AERIFICATION TINE EFFECTS ON TIFWAY BERMUDAGRASS ATHLETIC FIELDS

Except where reference is made to the work of others, the work described in this thesis is my own or done in collaboration with my advisory committee.

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AERIFICATION TINE EFFECTS ON TIFWAY BERMUDAGRASS ATHLETIC FIELDS

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AERIFICATION TINE EFFECTS ON TIFWAY BERMUDAGRASS ATHLETIC FIELDS

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Wyman Garlon Rainey III, son of Wyman and Patricia Rainey, was born October 26, 1971 in Mobile, Alabama. He graduated from Mobile Christian School in 1990. Prior to enrolling at Auburn University, he graduated *cum laude* from Faulkner State Junior College with an Associate in Science Degree in Agribusiness Economics. In the summer of 2000 he entered Auburn University and graduated *cum laude* in 2001 with a Bachelor of Science degree in Agronomy and Soils. In the summer of 2001 he was accepted into the Graduate School at Auburn University. He received a Master of Science degree in Agronomy and Soils in May, 2009.

THESIS ABSTRACT

AERIFICATION TINE EFFECTS ON TIFWAY BERMUDAGRASS ATHLETIC FIELDS

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Although commonly practiced, there is little research examining the effect of aerification tine type (hollow or solid) and length on athletic fields. The objective of this research was to evaluate different aerification tines of varying depth and shape (hollow versus solid), examining their effect on soil hardness, compaction, duration of effects, and turf quality on 'Tifway' bermudagrass. Treatments were: 1) standard depth hollow tine (GA60H) (10 cm long, 1.9 cm diam.), 2) standard depth solid tine (GA60S) (10 cm long, 1.9 cm diam.), 3) deep depth hollow tine (SRH) (20 cm long, 2.2 cm diam.), 4) deep depth solid tine (SRSDST) (20 cm long, 2.2 cm diam.), 5) pull behind drum type aerifier with hollow tines (PB) (9.5 cm long, 0.7 cm diam),and, 6) a non-aerified control. Four replications of each treatment were applied at the Auburn University football practice field in May, June, July, and August of 2001 and 2002, and five replications of each treatment were applied at the Auburn University Turfgrass Research Center in May, June, July and August of 2002 and 2004. The experimental design was an incomplete factorial arrangement of aerification equipment and tine type, arranged as a randomized complete block design with four replications at the Practice Field and five replications at the TGRU. Treatments were applied to a Marvyn loamy sand at each location. Collected data included soil resistance as measured by a penetrometer, surface hardness as measured with an impact hammer, shoot density, thatch depth and dry root weight. Penetrometer readings revealed hollow tine use reduced soil penetration resistance over a 0-24 cm depth. There was no difference in soil resistance in plots that were nonaerified or had been aerified with the pull behind equipment. Any treatment that utilized a hollow tine had a softer surface (as measured via impact readings) than those aerified with solid tines. After two years the beginning of an aerification hard pan was detected in treatments aerified with the standard depth solid tine. Although root density and shoot density were sometimes affected by treatment, the differences were not consistent across sites and years. Best long-term and deep relief of soil compaction was afforded by use of deep aerification tines that were hollow.

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DEDICATION

I would like to dedicate my thesis to my loving wife Holly, and my two wonderful children, Haley and Ella. Their love and support has been an inspiration throughout this project.

I would also like to dedicate this thesis to my parents who have given me every opportunity to be successful and have encouraged me to follow my dreams.

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I. LITERATURE REVIEW

Introduction

As athletic fields increase in number and quality in the southeastern U.S., a greater emphasis is being placed on the quality of the playing surface. The quality of an athletic field is determined by many factors, including field safety for the athletes, playability (correct ball bounce and roll, etc.), and appearance. To meet these diverse requirements, a playing surface must have secure footing, high shoot density and uniformity, be firm but not hard, and have a dark green color (Miller, 2003). Obtaining a high quality athletic field requires many inputs, including water, fertilizer, pest control and viable sod. As participation in recreational and interscholastic sports continues to increase, well-used and tired fields become overused, unplayable and even unsafe. Enhancing the recuperative potential of the turf with proper maintenance practices becomes even more important to field performance (Calhoun et al., 2002).

One key to the promotion of turf recuperation is cultivation. Turfgrass cultivation can take many forms, including vertical mowing, core or solid tine aerification and topdressing. Whatever the method, they are all similar in one respect: the cultivation method must not dramatically alter the turfed surface, as field playability must continue, regardless of the cultivation method. In general, turf cultivation helps relieve soil compaction, eliminate thatch accumulation, smooth and soften the playing surface, and help divots or tears repair (Landry and Murphy, 2001).

Unlike home lawns or golf courses, athletic field turf has a dual concern: one must have quality turf while protecting players against injury (Sanderson, 1979; Miller, 1969). For example, the ability of turf to absorb shock is an important factor in reducing knee and ankle ailments that result from a hard playing surface (Madison, 1971). A study conducted on high school football injuries showed that 20.9 percent of the 210 injuries were linked to field conditions (Harper et al., 1984). An overcompacted football field with thin turf or bare ground forces players to compete on a hard, less favorable surface that prevents good traction (or, in wet weather, on a field of mud) (Puhalla et al., 1999).

Bermudagrass

Turfgrasses are plants that form a more or less contiguous ground cover that persists under regular mowing and traffic (Turgeon, 1991). The turfgrass used on athletic fields in the southern U.S. is most commonly hybrid bermudagrass (*Cynodon dactylon* Burtt Davy *x C. transvaalensis*). Because these bermudagrasses are hybrids, they must be planted via sprigging or sodding, as viable seed is not available. Some southern athletic fields may also be common bermudagrass (*C. dactylon*), a coarser, more open turf than hybrid bermudagrass. In intensively managed sports fields, perennial ryegrass (*Lolium perenne L.*) will be overseeded into dormant bermudagrass during the fall and winter to add green color and wear resistance (Puhalla et al., 1999).

Ability to recover from injury and wear tolerance are characteristics that make bermudagrass a favorite sports turf (Boyd, 1990). ‘Tifway’, ‘TifSport’, and ‘Tifway II’ are the most commonly selected hybrid bermudagrasses. These hybrids are selected for their superior color, texture, density, and growth habits. Hybrid bermudagrass also tolerates close, frequent mowings, from 2.5 cm for athletic turf to 0.3 cm for putting greens (Trenholm et al., 2000; Hanna et al., 1997).

The most common turfgrass for athletic field use in the southeast is Tifway, also known as ‘419’. Tifway is a cross between *Cynodon transvaalensis* and *Cynodon dactylon*. Tifway bermudagrass is a highly disease-resistant selection with a very dark green color (Burton, 1966). Its dark green color, medium texture and aggressive growth habits have made it the most commonly chosen turfgrass for southern athletic fields. Tifway spreads rapidly and forms a dense turf that is exceptionally resistant to wear (Adams and Gibbs, 1994). Because it is a hybrid, Tifway is only available as vegetative material and must be sprigged or sodded for establishment. It is the current standard used in warm-season areas for quality fairways, most roughs, and sports fields (McCarty, 2001). It is a very resilient turfgrass that is capable of sustaining the heavy traffic that is often associated with athletic fields.

Tifway II is planted less frequently than Tifway or TifSport. Tifway II was developed by exposing dormant sprigs of Tifway to 9000 rads of gamma irradiation, growing plants from the treated sprigs, and selecting plants or sectors of plants that were altered. Tifway II looks similar to Tifway and has also many desirable characteristics. In addition to the benefits of Tifway, Tifway II was released because it makes a denser, more weed-free turf, is more resistant to nematodes, is more frost tolerant, establishes faster from sprigs, exhibits better quality, and often greens up earlier in the spring (Burton, 1985). In spite of these benefits, Tifway II never gained wide-spread use, and it failed to remove Tifway as the favorite bermudagrass for athletic fields.

TifSport (originally called Tift94), a 1997 hybrid release, has become a popular choice on athletic fields. An induced gamma irradiated mutant from ‘Midiron’ bermudagrass, TifSport is only available as a vegetative hybrid. TifSport has a growth habit and texture similar to Tifway. It tolerates close mowing, has good turf quality, good greenup characteristics and resists the southern mole cricket (Hanna et al., 1997). One of the main advantages of TifSport is superior cold tolerance (Hanna and Anderson, 2008). It has shown good winter hardiness in Georgia, Kentucky, Tennessee and Oklahoma (McCarty, 2001). TifSport has less contamination or “off types” than other grasses due to its relatively new release and stringent certification standards for ‘Tifsport’ producers (Tifsport.com).

Common bermudagrass (*Cynodon dactylon*) is a popular choice for lower budget athletic fields. Unlike the interspecific hybrids, common bermudagrass can be established from seed, sprigs or sod. This renders it more cost effective and easier to establish and maintain in low budget applications. However, common bermudagrass produces a more open turfgrass with a coarse texture, low shoot density, and a light green color (Brosnan and Deputy, 2008). Another reason to choose common bermudagrass is its cold tolerance. This trait allows it to be used farther north than many hybrids (Anderson et al., 2002).

Athletic Field Construction

One factor that affects the safety, playability and maintenance of an athletic field is the type of construction. The selection of a field is often dictated by site location and construction budget, with the suitability of the soil at that site often considered to be of secondary importance. A properly constructed sports field maintains a healthy turf under heavy use and under all weather conditions (Peterson, 1974). Design and construction choices affect the growing medium selected, which directly affects playing surface conditions and maintenance practices. There are various types of athletic field construction, but the most common are: 1) the sand-based type, which is based on recommendations from the United States Golf Association (USGA) for putting green construction, 2) native soil (‘push-up’ or ‘in-situ’), and, 3) a specialty field such as the prescription athletic turf field (Daniel et al., 1974). Each of these field types has advantages and disadvantages that vary based upon location, amount of play, and budget limitations.

The most common type of construction at the low to mid budget level is the native soil field. Historically, the construction of sports grounds has consisted only of leveling and planting of turfgrass (Peterson, 1974). These fields were the standard until the mid-1960s. The native field design is selected primarily because of lower construction and maintenance costs than those associated with sand-based athletic fields. Native soil fields are often too high in silt and clay content. Even with the best management, fine textured soils are often unsatisfactory for athletic field use as drainage can be an issue (Henderson et al., 2005). Additionally, field characteristics vary widely due to the variability of soil types among locations. In many cases native soil fields provide an adequate playing surface (Puhalla et al., 1999). Construction savings are achieved by utilizing the soil that is on site to construct the field, thereby eliminating the costs that are associated with transporting and purchasing root zone materials necessary for the construction of sand based fields.

Native soil fields are often constructed with a crown to aid in the removal of surface water. The use of a crown in the construction process is also a cost savings because it reduces the need for expensive underground drainage to remove the water from the playing surface. Native soil fields generally contain a higher cation exchange capacity, higher organic matter content, and a better pH buffering capacity than sand based athletic fields. This is because native fields will typically have a higher clay or silt content than sand-based fields. Such characteristics decrease the need for fertilizer and irrigation applications, making these fields a natural fit for lower budget facilities. However, fields constructed from soils with poor internal drainage or other limitations (layering, etc) may function poorly as an athletic field base. Disadvantages of a native soil field were demonstrated in a study that showed as clay and silt increased in field soil, the quality of the turf decreased (Peterson, 1974). The poor quality playing surface was determined to be a result of soil compaction, making a native soil field a poor choice in wet or high use situations.

In recent years sand-based athletic fields have become an increasingly popular choice of design among both newly constructed and renovated fields. Sand-based athletic fields use a root zone mix that is predominately sand, providing a root zone of uniform texture that is less prone to soil compaction (Hummel, 1993). Sand-based root zones also allow for rapid drainage, which allows play to resume shortly after rainfall. There are many different ways to construct a sand-based field, however two primary designs are most often used or modified when building a sand-based field.

The first and least complex method is the United States Golf Association (USGA) design (USGA Green Section Staff, 1993). This design was created for golf courses, but has been incorporated into athletic field design. This design incorporates a system of layering sand and gravel in an effort to achieve rapid drainage while maintaining a perched water table. The perched water table helps to compensate for the low water retention of the sand in the root zone (Emmons, 1984). The basic design is a 30 cm layer of root zone mix that is composed of medium-textured sand and a soil amendment. The amendment is usually an organic material such as reed sedge peat or sphagnum peat moss, mixed on a volume basis of 80% sand and 20% peat. Immediately below the root zone mix is a 5 to 10 cm intermediate layer of very coarse sand and fine gravel (1 mm to 4 mm). Below the intermediate layer is a 10 cm layer of (6 mm to 9 mm) pea gravel. Underneath the layer of pea gravel is a network of 10 mm corrugated pipes or drain tiles buried in pea gravel trenches. The pipe is spaced at 5 m intervals and is buried in pea gravel trenches that are a minimum of 15 cm wide and 20 cm deep (USGA Green Section Staff, 1993). The design allows the perched water table to work because the water will not pass through the root zone mix until a point near saturation is reached. At this point the water begins to drain through the root zone and through the gravel before reaching the drainage pipes (Puhalla et al., 1999).

The more complex Prescription Athletic Turf (PAT) system was designed to meet the demanding needs of an athletic field setting (Daniel et al., 1974). The system was invented by the late Dr. William Daniel at Purdue University. It consists of a flat subgrade with shallow, wide v-shaped trenches, which house the collector drainage mains. The subgrade is then covered with (10 mil) sheets of heavy plastic which overlap 30 cm and are fused together with tape to ensure a watertight seal. This step ensures that the soil moisture level can be controlled inside the system with little outside influence.

On top of the plastic sheeting a series of drainage pipes are connected to the collector mains at 5 m intervals. The removal of the water is achieved with the help of a dual diaphragm pump system capable of removing a minimum of 2.5 cm of rain/hour (Daniel et al., 1974). Above the drainage system is the root zone mix, which consists of a 30 to 50 cm sand layer of which more than two-thirds consists of medium and fine fractions. The top 10 cm is then amended with peat and fertilizer. PAT construction allows for a totally flat and level playing surface with no surface runoff. The lack of slope creates a uniform, consistent and unobstructed playing surface. However, the primary advantage of the PAT system is the total control over soil moisture. Safe, quality play can be maintained even during periods of high rainfall and heavy traffic. This is crucial because the degree of soil compaction resulting from traffic depends on force applied and soil properties, especially soil water content (Meek et al., 1992). With the pumping system in operation, infiltration rates as high as 60 cm/hour are achieved. The pumping system not only increases the hydraulic gradient for water removal, but it can also be used before a game to provide the exact root zone moisture desired for optimal playing surface conditions (Daniel et al., 1974). PAT systems are quite expensive, and are usually limited to use by top college and professional programs.

