EFFECT OF ROOTZONE CONSTRUCTION ON SOIL PHYSICAL PROPERTIES AND PLAYING QUALITY OF GOLF GREENS UNDER NEW ZEALAND CONDITIONS

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ABSTRACT

A field experiment was designed to examine the effect of five different rootzone constructions (partially amended sand, silt soil, pure sand, fully amended sand and partially amended plus zeolite sand) and aeration methods (untreated control, HydroJect, Verti-drain and scarifying) on soil physical properties, root development and playing quality of golf greens. The five rootzone constructions were randomly arranged in three blocks. A split plot design was superimposed on the rootzone constructions using different aeration methods. Aeration treatments were carried out in the spring and autumn of 1998. Measurements of bulk density, total porosity, volumetric moisture content, air-filled porosity, infiltration rate, oxygen diffusion rate, saturated hydraulic conductivity, root mass, organic matter content, surface hardness and green speed were made to monitor differences between treatments.

This study found there was no benefit of fully amended sand rootzone compared with partially amended sand rootzones (either plus or without zeolite). Although root development was greater in the pure sand rootzone, this occurred predominantly in the top 50 mm. Excessive accumulation near the surface of the profile can have detrimental impacts on turf growth. Rootzone construction had an important effect on surface hardness, i.e. pure sand rootzone produced the hardest surface, silt soil rootzone the softest and amended sand rootzones intermediate hardness. Rootzone construction had no effect on green speed in this study.

Aeration treatment had no effect on any of the soil, plant or playing quality parameters measured in this study. This suggests either aeration treatments were very short lived or that long term effects of aeration treatments were not yet apparent.

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1. Introduction

Soil physical properties of golf green rootzones strongly influence their ability to support a healthy turf. They also directly affect the playing quality of the surface. As early as 1916 sand and manure were used as amendments to soil to improve a green's rootzone (Hurdzan, 1985; cited in Hummel, 1993a). Since then there has been a considerable amount of work to identify factors that contribute to a high quality rootzone material. During the 1950s, sand-based greens, containing more than 85% of sand by volume, were introduced by the United States Golf Association (USGA) as part of their green construction specifications (Hummel, 1993a). The choice of high sand content was due to the belief that it could sustain good drainage and adequate air-filled pore space within the rootzone which in turn provided better conditions for grass growth (Baker *et al.*, 1997).

The use of sand-based greens (including USGA greens) world-wide has resulted in much research on the effects of type and amount of sand and on the effects of various amendment materials (Baker and Richards, 1993; Lodge and Baker, 1993; Hummel, 1993a; Cook and Baker, 1998). However, construction of a sand-based green does not necessarily guarantee satisfactory long-term performance. A common issue in this type of construction is the amount of organic matter (living or dead) that accumulates in the top 50 mm of the profile. Carrow (1995) stated this material could cause plugging of soil pores resulting in two immediate responses: a) decreased water infiltration, and b) reduced soil oxygen diffusion. This can adversely influence root development, root viability and shoot performance. It is also believed this is a major reason of "bentgrass summer decline".

Research has been carried out attempting to overcome this problem in the United States during last few years (1994-1997) (Carrow, 1995). However, no research has yet been carried out in the cool humid zones typical of New Zealand, northern Europe and the United Kingdom. As such, a research trial using materials and methods feasible for use in New Zealand was initiated in 1997.

The aim of this trial was to examine how selected methods of greens' construction combined with contrasting aeration treatments affected soil physical properties, root development and playing quality.

2. Review of Related Literature

The literature review for this thesis is divided into four sections: soil compaction, sand-based rootzones and amendments, aeration, and playing quality.

2.1 Soil Compaction

Compaction occurs whenever a load exceeds the soil's ability to support it. Golfers, golf carts, maintenance equipment or traffic of any nature can compact soil (Thien, 1994). In fact, any load on soil can become a compactive event under appropriate conditions. When soil is compacted, the downward movement of nutrients, moisture, pesticides, air and roots is restricted. Root restriction produces a shallow rooted turf that lacks vigour and is more prone to injury during stress periods (Daniel and Freeborg, 1987).

2.1.1 The Process of Compaction

Soil compaction is the pressing together of soil particles into a more dense mass, resulting in a reduction of air-filled pore space (Agnew, 1990). The impact of a compressive force on soil depends on the relationship between load weight, area supporting the load and several soil conditions. Changing any factor can alter the impact of a compactive event. A heavy load does not always cause more compaction than a light load. A light load on soil wet enough to be plastic may cause more compaction than a heavy load on dry or frozen soil. Unfortunately, the same moisture range considered most suitable for turf growth is also the range where soils are susceptible to compaction (Thien, 1994).

The complex nature and almost infinite variability of soil conditions challenge a complete understanding of compaction. Many soil conditions alter the impact of compaction, but water content, texture and organic matter content are the most notable. In general, moist, fine-textured soils, low in organic matter are most easily compacted (McCoy, 1991; Thien, 1994; Emmons, 1995). However, it is notable that compaction is not limited to silt and clay based soils. It may occur on sand-dominant soil, for example those used to build golf greens, especially if the greens are poorly constructed (Agnew, 1990).

With so many variable conditions surrounding compaction, predicting the effects of compactive events proves impossible. Rather, the effects of compaction can be evaluated after the event by measuring the degradation of associated soil properties. As compaction problems can be expressed through so many soil and turf characteristics, no single property adequately describes the true scale of compaction (Thien, 1994).

Compaction creates complex relationships that permeate through many other soil properties. Deterioration of turfgrass may be delayed until one of these secondary properties becomes limiting in the total turf environment. For example, in a field study Agnew and Carrow (1983) found no difference in visual quality of turf caused by compaction treatments until heat stress occurred later in the season. After the heat stress period, quality of the turf decreased as the compaction level increased (Agnew, 1990).

Eventually compaction degrades physical, chemical, water and biological conditions in ways that may mask obvious connections back to compaction, and thus hinder corrective recommendations. For example, poor turf quality may be linked to a plant disease problem that took hold when compaction first reduced permeability enough to cause an oxygen deficiency in the soil atmosphere. Under low oxygen conditions, plants will stress, becoming more sensitive to attack by certain disease organisms, such as summer patch (Emmons, 1995). Also, low oxygen can suppress beneficial soil organisms. Even if the turf's condition is properly diagnosed and the correct disease management applied, only the symptom and not the cause of the problem will have been addressed (Thien, 1994).

2.1.2 Effects on Soil Properties

Compaction directly degrades four soil physical properties: bulk density, soil strength, pore size distribution and aeration (Lodge and Baker, 1993). All four provide a conceptual description of compaction as well as benchmarks for measuring and quantifying change. Changes to these four physical properties subsequently lead to degradation of several soil chemical and biological properties and ultimately, turf growth (Thien, 1994).

2.1.2.1 Increased Bulk Density

Soil bulk density, or volumetric mass, is the weight of soil material in a given volume of soil. For laboratory analysis, an undisturbed volume of soil is extracted from its natural site, dried to remove water and weighed. Bulk density is calculated by dividing the dry weight of a sample by its volume. Bulk density values typically range between 0.8 and 2.0 g/cm^3 depending on soil texture and state of compaction (McLaren and Cameron, 1996). Sandy soils have the highest uncompacted bulk densities and change least when subjected to compaction. High clay content soils have lowest uncompacted bulk densities and will change most as a result of compaction (Thien, 1994).

Bulk density changes are not proportional to the load increase. Each increase in compactive load raises bulk density, but changes come in smaller increments as bulk density approaches a maximum (Singer and Munns, 1987).

