxygen in soil water, shifts in soil pH, and the subsequent chemical processes that create circumneutral pH after flooding of more acidic forest soils. Accumulation of potentially toxic compounds (increased levels of CO_2, ethanol, sulfides, nitrates, aluminum, iron, and manganese) occur in the plant, the rhizosphere, and in bulk soil solution. Reduced forms of most redox sensitive essential nutrients are less desirable for plant uptake and assimilation (Teskey and Hinkley, 1977).

Teskey and Hinkley (1977) emphasized that the key to plant survival in flooded or saturated conditions is the adaptability of the root system. The inability of flood intolerant species to absorb and use water and nutrients leads to foliar water deficits, stomatal closure, and reduced gas exchange. Consequently, transpiration and photosynthetic rates are slowed, cellular synthesis requiring unavailable nutrients is curtailed, and overall plant growth is impeded (Teskey and Hinkley, 1977). The plants die of dehydration while in flooded conditions. Plant adaptations to flood stresses are either physical or metabolic and there is a gradient of tolerance. In practice, plants that have tolerance to water are denoted as ranging from facultative to obligate wetland species and are also known as hydrophytic vegetation.

The effects of flooding are most critical during the growing season, particularly during the period of leaf out (Wharton et al., 1982). Floods during the dormant season have relatively little effect on the physiology and survival of hardwood species, other than possible damage due to mechanical abrasion or breakage (Wharton et al., 1982). The depth of the flooding event is critical because even plants with physiological adaptive strategies that are submersed for long periods of time do not survive. Duration of a flooding event is also important to most hardwood species, the majority of these species would not survive two years of continuous flooding. The duration of flooding that is survivable is unique to each plant species and survival strategy (Broadfoot and Williston, 1973).

Today, most plant communities in the Dismal Swamp are second- or third-growth forests or dense brushlands that represent a variety of seral stages. Stands on mineral soils were more species diverse than forests on peat substrate. In mixed deciduous swamps, which generally occur on mineral soils, red maple and blackgum (*Nyssa sylvatica* Marsh.) are less abundant and species diversity is greater. Carolina ash (*Fraxinus caroliniana* P. Mill.), green ash (*F. pennsylvanica* Marsh.), and pumpkin ash (*F. profunda* Bush.) are more abundant in wetter areas, while sweet gum and loblolly pine are more abundant in the relatively drier areas. Holly (*Ilex opaca* Ait.), blackgum, and red bay (*Persea borbonia* L.) are abundant in areas that fluctuate between wetter and drier extremes (Levy and Walker, 1979). The current Dismal Swamp community is much less diverse than in the past, and is most diverse in openings and forest margins that serve as habitat for herbaceous plants that would not otherwise be found in dense forest stands (LeGrand, 1998).

Soils

The Dismal Swamp contains a mosaic of organic and mineral soils. Significant drainage and oxidation have lessened the original extent of organic soils (Day, 1982). Soils within the Dismal Swamp are predominantly very poorly drained, poorly drained, and somewhat poorly drained (Soil Survey Division Staff, 1993). Many of the soils are subject to flooding for long periods. The soils were formed in silty to loamy marine and fluvial sediments of mixed mineralogy in the lower Coastal Plain and are found primarily on broad inland flats. Most mineral soils have loamy or clayey subsoils and a substratum that is very sandy.

A common association on the landscape includes Levy-Rains-Lynchburg complex on the western portion of the Dismal Swamp within the boundary of the City of Suffolk. Many of the soils are drained and farmed or otherwise managed (Reber et al., 1981). This association is found in the area in and around the Bruff study area. The City of Suffolk Soil Survey describes the Levy-Raines-Lynchburg association as very poorly drained, poorly drained, and somewhat poorly drained soils that have mostly clay, loam, and sandy clay loam below the sandy loam to silt loam surface layer. This soil association is typically mapped in low or nearly level areas (0-2 % slope) (Reber et al., 1981).

The eastern portion of the Dismal Swamp is mapped in the City of Chesapeake Soil Survey. This soil survey was published in 1965 as Norfolk County, but is no longer available to the public and is currently being updated. A common association on the landscape includes the Othello-Fallsington complex, poorly drained fine sandy loam soils, on the eastern margin of the Dismal Swamp within the boundary of the City of Chesapeake. This association is found in the area in and around the Hall study area. The soils in the adjacent 330 ha forested area, are Othello-Fallsington or named "Wet Soils" in the original survey, indicating an extensive area of unmapped land that was obviously wetlands. However, large portions of the eastern side of the Dismal Swamp are currently being mapped as the Acredale-Tomotley-Nimmo association with inclusions of Roanoke (Hammer, pers. comm., 2002). Acredale and Tomotley are essentially identical to Othello-Fallsington association, except the Othello-Fallsington soils are in the mesic soil temperature regime.

Study Sites

General Description

This study was conducted on two wet flat systems within the historic reaches of the Dismal Swamp ecosystem in the Atlantic Coastal Plain Region of Southeast Virginia, between the Suffolk and Hickory Scarps. Specifically, these sites were once considered hardwood mineral wet flats based on remnant vegetation. Both sites have been subject to drainage and intense management documented since the 1960's. Past land use included forestry and cultivation. Drainage ditches have been active for several decades (1960's) to lower the water tables for these land uses.

The first site (Bruff study area) is managed by the FWS and is located on the west side of the Great Dismal Swamp National Wildlife Refuge. The site is in the City of Suffolk County, at an elevation of 15 m and centered at 36^o 37' 02" (36.61719) N, 76^o 33' 28" (76.55783) W. The Bruff study area is a 4.3 ha parcel adjacent to a mature forest stand within the boundaries of the Great Dismal Swamp National Wildlife Refuge and in close proximity to the refuge office (Figure 2-4).

The Bruff study area was drained and managed as an agronomic field until 1999. The field was rotated between soybeans, corn, and cotton. These crops failed one out of five years due to soil moisture; cotton was destroyed by boll weevil infestation (land owner Bruff, pers. comm.). The forested area, planted to loblolly pine in 1975, is nestled between Railroad Ditch and a ditch formerly used to manage hydrology in the field; the forest margin is 40 m wide. Ditches were

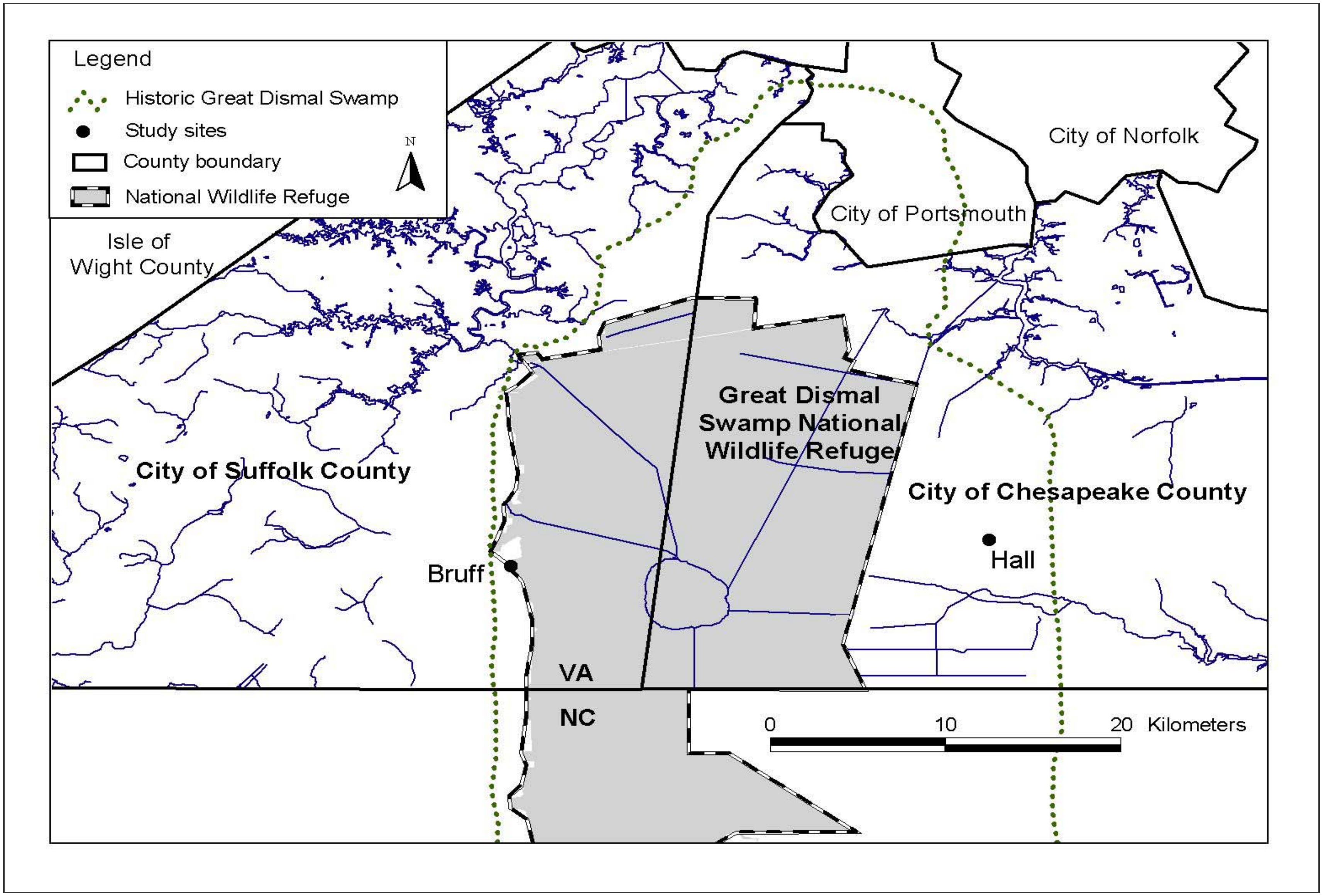


Figure 2-4. Study area locations in reference to Great Dismal Swamp National Wildlife Refuge.

plugged to restore hydrology in the spring of 2000.

The second site (Hall study area) is located on the eastern margin of the Great Dismal Swamp National Wildlife Refuge and is maintained by the Nature Conservancy. The site is in the City of Chesapeake, at an elevation of 10 m and centered at 36^{o} 37’ 57” (36. 63249) N, 76^{o} 18’ 50” (76. 31396) W. The Hall study area is a 12.5 ha. parcel located along the east side of Twelve-Foot Ditch in the watersheds of the North Landing and Northwest Rivers. The adjacent property is an extensive forested wetland area with newly restored hydrology; also owned and managed by the Nature Conservancy (Figure 2-4).

The Hall study area was drained and managed as an agronomic field until 1998. The field was rotated between corn and soybeans. These crops failed two out of three years due to persistent soil moisture (land owner, Davie, pers. comm.). The adjacent forest was managed by a private forestry company and left to regenerate naturally. The last harvest occurred in the early 1980’s. In the spring of 2000, the hydrology was restored by ditch plugging and filling.

Soils

The soils found on the Bruff study area are Lynchburg fine sandy loam (Fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults) and Rains fine sandy loam (Fine-loamy, siliceous, semiactive, thermic Typic Paleaquults) (Soil Survey Division, 2002). Lynchburg is found on 60% of the field typically on the south side, and Rains is found on 40% of the field on the north side. Lane Environmental Consultants mapped the field in 1999, and concurred with the soil survey.

The Norfolk County Soil Survey of 1965 describes the Hall field as consisting of half Dragston fine sandy loam (Coarse-loamy, mixed, semiactive, thermic Aeric Endoaquults) and half Othello-Fallsington fine sandy loam (Fine-silty, mixed, active, mesic Typic Endoaquults and Fine-loamy, mixed, active, mesic Typic Endoaquults (Soil Survey Division, 2002). Dragston is a somewhat poorly drained soil and the Othello-Fallsington complex is poorly drained. In 1999, Lane Environmental Consultants mapped the field at Hall. Lane indicated a general concurrence with the published soil mapping, yet noted that the Dragston series appeared to be less extensive than indicated in the soil survey. Lane also identified a transitional drainage phase, somewhat poorly to poorly drained on the property. Lane indicated that depleted matrix colors were often found between 25 cm to 41 cm of the surface in the somewhat poorly drained soils (Lane, unpublished data, 1999). These soils were mapped based on hydric soil morphology.

Vegetation

Tree seedling species were planted to facilitate restoration in both study areas. The tree seedlings were purchased locally from Virginia seedling stock from the Department of Forestry in Augusta, GA and from Greentree Nursery, a regional nursery located in North Carolina.

Tree seedlings were planted 1 m apart, in rows 3 m apart at the Bruff study area. These species included water oak (*Quercus nigra* L.), willow oak (*Q. phellos* L.), cherrybark oak (*Q. pagoda* Raf.), swamp chestnut oak (*Q. michauxii* Nutt.), blackgum, and bald cypress. Observation of seedling survival indicated that approximately 50 percent of the planted species survived. An extensive vegetative analysis was conducted in the forest and field at Bruff. A species identification list for the forest strata and in the field is presented by alphabetical arrangement in Appendix 1a.

Approximately 5,000 tree seedlings were planted at Hall study area with identical variety and spacing as at Bruff. A seedling survivability study was conducted on the Hall study area two years after planting. The study found that seedlings planted on the site had 65% survivability. An extensive vegetative analysis was conducted in the forest and field at Hall. A species identification list is presented by alphabetical arrangement in Appendix 1b.

Chapter 3. Growing Season by Land-use Treatment in Mitigated Wet Flats of Southeastern Virginia

Introduction

Regulations concerning wetland delineation and mitigation use the growing season concept to specify limits on duration of saturation as part of the definition of wetland hydrology and hydric soil requirements. The growing season construct is important because lands that are saturated or inundated only while plants are dormant are not morphologically affected and do not perform the same functions as lands that are wet during periods of plant activity. Extended inundation or prolonged saturation within 30 cm during the growing season exerts considerable physiological stress on most plants, favoring the growth of hydrophytic vegetation used in the identification of wetlands (Teskey and Hinkley, 1977). Formation of redoximorphic (redox) features and accumulation of humified organic matter are thought to occur only during the growing season (Environmental Laboratory, 1987). Thus, accurate definition and identification of the growing season has critical implications to all three components of wetlands: hydrology, vegetation, and soils.

The growing season definition in use by the US Army Corps of Engineers (ACOE) has been questioned by previous studies because the ACOE has applied growing season definition across wetlands systems regardless of presence of water, vegetation type or land use, all of which influence soil temperature (Day and Megonigal, 1993; Cole and Brooks, 2000). The growing season definition was intended to identify periods of biological activity in the upper 50 cm of soil but has been of limited utility because: (1) it was not specific to land use or type of organism, and (2) it allowed frost-free days as a surrogate parameter for measured soil temperature. The National

Research Council (NRC) (1995) recommended the growing season concept be replaced altogether with another approach that better addresses the hydrologic, biotic, physical, and climatic differences in wetlands by region across the country based upon studies of natural wetland communities and ecosystem processes. Since that is unlikely to happen in the near future, this paper will critique the accuracy of the growing season definition and compare indicators of its starting and ending dates in determining hydrology requirements used in identification and mitigation regulations of wet flat wetlands in southeastern Virginia.

According to the ACOE, an area has wetland hydrology if it is inundated or saturated to the surface continuously for at least 5% of the growing season (Environmental Laboratory, 1987). Observed water tables must be continuously saturated within 30 cm in loamy and clayey soils in order to effectively meet the surface depth criteria. A minimum duration of 5% is considered the wetland hydrology threshold and hydrology may be considered over duration of 5 to 12.5% of the growing season. The specific period required to indicate successful mitigation is open to discretion by individual ACOE districts. The Norfolk district ACOE requires wetland hydrology in mitigated areas and marginal wetlands for at least 12.5% of the growing season.

The ACOE uses the growing season as a standard for wetland hydrology according to their wetland delineation manual (1987 Manual) in identifying wetlands subject to the Clean Water Act (Public Law 92-500, 33 U.S.C 1251) (Environmental Laboratory, 1987). The 1987 Manual defined growing season is “the portion of the year when soil temperature measured at 50 cm below the surface is above biological zero”. The 50 cm depth was originally established because it is considered to be the middle of the primary root zone for plant growth (Soil Survey Staff, 1975). This depth is also below the zone affected by diurnal fluctuations (Buol, 1977). Microbial activity has been found to occur in temperatures below 5 °C in some wetlands and certain ecological regions that may have specific adaptations (Flanagan and Bunnell, 1980; Grishkan and Berman, 1993; Zimov et al., 1993; Clark and Ping, 1997). However, temperatures lower than 5 °C are considered below the threshold of biological activity (biological zero), when microbial populations and plant activity are assumed to be insignificant and insufficient to alter biogeochemical processes (Williams, 1992), and this concept was fully adopted by the ACOE based on the definition of biological zero in Soil Taxonomy (Soil Survey Staff, 1999).

Mean annual soil temperature is related to mean annual air temperature, soil moisture, shading, and the presence of O horizons (Mount and Paetzold, 2002). Soil color, texture, and amount of organic matter can also affect soil temperature (Soil Survey Staff, 1975). The vegetation type and surface litter cover are affected by the land use and climate. Temperature differences at the soil surface caused by surface characteristics can mediate local air temperatures (Hillel, 1982; Scott, 2000). However, minimal research has addressed the effect of land use on soil temperature. Wagai et al. (1998) reported that soil temperature at 10 cm decreased from tilled to no-till to prairie plots before July. Soil temperatures were similar between land uses after the corn developed a full canopy in July. Aust and Lea (1991) found that soil temperature increased with timber-harvesting disturbance. Cooler growing season temperatures occurred in the reference forest stand than stands associated with helicopter, skidded or herbicide treatment, 1-yr after the areas were affected.

The biological zero threshold at 50 cm can either be measured directly or indicated by surrogate data (growing season indicator, GSI). The ACOE issued guidance to its personnel to clarify the 1987 Manual growing season concept and facilitate regulation because wetland scientists seldom measure soil temperatures (Williams, 1992). According to the 1992 memorandum of agreement, the 1987 Manual growing season can be approximated by the number of frost-free days because of the impracticality of obtaining representative soil temperatures at 50 cm at every potential wetland site throughout the year. The number of frost-free days is calculated from the average freeze dates published in NRCS county soil survey reports or downloaded from the NRCS Water and Climate Center in Portland, Oregon (ftp.wcc.nrcs.usda.gov) for most weather stations in the country. Freeze dates in the soil survey reports are based on three different freezing temperatures, -4.4, -2.2, and 0.0 °C. The ACOE in the Southeast has chosen to use the -2.2 °C freezing air temperature to calculate the number of frost-free days at a frequency of 5 in 10 years (Williams, 1992) as their indicator of soil temperatures at 50 cm (ST 50) above biological zero and to define a jurisdictional growing season (FFD -2.2 GSI). Other listed suggestions include the freezing air temperature limit of -4.4 °C (FFD -4.4 GSI).

The freezing dates in the soil survey reports were intended for farmers as a guide for proper planting dates of annual crops because soil temperature affects seed germination in spring, and farmers plant on dates appropriate to the crop grown (Mount and Paetzold, 2002). Freezing air temperatures can damage or kill crop seedlings. Thus, the latest soil survey freeze date for 0 °C in the spring has been used to define the start of the growing season applicable to agronomic crops.

The agronomic growing season dates may not appropriately define periods of appreciable biological activity for microbes, other plants, or wetland ecosystems (Day and Megonigal, 1993; Tiner, 1999). The annual native biota have more adaptations to cold temperatures than introduced agronomic crops and perennial biota have underground root systems that carry on physiological activity even when air temperatures dip below freezing. A study in New Hampshire found good correlation between bud swell of red maple (*Acer rubrum* L.) and changes in soil temperature and redox potential while air temperature was poorly related these processes (Whited, unpublished data). Therefore, using physiological GSI such as leaf growth, bud swell, or abscission layer development of native plants may be a more reasonable way to indicate their period of biological activity or growing season.

The growing season can be separately identified based on fundamental processes of which one is concerned. Soil temperature regulates microbial processes and some plant processes such as root growth (Megonigal et al., 1996). Tiner (1999) indicates that many native plant species begin growing in advance of the frost-free period such as angiosperms that flower in the spring, and many gymnosperm trees and shrubs. Bernard and Gorham (1978) reported that most shoots in sedges in New York had appeared in October, after the ending date of frost-free days, and some new shoots emerged in December. DeWald and Feret (1987) found that root growth in loblolly pine (*Pinus taeda* L.) plantations in Virginia continued upon cessation of shoot growth in late October, and throughout most of the winter months plant activity was supported by elevated root metabolic activity and photosynthesis. The growing season is therefore plant-specific and should include growth of any kind including both shoot and root elongation.

While defining a growing season based on the concept of biological activity is better than using the agronomic growing season, it still may not be as predictive as a growing season based on microbial activity or anaerobiosis of the soil (Tiner, 1999). Recent studies have looked at microbial respiration and subsequent CO_2 efflux from the soil, oxygen consumption, and microbial reproduction as proper indicators of the microbial GS (Pickering and Veneman, 1984; Groffman et al., 1992; Megonigal et al., 1996). Microbes in saturated wetland systems effectively generate the biogeochemical processes that create hydric soil indicators, such as anaerobiosis and Fe reduction. Reduced soil environments that are limiting to plant growth can occur outside of the agronomic growing season (Day and Megonigal, 1993) because microbes that exist below ground are well insulated from short-term freezing air temperatures. Anaerobic conditions may occur during any period where microbes are active, which is evidenced by O_2 and CO_2 flux (Megonigal et al., 1996). Thus, elevated levels of CO_2 efflux may be a more reasonable indicator (CO_2 ER GSI) of the period of microbial activity or growing season.

Previous studies indicate that the relation between the FFD GSI and measured soil temperature of 5 °C do not correspond. Thompson and Bell (1998) indicated that within a intensively farmed Mollisol catena, the microbial activity season started in April and extended through the beginning of December; longer than the FFD GS assigned to that area by the ACOE. Hydrology was also reported to affect soil temperature along a forested toposequence in Central Massachusetts. Poorly drained soils had continued biological activity and significant reduction even during winter months, while microbial activity in the better drained soils along the toposequence did cease (Pickering and Veneman, 1984). Soil temperatures were above the biological zero threshold in the better drained soils from April to mid-November, longer than that of the regulated FFD GS in this region. Megonigal et al. (1996) reported a 12-mo microbial activity growing season in South Carolina, Mississippi, and Louisiana for bottomland hardwood forests based on soil temperature and O_2 consumption. A study in a tidal flat in Virginia indicated that biological zero was never reached at the 50-cm depth and was reached for about 2% of the time at the 20-cm depth during the 12-mo study (Seybold et al., 2002). Huddleston and Austin (1996) found that in Oregon microbes were active year-round and that the growing season for soil microbes could not be predicted from either the -2.2 or 0 °C air temperatures as currently done for federally regulated wetlands. Based on these studies, the FFD -2.2 GSI used by regulators appears to underestimate the length of time that soil temperature at 50 cm stays above biological zero (5 °C) across the forested wetlands. However, very little soil temperature data is available in wet flat ecosystems.

The National Technical Committee for Hydric Soils recommends using soil temperature regime dates in Soil Taxonomy (Soil Survey Staff, 1999) as an acceptable growing season indicator (STR GSI). However, using a soil temperature regime based growing season to indicate biological zero is impractical for regulatory purposes because it results in sudden discontinuities at regional boundaries when soils with different soil temperature regimes are mapped side-by-side (Lynn et al. 1996).

Based on existing literature, the current FFD -2.2 GSI is not accurate in predicting soil temperature at 50 cm below biological zero and underestimates the period of activity for microbes or native vegetation. The actual soil temperature based growing season should vary depending on the land use, vegetation, and litter cover. The objectives of this study were to (i) compare measured air temperature with the established frost-free days table dates, (ii) compare the starting and ending GS dates by various GSI with measured soil temperature at 50 cm, and (iii) compare the affect of land use on soil temperature at 50 cm at two wet flats in southeastern Virginia.

Materials and Methods

Study areas

The two study areas are located approximately 24 km apart in Major Land Resource Area 153B, the Tidewater Area of the lower Coastal Plain of southeastern Virginia (Figure 3-1) (USDA-SCS, 1981). The study areas are within the historic reaches of the Great Dismal Swamp ecosystem (Lane, 1998; Lichtler and Walker, 1979). The region has been logged, cleared, and dissected by a series of drainage ditches over the past century and is currently primarily a mixture of agricultural, silvicultural, and urban land use

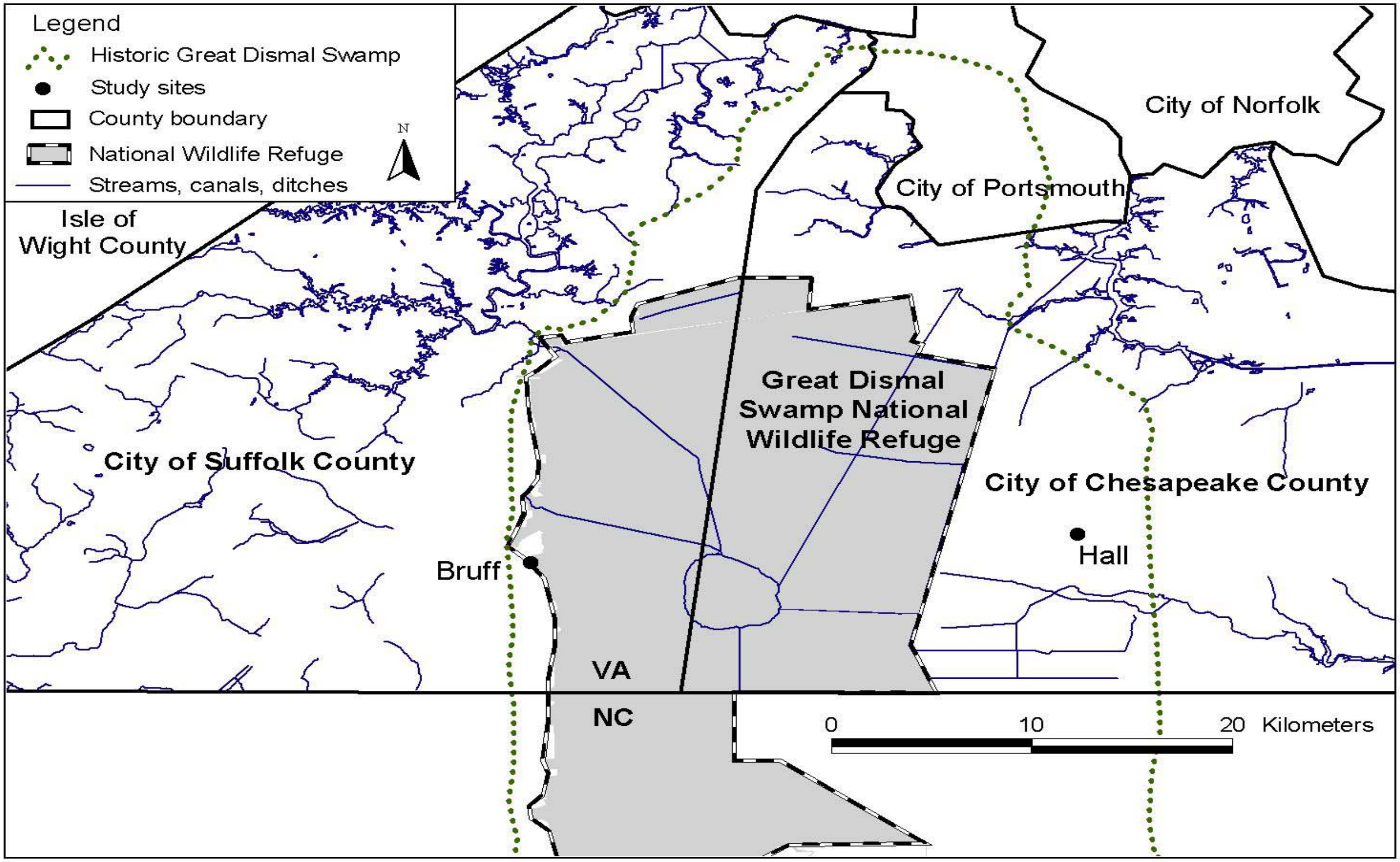


Figure 3-1. Study area locations in reference to the Great Dismal Swamp National Wildlife Refuge.

The 30-yr average annual precipitation for the region was reported as 122 cm (Reber et al., 1981). The summer months have higher precipitation than winter months, but there is no extended dry season. The wettest month is August and the driest month is November. The coldest month of the year is January, with an average daily minimum air temperature of -1.08 °C, and the warmest month of the year is July, with an average daily maximum air temperature of 35.20 °C. The mean annual winter air temperature was 6.71 °C, the mean annual summer air temperature was 23.32 °C, and the mean annual air temperature was 15.17 °C.

Soils in the area developed in Holocene-aged marine deposits of mixed mineralogy. In general, the soils consisted of poorly drained, moderately permeable soils with sandy loam surfaces, sandy clay loam to clay subsoils, and sandy substratum. Topographic relief was generally less than 10/1000 m, and the area was from 5 to 7 m above current mean sea level. Slopes within the study area ranged up to 2%.

The western study area (Bruff) is located in Suffolk County, Virginia centered at 36^{o} 37' 02" (36.61719) N, 76^{o} 33' 28" (76.55783) W. (Figure 3-1). The Bruff study area is composed of a 4.3 ha former cropland field and adjacent forested area. The study area was formerly ditched and drained to 0.5 m but the hydrology was restored to former wetland conditions by local ditch plugging in March 2000. The soil in the study area was identified on the Suffolk County Soil Survey as Rains loamy sand (fine-loamy, siliceous, semiactive, thermic Typic Paleaquults) (Reber et al., 1981). The undrained phase of the Rains series appears on the national hydric soils list (USDA-SCS, 1991). An inventory of the plants identified at Bruff along with their wetland indicator status is found in Appendix 1a. The field is in early successional stage of wetland reforestation. The herbaceous vegetation is predominantly weedy perennials and grass species such as Chinese lespedeza (*Lespedeza cuneata*, Dum. Cours.), panicled ticktrefoil (*Desmodium* *paniculatum* Lam.), trumpet creeper (*Campsis radicans* L.), and tall fescue (*Festuca arundinacea* Schreb.) that make up 50% of the herbaceous cover. Hardwood seedling species including water oak (*Quercus nigra* L.), willow oak (*Q. phellos* L.), cherrybark oak (*Q. pagoda* Raf.), swamp chestnut oak (*Q. michauxii* Nutt.), blackgum (*Nyssa sylvatica* Marsh.), and bald cypress (*Taxodium distichum* L.) were planted 1 m apart, in rows 3 m apart, in the former cropland field as part of the restoration project in 2000. The planted species are currently at breast height (1.37 m). There are numerous volunteer seedlings of loblolly pine and sweetgum invading the former cropland field. The forest has been logged several times and was planted to loblolly pine in the early 1970's. Predominant vegetation in the forested area consisted of loblolly pine and red maple that made up 90% of the overstory cover. The ACOE endorsed GS by frost-free days determination is the 222 days between March 29 and November 7 (Reber et al., 1981).

The eastern study area (Hall) is located in City of Chesapeake County, Virginia centered at 36^{o} 37' 57" (36. 63249) N, 76^{o} 18' 50" (76. 31396) W (Figure 3-1). The Hall study area is composed of a 12.5 ha former cropland field and an adjacent forested area. The entire area was formerly ditched and drained to 0.5 m, but hydrology was restored to former wetland conditions in March 2000 by plugging and filling the ditches. Soils in the study area were identified as Acredale silt loam (fine-silty, mixed, active, thermic Typic Endoaqualfs), Tomotley fine sandy loam (fine-loamy, mixed, semiactive, thermic Typic Endoaquults), and Roanoke silt loam (fine, mixed, semiactive, thermic Typic Endoaquults) in an unpublished NRCS soil survey. All three series appear on the national hydric soils list (USDA-SCS, 1991). An inventory of the plants identified at Bruff along with their wetland indicator status is found in Appendix 1b. The field is in an early successional stage of wetland reforestation. The herbaceous vegetation is predominantly ragweed (*Solidago canadensis* L.) and broomsedge bluestem (*Andropogon* *virginicus* L.) that make up 40% of the herbaceous cover. The field was planted in 2000 with the same hardwood seedling varieties and spacing as at Bruff. There are numerous volunteer seedlings of sweetgum, red maple (*Acer rubrum* L.), and loblolly pine invading the former cropland field. The forest has been logged several times and a section of the forest was clear-cut as recently as 1986. Predominant vegetation in the forested area consisted of sweetgum (*Liquidambar styraciflua* L.), red maple, swamp chestnut oak, and sourwood (*Oxydendrum arboretum* L.) that made up 80% of the overstory cover. The ACOE endorsed GS by frost-free days determination is the 259 days between March 14 and November 29 (ftp.wcc.nrcs.usda.gov).

Treatments

The eight sampling sites that represented two land-use treatments were randomly located across the hydric soil area within the early successional fields. There were four sampling points in the early successional vegetation and four within 10 m^2 bare ground treatment plots (Figure 3-2, 3-3, and 3-4). The bare ground plots were tilled four times a year beginning in April 2001. Weeds were mechanically removed from the 3 m^2 area around the thermistors bi-monthly throughout the study. The four sampling sites that represented the forested land-use treatment were randomly located adjacent to the fields. Treatment areas were selected from areas of similar soils but spread across the study area. Precise sampling locations were inspected and soils described to confirm the soil resource similarity and presence of hydric soils. There is a continuum of wetness for each treatment at both properties. Well locations were chosen based on the presence of hydric soil. The wettest and driest pairs of wells in the field were identified and split between field and bare ground treatments.

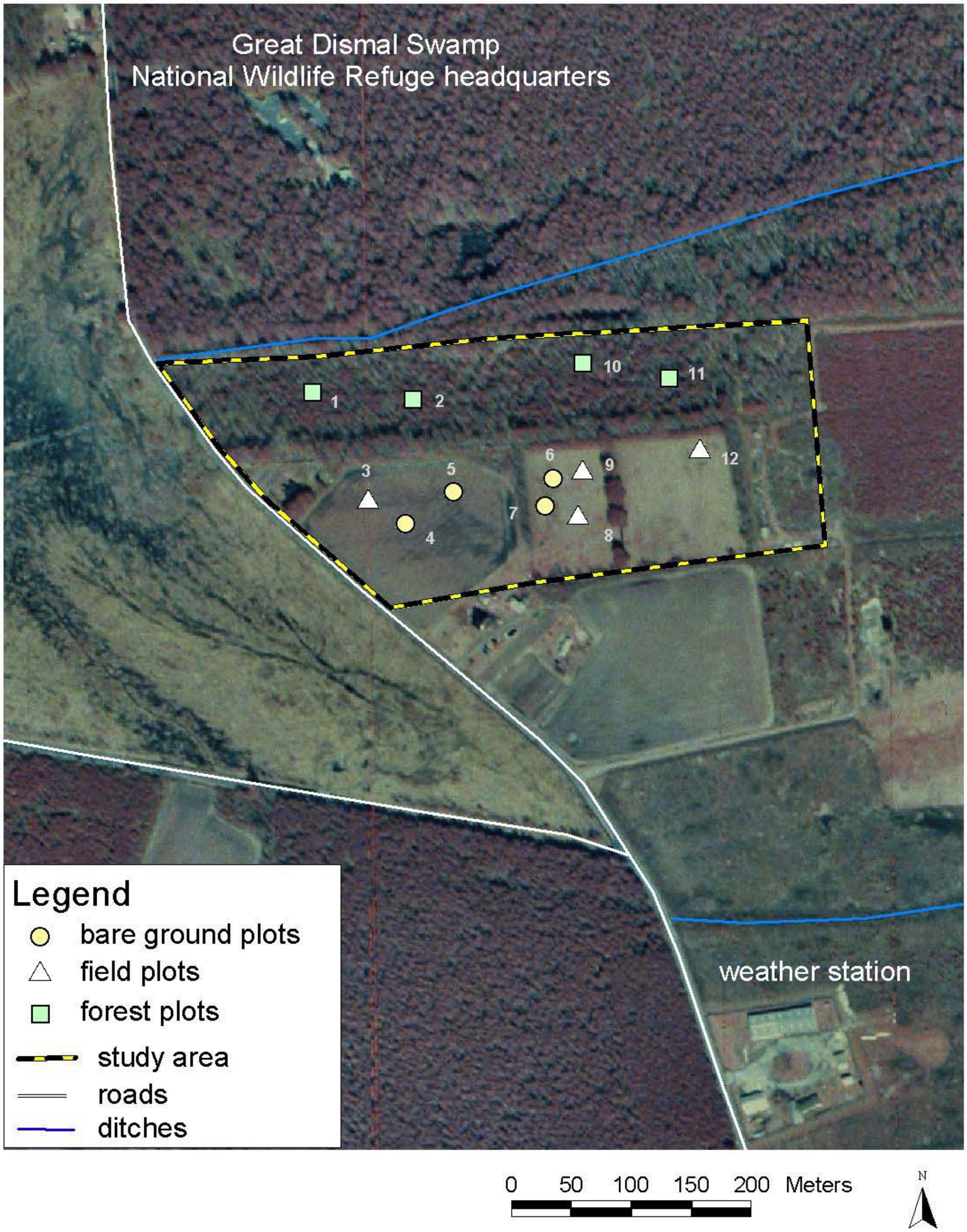


Figure 3-2. Bruff study area well and treatment plot locations.

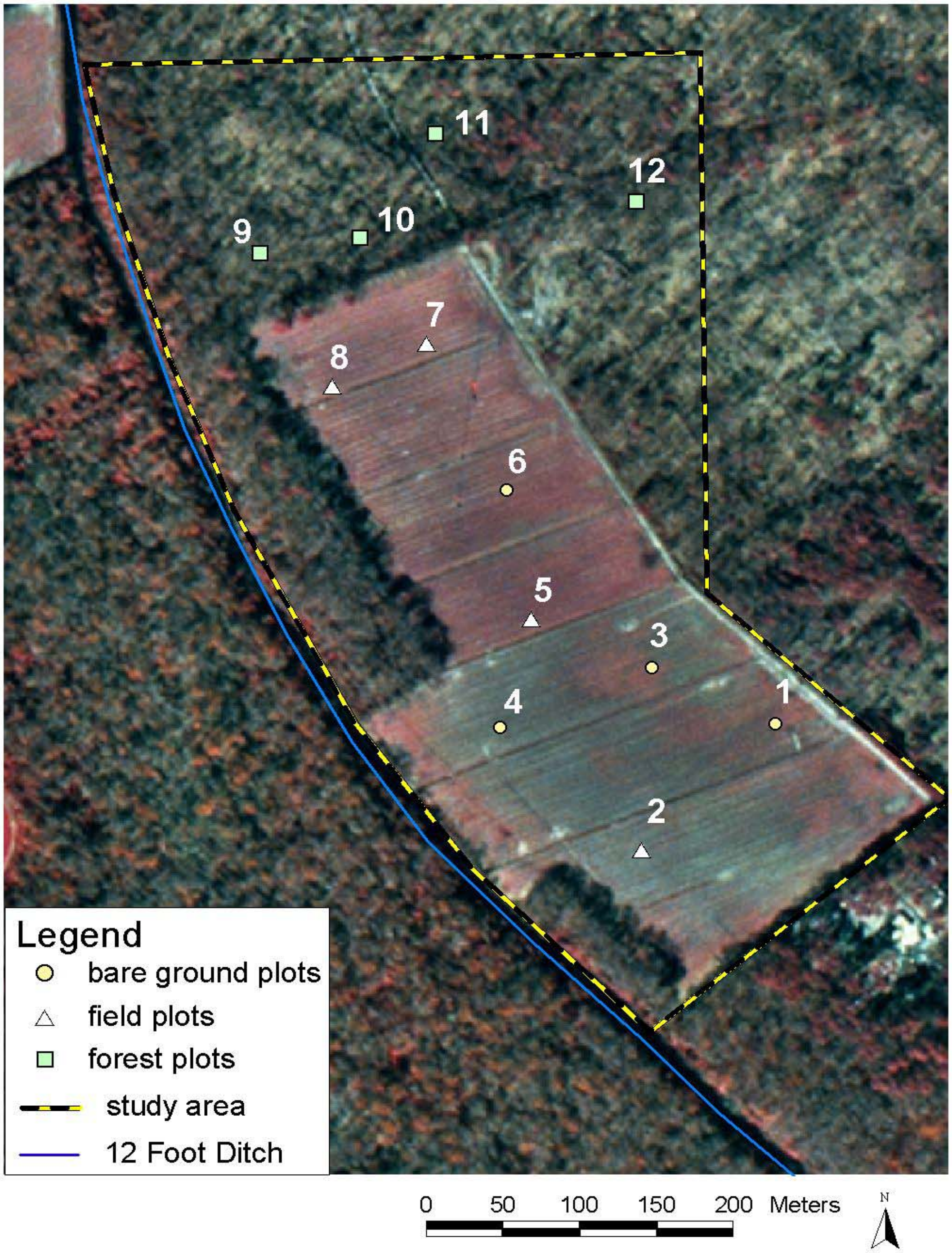
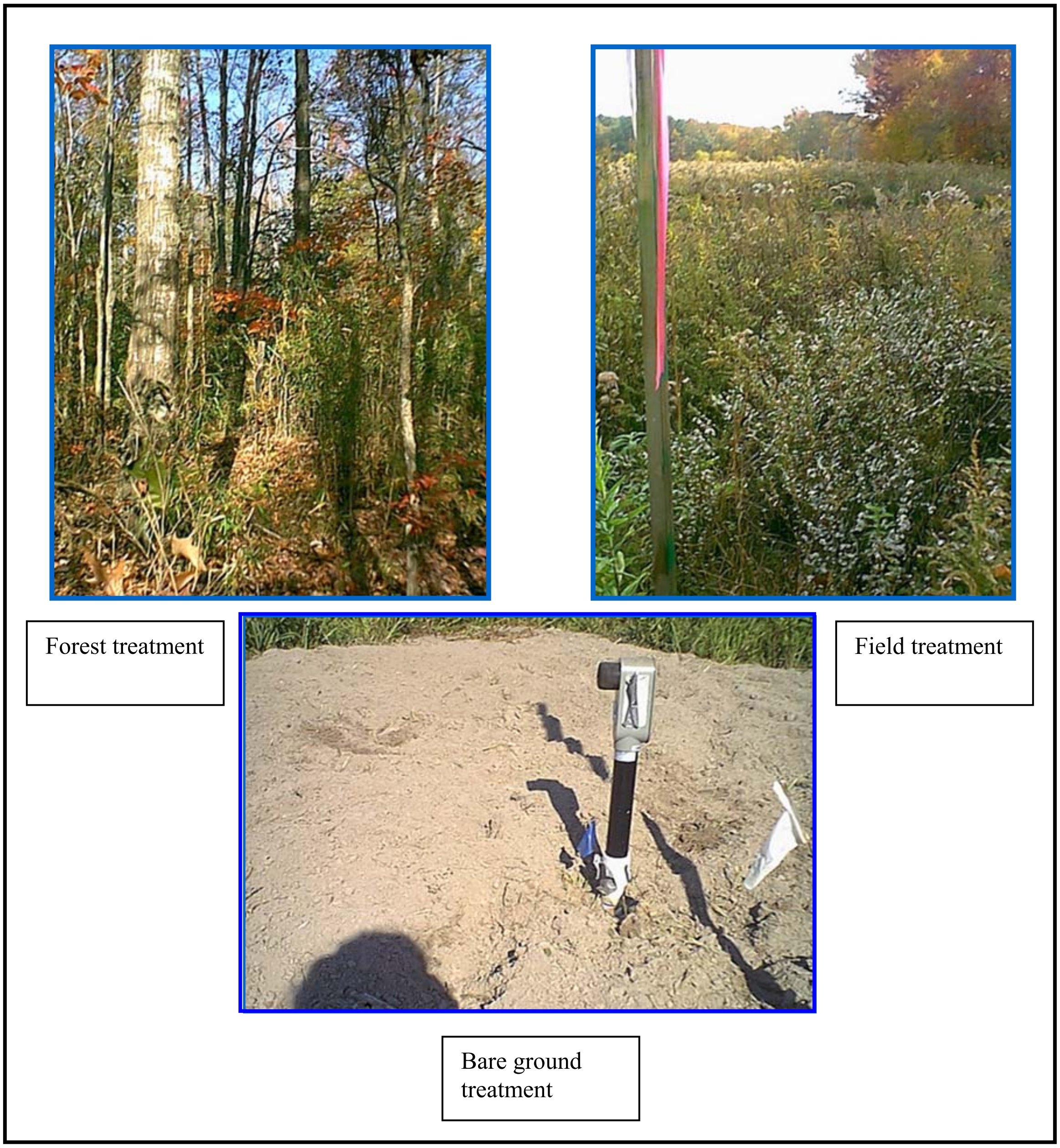


Figure 3-3. Hall study area well and treatment plot locations.