Athletic Field Management Practices

Increased publicity through television, combined with increasing player salaries and safety concerns, have raised expectations for athletic field quality to a higher level. Turf quality has been directly linked in reducing athletic injuries (Gramckow, 1968). The reduction and prevention of injuries in a violent contact sport such as football is a major concern (Harper et al., 1984). To ensure a healthy stand of turf, acceptable cultural practices must be employed. Acreage maintained on an athletic field is small in comparison to a golf course. For example, a football field, with sidelines and end zones, represents about 1 ha of turfed surface. However, traffic on athletic fields is often more rigorous and highly concentrated, creating very difficult conditions to manage. This is especially true on multi-use fields where even the best management practices cannot overcome excessive traffic.

Mowing

Mowing is one of the most routine and important practices required to maintain a quality stand or turfgrass. Two important factors involved with mowing are frequency of cut and mowing height. Bermudagrass responds to frequent and close mowing by initiating new shoots, which is conducive to a thicker and more wear resistant turf (Duble, 1996). Recommended mowing heights vary between species and varieties. Mowing frequency is often determined by the one-third rule (Puhalla et al., 1999). This rule states that in order to maintain a healthy turfgrass system, no more than one-third of the leaf blade should be removed in one mowing. The type of mower selected also plays a vital role in the quality of the turfgrass being maintained. The 3 major types of mowers are reel, rotary, and flail.

The most desirable mower on athletic fields is a sharp, well adjusted reel mower (Peacock, 1984). The reel is constructed of a series of blades that form a horizontal cylinder that guides the leaf blades to the bed knife. The bed knife in conjunction with the reel blades provide a clean scissor-type cut (Beard, 1973). The reel mower cut is more aesthetically pleasing and injury related to mowing is reduced. Due to the close proximity of the front and rear rollers and the scissor-type action on reel mowers, scalping is reduced and undulations are followed closely, as compared to other types of mowing equipment. Reel mowers are the best option on closely mowed turf less than 2.5 cm. Effective reel mower cutting heights range from 0.3 to 0.6 cm.

Rotary mowers are also commonly used to maintain athletic fields and are the most affordable method of mowing (Puhalla et al., 1999). Cutting is achieved by a horizontal sharpened blade, attached to a vertical shaft which rotates at high speeds. Grass blades are cut by impact alone. The primary advantage of rotary mowers is their overall economy and ability to reduce taller grasses and weeds to smaller clippings or mulch (Madison, 1971). The quality of cut produced is not acceptable for highly maintained turf areas (Emmons, 1984). The result of using rotary mowers is more frequent scalping and grass blade mutilation, which appears as brown, torn leaf tips (Beard, 1973). Rotary mowers are generally limited to cutting heights of 2.5 cm or greater.

Flail mowers are constructed of vertical free swinging blades or knives attached around a horizontal rotating drum. The blades are held out by centrifugal force as the drum rotates. The discharge associated with flail mowers is not as severe as with rotary mowers due to the give of the free swinging blades (Puhalla et al., 1999). The quality of cut is determined by blade spacing and sharpness and is generally between that of the reel and rotary mowers. The small diameter of the drum, combined with full width front and rear rollers make scalping less frequent than with rotary mowers (Beard, 1973). Flail mowers are often used on utility and roadside turf, although newer models are being used on higher-end turf such as fairways or athletic fields. Flail mowers have a range of effective cutting heights from 2 to 15 cm.

Fertilization

Proper fertilization is also a critical component of athletic field management. Not all nutrients are needed in large quantities, but there are at least 16 essential elements for optimal turfgrass growth. Three of these elements: carbon, hydrogen, and oxygen, can be obtained from air and water and are readily available to turfgrass (Emmons, 1994). Fertility levels affect color, form, density, vigor, weediness, and levels of stress (Madison, 1971). The essential elements most commonly applied to turfgrass are the macronutrients nitrogen (N), phosphorous (P), and potassium (K).

Nitrogen is the single most applied element for the management of turfgrass. It is an essential component of plant biochemical make-up such as chlorophyll, amino acids, proteins, enzymes, vitamins and many other areas (Christians, 1998). Nitrogen supply is also directly related to both root/shoot ratio and rooting patterns (Adams and Gibbs, 1994). Application recommendations for warm season athletic fields generally range from .56 kg/ha to 1.1 kg/ha/month during the active growing season. Factors that are associated with higher N fertility include more aeration, lower bulk density, fewer weeds and greater cover (Harper et al., 1984). To maintain an adequate supply of plant available N in the root zone, frequent, small applications of N should be made to meet the recommendations (Schroeder and Sprauge, 1994). Due to the different processes through which N can be lost, and the potential for rapid loss, soil testing is not a reliable method to detect deficiencies. The primary method for identifying N deficiencies is through color and quality.

Phosphorus is another major element involved in turfgrass maintenance. Phosphorus is involved in the transfer of energy and in storage (Christians, 1998).

Although present in large quantities in the soil, a large portion of that P is unavailable to plants. This is because P is rapidly converted into plant unavailable forms via complexation with iron, calcium or aluminum in the soil. Although the pool of total P in the soil is large, the plant available P is small. The primary source of P for turfgrass is through fertilization, with P applied according to soil test recommendations (Duble, 1996). P soil test recommendations required to maintain adequate soil P levels, are highly variable and depend upon the soil type, climate, crop being grown and extraction method (Carrow et al., 2004). These levels should be based on soil testing.

Potassium is the last of the 3 elements most often applied to turfgrasses. Potassium is a cofactor in plants, in that it aids in forming plant constituents, but does not become part of them (Spalding et al., 1999). It serves an important role in controlling plant stress. One of the primary functions of K is opening and closing the stomates as environmental conditions change. This controls the exchange of gases and controls water loss. In turfgrass, K is often over-applied because of the perception that K prevents winter kill. Although fairly widely studied, turfgrass response to excess K application is mixed and positive benefits such as reduced winter kill or greater quality were not always shown. Some research has shown that balanced fertility with adequate late summer potassium can improve cold resistance in bermudagrass (Gilbert and Davis, 1971). The primary method for analyzing potassium is through soil testing.

Topdressing

Topdressing is an essential practice in maintaining athletic fields. Topdressing is defined as the application of a soil or other granulated material over a turfgrass area (Christians, 1998). Topdressing of athletic fields is usually accomplished by applying coarse sand. This is commonly used to help smooth playing surfaces, control thatch, aid in injury recovery, and to modify the existing soil (Turgeon, 1991). Alternative topdressing materials such as crumb rubber have also been shown to increase wear tolerance of turfgrass under traffic (Rogers et al., 1998). Topdressing has been shown to speed thatch decomposition and assist in successful overseeding (Duble, 1996). A study by (Dunn et al., 1995) showed that topdressing increased root growth and decreased mat organic matter. Topdressing material is often applied immediately following cultivation and is incorporated with the help of a drag mat. The use of improper particle sized material or excessive amounts of topdressing can create layers which can restrict air and water movement, so a topdressing material that matches the underlying sand base of the athletic field is often used.

Turfgrass cultivation refers to the use of specialized tillage equipment to modify physical and other characteristics of the turf and soil (Turgeon, 1991). Unlike conventional crops which can be highly disturbed by plowing, turfgrass areas must be cultivated in a manner that does not hinder their function or use (Duble, 1996). The most common types of cultivation are hollow tine (or coring tine), solid tine (or spiking), vertical mowing, and slicing. It is essential that cultivation is carried out with minimal disruption and damage to the surface.

Vertical Mowing

Vertical mowing is used to remove thatch from the soil matrix and crown area. It has been shown to be an effective method of thatch reduction (Johnson, 1979). Thatch removal is accomplished by blades or knives mounted vertically on a horizontal shaft which rotates at high speeds. The rotating blades are lowered into the thatch layer and pull out pieces of the thatch layer. Vertical mowers have an effective depth of 2 (5.1 cm) to 3 inches (7.6 cm). Vertical mowing should only be carried out after spring green up or during the active growing season (McCarty and Cisar, 1990). Other cultivation practices will be discussed in the section entitled ‘methods for compaction relief’.

Soil Compaction

Amir et al., (1976) defined soil compaction as a function of contact pressure and soil moisture. Hillel (1980) describes compaction as the process of soil densification or compression, which leads to the reduction of air volume in an unsaturated soil or water in a saturated soil, respectively. This can create problems when soil configuration is reduced below the optimal range of approximately 50 percent solid matter and 50 percent pore space. The 50 percent pore space should consist of approximately one-half water and one-half air. Pore spaces are critical to the root function because of the oxygen they contain (Grant, 1993). Surface compaction can also result in excessively hard playing surfaces. Research has also shown compacted soils can reduce root elongation (Agnew, 1983; Grant, 1993).

Soil compaction is a problem in many turf areas (Sills and Carrow, 1983). Research has shown that soil compaction reduces water, heat, and gas exchange (Warkentin, 1971; Willis and Raney, 1971; Grable and Siemer, 1968; Linn and Doran, 1984), reduces root penetration (Taylor et al., 1966), and as a result crop production (Hakansson et al., 1988). Compacted soil restricts air and water movement to roots (Bruneau et al., 2004). There is very little soil compaction research on athletic fields, where it is a common and serious problem. This is especially true when fields are subjected to excessive amounts of traffic. One study conducted on athletic fields reported that as soil moisture increases, the compactibility of the soil increases due to the lubrication effect (Van Wijk and Beuving, 1980). Meek et al., (1992) stated that a reduction in compaction can be achieved by applying traffic to the soil when it is as dry as possible. Compaction leads to decreased soil infiltrability (Akram and Kemper, 1979), decreased saturated hydraulic conductivity (Dawidowski and Koden, 1987) and decreased air entry values, while increasing saturated water content (Croney and Coleman, 1954; Laliberte et al., 1966; Smith and Woolhiser, 1971; Libardi et al., 1982).

Soil Components affected by Compaction

Total porosity is a measurement of the percentage pore volume in a soil (Hillel, 1980). Total porosity is separated into two groups, based on pore size. Macropores are between 30 and 100 um in width, while micropores include anything smaller than 30 um (Sylvia et al., 1999). Total porosity can range from 25% in compacted subsoils to greater than 60% in well aggregated surface soils. Air porosity can be greatly altered by tillage and drainage (Grable and Siemer, 1968). Optimal total porosity for most agricultural uses is considered 50% of the total soil volume (Brady and Weil, 1999).

In an amended soil for turfgrass, the USGA recommends 35-55 percent pore space. Waddington and Baker (1965) found non-capillary pore space in a compacted soil to be in the 12-18 percent range. In native soils, the formation of soil aggregates creates fractures in the soil that are the primary source of soil pore space. In one study where compaction was applied comparable to that received on athletic fields, aeration porosity decreased from 12.1 to 9.2 percent (Carrow, 1980). As porosity decreases so does the rate of surface water removal, which is undesirable for athletic fields. Cordukes (1969) and O’Neil and Carrow (1982) also reported reduced aeration porosity as a result of compaction. A study by O'Neil and Carrow (1983) found that aeration porosity varied from 25 percent in an uncompacted soil to 17 percent in soils receiving heavy traffic treatments. It is thought that reduced porosity due to compaction is linked to decreased turf quality.

Hydraulic Conductivity

Hydraulic conductivity (*K*) is also directly related to soil compaction. It is the measure of resistance water encounters as it flows downward through the soil, in relation to a potential gradient. Hydraulic conductivity is also related to pore size. Macropores are responsible for the greatest amount of water movement in the soil. Thus, saturated coarse sand conducts water much more rapidly than a clayey soil (Hillel, 1982). Saturated hydraulic conductivity (K_s) is a measure of ability of a soil to transmit water (Wu et al., 1999). As compaction increases, pore space decreases, which leads to reduced hydraulic conductivity. Clay and silt particles are often undesirable because of their ability to flow into larger pore spaces and clog them. Van Wijk and Beuving (1980) found that increased levels of organic matter reduced the rate of hydraulic conductivity. Hydraulic conductivity is highly variable within a single location and is difficult to measure in the field.

Infiltration

Infiltration is the downward movement of water into the soil through the soil surface. It is directly related to the soil properties or structure and therefore affected by soil compaction. Where infiltration is restricted the rate of water entering the soil is reduced which causes pooling of water runoff and increased runoff. This is an undesirable characteristic and danger on an athletic field that is designed for use in all weather conditions. A study conducted by Akram and Kemper (1979) reported that soil compaction is a primary contributor in reducing soil infiltrability.

Bulk Density

Soil dry bulk density is a ratio of the mass of dry soil to its total volume, solids and pores included (Hillel, 1980). Bulk density is generally accepted as a satisfactory indicator of soil compaction for a specific local (Waddington et al., 1974). Various factors influence bulk density, with traffic being the most prevalent contributor. One study using wheel traffic to apply compaction recorded increases in bulk density (Soane et al., 1982). As soil particles are compressed and the physical structure modified, bulk density is increased, leaving behind a less desirable medium for agronomic use. Bulk density values greater than 1.5 g cm^{-3} are generally indicative of a soil compacted to a point where turfgrass root growth is seriously impaired (Taylor and Gardner, 1963). One study reported that an increase in bulk density caused a decrease in gas diffusion rates and water desorption characteristics. Rogers et al. (1988) also found that increases in bulk density were associated with an increase in field surface hardness. Bulk density can be reduced with the help of cultivation equipment. Roberts (1975) found that soils cultivated with an aerifier had a lower bulk density level as compared to non-aerified controls.

Mechanical Methods for Measuring Soil Compaction

There are many different techniques that are used to derive a quantitative figure that can be used to analyze soil compaction. Each of these different techniques is used to measure different physical characteristics of a soil in an effort to describe the degree of compaction. The degree of soil compaction can be described by measuring bulk density, porosity, penetrability, or infiltration (Meek et al., 1992). As the complexity of compaction research has increased, so too has the sophistication of the equipment used for data collection.

Soil Penetrability

Penetrability is the quantitative measure of a soils resistance to an object as it s physically inserted into the soil. Typically these measurements are collected through the use of a soil penetrometer and provide measurements of a soils resistance consistency at varying depths. In general, compaction increases bulk density and soil strength which increases penetrometer resistance. This was recorded in a study by Taylor et al., (1966). Other factors that affect resistance include soil structure, soil moisture and compressability.

The primary type of penetrometer used by soil scientists is the Rimik cone penetrometer (Agridry RIMIK Pty Ltd., 14 Molloy Street, Toowoomba, Queensland). It consists of a steel cone attached to a steel rod which is connected to the display which records the measurements. These units record resistance measurements in kilopascals (KPa) at incremental depths during insertion into the soil. Factors that can affect readings during insertion include cone angle, cone diameter, soil roughness, rate of penetration soil moisture and bulk density. Resistance to penetration is created by two principal forces: (i) force to deform the soil created by the wedge action of the conical point and (ii) soil to metal friction against the surface (Bradford, 1986). A practical application of this measurement was demonstrated by Sills and Carrow (1983) which linked increased cone penetrometer resistance to increases in compaction and bulk density.