2.1.2.2 Increased Soil Strength

Soil strength is a measure of penetration resistance of a soil. Compactive forces can overwhelm or weaken binding agents that "glue" soil particles into open aggregates with low resistance causing them to collapse. As particles come closer together, both interparticle attraction and penetration resistance increases (McLaren and Cameron, 1996). Unlike the effect with bulk density, increasing the compactive load continues to significantly increase soil strength. Thus, while a load may not cause any visual deformation indicative of compaction, soil strength could have increased significantly. This feature especially comes into play where repetitive loading occurs. Typically, approximately 70 percent of the total compaction occurs with the first compaction event. Subsequent compactions change bulk density only slightly, but soil strength continues to rise (Thien, 1994).

In uncompacted soil, penetration resistance typically rises with increases in depth and clay content. Penetration resistance decreases with increasing water and organic matter content. The ability to resist changes in soil strength is related to the complex behaviour of binding agents and soil mineral particles. Both the amount of surface area exposed and the physiochemical nature of the functional groups in binding agents influence their ability to protect soil colloids from reorientation into high strength configurations. Organic agents seem to provide some of the most effective binding agents to resist high soil strength (Harris, 1990).

2.1.2.3 Altered Pore Size Distribution

Soil is a porous medium of interconnected openings. Inside these pores roots grow, microbes live, water moves and is stored and gases flow. Soil in good physical condition typically contains approximately 50 percent pore space. More important than total pore space, however, is pore size distribution. Variously sized pores all perform important but different roles in soil, so when compaction changes pore size distribution, vital soil functions are altered (Thien, 1994).

Macropores are the largest soil pores and function in aeration and drainage of excess water. Mesopore, the medium-sized pores, are most important in distributing water within the soil by capillary action. Capillarity conducts water downward for storage or upward for drying, supplies water to roots and redistributes water from wet to dry zones. Micropores are the smallest soil pores and function primarily as water-storage locations (McLaren and Cameron, 1996).

The process of compaction changes macropores into mesopores and micropores. While this change may reduce total porosity only slightly, its greatest impact is the change in pore function in the compacted zone. A macropore network at the soil surface that once facilitated soil aeration can be compacted into a series of unconnected micropores. That change in pore size distribution shifts the function of the soil surface from aeration to water storage, blocks gas exchange between soil and atmosphere and generally degrades the soil ability to support plant growth. Water-storage pores need to be located in the rootzone, not at the soil surface (Carrow, 1980; Thien, 1994).

A simple measurement that categorises pore size distribution would be very informative, but such analyses are rather complex and not routinely available from diagnostic labs. Changes in bulk density are only sensitive to changes in total pore space so one cannot readily reflect changes in pore size distribution. Instead of directly measuring the presence of various pore sizes, associated properties such as gas diffusion rates and water distribution (hydraulic conductivity) substitute as indicators of how compaction changes optimum pore activities (Thien, 1994).

It is reasonable to assume that compaction also disrupts continuous pore networks. When this happens, pores become sealed and isolated from each other. Thus, even though pores of optimum size may be present, their ability to function is diminished because of their isolation (Thien, 1994).

2.1.2.4 Reduced Aeration

Soil aeration must replenish the oxygen (O_2) content of the soil air and exhaust the accumulation of carbon dioxide (CO_2). Air that enters soil from the aboveground atmosphere contains 20 percent O_2 and approximately 0.03 percent CO_2. Normal respiration by turfgrass roots and soil microbes depletes O_2 content and increases CO_2 content (Singer and Munns, 1987).

Diffusion moves substances from an area of high concentration to an area of low concentration. Gas diffusion rates are highly dependent on the cross-sectional area available for diffusion, so a small reduction in pore size greatly diminishes the movement of gas through it. Thus, loss of aeration porosity (i.e. macropores) translates directly into reduced soil aeration. Smaller pores that result from compaction are more likely to be blocked by water films. Both conditions, fewer macropores and more blocked passageways, accelerate formation of anaerobic soils, as characterised by a deficiency of oxygen (anoxia) or a toxic build-up of carbon dioxide (Mclaren and Cameron, 1996).

A useful measure of soil aeration is the oxygen diffusion rate (ODR) because of its close correlation to turfgrass growth. While various ODR levels critical for turfgrass growth have been reported (O'Neil and Carrow, 1983; Bunt, 1991; Stepniewski and

Przywara, 1992; Tomar, 1993), ODR values below 0.2 μg cm^{-2} min^{-1} are suggested as limiting, and values above 0.4 μg cm^{-2} min^{-1} are suggested as being adequate. Agnew and Carrow (1985) showed the ODR after irrigation remains below critical values much longer in compacted than in uncompacted conditions. Also, since the smaller pores in compacted soils have to be water-free to allow aeration, compacted soils must be drier than uncompacted soils before ODR values return to adequate levels (Agnew and Carrow, 1985).

Attempts to model the relationship between soil porosity and gas diffusion through soil show best agreement with a fourth-degree exponential function. This means, that if compaction reduces air-filled pores to half their original value, gases will then diffuse through the soil 16 times slower than before compaction (Currie, 1984; cited in Thien, 1994). As soil pores remaining after compaction will be smaller, the likelihood of passages being blocked with water increases. This further reduces gas diffusion since gases like O_2 and CO_2 diffuse about 64 times slower through a water film than an open pore (Thien, 1994).

In addition to affecting O_2 and CO_2 levels, compaction can cause other gaseous by-products to accumulate in soils. It has been shown that when compaction causes O_2 to drop below 1 percent, ethylene (C_2H_4) rises as high as 20 ppm (Smith and Restall, 1971; cited in Thien, 1994). At 1 ppm C_2H_4, root elongation has been cut in half and stopped completely at 10 ppm (Smith and Restall, 1969; cited in Thien, 1994).

2.1.3 Effects on Soil Microbial Activities

Soil compaction not only alters soil properties, it also influences that environment's ability to support microbial activities through diminishing air, water or energy supplies. Soil microbial activity is dependent on levels of oxygen in the soil, with deficiencies severely limiting the level of activity. Adequate soil moisture levels are also essential in maintaining activity of the beneficial microbial population (Doyle, 1991).

2.1.3.1 Decomposition Delayed

Decomposition of organic matter by soil microbes promotes humus formation, nutrient cycling, soil aggregation, and capacity to adsorb and store water and nutrients (McLaren and Cameron, 1996). All of these functions are common and necessary in a healthy, high-quality soil. Compaction, however, can interrupt the normal decomposition processes in soil. Microbes carry out decomposition in favourable sites that permit ready aeration, water entry and drainage, and diffusion of soluble energy supplies. Macropores meet these criteria and they accommodate root growth. Roots promote high microbial populations as their exudates and sloughed cells provide a ready and renewable energy source for microbes in the immediate area (Hurdzan, 1987).

When compaction interrupts the pore network by completely sealing some pores, anoxic microenvironments quickly form inside these isolated spaces, and the continuity necessary for diffusion to re-supply life-supporting materials is lost. Microbes in sealed pores then revert to inactive propagules, a stage in which bacteria have been known to survive for many decades (Paul and Clark, 1989; cited in Thien, 1994).

2.1.3.2 Nitrogen Cycling Interrupted

Compaction can interrupt the important soil nitrogen cycle. In well-aerated soils, microbes make nitrogen available to plants by mineralising nitrogen from organic matter into the ammonium (NH_4^+) form. If compaction limits the O_2 supply, this conversion is slowed. Ammonium released from organic matter, or supplied from fertiliser sources, is further converted by microbes into nitrate (NO_3^-), a process called nitrification (McLaren and Cameron, 1996). Nitrate, like NH_4^+, is available to turfgrasses. When O_2 becomes limiting, facultative anaerobic organisms denitrify the NO_3^- to N_2, a gas unusable by turfgrasses and easily lost from the soil (Singer and Munns, 1987). Thus, compaction not only slows the formation of plant available forms of nitrogen, but also enhances nitrogen loss.