Forest treatment

Field treatment

Bare ground treatment

Figure 3-4. Forest, field and bare ground treatments. The picture of the forest treatment was taken in February 2001 and the field and bare ground treatments were taken in May 2001 one month after tillage occurred.

Soils

The soils within each plot were described from excavated pits to a depth of about 50 cm and from 10-cm diameter auger borings to 2 m on four plots. Morphological descriptions were made based upon standard soil survey criteria and nomenclature (Soil Survey Division Staff, 1993). Samples were collected by horizon to 2 m for lab analysis at one plot in the field and forest treatments at each site to verify the soil characteristics and series identification. The 2-m samples were chosen because these soil samples represent the mid-range of observed properties. Additional samples were collected where needed to verify soil classification. Detailed soil maps were created following the description and lab analyses.

Bulk density was collected on mineral horizons using the core method (Blake and Hartage, 1986). Mineral samples were oven-dried at 105 °C, manually ground with mortar and pestle, and passed through a 2 mm sieve. Particle-size distributions were determined by a modified pipette method (Gee and Bauder, 1986). Exchangeable Ca^{2+}, Mg^{2+}, and K^+, were extracted with NH_4^+ from a 1 *N* NH_4OAc solution buffered at pH 7 and were quantified using atomic absorption spectrophotometry (Soil Conservation Service, 1984). Exchangeable aluminum (Al^{3+}) was extracted with a 1 *N* KCl solution and quantified by titration (McLean, 1965). Exchangeable acidity (H^+) was determined by the pH 8.2 $BaCl_2$-TEA method (Peech, 1965). The cation-exchange capacity (CEC) was estimated by NH_4^+saturation from a 1 *N* NH_4OAc, pH 7, solution, displacement, and distillation method (Chapman, 1965). Total C (g kg^{-1}) and total N (g kg^{-1}) were measured by combustion with an Elementar CNS analyzer (Nelson and Sommers, 1996). The soil pH was measured with a pH meter in a 1:1 water dilution (Thomas, 1977).

Precipitation

Daily precipitation data for the 30-yr period from 1971 to 2000 were downloaded for the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) weather station at Lake Kirby, Suffolk, Virginia (NOAA-NCDC, 2003). The daily weather data were aggregated to calculate the average annual and monthly values for precipitation. The 30th and 70th percentiles were calculated to define the normal range of average annual precipitation and average monthly precipitation (USDA-SCS, 1985b). Study area precipitation information was collected by tipping-bucket rain gauges located 200 m south of the Bruff study area and onsite at the Hall study area.

Water table dynamics

Water table depth, assumed to be equal to the depth to the depth of the free water table, was monitored at each sampling site (24 total) with a 1-m deep WL-40™ water level monitoring well. The wells recorded depth to the free water table at 6-hour intervals (Calmon and Day, 1999). Recorded water levels were corrected for the distance between the ground and the calibration point (0-depth mark) on the instrument. The monitoring wells were installed in auger holes and backfilled with medium-grade sand throughout the screened interval of the well casing. The monitoring wells were capped at the soil surface with granular bentonite to ensure that surface runoff water did not enter the auger hole. Water levels were monitored for 18 months between January 2001 and June 2002. The number of continuous days of saturation within 30 cm (WL <30) in groups of $\geq$ 7 d were compared with different GS dates to determine if wetland hydrology and mitigation requirements were reached. The water levels throughout the year were plotted to determine the well that represented the median hydrograph for each treatment at each study area. These representative wells were the only reported values in this paper. Only wells that had complete data throughout the study were considered. For more complete analysis from each well refer to Chapter 4.

Temperature

Daily air temperature data for the 30-yr period from 1971 to 2000 were downloaded for the weather station at Lake Kirby, Suffolk, Virginia (NOAA-NCDC, 2003). The daily weather data were aggregated to calculate the average annual and monthly values for air temperatures. The average monthly low and high air temperatures were calculated, along with the 30th and 70th percentile to define the normal range of average annual air temperature and average monthly air temperature using the same methodology as for precipitation data (USDA-SCS, 1985b).

Air and soil temperatures were measured using Stowaway Tidbit® soil temperature thermistors (Onset Computer Corporation, Pocasset, MA) that were factory calibrated. The thermistors were then manually calibrated by checking the temperature variation while they were placed in water that was frozen to ice (Mount and Paetzold, 2002). Temperatures were recorded to the nearest 0.01 °C. Air temperature was measured by a thermistor mounted to a PVC pole approximately 1-m distance from each well. The air temperature thermistors were installed 1 m above the soil surface and covered with a 50 cm^2 Styrofoam block to shield them from direct solar radiation. Air temperatures were recorded hourly and the annual and monthly mean value calculated for each treatment at each study area.

Thermistors were installed at a depth of 50 cm approximately 1-m distance from each well to represent the soil temperature control section and to confirm the soil temperature regime as defined by Soil Taxonomy (Soil Survey Staff, 1999). The thermistors were installed in January 2001 at Hall and in February 2001 at Bruff. The soil was carefully extracted using a 4-cm diameter open-faced soil probe and the thermistor was inserted into undisturbed soil at 50 cm. The displaced soil columns and appropriate litter layer were then replaced and oriented to produce minimal horizon disruption. The upper few cm of soil were knit across the hole to prevent airflow to the thermistor. Soil temperatures were recorded at 4-hr intervals and the annual and monthly mean value calculated for each treatment at each study area.

Air and soil temperature was reported for each representative well. Frost-free period was determined by grouping the data from the four subsamples within each treatment and extracting the last date that air temperature was above -2.2 °C or -4.4 °C in the spring and the first date air temperature went below these thresholds in the fall. A similar method was used to identify the period when soil temperatures were above 5 °C at 50 cm.

Soil CO_2 efflux

Soil CO_2 efflux was monitored as an index of microbial and root activity in the near surface soil environment over an 18 month sampling period from February 2001 to June 2002. Soil CO_2 efflux was monitored monthly during the FFD -2.2 GS and bi-monthly during the rest of the year. Measurements began at 1000 hrs and continued until all plots were sampled on each sampling date. A complete set of treatment combinations were measured followed by another until all 4-block combinations were sampled. Blocking by subsample served to minimize external influences on CO_2 efflux rates that were not easily attributed to soil temperature or moisture (Pangle and Seiler, 2002). Soil CO_2 efflux was measured using LI-COR® 6400 infrared gas analyzer (LI-COR, Inc., Lincoln, NE) fitted with a PVC end cap that was placed on the soil surface with direct pressure. The end cap had an internal volume of 4150 cm^3 and was fitted with a foam sealing gasket and gas sampling and return ports, creating a closed chamber system with the soil surface. Soil CO_2 efflux rates in µmoles m^{-2} s^{-1} were measured over 30-s sampling periods and calculated to the nearest 0.01 µmoles m^{-2} s^{-1}. Soil CO_2 efflux measurements were initiated at internal chamber CO_2

concentrations equivalent to ambient conditions at the soil surface. The short 30-s duration was utilized to minimize the accumulation of CO_2 in the chamber headspace (Pangle and Seiler, 2002). Soil respiration was measured in triplicate at each well and the mean was reported.

Soil temperature for each treatment was measured using thermistors at the 15-cm depth to the nearest 0.1 °C in conjunction with the CO_2 efflux measurements. Field water content of the upper 15 cm was measured by gravimetric methods using the soil survey laboratory methods procedure 3B1 (Soil Survey Staff, 1996).

Statistical Analysis

Differences in CO_2 efflux rates for the study areas and differences between the study areas were assessed after one-way analysis of variance (ANOVA) ($\alpha = 0.05$) using Fisher's LSD in the Minitab statistical software (Version 13) (Minitab, Inc., State College, PA 16801-3008) (Snedecor and Cochran, 1989). The effects of land-use type and sampling date were tested using an ANOVA, with the land use × date as the error term. Descriptive statistics were then used to compare variability in and between treatment means.

The relationships between soil CO_2 efflux rates and soil temperature at 15 cm and soil moisture were analyzed using multiple regression analysis (Neter et al., 1996). CO_2 efflux regression analyses were performed using SAS™ software (Statistical Analysis Systems, Cary, NC). Significant variables that were included in individual regression models were initially selected using the SAS stepwise procedure and PROC GLM to develop models with high R^2 and optimal Cp statistic, while eliminating collinear variables and controlling for variance inflation of parameters.

Experimental design of the study

- 2 Study Areas
    - 3 Treatments (forest, field, bare ground)
        - 4 Subsamples per treatment

Results and Discussion

Soils

Representative soil descriptions are presented in Table 3-1. The remaining soil descriptions are listed in Appendix 2a and 2b, and all laboratory analysis results in Appendix 3a and 3b. The soil at each plot met one or more of the F3, F4, or F6 field indicators of hydric soils (Table 3-2) (USDA-NRCS, 2002). All of the soil series were found on the National List of Hydric Soils (Soil Survey Division, 2002). In general, the soils at Bruff had more clay in the upper subsoil and lower pH throughout the subsoil than those at Hall. The lower pH may have been due to increased leaching opportunities because the Bruff area was 5 m higher in elevation and further west (further from the ocean and closer to the edge of the Suffolk scarp). The soils had relatively high bulk density in the upper subsoil because of compaction by long-term farming of wet soils and because of the large clay increase at the top of the subsoil that may have resulted in plugging of pores by translocated clay. The description of a change in parent materials was supported by distinct changes in the total amount and ratios of sand fractions. A complete discussion of the physical properties is found in Chapter 4. The soil near well 2 at Bruff representing the forest treatment contained a lower horizon described as a 2Bh and a 2Bs horizon. The lowest horizon in the field treatment at Bruff (2Cg2) was similar but had weaker expression of colors representing a Bs horizon. The laboratory data indicate that both horizons contained the expected increased levels of exchangeable H^+, CEC at pH 7, extractable Al^{3+}, and total C than adjacent horizons with similar

Table 3-1. Morphological descriptions for representative soils within the field and the forest at each study area.

Location: Bruff Plot 9
Land use Represented: Field

Oi--0 to 2 cm; dark brown (10YR 3/3 broken face and rubbed) mucky peat (hemic material); abrupt smooth boundary.

Ap1--2 to 10 cm; very dark grayish brown (10YR 3/2) fine sandy loam; few (1%) fine faint brown (10YR 4/3) masses of iron accumulations; common (2%) fine distinct light brownish gray (10YR 6/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; moderate medium granular structure; many very fine to fine roots; abrupt smooth boundary.

Ap2--10 to 18 cm; very dark grayish brown (10YR 3/2) loam; few (1%) fine faint brown (10YR 4/3) masses of iron accumulations; common (2%) fine distinct light brownish gray (10YR 6/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; weak coarse subangular blocky structure; few very fine to fine roots; abrupt smooth boundary.

Eg--18 to 40 cm; 90% grayish brown (2.5Y 5/2) loam E material with 10% pockets of grayish brown (2.5Y 4/2) clay loam Btg material; common (10%) coarse distinct olive yellow (2.5Y 6/6) and common (10%) coarse prominent yellowish brown (10YR 5/6) masses of iron accumulations; common (10%) coarse faint light brownish gray (2.5Y 6/2) masses of iron depletions; weak coarse subangular blocky structure; few very fine and few roots; clear wavy boundary.

Btg1--40 to 92 cm; dark grayish brown (2.5Y 4/2) clay loam; common (5%) coarse prominent yellowish brown (10YR 5/8), common (10%) coarse prominent yellowish brown (10YR 5/6) and common (5%) medium prominent brownish yellow (10YR 6/6) masses of iron accumulations; common (5%) coarse faint grayish brown (2.5Y 5/2) and common (5%) medium faint light brownish gray (10YR 6/2) masses of iron depletions; common (5%) pockets of clean washed sand grains; moderate medium subangular blocky structure; few very fine and fine roots; gradual wavy boundary.

Btg2--92 to 130 cm; gray (5Y 5/1) clay; many (20%) medium prominent brownish yellow (10YR 6/8) and common (10%) medium prominent olive brown (2.5Y 6/8) masses of iron accumulations; common (2%) medium prominent white (2.5Y 8/1) masses of iron depletions; common (2%) pockets of clean washed sand grains; moderate medium subangular blocky structure; few very fine roots; abrupt wavy boundary.

2BCg--130 to 140 cm; gray (5Y 5/1) fine sandy loam; weak medium subangular blocky structure; abrupt wavy boundary.

2Cg1--140 to 192 cm; grayish brown (2.5Y 5/2) fine sand; many (40%) medium distinct light gray (10YR 7/1) and common (10%) medium faint gray (2.5Y 6/1) masses of iron depletions; structureless, massive; gradual wavy boundary. Apparent water table at 163 cm.

2Cg2--192 to 210 cm; light brownish gray (2.5Y 6/2) medium sand; many (20%) medium distinct light yellowish brown (2.5Y 6/4) masses of iron accumulations; common (10%) medium faint light gray (10YR 7/1) masses of iron depletions; structureless, massive.

Location: Bruff Plot 2
Land use Represented: Forest

Oi--0 to 2 cm; brown (7.5YR 4/4) peat (fibric material) structureless, massive; many very fine to coarse roots; abrupt smooth boundary.

Oe--2 to 3 cm; dark brown (7.5YR 3/4 broken face and rubbed) mucky peat (hemic material) structureless, massive; many very fine to medium roots; abrupt smooth boundary.

Oa--3 to 3.5 cm; black (7.5YR 2.5/1 broken face and rubbed) muck (sapric material) weak thin platy structure; many very fine to medium roots; abrupt smooth boundary.

A--3.5 to 13 cm; very dark gray (10YR 3/1) fine sandy loam; strong medium granular structure; common very fine to coarse roots; abrupt smooth boundary.

A/E--13 to 23 cm; dark gray (10YR 4/1) fine sandy loam; common (2%) fine prominent yellowish red (5YR 4/6) pore linings, common (2%) fine prominent strong brown (7.5YR 5/6) pore linings and common (2%) fine prominent dark yellowish brown (10YR 4/6) masses of iron accumulations; weak coarse subangular blocky structure; common very fine to medium roots; abrupt wavy boundary.

Eg--23 to 27 cm; grayish brown (2.5Y 5/2) fine sandy loam; few (1%) fine prominent dark yellowish brown (10YR 4/6) pore linings and common (15%) fine faint light olive brown (2.5Y 5/3) masses of iron accumulations; weak coarse subangular blocky structure; few fine to medium roots; abrupt wavy boundary.

Btg1--27 to 90 cm; dark grayish brown (2.5Y 4/2) clay loam; common (5%) fine distinct dark yellowish brown (10 YR 4/4), common (15%) fine prominent yellowish brown (10YR 5/6), and common (5%) fine prominent yellowish brown (10YR 5/8) masses of iron accumulations; common (10%) fine faint dark gray (2.5Y 4/1), common medium distinct light brownish gray (10YR 6/2) and common fine faint gray (2.5Y 5/1) masses of iron depletions; moderate medium subangular blocky structure; few very fine and fine roots; gradual wavy boundary.

Btg2--90 to 142 cm; gray (2.5Y 5/1) clay; common (10%) fine prominent brownish yellow (10YR 6/8) and common (10%) fine prominent reddish yellow (7.5YR 6/8) masses of iron accumulations; common (5%) fine faint light gray (2.5Y 7/1) masses of iron depletions; moderate medium subangular blocky structure; few very fine and fine roots; gradual wavy boundary.

2E--142 to 152 cm; light gray (10YR 7/1) fine sand; structureless, single grained; clear wavy boundary.

2Bs--152 to 168 cm; olive brown (2.5Y 6/8) fine sand; many (20%) medium faint brownish yellow (10YR 6/8) masses of iron accumulations; many (20%) medium prominent light brownish gray (2.5Y 6/2) and common (10%) medium faint light olive brown (2.5Y 5/6) masses of iron depletions; structureless, massive; gradual wavy boundary. Upper 5 cm (not sampled) was 2Bhs dark brown (7.5YR 3/3) fine sand. Apparent water table at 163 cm.

2Cg--168 to 210 cm; light gray (2.5Y 7/2) fine sand; many (20%) medium distinct light yellowish brown (2.5Y 6/4) masses of iron accumulations; single grained, structureless, massive.

Location: Hall Plot 3

Land use Represented: Field

Ap1--0 to 6 cm; brown (10YR 4/3) fine sandy loam; few (1%) fine distinct strong brown (10YR 4/6) pore linings of iron accumulations; moderate medium granular structure; many very fine to fine roots; clear smooth boundary

Ap2--6 to 12 cm; dark grayish brown (10YR 4/2) fine sandy loam; common (2%) fine distinct strong brown (10YR 4/6) pore linings and masses of iron accumulations; moderate medium subangular blocky structure; many very fine to fine roots; abrupt smooth boundary.

Ap3--12 to 22 cm; dark grayish brown (10YR 4/2) fine sandy loam; common (2%) fine distinct dark yellowish brown (10YR 4/6) masses, common (3%) fine prominent strong brown (7.5YR 5/6) masses and common (5%) fine prominent strong brown (7.5YR 4/6) pore linings of iron accumulations; common (2%) fine faint grayish brown (10YR 5/2) masses of iron depletions; common pockets of clean washed sand grains; weak thin platy structure; few very fine to fine roots; abrupt smooth boundary.

Eg--22 to 30 cm; light brownish gray (2.5Y 6/2) fine sandy loam; common (10%) fine prominent yellowish brown (10YR 5/6) pore linings, common (3%) fine prominent strong brown (7.5YR 4/6) masses and common (2%) medium distinct light olive brown (2.5Y 5/4) masses of iron accumulations; few (1%) fine distinct light gray (2.5Y 7/1) and few (1%) medium distinct gray (2.5Y 6/1) masses of iron depletions; common pockets of clean washed sand grains; weak thin platy structure; few very fine and fine roots; clear wavy boundary.

Eg/Btg--30 to 40 cm; 60% grayish brown (2.5Y 5/2) loam E and 40% Btg material; common (10%) fine prominent yellowish brown (10YR 5/6) pore linings, common (5%) fine prominent yellowish brown (7.5YR 5/6) masses, common (5%) medium distinct red (2.5YR 5/8) masses, common (5%) coarse prominent olive yellow (2.5 Y 6/6) masses of iron accumulations; common (5%) medium distinct light gray (2.5Y 7/1) and common (5%) medium distinct gray (2.5Y 6/1) masses of iron depletions; common pockets of clean washed sand grains in the Btg material; moderate medium subangular blocky structure; few faint clay films on faces of peds in pockets of Btg material; few fine and medium roots; clear smooth boundary.

Btg1--40 to 90 cm; grayish brown (2.5Y 5/2) sandy clay loam; common (10%) coarse prominent brownish yellow (10YR 6/8) masses, common (10%) fine prominent yellowish brown (10YR 5/6) pore linings, common (10%) fine prominent strong brown (7.5YR 5/6) masses, common (5%) coarse prominent dark grayish brown (2.5Y 4/2) masses of iron accumulations; common (5%) coarse distinct light gray (2.5Y 7/1) and common (5%) coarse distinct gray (2.5Y 6/1) masses of iron depletions; common pockets of clean washed sand grains; moderate medium subangular blocky structure; few fine and medium roots; clear smooth boundary.

Btg2--90 to 120 cm; light olive gray (5Y 6/2) fine sandy loam; common (10%) medium prominent light olive brown (2.5Y 5/6) and many (20%) coarse prominent yellowish brown (10YR 5/6) masses of iron accumulations; common (10%) coarse faint gray (5Y 6/1) and common (15%) coarse faint light gray (5Y 7/1) masses of iron depletions; weak medium subangular blocky structure; few distinct clay films on faces of peds; strongly acid; clear smooth boundary.

Bt--120 to 165 cm; light olive brown (2.5Y 5/6) fine sandy loam; many (20%) coarse prominent yellowish brown (10YR 5/6) masses of iron accumulations; common (10%) coarse prominent gray (2.5Y 6/1) and common (10%) coarse prominent light gray (5Y 7/1) masses of iron depletions; weak coarse subangular blocky structure; few distinct clay films on faces of peds; gradual wavy boundary.

2BC--165 to 180 cm; olive yellow (2.5Y 6/6), fine sand; many (20%) coarse distinct light yellowish brown (2.5Y 6/4) and common (10%) coarse faint light olive brown (2.5Y 5/6) masses of iron depletions; structureless, massive; loose; clear smooth boundary.

2Cg-- 180 to 205 cm; light gray (5Y 7/1) fine sand; common (10%) medium prominent olive yellow (2.5Y 6/6) masses of iron accumulations; structureless, massive; loose. Apparent water table at 195 cm.

Location: Hall Plot 11

Land use Represented: Forest

Oe--0 to 1 cm; dark reddish brown (5 YR 2.5/2 broken face and rubbed) mucky peat (hemic material) weak thin platy structure; many very fine to coarse roots; abrupt smooth boundary.

A--1 to 8 cm; very dark grayish brown (2.5Y 3/2) mucky fine sandy loam; few (1%) fine prominent yellowish brown (10YR 5/6) pore linings; strong medium granular structure; common fine and very fine roots; clear smooth boundary.

AE--8 to 13 cm; dark gray (2.5Y 4/1) silt loam; common (3%) medium distinct dark brown (7.5YR 3/4) and common (3%) medium prominent yellowish brown (10YR 5/6) masses of iron accumulations;; few (1%) fine prominent yellowish red (5YR 4/6) pore linings of iron accumulations; common (5%) fine faint gray (2.5Y 5/1) masses of iron depletions; moderate medium subangular blocky structure; common very fine to coarse roots; very strongly acid; abrupt smooth boundary.

Eg--13 to 35 cm; 90% gray (7.5YR 6/1) silt loam E with 10% pockets of Btg coated and bridged with clay; common (2%) fine prominent dark yellowish brown (10YR 4/6) pore linings and common (5%) fine distinct red (2.5YR 6/6) masses of iron accumulations; common (10%) fine distinct reddish gray (2.5YR 6/1) masses of iron depletions; weak coarse subangular blocky structure; common very fine to fine roots; gradual wavy boundary.

Btg/Eg--35 to 50 cm; 75% grayish brown (2.5Y 5/2) clay loam Btg material and 25% grayish brown (2.5Y 5/2) fine sandy loam E horizon material; common (5%) fine prominent red (2.5YR 6/6), common (5%) fine prominent strong brown (7.5YR 5/6) and common (5%) fine prominent reddish yellow (7.5YR 6/8) masses of iron accumulations; common (10%) fine prominent reddish gray (2.5YR 6/1) masses of iron depletions; common (10%) very fine sand grains; weak medium subangular blocky structure; few very fine to fine roots; gradual wavy boundary.

Btg1--50 to 100 cm; gray (2.5Y 5/1) clay; common (10%) medium distinct pale olive (5Y 6/3) and common (10%) medium prominent yellowish brown (10YR 5/8) masses of iron accumulation; moderate medium subangular blocky structure; few very fine to coarse roots; gradual wavy boundary.

Btg2--100 to 130 cm; grayish brown (2.5Y 5/2) clay loam; common (10%) medium distinct light olive brown (2.5Y 5/6), common (15%) medium distinct pale olive (5Y 6/3) and common (10%) medium prominent yellowish brown (10YR 5/8) masses of iron accumulations; common (10%) medium distinct light gray (5Y 7/1) masses of iron depletions; common (10%) pockets of clean washed sand grains; weak medium subangular structure; few very fine roots; clear wavy boundary.

2BCg--130 to 160 cm; gray (2.5Y 6/1) loamy fine sand; common (10%) medium distinct light olive brown (2.5Y 5/6) and common (15%) medium prominent yellowish brown (10YR 5/8) masses of iron accumulations; common (10%) medium distinct light gray (5Y 7/1) masses of iron depletions; common (10%) pockets of clean washed sand grains; structureless, massive structure; loose, few very fine roots; clear wavy boundary.

2BC--160 to 180 cm; dark yellowish brown (10YR 4/6) fine sand; many (20%) coarse distinct yellowish brown (10YR 5/8), common (10%) medium distinct light olive brown (2.5Y 5/6) and common (10%) medium prominent yellowish brown (10YR 5/6) masses of iron accumulations; common (10%) medium distinct light gray (5Y 7/1) masses of iron depletions; structureless, massive structure; loose, few very fine roots; clear wavy boundary.

2Cg--180 to 210 cm; light gray (2.5Y 7/1) fine sand; common (10%) medium faint light yellowish brown (2.5Y 6/3) masses of iron accumulations; structureless, single grain. No apparent water table observed within 200 cm but the sand in this layer appeared saturated.

Table 3-2. Hydric soil properties by treatment type at each study area.

Well	Soil Series	Indicator present	Depth to indicator (cm)	
			F3† & F4‡	F6§
Bruff				
1	Roanoke¶	F3	18	8
2	Roanoke¶	F3, F4 & F6	10	
10	Roanoke¶	F3 & F4	10	
11	Roanoke¶	F3 & F4	24	
3	Roanoke¶	F3 & F4	23	0
8	Roanoke¶	F3 & F4	19	
9	Roanoke¶	F3 & F4	18	
12	Roanoke¶	F3 & F4	8	
4	Roanoke¶	F3, F4 & F6	20	10
5	Roanoke¶	F3, F4 & F6	11	
6	Roanoke¶	F3 & F4	20	
7	Roanoke¶	F3 & F4	24	
Hall				
9	Acredale	F3	21	
10	Acredale	F3	15	7
11	Roanoke¶	F3	8	
12	Roanoke¶	F3	12	
2	Tomotley¶	F3	0	
7	Tomotley¶	F3	0	
8	Tomotley¶	F3	0	
5	Tomotley¶	F3	2	
1	Tomotley¶	F3	12	
3	Tomotley¶	F3	6	
4	Acredale	F3	0	
6	Tomotley¶	F3	0	

† Hydric soil indicator F3 - Depleted Matrix. Defined as a layer at least 15 cm thick with a depleted matrix that has 60% or more chroma 2 or less starting within 25 cm of the surface (USDA-NRCS, 2002).

‡ Hydric soil indicator F4 - Depleted Below Dark Surface. Defined as a layer at least 15 cm thick with a depleted matrix that has 60% or more chroma 2 or less starting within 30 cm of the surface. The layer(s) above the depleted matrix have a value 3 or less and chroma 2 or less (USDA-NRCS, 2002).

§ Hydric soil indicator F6 - Redox Dark Surface. Defined as a layer at least 10 cm thick entirely within the upper 30 cm of the mineral soil that has: either a. matrix value 3 or less and chroma 1 or less and 2% or more distinct or prominent redox concentrations as soft masses or pore linings, or b. matrix value 3 or less and chroma 2 or less and 5% or more distinct or prominent redox concentrations as soft masses or pore linings (USDA-NRCS, 2002).

¶ Taxajunct to the series because high base saturation makes these Alfisols instead of Ultisols.

textures as predicted by the morphology. Buried A horizons at about the 2-m depth were found in the area containing partially decomposed herbaceous vegetation fragments. These data indicated that the lower parts of the soils were probably stable long enough to have started developing diagnostic horizons before being buried by the upper parent material, or that the water table fluctuates enough to allow podzolization to proceed on a limited basis.

The soils at Bruff were found to be outside of the range of the Rains series and most closely fit the Roanoke series because they had a fine control section and had a decrease in clay within 150 cm of the surface (Soil Survey Division, 2002). However, the soils did not match Roanoke criteria because they had higher base saturation and classified to Alfisols instead of Ultisols. The base saturation was high (nearly 100%) in the lower subsoil horizons because the textures were very sandy (> 91% sand) and low in clay ($\leq$ 3%) (Appendix 3a and 3b). These lower subsoil horizons had very low exchangeable H^+ in relation to the sum of the bases extracted by NH_4OAC at pH 7. The low exchangeable H^+ was probably due to the low pH, the landscape position and elevation, and/or the age of the soils all of which did not promote intense weathering and leaching of the system. The low concentration of the bases was probably due to the sandy nature of the parent material as well. There are no soil series that are an Alfisol equivalent to Roanoke so the soils were identified as taxajuncts to that series with a silt loam surface texture. The soils in slightly higher positions at Bruff most closely fit the Dragston series, even though they were mapped as Lynchburg. They were correlated to Dragston taxajunct because they had higher base saturation and classified to Alfisols instead of Ultisols, and because the clay content in the subsoil was higher than allowed. The Dragston taxajunct fine sandy loam soils at Bruff were classified as Fine-loamy, mixed, semiactive, thermic Aeric Endoaqualfs rather than Coarse-loamy, mixed, semiactive, thermic Aeric Endoaquults based on field descriptions and on the soil survey by Lane (unpublished data). The soils at Hall were identified as Acredale, Tomotley taxajunct, and Roanoke taxajunct based on the descriptions and laboratory analysis (Appendix 3a and 3b). The soils did not match the Tomotley and Roanoke series concepts because they had higher base saturation and were Alfisols instead of Ultisols, similar to the soils at Bruff. Detailed soil maps were drawn to reflect the field and lab analysis results (Figure 3-5 and 3-6).

Precipitation

The 30-yr average monthly and annual precipitation and the average monthly and annual precipitation measured during this study at the Lake Kirby weather station are plotted in Figures 3-7 and 3-8. Daily precipitation at each study area is reported in Appendix 4. The 30-yr data was ranked according to percentile of the measured data. The 30-yr average annual precipitation was 125 cm, with a normal range of 109 to 135 cm. The 30-yr average for the first six months of the year was 59 cm with a normal range of 51 to 68 cm. The 30-yr average for the first two months of the year was 19 cm with a normal range of 16 to 22 cm. The measured annual precipitation was only 81 cm in 2001, well below normal and within the 10th percentile of the 30-yr average. The measured precipitation during the first six months of 2002 was 59 cm and within the 60th percentile of the 30-yr average. The measured precipitation during the first two months of 2002 was 19 cm, which were within normal range and within the 60th percentile of the 30-yr average. Precipitation was below normal in January (10%), February (30%), May (20%), September through November (<10%), and December (30%), normal in March (70%), April (30%), July (70%), and August (30%) and above normal in June (90%) 2001. There was almost no precipitation in November 2001. In 2002, precipitation was higher than normal in January (90%), lower than normal in February (10%) and normal during the remainder of the study,

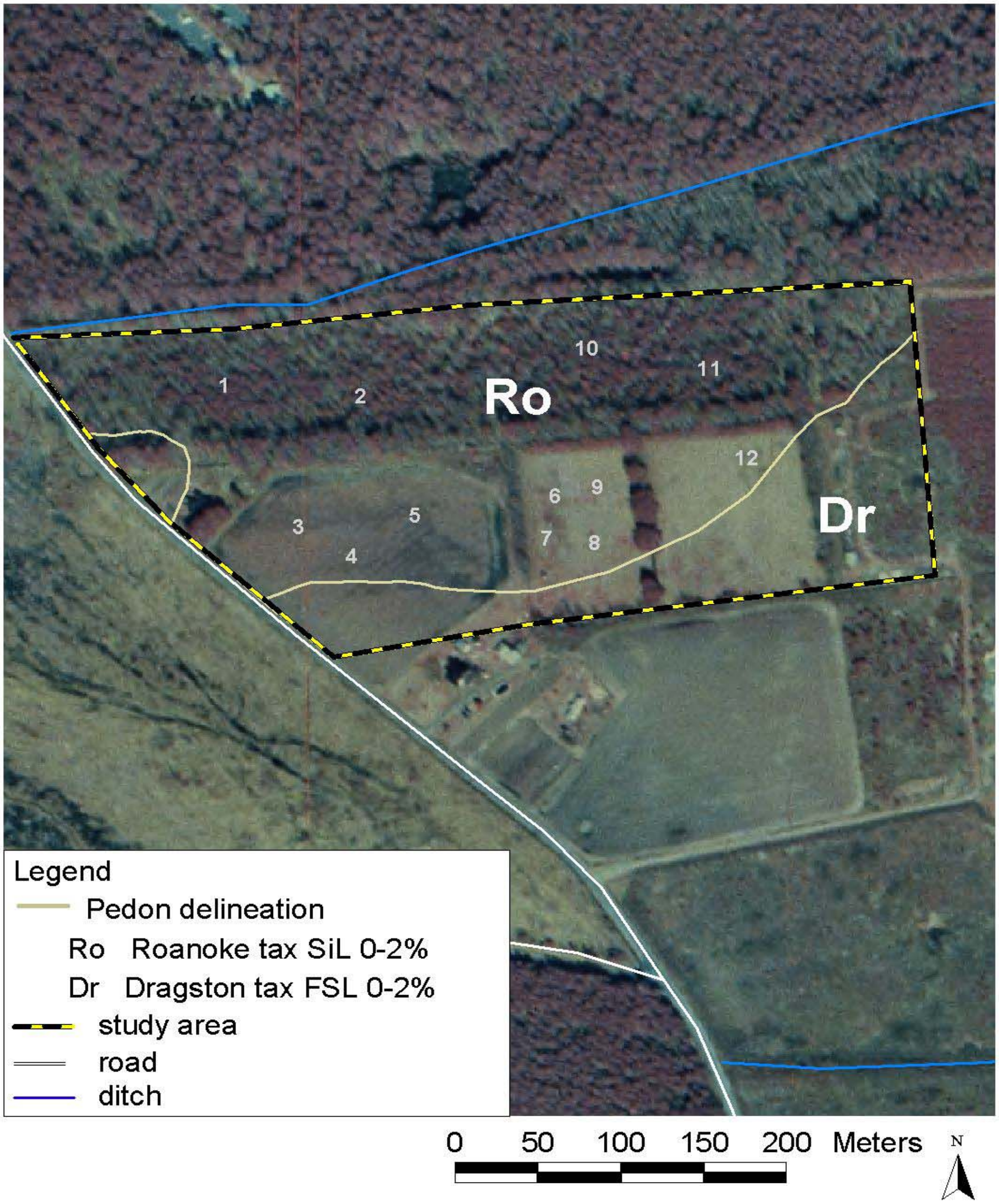


Figure 3-5. Soil survey of the Bruff study area based on field mapping and laboratory analysis. Well locations identified by number.

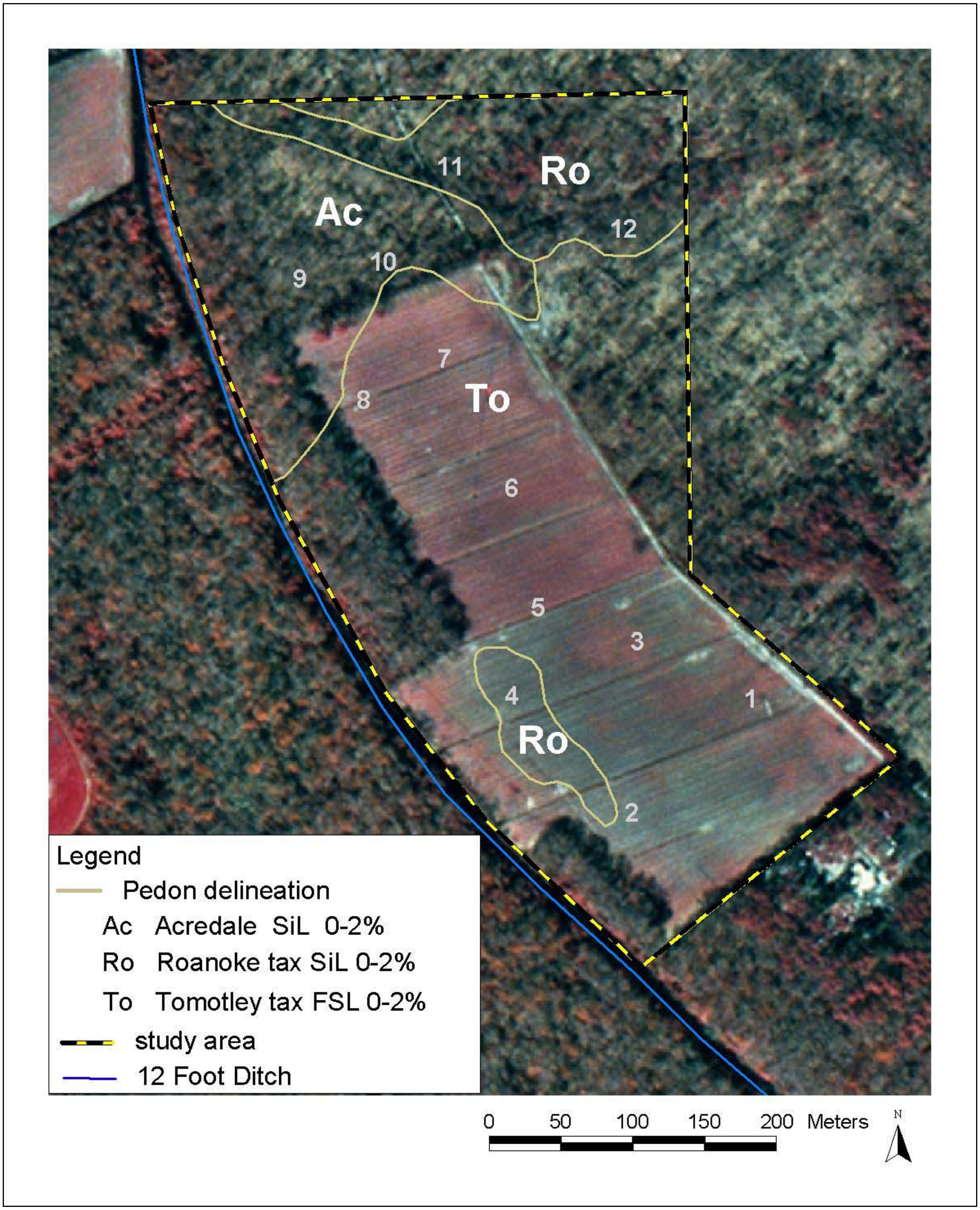


Figure 3-6. Soil survey of the Hall study area based on field mapping and laboratory analysis. Well locations identified by number.

March through May (70%) and June (90%).

The annual precipitation at Bruff in 2001 was 76 cm, well below normal (Figure 3-7). Precipitation at Bruff was similar to the Lake Kirby data in 2001 except that August was below normal. Precipitation was normal (54 cm) for the first six months of 2002 (Figure 3-8). Monthly precipitation was similar to the Lake Kirby data in 2002. There was a drought in the state of Virginia during the months proceeding and throughout most of the study period (Michaels, 2002).

The annual precipitation at Hall in 2001 was 95 cm, well below normal (Figure 3-7). Precipitation at Hall was similar to the Lake Kirby data in 2001. Precipitation was below normal in August, normal during March, April, and July, and above normal in July 2001. The rain gauge at Hall study area malfunctioned during March, so January and February were the only two months data could be collected. Precipitation was normal (20 cm) for the first two months of 2002 (Figure3-8). Monthly precipitation was similar to the Lake Kirby data in 2002. Precipitation was assumed to be normal for the rest of the study in 2002, since the data had been similar throughout the study at Hall and Bruff.

Hydrology

Daily minimum water levels (hydroperiod) measured during this study and reported in Appendix 5a and 5b. The relative elevation of each well to AMSL is reported in Appendix 6. The daily water levels supported the hydric soil determinations and the presence of field indicators (Table 3-2, Figures 3-9 and 3-10). Both study areas had an intermittently-saturated hydroperiod, typical of wet flats (Rheinhardt et al., 1999). Water saturated the upper soil predominantly during the winter months because ET is lowest during the winter months (Lichtler and Walker, 1979). Soon after the bud break occurred, the water levels sharply decreased below the depth monitored in this study.

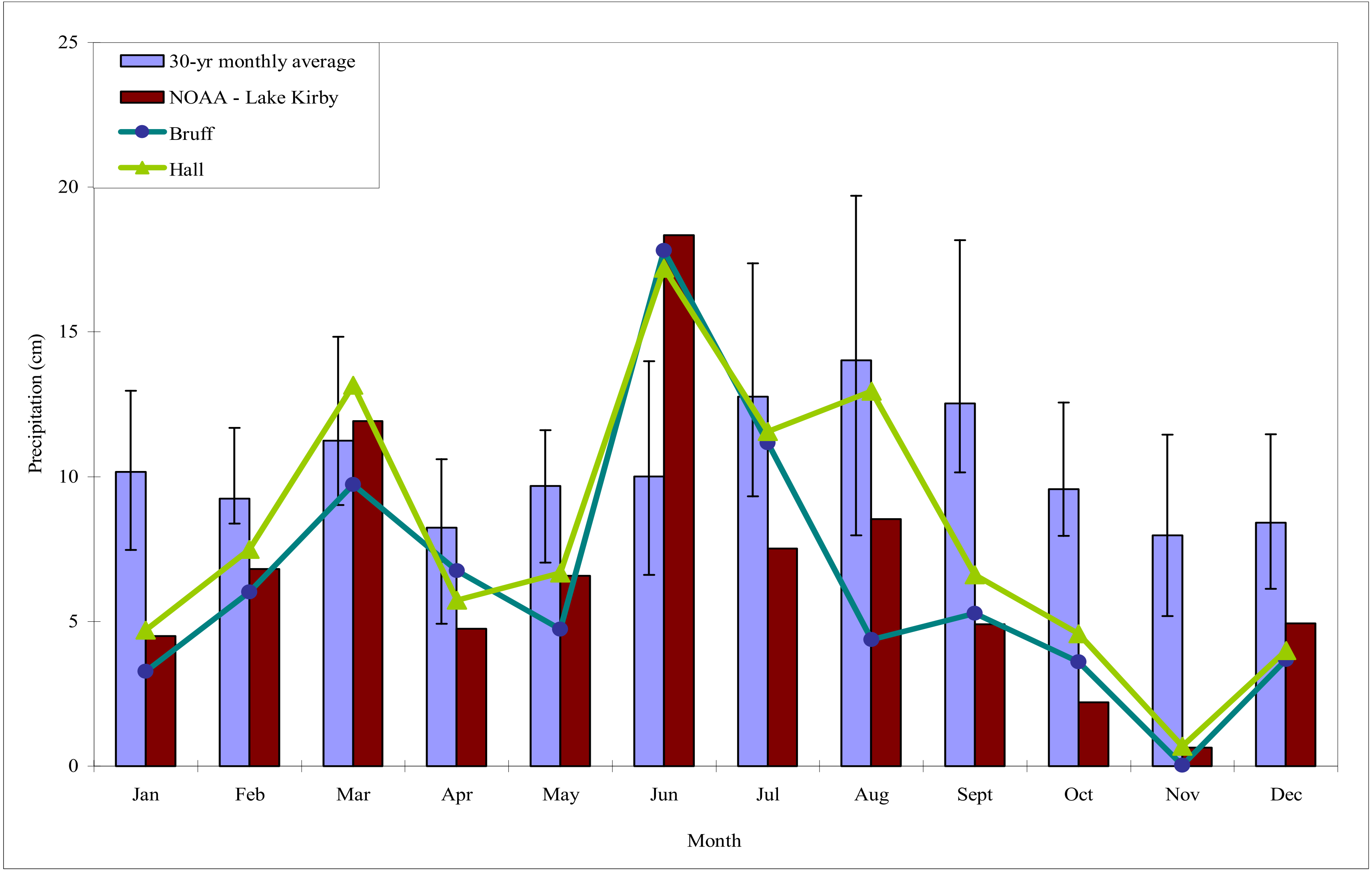


Figure 3-7. 30-yr average monthly Lake Kirby precipitation shown with 30th and 70th percentile bars along with 2001 measured precipitation.