Surface Hardness

Surface hardness can also be used to measure the level of surface compaction on a playing surface (Gramckow, 1968). Quantitative numbers are recorded by measuring soil surface impact absorption characteristics. The instrument commonly used to measure athletic field hardness is the Clegg® impact soil tester (2/23 Bishop Street, Jolimont, Western Australia 6014). It was developed for testing dirt road surfaces but has since been used extensively in Europe and Australia for measuring impact characteristics of turf surfaces (Lush, 1985; Canaway, 1985; Holmes and Bell, 1986). Measurements are achieved by dropping a missile or hammer to the soil surface. The display on the Clegg® device records peak deceleration which is reported as $\boldsymbol{g}_{\mathrm{max}}$ (Bell et al., 1985). Variables that shown to affect these measurements include mowing height, turf cover, soil compaction, thatch, core cultivation and soil moisture (Rogers and Waddington, 1989; 1990; 1992).

Methods for Reducing Soil Compaction

Most of the research related to reducing soil compaction has been conducted in conventional tillage row crops. This type of tillage causes surface disruption as the soil is turned over and fractured. Turfgrass managers cannot significantly disrupt the surface and therefore cannot turn the soil. Turfgrass cultivation is the process of mechanically inserting a hollow or solid tine into the soil in an attempt to break up or fracture the soil, and relieve compaction while causing minimal disturbance to the turfgrass plants and playing surface (Younger and Fuchigami, 1958). This type of cultivation is designed to reduce the adverse effects of soil compaction (Agnew and Carrow, 1985). Other strategies to control and reduce compaction include traffic control, water management, soil modification, improved drainage and irrigation design and turfgrass selection.

Turfgrass aerification is achieved by using either hollow or solid tines. Tine lengths can vary with shallow tines ranging from 1.5 to 10 cm and deep tines ranging from 15 to 30 cm. Tine diameters also vary depending upon use and generally range from 0.8 to 2.5 cm. Hollow tines remove a soil core and deposit it on the soil surface, providing room for the compacted soil to expand (Peacock, 1984). These cores can then be broken up by dragging a steel mat or by verticutting and incorporating as topdressing material. Where soil modification is the goal, cores can be removed and replace with an amendment. Solid tine aerification creates a hole and does not remove a core which makes it less disruptive and it is often used for this reason.

There are many different aerator designs, with two main types used most often. The most commonly utilized machines are mechanically driven and have tines that are raised and lowered vertically into the soil. Other units have hollow, solid or spoon tines mounted to a drum which turns when pulled and rely on the weight of the unit to drive the tine into the soil. Since these units only rely on their own weight they have limited depth capabilities. Vertically inserted tines as opposed to the rolling drum tines create less surface disturbance (Beard, 1973).

Turfgrass aerification research is limited and varies widely in research methods. Engle and Alderfer (1967), reported that over a ten year period that vertically operated machines did not increase oxygen diffusion rates while drum spoon type units did. Core aerification has been shown to cause turf injury which results in reduced turf quality (Murphy et al., 1992). It has also been shown to be ineffective in an uncompacted soil and only useful when applied to severely compacted soils (Murphy et al., 1992). There is also much debate as to the effectiveness of solid tine aerification. The speculation lies in the fact that no core is removed to allow for soil expansion. In fact the insertion of a solid tine into the soil could create sidewall compaction and a hardpan at the bottom of the hole. This has not been proven to date. A study which looked at solid tine compaction on a bentgrass putting green found that solid tine aerification reduced soil strength by 45 percent but the benefits were short lived (Murphy et al., 1992).

Summary

In the turfgrass literature, research which examines the impact of aerification on turf quality and performance is limited. Moreover, almost all of the published literature has been conducted on cool-season grasses, and predominately on putting greens. Research which examines aerification impacts on compacted hybrid bermudagrass athletic fields is largely absent, and there is no research which examines different types of aerification tines (depth and diameter).

Research Objectives

The objective of this research is to: examine the effects of aerification tine depth and type (hollow versus solid) on penetrometer cone resistance, surface hardness, bermudagrass thatch depth, and bermudagrass shoot density and root weight on trafficked athletic fields.

II. MATERIALS AND METHODS

The research study was conducted at two locations, both in Auburn, AL. The first location was the Auburn University West football practice field (hereafter called 'AU Practice Field') and the second location was the Auburn University Turfgrass Research Unit (hereafter called 'TGRU'). Both locations had Tifway hybrid bermudagrass playing surfaces that were maintained at a mowing height of 2.54 cm. Soil type for both fields was a native soil Marvyn loamy sand (Fine-loamy, siliceous, thermic Typic Kanhapludult), with the Practice Field likely disturbed via construction over its 20-year history. The study was initiated in January 2001 at the Practice Field and in April 2002 at the TGRU. The study was conducted for two years at each location: 2001 and 2002 at the Practice Field, and 2002 and 2004 at the TGRU. No treatments were imposed at the TGRU location in 2003, and during that year the study site was maintained without any applied compaction. At the time of the experiment initiation the practice field was at least 10 years old (from the last sod installation) and the TGRU field was 1 year old.

The experiment design was an incomplete factorial arrangement of aerification equipment and tine type, arranged as a randomized complete block design with four replications at the Practice Field and five replications at the TGRU. The treatments were: 1) standard depth hollow tine (GA60H) (10 cm long, 1.9 cm diam.), 2) standard depth solid tine (GA60S) (10 cm long, 1.9 cm diam.), 3) deep depth hollow tine (SRH) (20 cm long, 2.2 cm diam.), 4) deep depth solid tine (SRS) (20 cm long, 2.2 cm diam.), 5) pull behind drum type aerifier with hollow tines (PB) (9.5 cm long, 0.70 cm diam.), and 6) a non-aerified control. Between-tine spacing was 15 cm, 10 cm and 14 cm for the SR, GA60 and pull-behind treatments, respectively.

Aerification treatments were applied using three different aerification machines. They were: 1) the Model SR-48 Southern Green® Soil Reliever (Southern Green Turf Machinery, 21126 Plank Road, Zachary, Louisiana 70791, USA), used to apply the deep depth treatments, 2) the Ryan GA-60 (A Textron Company, 11108 Quality Drive, Charlotte, North Carolina 28273, USA), used to apply the standard depth treatments, and, 3) the pull behind Brinly-Hardy PA-48BH (Brinly Hardy Inc., 3230 Industrial Parkway, Jeffersonville, IN 47130).

Aerification treatments were applied for two years at each location four times per year at four week intervals during the summer months (May, June, July, August). These months were chosen because it is a recommended practice to apply aerification treatments during the active bermudagrass growing season, to aid turfgrass recovery. A non-aerification control was used in each replication at both locations as a baseline to help evaluate differences in aerification effectiveness. Plot size at the AU Practice Field was 6.1m x 6.1m with 6.1m alleys, and plot size was 2.4m x 3.1 m at the Turfgrass Research Unit, with 3.05 m wide alleys between each replication to aid in equipment turning.

Immediately following aerification treatments, topdressing was applied using a Cushman® Turf Truckster (A Textron Company, 11108 Quality Drive, Charlotte, North Carolina 28273, USA) to all plots at rate to produce a 7mm surface layer of sand. Using a

1.2 m x 1.8 m steel mat, topdressing sand was then dragged into the turf canopy from four directions until sand was no longer visible on the turf surface.

Both sites were maintained with automatic irrigation systems that supplied 3.0 cm of water per week, unless rainfall exceeded that amount. The AU Practice Field had compaction applied via human or vehicular traffic. Human traffic was applied year round by both off season football workout programs and regular football practices. Vehicular traffic was the result of turfgrass maintenance equipment and AU Athletic Department support equipment. At theTGRU, traffic was simulated and compaction applied using a 61 cm x 121.9 cm water filled steel Agri-Fab (809 South Hamiliton Street, Sullivan, IL 61951. roller which was pulled across the plots with a Cushman® Turf Truckster. Each replication received 50 passes with the roller 4 weeks after aerification treatments were applied and prior to the first treatment and after the last treatment each year (Murphy et al., 1992). Additional compaction was applied via turf maintenance equipment and human traffic.

Data Collection

To measure surface hardness, impact absorption was measured using a Clegg impact soil tester (Lafayette Instrument Company, 3700 Sagamore Parkway, P. O. Box 5729, Lafayette, Indiana 47903, USA) (Clegg, 1976). Measurements were taken prior to aerification each year, and then at one week and four weeks after treatment thereafter. After the last treatments (August) were applied each year, measurements were take each week for six weeks. Measurements at the Practice Field were taken in April, May, June, July, August and September of 2001 and 2002. At the Turfgrass Research Unit, measurements were taken in April, May, June, July, August and September of 2002 and

2004. Impact absorption was measured through peak deceleration measurements and was achieved by 2.25 kg missile whose impact was measured in gravities ($\boldsymbol{g}_{\max}$). Five individual measurements were taken randomly from each plot and averaged for surface hardness.

Soil penetration resistance was measured throughout the soil profile to determine the level of compaction from the soil surface to a depth of 240 mm. Soil resistance was measured using cone resistance or the cone index, which is defined as the force required to push the soil cone penetrometer into the soil divided by the cross-sectional area of the base of the cone (ASAE, 2000). Cone index measurements were taken using a Rimik® CP-20 manual soil cone penetrometer (Agridry Rimik Pty. Ltd., 331 Taylor Street, Toowoomba, Queensland 4350, Australia). The penetrometer mounted cone had a base area of 130 mm^2 and was changed after each set of monthly measurements to maintain cone diameter for accuracy. Soil cone resistance was measured in 10 mm increments continuously throughout the soil profile to a maximum depth of 240 mm. Five individual penetrometer readings were taken randomly in each plot, at each sampling date, with care taken not to insert the probe into an aerification hole. Measurement output was recorded in KPa. All resistance measurements were averaged and reported as soil resistance per 10 mm increment for each plot per month. Penetrometer readings were measured prior to treatment applications each year and one week after treatment and four weeks after treatment. After the August treatment each year measurements were taken each week for six consecutive weeks.

To assure accurate soil strength data, which is moisture dependent (Vaz and Hopmans, 2001; Meek et al., 1992), soil moisture measurements were taken following soil strength measurements to determine if field conditions were near field capacity. To ensure that field capacity was reached every site was irrigated the evening prior to data collection. To measure moisture content gravimetric soil moisture contents were determined. Five soil samples (2 cm diam. x 15 cm deep) were taken randomly from each plot with care taken not to remove the sample from recent aerification holes. Samples were collected at the same time Clegg® impact readings and cone resistance measurements were taken. The samples had the thatch and mat layer removed, leaving only soil for measurement. Cores were mixed together and stored in a plastic bag. Wet weights were then recorded for each sample prior to being placed in an air-circulation oven for 24 hours. Samples were dried at a temperature of 105º C and then dry weights were measured to determine gravimetric soil moisture content.

Shoot density data was collected in May and Oct (2002, TGRU), Oct. (2004, TGRU) and Sept. (2001, Practice Field). In each sampling three 4.1 cm. diam. X 15.2 cm deep cores were collected from each plot using a truck mounted hydraulic Giddings® probe machine (Giddings Machine Company, 631 Technology Circle, Windsor, CO., 80550). The number of shoots in each core were hand counted and recorded to calculate shoot density.

Thatch and mat measurements were also taken in September of 2001 (Practice Field only). Using the three cores collected from each plot using the Giddings® probe, careful measurements were taken with a micrometer to measure the depth (mm) of both thatch and mat in each core.

Using the same core technique as described for shoot density, root mass was also determined. This occurred in July and Oct. (2002, TGRU), Oct. (2004, TGRU), Sept.

(2001, Practice Field) and Aug. and Sept. (2002, Practice Field). Plant material, thatch and mat were removed from each core prior to root weight determinations. The collected core was trimmed to a 240 mm depth, and in some cases separated into 0-120 and 120-240 mm depth increments. Cores were hand washed to remove soil, with soil washed through 10 mm mesh sieves to collect all root material. The roots were then dried at 105°C for 24 hours and weight determined.

All data was analyzed via Analysis of Variance, with each tine type/depth analyzed as a separate treatment effect. Because these are independent tillage-type effects means separation using an alpha of 0.10 was used to separate treatment effects.

III. RESULTS AND DISCUSSION

Aerification Effects on Dry Weight of Roots

AU Practice Field

In Sept. 2001, the application of any aerification treatment increased the dry weight of bermudagrass roots as compared to those from the non-aerified control (Table 1). There were no significant differences in the dry weight of roots among aerification treatments. In 2002, harvested roots were separated into two depths: 0-7.5 and 7.6-15 cm (Table 2). Aerification treatment had no effect on the dry weight of roots in the 0-7.5 cm depth, and there was no significant difference in root weight in treated plots from those measured in the no aerification control plots. There were differences at the 7.6-15 cm depth, but dry root weights were rarely different from those measured in the non-aerified plots and only for the GA60S in August. On 1 Aug, 2002 the dry weight of roots collected from the GA60S treatments was less than that measured in the non-aerified control. Although the root weight in the GA60S treatments was still low when roots were collected a second time (23 Sept., 2002), it was not significantly less than measurements in other aerification treatments, and the non-aerified control. This trend for reduced root weights in the GA60S plots may be a function of the development of a hardpan at the bottom of the aerification depth. Collected penetrometer data (discussed later in this thesis) will support this hypothesis. The development of an 'aerification pan' has also been hypothesized by others (Murphy et al., 1992).

Although not always significant, plots aerified with the SR (H or S tines) had a trend for greater root mass at the 7.6-15 cm depth, as compared to roots weighed from plots aerified with the GA60 (H or S). This trend is probably due the deeper depth of soil aerified with the SR unit and its' attached tines, and the aerification effect it produced.

Turfgrass Research Unit

Similar to results from the Practice Field, in 2002 the dry weight of roots harvested from the TGRU were largely unaffected by aerification in the 0-7.5 cm sampling depth (Table 3). In the 19 July sampling plots that were aerified with the SRH had a greater root mass (0-7.5 cm) as compared to roots from the GA60H treatment, but that was the only significant difference. In the 7.6-15 cm depth, however, there were differences due to aerification treatment, but the differences were not consistent between the July and October samplings. In Oct., plots receiving the SRS treatment had the greatest root mass, significantly more than measured in the GA60S or pull-behind treatments (Table 3). At the July measurement, however, bermudagrass from the GA60S treatment had the greater root mass, significantly greater than measured in the GA60H, pull-behind or non-aerified treatments. In 2004 the results were different, with roots harvested from the GA60H treatments having a significantly greater dry root weight than roots harvested from the SRH, SRS, pull behind or non-aerified treatments (Table 5). The October data set may provide the most valuable data because it represents data collected after 4 cycles of aerification (May-August). Data collected in July would only represent 3 cycles of aerification (May-July).