Nitrogen losses by denitrification in poorly aerated soil can be quite rapid and rather large. Losses between 20 and 500 ppm N per day have been reported (Grable, 1966; cited in Thien, 1994). Losses increase as the O_2 supply declines and the soil temperature and energy supply for soil microbes increase. Undoubtedly, the N deficiency that can occur in warm, wet compacted soils can contribute to the poor turf quality observed on these sites.

2.1.3.3 Aggregate Stability

Organic matter plays an important role in stabilising soil aggregates that can resist deformation during compactive events. Stable aggregates have been described as a product of temporary mechanical binding by roots, fungal hyphae and short-lived organic adhesives (polysaccharides) produced by microbes in conjunction with long-term cementing action of more resistant humus components (Tate, 1987). These aggregates benefit from continual renewal of the polysaccharide component. The most abundant, recurring sources of fresh organic material for polysaccharide production are root exudates and associated debris. While fungi, actinomycetes and bacteria all produce aggregates, fungi produce the most (Doyle, 1991). Only organisms actively decomposing fresh organic materials in the soil appear to renew the polysaccharide component and encourage stable aggregate formation. Isolation or fabrication of these same microbial by-products and their subsequent addition to soil has not proved equally effective in stabilising aggregates (Thien, 1994).

Thus, conditions that encourage actively growing roots and fungi will enhance aggregate stability and provide some natural resistance to compaction. However, once compaction does limit soil aeration, fungal activity is one of the first to be diminished due to these organisms' low tolerance to anaerobic conditions. So, in a "catch-22" scenario, in order for natural processes to remedy compaction, fungal decomposition of organic materials should be encouraged, but that is not likely to occur because compaction creates anoxic conditions (Thien, 1994).

2.1.3.4 Pathogens Enhanced

Plant diseases are disorders caused by microorganisms such as fungi, bacteria, and viruses. Their formation requires a susceptible host, a viable pathogen population and a suitable environment (Daniel and Freeborg, 1987). Essentially, all major turf diseases are caused by fungi and fungal activity. The fungi and fungal activity are closely related to the status of the soil environment, especially water content (Emmons, 1995). Wherever compaction significantly increases waterlogging and poor aeration, several turf diseases are typically more pronounced. It is believed that high soil water content stresses some turfgrasses to the point of making them more susceptible hosts and aids in the dispersion of pathogen spore. (Thien, 1994)

Some stress in wet soils undoubtedly relates to reduced aeration. In soils with adequate aeration and a readily available supply of decomposable compounds, beneficial organisms compete better against pathogens (Doyle, 1991). Fungi favour aerobic environments, but under marginal aeration, pathogenic virulence of soil fungi can increase. The incidence of anthracnose, damping-off, grey leaf spot, *Pythium* blight, *Rhizoctonia* brown patch and spring dead spot diseases are all enhanced by prolonged wet soil conditions, and thus, may ultimately be accentuated in compacted soils (Turgeon, 1980; cited in Thien, 1994).

2.1.4 Effects on Turfgrass

Soil compaction indirectly affects plant growth by decreasing aeration and increasing soil strength, soil water holding capacity and soil temperatures. Turfgrass tolerance to compaction depends on the turf species and the status of other stress factors such as wear, temperature, drought and disease (Thien, 1994).

2.1.4.1 Root Growth

A healthy root system explores a soil volume large enough to supply sufficient requirements. Compaction can create conditions that exclude roots from some zones and limit their physiological activities (Thien, 1994).

Root development generally declines in compacted soils. Some combination of reduced root mass, extension rate, or density typically occurs in response to soil compaction. Data from research conducted by Agnew and Carrow in 1984, indicated that soil compaction results in increased root growth near the surface, while deep rooting decreases. Shallow roots result in decreased water and nutrient absorption. Thus, the golf course superintendent needs to irrigate lightly and frequently in compacted soils. This results in poor use of valuable irrigation water (Agnew, 1990). In another study, compaction reduced root weight by 23 percent in Kentucky bluegrass and 39 percent in perennial ryegrass, but caused a 28 percent increase for tall fescue root systems (cited in Thien, 1994). The growth rate of roots may be limited by either a lack of O_2 or by an excessive accumulation of CO_2 near the roots.

Root growth is reduced by compaction when soil strength exceeds the force roots can exert as they enter into or expand within soil pores. Root pressure is greatest when the soil air contains neither deficient levels of O_2 nor too much CO_2. Root elongation through soil layers decreases when soil strength increases, regardless of whether soil strength was raised by compaction or drying (Taylor, 1971; cited in Thien, 1994). After irrigation, when water still fills most of the pores, gas diffusion can be virtually stopped until drainage opens some of the pores. O'Neil and Carrow (1983) found that compaction decreased ODR below the critical level for perennial ryegrass for 53 hours following irrigation. Shoot growth was immediately limited and root growth was also eventually reduced. In contrast, ODR values were below the critical level for only 5 hours following irrigation in non-compacted soils.

In summary, compaction appears to have a twofold impact on root O_2 status. The same conditions that limit O_2 supply to roots increase O_2 demand by roots. These circumstances undoubtedly trigger the deterioration of turfgrass quality associated with soil compaction.

2.1.4.2 Shoot Growth

The effects of soil compaction on shoot growth have been documented as reduced visual quality and shoot density, decreased rhizome development, and reduced clipping production (Agnew, 1990). These responses are understandable because water and nutrient uptake are adversely affected by altered root distribution. In a field study (Agnew and Carrow, 1983), visual quality was not affected by soil compaction until after the onset of high temperatures in July. Before the July heat stress, little difference was recorded in quality. After the July heat stress period, quality decreased as the compaction level increased. Shoot density and rhizome development are decreased by soil compaction. Reduction in shoot density and rhizomes is not always exhibited immediately after soil compaction. This response to soil compaction may be a result of the combined altered root growth and high evaporative demand. Clipping yields were also decreased by soil compaction. Unlike other shoot responses, the decrease in clipping yield is an immediate response. Vertical leaf growth can be decreased by 70 percent following soil compaction (Agnew, 1990).

Plants growing under compacted conditions exhibit less resistance to other environmental stresses. Turf recovery and hardiness traits are linked to an adequate sugar and carbohydrate content. In one study of three turfgrass species, carbohydrate levels declined as compaction stress increased (Carrow, 1980). These results suggest that delaying or failing to treat compacted soil places the weakened turf at risk of succumbing to an environmental stress it might otherwise withstand.

2.1.4.3 Nutrient Relations

Plant nutrient relationships dealing with both availability and absorption can be altered in compacted soils. Nutrient availability is often limited by complex interactions with soil aeration and pH changes triggered by compaction. Nutrient uptake is an aerobic process that will be limited to the extent that O_2 deficiency accompanies compaction. While compaction is a physical process, the reduced aeration it causes can affect chemical and physiological processes that ultimately impact plant nutrition. Early research reports have documented the effects of soil compaction on nutrient uptake, which appears to be reduced in the following order: K>N>P>Ca>Mg (Agnew, 1990).

2.1.4.4 Water Relations

Compaction significantly alters the water relations necessary for optimum turfgrass growth. Depending on conditions, compaction can cause the soil water content to be inadequate or excessive. Both conditions limit turfgrass growth, either because of insufficient water or inadequate aeration (Thien, 1994). The balance between the soil's ability to supply water and the plant's water requirements ultimately determines the level of impact.