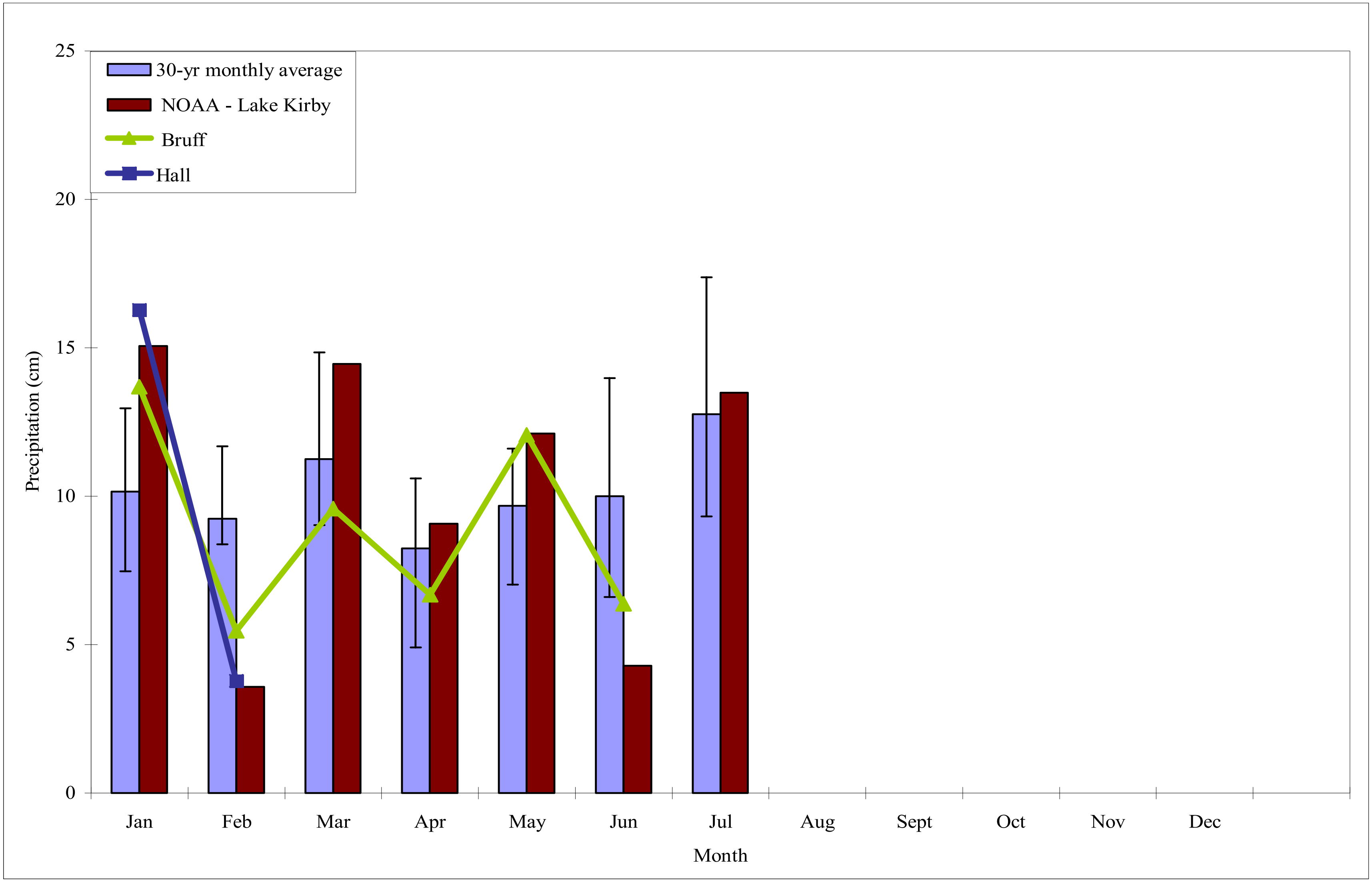


Figure 3-8. 30-yr average monthly Lake Kirby precipitation shown with 30th and 70th percentile bars along with 2002 measured precipitation.

Spikes in water levels occurred throughout the year in response to precipitation events, and were more pronounced in the field and bare ground treatment than in the forest. Water in the bare ground treatments took longer to infiltrate because perching occurred where tilling destroyed the structure in the surface horizon and compacted the soil below the tines. Also lack of vegetation resulted in lower relative ET. In the field and forest plots water perched at the bottom of the remnant tractor plow layer and again where a large clay increase occurred at the top of the subsoil.

Water levels at Bruff in the forest plot (well 1) were near the surface from January to April in 2001 (Figure 3-9). The water levels rose again and the forest plot was inundated after one intense precipitation event in June 2001, but did not stay saturated near the surface as long as the field and bare ground plots because of higher transpiration losses and increased infiltration. Water levels were at or near the surface in the field and bare ground plots through the winter months of 2001, but did not inundate the surface region for appreciable periods until March through May 2002.

The Water levels at Hall showed similar patterns to those at Bruff during the study (Figure 3-10). All plots were characterized by a period of long saturation or inundation near the surface during the winter months for both years. The forest plots at Hall were not saturated near the surface as long as the field and bare ground plots because of higher transpiration losses.

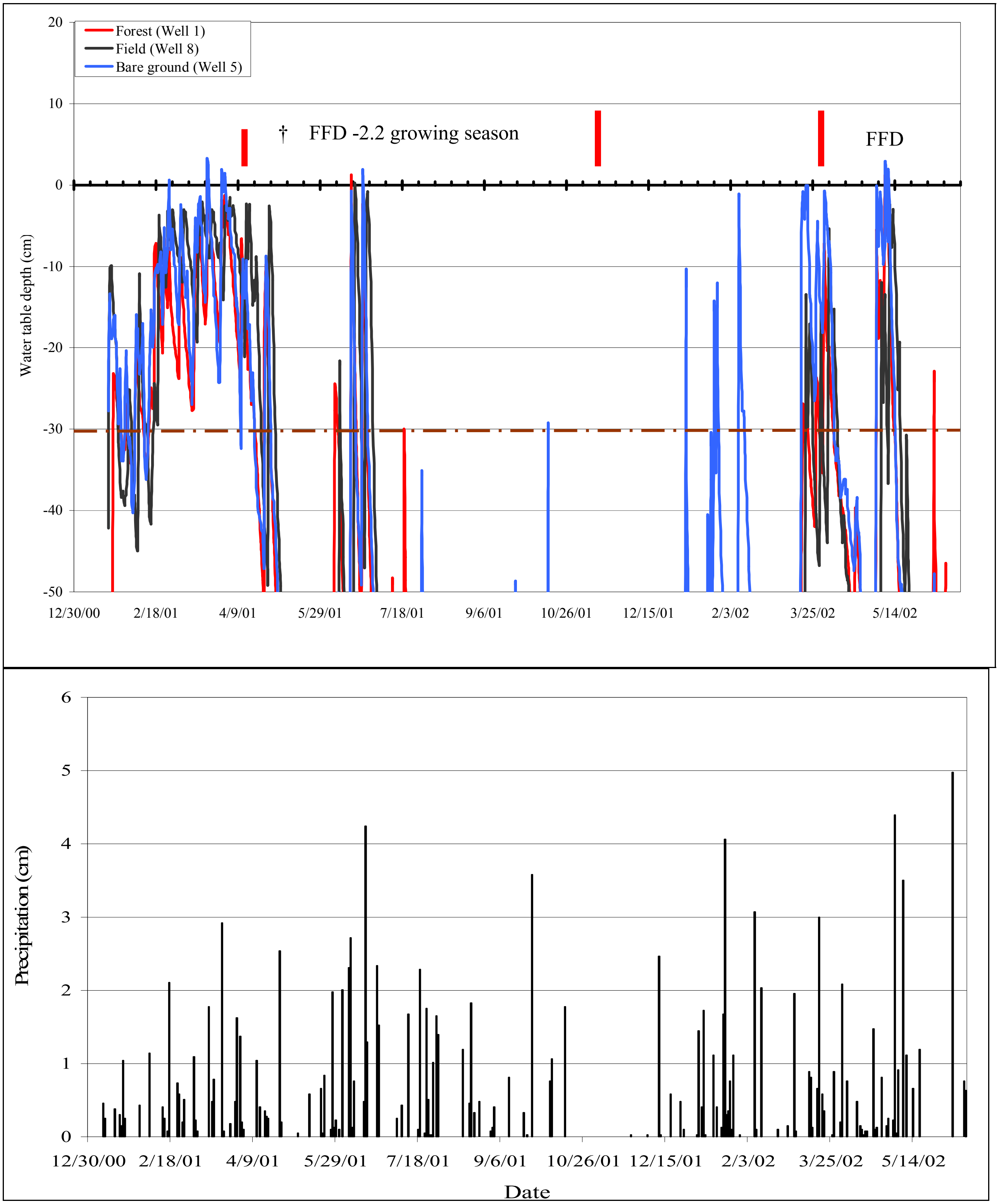
The water levels at Bruff may have been lower than at Hall because of precipitation or vegetative differences. The plots at Bruff received about 20 cm less precipitation during the study. The Bruff forest was predominantly loblolly pine and the field was covered with tall fescue while the Hall forest had a mixed hardwood deciduous overstory and the field was covered with annual and perennial weeds. The dominant plants at Bruff probably increased the transpiration losses during the study and enhanced the effect of the low precipitation on the water depths. Loblolly pine is known to respire during winter months and to use more water, if available (Martin, 2000; Pangle and Seiler, 2002). The lower water levels at Bruff could also be due to overuse of the Norfolk aquifer. The Norfolk aquifer underlies the Dismal Swamp and is heavily used at the Suffolk scarp by the City of Suffolk, which could have led to lower ground-water levels and a cone of depression affecting the Bruff study area.

Air Temperature

The 30-yr average monthly and annual air temperature data and the average monthly and annual air temperatures measured at the Lake Kirby weather station are reported in Table 3-3. The 30-yr average annual air temperature was 15.2 °C, with a normal range of 14.1 to 16.4 °C. The average monthly air temperature was colder than normal in July and September 2001, within the 20th percentile, and warmer than normal in June, August, November, and December 2001, January, February, March, April and June 2002 within the 90th percentile, and April 2002, within the 80th percentile, but within the normal range in all other months. This warming trend agrees with DeGaetano and Allen (2002), who reported that trends of daily minimum and maximum air temperatures from 1900 to 1996 show that there are increased minimum and maximum temperatures over the most recent 30-yr period.

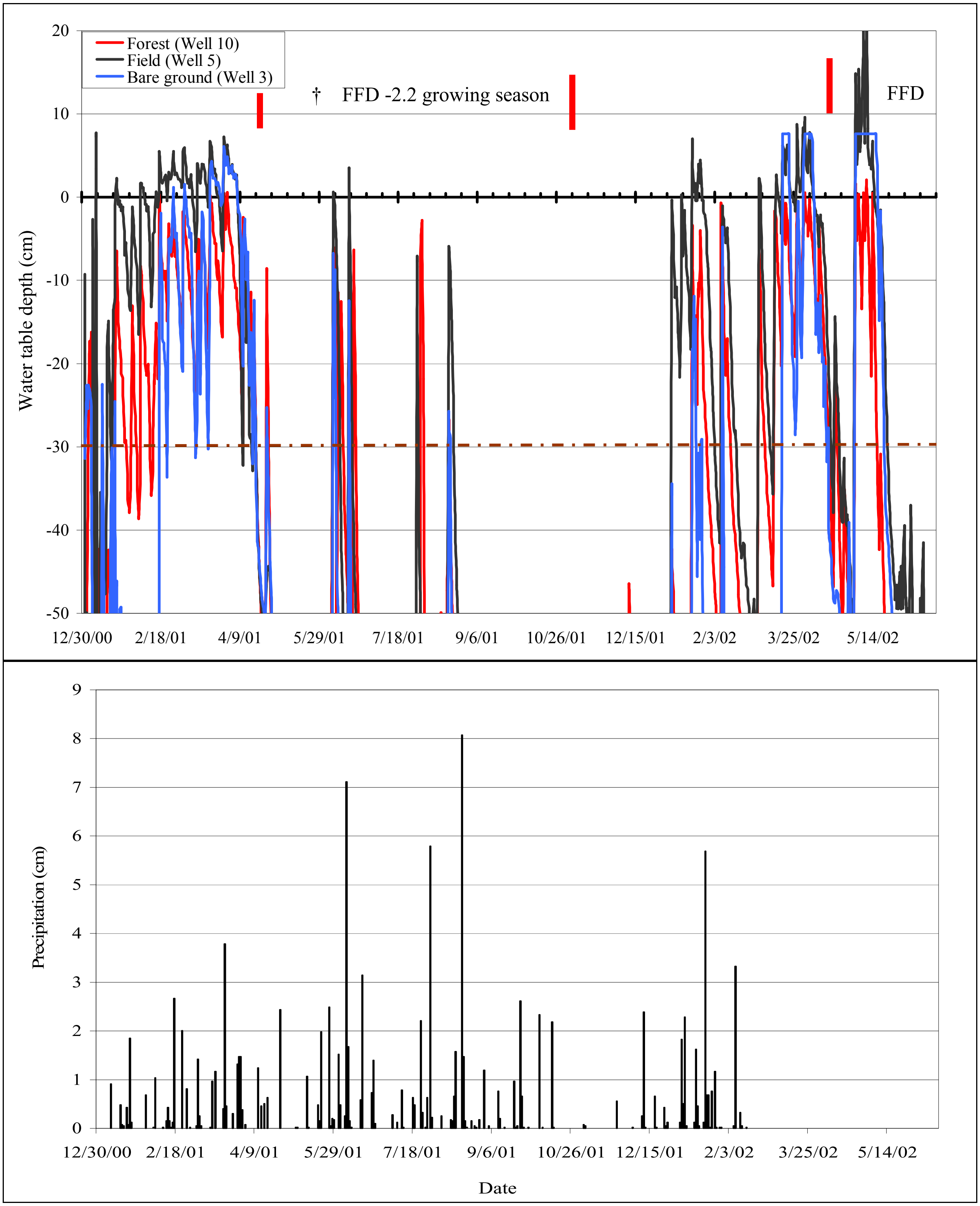
The average monthly and annual air temperatures measured at the representative plots are reported in Tables 3-4 and 3-5. Maximum, minimum, and average daily air temperatures measured at all plots are reported in Appendix 7a and 7b.

At Bruff, the 2001 measured average annual air temperatures were 15.5, 16.2, and 16.4 in the representative forested, field, and bare ground plot, all slightly warmer than average but within the range of normalcy (Table 3-4). The average monthly air temperatures varied by month and were not always within the range of normalcy in the 18-mo study. All of the representative plots



† Indicates the start and stop of the growing season for the study period.

Figure 3-9. Hydrograph of the Bruff representative wells with respect to the measured precipitation and FFD -2.2 °C regulated growing season.



† Indicates the start and stop of the growing season for the study period.

Figure 3-10. Hydrograph of the Hall representative wells with respect to the measured precipitation and FFD -2.2 °C regulated growing season.

Table 3-3. Thirty year average and measured air temperature distributions for the weather station at Lake Kirby, VA.

Month	30th percentile	Average	70th percentile	Average maximum	Average minimum	Extreme minimum	Measured 2001	Measured 2002
	----------	----------	----------	---------- °C ----------	----------	----------	----------	----------
January	2.14	4.08	6.50	20.75	-1.08	-10.48	4.72	6.89
February	4.47	5.65	7.50	22.53	0.03	-8.03	7.22	7.78
March	8.50	9.72	11.06	26.54	3.75	-3.87	8.89	11.56
April	13.58	14.50	15.47	30.04	8.18	0.32	15.28	17.06
May	18.58	19.20	20.00	32.04	13.38	6.16	19.61	19.22
June	22.69	23.42	24.39	34.27	17.82	11.45	24.50	24.89
July	25.08	25.80	26.53	35.20	20.48	15.36	24.06	-
August	24.11	24.87	25.67	34.59	19.64	14.43	25.94	-
September	21.28	21.86	22.56	32.94	16.65	9.34	21.17	-
October	14.44	15.83	17.22	28.91	10.11	2.01	16.06	-
November	9.75	10.81	11.86	25.38	5.02	-2.96	13.89	-
December	4.64	6.30	8.03	22.11	0.93	-7.46	9.67	-
Annual	14.11	15.17	16.40	28.78	9.58	2.19	15.92	-

were warmer than normal in January 2001 and April 2002. The field plot was warmer than normal for an additional seven months (February, April, June, November, and December 2001 and March and June 2002). The bare ground plot was warmer than normal for an additional ten months (February, April, May, June, August, November, and December 2001 and March, May, and June 2002). All representative plots were colder than normal in September 2001. The forest and field plots were also colder than normal in July and October 2001. The forest plot was cooler than in the field and bare ground plots throughout the study and especially during summer months (June to August) because the thick canopy cover and litter layer protected the soil and the surface air from direct sunlight as reported by Hillel (1982) and Scott (2000). The field plots were colder than in the bare ground plots throughout the study because the field was under fescue and other persistent weeds that prevented the soil surface from warming up in the direct sunlight. The increased reflection of sunlight (albedo) from the bare ground warmed the air

Table 3-4. Measured average monthly air temperature at Bruff. Average air temperature by treatment was ranked as a percentile of the 30-yr average annual air temperature data. The annual average is measured from February 2001 to January 2002.

Month	Year	Forest	Ranking	Field	Ranking	Bare ground	Ranking
		°C		°C		°C	
January	2001	11.65	100%	11.92	100%	11.98	100%
February		6.97	70%	7.66	80%	7.99	80%
March		8.54	30%	9.02	40%	9.11	40%
April		15.25	70%	15.73	80%	16.27	100%
May		19.02	40%	19.91	80%	20.81	90%
June		23.52	60%	24.59	100%	25.28	100%
July		23.16	10%	24.27	10%	25.29	50%
August		24.68	50%	25.46	70%	26.30	100%
September		19.30	10%	20.24	10%	21.02	20%
October		13.27	10%	14.26	20%	14.73	40%
November		11.54	60%	12.53	90%	12.77	90%
December		8.01	80%	8.79	90%	8.93	90%
January	2002	5.51	70%	6.27	80%	6.45	80%
February		6.45	70%	7.29	80%	7.43	80%
March		11.05	80%	11.54	90%	11.46	80%
April		16.46	100%	17.10	110%	17.24	110%
May		18.65	40%	19.42	60%	20.07	80%
June		23.78	60%	24.87	100%	25.63	100%
Annual	2/01-1/02	14.90	50%	15.73	70%	16.25	80%

above the plot more than above the field plots by at least 1 °C during late spring and early summer because the bare ground surfaces heated faster without litter layer or residual vegetation. Temperature differences at the soil surface can mediate local air temperatures (Hillel, 1982; Scott, 2000). In the months of May to August 2001 and May and June 2002 the field and forest plots were particularly warmer than the forest plots. In March of both years the daily air temperature range was greater than in any other month during the year, with cool nightly air temperature and warm daytime temperatures, these temperature extremes yielded the least difference in air temperatures for the study. March was the crossover month for these plots, where temperature changes due to vegetation and litter layer effects was the least. There was little (< 0.5 °C) is this an average or a maximum difference between field and bare ground plots before the first mechanical tillage occurred in April 2001. The bare ground plots were weeded and kept relatively free of vegetation before the first tillage. After the initial tillage occurred, the bare ground plots were slightly (<0.9 °C) warmer than the field plots in all months. In March of 2002, the field plots were slightly warmer (<0.1 °C) than the bare ground plots, possibly due to ponded conditions at the bare ground plots. March was the only month where the bare ground plots were ponded when the field plots were not. The presence of water could have a slight ameliorating effect on air temperature, even within this small area (Gannon et al., 1978).

At Hall, the 2001 measured average annual air temperature was 15.6, 16.4, and 16.4 °C in the forested, field, and bare ground plots, all warmer than average but within the range of normalcy (Table 3-5). There were four months (November and December 2001; March and April 2002) where temperatures were warmer than normal in all plots. The field plot was warmer than normal for an additional six months (February, April, May, June, and August 2001 and June 2002). The bare ground plot was warmer than normal for an additional four months (April, May, June, and August 2001). The field plot was colder than normal in September 2001. The forest plot was colder than normal for an additional five months (March, June, July, and October 2001 and May 2002). The bare ground plot was colder than normal for one additional month (July 2001).

The field and bare ground plots were warmer than the forest plots, especially once the hardwood canopy fully developed in April. Like the Bruff study area, there was little difference (< 0.5 °C) between field and bare ground plots before the first mechanical tillage occurred in April 2001. However, the field plot was < 1.4 °C warmer than the bare ground plot after the initial tillage for all months except September, October, and December 2001, and January 2002, the opposite

Table 3-5. Measured average monthly air temperature at Hall. Average air temperature by treatment was ranked as a percentile of the 30-yr average annual air temperature data. The annual average is measured from February 2001 to January 2002.

Month	Year	Forest	Ranking	Field	Ranking	Bare ground	Ranking
		°C		°C		°C	
February	2001	6.82	70%	7.51	80%	7.31	80%
March		8.48	30%	9.31	40%	9.23	40%
April		14.81	60%	16.29	100%	15.82	90%
May		18.33	30%	20.89	100%	20.23	90%
June		22.63	30%	25.65	110%	24.77	100%
July		22.82	10%	25.38	50%	24.74	20%
August		24.26	40%	26.04	90%	25.96	90%
September		19.16	10%	20.73	10%	21.07	20%
October		13.89	20%	13.66	20%	14.88	40%
November		11.88	80%	12.10	90%	11.99	90%
December		8.11	80%	8.29	80%	8.73	90%
January	2002	5.77	70%	5.57	70%	6.17	70%
February		6.56	70%	7.54	80%	7.32	80%
March		11.27	80%	11.70	90%	11.51	90%
April		16.46	100%	17.34	120%	17.00	110%
May		18.22	30%	19.63	70%	19.62	70%
June		23.07	50%	24.96	100%	24.36	90%
Annual	2/01-1/02	14.75	40%	15.95	70%	15.91	70%

trend than at Bruff. The field plot at Hall was warmer than the bare ground plot in several months when surface ponding ameliorated surface temperatures and albedo on the bare plots while the field plots had a higher ET and lower compaction and a drier surface.

Air temperature was measured along a continuum, and minute differences in the average monthly air temperatures not be consequential when describing data by month, but these differences show an overall trend by land use The field and bare ground plots were warmer than the forest plots in summer months due to the insulating effects of the forest canopy and litter layer on direct solar radiation and wind. However, in some winter months the forest plots were warmer than the field plots because the forest structure provided better protection from cold winds. The bare ground plots were not insulated from the solar radiation and the air above them warmed more than in the forest. The bare ground plots were warmer than the forest plots in all months because the solar radiation was absorbed into the soil or was reflected back to heat the near-surface air. The magnitude of difference between the three plots was largest in the summer months and the least in winter months because of the great moderating influence of the summer canopy on air temperatures (Mount and Paetzold, 2002).

Soil Temperature

The average annual soil temperature at 50 cm was calculated from February 2001 to March 2002 (Table 4-5). The daily minimum, maximum, and average soil temperatures at each sampling depth are reported in Appendix 8a through 8f. The average annual soil temperature at 50 cm in the representative forest plots were 15.31 and 15.24 °C, 16.02 and 15.70 °C in the field plots, and 17.38 and 16.85 °C in the bare ground plots at Bruff and Hall, respectively. The thermic temperature regime was confirmed because the average annual 50 cm temperature at all plots was between 15 and 22 °C and the difference between the average summer (24.2 °C) and winter (8.9 °C) temperatures was greater than 6 °C. The ST 50 at the representative plots for each treatment at each study area were graphically shown to illustrate the daily variation in ST 50 cm (Figure 3-11 and 3-12). The soil temperature data were not compared statistically in this chapter. For a more complete analysis please refer to Chapter 4.

At the Bruff study area, the forest plot had a smaller range in ST 50 than the field and bare ground plots, and the field plot had a smaller range in ST 50 than the bare ground plot (Figure 3-11). ST 50 variation was much greater in the summer and winter than in the spring and fall because those were the seasons of maximum and minimum monthly air temperatures. The thick,

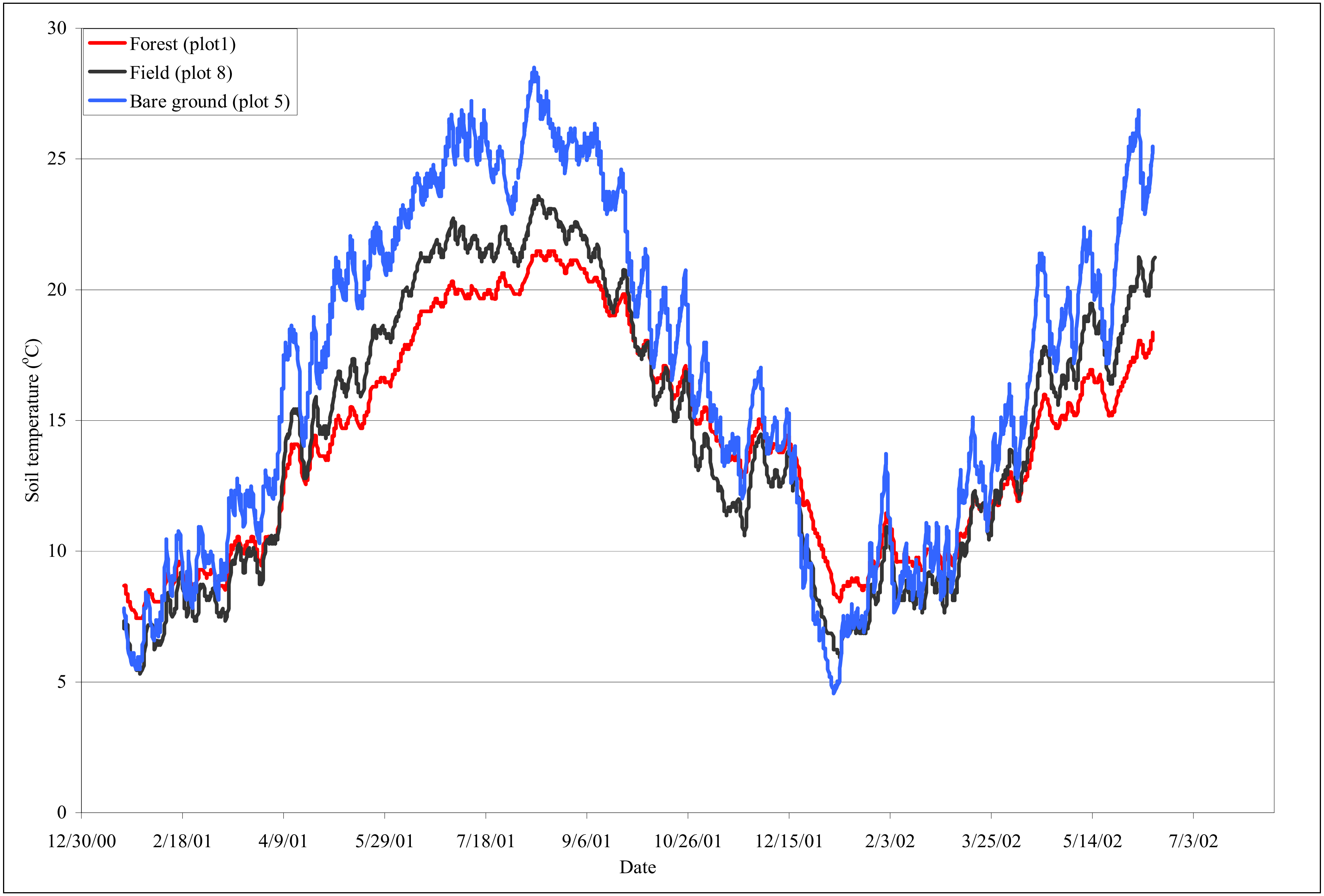


Figure 3-11. Daily soil temperature at 50 cm at the Bruff representative plots.

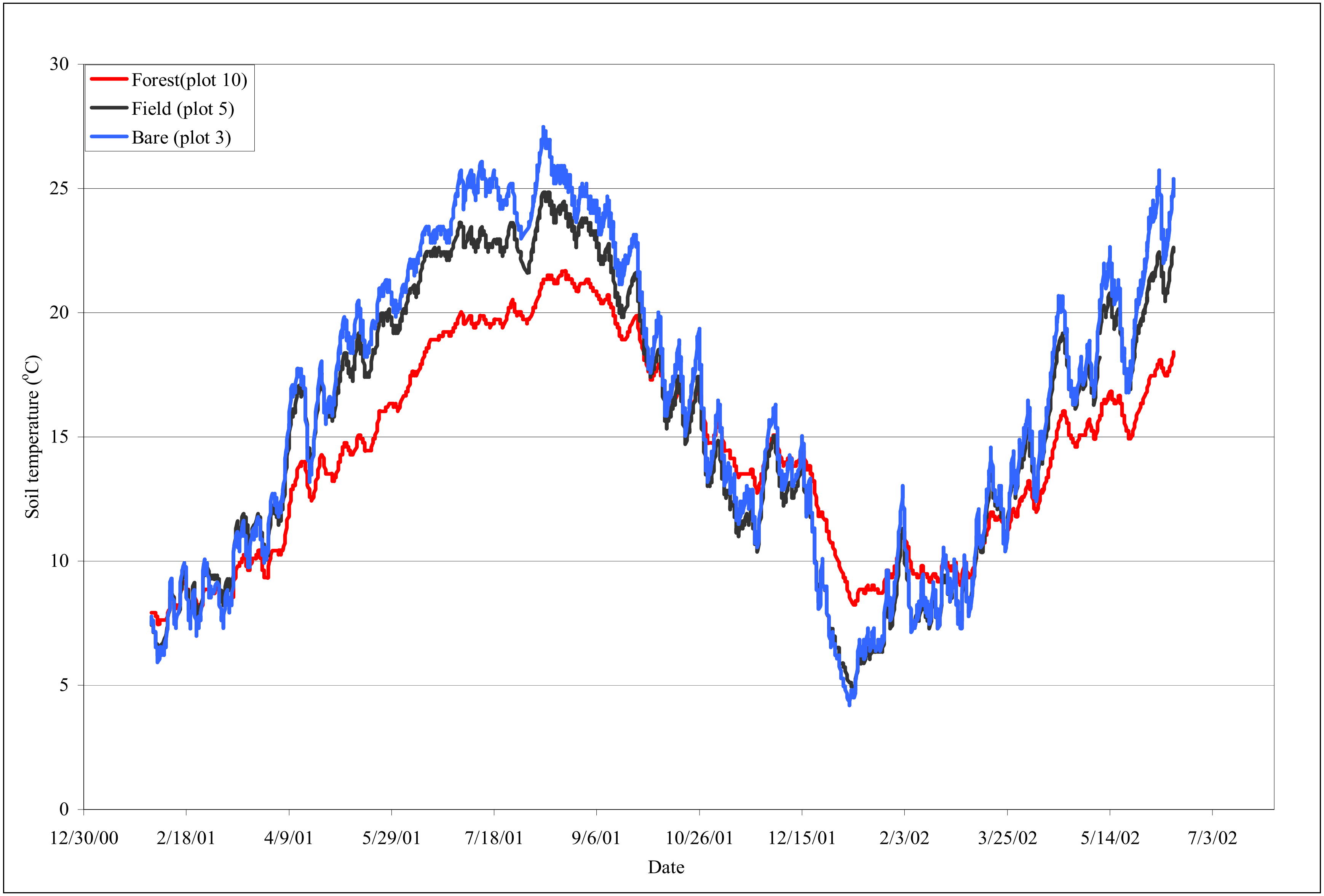


Figure 3-12. Daily soil temperature at 50 cm at the Hall representative plots.

continuous surface litter in the forest plot produced a marked lag period in response to changes in air temperature that was more pronounced than the field or bare ground plots that did not have a litter cover. The lag period was especially evident in August 2001, when a period of intense hot air temperatures effected soil temperature in all three treatments. The magnitude of change due to the heating event was very large in the bare ground plot, but quite small in the forest. The forest plot ST 50 was warmer than the other plots in the winter but cooler than the others in the summer because of the insulation of the surface litter. The crossovers occurred approximately in March and December in 2001. A prolonged crossover (from February to April) occurred in 2002, where the bare ground and field plot were fluctuating with respect to the forest plot. The absolute coldest ST 50 in the forest plots during the study period was 7.4 °C. The forest plots never fell below biological zero, indicating that the overstory, leaf litter, and organic accumulations in the soil had an ameliorating effect on ST 50. The field plot at ST 50 was intermediate in temperature most of the year. The field and forest plot ST 50 seemed to mirror each other. The extreme lowest ST 50 measured in the field plots was 5.3 °C during the study. Both the forest and the field treatments failed to reach biological zero temperatures during the study. The bare ground plot ST 50 was colder than the forest or the field plot in the summer and warmer in the winter because it had no insulation against heat gain or loss. The field cover of dehiscent yet persistent vegetation had a slight buffering effect on ST 50, allowing it to stay above biological zero for longer. The magnitude of change in the bare ground plots was much greater than the other plots because of the lack of surface litter insulation. The extreme lowest ST 50 of the bare ground plots was 2.6 °C.

At Hall study area the ST 50 data and relationship between treatments was similar to the Bruff study area data. The forest ST 50 data and trends were almost identical in the two study areas (Figure 3-12). The extreme lowest ST 50 of the forest plots was 7.5 °C, well above biological zero (5 °C). The ST 50 of the field and bare ground plots at Hall were less variable than at Bruff because the soil was wetter and more insulated against temperature change. The lowest ST 50 recorded in the field plots was 4.6 °C. The bare ground plot ST 50 at Hall was more variable than at Bruff because the weeds and annual grasses grew back more quickly at Bruff and insulated the surface more effectively. The extreme lowest ST 50 of the bare ground plot was 2.5 °C, well below the biological zero of 5 °C.

The forest plot at Bruff had slightly lower ST 50 than at Hall. The slightly colder temperatures could be due to increased winter shading, because the Bruff loblolly forest had a more complete canopy and was relatively drier in winter months. The magnitude of variability in ST 50 between the forest and the other treatment plots was lower at Hall because the Bruff area had drier field conditions. The field plot at Bruff was warmer during summer months that at Hall because of the drier field conditions and a thick grassy layer that insulated heat loss from the surface. Winter temperatures were very similar. The bare ground plots at Bruff were warmer than those at Hall during summer months due to moisture differences, the surface texture was siltier and moisture conditions were drier, all of these factors positively affect soil heat flux (Mount and Paetzold, 2002).

The ST 50 in all forest and field plots at Bruff stayed above biological zero, but fell below the biological zero threshold in January and February 2001 and January 2002 in the bare ground plots. The ST 50 in all forest plots at Hall stayed above biological zero, but went below the biological zero threshold for a few days in January and February 2001 and January 2002 in the field and bare ground plots, there was a difference of a few days between the length of biological zero temperatures in these two plots. These results agree with reported ST 50 above biological zero in thermic soil temperature bottomland hardwood wetlands in Mississippi, South Carolina, and Louisiana (Megonigal et al., 1996). Additionally, Seybold et al. (2002) reported that ST 50 did not drop below biological zero in a Southeast Virginia tidal flat. Research results for ST 50 in wet flats have not been published.

Soil CO_2 Efflux

The soil CO_2 efflux rates (CO_2 ER), soil moisture, and ST 15 at the time of each sampling are reported in Appendix 9a and 9b. The average treatment soil CO_2 efflux rates (CO_2 ER) for the entire study were different (Forest > Field > Bare ground) at each study area (Table 3-6). The forest plots at Hall had higher ($P = 0.001$) CO_2 ER than the forest plots at Bruff because of the different vegetative structure of the forest vegetation (hardwoods versus conifers). The field plots at Hall had the same ($P = 0.530$) CO_2 ER as the field plots at Bruff because they both had herbaceous vegetation and similar soil temperatures. The bare ground plots at Bruff had higher ($P < 0.001$) CO_2 ER than the bare ground plots at Hall because they had warmer soil temperatures.

Table 3-6. One-way ANOVA of mean monthly (N = 24) and total study (N = 570) soil CO_2 efflux rates by treatment at each study area.

Site	Treatment	Soil CO2 efflux rates†	Standard Deviation
		μmol m^{-2} s^{-1}	μmol m^{-2} s^{-1}
Bruff	Forest	1.850c	1.433
	Field	1.596b	1.399
	Bare ground	1.383a	1.649
Hall	Forest	2.107c	1.778
	Field	1.628b	1.634
	Bare ground	1.097a	1.302

† Within hatched blocks, means in any column followed by different letters differ significantly at P = 0.01 by a one-way ANOVA

Average sampling date soil CO_2 ER at Bruff were plotted to determine differences between treatments, and these means were compared using ANOVA $P<0.05$ (Figure 3-13). The CO_2 ER at Bruff was different in 14 of the 24 sampling periods during the 18-month study. The forest plots had higher CO_2 ER than the field and bare ground plots when soil temperature at 15 cm (ST 15) and soil moisture were the same. The forest plot means were higher than the field and bare ground plots CO_2 ER in eight months (generally the winter months), due to increased rates of root respiration. The contribution of root and rhizosphere respiration to total CO_2 ER is well documented and can range from 30 to 60% (Schlesinger, 1977; Hanson et al., 2000; Raich and Tufekcioglu, 2000). Based on this information soil CO_2 ER could be considered an indicator of biological activity, instead of primarily an indicator of microbial activity. Throughout the study, the forest plots were very similar to field plots CO_2 ER. However, on four sampling occasions the bare ground plots were more similar to the forest plots than to the field plots CO_2 ER. The field plots were higher than the forest and bare ground plots CO_2 ER in May and June 2001. The bare ground plots were higher in July 2001 and much lower on four dates than the forest and the field plots CO_2 ER. During much of the year, the CO_2 ER in field and bare ground plots were not different, and in many sampling periods there were no differences between any plots.

Average sampling date soil CO_2 ER at Hall was plotted to determine differences between treatments, and these means were compared using ANOVA $P<0.05$ (Figure 3-14). The CO_2 ER at Hall was different in 11 of the 24 sampling periods during the 18-month study. The forest had higher CO_2 ER than both the field and bare ground plots on 8 of the sampling occasions, mainly in the summer when root and rhizosphere respiration were at their highest rate during the year (Raich and Tufekcioglu, 2000). The CO_2 ER in the forest plots was more comparable to those in the field plots than to the bare ground plots. The CO_2 ER in the bare ground plot was lower than the CO_2

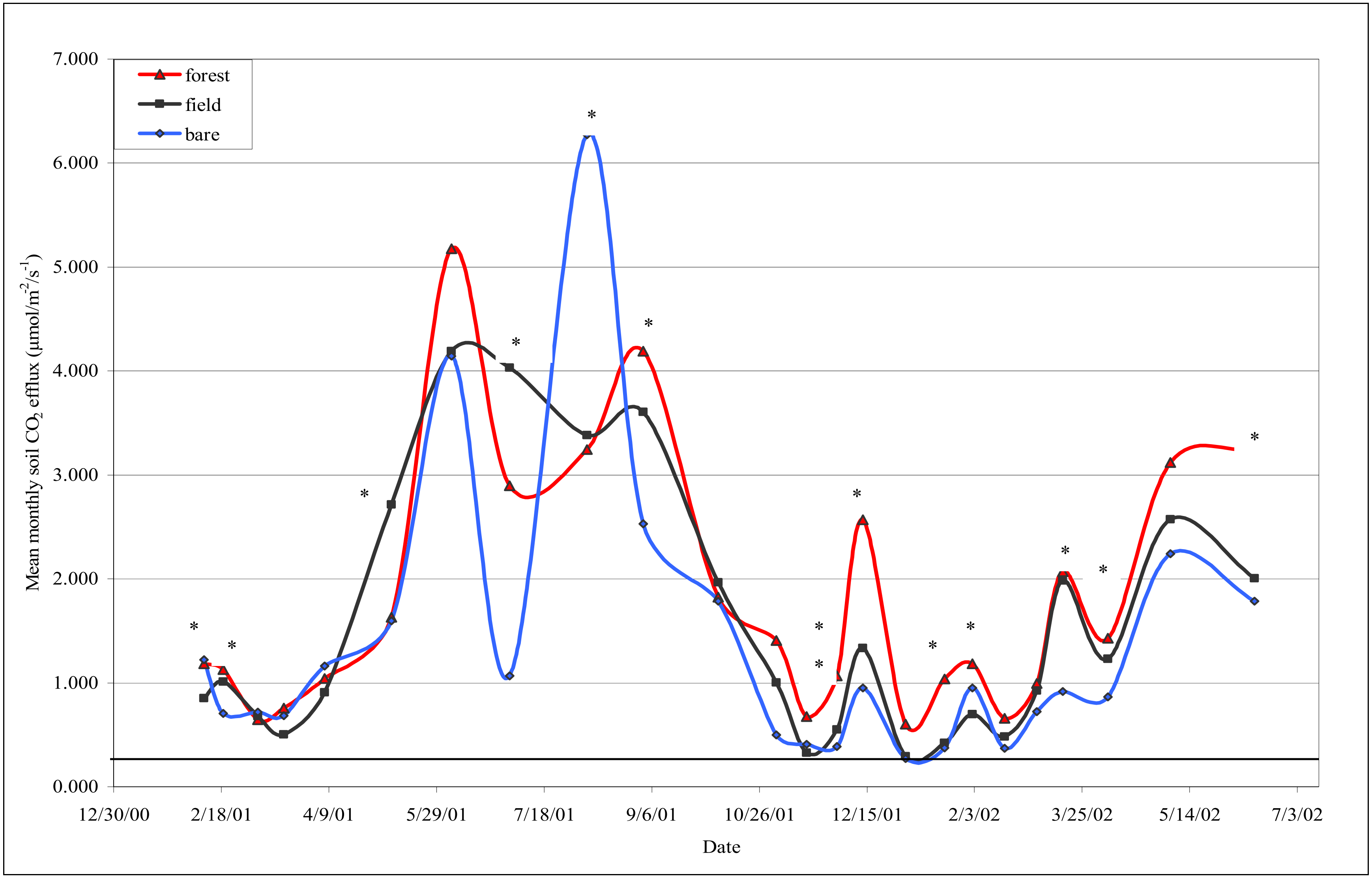


Figure 3-13. Monthly mean separation of CO_2 efflux by treatment at Bruff study area measured over an 18 month sampling period from February 2001 to June 2002. Black line represents the limit of appreciable soil CO_2 efflux at biological zero.*Significant difference in mean CO_2 efflux rates of at least one plot type at P=0.05 using ANOVA.