In general, application of aerification treatments had slight and varying effects on the dry root weights of bermudagrass. Results were not the same from year-to-year. There was slight (and not always significant) evidence that treatments that aerified deeper into the soil produced greater root weight at the deeper depths.

Aerification Effects on Shoot Density

Turfgrass Research Unit

May, 2002 (TGRU) shoot density determinations were unaffected by aerification treatment (Table 4). These treatments were only one week after the first set of aerification treatments, and as such demonstrate little response to the treatments. At the end of the years' treatments, however, the effect of four aerifications was evident, with several aerification treatments having greater shoot density than measured in the non-aerified control. These treatments were SRH and GA60S treatments. Thus, the use of a solid or hollow tine did not have a consistent effect on shoot density, as bermudagrass from the SRS treatment had the overall lowest shoot density, and that density was equal to that measured in the non-aerified control.

In 2004 shoot density was significantly reduced in the GA60H treatments, with fewer shoots counted in Oct. when compared to any other treatment. Shoot density in any other treatment that received aerification was no different from that measured in the non-aerified control (Table 5). The GA60H treatment has the potential to remove the greatest amount of plant material. Between-tine spacing with the standard tines is 10 cm (H or S), while on the deep-aerification units the tine spacing is at 15 cm. Hollow tines physically remove the turf and attached soil from the field, depositing it on the surface. That debris is often removed from the field, which could result in a substantial number of shoots being removed from the field. Although this is now hindsight, it would have been interesting to have counted shoot densities in a representative sample of harvested aerification plugs.

AU Practice Field

After the conclusion of the 2001 treatment year there were many significant differences in shoot density (Table 1). Bermudagrass from plots aerified with the SRS and pull behind equipment had the greatest shoot density, with the SRH and GA60S treatments producing bermudagrass with the lowest shoot density. Thus, results were highly variable, with one of the most (SRS) and least severe (pull behind) treatments producing the highest shoot density.

Greater difference in shoot density at the site may also be a function of greater traffic at this site. By September this field had received almost 4 months of daily heavy football practice, which certainly affected turf quality. However, differences in shoot density due to tine type (H versus S) observed at the TGRU were not evident here.

Shoot density data was not collected from the 2002 Practice Field site due to coaching decisions about field availability.

Aerification Effects on Clegg® Impact Hammer Peak Deceleration

In 2001, data from the Practice Field for May, June and July (Tables 6 and 7) revealed that the SRH treatment typically reduced peak deceleration, or surface hardness, when compared to control plots. Readings taken one week after the July aerification showed that the SRH treatment had a significantly softer surface than measured in any other treatment. At four weeks after the June aerification the SRH treatment was still softest, but it was not significantly softer than the GA60H or pull-behind treatments. Hardest surfaces were measured in the SRS, GA60S and no aerification treatments. Similar results were observed at 4 weeks after the July aerifications, with any treatment that was aerified with a hollow tine (SRS, GA60H) typically having a softer surface than treatments aerified with a solid tine (GA60S). All of the readings on the sample dates were well below the values measured on natural and artificial athletic fields, with typical values on a hybrid bermudagrass soccer field averaging around 120 **g** (Beard and Sifers, 1993).

At the end of the August 2001 aerifications Clegg data was collected each week for 6 weeks (Table 7). Results followed the same trend as the May, June and July data, with softest treatments occurring in the SRH treatment. This trend remained for the entire 6 weeks of sampling, even though the Practice Field was receiving a great deal of traffic through football practice at this time. At 6 weeks after the August aerification the SRH, SRS and GA60H treatments all had the softest surface, and these surfaces were still softer than measured in the non-aerified control.

In 2002 a very busy spring practice and weather kept us off the field for several sampling periods. Thus, data was collected for the first week after May and 4 weeks after July treatments (Table 8). While the May data was unaffected by treatment, the 2002 July data showed similar results as the 2001 data, with the SR treatments (H or S) producing the softest surfaces. August data also demonstrated a similar trend (Table 9), with deeper aerification producing a softer surface. Unlike August 2001 (Table 7), measurements were higher 6 weeks after treatment than at 1 week. Differences between hollow and solid tines were not as pronounced as with the 2001 data, with the depth of aerification having more of an impact than a hollow versus solid tine.

Turfgrass Research Unit

Data collected at the TGRU in 2002 had some results that were similar to those measured at the AU Practice Fields (Table 10). At one week after the May aerification the use of any aerification treatment (with the exception of the pull behind unit) increased surface softness compared to the control, and the softest treatment at 4 weeks after the July treatments was, as with the TGRU readings, the SRH treatment (Table 10). Data collected after the August treatments (Table 11) was also similar to that collected at the TGRU, with softer surfaces sometimes measured in plots that received aerification. The softest plots (significantly softest at 3 and 4 weeks after aerification) were the SRH treatments, and it was the only treatment significantly softer than the nonaerified control during this period. All of the measurements were in a generally accepted range of 60 to *95* $\boldsymbol{g}_{\max}$ (Popke, 2002). In unpublished work, Miller (1999, personal communication) found that $\boldsymbol{g}_{\max}$ readings between 90 and 120 could not be differentiated between by college and professional soccer players. The lowest measurement recorded at the TGRU was 52 and the highest was 140.

In 2004 (Tables 12 and 13), results were similar to 2002, as softest surfaces were often measured in the SRH treatment. On 9 of 11 sample dates, plots receiving the SRH or GA60H treatments were significantly softer than as measured in the non-aerified plots.

These differences were also most apparent after at least two aerification treatments had been applied. On 8 of 11 sampling dates (Tables 12 and 13), the surface of plots that received the SRS treatment were significantly softer than measured in the non-aerified plots. At every sampling non-aerified plots had the highest Clegg reading (if statistical significance is ignored), showing the ability of any aerification to help soften the turf surface. In fact, in measurements collected after the July aerification, the application of any aerification treatment produced a significantly softer surface (as compared to non-aerified) at 4 of 7 data collections.

Aerification Effects on Soil Cone Penetration Resistance

Changes in cone resistance for each aerification treatment are reported using Tables (Tables 14 and 15) and figures (Figs. 1-15). The two tables are for illustrative purposes, and show typical data collected after aerification treatments were applied. Data was analyzed within each depth increment, and therefore the means separation are used to separate the quantitative variables of aerification equipment. Data in Tables 14 and 15 should be examined at each measurement depth, with means compared across each horizontal line.

The data shown in Tables 14 and 15 is typical for all years of the experiment. Resistance typically increases with depth, with the impact of the different aerification tines becoming significant as the various aerification tines reach their relative depth. For example, the GA60H treatment had significant reductions in soil resistance (as compared to the non-aerified control) in the 30-75 mm depth range, a likely response since the GA60 tines have about a 90-100 mm aerification depth. Use of the SR equipment produced reduced soil resistance at deeper depths (often significant to 225 mm) compared to all other treatments, a likely result since those tines have an effective aerification depth of around 200-230 mm (Tables 14 and 15).

Penetrometer data is perhaps better shown in graphic form, and thus all remaining discussion will primarily center on the attached Figures. Representative dates and treatments have been selected to best show treatment responses.

Figures 1 and 2 compare all treatments to the non-aerified control 1 and 4 weeks after the June treatment 2001 (AU Practice Field). The SRH and GA60H reduced cone resistance significantly as compare to the control and were more effective at reducing soil compaction when compared to the other treatments and the control. Figure 2 compares all treatments, with data taken 4 weeks after the June 2001 treatments were applied at the AU Practice Field. Figure 3 compares the SRH to the control and shows decreased resistance over the control and at some depths less resistance than any other treatment. Regardless of the year or location, all the penetrometer data behaved in a similar fashion: low resistance at the surface thatch: soil layer, with an increase in soil resistance as soil depth increased. For ease of illustration all remaining figures will only contain one or two treatments, allowing statistical comparisons of those treatments.

At almost every sampling event, greatest reductions in soil penetration resistance occurred with the 20 cm deep tines (S or H). For example, Figure 4 illustrates soil resistance at four weeks after the August, 2001 treatments were applied (AU Practice Field). Depths near the end of the tines effective aerification stroke (~150-200 mm) often had a measured soil resistance that was significantly lower than measured in any other treatment (Figure 4). This effect was observed regardless of the time after aerification.

For example, Figure 5 illustrates similar data collected at four weeks after the August, 2001 treatments were applied (AU Practice Field).

Similar results were observed in 2002 at the AU Practice Field. Samples collected 1 week after August 2002 treatments (Figure 6) show that the SRH treatment reduced soil compaction (as compared to non-aerified plots) from 90 to 180 mm in depth. This reduction in compaction was significantly better than any other treatment (including all other aerification treatments) from 90 to 150 mm. Additionally, this effect was most evident when hollow tines were used.

Differences in soil compaction due to the application of other aerification treatments (the GA60 or PB treatments) were often less evident, with soil resistance affected by use of the standard-depth tines (GA60S or GA60H) in the upper soil layers (Figure 7). In Figure 7, for example, the only significant reduction in soil resistance from use of the standard depth hollow tine (GA60H) occurred in the top 45 mm of soil. Similar results were also observed in the following week, at four weeks after the application of August, 2002 treatments (AU Practice Field) (Figure 8).

In fact, when hollow tines on the standard depth unit were replaced with solid tines the only significant effect that occurred was that soil resistance increased at some depths, when compare to the non-aerifed control (Figure 9). At the final data collection at the AU Practice Field (6 weeks after the August, 2002 aerification) the aerification pan caused by the use of the GA60S tine created a layer of soil (from 75-105 mm) that was significantly harder than the control (Figure 13) and that measured in any other treatment (Figure 10). This result was only observed with the GA60S treatment, and not when the solid tine was replaced with the hollow (Figure 6, Figure 7, Figure 8, Figure 14).

As with results from the AU Practice Field, the use the deep depth hollow tine (SRH) produced the best relief from soil compaction, with this reduction in soil compaction often measurable for the majority of the soil depth (Figure 11). In every case (both locations and years) the use of the pull behind aerifier did not relief soil compaction, when compared to the non-aerified control (Figure 1, Figure 2, Figure 12). This ‘non-result’ is important, because a pull-behind small scale aerifier is a widely-used piece of equipment, and the type most often purchased by school or municipal athletic management facilities.

The development of the aerification pan observed with the use of the GA60S treatment observed at the AU Practice Field was also observed at the TGRU (Figure 13). In this case, however, the ability of the tine to relieve compaction was shown near the soil surface (significant at 45-60 mm), yet once again the impact of the tine near the end of the aerification stroke (105- 135 mm) produced a layer with greater compaction than measured in the non-aerified control plots (Figure 13). Again, this negative impact was only measured in plots receiving the GA60S treatment, and not in the SRH (Figure 14, Figure 15), GA60H or SRS treatments (data not shown).

IV. CONCLUSIONS

1. The use of deep depth aerification tines (SRH or SRS) often significantly reduced soil resistance beyond that measured in other aerification treatments and the non-aerified control.
2. This reduction in soil resistance occurred throughout much of the 240 mm sampling depth.
3. Use of hollow tines (regardless of depth) often produced a softer turf surface.
4. Continued use of the GA60S treatment often produced a aerification pan at the bottom of the stroke of the tine.
5. The pull behind treatment never affected soil softness or resistance beyond that measured in the non-aerified control.
6. Root and shoot density was affected by aerification treatment, but differences were not consistent and differed from year-to-year and location-to-location.

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Table 1. Root weight and shoot density of Tifway hybrid bermudagrass as affected by aerification treatments, Sept 7th, 2001, AU Practice Field.

	Dry weight of roots	Shoot density
Treatment	g core^{-1}†	number core^{-1}
SRH§	3.9 a‡	101.1 c
SRS¶	4.4 a	120.7 a
GA60H#	5.3 a	105.7 bc
GA60S††	6.0 a	99.8 c
Pull Behind‡‡	4.8 a	115.3 a
No Aerification	1.6 b	105.9 bc

† Three cores were removed per plot, and the results averaged. One core measured 32 cm^{-2} in surface area and was 15 cm in depth.

‡ Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH§ - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS¶ - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H# - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S†† - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind‡‡ - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 2. Root weight of Tifway hybrid bermudagrass as affected by aerification treatments, 1 Aug. 2002 and 23 Sept. 2002 , AU Practice Field. Roots separated into two depth increments, 0-7.5 and 7.6-15 cm.

	Dry weight of roots			
	1 Aug		23 Sept	
	g core^{-1}†			
Treatment	0-7.5 cm	7.6-15 cm	0-7.5 cm	7.6-15 cm
SRH§	0.58 a‡	0.075 a	0.18 a	0.047 ab
SRS¶	0.78 a	0.058 ab	0.18 a	0.053 a
GA60H#	0.63 a	0.046 ab	0.19 a	0.043 ab
GA60S††	0.75 a	0.041 b	0.16 a	0.025 b
Pull Behind‡‡	0.43 a	0.067 ab	0.16 a	0.024 b
No Aerification	0.51 a	0.076 a	0.20 a	0.034 ab

† Three cores were removed per plot, and the results averaged. One core measured 32 cm^{-} in surface area and was 15 cm in depth, with this depth split in half to measure roots.

‡ Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH§ - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS¶ - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H# - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S†† - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind‡‡ - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 3. Root weight of Tifway hybrid bermudagrass as affected by aerification treatments, 19 July 2002 and 1 Oct. 2002 , Turfgrass Research Unit, Auburn, AL. Roots separated into two depth increments, 0-7.5 and 7.6-15 cm.

	Dry weight of roots			
	19 July		1 Oct.	
	g core^{-1} †			
Treatment	0-7.5 cm	7.6-15 cm	0-7.5 cm	7.6-15 cm
SRH§	0.81 a‡	0.19 ab	0.18 a	0.047 ab
SRS¶	0.53 ab	0.20 ab	0.18 a	0.053 a
GA60H#	0.45 b	0.17 b	0.19 a	0.043 ab
GA60S††	0.64 ab	0.27 a	0.16 a	0.025 b
Pull Behind‡‡	0.53 ab	0.17 b	0.16 a	0.024 b
No Aerification	0.52 ab	0.17 b	0.20 a	0.034 ab

† Three cores were removed per plot, and the results averaged. One core measured 32 cm^{-} in surface area and was 15 cm in depth, with this depth split in half to measure roots.

‡ Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH§ - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS¶ - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H# - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S†† - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind‡‡ - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 4. Shoot density of Tifway hybrid bermudagrass as affected by aerification treatments, 29 May and 1 Oct, 2002, Turfgrass Research Unit, Auburn, AL.