Surface compaction reduces infiltration through loss of macropores. If water application, either through rainfall or irrigation exceeds the infiltration capacity of the soil, the excess either runs off sloped sites or ponds and evaporates in depressions. Non-uniform wetting patterns can result with the compacted spots showing premature dryness compared to nearby non-compacted soil (Thien, 1994).

Subsurface compaction can limit water percolation and cause it to accumulate above the affected layer. These conditions can develop when compaction depth exceeds the depth of aeration cultivation (McLaren and Cameron, 1996). Whenever water application exceeds drainage, soils develop perched waterlogged zone that restrict aeration and reduce root activity.

2.1.5 Preventing and Alleviating

The best approach to compaction problem is prevention. Prevention involves construction with a sand-based rootzone that has low compaction proneness and proper contouring for good surface drainage (Beard, 1982). Many forms of mechanical cultivation (aeration) are available to alleviate soil compaction after it has occurred. The methods of cultivation including: coring, spiking, slicing, Verti-drain and HydroJect (Carrow, 1990). The details of sand-based rootzone and aeration methods will be reviewed later.

2.2 Sand-based Rootzone and Amendment

Sand is now the major component of golf greens as it provides good drainage, compaction resistance and aeration for root growth despite heavy traffic that golf greens receive. The idea of using pure sand as a rootzone was put forward by Lunt (1956) and Bingaman & Kohnke (1970) and subsequently developed by Davis (1973) (cited in Lodge and Baker, 1993). However, sand-based greens have the disadvantages of low water and nutrient retention and poor pH buffering capacity (Voroney and Straaten, 1988). Moreover, disease problems often are much more severe on pure sand greens, because pure sand greens have extremely low microbial activity (Snow, 1992). In order to reduce the undesirable characteristics of sand, many types of amendments have been used to modify them.

2.2.1 Organic Materials

Organic materials used in green rootzones as an amendment include peats, rice hulls, sawdust, shredded bark, seaweed and various composts (Huang and Petrovic, 1995).

2.2.1.1 Peat

Peat has commonly been employed in sand-based greens to improve moisture and nutrient retention, to decrease bulk density and increase soil resilience (Carlson *et al.*, 1998). In a sense, these materials provide a physical and chemical management of turfgrass. The increased moisture retention delays the onset of injurious drought conditions between irrigations. The increased nutrient retention maintains a stable supply of nutrients to the grass between fertiliser applications. The decreased bulk density and increased soil resilience help to provide an open and mechanically stable pore space for root penetration. (McCoy, 1991).

Peats from different sites vary significantly in their properties, including pH, water-holding capacity, ash content, bulk density and degree of decomposition (Bethke, 1988). Peats can be classified into three groups based on their source materials and age of decomposition: moss peats, reed sedge peat and peat humus (Lucas, 1965; cited in Nus, 1994).

Moss peats are derived from sphagnum, hypnum and other mosses. Sphagnum peat is generally very porous and has a low ash content and very low bulk density. At least two-thirds of the material must be recognisable fibers of sphagnum moss, according to the American Society of Testing Materials (ASTM), to be called sphagnum peat (Bethke, 1988). Hypnum peats are those with at least one-third of their content as identifiable hypnum fibers, and which have a larger ash content and bulk density compared to sphagnum (Bethke, 1988). Reed sedge peat is formed from marsh grasses, sedges and plants typical of swampy areas such as cattails. Reed sedge peat can be low-lime or high-lime, depending on the amount of calcium and magnesium available during their development (Bethke, 1988). Peat humus is characterised by an advanced stage of decay and has a much higher bulk density and ash content than moss peat or reed sedge peat. Peat humus is considered an excellent source of organic matter, and its finer texture makes it more desirable to improve porosity of sand compared to other organic amendments (Nus, 1994).

McCoy (1991) concluded that a suitable peat should contain in excess of 80 percent organic matter by weight and have fiber contents between 20 to 45 percent for mixes with sand. A well decomposed, fractionated peat with minimum mineral content is preferred. The ranking of types of peat from excellent to poor would be: peat humus, reed sedge peat, hypnum peat, sphagnum peat (Beard, 1982). It is notable that some peat is not suitable for amending sand. McCoy (1992) reported that a muck peat with an organic matter content of 40 percent and a fiber content of 7 percent mixed with sand at 20 percent by volume had a saturated conductivity of 21 mm/hr and a very low compression index.

2.2.1.2 Rice Hulls

Rice hulls are characterised by a high silicon content that serves to slow down their degradation. However, due to this natural high silicon content, rice hulls will have a low organic matter content as determined by loss on ignition (i.e. less than 75 percent) (Nus, 1994). Addition of rice hulls to medium sand has been shown to decrease moisture retention and saturated conductivity (Carlson *et al.*, 1998), but increase saturated conductivity on fine sand (Davis *et al.*, 1970; cited in Hummel, 1993a). Nonetheless, rice hull composts can serve as an exceptionally good organic amendment for putting green construction in fine sand which already has a high moisture holding capacity (Nus, 1994).

2.2.1.3 Sawdust and Shredded Bark

Research has shown that sawdust and bark has resulted in improved as well as poor soil physical properties when mixed with sand (Hummel, 1993a).

However, sawdust and shredded bark can result in inferior turfgrass performance (stunted growth and discoloration) because of the depletion of available nitrogen by decomposer organisms (Nus and Brauen, 1991). Wood products are not as stable as peat and can deteriorate after a 13 month incubation period (Hummel, 1993a). Results suggest that sawdust and bark are generally considered a poor choice as an organic soil amendment, unless they have been composted for several months (Waddington *et al.*, 1967).

2.2.1.4 Composts

Compost is an inexpensive and easily obtained source of organic matter. Organic waste materials such as leaves, grass clippings, straw, sawdust, shredded bark, various animal/vegetable by-products and even garbage can be composted (Emmons, 1995). These decomposed materials can function as well as peat in a sand-based rootzone if certain criteria are met (Beard, 1982).

All composts are relatively high in organic matter (30 to 60 percent) compare to soil, though lower than peat (more than 80 percent). However, as a sand amendment, compost will significantly raise the organic matter content of sand-based rootzone (Wilkinson, 1994). Despite the lower organic matter content that composts have, they do have an advantage. Results of research at Cornell and findings from other university research projects indicate composts have the ability to suppress a number of turf diseases (brown patch, dollar spot, necrotic ring spot, pythium blight, pythium root rot, red thread and typhula blight). Though suppression is not always consistent, it appears to be broad-based in terms of the number of diseases suppressed and turfgrasses on which it is effective (Doyle, 1991). It is believed that composts have a high and varied level of microbiological activity, containing organisms that suppress the pathogenic organisms that cause turf diseases. As peat is highly decomposed, its level of biological activity is low, therefore, it does not suppress diseases (Wilkinson, 1994).

2.2.2 Inorganic Materials

Several types of inorganic materials have been used to modify sand-based rootzones, including calcined clay, calcined diatomites, vermiculite, perlite, pumice, expanded shale, slag, sintered fly ash and clinoptilolitic zeolite (Waddington, 1992; Carrow, 1993).

2.2.2.1 Calcined Clay

Calcined clay materials have been used in turfgrass production for years and are still being marketed for that purpose (i.e. Turface, Terra-Green, Profile and GreensChoice). Calcining refers to the firing process that heats clays up to 980 °C or more, although the exact temperature and resultant properties of the product vary with the manufacturer (Nus, 1994). Because they have a clay base, these materials possess a relatively high CEC. Calcining produces a hardened, porous structure capable of improving the water retention capabilities of sand- based rootzones. However, much of this water is held at high tension and is unavailable for turfgrass use (Hummel, 1993a).