ER in the field or forest plots. The effect of soil moisture was apparent in the bare ground treatment CO_2 ER. Two of these periods occurred where the bare ground plots water levels were much lower were during the fall and spring and when water was ponded at the surface of the treatment due to low permeability of the tilled plots. On the third occasion, soil moisture may have been the limiting factor, exhibiting a depressed soil CO_2 efflux rate despite warm soil temperatures. Extreme soil moisture status inhibits microbial communities and their efficiency, therefore soil CO_2 ER tend to be inhibited by anaerobic soil conditions at low soil temperatures and by drought at high temperatures (Ino and Monsi, 1969; Howard and Howard, 1993). This interaction was found to be common for depressed soil CO_2 efflux rates to occur in drought conditions even during warm periods (Pangle and Seiler, 2002; Kirshbaum, 2002). Major differences seem better explained when soil temperature and moisture are used as a covariate to soil CO_2 ER than can be explained by the type of treatment.

CO_2 ER from the site was strongly influenced by temperature and changes occurred seasonally. The highest CO_2 ER during the study were during summer months, June to August in 2001 and May to June in 2002, when soil temperatures were their greatest (Figure 3-15). Monthly mean CO_2 ER ranged from a June 2001 high of 4.84 μmol m^{-2} s^{-1} when mean soil temperature was 24.82 °C to a low of 0.30 μmol m^{-2} s^{-1} when mean soil temperature was 4.92 °C in January 2002.

Gravimetric soil moisture ranged from a mean high of 31% in the January, March, April, and May, during super-saturated soil conditions and a mean low of 12% in November and December during a prolonged drought. The effect of moisture was evident in August, the first month sampled for soil moisture, when CO_2 ER was depressed despite warm temperatures (Figure 3-15). Soil moisture limitations often increased with temperature on many seasonally dry sites, compared to constantly moist sites where increasing temperatures may not produce moisture

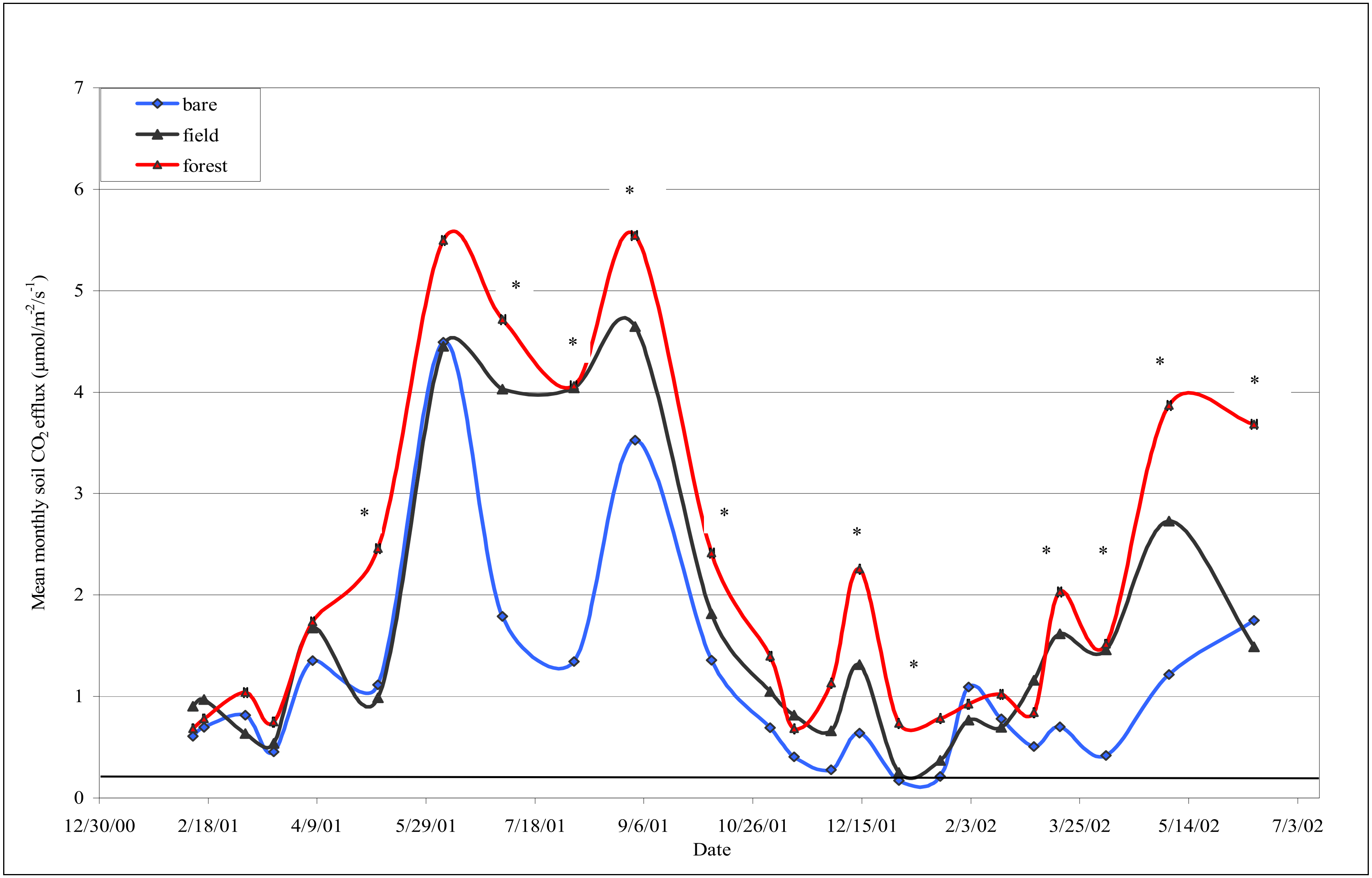


Figure 3-14. Monthly mean separation CO_2 efflux by treatment at Hall study area measured over an 18 month sampling period from February 2001 to June 2002. Black line represents the limit of appreciable soil CO_2 efflux at biological zero. *Significant difference in mean CO_2 efflux rates of at least one plot type at P=0.05 using ANOVA.

limitation on soil respiration and plant growth (Kirshbaum, 2002; Pangle and Seiler, 2002). High soil moisture content seriously affected measurements made by the infrared gas analyzer, by overestimation of soil CO_2 ER up to 17% (Widen and Lindroth, 2003). This is evident in the bare ground plot soil CO_2 ER in February (Figure 3-14). The interaction between soil CO_2 ER, soil temperature, and soil moisture was statistically analyzed to help clarify these observations.

A simple model was made to determine if all CO_2 ER values could be placed together, regardless of treatment. However, this was rejected because the coefficient of variation ($R^2 = 0.33$, $P < 0.001$) was not as strong as when each treatment was analyzed separately (Forest: $R^2 = 0.52$, $P < 0.001$, Field: $R^2 = 0.38$, $P = 0.1$ and Bare ground: $R^2 = 0.31$, $P < 0.1$). Treatments were then analyzed to see the relationship between temperature, moisture and the interaction between temperature and moisture. The relationship between CO_2 ER and temperature was strong (Forest: $R^2 = 0.46$, $P < 0.001$, Field: $R^2 = 0.34$, $P < 0.001$ and Bare ground: $R^2 = 0.24$, $P < 0.001$). The relationship between CO_2 ER and soil moisture did not explain much of the variability (Forest: $R^2 = 0.03$, $P < 0.001$, Field: $R^2 = 0.01$, $P = 0.1$ and Bare ground: $R^2 = 0.01$, $P = 0.1$). Studies have indicated a strong positive correlation between soil temperature, soil moisture, and CO_2 ER (Wildung et al., 1975; Wagai et al., 1998; Pangle and Seiler, 2002). Wildung et al. (1975) observed that CO_2 efflux had a strong correlation with soil temperature when soil moisture was greater than 10% ($R^2 = 0.93$, $P < 0.01$) and a strong positive correlation with soil moisture at soil temperatures above 15 °C.

Since there was no study area difference in the multiple regression analysis, the data from the two study areas were combined. These trends were not evident in the data. Instead CO_2 ER seemed well correlated to soil temperature and modified by moisture only in extreme cases of saturation or drought. The soil temperature and moisture interaction explains most of the variation

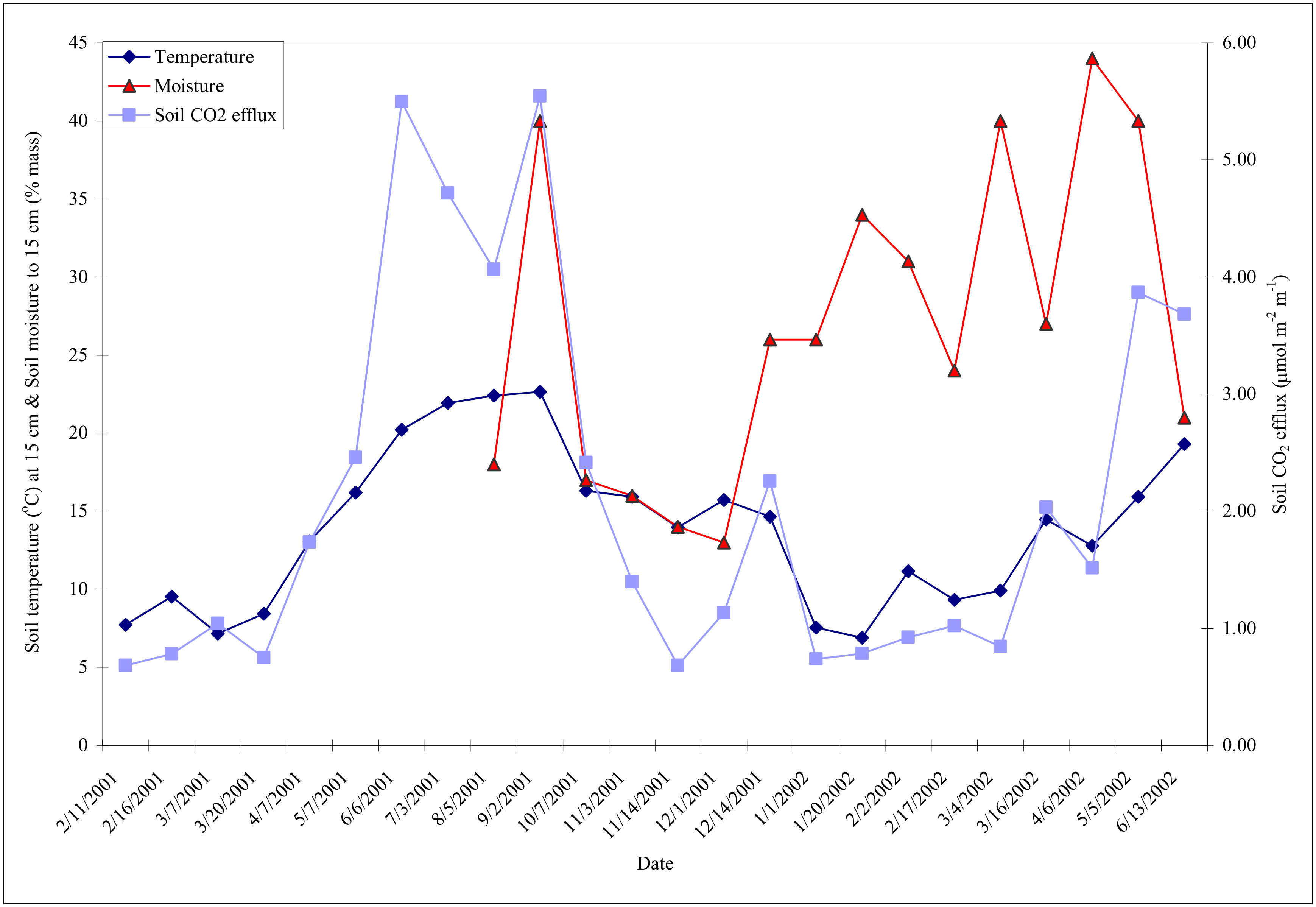


Figure 3-15. Mean monthly soil CO2 efflux rates, soil temperature, and soil moisture during monthly sampling periods in a forest plot

in log transformed CO_2 ER for each measurement. However, soil temperature explained the greatest amount of variation in the mean CO_2 ER for each plot type (Forest: $R^2 = 0.71$, Field: $R^2 = 0.65$, and Bare ground: $R^2 = 0.49$) (Figure 3-16). Soil temperature was correlated to average CO_2 ER to understand seasonal changes in CO_2 ER. At high temperatures, high CO_2 ER occurs, at low temperatures, low CO_2 ER occurs. The rate of unappreciable CO_2 ER at low temperature was then determined (Figure 3-16). The average CO_2 ER measured when temperatures were lower than biological zero was considered the value at which unappreciable levels of CO_2 evolved from the soil surface. The mean of all unappreciable CO_2 ER in this study was 0.3021. The unappreciable level of CO_2 ER was plotted on Figure 3-13 and 3-14 and used to determine when the microbial activity season began and ended.

Indicators of the Growing Season

Growing season measurements and indicators

The study was not implemented until January 21, in 2001, so the growing season was investigated for duration of 344 days in 2001. The study concluded on June 14, so a period of 167 days was investigated in 2002. The ST 50 values were considered a control because they are direct measurements of the point when soil temperatures reach biological zero. All other GSI try to approximate the dates when ST 50 $\leq$ 5 °C, estimating the starting and ending GS dates by using surrogate information. The ST 50 GS was compared and contrasted to ACOE FFD -2.2 and various other GSI, measured air temperatures, and biological activity as indicated by CO_2 ER (Figures 3-17 to 3-20). The various GS measurements and indicators are detailed below. Preliminary data suggest that there was little correlation between the listed growing season dates and the measured data in the study areas.

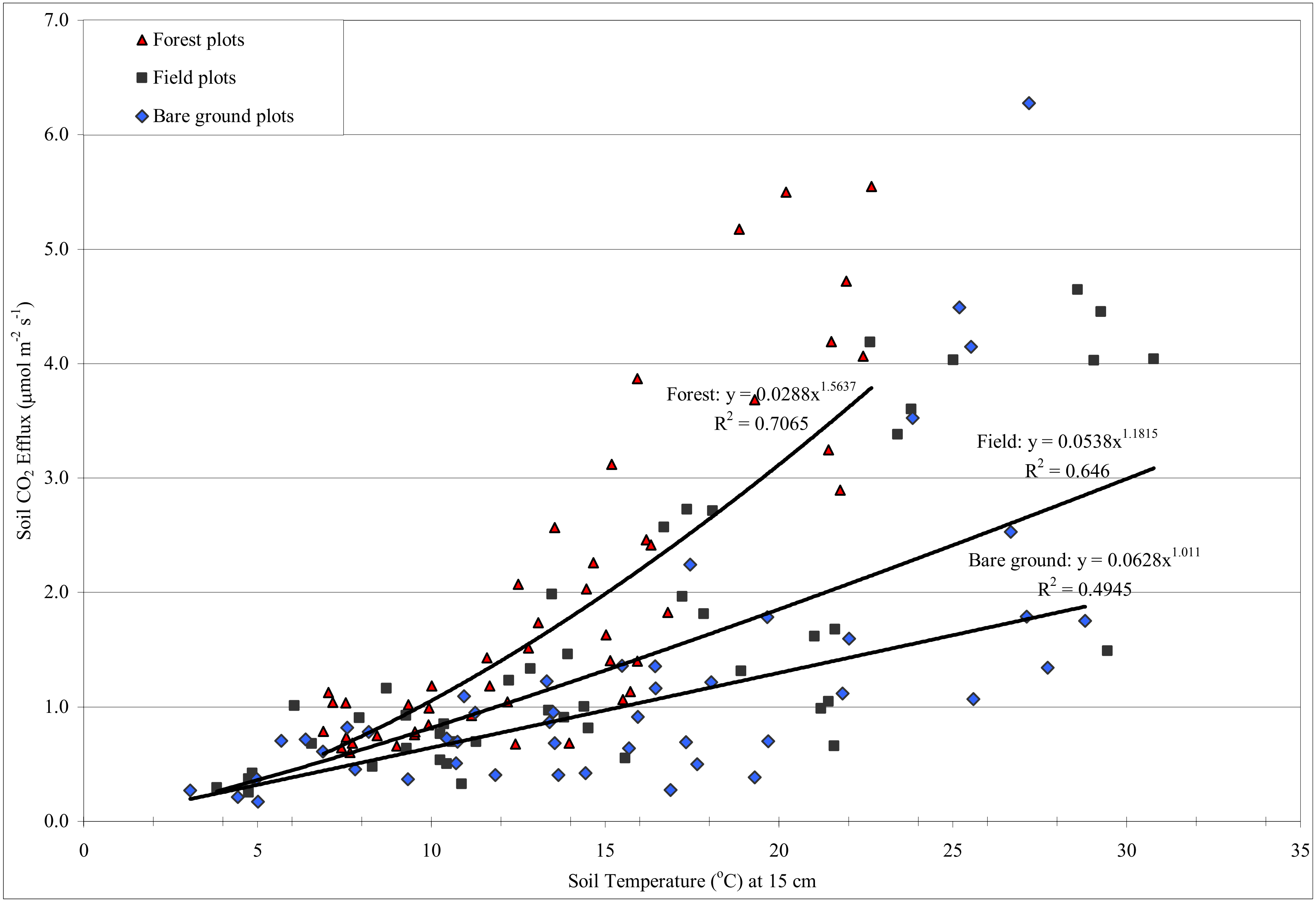


Figure 3-16. Monthly mean soil CO_2 efflux by plot measured over an 18 month sampling period from February 2001 to June 2002.

Differences in land use and vegetation type were evident in the duration and the timing of the GS defined by measured data, regardless of the data source or GSI criteria. The role of land use is discussed in the context of each GS defined below. Although no study has looked at differences between land use within the same area, studies that have one or more matching treatments have found similar results to those in this study (Megonigal et al., 1996; Pickering and Veneman, 1984; Seybold et al., 2002; Thompson and Bell, 1998).

The vegetative growing season was assessed by the earliest date when the first dominant hardwood overstory species began to show visual signs of bud break. In the Bruff study area, bud break of red maple was observed as early as the first week of February of 2001. At Hall bud break was not observed in red maple or sweetgum until the middle of February in 2001. In the middle of November 2001 the overstory species began to senesce and loose their leaves, this terminated the vegetative growing season as indicated in figures 3-17 through 3-20. In 2002, buds began to swell early due to unseasonably warm temperatures. By the middle of January, bud break was initiated in the deciduous tree species at Bruff study area and by the end of January the Hall study area exhibited signs of leaf out.

The ST 50 of the forest plots at Bruff and Hall approached but never went below biological zero during the study. The ST 50 GS had already started when this study began on January 21, 2001. Based on the data from 2002 in Figures 3-19 and 3-20, the forest GS never ceased, lasting for the entire 365 d each year. This is equivalent to the 12-mo microbial GS that Megonigal et al. (1996) reported in South Carolina, Mississippi, and Louisiana bottomland hardwood forests. The broad extent of this study, along with supporting reports throughout the Southeast, allowed the authors to conclude that most southeastern bottomland hardwood forests should have comparable year-round biological activity seasons.

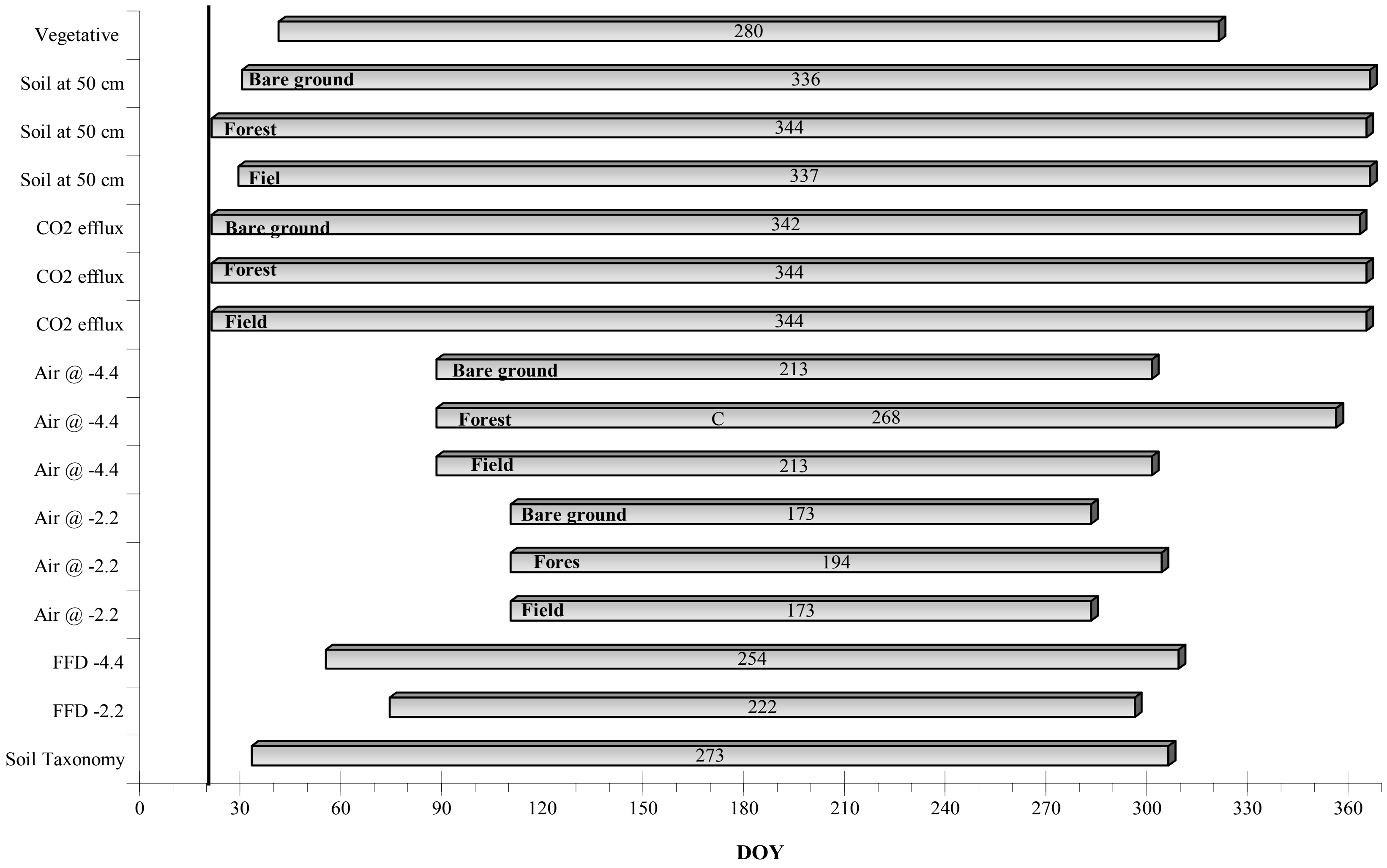


Figure 3-17. Extent of various growing seasons in 2001 at Bruff with length in days indicated. Start of study indicated by vertical line.

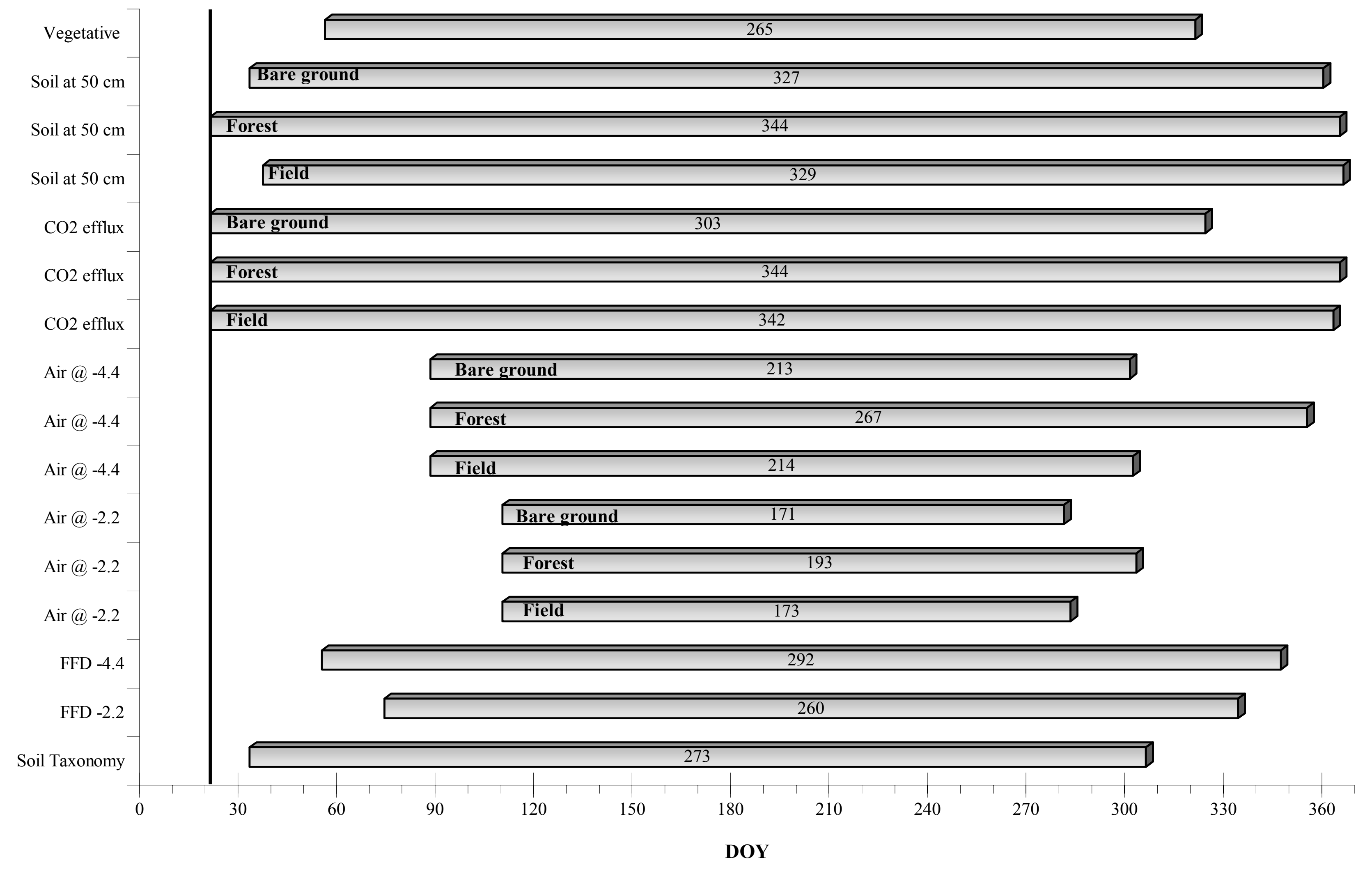


Figure 3-18. Extent of various growing seasons in 2001 at Hall with length in days indicated. Start of study indicated by vertical line.

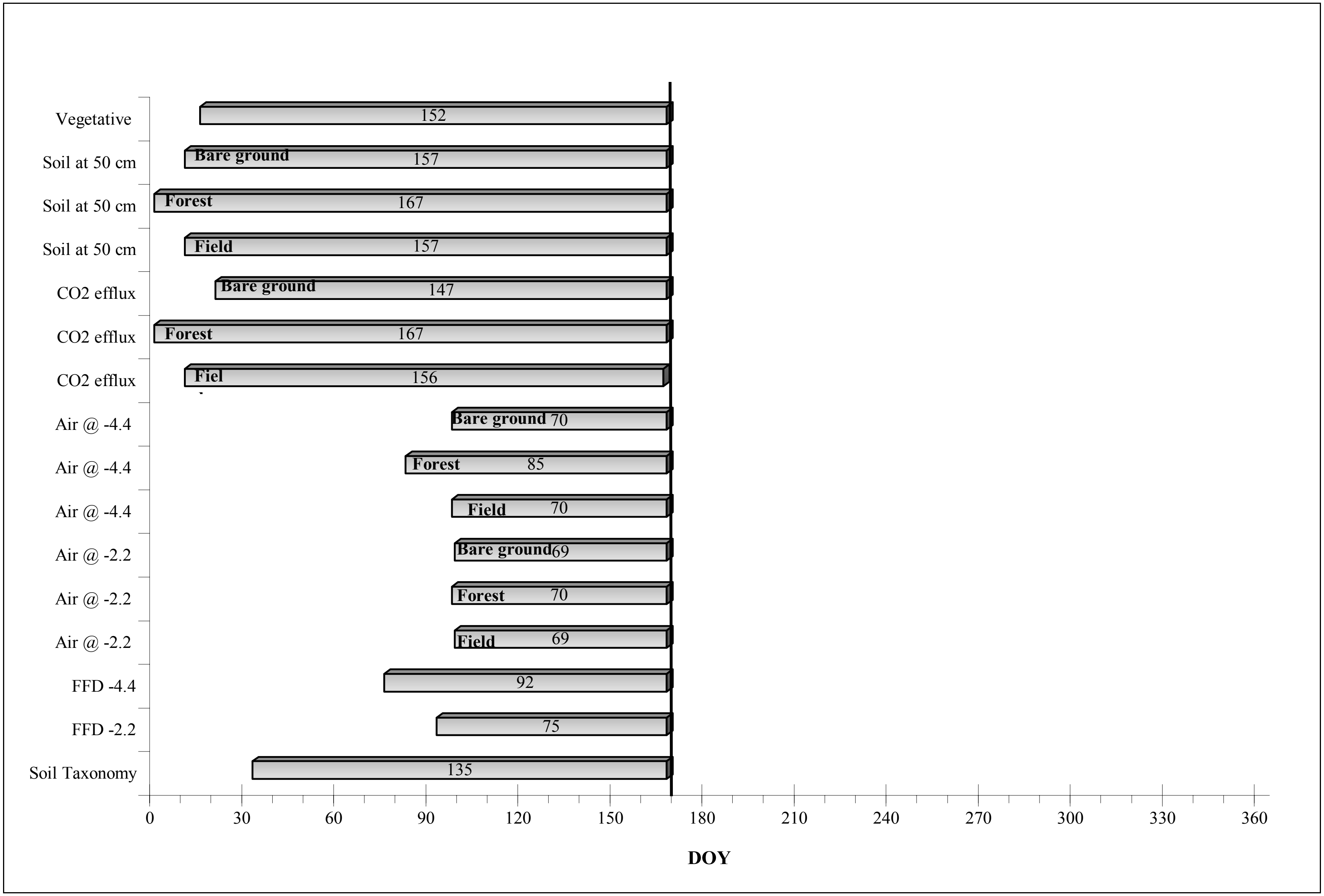


Figure 3-19. Extent of various growing seasons in 2002 at Bruff with length in days indicated. End of study indicated by vertical line.

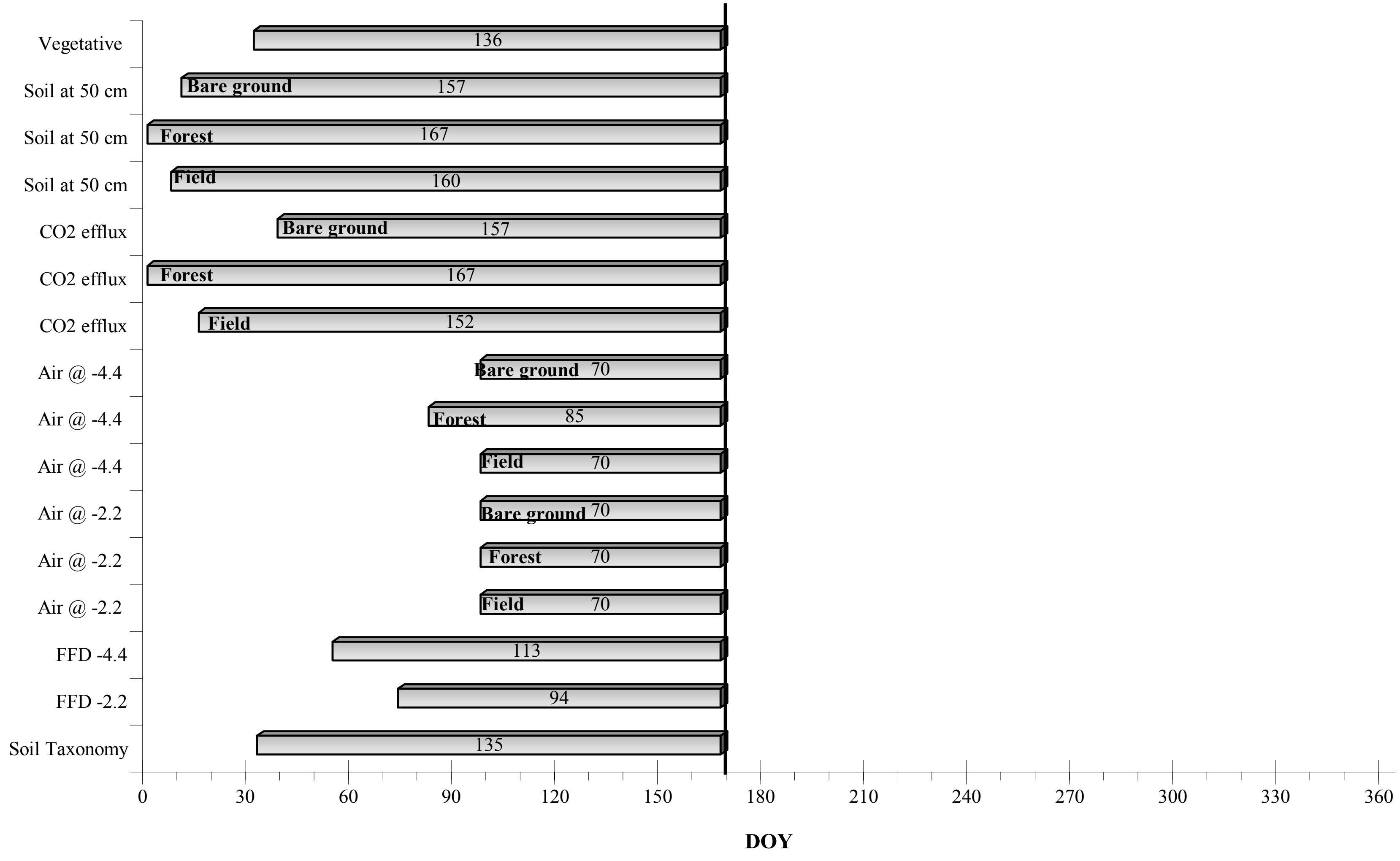


Figure 3-20. Extent of various growing seasons in 2002 at Hall with length in days indicated. End of study indicated by vertical line.

The ST 50 in the field and bare ground plots at Bruff stayed above 5 °C between January 29, 2001 until early January 2002 for a combined length of about 340 d. The field plots were above biological zero 338 d in 2001 and for 5 more days in 2002. The bare ground plots were above biological zero 336 d in 2001 and for 3 more days in 2002. The ST 50 stayed below 5 °C for less than 10 d, until January 10, 2002. The ST 50 in the field plots at Hall stayed above 5 °C between about February 7, 2001 until early January 2002 for a combined length of about 333 d. The field plots were above biological zero for 329 days in 2001 and for an additional 4 d in 2002. The ST 50 stayed below 5 °C for less than 5 d until January 7, 2002. The ST 50 in the bare ground plots at Hall stayed above 5 °C between about February 5, 2001 until late December 2001 for a length of about 330 d. The bare ground plots were above biological zero for 327 d in 2001 and an additional 3 d in 2002. The ST 50 stayed below 5 °C for less than 15 d until about January 15, 2002.

The CO_2 ER data supported the results gathered from ST 50 measurements and appear to be a good indicator of microbial or biological activity. The microbial and biological activity was assumed to be significant when the CO_2 ER were above the appreciable level calculated earlier (Figure 3- 13 and 3-14). Assuming that appreciable CO_2 ER indicated biological activity, the GS continued through the entire 365 d because CO_2 ER never ceased in the forest plots at either site. The CO_2 ER in the field plots at Bruff was appreciable from the first monitoring date of the study on January 21, 2001 until the end of the year for a length of about 344 d. The CO_2 ER was unappreciable until about January 15, 2002, indicating a period of 15 d where CO_2 ER was unappreciable. The CO_2 ER in the bare ground plots at Bruff was appreciable from the first monitoring date of the study on January 21, 2001 until the last week in December 2001 for a length of about 342 d. The CO_2 ER stayed unappreciable for the month of January 2002.

The CO_2 ER in the field plots at Hall was appreciable from the beginning of the study on January 21, 2001 until the last week in December 2001, a length of about 342 d. The CO_2 ER stayed unappreciable for less than 17 d until about January 15 2002. The CO_2 ER in the bare ground plots at Hall were appreciable from the between the beginning of the study on January 21, 2001 until November 20, 2001 for a length of about 303 d. The CO2 ER was unappreciable for less than 80 d until about February 15, 2002.

The differences between the ST 50 GS dates and lengths and the CO_2 ER GS was generally because soil temperature is not the only factor influencing soil CO_2 efflux. Efflux is dependent upon soil carbon source, soil moisture, and soil temperature. There is a strong positive correlation between efflux rates and soil moisture, such that under drought conditions soil CO_2 efflux rates would be depressed. In addition, the bare ground plots had a lower efflux rate in the winter months than the other treatments; this could be due to the lack of contributing root and shoot respiration to the overall soil CO_2 efflux. Generally, the CO_2 ER GS was a better indicator of ST 50 GS than the other growing season indicators, however compounding factors limit the use of CO_2 ER.

This indicates that the forest plots have a year-round microbial activity season and the soils are effectively undergoing saturation-reduction events during winter months. In the field and bare ground plots, microbial activity ceased for a few weeks during the winter, however there were many months where water was at or near the surface and soil CO_2 efflux was measured. The water table in the wet flats was high during winter months and typically dipped below the detection limit during spring and summer months. Thus, the redox depletions and concentrations may be attributed to winter saturation events and microbial reduction during periods not before considered.

The air temperatures at Bruff and Hall stayed above -2.2 °C starting at about April 19, 2001 for all treatments. The forest plots at Bruff and Hall air temperature went below -2.2 °C on

October 30, 2001 for a GS length of 194 d. The field and bare ground plot air temperature passed below -2.2 threshold again on about October 9, 2001 for an AT -2.2 GS length of 173 d. The air temperature was moderated in the forest for an extra 21 d because of the canopy protected the thermistors from the cold winds. In 2002, all plots stayed above -2.2 °C after April 7 2002. The vegetation in the field treatments was no higher than 2 m and did not alter the measured air temperature compared to the bare ground treatments.

The differences dates and lengths of ST 50 GS and the AT -2.2 GS indicate that measuring on-site air temperature in a specific year would not yield an accurate assessment of the biological growing season or ST 50 GS in most years. The Lake Kirby air temperatures were higher than normal from November 2001 through April 2002 (Table 3-3) and yet the measured air temperatures still underestimated the ST 50 GS by over 150 days in 2001 and by 80 days in first half of 2002.

Air temperatures at Bruff stayed above -4.4 °C starting at about March 28, 2001 for all treatments. In the forest plot at Bruff and Hall air temperatures went below -4.4 °C December 21, 2001 for a GS length of 268 d. There were no differences in the length of AT -4.4 GS between the field and bare ground plots at either study area. The field and bare ground plot air temperatures went below -4.4 again on about October 27, 2001 for an AT -4.4 GS length of 213 d. The air temperature was moderated for an extra 55 d in the forest because of the canopy protected the thermistors from the cold winds. In 2002, the field and bare ground plots stayed above -4.4 °C starting at about April 7 but the forest plots stayed above -4.4 °C starting about 14 d earlier on March 23. This indicates that the AT -4.4 GS starts a few weeks earlier in the forest and lasts about 8 weeks longer than in the field or bare ground treatments.

The differences between the ST 50 GS dates and lengths and the AT -4.4 GS were great in all treatments (Figure 3-17 to Figure 3-20). Generally, the field and bare ground plots had a 120 day longer ST 50 GS than the AT -4.4 GS in 2001, and 80 day longer ST 50 GS dates than AT -4.4 GS for half of the year in 2002. The forest AT -4.4 GS was 77 days shorter in 2001 and 80 days shorter in the first half of 2002 than the ST 50 GS. The AT -4.4 GS was measured to determine if lower air temperatures were a better fit to the ST 50 than air temperatures at -2.2 °C. Although the AT -4.4 GS was a better fit, the parameter did not approach dates indicated by ST 50 GS. In 2002, a cold frost dropped air temperatures below both thresholds on the same day.

The study areas are in neighboring counties but are regulated by different FFD -2.2 GSI. The ACOE uses -2.2 FFD as listed in the City of Suffolk County soil survey for the Bruff study area and tables requested from the NRCS Water and Climate Center in Portland, OR for the City of Chesapeake County for the Hall study area. The FFD -2.2 GS for Suffolk begins March 29 and ends November 7 for a length of 222 d. The FFD -2.2 GS for Chesapeake begins March 14 and ends November 29 for a length of 260 d.

The FFD -2.2 GS was generally 100 days shorter than the ST 50 GS and 50 days longer than the AT -2.2 GS. Clearly, the FFD -2.2 GS ending dates in November and beginning dates in March do not accurately reflect the ST 50 data and relationships shown in the forest, field or bare ground treatments in this study. The FFD -2.2 GS dates, as used by the ACOE, are designed to be representative of the region for a normal year and are probable in most years. The air temperatures in 2001 and 2002 were well above normal for the region, the measured air temperature should have been very similar, if not an overshot of the FFD -2.2 GS dates. Instead, FFD -2.2 GS dates were much shorter than the ST 50 GS dates and much longer than the AT -2.2 GS, indicating a poor match to either parameter. In the Bruff study area, FFD -2.2 GS dates used were compiled in

1981, indicating that the average air temperature has changed over time and the older FFD estimates based on previous decades of air temperatures are not representative of current conditions. However, the FFD -2.2 GS dates used at the Hall study area were recently compiled, this indicates that this estimate, although longer, is in error and should be avoided both for agronomic planting dates and wetland regulation.

The ACOE does not use -4.4 °C FFD in their regulation but it was compared because it gives a longer growing season than the FFD -2.2 GS and is listed in the same table. The FFD -4.4 GS for Suffolk begins March 11 and ends November 21 for a length of 254 d. The FFD -4.4 GS for Chesapeake begins February 23 and ends December 12 for a length of 292 d.

The FFD -4.4 GS is 32 d longer than the FFD -2.2 GS in both counties. Although this indicator is a slightly better fit, it still is a poor estimate of the ST 50 GS dates and lengths. The FFD -4.4 GS underestimates the control ST 50 GS dates by 60 to 100 d in the forest plots at Hall and Bruff and 50 to 120 d in the field and bare ground plots at these locations. The use of FFD -4.4 GS would be an improvement to the regulated FFD -2.2 GS, but would not estimate the ST 50 GS properly. The FFD -4.4 GS corresponded to vegetative indicators such as initial bud break and senescence of eastern redbud (*Cersis canadensis* L.), sweet gum, and red maple species at the two study areas.