	Shoot density	
Treatment	number core^{-1}	
	29 May	1 Oct
SRH[§]	157.2 a[‡]	149.5 a
SRS[¶]	143.0 a	125.7 b
GA60H[#]	140.8 a	140.7 ab
GA60S[††]	158.8 a	162.3 a
Pull Behind[‡‡]	152.2 a	142.6 ab
No Aerification	155.6 a	127.7 b

[†] Three cores were removed per plot, and the results averaged. One core measured 32 cm^{-} in surface area and was 15 cm in depth.

[‡] Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH[§] - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS[¶] - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H[#] - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S[††] - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind[‡‡] - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 5. Root weight and shoot density of Tifway hybrid bermudagrass as affected by aerification treatments, October 14th, 2004. Turfgrass Research Unit, Auburn, AL.

	Dry weight of roots	Shoot density
Treatment	g core^{-1}†	number core^{-1}
SRH§	0.20 b‡	162.9 a
SRS¶	0.27 ab	175.3 a
GA60H#	0.30 a	139.6 b
GA60S††	0.22 ab	161.9 a
Pull Behind‡‡	0.21 b	177.8 a
No Aerification	0.20 b	173.9 a

† Three cores were removed per plot, and the results averaged. One core measured 32 cm^{-} in surface area and was 15 cm in depth.

‡ Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH§ - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS¶ - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H# - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S†† - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind‡‡ - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 6. Clegg impact hammer readings as affected by aerification treatments at 1 and 4 weeks after the May, June and July aerification treatments, 2001, AU Practice Field.

	Month	
	1 week after aerification	4 weeks after aerification
Treatment	Clegg† reading (g_{max})	
	24 May	no data for this date
SRH§	30 b‡	
SRS¶	37 a	
GA60H#	32 b	
GA60S††	35 ab	
Pull Behind‡‡	34 ab	
No aerification	34 ab	
	24 June	12 July
SRH§	55 b	44 c
SRS¶	62 a	51 a
GA60H#	59 ab	47 bc
GA60S††	62 a	50 ab
Pull Behind‡‡	61 a	47 bc
No aerification	63 a	50 ab
	20 July	8 August
SRH§	52 b	43 b
SRS¶	61 a	50 ab
GA60H#	61 a	44 b
GA60S††	66 a	54 a
Pull Behind‡‡	60 a	49 ab
No aerification	64 a	53 a

† Five readings randomly taken per plot, readings recorded as the last of 3 drops of the hammer at each spot.

‡ Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH[§] - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS[¶] - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H[#] - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S[††] - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind[‡‡] - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 7. Clegg impact hammer readings as affected by aerification treatments at 1, 2, 3, 4, 5 and 6 weeks after the August aerification treatment, 2001, AU Practice Field.

	Week after the August, 2001 aerification					
Treatment	1 17 Aug	2 24 Aug	3 31 Aug	4 7 Sept	5 14 Sept	6 21 Sept
	Clegg[†] reading ($\boldsymbol{g}_{\max}$)					
SRH[§]	44 d[‡]	50 c	49 b	41 b	39 b	39 c
SRS[¶]	48 bc	57 b	54 ab	47 a	43 ab	42 c
GA60H[#]	46 cd	59 ab	54 ab	46 a	41 ab	42 c
GA60S[††]	53 a	63 a	63 a	51 a	44 a	50 a
Pull Behind[‡‡]	51 ab	60 ab	61 a	47 a	42 ab	44 bc
No aerification	53 a	61 ab	61 a	51 a	45 a	46 ab

[†] Five readings randomly taken per plot, readings recorded as the last of 3 drops of the hammer at each spot.

[‡] Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH[§] - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS[¶] - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H[#] - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S[††] - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind[‡‡] - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 8. Clegg impact hammer readings as affected by aerification treatments at 1 week after the May aerification treatments and 4 weeks after July aerification treatment, 2002, AU Practice Field.

	1 week after aerification	4 weeks after aerification
Treatment	Clegg† reading ($\boldsymbol{g}_{max}$)	
	22 May	31 July
SRH§	46 a‡	54 c
SRS¶	50 a	57 bc
GA60H#	50 a	59 ab
GA60S††	55 a	63 a
Pull Behind‡‡	52 a	61 ab
No aerification	51 a	62 ab

† Five readings randomly taken per plot, readings recorded as the last of 3 drops of the hammer at each spot.

‡ Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH§ - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS¶ - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H# - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S†† - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind‡‡ - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 9. Clegg impact hammer readings as affected by aerification treatments at 1, 2, 3, 4, 5 and 6 weeks after the August aerification treatment, 2002, AU Practice Field.

	Week after the August, 2002 aerification					
Treatment	1 9 Aug	2 16 Aug	3 22 Aug	4 30 Aug	5 6 Sept	6 13 Sept
	Clegg† reading ($\boldsymbol{g}_{max}$)					
SRH§	46 a‡	36 b	38 b	51 b	44 c	53 d
SRS¶	50 a	38 b	42 ab	54 ab	46 bc	57 bc
GA60H#	50 a	41 a	45 a	56 ab	50 a	59 ab
GA60S††	55 a	43 a	42 ab	58 a	48 ab	63 a
Pull Behind‡‡	52 a	41 a	41 ab	55 ab	48 ab	58 bc
No aerification	51 a	41 a	43 ab	52 b	46 bc	54 cd

† Five readings randomly taken per plot, readings recorded as the last of 3 drops of the hammer at each spot.

‡ Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH§ - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS¶ - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H# - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S†† - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind‡‡ - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 10. Clegg impact hammer readings as affected by aerification treatments at 1 week after the May aerification treatments and 4 weeks after July aerification treatment, 2002, Turfgrass Research Unit, Auburn, AL.

	1 week after aerification	4 weeks after aerification
Treatment	Clegg[†] reading ($\boldsymbol{g}_{\max}$)	
	21 May	30 July
SRH[§]	54 b[‡]	78 b
SRS[¶]	54 b	83 ab
GA60H[#]	52 b	80 ab
GA60S[††]	55 b	83 ab
Pull Behind[‡‡]	57 ab	82 ab
No aerification	64a	86 a

[†] Five readings randomly taken per plot, readings recorded as the last of 3 drops of the hammer at each spot.

[‡] Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH[§] - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS[¶] - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H[#] - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S[††] - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind[‡‡] - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 11. Clegg impact hammer readings as affected by aerification treatments at 1, 2, 3, 4, 5 and 6 weeks after the August aerification treatment, 2002, Turfgrass Research Unit, Auburn, AL.

	Week after the August, 2002 aerification					
Treatment	1 9 Aug	2 15 Aug	3 22 Aug	4 29 Aug	5 5 Sept	6 12 Sept
	Clegg† reading (g_{max})					
SRH§	63 a‡	90 b	82 c	72 b	82 a	79 ab
SRS¶	68 a	140 a	83 bc	75 ab	84 a	77 b
GA60H#	65 a	92 b	84 bc	75 ab	83 a	78 b
GA60S††	70 a	96 b	88 ab	76 ab	87 a	80 b
Pull Behind‡‡	69 a	88 b	84 bc	78 ab	86 a	78 b
No aerification	71 a	106 ab	92 a	80 a	88 a	84 a

† Five readings randomly taken per plot, readings recorded as the last of 3 drops of the hammer at each spot.

‡ Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH§ - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS¶ - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H# - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S†† - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind‡‡ - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 12. Clegg impact hammer readings as affected by aerification treatments at 1 and 4 weeks after the May, June and July aerification treatments, 2004, Turfgrass Research Unit, Auburn, AL.

	Month	
	1 week after aerification	4 weeks after aerification
Treatment	Clegg[†] reading (g_{max})	
	27 May	16 June
SRH[§]	57 ab[‡]	50 ab
SRS[¶]	57 ab	48 b
GA60H[#]	53 b	53 ab
GA60S[††]	56 ab	53 ab
Pull Behind[‡‡]	58 ab	54 ab
No aerification	61 a	57 a
	24 June	14 July
SRH[§]	46 c	52 bc
SRS[¶]	46 c	50 c
GA60H[#]	50 bc	54 abc
GA60S[††]	52 abc	56 abc
Pull Behind[‡‡]	55 ab	60 ab
No aerification	58 a	61 a
	3 Aug	20 August
SRH[§]	58 b	47 b
SRS[¶]	55 bc	49 b
GA60H[#]	49 c	47 b
GA60S[††]	58 b	50 b
Pull Behind[‡‡]	61 b	51 b
No aerification	65 a	60 a

[†] Five readings randomly taken per plot, readings recorded as the last of 3 drops of the hammer at each spot.

‡ Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH§ - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS¶ - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H# - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S†† - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind‡‡ - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 13. Clegg impact hammer readings as affected by aerification treatments at 1, 2, 3, 4 and 5 weeks after the August aerification treatment, 2004, Turfgrass Research Unit, Auburn, AL.

	Week after the August, 2004 aerification				
Treatment	1 31 Aug	2 9 Sept	3 14 Sept	4 24 Sept	5 7 Oct
	Clegg[†] reading ($\boldsymbol{g}_{max}$)				
SRH[§]	51 b[‡]	51 b	56 b	55 b	52 bc
SRS[¶]	51 b	53 ab	55 b	58 ab	55 bc
GA60H[#]	43 c	44 c	50 c	54 b	46 c
GA60S[††]	52 b	51 b	59 b	63 a	56 bc
Pull Behind[‡‡]	55 b	58 a	59 b	59 ab	57 ab
No aerification	60 a	58 a	66 a	63 a	63 a

[†] Five readings randomly taken per plot, readings recorded as the last of 3 drops of the hammer at each spot.

[‡] Within each set of data, means followed by the same letter are not significantly different from each other at alpha = 0.10.

SRH[§] - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS[¶] - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H[#] - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S[††] - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind[‡‡] - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 14. Soil penetration resistance measurements from a 0 to 240 mm sampling depth as affected by aerification treatments, data taken 4 weeks after the August aerification, AU Practice Field, 2001.

Depth (mm)	Aerification treatment					
	SRH§	SRS¶	GA60H#	GA60S††	Pull behind‡‡	No aerification
	Soil resistance reading (kPa)					
0	0 a†	0 a	0 a	0 a	0 a	0 a
15	991 b	1138 ab	1055 ab	1193 a	1049 ab	1201 a
30	1616 bc	1759 ab	1548 c	1655 bc	1710 bc	1901 a
45	1505 bc	1636 ab	1425 c	1601 ab	1588 ab	1718 a
60	1343 b	1591 a	1488 ab	1598 a	1576 a	1648 a
75	1289 b	1608 a	1611 a	1679 a	1630 a	1528 ab
90	1380 a	1756 a	1867 a	1907 a	1832 a	1882 a
105	1621 b	2018 a	2280 a	2294 a	2216 a	2333 a
120	2006 c	2469 b	2916 a	2829 ab	2755 ab	3004 a
135	2575 c	3083 b	3559 ab	3450 ab	3419 ab	3740 a
150	3166 c	3472 ab	4049 a	3983 ab	3950 ab	4335 a
165	3470 b	3780 b	4529 a	4353 a	4368 a	4767 a
180	4258 b	4382 b	4971 a	4803 a	4902 a	5129 a
195	4935 bc	4677 c	5358 b	5322 ab	5290ab	5532 a
210	4990 c	5217 bc	5600 ab	5546 ab	5439 ab	5833 a
225	5028 c	5163 bc	5600 ab	5497 abc	5182 bc	5693 a
240	4709 c	4910 bc	5509 a	5315 ab	5144 abc	5389 ab

† For use of means separation, letters followed by the same letter are not significantly different from each other, within each depth increment, analyzed across aerification treatments.

SRH§ - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

SRS¶ - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H[#] - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S[††] - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

Pull Behind[‡‡] - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Table 15. Soil penetration resistance measurements from a 0 to 240 mm sampling depth as affected by aerification treatments, data taken 2 weeks after the August aerification, AU Practice Field, 2002.

Depth (mm)	Aerification treatment					
	SRH§	SRS¶	GA60H#	GA60S††	Pull behind‡‡	No aerification
	Soil resistance reading (kPa)					
0	0 a†	0 a	0 a	0 a	0 a	0 a
15	483 a	565a	477 a	425 a	428	516 a
30	1205 a	1224 a	964 c	1171 b	1029 bc	1322 a
45	1115 bc	1145 abc	909 d	1216 ab	1048 c	1253 a
60	1057 b	1189 a	983 c	1186 a	1080 b	1213 a
75	1088 c	1284 a	1171 b	1318 a	1179 b	1209 b
90	1133 c	1406 a	1305 b	1475 a	1295 b	1299 b
105	1222 c	1536 ab	1484 ab	1594 a	1436 b	1518 ab
120	1463 b	1787 a	1872 a	1876 a	1776 a	1859 a
135	1763 c	2099 b	2482 a	2379 ab	2246 ab	2381 ab
150	2150 b	2449 b	3061 a	3003 a	2786 a	2972 a
165	2678 b	2832 b	3449 a	3447 a	3167 a	3465 a
180	3187 c	3340 c	3843 ab	3827 ab	3485 bc	3908 a
195	3732 c	3901 bc	4298 ab	4209 abc	3914 bc	4445 a
210	4205 b	4358 ab	4739 b	4592 ab	4399 ab	4935 a
225	4628 a	4675 a	4976 a	4966 a	4679 a	5205 a
240	4875 a	4783 a	5068 a	4902 a	4696 a	5135 a

† For use of means separation, letters followed by the same letter are not significantly different from each other, within each depth increment, analyzed across aerification treatments.

SRH§ - Deep depth, hollow tines (20 cm long x 2.2 cm diam.)