Calcined clays that were used several years ago (1960-1990s) were subject to particle breakdown and could lead to unwanted layering of putting green rootzones. Today's porous ceramics use a more controlled firing process, which manufacturers claim drastically reduces particle breakdown (Nus, 1994).

2.2.2.2 Calcined Diatomites

Calcined diatomites are naturally occurring minerals derived from diatoms, and processed to varying degrees. Although similar to sand chemical composition, the structure of the fossilised diatoms creates an abundance of pore space. It is this abundance of pore space that providing additional capillary (water-filled) pore space to sand-based rootzones. However, the availability of this water for turfgrass use and particle degradation is highly questionable (Daniel and Freeborg, 1987).

2.2.2.3 Vermiculite

Vermiculite is a very porous material with a high moisture holding capacity and a low bulk density (Hummel, 1993a). Reports (cited in Hummel, 1993a) have shown that vermiculite improves turfgrass yield and quality when compared to unamended sand. It also decreases permeability, increases available water and increases CEC. While vermiculite seems to benefit the characteristics of sand-based rootzone field data are lacking.

2.2.2.4 Perlite

Perlite is extremely porous and lightweight, commonly used for greenhouse and nursery media. Crawley and Zabcik (1985) found no effect at 10 percent, but at 20 percent by volume in medium sand, there was a slight increase in moisture retention, an increase in total and air-filled porosity, and a decrease in saturated conductivity. In the same study they also found that a 20 percent perlite by volume added to medium sand decreased bulk density from 1.62g/cm^3 to 1.42 g/cm^3, a level which falls in the middle of the range that the USGA recommends to reduce problems associated with compaction. While perlite does not degrade, it is fragile and easily crushed to a fine dust with compaction or cultivation. Again, there is inadequate field data for perlite to recommend its use.

2.2.2.5 Slag and Fly Ash

Slag and fly ash waste from industries may be crushed, screened, and made available for incorporating into rootzones. However, such materials need to be checked for toxic chemicals or high salt content before use (Beard, 1982; Daniel and Freeborg, 1987). There is insufficient field data or experience with these materials to recommend their use.

2.2.2.6 Clinoptilolitic Zeolite

Clinoptilolitic zeolite (CZ) is found predominantly in sedimentary deposits formed from volcanic rock, differing from other zeolite in having substantial substitution of Al^{3+} with Si^{4+}, thereby giving it a higher cation exchange capacity (Mercer *et al.*, 1970; cited in Huang and Petrovic, 1994). CZ has been investigated for its usefulness as a sand-based rootzone amendment because of its selective retention of ammonium and potassium ions, water-absorbing capacity and high CEC.

As an amendment to sand, CZ has been shown to increase water holding capacity and CEC (Ferguson *et al.*, 1986; Voroney and van Straaten, 1988; Nus and Brauen, 1991; Huang, 1992; Mannion and Kline, 1996), and improve turfgrass establishment when compared to sand alone (Ferguson *et al.*, 1986; Voroney and van Straaten, 1988; Nus and Brauen, 1991). Huang, 1992 (Hummel, 1993a) reported that 5 percent and 10 percent additions of CZ in the 0.25 to 0.5 mm size range had no effect on saturated conductivity.

Compared to sphagnum peat, CZ exhibits higher volumetric exchange capacity and exchangeable K (Nus and Brauen, 1991; Mannion and Kline, 1996). The high exchange capacity can result in reduced nitrate and ammonium leaching losses (MacKown and Tucker, 1985; Ferguson and Pepper, 1987; Petrovic, 1993; Huang and Petrovic, 1994) and can provide superior turfgrass performance (Ferguson *et al.*, 1986; Voroney and van Straaten, 1988; Petrovic, 1990).

CZ appears to have potential as an inorganic amendment. However, the particle stability of CZ has been questioned (Hummel, 1993a). Also, a further consideration is that CZ from some sources may be harmful to turfgrass. For example, some deposits are naturally high in sodium, potassium, ammonium and clay. CZ naturally high in sodium content should be leached where possible to prevent ill effects to grass health (Allen and Andrews, 1997).

2.2.3 Other Materials

2.2.3.1 Water-absorbing Polymers

Insoluble water-absorbing polymers (starch-graft copolymers, polyacrylates, and acrylamide-acrylate copolymers) are being promoted as amendments to sand-based rootzones to increase moisture retention (Nus, 1992). Although numerous researchers have reported that the use of polymers increases moisture retention and increases turfgrass cover (Nus, 1992; Baker, 1991), other research results have shown the polymers do not have beneficial effects or are even detrimental to turf germination and stand density (Hummel, 1993a). Nonetheless, water-absorbing polymers (e.g. Terracottem) are widely used successfully in the horticultural industry (Gibbs, Pers. Comm.).

2.2.3.2 Rootzone Stabilising Agents

Reinforcement materials such as mesh elements and polypropylene fibres have been used in sand-based sports fields to provide stability, especially in high-wear areas. Because of potential interference with cup cutting on greens, only few can be applied in a green situation (Hummel, 1993a). Some of the materials have also been claimed as an element for alleviating compaction in the rootzone (Carrow, 1993). However, they are not currently recommended by USGA.

2.2.4 Amendments' Selection

The turfgrass marketplace offers several options when selecting sand amendments. However, lack of availability and high costs often make choice for amendment difficult in some areas or countries. Turf researchers have been looking for amendments that can meet cost and availability factors. For example, turf researchers have paid a lot of attention to zeolite in New Zealand because there are several companies producing this product.

However, the physical and chemical properties of amendments can vary from different countries or even within a country. For example, Yang (1997) found two zeolites, both extracted in New Zealand, had a significant difference in their influence on the physical properties of a rootzone. It is necessary to undertake laboratory tests of both sand and amendment as the quality of sand and amendment differs substantially from area to area. Laboratory procedures can test whether a specific amendment is appropriate for a particular sand and how much of the amendment will be necessary for the quality of the sand. However, local field experience is needed before any recommendation can be made.

2.3 Aeration

Aeration is a mechanical process involving the cultivation of soil or the removal of organic matter that has accumulated at the soil surface. As the amount of traffic continues to increase on golf courses and high level of maintenance practices are pursued, aeration is becoming more of an essential part of turf maintenance programs. Due to various rootzones, climate conditions and techniques available in different countries or areas, aeration programs on golf greens are greatly varied. For example, in some areas of the USA aeration is done biweekly or monthly during the summer compared to New Zealand where it may be carried out only two or three times each year.