The thermic temperature regime GS is 273 days from February 1 to the end of October (Soil Survey Staff, 1999). The thermic temperature regime was classified correctly in this area however, the documented growing season did not match the ST 50 or vegetative indicators used in this study and should be re-evaluated. The thermic GS ends two months before temperatures approached the biological zero threshold of the ST 50 GS in the two years studied. However, the start date of the beginning of February was a good fit to the ST 50 GS.

Vegetative indicators

Vegetative indicators do not necessarily coincide with biological zero temperatures, and in fact do not coincide with these temperatures in the two mitigation wet flat ecosystems investigated. As with the air temperature, the ST 50 GS is a mismatch. The forest treatments exhibited definite termination of growth in the deciduous mixed hardwood cover, while the loblolly pine cover was suspect. Other studies have indicated that pine species continue to undergo sap flow and stand transpiration even in winter months (Martin, 2000).

In the Bruff study area, the forest canopy had a loblolly pine dominated overstory, with some hardwood species scattered throughout. Bud break of red maple and eastern redbud were observed starting in the first week of February and continuing in concurrent visits throughout that month in 2001. Sweetgum started bud break in early March and most of the hardwood species (90%) at Bruff were leafing out and starting to produce the new leaves by the March 20 visit in 2001. Forest species at Hall had a similar response. Eastern redbud was producing floral material in early February, while bud break was not observed in red maple or sweetgum until the middle of February in 2001. Buds were swelling in oak species by the first week in March. By the middle of March almost all overstory cover (80%) was budding or had already produced leaf material in 2001. Most of the shrub and saplings species in the understory of the forests were exhibiting leaf out by the middle of March in 2001. Studies have indicated that in mesic and frigid regions of the United States eastern redbud is among the first species to undergo bud break, flowering of eastern redbud generally requires a 30-d period of average air temperatures greater than 10 °C (Afanasiev, 1944). A study in New Hampshire indicated that observation of bud swell and leaf senescence of red maple was a good indicator of growing season and correlated with redox potential raises in the spring and drops of redox potential in the fall (Whited, unpublished data).

In the middle of November 2001 the overstory species began to senesce and loose their leaves, by December there was widespread loss of chlorophyll, evidenced by browning, and leaf loss in both study areas. In 2002, buds began to swell early due to unseasonably warm temperatures. Air temperature in January was warmer than normal air temperatures in that month. By the end of January, full bud break was complete in the deciduous tree species at the Bruff study area and most of the deciduous overstory at Hall study area exhibited signs of leaf out. Spring vegetative development was slower at Hall as compared to the Bruff study area. The majority of the vegetation was not yet green, but many of the trees had exposed leaves not yet pigmented with chlorophyll. By February of 2002, there was widespread leaf development at both study areas.

In the Bruff study area, vegetation in the field was predominantly grasses. These grasses and some weedy species were starting to sprout under residual vegetation and litter as early as February in 2001, by the middle of March there was 40% new vegetative cover. By the beginning of April, saplings planted in the field had leafed out and vegetative species were in flower or had new growth. In the Hall study area, 80% of the vegetation in the field was either in flower or starting to green by March in 2001. Vegetation started to senesce in both study areas in the beginning of November in 2001 and continued through December. In 2002, the vegetative re-growth was more gradual in both study areas, by the end of January sprouts started to emerge, however the fields were not fully blooming or actively green until the beginning of April.

The bare ground plots had similar vegetation growth responses at both study areas. Vegetative growth occurred year-round at all plot locations in the study areas. The treatment required an upkeep and maintenance throughout the year, but at varying rates. During the winter months vegetation needed to be removed, yet there was much less rigorous growth in these treatment areas than in summer months.

Effects of GS dates on Wetland Hydrology Requirements

The number of continuous days of saturation within 30 cm (WL <30) were compared with wetland hydrology and mitigation requirements based on four different GSI (Table 3-7).

Using the GS as defined by the measured ST 50, all wells at Bruff met the continuous saturation requirement at both the 5 and 12.5% hydrology threshold levels in 2001. In 2002, however, only three plots met even the 5% threshold at Bruff because of the low rainfall. All wells at Hall met both the 5 and 12.5% continuous saturation requirements in 2001. At Hall, all of the plots were continuously saturated for the 5% threshold and four also met the 12.5% threshold because of the higher precipitation.

Using the GS as defined by the measured AT -2.2, all wells at Bruff and Hall met the 5% hydrology thresholds in both years. However, only one plot met the 12.5% threshold in 2001 and one in 2002. The lower number of days with WL <30 hydrology was caused by the late starting date of the AT -2.2 GS that missed most of the time when the WL were high, and did not reflect the hydroperiod of the mitigated wetlands. At Bruff, there were four substantial periods of WL <30 during the FFD -2.2 GS (Figure 3-9). The wetland hydrology threshold of 5% required WL <30 of 11 consecutive days and the 12.5% wetland mitigation and marginal wetland threshold required 27 days. In both years, all of the plots at Bruff met the wetland hydrology threshold, but only two wells satisfied the Norfolk ACOE wetland mitigation and marginal wetland threshold in 2001 and no wells satisfied the requirement in 2002 (Table 3-7). Wells 2, 10 and 11 had failed at the beginning of the study and were replaced in June 2001.

In the Bruff forest plot, saturation occurred for a long period before the start of the FFD -2.2 GS, however the forest plot was only saturated continuously for 25 days in the GS (Figure 3-9). During the summer months water in the well was within the upper 30 cm for three short periods, all less than the minimal 11-day requirement in 2001. In 2002, water was within the upper 30 cm for less than 11 days at the start of the GS, but met the jurisdictional requirements in May with a saturation period of 14 days. However, in 2002 the 12.5% minimum was not met for the mitigation requirement set forth by the Norfolk ACOE, due to the long period of drought during the study. In the Bruff field plot saturation occurred for a long period before the start of the GS in 2001, however only the last 27 days of continuous saturation was within the jurisdictional requirements of the growing season (Figure 3-9). After the initial saturation event during the growing season of 27 days, water was within the 30 cm depth for a series of short intervals, all less than the minimum 11-day requirement. The hydrology in 2002 satisfied the minimum requirement for wetland identification, but would not have met the more stringent Norfolk ACOE wetland mitigation requirement. In the Bruff bare ground plot saturation occurred for a long period before the start of the GS in 2001, however only the last 14 days of continuous saturation was counted by the jurisdictional regulations (Figure 3-9). After the initial saturation event, water was within the 30 cm depth for a series of short intervals associated with precipitation events. Water levels during the second growing season were within 30 cm for 13 days. Water levels in both 2001 and 2002 barely satisfied the minimum requirement for wetland identification, but would not have met the Norfolk ACOE requirement.

At Hall, there were five substantial periods of WL <30 during the FFD -2.2 GS (Figure 3-10). The wetland hydrology threshold of 5% required WL <30 of 12 consecutive days and the 12.5% wetland mitigation threshold required 32 days. In both years, all of the plots at Hall met the wetland hydrology requirements (Table 3-7). The mitigation and marginal wetland threshold was exceeded at all plots except field plots 5 and 7, forest plot 12, and bare ground plot 6 in 2001, and was exceeded at all wells in the first half of 2002 except bare ground plot wells 1 and 3.

Table 3-7. Number of days (min. ≥ 7 d) of continuous saturation within 30 cm during 5% of various growing seasons (G.S.).

Treatment	Well	Saturation during Air Temp. -2.2 °C G.S.[†]		Saturation during frost-free days -2.2 °C G.S.		Saturation during Soil Temp. 50cm G.S.[†]		Saturation during Year-round G.S.	
		2001	2002	2001	2002	2001	2002	2001	2002
		---------------------------------- Measured vs. required growing season days -----------------------------------							
Bruff Forest		G.S. = 194 d	G.S. = 70 d	G.S. = 222 d	G.S. = 75 d	G.S. = 344 d	G.S. = 167 d	G.S. = 344 d	G.S. = 167 d
	1	10 = 10	13 > 7	36 > 11	13 > 7	70 > 17	13 > 8	70 > 17	13 > 8
	2	‡	14 > 7	‡	14 > 7	‡	14 > 8	‡	14 > 8
	10	‡	12 > 7	‡	12 > 7	‡	12 > 8	‡	12 > 8
	11	‡	17 > 7	‡	17 >7	‡	17 > 8	‡	17 > 8
Bruff Field		G.S. = 173 d	G.S. = 69 d	G.S. = 222 d	G.S. = 75 d	G.S. = 337 d	G.S. = 157 d	G.S. = 344 d	G.S. = 167 d
	3	69 > 9	13 > 7	79 > 11	22 > 7	139 > 17	36 > 8	148 > 17	36 > 8
	8	17 > 9	13 > 7	27 > 11	13 > 7	60 > 17	13 > 8	69 > 17	13 > 8
	9	16 > 9	15 > 7	26 > 11	15 > 7	86 > 17	15 > 8	95 > 17	15 > 8
	12	13 > 9	11 > 7	23 > 11	11 > 7	83 > 17	11 > 8	92 > 17	11 > 8
Bruff Bare ground		G.S. = 173 d	G.S. = 69 d	G.S. = 222 d	G.S. = 75 d	G.S. = 336 d	G.S. = 157 d	G.S. = 344 d	G.S. = 167 d
	4	§	§	14 > 11	13 > 7	49 > 17	24 > 8	59 > 17	24 > 8
	5	§	13 > 7	14 > 11	13 > 7	59 > 17	21 > 8	59 > 17	21 > 8
	6	14 > 9	§	27 > 11	14 > 7	86 > 17	16 > 8	86 > 17	16 > 8
	7	13 > 9	13 > 7	26 > 11	14 > 7	85 > 17	16 > 8	85 > 17	16 > 8

† Indicates broken or damaged well where information was lost for a period of the year.

‡ Indicates the column was determined by measured data, an approximation of days is shown here.

§ Less than 7 consecutive days measured during the growing season.

Table 3-7. Continued.

Treatment	Well	Saturation during Air Temp. -2.2 °C G.S.[†]		Saturation during frost-free days -2.2 °C G.S.		Saturation during Soil Temp. 50cm G.S.[†]		Saturation during Year-round G.S.	
		2001	2002	2001	2002	2001	2002	2001	2002
		---------------------------------- Measured vs. required growing season days ------------------------------------							
Hall Forest		G.S. = 193 d	G.S. = 70 d	G.S. = 260 d	G.S. = 94 d	G.S. = 344 d	G.S. = 167 d	G.S. = 344 d	G.S. = 167 d
	9	7 < 10	18 > 7	40 > 13	42 > 7	77 > 17	55 > 8	78 > 17	55 > 8
	10	§	11 > 7	38 > 13	35 > 7	92 > 17	37 > 8	93 > 17	37 > 8
	11	§	11 > 7	34 > 13	35 > 7	70 > 17	46 > 8	89 > 17	46 > 8
	12	§	11 > 7	26 > 13	35 > 7	56 > 17	35 > 8	56 > 17	35 > 8
Hall Field		G.S. = 173 d	G.S. = 70 d	G.S. = 260 d	G.S. = 94 d	G.S. = 329 d	G.S. = 160 d	G.S. = 344 d	G.S. = 167 d
	2	15 > 9	23 > 7	39 > 13	36 > 7	66 > 16	29 > 8	69 > 17	29 > 8
	7	§	20 > 7	28 > 13	35 > 7	61 > 16	35 > 8	61 > 17	35 > 8
	8	18 > 9	22 > 7	48 > 13	43 > 7	86 > 16	55 > 8	111 > 17	55 > 8
	5	§	23 > 7	29 > 13	36 > 7	81 > 16	36 > 8	84 > 17	37 > 8
Hall Bare ground		G.S. = 171 d	G.S. = 70 d	G.S. = 260 d	G.S. = 94 d	G.S. = 327 d	G.S. = 157 d	G.S. = 344 d	G.S. = 167 d
	1	15 > 9	22 > 7	39 > 13	28 > 7	65 > 16	28 > 8	65 > 17	28 > 8
	3	13 > 9	20 > 7	37 > 13	29 > 7	57 > 16	29 > 8	57 > 17	29 > 8
	4	15 > 9	32 > 7	39 > 13	45 > 7	65 > 16	52 > 8	68 > 17	56 > 8
	6	§	‡	29 > 13	‡	55 > 16	†	59 > 17	‡

† Indicates broken or damaged well where information was lost for a period of the year.
‡ Indicates the column was determined by measured data, an approximation of days is shown here.
§ Less than 7 consecutive days measured during the growing season.

Table 3-8. Number of days (min. ≥ 7 d) of continuous saturation within 30 cm during 12.5% of various growing seasons (G.S.).

Treatment	Well	Saturation during Air Temp. -2.2 °C G.S.[†]		Saturation during frost-free days -2.2 °C G.S.		Saturation during Soil Temp. 50cm G.S.[†]		Saturation during Year-round G.S.	
		2001	2002	2001	2002	2001	2002	2001	2002
		---------------------------------- Measured vs. required growing season days -----------------------------------							
Bruff Forest		G.S. = 194 d	G.S. = 70 d	G.S. = 222 d	G.S. = 75 d	G.S. = 344 d	G.S. = 167 d	G.S. = 344 d	G.S. = 167 d
	1	10 < 24	13 > 9	36 > 28	13 > 9	70 > 43	13 < 21	70 > 43	13 < 21
	2	‡	14 > 9	‡	14 > 9	‡	14 < 21	‡	14 < 21
	10	‡	12 > 9	‡	12 > 9	‡	12 < 21	‡	12 < 21
	11	‡	17 > 9	‡	17 > 9	‡	17 < 21	‡	17 < 21
Bruff Field		G.S. = 173 d	G.S. = 69 d	G.S. = 222 d	G.S. = 75 d	G.S. = 337 d	G.S. = 157 d	G.S. = 344 d	G.S. = 167 d
	3	69 > 22	13 > 9	79 > 28	22 > 9	139 > 42	36 > 20	148 > 43	36 > 21
	8	17 > 22	13 > 9	27 < 28	13 > 9	60 > 42	13 < 20	69 > 43	13 < 21
	9	16 > 22	15 > 9	26 < 28	15 > 9	86 > 42	15 < 20	95 > 43	15 < 21
	12	13 > 22	11 > 9	23 < 28	11 > 9	83 > 42	11 < 20	92 > 43	11 < 21
Bruff Bare ground		G.S. = 173 d	G.S. = 69 d	G.S. = 222 d	G.S. = 75 d	G.S. = 336 d	G.S. = 157 d	G.S. = 344 d	G.S. = 167 d
	4	§	§	14 < 28	13 > 9	49 > 42	24 > 20	59 > 43	24 > 21
	5	§	13 > 9	14 < 28	13 > 9	59 > 42	21 > 20	59 > 43	21 = 21
	6	14 > 22	§	27 < 28	14 > 9	86 > 42	16 < 20	86 > 43	16 < 21
	7	13 > 22	13 > 9	26 < 28	14 > 9	85 > 42	16 < 20	85 > 43	16 < 21

† Indicates broken or damaged well where information was lost for a period of the year.

‡ Indicates the column was determined by measured data, an approximation of days is shown here.

§ Less than 7 consecutive days measured during the growing season.

Table 3-8. Continued.

Treatment	Well	Saturation during Air Temp. -2.2 °C G.S.†		Saturation during frost-free days -2.2 °C G.S.		Saturation during Soil Temp. 50cm G.S.†		Saturation during Year-round G.S.	
		2001	2002	2001	2002	2001	2002	2001	2002
		---------------------------------- Measured vs. required growing season days ------------------------------------							
Hall Forest		G.S. = 193 d	G.S. = 70 d	G.S. = 260 d	G.S. = 94 d	G.S. = 344 d	G.S. = 167 d	G.S. = 344 d	G.S. = 167 d
	9	7 < 24	18 > 9	40 > 33	42 > 12	77 > 43	55 > 21	78 > 43	55 > 21
	10	§	11 > 9	38 > 33	35 > 12	92 > 43	37 > 21	93 > 43	37 > 21
	11	§	11 > 9	34 > 33	35 > 12	70 > 43	46 > 21	89 > 43	46 > 21
	12	§	11 > 9	26 < 33	35 > 12	56 > 43	35 > 21	56 > 43	35 > 21
Hall Field		G.S. = 173 d	G.S. = 70 d	G.S. = 260 d	G.S. = 94 d	G.S. = 329 d	G.S. = 160 d	G.S. = 344 d	G.S. = 167 d
	2	15 < 22	23 > 9	39 > 33	36 > 12	66 > 41	29 > 20	69 > 43	29 > 21
	7	§	20 > 9	28 < 33	35 > 12	61 > 41	35 > 20	61 > 43	35 > 21
	8	18 < 22	22 > 9	48 > 33	43 > 12	86 > 41	55 > 20	111 > 43	55 > 21
	5	§	23 > 9	29 < 33	36 > 12	81 > 41	36 > 20	84 > 43	37 > 21
Hall Bare ground		G.S. = 171 d	G.S. = 70 d	G.S. = 260 d	G.S. = 94 d	G.S. = 327 d	G.S. = 157 d	G.S. = 344 d	G.S. = 167 d
	1	15 < 21	22 > 9	39 > 33	28 > 12	65 > 41	28 > 20	65 > 43	28 > 21
	3	13 < 21	20 > 9	37 > 33	29 > 12	57 > 41	29 > 20	57 > 43	29 > 21
	4	15 < 21	32 > 9	39 > 33	45 > 12	65 > 41	52 > 20	68 > 43	56 > 21
	6	§	‡	29 < 33	‡	55 > 41	†	59 > 43	‡

† Indicates broken or damaged well where information was lost for a period of the year.

‡ Indicates the column was determined by measured data, an approximation of days is shown here.

§ Less than 7 consecutive days measured during the growing season.

In the Hall forest plot saturation occurred within 30 cm for a long period prior to the beginning of the FFD -2.2 GS, once the growing season officially began the increasing ET lowered the WL (Figure 3-10). There were 38 consecutive days of saturation within the 30-cm depth. There were two other occasions during the 2001 growing season where saturation was within the 30-cm depth. However these events were less than the minimum 12-day continuous saturation required for the county. In 2002, there were two saturation events during the monitored period, the first was continuous from the start of the growing season and encompassed 35 days, while the second was 15 days in duration. The forested plot satisfied the wetland hydrology and wetland mitigation requirements for both years. In the Hall field plot saturation events were slightly longer in 2001 and 2002 than the Hall forested plot (Figure 3-10). Within the regulated FFD -2.2 GS, saturation was less in the field plot. Saturation events occurred three times in the 2001 GS, the first period was much longer than the 29 consecutive days counted during the GS, while the other two saturation events were less than the required 12-day period. In 2002 there were two saturation events, the first period, at the beginning of the GS equaled 36 days and the second period encompassed 23 days where the water was within the regulated 30-cm depth. The field plot satisfied both requirements in 2002, but failed to meet the mitigation requirement in 2001. In the Hall bare ground plot the period of saturation was shorter than the forest or field plots (Figure 3-10). However, saturation was better matched to the regulated FFD -2.2 GS, so within that period the discrepancy is unnoticed. Within the regulated FFD -2.2 GS, the bare ground plot was saturated within 30 cm for 37 d in 2001; additional saturation events were less than the required 12-day period. In 2002, there were two saturation events, the first period, at the beginning of the GS encompassed 29 days, and the second period was 20 days. The bare ground plot satisfied the both requirements in 2001, but failed to meet the mitigation requirement in 2002.

The actual hydroperiod of these wet flat wetlands did not coincide with the regulated FFD -2.2 GS in 2001. Precipitation was drastically lower than the normal range during the duration of this study that could have confounded the hydromorphology of the wetland and may have caused shorter periods of saturation within the regulated depth within the year.

Summary and Conclusions

Wet flats are important systems of great ecological, aesthetic, and economic value. The FFD -2.2 GS definition in use by the ACOE is limited in its effectiveness as a regulatory tool because of the disregard for vegetation type and land use, which affect soil temperature. In this study, forests were found to buffer the soil against changes in temperature because they provide shade in the summer and the surface litter acts as insulating mulch. Fields with early successional vegetation had a shorter growing season because of the short open vegetation stature and lack of surface litter. The bare ground that was intended to simulate cropland or plowed areas had much more dynamic and shorter measured growing season because they provided little to no buffering of the soil surface from sunlight or wind. Further, both measured air and soil temperatures were modified by land-use differences.

The ACOE growing season definition was intended to identify periods of biological activity and probably does so when the criteria are measured directly. Instead, surrogate measurements are used which are not accurate and underestimate the growing season starting dates and length in Southeast Virginia wet flats compared to the original growing season definition of biological zero at 50-cm depth in the soil.

Currently, the ACOE frost-free days growing season in use is not an accurate representation of vegetative growing season, nor is it an accurate assessment of microbial activity or reducing hydric soil conditions. The intent of the growing season must be reassessed. If the growing season was intended as a vegetative parameter, then more data should be gathered or existing data should be analyzed on natural systems, including higher vegetative life forms. The growing season determination should be regulated from bud break to senescence, and the dates associated with the growing season should mirror this intent. Should anaerobic conditions and microbial activity be the premise of the growing season determination, then more data should be gathered as to the depth appropriate for measurement in wetlands, biological zero temperatures, and the dates that correspond to these temperatures in different ecosystems. For example, The National Research Council (1995) recommended that the upper part of the soil be defined at 30 cm rather than 50 cm because the 30-cm depth is the bottom of the rooting zone in most wetlands with high water tables.

The problem with using inaccurate growing season indicators is that the starting date and length are integral components of wetland hydrology and hydric soils identification. The 5% wetland hydrology threshold and the 12.5% mitigation hydrology threshold are controlled by the actual starting dates and growing season lengths reflective of naturally occurring processes. The measured wetland hydrology is seasonal and dependent upon nature, while the growing season criteria applied against it are subjective and polemical. The only way to ensure that the intent of the 1987 Manual GS definition are applied correctly in mitigation cases is to require on-site measurement of soil temperature along with required hydrologic monitoring, so that the timing of the surface saturation and the period of biological activity are properly matched. A mandatory soil temperature analysis of the site could yield a better understanding of when biological zero temperatures occur, as well as yield a site specific growing season for each mitigated area.

The wetland hydrology thresholds may be estimated by models developed through further studies that collect air temperature and soil temperature data by major wetland type and prescribe a growing season that is land-use specific. At the very least, forests and fields must be treated differently based on results of this study.

Chapter 4. Land-use Effects on Temperature and Hydrology in Southeast Virginia Wet Flats

Introduction

Wet flats in the Great Dismal Swamp ecosystem of Southeast Virginia have undergone drastic changes in land use over the last two hundred years that have resulted in the present mosaic of altered and degraded natural plant community types and hydrologic conditions. Land use determines the dominant type of vegetation and physical properties such as soil temperature and moisture content. Air and soil temperatures can be affected by the mulching effects of surface litter, protection from wind, soil moisture content, and albedo from bare ground. The hydroperiod and perching of water in the near-surface can be affected through differences in evapotranspiration (ET), infiltration, and percolation rates. Thus there is a probable interaction between soil moisture content and temperature that must be determined to facilitate management decisions. This study will compare the effect of three major land uses on air and soil temperature and hydrology in order to understand the relationships between land use and site properties in mitigated wet flats ecosystems common in Southeast Virginia.

Smith et al. (1964) stated that soil temperature is one of the most important properties of soil, because within limits it controls the possibilities of plant growth, soil formation, soil microbial activity, and soil chemical and physical processes. The effect of temperature on pedogenesis (soil formation) is mainly an indirect relationship as the rate and magnitude of all physical and chemical process increase with increasing temperature (Yaalon, 1983). Temperature partially controls the rates of evaporation and thus the effectiveness of precipitation and the moisture status of the soil. Soil temperature affects plant growth, seed germination, root development, respiration, and absorption of water and nutrients. Frost heaving and mineral weathering are physical processes affected by temperature, while redox processes, hydrolysis, nutrient release, phytotoxin production, and organic matter decomposition are chemical processes affected by soil temperature (Ponnamperuma, 1976). Since soil temperature is such a dominant feature of the physical system, changes or variance in soil temperature could be an indicator of ecosystem change (Aust and Lea, 1991).

Heat exchange by radiation, convection, and conduction occurs from the surface downward or in the opposite direction, depending on temperature gradients. Changes in soil temperature over time and with depth are determined by the temperature conductivity and thermal gradient of the soil. Conduction is the most important of these processes, and it is strongly influenced by bulk density and water content (Hillel, 1982). Soils with different particle size distributions have different thermal properties. Soils with sand textures have a higher variation in soil temperatures than those soils with finer particle size classes (Hillel, 1982; Mount and Paetzold, 2002). Thermal conductivity is positively influenced by increased bulk density at a given water content and by increased moisture content at a given bulk density. Abu-Hamdeh and Reeder (2000) investigated the effects of soil texture, bulk density, and soil water content in a laboratory study. The researchers found that increased water content caused higher temperature variability than increased bulk density (Abu-Hamdeh and Reeder, 2000). The specific heat of air is negligible compared to water because water has a thermal conductivity 23 times greater than that of air. Therefore, soils with the same physical properties but different moisture contents would possess different thermal properties. However, most soil temperature studies have focused on well-drained or dry soils (Hillel, 1982; Taylor and Jackson, 1986; Mount et al., 1992).

Chang (1958) reported that the presence of water in soil can reduce seasonal fluctuations of soil temperature. In wetland settings, the heat capacity of waterlogged soils is increased over that of the surrounding unsaturated soils, causing wetland soil temperatures to be cooler in the spring and warmer in the fall (Buol and Rebertus, 1988; Thompson and Bell, 1998). Bonneau (1982) found that soil temperature was less variable in flooded soils than in well-drained soils because of the buffering effect of moisture. The average temperature difference in the surface layer was 6 °C between well and poorly drained soils. Wang (2002) investigated soil temperatures response to irrigation with cold water in dry sand textures in a laboratory study and reported that temperature at the surface and 25 cm decreased from ambient air temperature to that of the water immediately after irrigation commenced. In a component field investigation, soil temperature at the 5 and 10-cm depths decreased to that of the water, but there was no thermal response to irrigation water at greater depths. Mount and Paetzold (2002) measured soil temperature in poorly drained and well drained Coastal Plain soils from 1998 to 1999, and reported that poorly drained soils had marginally significant warmer mean annual soil temperatures in North Carolina sites but had colder mean annual soil temperatures in Virginia sites. However, the discrepancies in the results were not explained and further study is needed to resolve these differences.

Pickering and Veneman (1984) found that variation in soil temperature at 50 cm was less in a poorly drained soil than a well drained soil on a drumlin toposequence in Massachusetts. The authors noted the range in soil temperature extremes diminished as the moisture regime became wetter. Jenkinson and Franzmeier (1996) reported similar results at 25-cm depth along a toposequence of glaciated soils in Indiana. Seybold et al. (2002) reported that most soil temperatures in a Virginia freshwater tidal flat exhibited less temperature flux at a depth of 50 cm when compared to the 20 cm depth. They also found that soil temperatures closest to the tidal creek were moderated from temperature changes due to the input of moving water from the creek. The relationship between hydrology and soil temperature at different depths has not been published for wetland soils in Southeast Virginia.

Temperature differences at the soil surface caused by surface characteristics can mediate local air temperatures (Hillel, 1982; Scott, 2000). The magnitude of heat exchange between air and soil is dependent upon the presence, height, and character of plant cover (Mount and Paetzold, 2002). Plant cover generally slows down the intake of heat by the soil, and affects the amplitude of temperature flux. Bare soils were reported to be warmer at mid-day than soils under natural cover (Shul'gin, 1965). Based on a broad analysis of global temperature regimes, Smith et al. (1964) observed that trees seem to have little effect on soil temperature or direct insulating ability of soil and that the difference in soil temperature between grass, crops, and trees shading or insulating the soil are minor if O horizons are transient or absent. The researchers reported that soils under hardwood stands were more susceptible to extreme daily and seasonal temperature fluctuations than soils under conifer stands. Recently studies have indicated that vegetative cover can have a significant influence on season fluctuations of soil temperature. A study in Nigeria indicated that land use in well drained Kandiudalfs had a profound effect on soil temperature (Ogunkungle and Eghaghara, 1992). The study compared soil temperature measured along a land-use continuum from dense forest to different types of cropland and found much warmer temperatures in the croplands than in the forest.

Wagai et al. (1998) found that soil temperatures at 10-cm depth were significantly warmer in tilled areas as compared to no-till regions. Rosset et al. (2001) found that in abandoned and mowed subalpine fields litter layer had a profound effect on soil temperature. Initially, the litter layer in the abandoned field exhibited minor influences on radiation, but influences became more dominant with increased litter accumulation. The decreased heat flux and net radiation reduced ET losses and resulted in higher soil water content. Over time there was a marked negative effect on heat flux in the abandoned field. Soil temperature changes were delayed up to 1 mo in the abandoned field as compared to the mowed treatment. Soil temperature flux declined with advancing succession and generally increased as a consequence of clearing (Rosset et al., 2001; Van Cleve et al., 1993). Litter layer type may also have a significant impact on soil temperature (Scott, 2000). Litter layers of woody evergreen species have a negative effect of soil temperature, retarding soil temperature dynamics at the surface (Eckstein, 2000).

There are few published studies that have addressed the effect of land use on soil temperature in wetland areas. Stolt et al. (2000) measured soil temperatures in freshwater mitigation and reference wetlands in Virginia. Soil temperatures at 10 cm in the mitigated wetland tended to be consistently 3 to 6 °C higher, than in the reference (undisturbed wetland), while temperatures at 95 cm were similar in both wetlands. Soil temperatures were also elevated in the mitigated wetland in late summer and early fall. Aust and Lea (1991) investigated soil temperature in a forested wetland subject to different forestry practices and found a gradient of soil temperature differences based on vegetative disturbances. The reference wetland had cooler temperatures relative to revegetated and devegetated areas. Soil temperatures were also influenced by water content in a season. The warmest soil temperatures were associated with the lowest water table height, while the coldest soil temperatures were associated with the highest water table.

The interaction between land use, hydrology, air and soil temperature in wetlands is under reported in current literature, especially for wet flats. Wet flats in the Great Dismal Swamp ecosystem of Southeast Virginia have undergone drastic changes in land use over the last two hundred years that have resulted in the present mosaic of altered and degraded natural plant community types and hydrologic conditions. Plant community type and land use affects hydrology and air temperature and thus soil properties and temperature in wet flat ecosystems. The objectives of this paper were to determine and contrast the relationships between the hydrology, air temperature at 1-m height, and soil temperature at 15-, 30-, and 50-cm depths on different common plant communities and land-use types on two wet flat study areas in the Great Dismal Swamp ecosystem of Southeast Virginia.

Materials and Methods

Complete description of the study areas, along with the materials and methods used to measure, describe, and analyze the treatments, precipitation, hydrology, and air temperature found in Chapter 3 apply equally to this chapter. The number of depth-days was calculated for each subsample by resetting water levels above the surface to a depth value of 0, accepting all depth values between) and 30, and resetting all other larger values to 30. These depths (cm) were summed over the period from June 1 2001 to May 31 2002 as a cumulative aerated depth counter to determine the relative wetness regimes of the two study areas. Soil temperature was collected in the same manner as described in Chapter 3, except that thermistors were installed at three depths 15-cm (ST 15), 30-cm (ST 30), and 50-cm (ST 50) in this study rather than only at 50 cm (Figure 4-1). At the 15 cm depth, a core was extracted with a shovel and a knife was used to burrow sideways into the undisturbed soil at 15 cm. The thermistor was inserted into the burrow and the soil replaced behind it. The soil core was then re-inserted and the edges knit with the undisturbed soil to insure that no air reached the thermistor through open cracks. Data was analyzed over a period of 16 mos since soil and air temperatures in January 2001 or June 2002 were not collected for the entire month. Annual air and soil temperature averages were reported from February 2001 to January 2002.

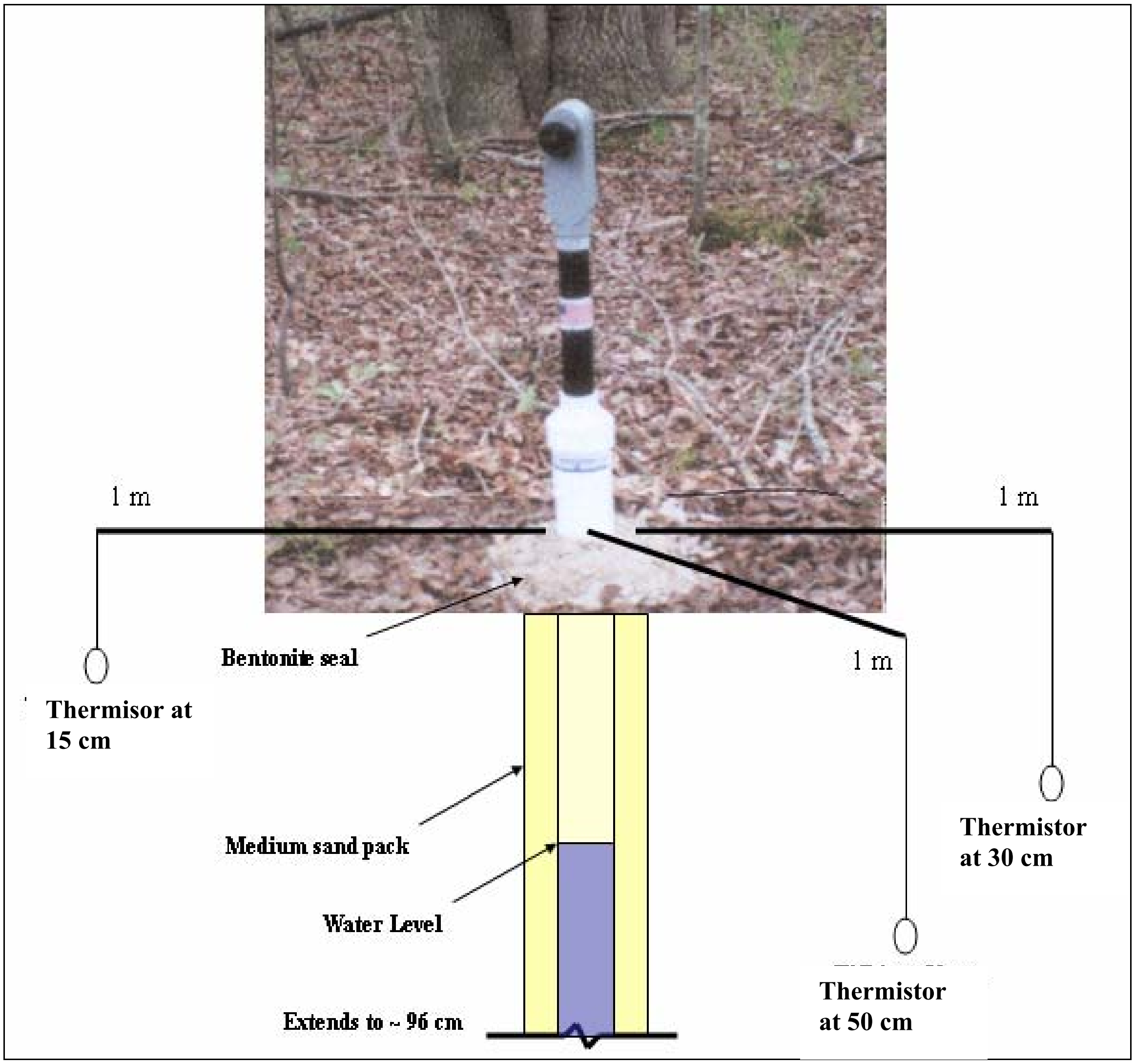


Figure 4-1. Typical distribution of soil temperature measurements around the well.

Statistical Analysis

The study was analyzed using an incomplete block design due to equipment loss and failure. The experimental design was identical to that found in Chapter 3. Treatment differences within and between study areas were determined by comparing the cumulative aerated depth counters using the Mann-Whitney nonparametric t-test in Minitab™ (Version 13.x) at the 90% confidence level (Minitab, Inc., State College, PA). Statistical analyses were performed on air temperature and soil temperature data using an analysis of variance (ANOVA) approach for differences at 15, 30, and 50-cm depths between treatments in each month using the PROC GLM in SAS™ software (Snedecor and Cochran, 1989; Statistical Analysis Systems, Cary, NC). Treatments were then contrasted by each study area using Fisher's Protected Least Significant Difference (LSD) test (Lentner and Bishop, 1993). Average monthly soil temperature at 15, 30, and 50-cm depths were then compared to one another for each study area. Treatments were pooled and differences by depth were analyzed using the LSD test. Soil temperature at 15 and 30 cm and air temperatures were collected hourly throughout the study, while soil temperature at 50 cm was collected every 6 hrs. Monthly soil temperature averages were compiled from the same monitoring times (4/d) at all three depths in order to standardize the data. Linear regression, by the "GLM procedure" in SAS™, was used to relate the depth to specific redoximorphic features and the number of days of saturation at or above that depth, expressed as a percentage of total days during the study. Data from wells with incomplete records were excluded. All statistical analyses for temperature data were investigated at the 95% confidence level.

Results and Discussion

Soils

Soils of the study area were described, sampled, and mapped as reported in Chapter 3. The bulk densities in the field soil surface horizon were high due to their high sand and silt, low OC content, and years of compaction during farming (Appendix 3a, 3b, and 3c). This was especially evident when compared to the low bulk density in the forest surface samples. Compaction reduced infiltration and percolation and resulted in surface ponding in the fields. The apparent water table at Hall plot 2 (field treatment) in January 2003 was 30 cm below the surface, even though there was water 10 cm deep standing on the surface. Ponding occurred because of severe surface compaction and low evapotranspiration losses. The surface tillage in this study resulted in further surface compaction and reduced connective and natural aggregate porosity. For example, in August 2002 bulk density taken at Hall in the field, closest to plot 3 (tilled treatment), was 1.22 Mg m^{-3}. The field has not been plowed since 1999. The area 1 m closer to the well that was last tilled 3 mos prior was 1.53 Mg m^{-3}. The only forest well that exhibited ponded conditions was located adjacent to a weakly-expressed drainageway (Hall 11). There was an abrupt increase in clay content (usually $\geq$ 25% absolute difference) and an increase in bulk density at the top of the subsoil of most soils that undoubtedly decreased the hydraulic conductivity and resulted in periodic perching of water within the soil. The clay increase was not as substantial (< 10% absolute increase) in the field soils at Hall, which substantiates the soil survey by Lane (unpublished data, 2000).

High chroma colors in the Bt and 2BC horizons at Hall plot 3 (tilled treatment) and in the 2BC horizon at Hall plot 11 (forest treatment) indicate the separation between the upper perched water tables and lower water table. These oxidized horizons contained enough clay and probably enough biologically-available OC and Fe^{3+} that reduction should have occurred if water was within the horizon for long enough periods during the microbial growing season. The apparent water table was observed at about 195-200 cm at Hall in August 2002, slightly deeper than the horizons in question and allowing aeration. A study in the Coastal Plain of North Carolina found that high chroma colors were associated with Fe^{2+} rich water movement through soils and aeration of that water due to ditching effects (Hayes and Vepraskas, 2000). However, this explanation does not account for the high-chroma matrix at Hall because of the distance from drainage ditches in a broad, low elevation physical setting and the slow rate at which water might move laterally or vertically through the fine textured soils. The Bruff plot 2 (forest treatment) had a bright 2E horizon above the 2Bs horizon that might also have formed under separation of two water tables. An apparent water table was observed at about 163 cm at Bruff during the August 2002 sampling. The 2E ended at 152 cm and was above the apparent water table. The 2E did not have apparent redoximorphic features and was dry during sampling, but the process of auger extraction may have destroyed evidence of Fe^{3+} concentrations.

The particle-size distribution changed with depth and may have influenced hydraulic conductivity. There was a large amount of silt and clay in the upper subsoil horizons that resulted in a higher water potential and capillary suction than in the sandy horizons below. This water potential difference may have caused these horizons to retain percolating rainfall until they reached saturation, and may be the reason that they were reduced while some horizons below were not.

Precipitation

Precipitation data were plotted by month and discussed in Figures 3-7 and 3-8 in Chapter 3. The daily, monthly, and annual precipitation is reported in Appendix 4. In general, the precipitation in the region was below normal most months in 2001 and 2002. The dry period ended in March, 2002 and precipitation was normal for most of the remainder of the study.

Hydrology

Average daily water levels measured during this study are reported in Appendix 5a and 5b. The relative elevation of each well to AMSL is reported in Appendix 6. Hydrographs for representative wells were plotted in Figures 3-9 and 3-10 and discussed in Chapter 3. In general, water levels measured during this study (hydroperiod) supported the hydric soil determinations and the presence of the field indicators (Table 3-2). The full set of hydrographs is presented in Figures 4-2 to 4-7.

The study areas had an intermittently saturated hydroperiod, typical of wet flats (Rheinhardt et al., 1999). The relationship of cumulative aerated depth counts within and between the study areas and plots were compared (Table 4-1). The Bruff study area was drier (had greater cumulative aerated depth) than the Hall study area (P=0.01), mainly because the forest treatment at Bruff was drier than the forest at Hall (P=0.10). The Bruff forest received 20 cm less precipitation in 2001 and was predominantly loblolly pine and had greater cumulative winter transpiration (Pangle and Seiler, 2002) than the mixed hardwood deciduous forest at Hall. Differences between the study areas were not apparent in the other two treatments. In each case the Hall study area was relatively wetter (P>0.10) than the same treatment at Bruff mainly due to differences in precipitation. At Bruff study area, the forest was the driest treatment and the bare ground and field treatments were not different (P=0.10). There were no differences in hydrology based on treatment effects at Hall property (P=0.10).

Table 4-1. Cumulative aerated depth count of hydrology summed over the 12 mo period from June 1 2001 to May 31 2002.

Study area	Treatment	Cumulative aerated depth count	Number of samples	Std. Dev.
		----------- cm ---------		---------- cm --------
Bruff	Forest	10718a*†	4	192
	Field	9834b	4	1049
	Bare ground	9705b	4	447
Hall	Forest	9454a†	4	647
	Field	8368a	4	674
	Bare ground	8921a	3	1203
Bruff	All	121064a**†	12	764
Hall		98053b	11	887
Bruff	Forest	10718a*†	4	192
Hall		9454b	4	647
Bruff	Field	9834a†	4	1049
Hall		8368a	4	674
Bruff	Bare ground	9705a†	4	447
Hall		8921a	3	1203

† Within hatched blocks, means in the cumulative aerated depth count column followed by the same letter are not significantly different using a series of Mann-Whitney t-tests at the P=0.1 level. Significance at P=0.1, and 0.01 indicated by * and **.

As the hydrographs indicate, water saturated the entire soil during winter months at all plots. The underlying groundwater appeared to recharge the wetland from below for about three months where lower ET occurred. There may also have been water perching above the top of the more clayey upper subsoil horizons in the winter whenever precipitation exceeded ET rates. The water levels decreased to a depth below the detection limit of the wells soon after plant leaves opened. Spikes in water levels occur throughout the year due to large precipitation events because there was a subsequent lag period when water permeated slowly through the upper subsoil horizons. Without piezometer data, it was not possible to determine if these spikes represented a rise in the deeper groundwater or a temporarily perched water table.