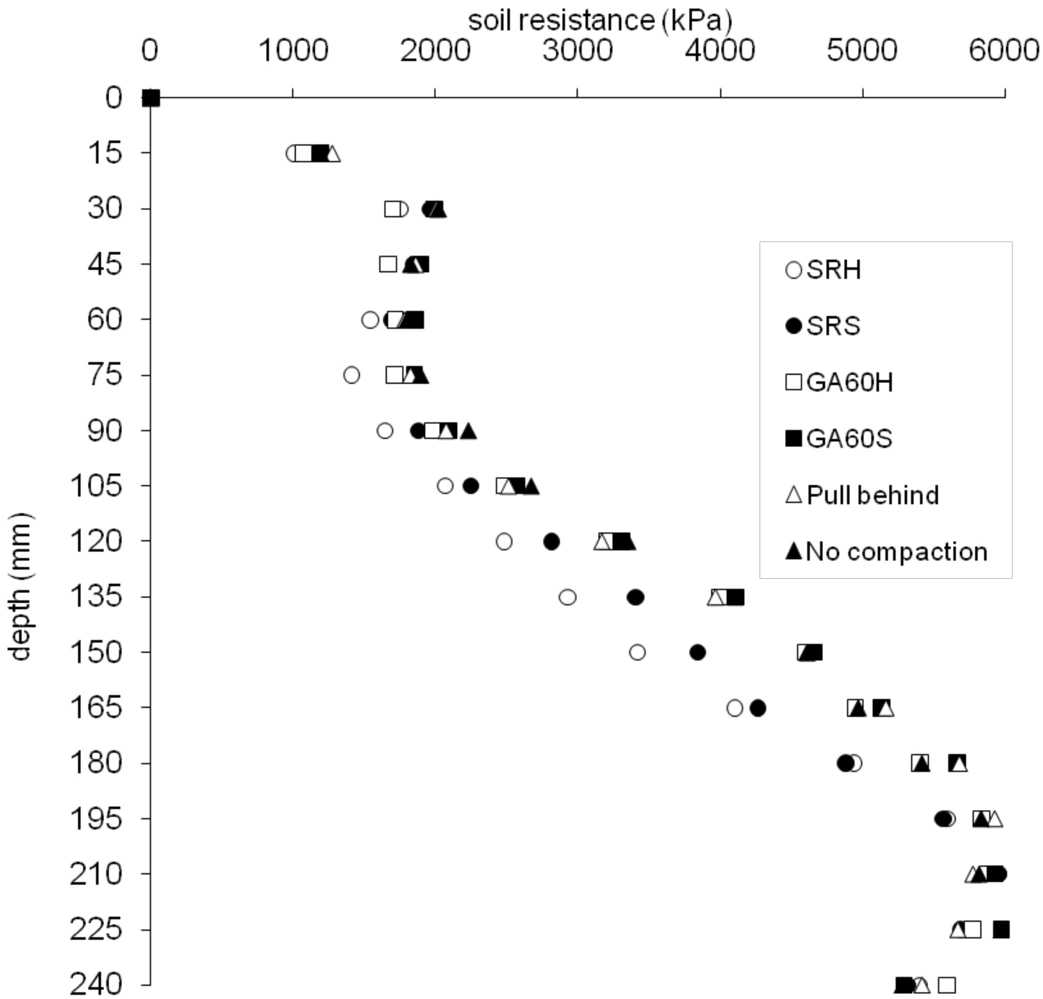
SRS¶ - Deep depth, solid tines (20 cm long x 2.2 cm diam.)

GA60H[#] - Standard depth, hollow tines (10 cm long x 1.9 cm diam.)

GA60S[††] - Standard depth, solid tines (10 cm long x 1.9 cm diam.)

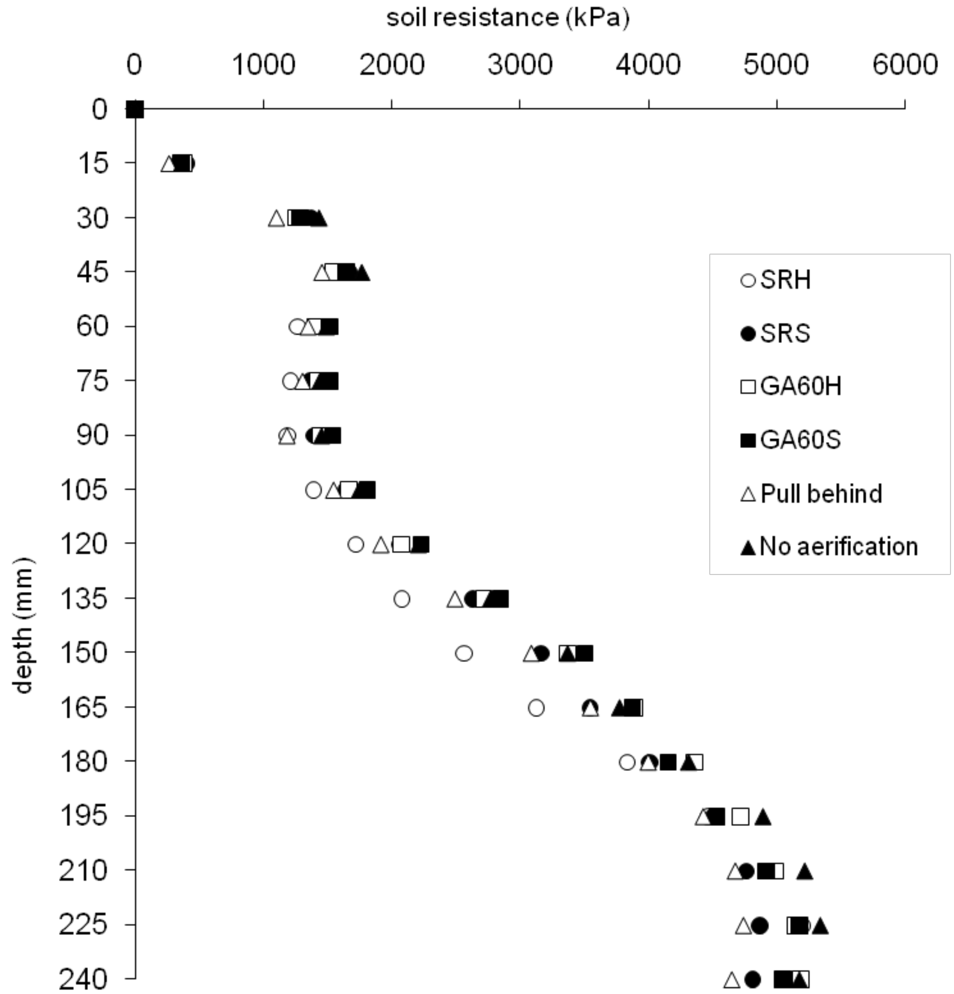
Pull Behind[‡‡] - Rolling type aerifier, hollow tines (9.5 cm long x 0.70 cm diam.)

Figure 1. Soil resistance as measured via a Rimik penetrometer as affected by aerification, one week after June, 2001 treatments, AU Practice Field.



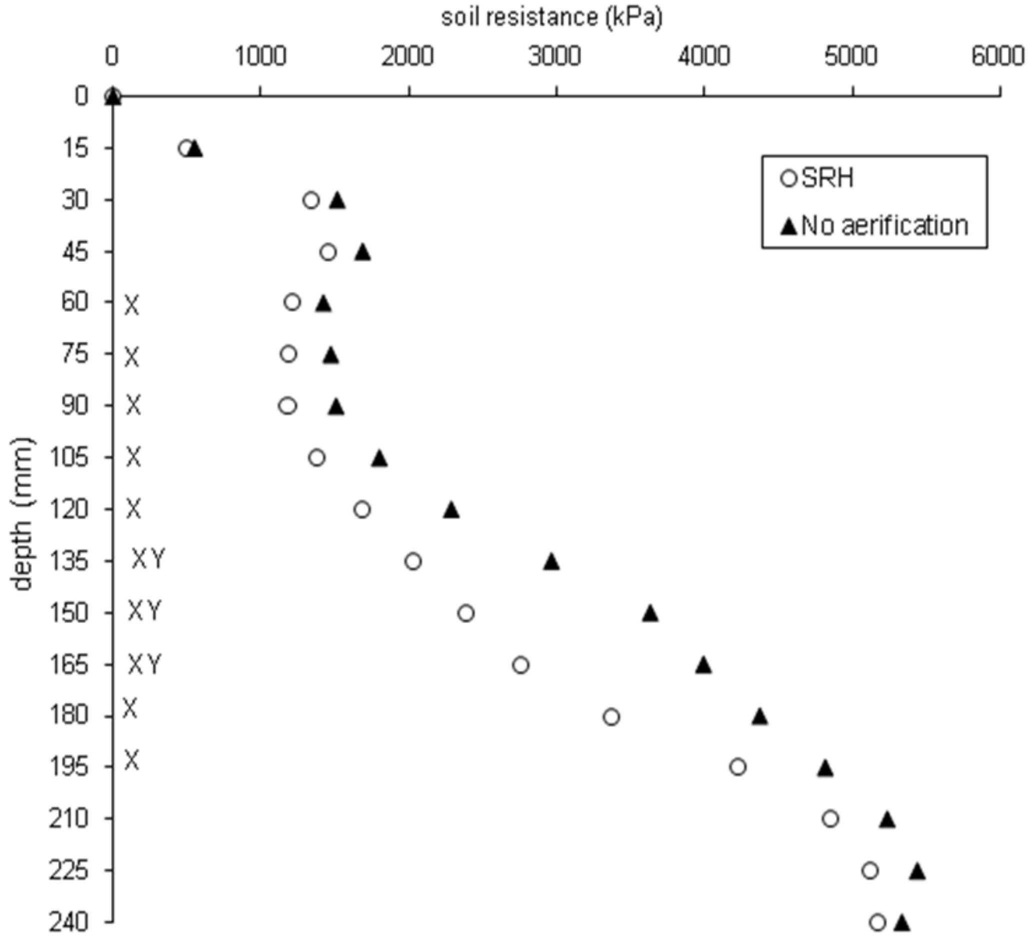
At each sampling depth, if that depth is marked with an 'X' then it had significantly different soi resistance (at alpha=0.10) than the corresponding measurement from the non-aerified control. If the depth is marked 'XY', the soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 2. Soil resistance as measured via a Rimik penetrometer as affected by aerification, four weeks after the June, 2001 treatments, AU Practice Field.



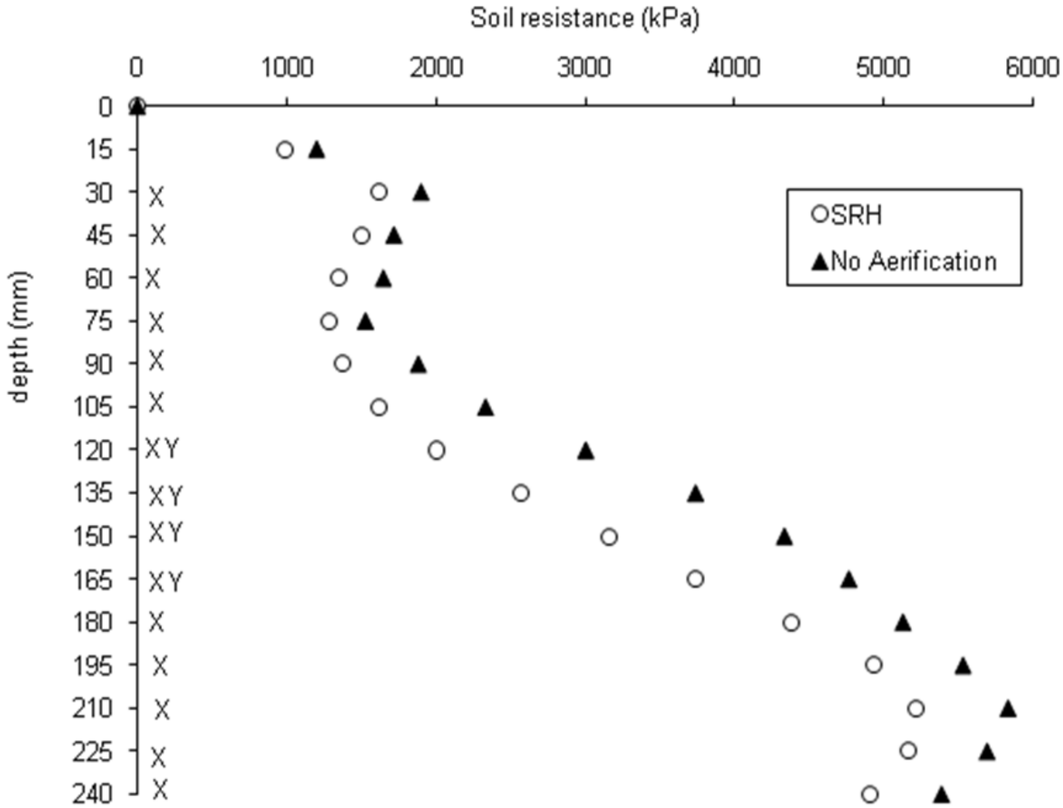
At each sampling depth, if that depth is marked with an 'X' then it had significantly different soi resistance (at alpha=0.10) than the corresponding measurement from the non-aerified control. If the depth is marked 'XY', the soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 3. Soil resistance as measured via Remik pentrometer as affected by aerification, one week after August, 2001 treatments, AU Practice Field.



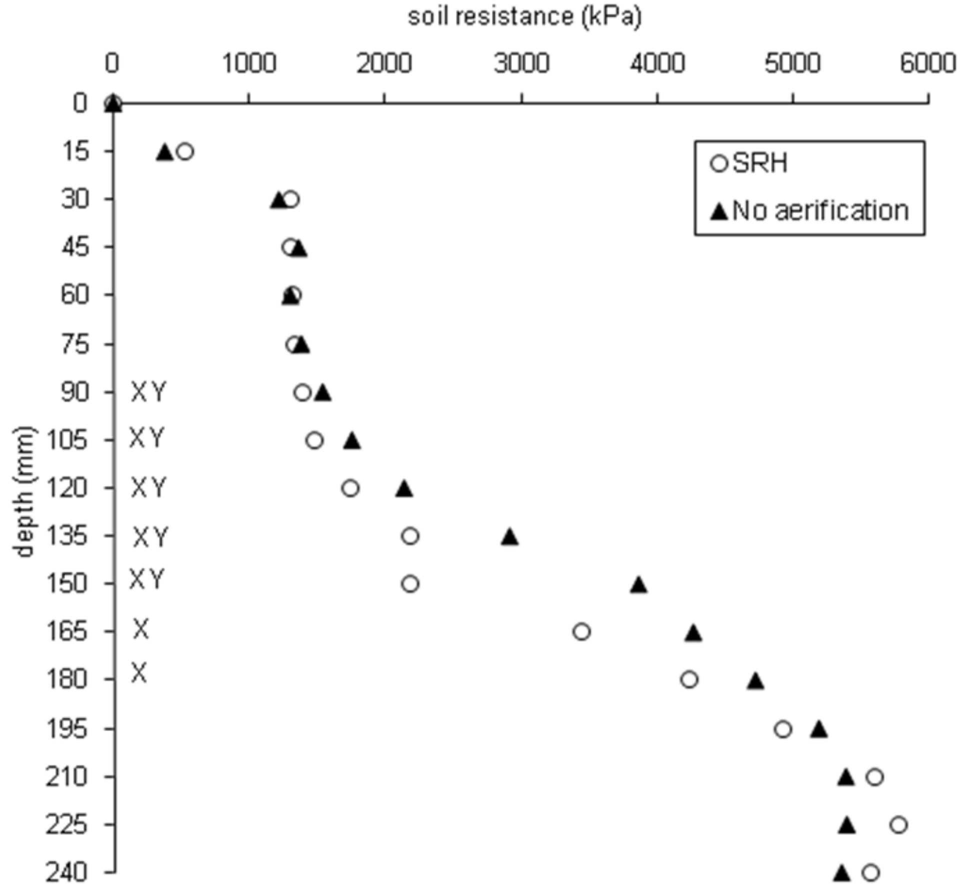
At each sampling depth, if that depth is marked with an 'X' then it had a significantly different soil resistance (at alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the depth is marked with an 'XY', than that soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 4. Soil resistance as measured by a Remik penetrometer as affected by aerification, four weeks after August, 2001 treatments. AU Practice Field