2.3.1 Soil Aeration

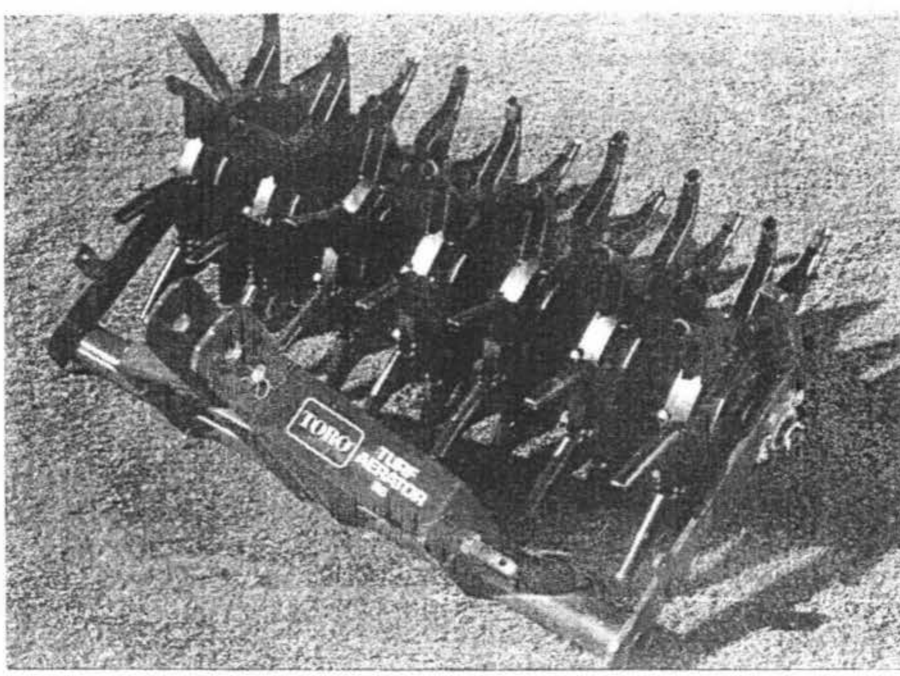
Soil aeration is a mechanical form of cultivation that loosens the soil and/or removes cores leaving holes or rearranges pore size distribution in the soil. It is performed to improve turf performance when soil compaction becomes a problem. There are several types of cultivation practices available to alleviate soil compaction, including core cultivation, water injection, Verti-draining, spiking/slicing and mole ploughs.

2.3.1.1 Core Cultivation

Core cultivation involves the removal of cores with either hollow tines or spade-like spoons. In 1990, Agnew considered core cultivation to be the best means of alleviating soil compaction (Agnew, 1990). The distance between the holes and their diameter and depth depend upon the type of machine used. Holes are typically spaced 25 to 150 mm apart, 6 to 20 mm in diameter and are normally 50 to 100 mm in depth. A machine with 20 mm diameter tines making holes 50 mm apart will remove over 5 percent of the surface soil in one pass. The deeper the holes, the more effective the core cultivation (Emmons, 1995).

One type of core cultivator has open tines or spoons mounted on a drum or metal wheels (Fig. 1). The drum or wheels turn in a circular motion and force the tines or spoons into the soil. The depth of penetration is highly dependent on the degree of soil compaction and the moisture content of the soil, and close spacing is sacrificed for speed. If soil conditions are not ideal, these units tend to ride over compacted sites producing the least effect where penetration is needed the most. The holes can be quite ragged, which limits use of most drum units on greens. However, these rotating units core cultivate turf more quickly than the vertical type and are preferred for aeration of larger areas (Vavrek, 1992).

Figure 1. Circular motion corer



Another type of cultivator has hollow tines mounted on a crankshaft (Fig. 2). Tines move up and down vertically and allow deep penetration minimising damage or disruption to the turf. These machines are popular for golf greens because they cause minimal disturbance to the putting surface. However, vertical motion aerators have a slow operating speed (Emmons, 1995).

When performed properly and under the right conditions, core cultivation can:

- Relieve soil compaction.
- Increase the exchange of oxygen and other gases between the soil and atmosphere.

- Enhance absorption and reduce runoff of water, while increasing soil infiltration and water retention.
- Enhance nutrient placement and uptake.
- Modify the soil surface profile (topdressing).
- Improve depth and extent of turfgrass rooting.
- Relieve summer stress on greens.
- Encourage the breakdown of thatch.
- Prepare a "seedbed". Seed germinates in core cultivation holes and is protected from traffic until well established.
- Open up the thatch layer for chemical application.

(Anon., 1992)

Figure 2. Vertical motion corer

Routine use of a coring machine without other compaction relief will create a layer of compaction called a cultivation pan located just beyond the depth of tine penetration. A cultivation pan slows the movement of water through the soil profile and restricts root penetration (Vavrek, 1992). A deep-tine aerator (Verti-drain) can break this and also penetrate through different soil layers that may impede water movement and root development (Vavrek, 1992; Emmons, 1995).

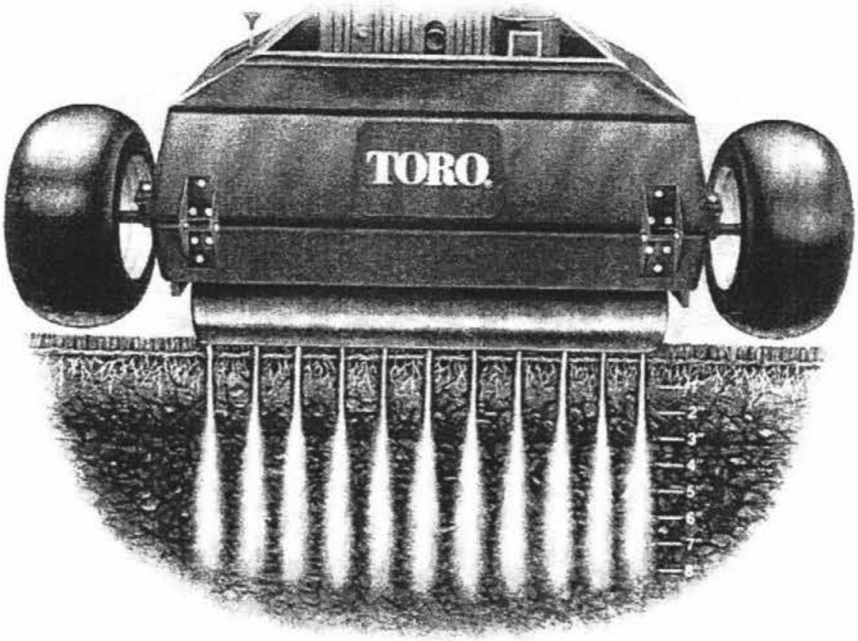
Core cultivation should not be performed when the soil is too dry or wet. A dry soil is hard and difficult to penetrate. Damage to the turf is more likely if the soil is wet. Opening up the soil can cause root desiccation during hot, dry weather. Irrigation is necessary after core cultivation. Core cultivation is generally avoided in midsummer because the open holes can lead to severe wilting. The best time to perform this practice on warm season turf is in late spring or early summer. The ideal time on cool season turf is late summer or early fall (Emmons, 1995).

2.3.1.2 Water Injection

The Toro Co. introduced the HydroJect 3000 (Fig. 3) as a water injection cultivation tool in 1990. This machine utilises high-pressure water to cultivate soil while minimising surface disruption. Water pressurised to 5,000 psi, is released through small diameter nozzle orifices, creating a high velocity stream of water. The water stream or pulse “cuts” cleanly through the turf surface and creates a channel in the soil (Murphy and Rieke, 1991).

The shape and depth of the channels created are largely dependent on soil conditions. A study conducted by Murphy and Rieke in 1991 found that water injection on a highly compacted or relatively dry soil resulted in 76 to 127 mm deep channels with a maximum channel diameter of 13 mm. Under less compacted or moist soil conditions, channel depths reached 127 to 203 mm with a maximum channel diameter of 6 mm. Variable channel depth is considered positive because any compaction that might occur as a result of water injection will be located at different depths in the soil profile. Conversely, mechanical tines tend to cultivate to very consistent depths. Therefore, they are more likely to compact at a uniform depth, resulting in a cultivation pan.

Figure 3. The mode of action of the HydroJect



Results of research at Michigan State University indicated water injection generally performed as well or better than standard aeration (core aeration). However, only hollow-tine aeration limited thatch accumulation, as water injection neither removed thatch nor brought soil to the playing surface (Vavrek, 1992).