Three forest treatment wells malfunctioned during the first six months of the study at Bruff property and were replaced in June 2001. They were functional for 380 d compared to 510 d for the other wells. Water levels were within the upper 30 cm in the winter of 2001 until February and approached the surface again in the middle of March 2001 before gradually decreasing (Figure 4-2). The water levels did not rise again until the winter of 2002 and did not saturate or inundate the surface region for appreciable periods because of the very low precipitation in the fall months of 2001. Bruff wells 1 and 2 were relatively wetter than wells 10 and 11. The field treatment plots were saturated near the surface longer than the forested plots (Figure 4-3) because they had lower transpiration losses and may have had water perching near the surface above the compacted bottom of the agricultural plow layer. Water levels were nearer to the surface in field plot 3 for longer than the other field plots because well 3 was in a relatively low topographic area in the corner of the field where water accumulated and occasionally inundated the surface (Figure 3-3). The bare ground plots were wetter than the forest plots and slightly wetter than the field plots because of water percolation differences due to tilling, and slightly lower evapotranspiration losses (Figure 4-4). Water inundated the surface in the bare ground plots but in no other plots in the field except plot 3. Water was ponded due to the tillage treatment, which reduced the porosity of the surface horizon, formed a compacted layer at 10 cm, and had no vegetation or transpiration losses. However, there was little evidence of long periods of inundation after the winter of 2001 due to the drought conditions.

The Hall wells and treatment plots had similar water level relationships to those at Bruff. The forest plots at Hall were characterized by a longer period of surface saturation (or inundation at plot 11) during the winter months for both years (Figure 4-5). Plot 11 was wetter than the other three forest plots because it was located adjacent to a poorly defined drainageway. The field plots were slightly, but not significantly wetter than the forest plots, with saturation near the surface for a longer period of time for both years (Figure 4-6). Field well 8 had the longest period of saturation within 30 cm and may have been inundated at times because it was in a concave topographic position compared to the rest of the wells in the field. Water was ponded on some field plots at Hall for much longer durations than well 3 at Bruff (Figure 4-7). Water was ponded on the surface of the bare ground plots for short periods of time after large precipitation events until that water was able to evaporate or penetrate the surface, whereas water infiltration was not slowed in the other treatments until the bottom of the deeper plow layer or where a change in texture occurred. More ponding occurred in 2002 than 2001 because of the increased precipitation. Plot 6 was slightly wetter than the other plots in the bare ground treatment, but malfunctioned in February of 2002. Well 6 was functional for 366 d compared to 530 d for the other wells at Hall.

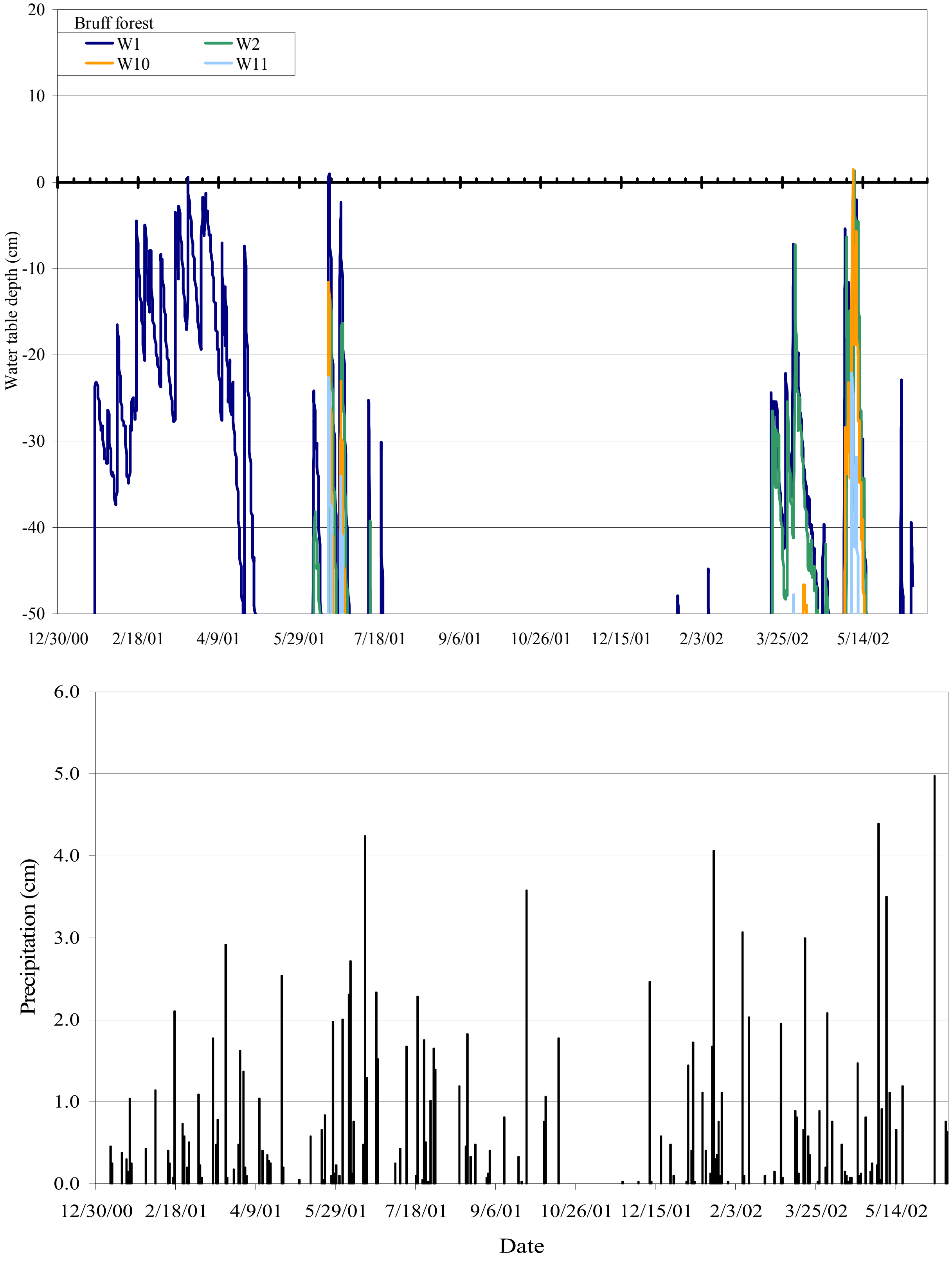
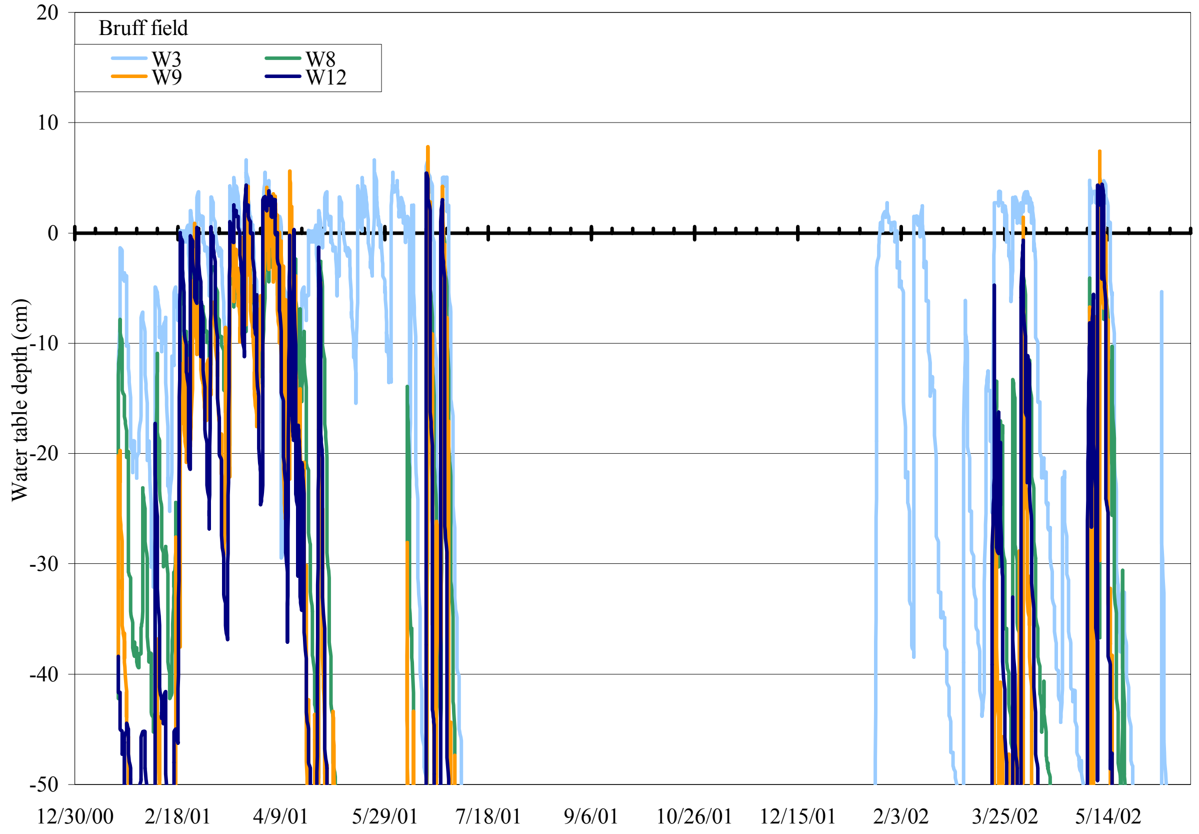


Figure 4-2. Hydrograph of the forest treatment at Bruff study area.



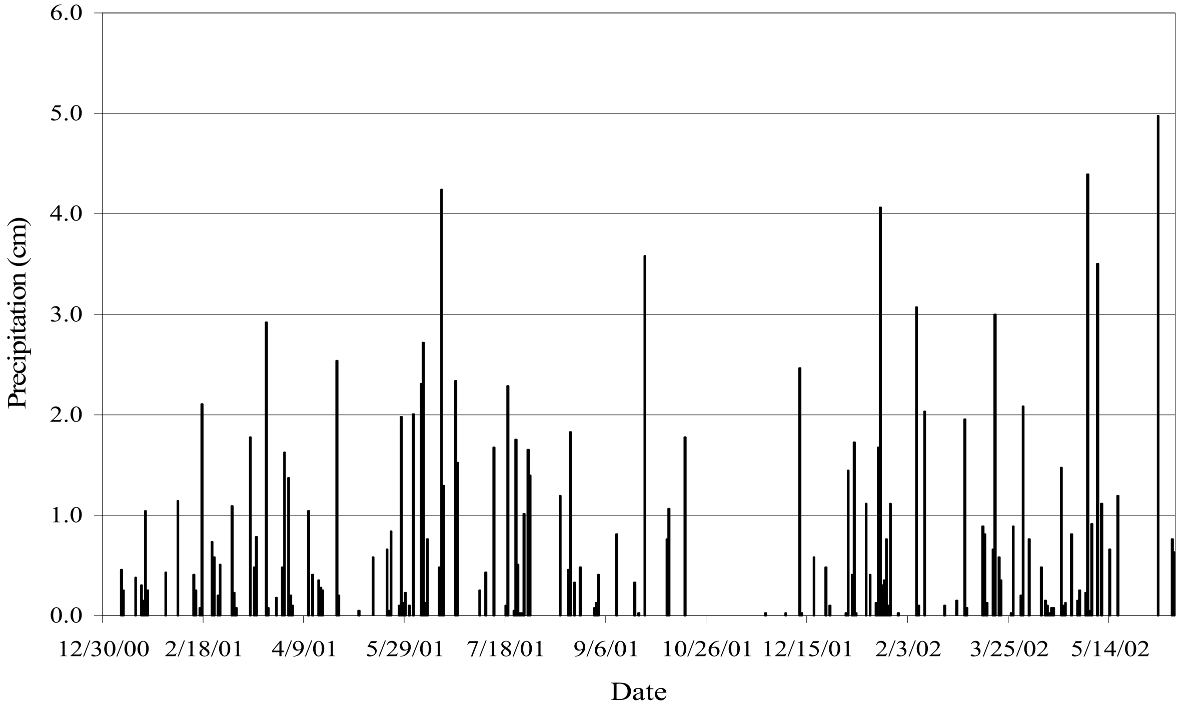


Figure 4-3. Hydrograph of field treatment at Bruff study area.

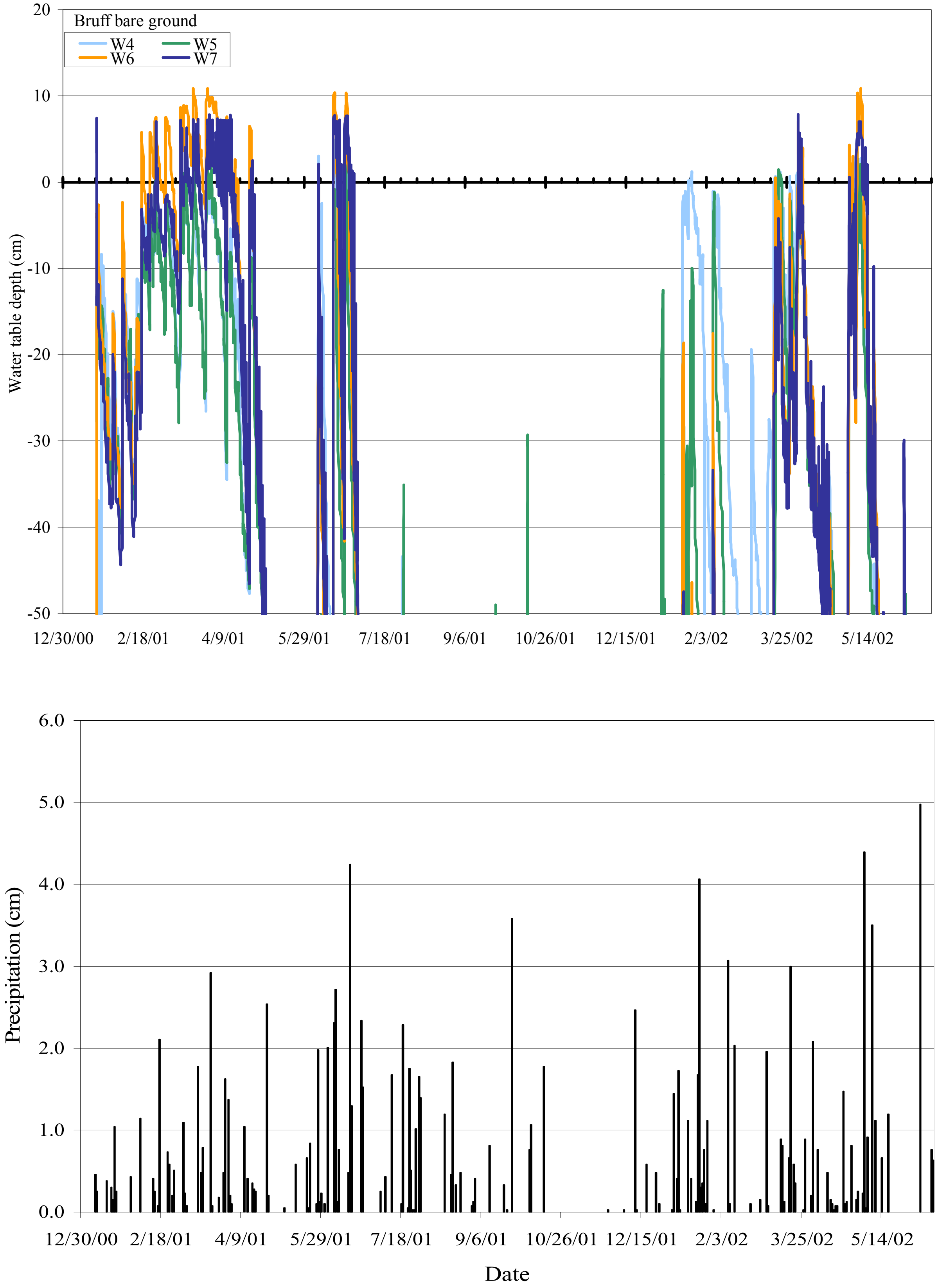
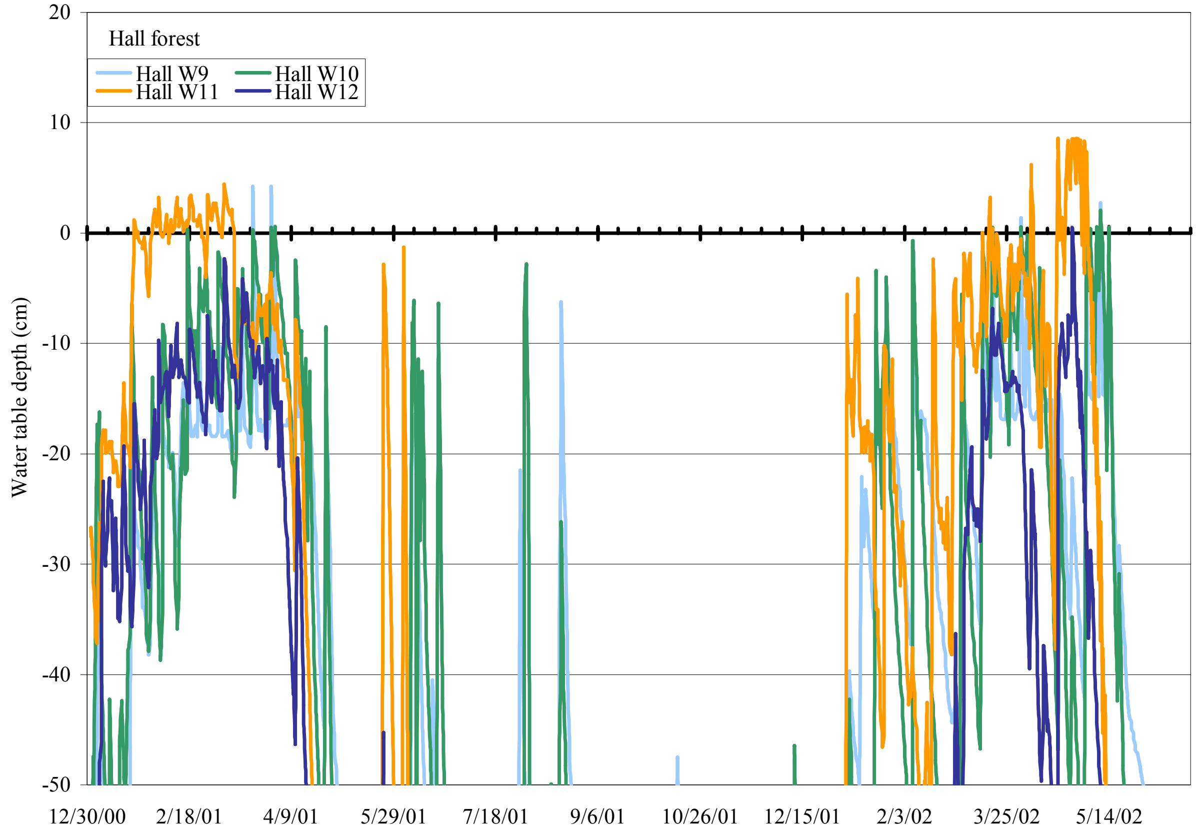


Figure 4-4. Hydrograph of bare ground treatment at Bruff study area.



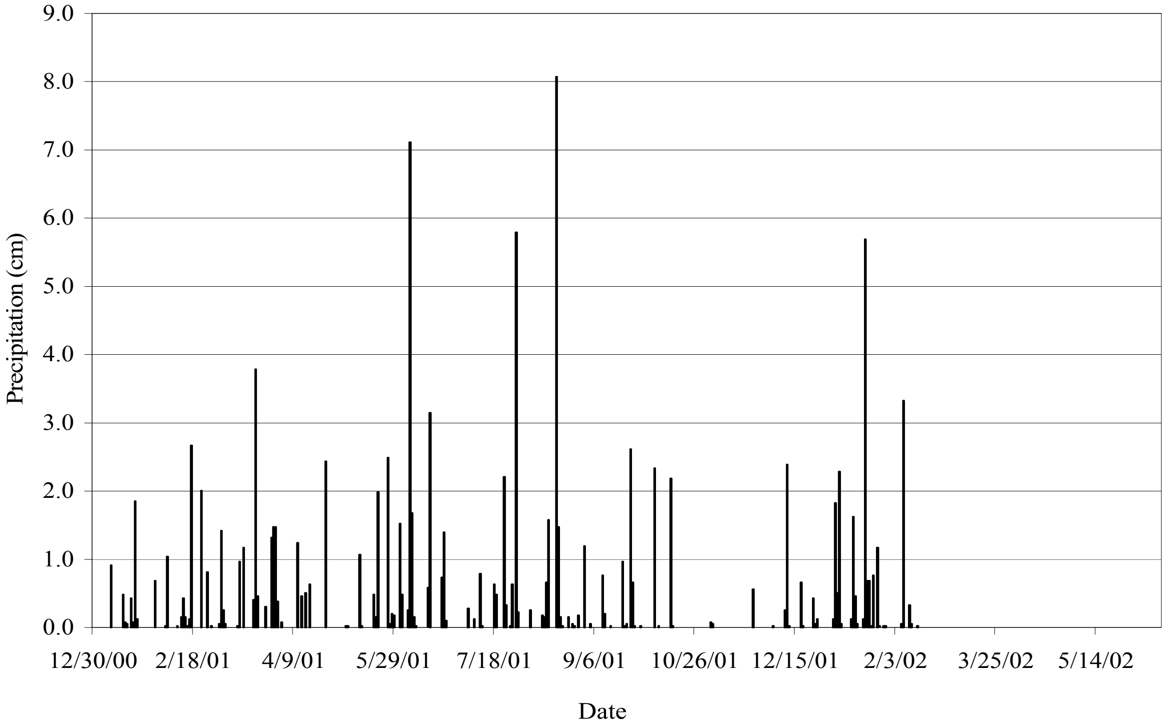


Figure 4-5. Hydrograph of forest treatment at Hall study area.

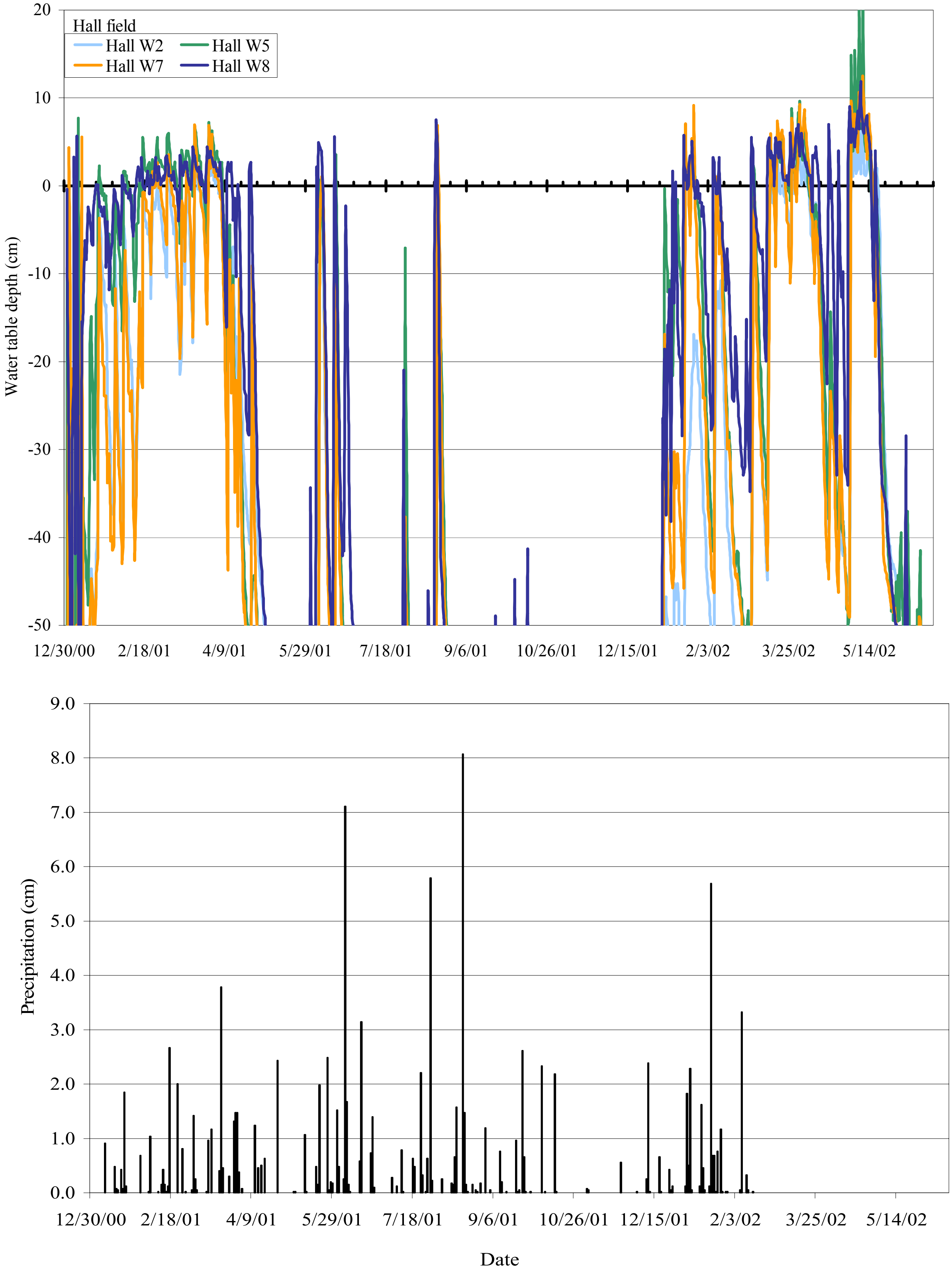


Figure 4-6. Hydrograph of field treatment at Hall study area.

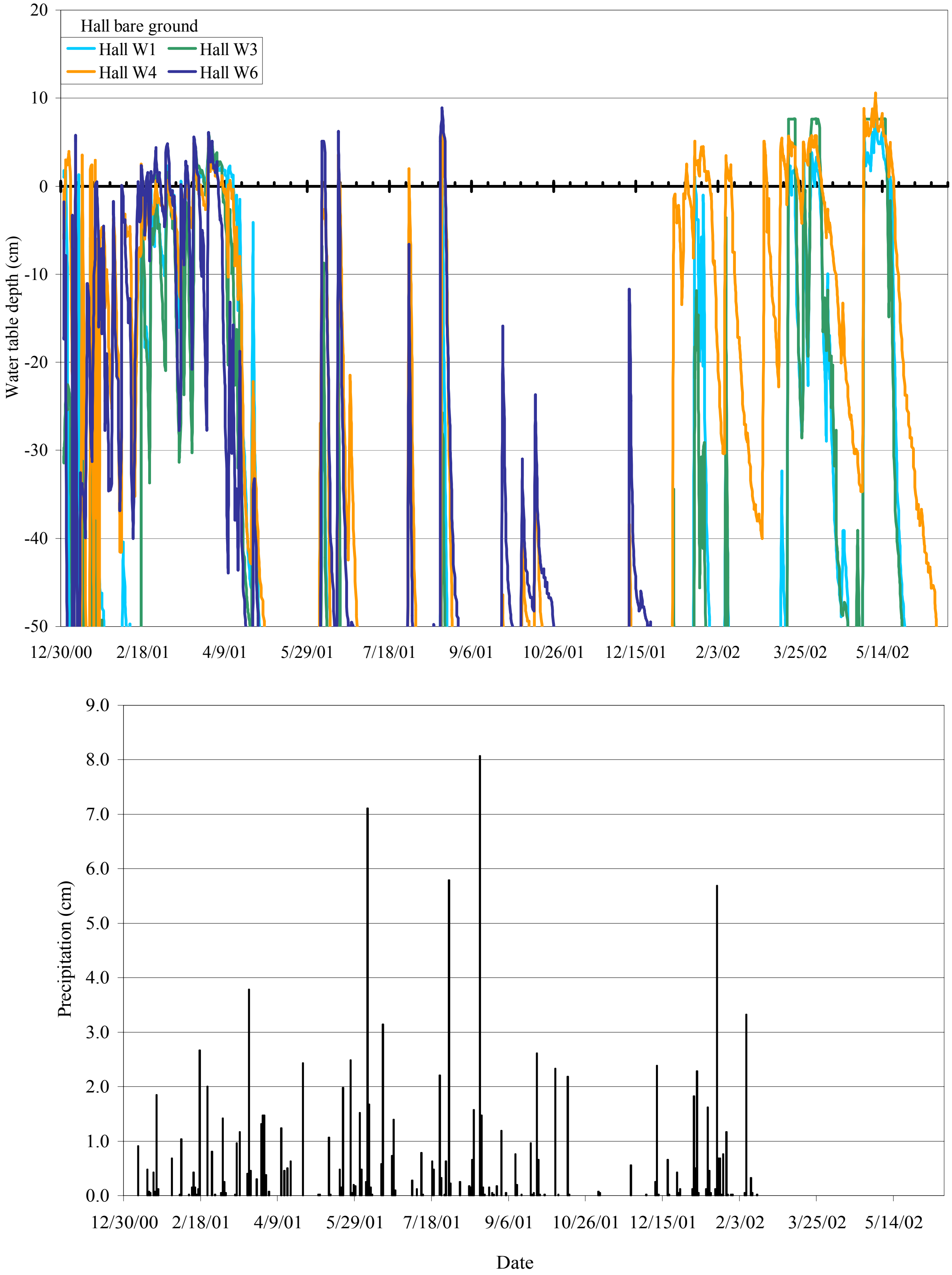


Figure 4-7. Hydrograph of bare ground treatment at Hall study area.

Redoximorphic Features

The correlation between water table depths and redox features is shown in Table 4-2. In general, the depleted matrices were deeper than the depth to redox depletions at Bruff but the opposite was true at Hall. At Bruff, many of the depleted matrices in the field and bare ground plots were the Eg or Btg horizons because most surface horizons had a matrix color of 10YR 3/2 and less than half contained common distinct or prominent redox concentrations. At Hall, many of the depleted matrices in the field and bare ground plots were the uppermost horizon because they had a matrix color of 10YR 4/2 and contained common distinct or prominent redox concentrations.

Results of the regression analysis vary by feature. The regression equation for days of saturation versus shallowest depleted matrix depth is DM *depth = 15.6 + 0.108* * days of saturation at depleted matrix depth ($R^2 = 0.09$), which indicates an almost nonexistent relationship. The regression equation for days of saturation versus shallowest depletion depth is *D depth* = 31.3 - 0.663 * days of saturation at depletion depth ($R^2 = 0.57$), which indicates that the depth to the shallowest redox depletion explains half of the variation in the number of days of saturation at that depth. The regression equation for days of saturation versus shallowest concentration depth is *C depth = 24.7 - 0.180* * days of saturation at concentration depth ($R^2 = 0.04$), which means that the depth to the shallowest redox concentration explains very little of the variation in the number of days of saturation at that depth. Generally, redox correlations were not strong in this study due to the drought year and the newly reinstated hydrology of the mitigation sites. In order to determine an accurate relationship between redox features and water table depth or days of saturation longer term records are needed that include normal and above normal precipitation years.

Table 4-2. Relationship between the depth above 30 cm to diagnostic redoximorphic features and the number of days when the water table was at or above the depth of the observed feature.

	Depleted Matrix †			Depletions ‡			Concentration §		
	Depth above 30 cm	Saturation ¶	Total Study	Depth above 30 cm	Saturation ¶	Total Study	Depth above 30 cm	Saturation ¶	Total Study
	cm	days	%	cm	days	%	cm	days	%
Bruff									
1	12	60	12	22	26	5	22	26	5
2	20	11	3	6	15	4	20	4	1
3	29	227	45	29	122	24	29	122	24
4	20	138	27	30	23	5	20	95	19
5	5	120	24	5	120	24	19	63	12
6	10	112	22	30	67	13	10	112	22
7	6	117	23	21	84	16	30	34	7
8	11	95	19	28	9	2	11	95	19
9	12	93	18	28	38	7	12	93	18
10	15	3	1	25	2	1	20	3	1
11	6	1	0	22	0	0	12	0	0
12	1	88	17	29	32	6	22	48	9
Hall									
1	18	99	19	18	99	19	18	99	19
2	30	40	8	4	177	33	30	40	8
3	24	68	13	0	125	24	24	68	13
4	30	102	19	10	175	33	30	102	19
5	28	129	24	28	129	24	28	129	24
6	30	42	11	4	107	29	30	42	11
7	30	71	13	30	71	13	30	71	13
8	30	180	34	-2	269	51	30	180	34
9	9	156	29	9	156	29	9	156	29
10	15	115	22	15	115	22	23	60	11
11	22	112	21	17	155	29	17	155	29
12	18	49	9	18	49	9	18	49	9

† Defined as horizons with specific low chroma high value matrix colors and possibly redoximorphic concentrations (USDA-NRCS, 2002).

‡ Defined as masses or pore linings with specific low chroma high value colors (USDA-NRCS, 2002).

§ Defined as masses or pore linings with specific high chroma colors (USDA-NRCS, 2002).

¶ Total number of days when water was at or above the feature depth.

Air temperature

The 30-yr average monthly and annual air temperature data and the average monthly and annual air temperatures measured at the Lake Kirby weather station are reported in Table 3-3. The average monthly and annual air temperatures measured at the study areas are reported in Tables 3-4 and 3-5. Maximum, minimum, and average daily air temperatures measured at are reported in Appendix 7a and 7b. In general, air temperatures were within the normal range in most months and for the entire 2001 year.

Average monthly and annual air temperatures were compared by treatment at each study area in Table 4-3. The annual average air temperatures were ranked in the following order: Bare ground > Field > Forest at Bruff and Bare ground = Field > Forest at Hall. There was no temperature separation between bare ground and field plots at Hall because the bare ground and field plots at Hall were inundated more often than at Bruff. In fact, the bare ground plots were sometimes inundated when the adjacent field plots were not due to compaction at 10 cm by the tillage operation and because they were subjected to less transpiration losses. High moisture contents prevented the soils in the bare ground treatment from warming differently than adjacent field plots. Explanations in the differences between treatments are included under the air temperature section in Chapter 3.

The forest plot air temperature was cooler than the other treatments in all months except March 2002 (Table 4-3). The field plot air temperature was warmer than the forest air temperature eight times during the study, mostly before the winter of 2001-2002. There were four months in early 2001 when the bare ground plot air temperature was warmer than the field plot air temperature, but the field plot air temperature was never warmer than the bare ground plot.

Table 4-3. Average monthly air temperature by treatment type at each study area. Monthly means made of four subsamples except Hall field treatment that had three subsamples. Annual means made of 48 subsamples except Hall field treatment that had 36 subsamples.

	2001											2002				
Month	Feb†	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	°C															
Bruff																
Forest	6.97b	8.54b	15.25c	19.02c	23.52b	23.16c	24.68b	19.30c	13.27b	11.54b	8.01b	5.51b	6.45b	11.05a	16.46b	18.65b
Field	7.66a	9.02a	15.73b	19.91b	24.59a	24.27b	25.46ab	20.24b	14.26a	12.53ab	8.79a	6.27ab	7.29a	11.54a	17.10ab	19.42ab
Bare ground	7.99a	9.11a	16.27a	20.81a	25.28a	25.29a	26.30a	21.02a	14.73ab	12.77a	8.93a	6.45a	7.43a	11.46a	17.24a	20.07a
Hall																
Forest	6.82b†	8.48b	14.81c	18.33b	22.63c	22.82b	24.26b	19.16b	13.89ab	11.88a	8.11a	5.77a	6.56b	11.27a	16.46b	18.22b
Field	7.51a	9.31a	16.29a	20.89a	25.65a	25.38a	26.04a	20.73a	13.66b	12.10a	8.29a	5.57a	7.54a	11.70a	17.34a	19.63a
Bare ground	7.31a	9.23a	15.82b	20.23a	24.77b	24.74a	25.96a	21.07a	14.88a	11.99a	8.73a	6.17a	7.32ab	11.51a	17.00ab	19.62a

Bruff	Annual†
	-- °C --
Forest	14.90c
Field	15.73b
Bare ground	16.25a
Hall	
Forest	14.75b
Field	15.95a
Bare ground	15.91a

† Within hatched blocks, means in each column followed by the same letter are not significantly different using LSD of air temperature reported at P = 0.05.

At Hall the forest air temperature was cooler than the other treatments in all months except, (November and December 2001, January and March 2002). The forest air temperature was not coolest during the winter months, by November the trees had begun to senesce, thereby lessening the canopy effect in the forest (Table 4-3). There was only one month when the bare ground air temperature was warmer than the field plot air temperature (October 2001) but there were two months (April and June 2001) when the field plot air temperature was warmer than the bare ground plot air temperature. The tillage-induced ponding was probably responsible for the similarity in air temperature. The field plot air temperature was warmer than the forest air temperature 11 times during the study, mostly before the winter of 2001-2002.

Air temperature was correlated to soil temperature at 15 cm by land-use treatment (Figure 4-8). There were no differences between the study areas, so the study areas were pooled. Air temperature was very well correlated to soil temperature in the bare ground and field treatments ($R^2 = 0.99$; $R^2 = 0.99$). The bare ground treatment was slightly warmer than the field treatment throughout the year (bare ground: $y = 1.0099x + 0.5621$, field: $y = 0.9182x + 1.0846$). Air temperature was also very well correlated to soil temperature in the forested treatment ($R^2 = 0.95$) but the slope of the line was less steep (forest: $y = 0.7519x + 3.9668$) than the other treatments indicating that the forest treatment had more buffering and less seasonal variation in temperature than the other treatments.

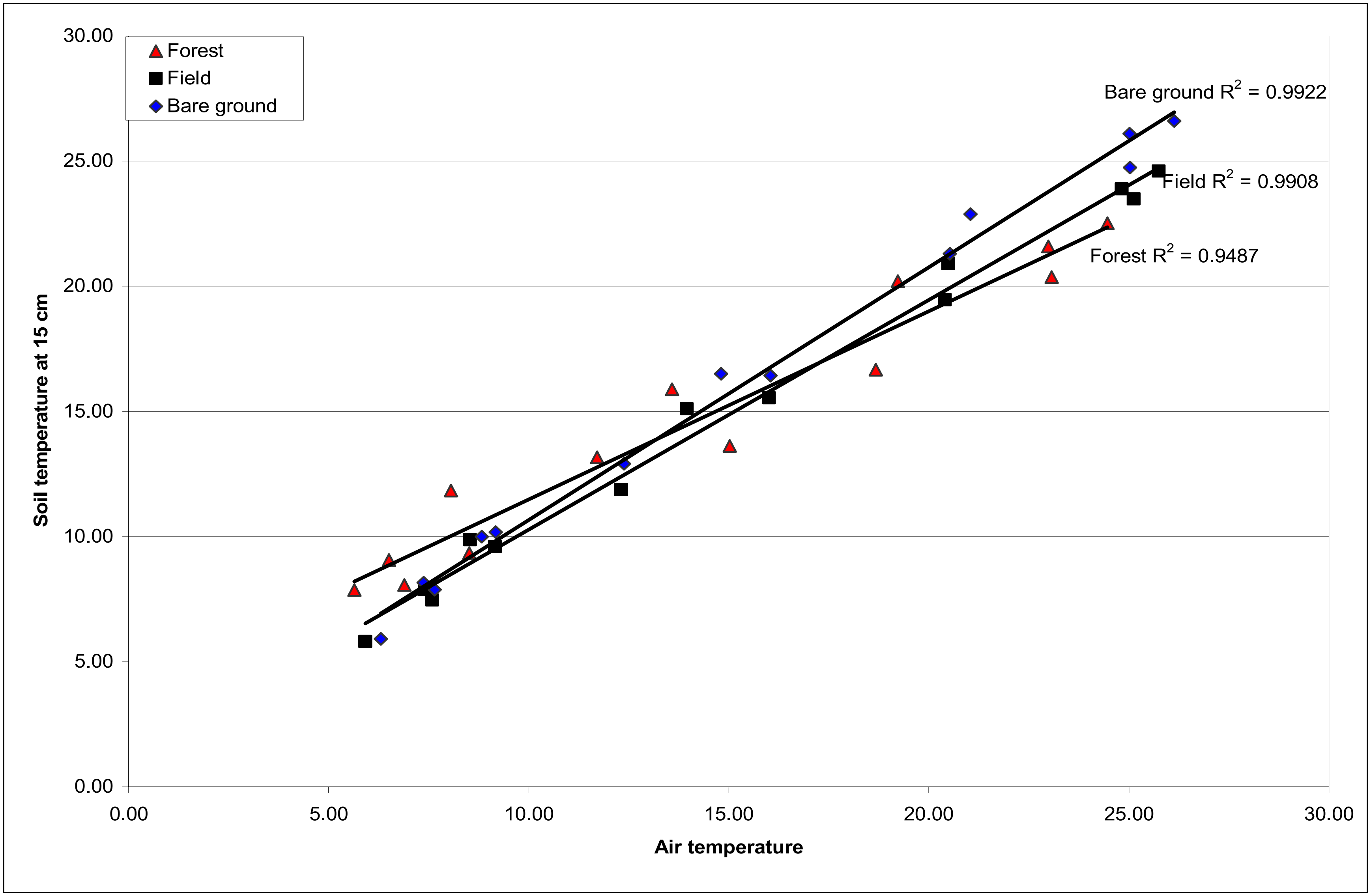


Figure 4-8. Regression analysis of air temperature to soil temperature for each land-use type.

Soil temperature

The average monthly and annual soil temperatures measured at 15, 30, and 50 cm are reported in Table 4-4 to 4-6. The daily soil temperatures are reported in Appendix 8a through 8f. The ST 50 at the representative plots for each treatment at each study area were plotted and discussed in Chapter 3 to illustrate the daily variation in soil temperature at 50 cm (Figure 3-12 and 3-13). In general, ST 50 at the representative plots fell within the bounds described for the thermic soil temperature regime and ranged from a high of about 27 to a low of about 4 °C. ST 50 values were most variable in the representative bare ground plots and least variable in the forest plots. The ST 50 data are presented and discussed below.

Average monthly and annual ST 15 values were compared by treatment at each study area in Table 4-4. The annual average ST 15 temperatures were ranked in the following order: Bare ground > Field > Forest at both study areas. There was greater difference in ST 15 between bare ground and field treatments at Bruff than at Hall because the plots at Bruff were generally drier during the study and their soil surface was less buffered against temperature change. The forest plots were well insulated by the surface litter layers from soil temperature change.

The forest plot ST 15 at both study areas was cooler than the bare ground plot ST 15 in March through October 2001 and beginning again in April 2002 (Table 4-4). The opposite was true in February 2001 and in December through February of 2002. The relationship reversed during the month of March each year and September 2001. The air temperature changes and resulting ST 15 changes were more extreme in the unprotected bare ground plots than in the insulated forest plots. The differences between the three treatments were greater in ST 15 measurements than in air temperatures throughout the study. The bare ground plot ST 15 was warmer than in the field plots in every month except April and June 2001 and again in December

Table 4-4. Average monthly ST 15 by treatment type at each study area. Monthly means made of four subsamples except Hall field treatment that had three subsamples. Annual means made of 48 subsamples except Hall field treatment that had 36 subsamples.