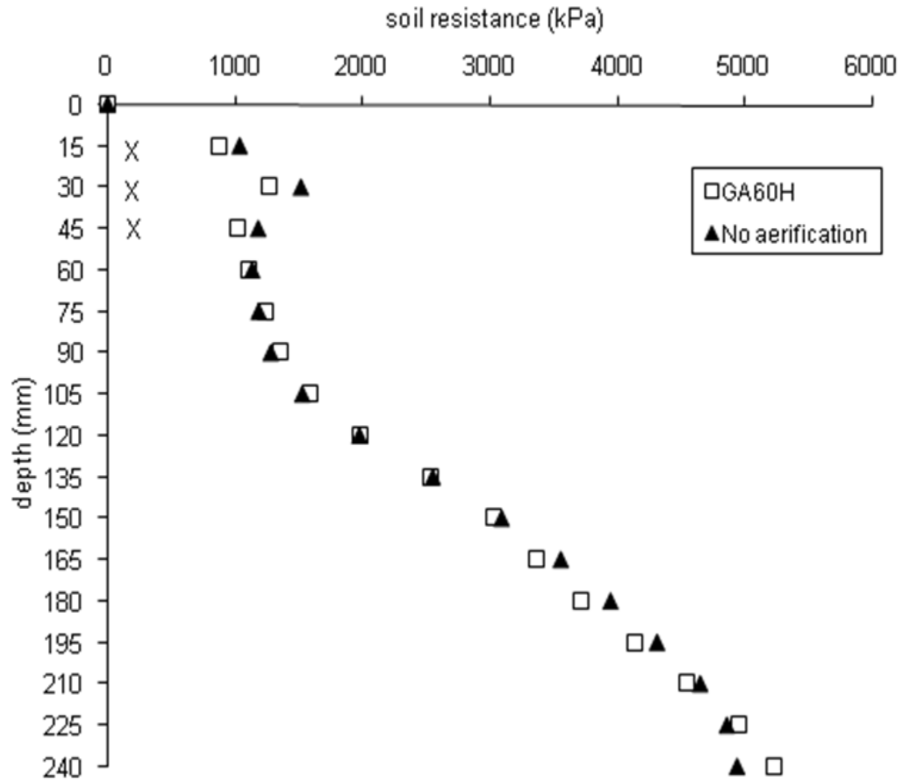
At each sampling depth, if that depthis marked with an 'X' then it had significantly different soil resistance at (alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the depth is marked with an 'XY' then that soil resistance mesurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 5. Soil resistance as measured by the Remik penetrometer as affected by aerification, one week after August, 2002 treatments, AU Practice Field



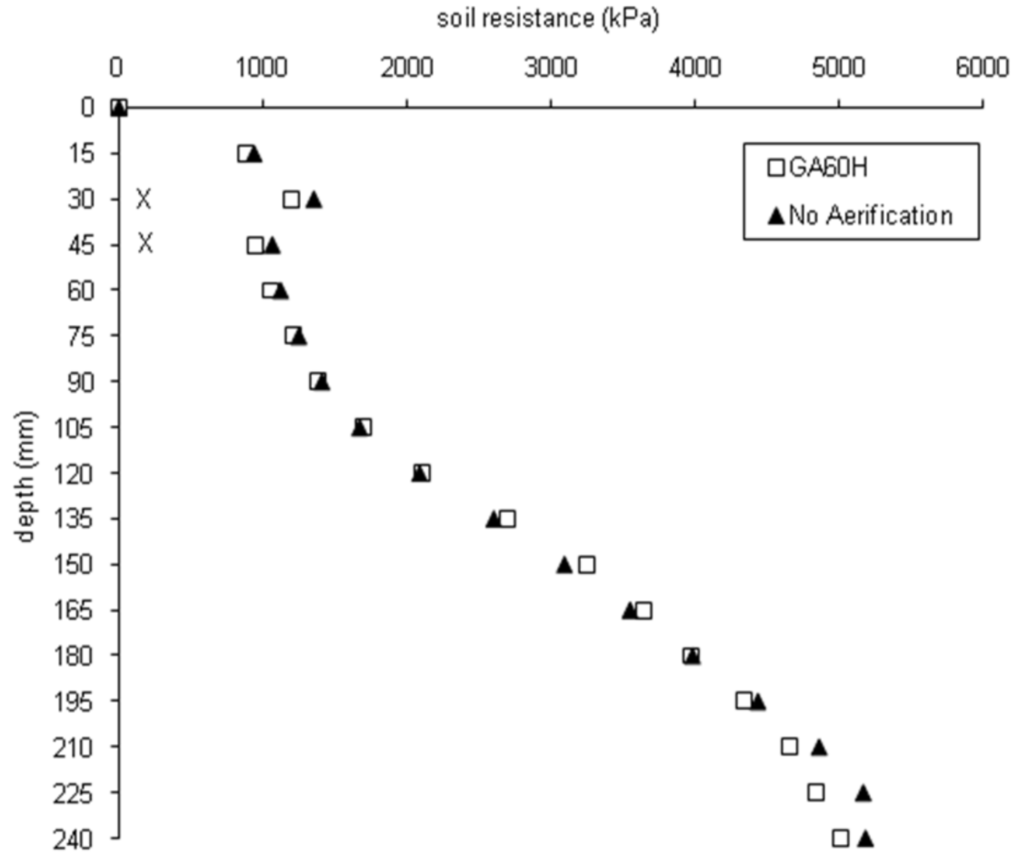
At each sampling depth, if that depth is marked with an 'X' then it had a significantly different soil resistance (at alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the depth is marked with an 'XY', than that soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 6. Soil resistance measured via a Remik penetrometer as affected by aerification, three weeks after the August, 2002, treatments. AU Practice Field



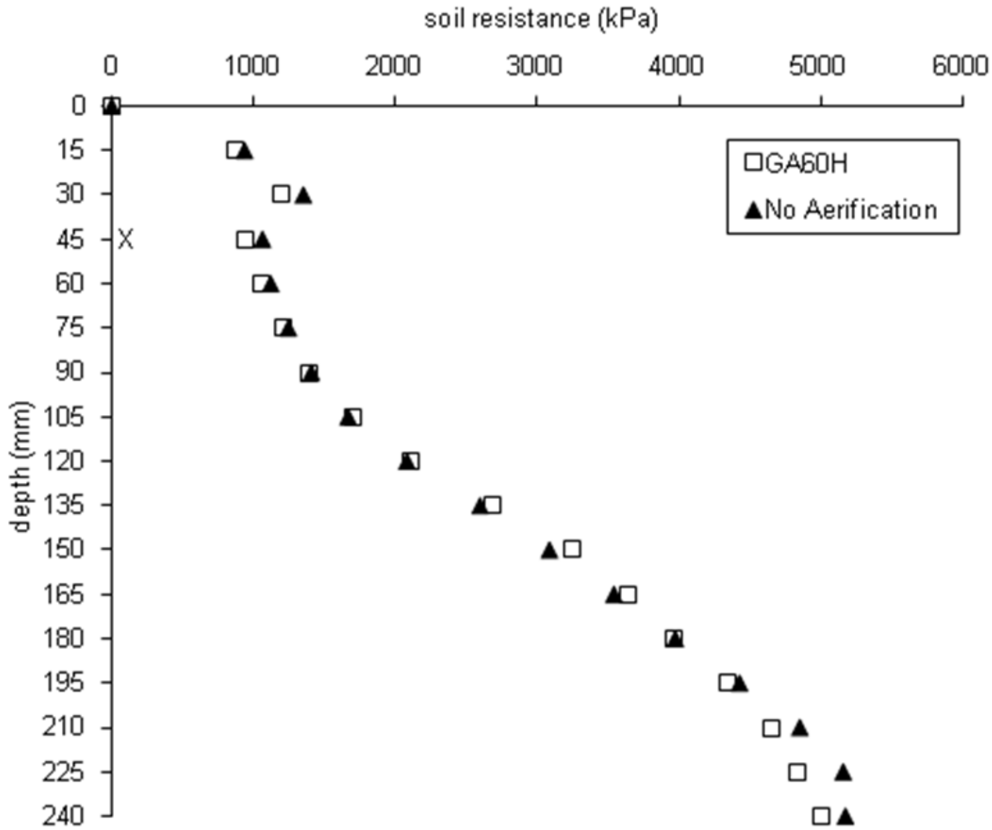
At each sampling depth, if that depth is marked with an 'X' then it had a significantly different soil resistance (at alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the depth is marked with an 'XY', then that soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 7. Soil resistance as measured by a Remik soil penetrometer as affected by aerification, four weeks after August, 2002, treatments. AU Practice Field



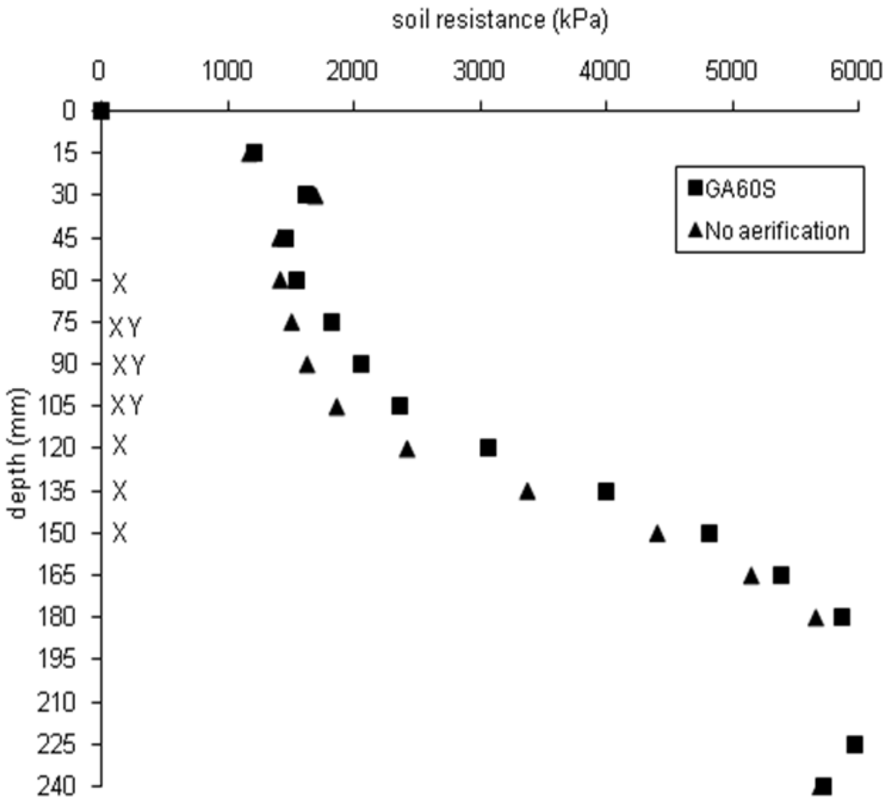
At each sampling depth, if that depth is marked with an 'X' then it had a significantly different soil resistance (at alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the depth is marked with an 'XY', than that soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 8. Soil resistance as measured by a Remik soil penetrometer as affected by aerification, four weeks after August, 2002, treatments. AU Practice Field.



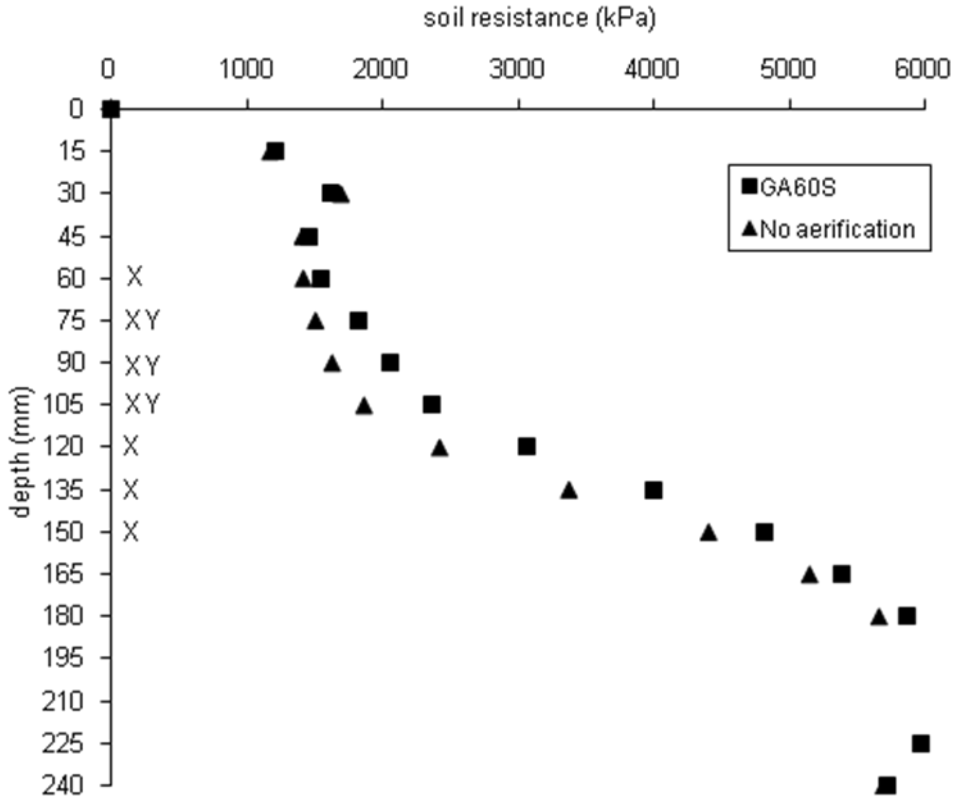
At each sampling depth, if that depth is marked with an 'X' then it had a significantly different soil resistance (at alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the depth is marked with an 'XY', than that soil resistance measurement was signficantly ldifferent than measured in any other treatment (including all other aerification treatments).