Water injection cultivation is well known to cause no disruption to play (Anon., 1994) and it can be performed during the summer (Vavrek, 1992; Anon., 1994; Emmons, 1995), and its injury to turf is minimal (Murphy and Rieke, 1991). In a field study conducted by Karcher, Nikolai and Rieke (1994), they found water injection cultivation has four benefits of reduced moisture stress, increased green speed, control of earthworm casting, and the ability to apply soluble materials (nitrogen) below the turfgrass surface. Furthermore, wetting agents can be added to the injection water and injected into the soil (Anon., 1994).

2.3.1.3 Verti-drain

The Verti-drain is a power driven unit (Fig. 4) using solid or hollow tines to penetrate into soil to a depth of 50 to 405 mm, with tine spacing of 50 to 203 mm forward, and with 64 to 178 between tines on the tine holders. Solid tines are available in diameters of 13, 20, and 25 mm and lengths of 305 to 405 mm. Hollow tines have 20 and 25 mm diameters and are 305 mm long (Carrow, 1992). When fully inserted, a "kicking action" is imparted on the tines which fractures the surrounding soil profile (Fig. 5). The depth of penetration and amount of kick are adjusted to minimise surface disruption. The kick has more effect when the soil is a little on the dry side as dry soil fractures more readily than wet soil (Vavrek, 1992).

Figure 4. Verti-drain operation

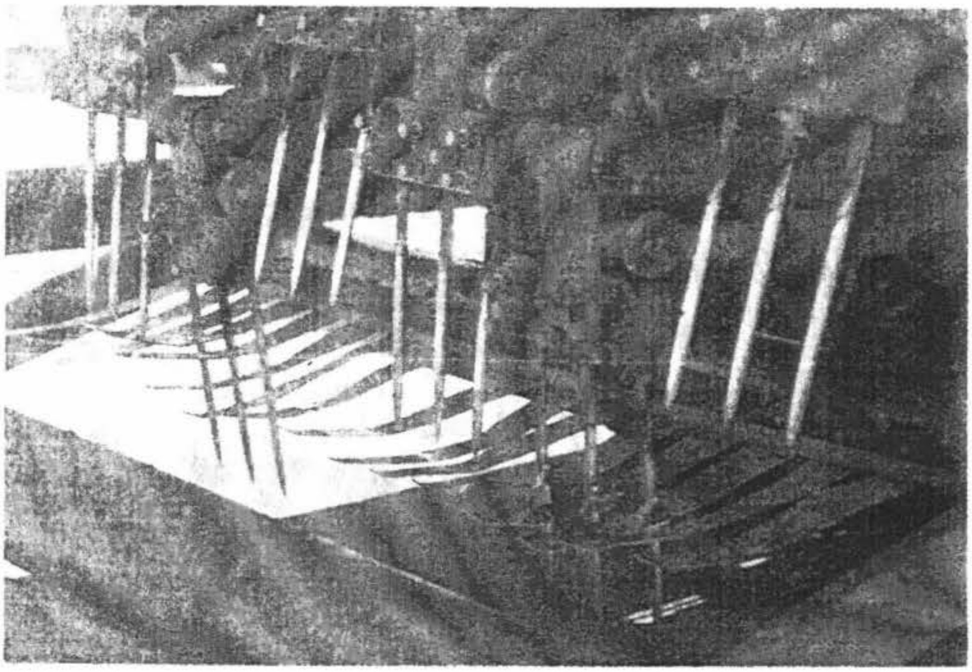
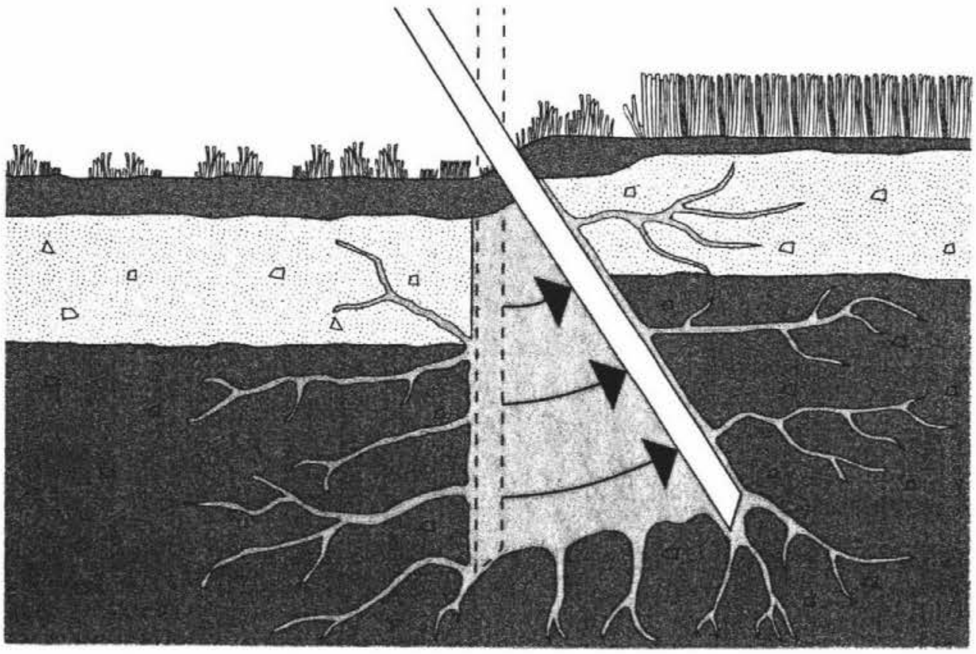


Figure 5. Improved aeration due to shattering effect of a solid tine



The Verti-drain can be effectively used to improve any subsurface (i.e. 150 to 405 mm deep) or a cultivation pan problems. The channel created by the Verti-drain tines and fracturing of soil between tines would be expected to improve water movement, air exchange, and rooting within the treated zone (Carrow, 1992). However, there are situations where other methods may be preferred or where the Verti-drain could actually be detrimental. For example:

- On a properly constructed USGA golf green, the coarse sand layer and pea gravel interface forms a desirable perched water table. Because this layer serves to prevent sandy soil in the rootzone from filtering into the gravel bed, coring through this layer would be counterproductive.
- In areas with shallow irrigation lines.
- If the soil physical problem is confined to the surface 75 mm, other techniques may be as effective or more effective. For instance, a high sand-based site without any subsurface layers that impede drainage may receive no benefit from deep cultivation.
- As with most techniques, Verti-drain cultivation when the turf has very shallow roots may cause severe turf disruption.

(Carrow, 1992)

2.3.1.4 Spiking/Slicing

Spikers use solid tines to punch shallow holes by forcing the soil downward and laterally (Fig. 6). These holes are extremely compacted at the bottom and along the sides as the hole is made by crushing the soil instead of removing it (Emmons, 1995). Spiking creates channels that allow water to drain off the surface and results in a temporary relief of surface compaction stress, but it does not alleviate low soil oxygen levels that exist in compacted soils (Agnew, 1990).

Slicers utilise triangular or rectangular knives mounted on a drum or axle (Fig. 7) that provide soil openings and loosen the soil. These units are simple to use and cause very little disruption to the playing surface. This operation is useful for breaking up a surface crust and promoting more rapid infiltration of water into the soil. The severing of stolons or rhizomes can improve turf density. Slicers, though, do not bring soil to the surface and have a limited depth of penetration on compacted site (Vavrek, 1992).