					2001										2002
Month	Feb[†]	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	--- °C ---															
Bruff																
Forest	8.26a	9.34b	13.42b	16.38c	20.15b	21.13c	22.10c	19.89c	15.90b	13.24a	12.10a	8.19a	9.25a	10.89a	14.57c	16.66c
Field	7.57b	9.41b	15.17a	19.29b	23.35a	23.76b	24.21b	21.00b	15.60b	11.99b	10.33b	6.15b	8.09b	10.95a	16.35b	19.04b
Bare ground	8.11a	10.32a	16.41a	21.39a	24.97a	25.99a	27.00a	23.41a	17.08a	13.43a	10.24b	6.07b	6.07b	8.31b	11.88a	17.71a
Hall																
Forest	7.87a	9.34b	13.84b	16.95b	20.59b	22.06c	22.94b	20.51b	15.88a	13.09a	11.57a	7.52a	7.52a	8.87a	11.05a	15.10b
Field	7.33b	9.78ab	15.92a	19.62a	23.63a	24.00b	25.00a	20.81b	14.59b	11.75b	9.41b	5.46b	5.46b	7.65b	10.37a	17.25a
Bare ground	7.66ab	10.03a	16.46a	21.23a	24.52a	26.21a	26.20a	22.36a	15.93a	12.37b	9.75b	5.75b	5.75b	7.99b	11.83a	17.53a

Bruff	Annual[†]
	-- °C --
Forest	15.01c
Field	15.65b
Bare ground	17.04a
Hall	
Forest	15.18c
Field	15.61b
Bare ground	16.54a

† Within hatched blocks, means in each column followed by the same letter are not significantly different using LSD of soil temperature reported at $P = 0.05$

Table 4-5. Average monthly ST 30 by treatment type at each study area. Monthly means made of four subsamples. Annual means made of 48 subsamples.

	2001										2002				
Month	Feb†	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	°C															
Bruff																
Forest	8.60a	9.51ab	13.05b	15.75c	18.11c	20.46c	21.47c	19.89c	16.34b	13.69a	12.74a	8.81a	9.71a	10.92b	14.23c	16.27c
Field	7.52c	9.25b	14.58a	18.42b	21.25b	23.03b	23.57b	20.95b	15.86b	12.22b	10.85b	6.46b	8.24b	10.63b	15.70b	18.36b
Bare ground	8.11b	10.20a	15.95a	20.58a	25.14a	25.66a	26.43a	23.61a	17.56a	13.86a	11.16b	6.50b	8.82b	11.79a	17.31a	20.57a
Hall																
Forest	7.97a	9.46a	13.80b	16.77b	18.84c	21.84b	22.69c	20.64b	16.27a	13.38a	11.95a	7.73a	9.02a	10.92a	14.92b	16.33c
Field	7.40b	9.86a	15.41a	18.82a	22.03b	23.26b	24.24b	21.23b	15.66b	11.86b	10.64b	5.96b	8.09b	11.00a	16.28a	18.70b
Bare ground	7.77ab	10.09a	16.25a	20.71a	24.87a	25.93a	25.92a	22.66a	16.33a	12.64b	10.43b	6.03b	8.29b	11.63a	17.19a	20.31a

Bruff	Annual†
	-- °C --
Forest	14.96c
Field	15.42b
Bare ground	16.98a
Hall	
Forest	15.23c
Field	15.56b
Bare ground	16.56a

† Within hatched blocks, means in each column followed by the same letter are not significantly different using LSD of soil temperature reported at P = 0.05

Table 4-6. Average monthly ST 50 by treatment type at each study area. Monthly means made of four subsamples except Bruff forest treatment that had three subsamples. Annual means made of 48 subsamples except Bruff forest treatment that had 36 subsamples.

	2001											2002				
Month	Feb†	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	°C															
Bruff																
Forest	8.86a	9.63b	12.63c	15.18c	18.40c	19.88c	20.87c	19.74c	16.66b	14.10a	13.29a	9.46a	10.11a	10.94b	13.80c	15.84c
Field	8.05b	9.71b	14.36b	18.08b	21.61b	22.67b	23.14b	21.23b	16.76b	13.07b	11.94b	7.37b	9.01b	10.87b	15.58b	18.30b
Bare ground	8.33b	10.29a	15.43a	19.89a	23.21a	25.07a	25.78a	23.66a	18.15a	14.40a	12.11b	7.10b	9.23b	11.61a	16.76a	19.96a
Hall																
Forest	8.33b	10.29a	15.43a	19.89a	23.21a	25.07a	25.78a	23.66a	18.15a	14.40a	12.11b	7.10b	10.85b	14.00c	15.86c	17.99c
Field	8.41a	9.38b	12.60b	15.01c	18.22c	19.82c	21.09c	19.93c	16.58b	14.02a	13.07a	9.00a	10.66b	15.54b	18.04b	20.92b
Bare ground	7.71b	9.94a	14.86a	18.28b	21.61b	22.85b	23.46b	21.15b	16.12b	12.31c	11.37b	6.58b	11.45a	16.55a	19.39a	23.31a

Bruff	Annual†
	-- °C --
Forest	14.89c
Field	15.67b
Bare ground	16.95a
Hall	
Forest	14.76c
Field	15.52b
Bare ground	16.46a

† Within hatched blocks, means in each column followed by the same letter are not significantly different using LSD of soil temperature reported at P = 0.05

through March 2002, when they were the same. The field plot ST 15 was never warmer than the bare ground plots. These results were similar to studies comparing land uses on well drained soils were soil temperature differences between different forest types, fallow fields and croplands were marked, these studies observed higher near surface soil temperatures in the sparsely vegetated or managed areas, in which the bare ground plots mimic (Ogunkunle and Eghaghara, 1992; Wagai et al., 1998). As indicated previously, there were differences in soil temperature based on land-use type, however, the relationship between litter layer depth and ST 15 was weak. At Bruff, where the litter layer ranged from 3 to 8 cm thick there was not a strong relationship between litter layer depth and heat flux (R^2= 0.05, P=0.05). At Hall, where the thickest litter layer was only 3 cm there was greater correlation (R^2= 0.46, P=0.05). Although differences were found in the thickness of litter between treatments, there was not a strong relationship between differences in annual soil temperature at 15 cm and depths of the litter layers at either site. These results indicate that the type of litter may be important, yet no strong relationship was found for the thickness of the litter to average annual soil temperature.

Soil moisture may have confounded the effects of litter layer thickness because higher moisture contents would provide additional buffering against temperature change. The Hall study area was much wetter than the Bruff study area, especially in the forested treatment where the litter occurred. Therefore, the effects of soil moisture on ST15 were investigated by land use and study area during the warmest and coldest mos (July 2001 and February 2002) in order to ensure that changes in temperature were affected from above and not influenced by temperature dynamics within the soil. The relationship between ST15 and hydrology was strongest in the field treatment (forest: R^2=0.07, field: R^2=0.42, and bare ground: R^2=0.05) and there was little overlap between the three regression lines.

Average monthly and annual ST 30 values were compared by treatment at each study area in Table 4-5. The annual average ST 30 temperatures were ranked in the following order: Bare ground > Field > Forest at both study areas. The Bruff study area indicated a greater difference in ST 30 between bare ground and field treatments than was apparent at Hall. Bruff plots were generally drier during the study; their soil surface was less buffered against temperature changes, due to the cumulative effect of increased heat accumulation and transfer from the surface. Studies have indicated that the range in soil temperature extremes diminish as moisture contents increase in soil horizons (Pickering and Veneman, 1984; Jenkinson and Franzmeier, 1996; Aust and Lea, 1991). The forest plots were insulated from soil temperature change in the forest by the surface litter layers.

The forest plot ST 30 at both study areas was cooler than the bare ground plot ST 30 in April through September 2001 and beginning again in March 2002 (Table 4-5). The opposite relationship was true in February 2001 and in December through February of 2002. The period of difference between bare ground and forest plot ST 30 was two months shorter than at 15 cm, indicating that the changes in ST 30 resulting from change in air temperature were less extreme at 30 cm than at 15 cm. There were less extreme changes in soil temperature in the forest plots than in the bare ground plots. The relationship reversed during the month of March each year. The bare ground plot ST 30 was warmer than in the field plots in every month except April 2001 and again in December through February 2002, when they were the same. The field plot ST 30 was never warmer than the bare ground plots.

Average monthly and annual ST 50 values were compared by treatment at each study area in Table 4-6. The annual average ST 50 temperatures were ranked in the following order: Bare ground > Field > Forest at both study areas. There was greater difference in ST 50 between bare ground and field treatments at Bruff than at Hall that may be attributed to moisture differences in the two study areas as discussed above. The ST 50 were warmer during the winter and cooler during the summer than either ST 30 or ST 15 measurements. The forest plots were well insulated from soil temperature change in the forest by the surface litter layers.

The forest plot ST 50 at both study areas was cooler than the bare ground plot ST 50 in March through October 2001 and beginning again in March 2002 (Table 4-6). The opposite relationship was true in February 2001 and December through February of 2002. The period of difference between bare ground and forest plot ST 50 was two months longer than at 30 cm, indicating that the changes in ST 50 resulting from change in air temperature were less extreme at 50 cm than at 30 cm. Changes in the forest plots ST 50 were less extreme than in the bare ground plots. In addition, the cooling flux could be seen to pass through the soil as a wave or pulse. The colder winter air cooled the soil at ST 15 more thoroughly than at ST 30, and to an even lesser extent at ST 50 cm, but also warmed again more quickly in the spring. The pulse of cooling was not reversed as quickly at 50 cm and the pulse of warming was delayed in the fall (until September). The relationship reversed during the month of March each year. The bare ground plot ST 50 was warmer than in the field plots in every month except February 2001 and again in January and February 2002, when they were the same. The field plot ST 50 was never warmer than the bare ground plots.

Average monthly soil temperatures measured at 15, 30, and 50 cm were compared graphically to each other in Figures 4-9 and 4-10. The relationships between the land uses were the same as described above. There were significant differences between the soil temperatures at depth in 15 of 18 mos. There were no differences by depth during the crossover months of March

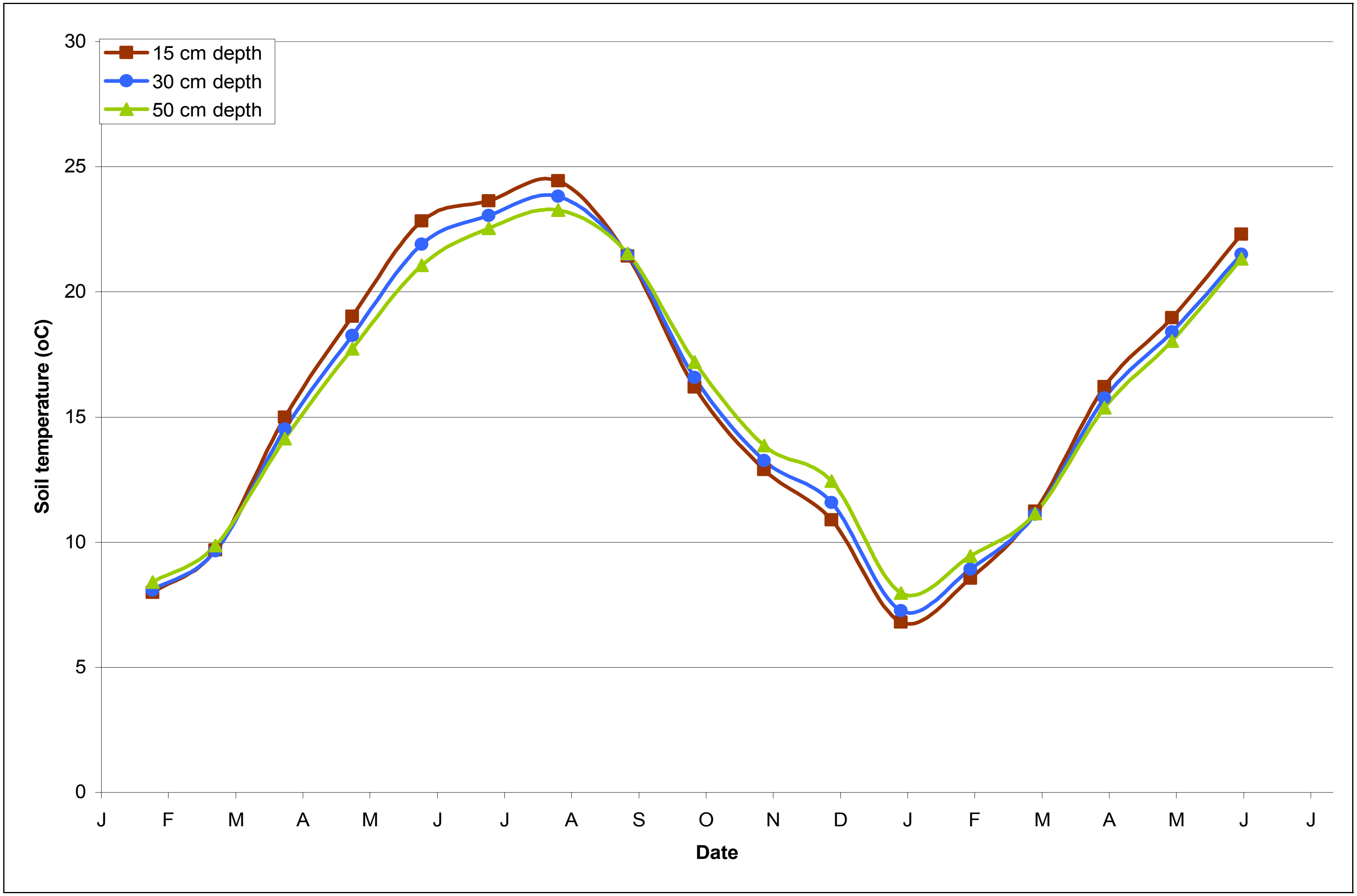


Figure 4-9. Soil temperatures at 15, 30, and 50-cm depth at Bruff study area.

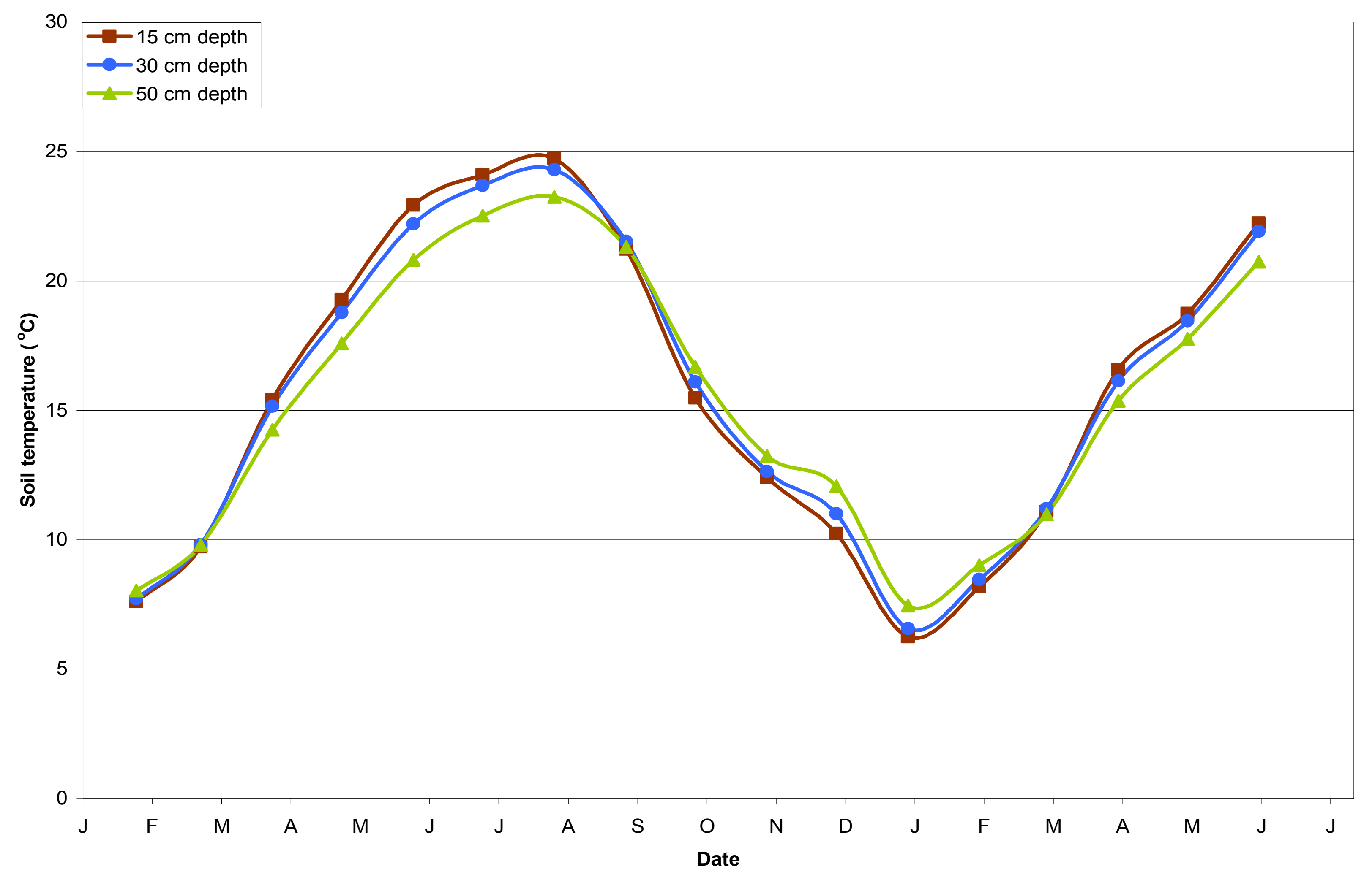


Figure 4-10. Soil temperatures at 15, 30, and 50-cm depth at Hall study area.

and September 2001 and March 2002. In April 2001 there was no difference between ST 15 and ST 30 and these were both warmer than ST 50.

Summary and Conclusions

Wet flats and other intermittently-saturated wetlands are unique ecosystems that are subject to land development and to restoration efforts, especially in the Great Dismal Swamp area of Southeast Virginia. Restoration and mitigation success depends on understanding the effect of vegetation type and land use on the hydrology and temperatures of these systems.

The soils in this study were probably subjected to both deep seasonal ground-water fluxes as well as more dynamic precipitation-driven perched water fluxes above the subsoil. The former cropland areas still contained plow layers at that impeded percolation at about 18 to 25 cm, and recent tilling produced another high-density water-restrictive layer very near the surface. The loblolly (artificial regeneration) and hardwood (natural regeneration) forest land uses showed little long-term adverse impact on the natural soil structure and bulk density and so did not have soil layers that would cause unnatural perching near the surface. The combination of poor soil structure and high bulk density caused the field (former cropland) and bare ground (tilled) treatments to have more frequent saturation in the near surface than the forested treatment and consequently a different hydroperiod.

The land uses studied had significant effects on air and soil temperatures at all depths. In summer months, canopy and mulching effects had a slight to drastic insulating effect on soil temperatures, depending on the type and consistency of those layers. In winter months, soil temperature was warmer where solar radiation was able to penetrate into the surface and high water content and vegetative effects tended to create a blanket or insulation from the cold.

The forests developed an insulating blanket of surface litter that moderated the soil's heat exchange rates and seasonal changes in temperature. The bare ground was warmer than the field which was warmer than the forest land-use treatment. The forests protected the air near the surface and the soil from direct solar radiation and winds, resulting in less variation in temperature extremes during the year. The surface litter mulch delayed conductance of cold and heat from the surface down to 50 cm. The bare ground treatment was intended to simulate active cropland, although the plots were not drained as active cropland would be. The bare ground plots were the most dynamic in temperature during the year and fluctuated from being the warmest treatment in summer to being the coldest in winter. The crossover months were March and September. The main reason for the temperature dynamics in the field and bare ground treatment plots was the lack of insulating litter mulch on the surface. Extremes in soil temperature decreased with increasing depth and water content. Inundation or surface saturation in the bare plots negated the temperature differences with the field plots, because the soil was wet to the surface in both treatments and had a very low adsorption and conductance of heat. The forest plots were drier in the surface than the field plots and bare ground in the summer because of higher transpiration losses. However, the increased heat conductance potential of the drier soil was more than offset by the presence of the protective surface litter mulch and the forest plots did not warm up more than the field and bare ground plots. The field plots were intermediate in temperature most of the year.

The soil temperature at 15 cm had more variation in extremes and was warmer in the summer and colder in the winter than the soil temperature at 30 and 50 cm, with crossover in March and September. This information implies that the soil temperature at 50 cm does not represent the soil temperature in the upper 30 cm of soil except in two mo yr^{-1}. These results should apply to the thermic soil temperature regime studied and to cooler soils.

The implications to planners and managers is that land use does alter the hydrology, air, and soil temperature of the system and should be taken into account when considering protection and mitigation of wet flats and other seasonally-saturated wetlands in the southeastern USA. The presence of high bulk densities near the surface and the lack of an insulating mulch produce harsh environments for reestablishment of wetland plants during mitigation. The results of this study can be used to modify growing season definitions based on soil temperatures and to help choose a proper depth for soil temperature measurement.

Chapter 5. Summary and Conclusions

Wet flat wetlands of southeastern Virginia are important ecosystems of great ecological, aesthetic, and economic value. These areas are identified and protected by federal regulations; the growing season is an integral part of these regulations. The accuracy of the growing season used by regulators in defining wetland hydrology requirements for wet flats and the validity of combining all land uses are questionable. This study found that the measured growing season based on the original growing season definition was longer than the regulated growing season and that measured growing seasons were land-use dependent.

Land use affected hydrology, air, and soil temperatures through the presence of surface litter and shading, albedo, and ET differences. The forest was drier than the bare ground treatment. Forest vegetation buffered the soil against changes in temperature because shade was provided in the summer and wind protection in winter. The surface litter acted as insulating mulch such that the forest plots were least dynamic in temperature change during the year, these plots were more buffered and had less seasonal variation in temperature. Fields with early successional vegetation had a shorter growing season than forest plots because of the short, open, stature of the vegetation and minimal surface litter. The bare ground that simulated cropland areas had shorter growing seasons and more dynamic soil temperature changes since they provided no buffering of the soil surface from sunlight or wind, having the largest albedo affect.

The former cropland areas had residual plow layers that impeded percolation starting within 18 to 25 cm. Recent tilling produced a second high-density water-restrictive layer very near the surface. The combination of poor soil structure, low intrinsic porosity, and high bulk density caused the field (former cropland) and bare ground (tilled) treatments to have more frequent saturation in the near surface than the forested treatment, and consequently a different hydroperiod. The forest surface horizons were drier than those of the field and bare ground plots in the summer because of higher transpiration losses. These treatment differences are expected to decrease as the vegetative restoration progresses, the surface compaction is broken by soil formation and root-growth, and as the field areas develop a surface litter layer.

The soil temperature at 15 cm had more variation in extremes and was warmer in the summer and colder in the winter than the soil temperature at 30 and 50 cm. Crossover of temperatures at the three depths occurred in March and September. This information implies that soil temperature at 50 cm does not represent soil temperatures within the upper 30 cm of soils, except in two mo yr^{-1}. These results should apply throughout the thermic soil temperature regime and in cooler soils. The upper 30 cm is considered the primary rooting zone in wetlands, while in uplands the 50 cm depth is within the primary rooting zone. Temperature and growing season regulations are focused on the critical depth for vegetation because of this the depth required to monitor biological zero temperatures should be reconsidered. Currently, the regulations require measurement at a depth that may not be representative of the major rooting and biological activity zone for wetlands.

The regulated growing season starting dates and length in Southeast Virginia wet flats are later and shorter than the measured growing season limit of 5 °C at the 50-cm depth, the originally published concept of the growing season. Based on CO_2 efflux and soil temperature at 50 cm, the biological growing season of native plants and microbes should be year-round for forested areas, one week shorter for early-successional fields, and two weeks shorter for active cropland rather than March to November for all land uses.

The AT -4.4 GS started earlier and lasted longer than the AT -2.2 GS. The growing season started at the same time for all treatments, but the forests continued longer. But the difference between the two air temperature thresholds was not great. A change in regulation should not incorporate using a cooler listed frost-free days period, instead soil temperature limits should be considered. The AT -2.2 GS started later and ended earlier than the regulated FFD -2.2 GS. That means that the measured air temperatures were much colder than the stated regulatory frost-free period, even though that air temperature recorded during the study were above normal ranges in air temperature. If while in a warmer than normal year these dates were not met, this is an indication that the long-term averages used in regulations are not accurate or that air temperatures have changed considerably over the last 30 years. The FFD -4.4 GS started earlier and ended later than the regulated FFD -2.2 GS. The STR GS started earlier and ended earlier than the regulated FFD -2.2 GS. The starting date compared well to the measured ST 50 GS but the ending date was much earlier. The regulated FFD -2.2 GS started later and ended earlier than the vegetative GS. The vegetation GS correlated well to the ST 50 and the CO_2 efflux GS. Therefore, the problem revealed by this study is that the FFD -2.2 GSI is not accurate as a surrogate for measured soil temperature at 50 cm, nor any other practical growing season indicator.

Using vegetative indicators of the growing season would be a better choice for ACOE regulations than the current FFD -2.2 GSI. Alternatively, the growing season in forested thermic wetlands could be changed to year-round. Changing the growing season definition to year-round would benefit these wet flats and similar study areas in qualifying for wetland hydrology thresholds due to the dominant winter wetness of these areas, but any alteration must be studied to ensure the proper level of wetland protection so that they do not jeopardize the wetland hydrology qualification of other wetlands. Further, the National Research Council recommended measuring wetland hydrology year-round and considering any area with continuous wetland hydrology for two weeks to be a jurisdictional wetland. This recommendation would assist in problems that measuring 5% of a year-round growing season would address. The decision should be made to lengthen the growing season or adjust the parameters considered within the current regulation.

While on-site measurement of soil temperature is not possible for wetland delineation, it is possible and should be required for mitigated wetlands. Soil temperature measurements could coincide with the required hydrologic monitoring, so that the timing of surface saturation and the period of biological activity are properly matched. A mandatory analysis of soil temperature for the site could yield a better understanding of when biological zero temperatures occur, as well as yield a site specific growing season for each mitigated area.

Planners and managers should note that land use does alter the hydrology, air, and soil temperature of the system and should be taken into account when considering protection, mitigation, and management of wet flats and other seasonally-saturated wetlands in the southeastern USA. The results of this study can be used to modify growing season definitions and to help choose a proper depth for soil temperature measurement.

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Appendices

Selected Appendices 1-3 begin on the next page.

Appendices 4-9 are found in the supplementary file “Amanda_Burdt_Appendices.pdf.”

Appendix 1a. Species list for the Bruff Study area ranked alphabetically.

Species	Source	Indicator Status
Forest Overstory		
Acer rubrum	L.	FAC
Ilex opaca	Ait.	FAC+
Liquidambar styraciflua	L.	FAC
Nyssa sylvatica	Marsh.	FAC
Oxydendrum arboreum	L.	NI
Pinus taeda	L.	FAC-
Quercus alba	L.	FACU-
Quercus laurifolia	Michx.	FACW-
Quercus michauxii	Nutt.	FACW
Quercus phellos	L.	FAC+
Forest Understory		
Acer rubrum	L.	FAC
Arundinaria gigantea	Walt.	FACW
Chasmanthium laxum	L.	FAC
Duchesnea indica	Andr.	FACU-
Fagus grandifolia	Ehrh.	FAC+
Gelsemium sempervirens	L.	FAC
Hypericum hypercodies	L.	FACU
Ilex cassine	L.	NO
Ilex glabra	L.	FACW-
Ilex opaca	Ait.	FAC+
Liquidambar styraciflua	L.	FAC
Lonicera japonica	Thunb.	FAC-
Magnolia virginiana	L.	FACW+
Mitchella repens	L.	FACU
Morella cerifera	L.	FAC
Oxydendrum arboreum	L.	NI
Persea borbonia	L.	FACW
Pinus taeda	L.	FAC-
Quercus michauxii	Nutt.	FACW
Quercus laurifolia	Michx.	FACW-
Quercus phellos	L.	FAC+
Rhus copallinum	L.	NI
Rubus hispidus	L.	FACW
Sassafras albidum	Nutt.	FACU-
Smilax rotundifolia	L.	FAC
Vaccinium corymbosum	L.	FAC
Vitis rotundifolia	Michx.	FAC-
Zanthoxylum clava-herculis	L.	FAC

Appendix 1a. (continued)

Species	Author	Wetland Indicator status
	Field	
Acer rubrum	L.	FAC
Allium vineale	L.	FACU-
Alopecurus brachystachus	Bieb.	FACW
Alopecurus pratensis	L.	FACW
Ambrosia artemisiifolia	L.	FACU
Andropogon virginicus	L.	FACU
Campsis radicans	L.	FAC
Carex albolutescens	Schwein.	FACW
Chasmaecrista fasciculata	Michx.	FACW
Desmodium paniculatum	Lam.	FACU-
Dichanthelium scoparium	Lam.	FACW
Diodia virginiana	L.	FACW
Eupatorium capillifolium	Lam.	FACU-
Euthamia tenuifolia	Pursh.	FAC
Festuca arundinacea	Schreb.	FACU
Ipomoea hederacea	Jacq.	FACU
Juncus tenuis	Willd.	FAC-
Lespedeza cuneata	Dum. Cours.	NI
Lespedeza sp.		
Liquidambar styraciflua	L.	FAC
Lolium arundinaceum	Schreb.	FACU
Mikania scandens	L.	FACW+
Paspalum distichum	L.	FACW+
Pinus taeda	L.	FAC-
Polygonum hydropiper	L.	OBL
Polygonum pensylvanium	L.	FACW
Prunus serotina	Ehrh.	FACU
Rhexia mariana	L.	OBL
Senna obtusifolia	L.	FAC
Solanum carolinense	L.	FACW-
Solidago gigantea	Ait.	FACW
Symphyotrichum dumosum	L.	FAC
Symphyotrichum pilosum	Willd.	UPL

Appendix 1b. Species list for the Hall Study area ranked alphabetically.

Species	Source	Indicator Status
Acer rubrum	L.	FAC
Agalinis fasciculata	Ell.	FACW-
Agalinis purpurea	L.	FACW-
Ambrosia artemisiifolia	L.	FACU
Andropogon virginiana	L.	FACU
Aster dumosus		
Bidens frondosa	L.	FACW
Campsis radicans	L.	FAC
Carex albolutescens	Schwein.	FACW
Carex lupulina	Muhl.	OBL
Cassia fasciculata	Michx.	FACU
Commelina communis	L.	FAC-
Cyperus odoratus	L.	FACW
Dicanthelium scoparium	Lam.	FACW
Dichanthelium dichotomum	L.	FACW
Diodia virginiana	L.	FACW
Diospyros virginiana	L.	FAC-
Echinochloa crus-galli	L.	FACU
Eleocharis obtusa	Willd.	OBL
Eupatorium capillifolium	Lam.	FACU
Eupatorium dubium	Willd.	FACW
Euthamia tenuifolia	Pursh.	FAC
Juncus acuminatus	Michx.	OBL
Juncus effusus	L.	FACW
Juncus marginatus	Rostk.	FACW
Juncus tenuis	Willd.	FAC-
Lespedeza sp.		
Liquidambar styraciflua	L.	FAC
Liriodendron tulipifera	L.	FACU
Ludwigia alternifolia	L.	FACW+
Ludwigia palustris	L.	OBL
Nyssa sylvatica	Marsh.	FAC
Paspalum dilatatum	Poir.	FAC+
Phytolacca americana	L.	FACU+
Pinus taeda	L.	FAC-
Pluchea foetida	L.	OBL
Polygonum hydropiperoides	Michx.	OBL
Polygonum pensylvanicum	L.	FACW
Proserpinaca palustris	L.	OBL
Prunus serotina	Ehrh.	FACU

Appendix 1b. (continued)

Species	Source	Indicator Status
Pseudognaphalium obtusifolium	L.	UPL
Quercus michauxii	Nutt.	FACW
Quercus pagoda	Raf.	FACW
Quercus phellos	L.	FAC+
Rubus argutus	Fern.	FACU
Salix nigra	Marsh.	FACW+
Scirpus atrocinctus	Fern.	FACW+
Scirpus pedicellatus	Fern.	OBL
Solanum caroliniense	L.	UPL
Solidago canadensis	L.	FACU
Solidago gigantea	Ait.	FACW
Symphyotrichum dumosum	L.	FAC
Symphyotrichum laeve	L.	FAC
Toxicodendron radicans	L.	FAC
Typha angustifolia	L.	OBL
Ulmus americana	L.	FACW-

Appendix 2a. Morphological descriptions at the Bruff study area.

Location: Bruff Plot 1
Land use Represented: Forest

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Oi--0 to 2 cm; brown (7.5YR 4/4) peat (fibric material); structureless, massive; many very fine to coarse roots; abrupt smooth boundary.
Oe--2 to 3 cm; dark brown (7.5YR 3/4 broken face and rubbed) mucky peat (hemic material); structureless, massive; many very fine to medium roots; abrupt smooth boundary.
Oa--3 to 4 cm; very dark brown (7.5YR 2.5/2 broken face and rubbed) muck (sapric material); weak thin platy structure; many very fine to medium roots; abrupt smooth boundary.
A--4 to 12 cm; black (10YR 2/1) fine sandy loam; common pockets of clean washed sand grains; strong medium granular structure; common very fine to medium roots; abrupt smooth boundary.
AB--12 to 21 cm; very dark grayish brown (2.5Y 3/2) loam; common (2%) fine distinct dark yellowish brown (10 YR 4/4) pore linings and masses, common (2%) fine faint olive brown (2.5Y 4/3) masses and common (5%) fine distinct olive brown (2.5Y 4/4) masses of iron accumulations; common (5%) fine faint dark grayish brown (2.5Y 4/2) masses of iron depletions; common (5%) pockets of clean washed sand grains; weak coarse subangular blocky structure; common very fine to medium roots; clear wavy boundary.
Btg--21 to 40+ cm; dark grayish brown (2.5Y 4/2) clay loam; common (5%) fine distinct dark yellowish brown (10 YR 4/4), common (15%) fine prominent yellowish brown (10YR 5/6) and common (5%) fine prominent yellowish brown (10YR 5/8) masses of iron accumulations; common (10%) fine faint dark gray (2.5Y 4/1) and common (5%) medium distinct light brownish gray (10YR 6/2) masses of iron depletions; strong medium subangular blocky structure; few fine roots.

Location: Bruff Plot 2
Land use Represented: Forest

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Please refer to Table 3-1.

Location: Bruff Plot 3
Land use Represented: Field

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Oi--0 to 1 cm; dark brown (10YR 3/3 broken face and rubbed) mucky peat (hemic material); abrupt smooth boundary.

Ap1--1 to 13 cm; very dark grayish brown (10YR 3/2) fine sandy loam; common (10%) fine distinct dark yellowish brown (10 YR 4/4) masses and common (3%) fine prominent strong brown (7.5YR 5/8) pore linings of iron accumulations; common (5%) fine faint dark grayish brown (10YR 4/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; moderate medium subangular blocky structure; many very fine to fine roots; clear smooth boundary.

Ap2--13 to 24 cm; very dark grayish brown (10YR 3/2) fine sandy loam; common (10%) fine distinct dark yellowish brown (10 YR 4/4) masses and few (1%) fine prominent strong brown (7.5YR 5/8) pore linings of iron accumulations; common (8%) fine faint dark grayish brown (10YR 4/2) masses of iron depletions; common (5%) pockets of clean washed sand grains; weak coarse subangular blocky structure; many very fine to fine roots; abrupt smooth boundary.

Btg--24 to 50+ cm; gray (10YR 5/1) clay; many (25%) coarse prominent yellowish brown (10YR 5/8), common (5%) medium distinct yellowish brown (10YR 5/6), and common (5%) fine distinct dark yellowish brown (10YR 4/6) masses of iron accumulations; common (5%) fine faint dark gray (10YR 4/1) masses of iron depletions; strong medium subangular blocky structure; few very fine roots.

Location: Bruff Plot 4
Land use Represented: Bare ground

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Ap1--0 to 10 cm; very dark grayish brown (10YR 3/2) fine sandy loam; few (1%) fine distinct dark yellowish brown (10 YR 4/4) masses and few (1%) fine prominent strong brown (7.5YR 5/8) pore linings of iron accumulations; common (5%) fine faint dark grayish brown (10YR 4/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; weak medium subangular blocky structure; many very fine to fine roots; clear smooth boundary.

Ap2--10 to 20 cm; very dark grayish brown (10YR 3/2) fine sandy loam; common (10%) fine distinct dark yellowish brown (10 YR 4/4) masses and few (1%) fine prominent strong brown (7.5YR 5/8) pore linings of iron accumulations; common (8%) fine faint dark grayish brown (10YR 4/2) masses of iron depletions; common (5%) pockets of clean washed sand grains; weak coarse subangular blocky structure; many very fine to fine roots; abrupt smooth boundary.

Btg--20 to 40+ cm; grayish brown (10YR 5/2) sandy clay loam; common (5%) medium distinct light olive brown (2.5Y 5/4), common (2%) medium prominent yellowish brown (10YR 5/8), common (10%) medium faint brown (10YR 5/3) and common (10%) coarse distinct dark yellowish brown (10YR 4/6) masses of iron accumulations; common (2%) fine faint dark gray (10YR 4/1) masses of iron depletions; strong medium subangular blocky structure; few very fine roots.

Location: Bruff Plot 5
Land use Represented: Bare ground

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Ap1--0 to 11 cm; dark grayish brown (10YR 4/2) fine sandy loam; few (1%) fine faint brown (10YR 4/3) masses of iron accumulation; common (2%) pockets of clean washed sand grains; weak coarse subangular blocky structure; many very fine to fine roots; abrupt smooth boundary.

Ap2--11 to 25 cm; dark grayish brown (10YR 4/2) fine sandy loam; common (2%) faint brown (10YR 4/3) masses of iron accumulations; common (2%) pockets of clean washed sand grains; weak coarse subangular blocky structure; many very fine to fine roots; abrupt smooth boundary.

Btg/Eg--25 to 58 cm; 75% grayish brown (10YR 5/2) sandy clay loam and 25% grayish brown (2.5Y 5/2) fine sandy loam; common (5%) medium distinct light olive brown (2.5Y 5/4), common (2%) medium prominent yellowish brown (10YR 5/8), common (10%) medium faint brown (10YR 5/3), and common (10%) coarse distinct dark yellowish brown (10YR 4/6) masses of iron accumulations; common (10%) medium faint light brownish gray (10YR 6/2) and common (2%) fine faint dark gray (10YR 4/1) masses of iron depletions; moderate coarse subangular blocky structure; few very fine roots; clear wavy boundary.

Btg--58 to 60+ cm; grayish brown (10YR 5/2) clay; common (5%) medium distinct light olive brown (2.5Y 5/4), common (2%) medium prominent yellowish brown (10YR 5/8), common (10%) medium faint brown (10YR 5/3), and common (10%) coarse distinct dark yellowish brown (10YR 4/6) masses of iron accumulations; common (2%) fine faint dark gray (10YR 4/1) masses of iron depletions; strong medium subangular blocky structure; few very fine roots.

Location: Bruff Plot 6
Land use Represented: Bare ground

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Ap1--0 to 10 cm; very dark grayish brown (10YR 3/2) fine sandy loam; common (2%) fine distinct light brownish gray (2.5Y 6/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; weak medium subangular blocky structure; common very fine to fine roots; abrupt smooth boundary.

Ap2--10 to 20 cm; very dark grayish brown (2.5Y 3/2) fine sandy loam; few (1%) fine distinct dark yellowish brown (10 YR 4/4) and few (1%) fine prominent dark yellowish brown (10YR 4/6) masses of iron accumulations; common (5%) fine faint grayish brown (2.5Y 5/2) masses of iron depletions; common (5%) pockets of clean washed sand grains; weak coarse subangular blocky structure; few very fine to fine roots; abrupt smooth boundary.

Eg/Btg--20 to 29 cm; 75% grayish brown (2.5Y 5/2) fine sandy loam and 25% grayish brown (2.5Y 5/2) clay loam; common (2%) medium distinct dark yellowish brown (10YR 4/4) and common (2%) medium distinct light olive brown (2.5Y 5/4) masses of iron accumulations; moderate medium subangular blocky structure; few very fine and fine roots; clear wavy boundary.

Btg/Eg--29 to 40+ cm; 75% dark grayish brown (2.5Y 4/2) clay and 25% dark grayish brown (2.5Y 4/2) fine sandy loam; common (2%) fine prominent strong brown (7.5YR 5/6) pore linings, many (20%) medium distinct yellowish brown (10YR 5/6) masses and common (10%) medium prominent yellowish brown (10YR 5/8) masses of iron accumulations; common (2%) fine distinct dark gray (2.5Y 4/1), common (10%) fine faint grayish brown (2.5Y 5/2), common (5%) fine faint gray (2.5Y 5/1) masses of iron depletions; strong medium angular blocky structure; few very fine and fine roots.

Location: Bruff Plot 7
Land use Represented: Bare ground

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Ap1--0 to 9 cm; very dark grayish brown (10YR 3/2) fine sandy loam; common (2%) fine distinct light brownish gray (2.5Y 6/2) masses of iron depletions; common pockets of clean washed sand grains; weak medium subangular blocky structure; common very fine to fine roots; abrupt smooth boundary.

Ap2--9 to 24 cm; very dark grayish brown (2.5Y 3/2) fine sandy loam; few (1%) fine distinct dark yellowish brown (10 YR 4/4) and few (1%) fine prominent dark yellowish brown (10YR 4/6) masses of iron accumulations; common (5%) fine faint grayish brown (2.5Y 5/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; weak coarse subangular blocky structure; few very fine to fine roots; abrupt smooth boundary.

AE--24 to 32 cm; grayish brown (2.5Y 5/2) fine sandy loam; common (2%) fine distinct yellowish brown (10YR 5/4) and many (20%) fine faint light olive brown (2.5Y 5/3) masses of iron accumulations; weak coarse subangular blocky structure; few very fine to fine roots; clear wavy boundary.

Btg/Eg--32 to 45+ cm; 75% dark grayish brown (2.5Y 4/2) clay and 25% dark grayish brown (2.5Y 4/2) fine sandy loam; common (2%) fine prominent strong brown (7.5YR 5/6) pore linings, many (20%) medium distinct yellowish brown (10YR 5/6) masses and common (10%) medium prominent yellowish brown (10YR 5/8) masses of iron accumulations; common (2%) fine distinct dark gray (2.5Y 4/1), common (10%) fine faint grayish brown (2.5Y 5/2), common (5%) fine faint gray (2.5Y 5/1) masses of iron depletions; strong medium angular blocky structure; few very fine and fine roots.

Location: Bruff Plot 8
Land use Represented: Field

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Oi--0 to 2 cm; dark brown (10YR 3/3 broken face and rubbed) mucky peat (hemic material); abrupt smooth boundary.

A--2 to 11 cm; very dark grayish brown (10YR 3/2) fine sandy loam; few (1%) fine faint brown (10YR 4/3) masses of iron accumulations; common (2%) fine distinct light brownish gray (10YR 6/2) masses of iron depletions; moderate medium granular structure; many very fine to fine roots; abrupt smooth boundary.

Ap--11 to 21 cm; very dark grayish brown (10YR 3/2) fine sandy loam; few (1%) fine faint brown (10YR 4/3) masses of iron accumulations; common (2%) fine distinct light brownish gray (10YR 6/2) masses of iron depletions; common pockets of clean washed sand grains; weak coarse subangular blocky structure; few very fine to fine roots; abrupt smooth boundary.

EA--21 to 29 cm; grayish brown (2.5Y 5/2) fine sandy loam; common (2%) fine distinct yellowish brown (10YR 5/4) and many (20%) fine faint light olive brown (2.5Y 5/3) masses of iron accumulations; weak coarse subangular blocky structure; few very fine to fine roots; clear wavy boundary.