Figure 9. Soil resistance as measured via a Remik penetromter as affected by aerification, six weeks after August, 2002, treatments. AU Practice Field



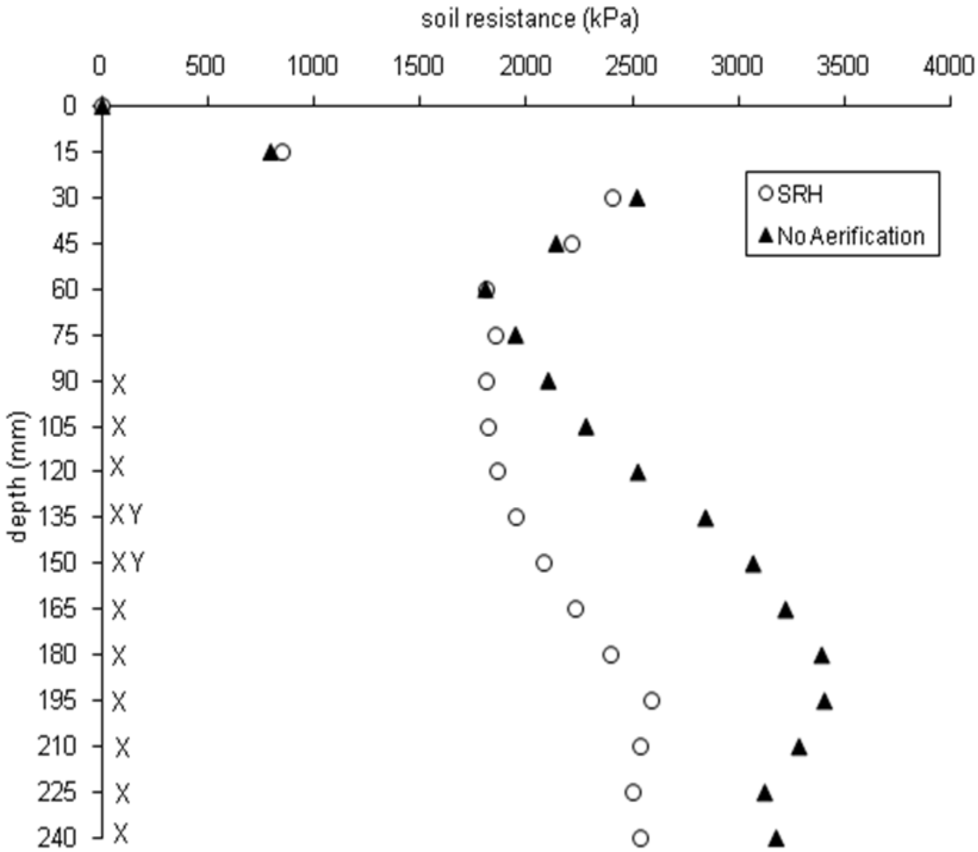
At each sampling depth, if that depth is marked with an 'X' then it had a significantly different soil resistance at (alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the thepth is marked with an 'XY' then that soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 10. Soil resistance as measured via a Remik penetromter as affected by aerification, six weeks after August, 2002, treatments. AU Practice Field



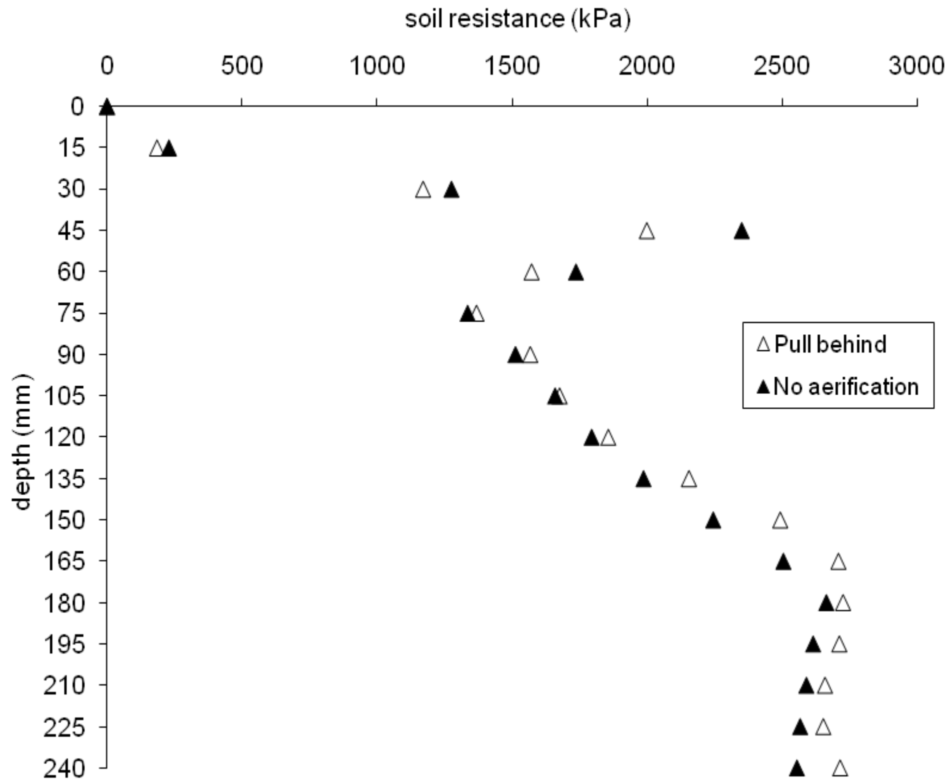
At each sampling depth, if that depth is marked with an 'X' then it had a significantly different soil resistance at (alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the thepth is marked with an 'XY' then that soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 11. Soil resistance measured via a Remik penetrometer as affected by aerification, one week after August, 2002 treatments. TGRU.



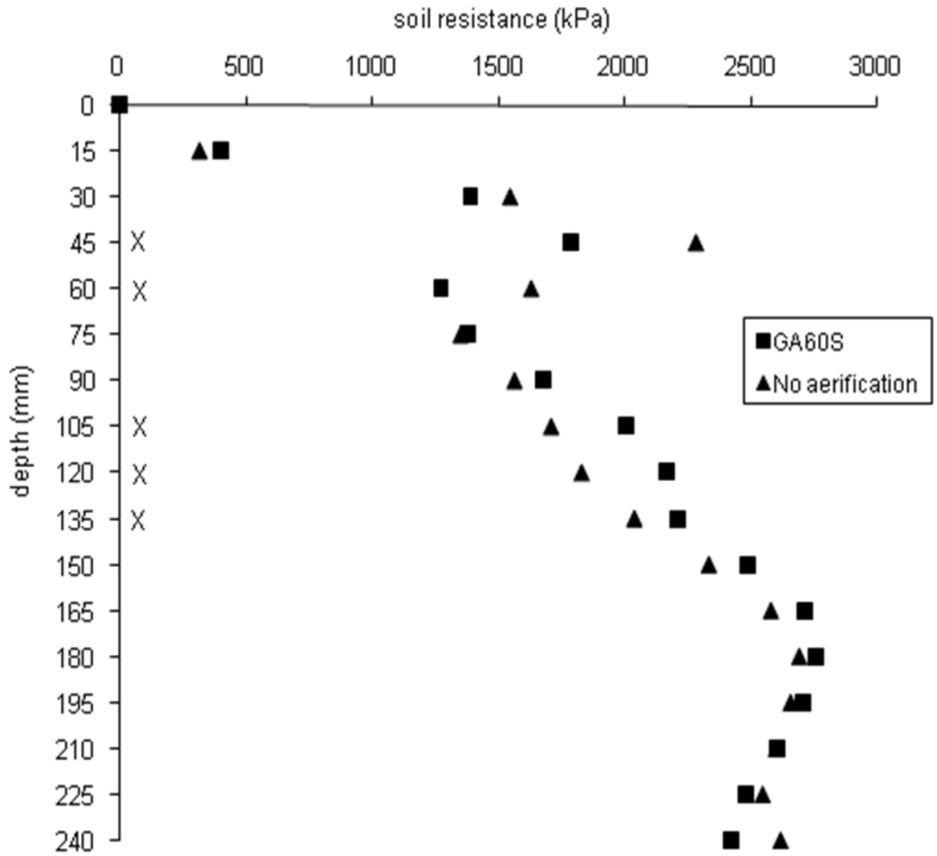
At each sampling depth, if that depth is marked with an 'X' then it had a significantly different soil resistance (at alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the depth is marked with an 'XY', than that soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 12. Soil resistance as measured via a Remik penetrometer as affected by aerification, one week after August, 2004 treatment. TGRU.



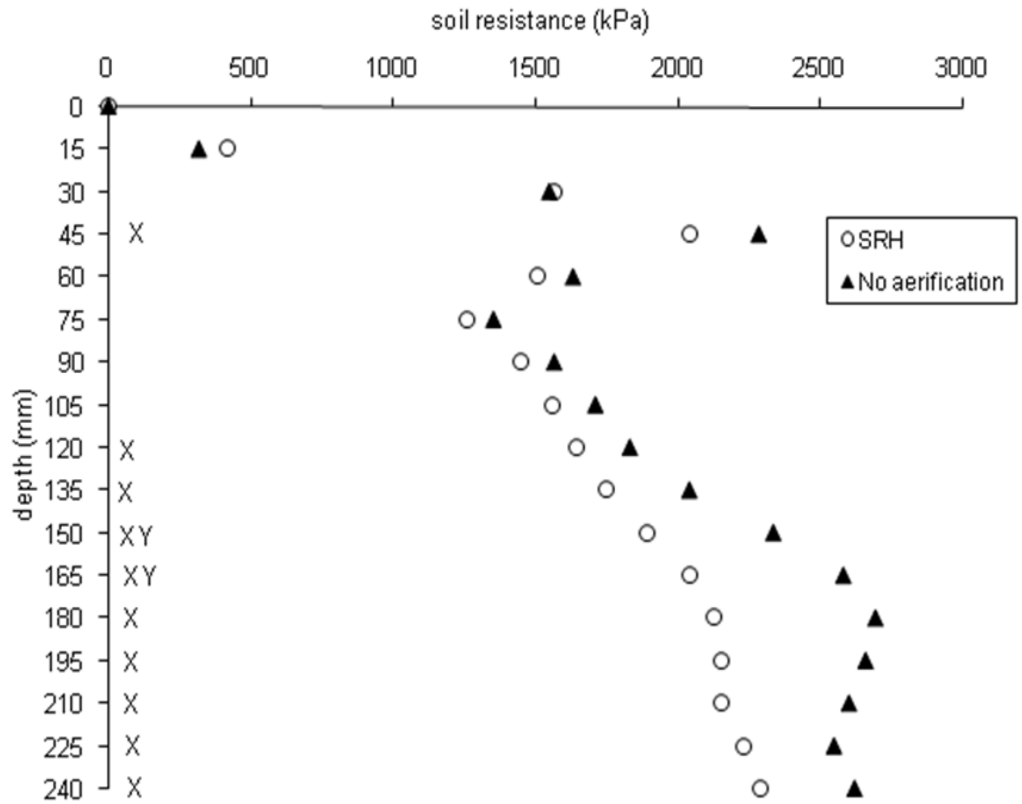
At each sampling depth, if that depth is marked with an 'X' then it had a significantly different soil resistance (at alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the depth is marked with an 'XY' , than that soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 13. Soil resistance as measured via a Remik penetrometer as affected by aerification, six weeks after August, 2004. TGRU



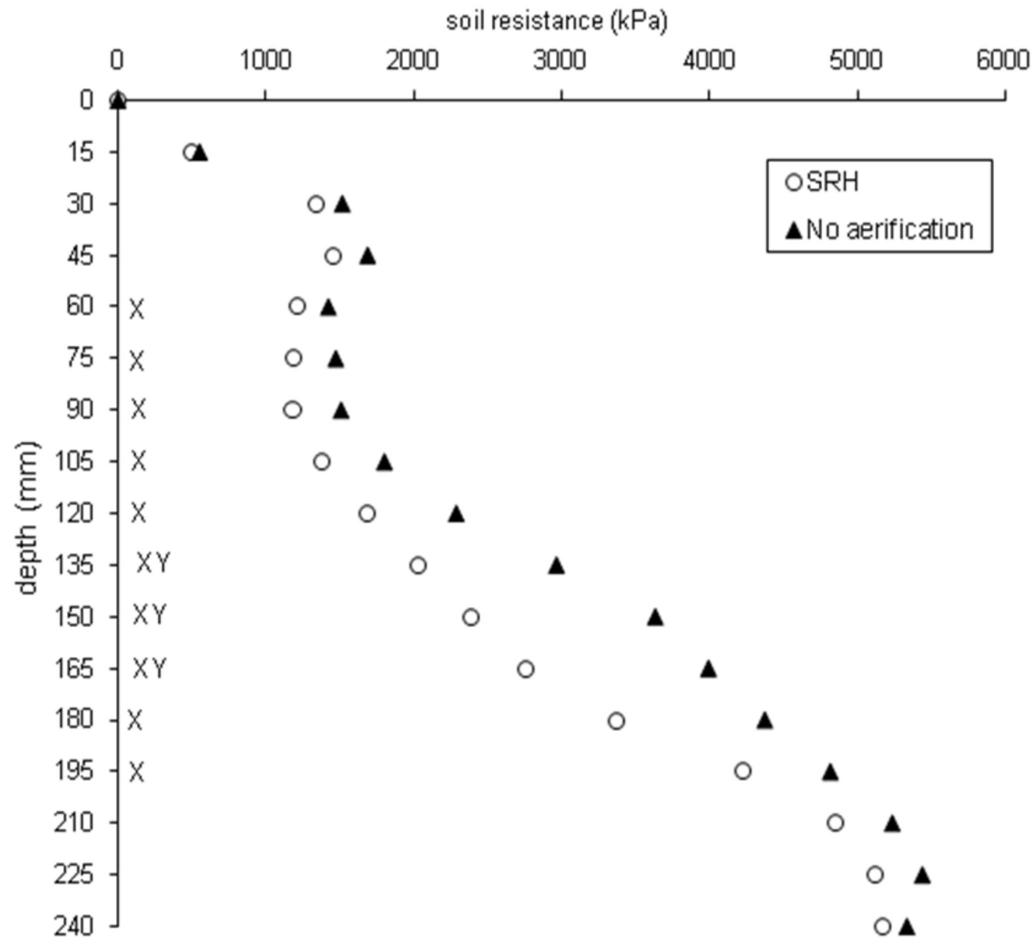
At each sampling depth, if that depth is marked with an 'X' then it had a significantly different soil resistance (at alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the depth is marked with an 'XY', than that soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 14. Soil resistance as measured via a Remik penetrometer as affected by aerification, six weeks after August, 2004 treatment. TGRU



At each sampling depth, if that depth is marked with an 'X' then it had a significantly different soil resistance (at alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the depth is marked with an 'XY', than that soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).

Figure 15. Soil resistance as measured via Remik pentrometer as affected by aerification, one week after August, 2001 treatments, AU Practice Field.



At each sampling depth, if that depth is marked with an 'X' then it had a significantly different soil resistance (at alpha = 0.10) than the corresponding measurement from the non-aerified treatment. If the depth is marked with an 'XY', than that soil resistance measurement was significantly different than measured in any other treatment (including all other aerification treatments).