Btg/Eg--29 to 40+ cm; 75% dark grayish brown (2.5Y 4/2) clay and 25% dark grayish brown (2.5Y 4/2) fine sandy loam; common (2%) fine prominent strong brown (7.5YR 5/6) pore linings, many (20%) medium distinct yellowish brown (10YR 5/6) masses and common (10%) medium prominent yellowish brown (10YR 5/8) masses of iron accumulations; common (2%) fine distinct dark gray (2.5Y 4/1), common (10%) fine faint grayish brown (2.5Y 5/2), common (5%) fine faint gray (2.5Y 5/1) masses of iron depletions; strong medium angular blocky structure; few very fine and fine roots.

Location: Bruff Plot 9
Land use Represented: Field

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Please refer to Table 3-1.

Location: Bruff Plot 10
Land use Represented: Forest

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Oi--0 to 2 cm; brown (7.5YR 4/4) peat (fibric material); structureless, massive; many very fine to coarse roots; abrupt smooth boundary.
Oe--2 to 3 cm; dark brown (7.5YR 3/4 broken face and rubbed) mucky peat (hemic material); structureless, massive; many very fine to medium roots; abrupt smooth boundary.
Oa--3 to 5 cm; black (7.5YR 2.5/1 broken face and rubbed) muck (sapric material) weak thin platy structure; many very fine to medium roots; abrupt smooth boundary.
A--5 to 15 cm; very dark grayish brown (10YR 3/2) fine sandy loam; common (10%) fine faint dark grayish brown (10YR 4/2) and common (10%) fine faint grayish brown (10YR 5/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; strong fine granular structure; many very fine to coarse roots; abrupt smooth boundary.
AE--15 to 31 cm; dark grayish brown (2.5Y 4/2) fine sandy loam; common (5%) fine prominent strong brown (7.5YR 5/8) pore linings and common (10%) fine faint olive brown (2.5Y 4/4) masses of iron accumulations; common (10%) fine faint dark grayish brown (10YR 4/2) and common (10%) fine faint grayish brown (10YR 5/2) masses of iron depletions; common (5%) pockets of clean washed sand grains; weak medium subangular blocky structure; few very fine to medium roots; clear wavy boundary.
Bt--31 to 40+ cm; light olive brown (2.5Y 5/3) clay loam; common (2%) fine prominent strong brown (7.5YR 5/6) pore linings, many (20%) medium distinct yellowish brown (10YR 5/6) masses and common (10%) medium prominent yellowish brown (10YR 5/8) masses of iron accumulations; common (10%)fine distinct dark gray (2.5Y 4/1), common (10%) fine faint grayish brown (2.5Y 5/2), common(10%) medium faint light brownish gray (10YR 6/2) and common (5%) fine faint gray (2.5Y 5/1) masses of iron depletions; moderate medium subangular blocky structure; few very fine and fine roots.

Location: Bruff Plot 11
Land use Represented: Forest

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Oi--0 to 3 cm; brown (7.5YR 4/4) peat (fibric material) structureless, massive; many very fine to coarse roots; abrupt smooth boundary.
Oe--3 to 4 cm; dark brown (7.5YR 3/4 broken face and rubbed) mucky peat (hemic material); structureless, massive; many very fine to medium roots; abrupt smooth boundary.
Oa--4 to 7 cm; black (7.5YR 2.5/1 broken face and rubbed) muck (sapric material) weak thin platy structure; many very fine to medium roots; abrupt smooth boundary.
A--7 to 22 cm; very dark grayish brown (10YR 3/2) fine sandy loam; common (10%) fine faint dark grayish brown (10YR 4/2) and common (10%) fine faint grayish brown (10YR 5/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; strong medium granular structure; many very fine to coarse roots; abrupt smooth boundary.
AE—22 to 28 cm; very dark grayish brown (2.5Y 3/2) and light olive brown (2.5Y 5/3) fine sandy loam; common (10%) fine prominent yellowish brown (10YR 5/6), common (10%) fine distinct olive brown (2.5Y 4/4) and common (5%) medium distinct light yellowish brown (2.5Y 6/4) masses of iron accumulations; common (20%) medium distinct light brownish gray (2.5Y 6/2) masses of iron depletions in the E horizon; common (5%) pockets of clean washed sand grains; weak medium subangular blocky structure; common very fine to medium roots; clear wavy boundary.
Btg/Eg--28 to 36 cm; 75% grayish brown (2.5Y 5/2) clay loam and 25% grayish brown (2.5Y 5/2) fine sandy loam; common (5%) medium faint light olive brown (2.5Y 5/3) masses, common (2%) fine prominent strong brown (7.5YR 5/6) pore linings and common(6%) medium prominent yellowish brown (10YR 5/8) masses of iron accumulations; common (8%) fine distinct dark gray (2.5Y 4/1), common (5%) medium faint light brownish gray (10YR 6/2) and common (10%) fine faint gray (2.5Y 5/1) masses of iron depletions; strong medium angular blocky structure; few very fine and fine roots.

Btg--36 to 40+ cm; grayish brown (2.5Y 5/2) clay; common (2%) fine prominent strong brown (7.5YR 5/6) pore linings, many (20%) medium distinct yellowish brown (10YR 5/6) masses and common (10%) medium prominent yellowish brown (10YR 5/8) masses of iron accumulations; common (10%)fine distinct dark gray (2.5Y 4/1), common (10%) fine faint grayish brown (2.5Y 5/2), common(10%) medium faint light brownish gray (10YR 6/2), and common (5%) fine faint gray (2.5Y 5/1) masses of iron depletions; common (2%) pockets of clean washed sand grains; moderate medium subangular blocky structure; few very fine and fine roots; gradual wavy boundary.

Location: Bruff Plot 12
Land use Represented: Field

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Oi--0 to 1 cm; dark brown (10YR 3/3 broken face and rubbed) mucky peat (hemic material); abrupt smooth boundary.

A--1 to 9 cm; very dark grayish brown (2.5Y 3/2) fine sandy loam; few (1%) fine distinct olive brown (2.5Y 4/4) masses of iron accumulations; common (2%) fine distinct light brownish gray (2.5Y 6/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; moderate medium subangular blocky structure; many very fine to fine roots; abrupt smooth boundary.

Ap--9 to 24 cm; dark grayish brown (2.5Y 4/2) fine sandy loam; common (2%) fine distinct dark yellowish brown (10 YR 4/4), common (2%) fine faint olive brown (2.5Y 4/3) and few (1%) fine prominent yellowish brown (10YR 5/6) masses of iron accumulations; common (2%) fine distinct light brownish gray (2.5Y 6/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; weak coarse subangular blocky structure; common very fine to fine roots; abrupt smooth boundary.

A/Eg--24 to 31 cm; 60% very dark grayish brown (2.5Y 3/2) fine sandy loam and 40% light brownish gray (2.5Y 6/2) fine sandy loam; common (2%) fine prominent dark yellowish brown (10YR 4/6) and common (5%) fine prominent yellowish brown (10YR 5/6) masses of iron accumulations; common (5%) fine faint grayish brown (2.5Y 5/2), common (5%) medium faint dark grayish brown (2.5Y 4/2) and many (20%) medium faint light gray (2.5Y 7/2) masses of iron depletions; moderate medium subangular blocky structure; few very fine to fine roots; clear wavy boundary.

Btg/Eg--31 to 40+ cm; 75% dark grayish brown (2.5Y 4/2) clay and 25% dark grayish brown (2.5Y 4/2) clay; common (2%) fine prominent strong brown (7.5YR 5/6) pore linings, many (20%) medium distinct yellowish brown (10YR 5/6) masses and common (10%) medium prominent yellowish brown (10YR 5/8) masses of iron accumulations; common (10%)fine distinct dark gray (2.5Y 4/1), common (10%) fine faint grayish brown (2.5Y 5/2), common(10%) medium faint light brownish gray (10YR 6/2) and common (5%) fine faint gray (2.5Y 5/1) masses of iron depletions; common (2%) pockets of clean washed sand grains; strong medium angular blocky structure; few very fine and fine roots.

Appendix 2b. Morphological descriptions at the Hall study area.

Location: Hall Plot 1
Land use Represented: Bare ground

TOMOTLEY SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine-loamy, mixed, semiactive, thermic Typic Endoaqualfs

Ap1--0 to 6 cm; brown (10YR 4/3) fine sandy loam; few (trace) fine faint dark yellowish brown (10YR 4/4) pore linings of iron accumulations; moderate medium granular structure; many very fine to medium roots; clear smooth boundary

Ap2--6 to 12 cm; dark grayish brown (10YR 4/2) fine sandy loam; few (1%) fine distinct brown (7.5YR 4/4) pore linings of iron accumulations; moderate medium subangular blocky structure; many very fine to medium roots; abrupt smooth boundary.

Ap3--12 to 18 cm; dark grayish brown (10YR 4/2) fine sandy loam; common (2%) fine distinct dark yellowish brown (10YR 4/6) masses, common (3%) fine prominent strong brown (7.5YR 5/6) masses and common (5%) fine prominent strong brown (7.5YR 4/6) pore linings of iron accumulations; common (2%) fine faint grayish brown (10YR 5/2) masses of iron depletions; common fine pockets of clean washed sand grains; weak thin platy structure; few very fine to fine roots; abrupt smooth boundary.

Eg--18 to 25 cm; grayish brown (2.5Y 5/2) fine sandy loam; common (10%) fine prominent yellowish brown (10YR 5/6) pore linings, common (3%) fine prominent strong brown (7.5YR 4/6) masses and common (2%) medium distinct light olive brown (2.5Y 5/4) masses of iron accumulations; (2%) common fine distinct light gray (2.5Y 7/1) and few (1%) medium distinct gray (2.5Y 6/1) masses of iron depletions; common pockets of clean washed sand grains; weak thin platy structure; few very fine and fine roots; clear wavy boundary.

Eg/Btg--25 to 35 cm; 75% grayish brown (2.5Y 5/2) fine sandy loam and 25% grayish brown (2.5Y 5/2) fine sandy loam; common (10%) fine prominent yellowish brown (10YR 5/6) pore linings, common (5%) fine prominent yellowish brown (7.5YR 5/6) masses and common (5%) medium distinct red (2.5YR 5/8) masses of iron accumulations; common (5%) medium distinct light gray (2.5Y 7/1) and common (5%) medium distinct gray (2.5Y 6/1) masses of iron depletions; common pockets of clean washed sand grains; moderate medium subangular blocky structure; few faint clay films on faces of peds in pockets; few fine and medium roots; clear smooth boundary.

Btg/Eg--35+ cm; 75% grayish brown (2.5Y 5/2) loam and grayish brown (2.5Y 5/2) loam; common (10%) coarse prominent brownish yellow (10YR 6/8) masses, common (10%) fine prominent yellowish brown (10YR 5/6) pore linings, common (10%) fine prominent strong brown (7.5YR 5/6) masses, common (5%) coarse prominent dark grayish brown (2.5Y 4/2) masses of iron accumulations; common (5%) coarse distinct light gray (2.5Y 7/1) and common (5%) coarse distinct gray (2.5Y 6/1) masses of iron depletions; common pockets of clean washed sand grains; moderate medium subangular blocky structure; few fine and medium roots.

Location: Hall Plot 2
Land use Represented: Field

TOMOTLEY SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine-loamy, mixed, semiactive, thermic Typic Endoaqualfs

Oe and Oi --0 to 0.5 cm dark grayish brown (10 YR 4/2) hemic and fibric material; structureless, massive; abrupt smooth boundary.

Ap1—0.5 to 10 cm; dark grayish brown (10YR 4/2) silt loam; common (5%) fine distinct brownish yellow (10YR 6/6) masses and common (5%) fine prominent strong brown (7.5YR 5/6) pore linings of iron accumulations; weak medium subangular blocky structure; many very fine to medium roots; abrupt smooth boundary.

Ap2--10 to 26 cm; dark grayish brown (10YR 4/2) silt loam; common (5%) fine distinct brownish yellow (10YR 6/6) masses and common (5%) fine prominent strong brown (7.5YR 5/6) pore linings of iron accumulations; weak coarse subangular blocky structure; common very fine to fine roots; abrupt smooth boundary.

Eg--26 to 36 cm; light brownish gray (2.5Y 6/2) silt loam; common (5%) medium, prominent reddish yellow (7.5YR 6/8), common (10%) medium prominent dark red (2.5YR 3/6), many (20%) medium prominent brown (7.5YR 5/4), and common (10%) fine distinct dark yellowish brown (10YR 4/4) masses of iron accumulations; common (5%) coarse faint gray (10YR 6/1) masses of iron depletions; common pockets of clean washed sand grains; moderate medium subangular blocky structure; few faint clay films on faces of peds in pockets; few very fine to fine roots.

Eg/Btg-- 36 to 50+ cm; 75% light brownish gray (2.5Y 6/2) silt loam and 25% light brownish gray (2.5Y 6/2) clay loam; common (10%) medium, prominent reddish yellow (7.5YR 6/8), common (10%) medium prominent dark red (2.5YR 3/6), many (20%) medium prominent brown (7.5YR 5/4), and common (10%) fine distinct dark yellowish brown (10YR 4/4) masses of iron accumulations; common (5%) coarse faint gray (10YR 6/1) masses of iron depletions; common pockets of clean washed sand grains; moderate medium subangular blocky structure; few faint clay films on faces of peds in pockets; few very fine to fine roots.

Location: Hall Plot 3
Land use Represented: Bare ground

TOMOTLEY SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine-loamy, mixed, semiactive, thermic Typic Endoaqualfs

Please refer to Table 3-1.

Location: Hall Plot 4
Land use Represented: Bare ground

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine-silty, mixed, active, thermic Typic Endoaqualfs

Ap1--0 to 8 cm; dark grayish brown (10YR 4/2) silt loam; common (2%) fine prominent strong brown (7.5YR 5/8) pore linings and common (10%) fine distinct brownish yellow (10 YR 6/6) masses of iron accumulations; moderate medium granular structure; common fine and very fine roots; abrupt smooth boundary.

Ap2--8 to 26 cm; grayish brown (10YR 5/2) silt loam; common (5%) medium distinct brown (10 YR 5/3) masses and common (15%) fine prominent yellowish red (5 YR 4/6) pore linings of iron accumulations; few (1%) prominent Manganese masses; common (5%) medium faint brown (10YR 5/3) masses of iron depletions; common (2%) fine pockets of clean washed silt and sand grains; weak coarse subangular blocky structure; common fine and very fine roots; abrupt smooth boundary.

Btg--26 to 40+ cm; grayish brown (10YR 5/2) silty clay loam; common (15%) medium distinct dark brownish yellow (10YR 4/6) , common (10%) coarse prominent yellowish red (5YR 4/6), and common (3%) medium prominent yellowish red (5YR 5/8) masses of iron accumulations, and common (2%) medium prominent yellowish red (5YR 5/8) iron pore linings; common (10%) medium faint gray (10YR 5/1) masses of iron depletions; common (2%) medium pockets of clean washed silt grains; weak coarse subangular blocky structure; few fine and very fine roots.

Location: Hall Plot 5
Land use Represented: Field

TOMOTLEY SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine-loamy, mixed, semiactive, thermic Typic Endoaqualfs

Oe and Oi --0 to 0.5 cm dark grayish brown (10 YR 4/2) hemic and fibric material; structureless, massive; abrupt smooth boundary.

A—0.5 to 2 cm; dark grayish brown (10YR 4/2) fine sandy loam; moderate fine granular structure; many very fine to medium roots; abrupt smooth boundary.

Ap--2 to 18 cm; dark grayish brown (10YR 4/2) fine sandy loam; common (2%) fine distinct strong brown (7.5YR 5/6) pore linings and masses few (1%) fine prominent yellowish red (5YR 4/6) pore linings of iron accumulations; few (1%) fine manganese concretions; common (5%) fine distinct pale red (2.5 YR 7/2) masses of iron depletions; few (1%) clean washed sand grains; weak coarse subangular blocky structure; many fine and medium roots; abrupt wavy boundary.

Eg--18 to 24 cm; light brownish gray (2.5Y 6/2) fine sandy loam; common (5%) fine prominent yellowish brown (10YR 5/8) and common (15%) medium prominent light yellowish brown (2.5Y 6/3) masses of iron accumulations; common (10%) fine distinct light gray (2.5Y 7/2) masses of iron depletions; common (2%) clean washed sand grains; weak coarse subangular blocky structure; few very fine and fine roots; clear wavy boundary.

Btg/Eg--24+ cm; 75% grayish brown (2.5Y 5/2) sandy clay loam and 25% grayish brown (2.5Y 5/2) fine sandy loam; many (25%) medium prominent brownish yellow (10YR 6/6) masses, common (5%) fine prominent yellowish brown (10YR 5/8)masses, common (15%) medium distinct light yellowish brown (2.5Y 6/3) masses, and common (5%) fine prominent yellowish red (5YR 4/6) pore linings of iron accumulations; common (10%) fine distinct light gray (2.5Y 7/2) and common (5%) medium distinct gray (10YR 6/1) masses of iron depletions; common clean washed sand grains; moderate coarse subangular blocky structure and weak coarse subangular blocky structure; few faint clay films on faces of peds in pockets; few very fine and fine roots.

Location: Hall Plot 6
Land use Represented: Bare ground

TOMOTLEY SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine-loamy, mixed, semiactive, thermic Typic Endoaqualfs

Ap--0 to 13 cm; dark grayish brown (10YR 4/2) fine sandy loam; common (2%) fine distinct strong brown (7.5YR 4/6) masses and many (15%) fine distinct strong brown (7.5YR 5/6) pore linings of iron accumulations; common (2%) pockets of light yellowish brown (2.5Y 6/3) E horizon material; moderate medium granular structure; many very fine and medium roots; abrupt smooth boundary

Eg--13 to 26 cm; light brownish gray (2.5Y 6/2) fine sandy loam; common (2%) fine prominent yellowish brown 10YR 5/8 pore linings; common (10%) fine prominent strong brown (7.5YR 5/6) and common (10%) fine prominent brownish yellow (10YR 6/6) masses many (30%) medium faint light yellowish brown (2.5Y 6/3) masses of iron accumulations; weak coarse subangular blocky structure; few very fine and fine roots; clear wavy boundary.

Btg/Eg--26 to 45+ cm; 75% light brownish gray (2.5Y 6/2) clay loam and 25% light brownish gray (2.5Y 6/2) fine sandy loam; many (20%) medium prominent strong brown (7.5YR 5/6) and common (10%) fine prominent brownish yellow (10YR 6/6) masses of iron accumulations; common (10%) medium faint gray (2.5Y 6/1) masses of iron depletions; moderate medium subangular blocky structure; few very fine and fine roots.

Location: Hall Plot 7
Land use Represented: Field

TOMOTLEY SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine-loamy, mixed, semiactive, thermic Typic Endoaqualfs

Oe and Oi --0 to 0.5 cm dark grayish brown (10 YR 4/2) hemic and fibric material; structureless, massive; many very fine and fine roots; abrupt smooth boundary

Ap—0.5 to 15 cm; dark grayish brown (10YR 4/2) fine sandy loam; few (1%) fine prominent yellowish red (5YR 4/6) pore linings and common (2%) fine prominent strong brown (7.5YR 5/6) pore linings and masses of iron accumulations; common (5%) fine prominent light gray (2.5Y 7/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; moderate coarse subangular blocky structure; many very fine to fine roots; abrupt wavy boundary.

E--15 to 22 cm; light yellowish brown (2.5Y 6/3) fine sandy loam; common (5%) fine prominent yellowish brown (10YR 5/8) masses of iron accumulations; common (10%) fine faint light gray (2.5Y 7/2) masses of iron depletions; common pockets of clean washed sand grains; structureless, massive; few very fine roots; clear wavy boundary.

E/Bt--22 to 45 cm; 75% light yellowish brown (2.5Y 6/3) fine sandy loam and 25% strong brown (7.5YR 5/6) sandy clay loam; common (5%) fine prominent yellowish brown (10YR 5/8) and common (10%) coarse prominent yellowish red (5YR 5/6) masses of iron accumulations; few (1%) manganese concentrations; common (10%) fine prominent light gray (2.5Y 7/2) and common (2%) fine faint light brownish gray (2.5Y 6/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; weak medium subangular blocky structure; few very fine roots; clear wavy boundary.

Bt/Eg--45+ cm; 75% yellowish brown (10YR 5/6) sandy clay loam and 25% light brownish gray (2.5Y 6/2) fine sandy loam; common (5%) fine prominent yellowish brown (10YR 5/8) and common (10%) coarse prominent yellowish red (5YR 5/6) masses of iron accumulations; few (1%) manganese concentrations; common (10%) fine prominent light gray (2.5Y 7/2) and common (2%) fine faint light brownish gray (2.5Y 6/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; moderate medium subangular blocky structure; few very fine roots.

Location: Hall Plot 8
Land use Represented: Field

TOMOTLEY SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine-loamy, mixed, semiactive, thermic Typic Endoaqualfs

Oe and Oi--0 to 1 cm dark grayish brown (10 YR 4/2) hemic and fibric material; structureless, massive; abrupt smooth boundary.

Ap1--1 to 16 cm; gray (10YR 5/1) silt loam; common (5%) fine prominent yellowish red (5YR 4/6) pore linings and common (5%) fine prominent strong brown (7.5YR 5/6) masses of iron accumulations; weak coarse subangular blocky structure; many very fine to fine roots; abrupt smooth boundary.

Ap2--16 to 32 cm; dark gray (10YR 4/1) silt loam; common (15%) fine prominent yellowish red (5YR 4/6) masses of iron accumulations; common pockets of clean washed sand grains; structureless, massive; common very fine and fine roots; abrupt wavy boundary.

Eg/Btg--32 to 42 cm; 75% gray (10YR 5/1) loam and 25 % gray (10YR 5/1) loam; common (5%) fine prominent strong brown (7.5YR 4/6) pore linings and common (5%) fine distinct brownish yellow (10YR 6/6) masses of iron accumulations; common (2%) medium prominent gray (2.5Y 6/1) masses of iron depletions; weak medium subangular blocky structure; few faint clay films on faces of peds in pockets; few very fine roots; clear wavy boundary.

Btg--42+ cm; dark gray (10YR 4/1) silt loam; common (5%) fine prominent strong brown (7.5YR 4/6) pore linings, common (5%) fine distinct brownish yellow (10YR 6/6) masses and common (5%) fine prominent dark red (2.5YR 3/6) masses of iron accumulations; common (10%) medium prominent gray (2.5Y 6/1) masses of iron depletions; moderate medium subangular blocky structure; common faint clay films on faces of peds; few very fine roots.

Location: Hall Plot 9
Land use Represented: Forest

ACREDALE SERIES

TAXONOMIC CLASS: Fine-silty, mixed, active, thermic Typic Endoaqualfs

Oi--0 to 1 cm; dark brown (7.5YR 3/4) peat (fibric material); structureless, massive; many very fine to coarse roots; abrupt smooth boundary.
Oe--1 to 2 cm; dark reddish brown (5YR 3/4 broken face and rubbed) mucky peat (hemic material); structureless, massive; many very fine to medium roots; abrupt smooth boundary.
Oa--2 to 3 cm; dark reddish brown (5YR 3/4 broken face and rubbed) muck (sapric material) weak thin platy structure; many very fine to medium roots; abrupt smooth boundary.
A1--3 to 12 cm; dark brown (7.5YR 3/2) very fine sandy loam; strong medium granular structure; many very fine to medium roots; abrupt smooth boundary.
A2--12 to 21 cm; very dark gray (10YR 3/1) very fine sandy loam; few (1%) fine distinct strong brown (7.5YR 4/6) masses of iron accumulations; common (2%) pockets of clean washed sand grains; moderate medium subangular blocky structure; common very fine to medium roots; abrupt smooth boundary.
AE--21 to 30 cm; dark grayish brown (10YR 4/2) very fine sandy loam; common (8%) fine distinct strong brown (7.5YR 4/6) masses of iron accumulations; common (10%) medium prominent light gray (2.5Y 7/2) masses of iron depletions; common (2%) pockets of clean washed sand grains; moderate coarse subangular blocky structure; common very fine to fine roots; abrupt smooth boundary.
Eg--30 to 40 cm; dark grayish brown (2.5Y 4/2) very fine sandy loam; common (15%) medium prominent brownish yellow (10YR 6/6) masses of iron accumulations; many (20%) medium prominent light gray (2.5Y 7/1) masses of iron depletions; common (4%) pockets of clean washed sand grains; weak coarse subangular blocky structure; few very fine to fine roots; clear wavy boundary.
Btg/Eg--40+ cm; 75% grayish brown (2.5Y 5/2) sandy clay loam and 25% grayish brown (2.5Y 5/2) fine sandy loam; common (15%) medium prominent strong brown (7.5YR 5/6) and common (15%) coarse prominent brownish yellow (10YR 6/8) masses of iron accumulations; common (10%) medium faint dark grayish brown (2.5Y 4/2) masses of Eg material; moderate coarse subangular blocky structure; few very fine roots.

Location: Hall Plot 10
Land use Represented: Forest

ACREDALE SERIES

TAXONOMIC CLASS: Fine-silty, mixed, active, thermic Typic Endoaqualfs

Oi--0 to 1 cm; dark yellowish brown (7.5YR 3/6) peat (fibric material); structureless, massive; many very fine to coarse roots; abrupt smooth boundary.
Oe--1 to 2 cm; dark reddish brown (5YR 3/2 broken face and rubbed) mucky peat (hemic material) weak thin platy structure; many very fine to medium roots; abrupt smooth boundary.
A--2 to 7 cm; very dark brown (10YR 2/2) fine sandy loam; strong medium granular structure; many very fine to medium roots; abrupt smooth boundary.
AE--7 to 15 cm; very dark grayish brown (10YR 3/2) fine sandy loam; common (5%) fine distinct dark yellowish brown (10YR 4/6) masses of iron accumulations; common (10%) pockets of clean washed sand grains; moderate medium subangular blocky structure; common very fine to fine roots; abrupt smooth boundary.
Eg--15 to 33 cm; grayish brown (2.5Y 5/2) fine sandy loam; common (15%) fine distinct yellowish brown (10YR 5/6) and common (10%) fine prominent strong brown (7.5YR 5/6) masses of iron accumulations; common(15%) medium distinct light gray (2.5Y 7/2) masses of iron depletions; many (20%) pockets of clean washed sand grains; weak coarse subangular blocky structure; few very fine to fine roots; clear wavy boundary.
Btg/Eg--33 to 40+ cm; 75% light brownish gray (2.5Y 6/2) sandy clay loam and 25% light brownish gray (2.5Y 6/2) fine sandy loam; common (10%) fine distinct yellowish brown (10YR 5/6), common (10%) fine prominent strong brown (7.5YR 5/6) and common (10%) fine prominent reddish yellow (7.5YR 6/8) masses of iron accumulations; many (20%) medium faint light gray (2.5Y 7/2) masses iron depletions; weak coarse subangular blocky structure; few very fine roots.

Location: Bruff Plot 11
Land use Represented: Forest

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Please refer to Table 3-1.

Location: Hall Plot 12
Land use Represented: Forest

ROANOKE SERIES taxajunct – Alfisol instead of Ultisol

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaqualfs

Oi--0 to 0.5 cm; dark reddish brown (5 YR 2.5/2 broken face and rubbed) peat (fibric material); structureless, massive; many very fine to coarse roots; abrupt smooth boundary.

Oe--0.5 to 1 cm; dark reddish brown (5 YR 2.5/2 broken face and rubbed) mucky peat (hemic material) weak thin platy structure; many very fine to coarse roots; abrupt smooth boundary.

A1—1 to 4 cm; black (7.5YR 2.5/1) fine sandy loam; strong fine granular structure; many very fine to coarse roots; abrupt smooth boundary.

A2--4 to 12 cm; dark gray (10YR 4/1) silt loam; few (1%) fine distinct yellowish brown (10YR 5/4) pore linings of iron accumulations; common (10%) medium faint gray (10YR 5/1) masses of iron depletions; moderate medium subangular blocky structure; common very fine to coarse roots; abrupt smooth boundary.

Eg--12 to 37 cm; gray (2.5Y 5/1) silt loam; common (5%) fine prominent strong brown (7.5YR 5/6) pore linings; common (10%) medium distinct light olive brown (2.5Y 5/4) masses of iron accumulations; common (10%) fine faint gray (2.5Y 6/1) and common (10%) medium faint light gray (2.5Y 7/1) masses of iron depletions; weak coarse subangular blocky structure; common very fine to fine roots; clear wavy boundary.

Btg--37 to 40+ cm; dark gray (2.5Y 4/1) silty clay; common (10%) fine prominent yellowish brown (10YR 5/6) pore linings, common (10%) fine prominent strong brown (7.5YR 5/6) masses and common (10%) medium prominent reddish yellow (7.5YR 6/8) masses of iron accumulations; common (10%) fine faint gray (2.5Y 5/1) masses of iron depletions;
moderate medium subangular blocky structure; few very fine roots.

Appendix 3a. Chemical data for selected soils at study areas Bruff and Hall.

				†				‡	§					
Well	Horizon Name	Lower Depth	pH	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	H^{+}	Al^{+3}	CEC-7	Base Sat.	Total C	Total N	C/N
		cm		Cmol$_c$kg^{-1} of soil										Ratio
	Bruff Field													
B9	Ap1	10	5.45	3.04	0.17	0.11	0.01	3.20	0.20	6.54	51	1.611	0.113	14.21
	Ap2	18	5.16	1.99	0.19	0.07	0.05	2.80	1.50	5.10	45	0.877	0.054	16.20
	Eg	40	4.61	0.90	0.32	0.04	0.04	2.40	4.00	3.70	35	0.197	0.022	9.16
	Btg1	92	3.55	1.15	0.27	0.10	0.02	12.40	11.80	13.93	11	0.332	0.042	7.81
	Btg2	130	4.04	0.88	0.26	0.11	0.01	19.40	14.90	20.66	6	0.257	0.041	6.19
	2BCg	140	4.67	0.67	0.20	0.06	0.00	4.60	6.30	5.54	17	0.137	0.019	7.35
	2Cg1	192	4.56	0.45	0.02	0.01	0.04	0.00	1.00	0.52	100	0.029	0.005	5.85
	2Cg2	210	4.83	0.63	0.06	0.01	0.04	2.40	4.00	3.70	24	0.047	0.006	8.09
	Bruff Forest													
B2	A	13	3.79	1.01	0.40	0.13	0.03	17.20	6.90	18.76	8	4.418	0.217	20.40
	Eg	27	4.01	0.48	0.06	0.04	0.01	2.40	5.10	2.98	20	1.516	0.064	23.63
	Btg1	90	4.14	0.53	0.17	0.08	0.05	2.20	13.90	3.03	27	0.263	0.035	7.610
	Btg2	142	3.80	0.40	0.30	0.21	0.08	19.20	17.10	20.19	5	0.024	0.005	5.14
	2E	152	2.76	0.43	0.12	0.00	0.04	0.00	0.80	0.59	100	0.022	0.005	4.76
	2Bs	168	4.40	0.40	0.31	0.01	0.01	2.60	1.30	3.32	22	0.061	0.006	9.45
	2Cg	210	4.30	0.54	0.24	0.01	0.01	0.00	0.60	0.80	100	0.030	0.005	5.61
	Hall Field													
H3	Ap	22	4.37	0.93	0.14	0.10	0.00	0.00	1.60	1.18	100	0.741	0.065	11.41
	Eg	30	5.14	1.21	0.28	0.07	0.01	0.00	0.90	1.57	100	0.41	0.028	14.41
	Eg/Btg	40	4.79	1.49	0.37	0.12	0.01	3.00	3.00	4.99	40	0.227	0.025	9.17
	Btg1	90	5.19	2.19	1.89	0.08	0.04	0.00	2.80	4.20	100	0.14	0.02	6.87
	Btg2	120	4.56	1.64	3.98	0.07	0.00	0.00	1.10	5.69	100	0.067	0.014	4.96

Appendix 3a. (continued)

				†				‡	§					
Well	Horizon Name	Lower Depth	pH	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	H^{+}	Al^{+3}	CEC-7	Base Sat.	Total C	Total N	C/N
		cm		-------------------------------------- $cmol_c kg^{-1}$ of soil --										Ratio
	Bt	165	6.05	1.25	2.03	0.06	0.05	0.00	0.30	3.39	100	0.057	0.011	4.96
	2BC	180	5.14	0.74	0.50	0.02	0.02	0.00	0.20	1.28	100	0.033	0.006	5.87
	2Cg	205	5.10	0.74	0.41	0.02	0.02	0.00	0.20	1.19	100	0.026	0.004	5.93
H7	Ap	15	4.55	1.05	0.21	0.12	0.00	1.60	0.90	2.99	46			
	E	22	4.84	0.92	0.16	0.08	0.00	6.00	1.90	7.17	16			
	E/Bt	45	4.95	1.23	0.32	0.06	0.01	2.80	1.50	4.42	37			
	Bt/E	45+	5.15	2.25	2.80	0.07	0.05	2.20	2.00	7.36	70			
H8	Ap1	16	5.10	3.28	1.18	0.22	0.02	10.40	1.70	15.10	31			
	Ap2	32	5.05	3.45	1.31	0.11	0.05	0.00	1.90	4.92	100			
	Eg/Btg	42	4.81	2.28	0.92	0.05	0.03	0.00	2.70	3.28	100			
	Btg	42+	4.70	3.64	3.53	0.11	0.21	12.60	6.20	20.09	37			
Hall Forest														
H11	A	8	3.73	1.77	0.84	0.21	0.02	33.60	7.40	36.44	8	9.886	0.501	19.73
	AE	13	4.18	0.57	0.14	0.06	0.03	0.00	5.30	0.80	100	1.591	0.089	17.91
	Eg	35	4.35	0.59	0.21	0.05	0.04	0.00	4.90	0.88	100	0.574	0.038	15.25
	Btg/Eg	50	4.64	1.15	1.25	0.08	0.12	0.00	7.20	2.60	100	0.250	0.030	8.43
	Btg1	100	4.97	2.02	8.21	0.16	0.40	0.80	8.70	11.59	93	0.188	0.03	6.20
	Btg2	130	4.96	2.10	17.76	0.15	0.48	0.00	3.30	20.48	100	0.088	0.016	5.47
	2BCg	160	5.50	1.39	1.99	0.05	0.14	0.00	0.40	3.57	100	0.029	0.009	3.31
	2BC	180	5.62	1.33	1.28	0.04	0.10	0.00	0.10	2.75	100	0.034	0.007	4.77
	2Cg	210	5.10	1.13	0.64	0.04	0.06	0.00	0.10	1.86	100	0.049	0.007	7.20

Appendix 3a. (continued)

				†				‡	§					
Well	Horizon Name	Lower Depth	pH	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	H^{+}	Al^{+3}	CEC-7	Base Sat.	Total C	Total N	C/N
		cm		-- $cmol_c kg^{-1}$ of soil --										Ratio
H12	A1	4	3.89	1.32	0.56	0.22	0.02	15.20	7.40	17.31	12			
	A2	12	3.77	1.01	0.42	0.16	0.00	0.00	7.00	1.59	100			
	Eg	37	4.71	1.77	0.37	0.04	0.04	8.40	5.10	10.61	21			
	Btg	40+	7.07	12.90	2.28	0.21	0.20	0.00	0.00	15.59	100			

† Extracted by NH_4Oac @ pH 7.0

‡ Extracted by $BaCl_2$-TEA @ pH 8.2

§ Extracted by KCl @ Soil pH

Appendix 3b. Particle-size distribution data for selected soils.

Well	Horizon	Lower Depth	Sand						Silt	Clay
			VC	C	M	F	VF	Total		
		cm	-- % ---							
			Bruff Field							
B9	Ap1	10	0.0	1.9	7.0	31.7	8.9	49.4	44.9	5.7
	Ap2	18	0.1	0.7	6.0	31.7	9.3	47.8	44.9	7.3
	Eg	40	0.1	0.2	4.0	30.6	8.0	42.9	41.6	15.4
	Btg1	92	0.1	0.1	1.9	15.9	5.3	23.4	37.5	39.1
	Btg2	130	0.0	0.1	1.1	8.2	5.0	14.5	38.9	46.6
	2BCg	140	0.0	0.1	4.4	56.4	9.7	70.6	13.8	15.6
	2Cg1	192	0.2	0.5	15.9	75.5	4.4	96.6	0.4	3.0
	2Cg2	210	0.4	1.5	39.6	53.3	1.4	96.2	1.8	2.0
			Bruff Forest							
B2	A	13	0.8	10.6	11.3	26.1	10.4	59.3	37.4	3.3
	Eg	27	0.2	1.6	7.1	26.9	12.5	48.3	47.4	4.3
	Btg1	90	0.0	0.3	2.1	16.7	9.4	28.4	40.2	31.4
	Btg2	142	0.0	0.2	1.8	8.2	3.1	13.3	38.9	47.8
	2E	152	0.0	0.4	19.3	73.2	2.6	95.5	3.6	0.9
	2Bs	168	0.2	0.1	8.5	85.3	3.0	97.1	0.2	2.7
	2Cg	210	0.1	0.0	4.5	87.5	4.9	97.0	2.6	0.4
			Hall Field							
H2	Ap	26	0.1	2.0	2.5	22.6	11.1	38.3	53.7	7.9
	Btg	50	0.2	0.2	0.5	15.3	10.6	26.8	52.9	20.3
H3	Ap	22	0.1	0.9	6.1	39.5	9.2	55.8	40.4	3.8
	Eg	30	0.0	0.3	3.3	50.6	8.1	62.3	33.9	3.8
	Eg/Btg	40	0.0	0.2	2.2	30.4	10.8	43.6	40.2	16.1
	Btg1	90	0.0	0.2	1.1	57.7	7.6	66.6	11.8	21.6

Appendix 3b. (continued)

Well	Horizon	Lower Depth	Sand						Silt	Clay
			VC	C	M	F	VF	Total		
		cm	--- % ---							
H3	Btg2	120	0.1	0.0	1.1	44.6	14.9	60.8	21.1	18.2
	Bt	165	0.0	0.1	1.3	57.2	14.2	72.8	16.7	10.5
	2BC	180	0.0	0.0	2.4	88.9	3.1	94.4	3.1	2.5
	2Cg	205	0.0	0.0	3.6	87.0	0.9	91.5	7.6	0.9
H4	Ap1	26	0.2	0.6	1.6	4.6	15.2	22.1	62.8	15.1
	Btg	40	0.2	0.5	0.8	0.3	11.7	13.6	46.4	40.0
H7	Ap	15	0.0	1.9	6.8	49.7	7.3	65.8	29.3	4.8
	E	22	0.1	0.3	2.2	36.5	13.6	52.7	38.5	8.8
	E/Bt	45	0.2	0.1	2.9	48.9	8.4	60.6	27.6	11.8
	Bt/E	45+	0.0	0.1	2.0	48.3	8.9	59.3	19.4	21.2
H8	Ap1	16	0.1	1.8	5.0	20.3	2.1	29.3	59.1	11.5
	Ap2	32	0.0	0.8	4.7	20.2	7.1	32.7	50.8	16.5
	Eg/Btg	42	0.1	0.2	2.7	23.3	6.3	32.7	46.3	21.1
	Btg	42+	0.1	0.1	1.5	15.6	4.3	21.5	52.2	26.3
			Hall Forest							
H11	A	8	11.4	18.4	14.8	17.2	10.3	72.1	21.9	5.9
	AE	13	0.3	3.6	6.3	23.5	8.8	42.5	49.0	8.5
	Eg	35	0.1	1.1	3.7	20.7	10.6	36.3	50.0	13.6
	Btg/Eg	50	0.0	0.1	0.8	13.8	7.8	22.6	48.2	29.2
	Btg1	100	0.1	0.1	0.6	7.7	11.3	19.8	36.8	43.4
	Btg2	130	0.0	0.2	1.5	25.7	9.6	37.1	35.1	27.9
	2BCg	160	0.0	0.1	4.8	80.3	0.1	85.3	6.8	7.9
	2BC	180	0.0	0.0	0.6	86.8	2.8	90.2	2.7	7.1

Appendix 3b. (continued)

Well	Horizon	Lower Depth	Sand						Silt	Clay
			VC	C	M	F	VF	Total		
		cm	--- % ---							
H11	2Cg	210	0.0	0.0	0.3	83.9	7.3	91.5	8.5	0.1
H12	A1	4	12.7	16.5	10.9	11.4	7.9	59.4	38.8	1.9
	A2	12	0.9	16.2	9.9	10.6	8.4	46.0	51.6	2.3
	Eg	37	0.3	0.7	1.4	8.9	6.5	17.8	65.9	16.3
	Btg	40+	0.7	0.5	0.7	2.7	4.2	8.9	48.2	42.9

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Appendix 3c. Bulk density data for selected soils.

Well	Horizon	Lower Depth	Bulk Density				
			1	2	3	4	Avg.
		-- cm --	-------------------- Mg m^{-3} ---------------------				
B9	Ap1	10	1.42	1.63	1.77	1.21	1.51
	Ap2	18	1.66	1.70	1.52		1.62
	Eg	40	1.79	0.00	1.84		1.21
	Btg1	92	1.68	1.65	1.76		1.70
B2	A	13	0.99	1.18	0.76		0.98
	Eg	27	1.47	1.50	1.39		1.46
	Btg1	90	1.58	1.45	1.57	1.66	1.56
H3	Ap (untilled)	22	1.31	1.37	1.06	1.13	1.22
	Ap (tilled)	22	1.56	1.52	1.53	1.51	1.53
	Eg	30	1.77	1.69	1.66	1.71	1.71
	Eg/Btg	40	1.63	1.72	1.54	1.73	1.65
H11	A	8	0.44	0.73	0.59		0.59
	AE	13	0.95	1.21	1.10		1.09
	Eg	35	1.38	1.61	1.67	1.71	1.59
	Btg/Eg	50	1.57	1.50	1.49		1.52

Vita

Amanda Corrine Burdt was born on June 20, 1978 in Baltimore, Maryland. Amanda is daughter to Stephen Burdt of Fairfax, Virginia and Diana Kies of Houston, Texas. She has three older sisters, Elizabeth Katan of Michigan, Sarah Burdt of California, and Christine Burdt of Florida. Amanda was raised in Fairfax, Virginia until graduation from J.W. Robinson Secondary School in 1996. In the fall of 1996, she became an undergraduate in the College of Natural Resources and the Environment at University of Florida, in Gainesville, Florida. During her junior year, Amanda began an undergraduate research project investigating the correlation of cation exchange activity classes to major land resource regions in Florida under Drs. John Galbraith and Mary Collins. In 2000, Amanda graduated cum laude with a major in Environmental Science and minors in Soil and Water Science and Agriculture and Environmental Ethics. Amanda began working with Dr. John Galbraith on a Master of Science degree in Crop and Soils Environmental Sciences (CSES) at Virginia Polytechnic Institute and State University in Blacksburg, Virginia. As a graduate student, Amanda was given the opportunity to assist in teaching several courses in the CSES department, including Basic Soils Laboratory and Soil Survey and Taxonomy. During her residence at CSES she was recognized with the Pi Sigma Biological Honor Society Outstanding Master's Research, the Virginia Tech Obenshain Scholarship, the Water Policy Institute Scholarship, and the Virginia Water Environment Association Scholarship. Amanda is a member of Soil Science Society of America, Society of Wetland Scientists, and Gamma Sigma Delta Honor Society. Amanda was hired as a wetland soil scientist by Wetland Studies and Solutions of Chantilly, Virginia and is currently pursuing professional certification. Amanda graduated from Virginia Polytechnic Institute and State University with a Master of Science degree in CSES in May 2003.