Figure 6. A simple home-made spiked roller

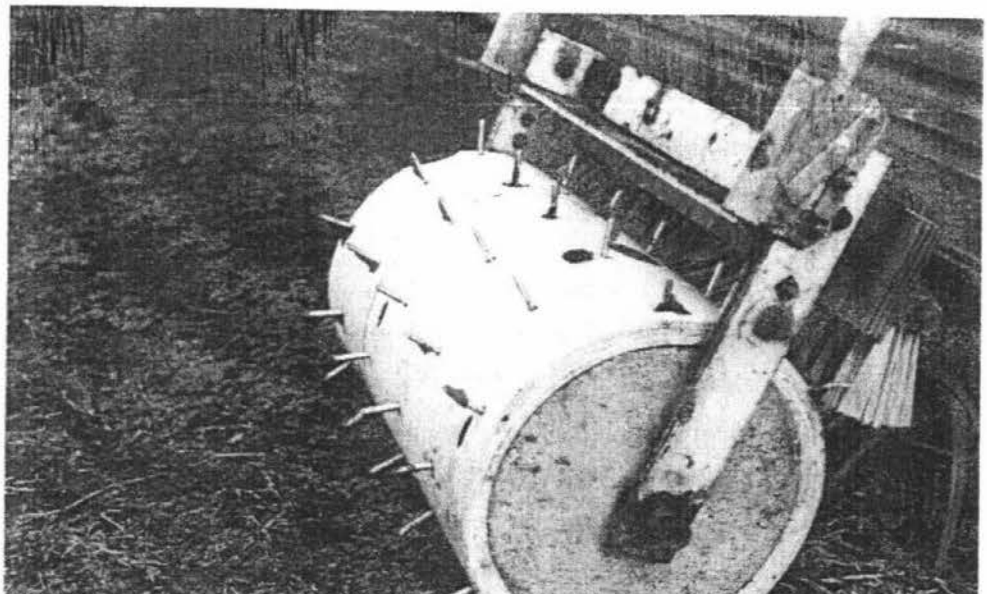
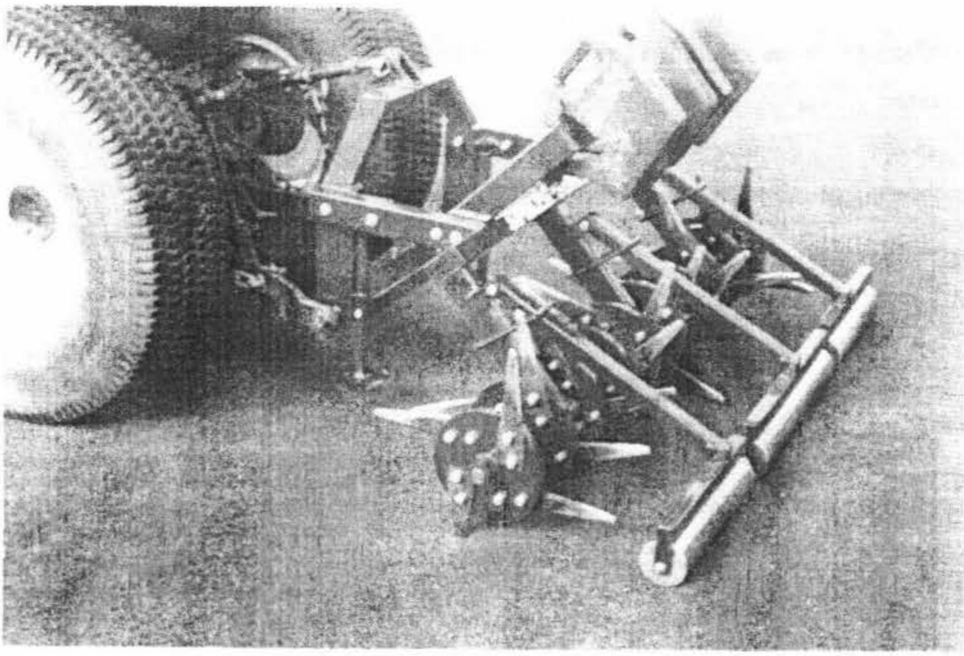


Figure 7. Slicer with restoration roller



2.3.1.5 Mole Ploughs

In New Zealand, mole ploughs are often used on large playing areas where deep compaction or soil of low permeability results in poor drainage. Moling creates a channel through the soil layers that allows water to be transmitted into an existing drainage system. As well as creating a drainage channel a mole plough also creates lift, thus relieving soil compaction (Wrigley, 1998). Due to its severe disruption of the surface this action is not suitable for greens.

A mini-mole plough (a small tractor-mounted mole plough), will relieve compaction to approximately 300 mm depth (Fig. 8). A disc coulter is placed immediately in front of the mole blade to cut the turf and prevent ragged edges being torn in the turf. A roller behind the blade helps to restore the original level of the field. The blade, to which the mole plough "bullet" is attached, creates a narrow channel and shatters the adjacent soil. The most effective result is carried out when the soil is moist and plasticine-like at the bullet depth but dryer above that depth (Wrigley, 1998).

Figure 8. A mini-mole plough

A Vibramole is a variation of the mole plough. It consists of three to five blades, similar, but smaller than the mole plough, attached to the main chassis. As they are drawn through the soil, the blades vibrate. The vibrations are produced by an offset drive from the PTO of the tractor. The blade depth varies from 140 to 200 mm depending on the machine used. The main effect of the vibrating mechanism is to make it easier to pull the implement through the soil, and it can also help to induce increased soil shattering (Wrigley, 1998).

2.3.1.6 Developing Cultivation Programs

Although cultivation techniques have been widely used on golf courses, reliable cultivation programs have not evolved. The main reasons are:

- Difficulty in determining the primary soil physical problem(s) and their location within a soil horizon. For example, the problem may be a surface compacted layer, fine textured subsoil or a clay lens at 300 mm.

- A lack of specific comparative data on how each cultivation method influences soil physical conditions and turfgrass growth.

The key to success with aeration is to determine the problem and then choose the most appropriate equipment and method of aeration. Carrow (1990) advised golf course superintendents to follow these key steps in formulating a sound cultivation program:

- Identify the problem(s).
- Select the best method(s).
- Determine the desired frequency and timing.
- Apply cultivation at correct soil moisture.
- Evaluate your results and determine future directions.

In the USA, research in aeration has focused on multiple use of techniques within each year. It is believed that combinations of techniques are more likely to produce better results than a single unit. For example, an early spring deep-tine aeration, supplemented by quadra-tine or HydroJect aeration during the summer, topped off with a standard hollow-tine aeration during the autumn could produce great results with limited disruption to the playing surface (Vavrek, 1992). In New Zealand, there has so far been limited study about aeration. The lack of local data results in turf managers having to use overseas information, which may not be applicable locally because the frequency of aeration in New Zealand is much less than USA.

2.3.2 Turf Aeration

Turf aeration is a mechanical process that improves the penetration of air, moisture, pesticides and nutrients into the sod layer. This is accomplished by raking, slicing or verticutting the turf, or a combination of these mechanical operations.

2.3.2.1 Organic Matter Accumulation

In the USA the amount of organic matter in the soil normally varies from 0 percent to 20 percent, with 5 percent most commonly found in mineral soils (Hurdzan, 1987). In turf the percentage of organic matter can be accumulated to a higher level, particularly near the surface (i.e., organic matter content within the 0 to 50 mm zone can be 10% on a weight basis compared to about 2% by weight for the initial rootzone mix) (Carrow, 1995). These organic matter layers have specific names in turf systems, thatch and mat. Thatch is a layer of partially decomposed and undecomposed plant tissue. It accumulates between the mineral soil horizons and the green vegetation, and is composed of dead and living roots and stems (tillers, rhizomes, and stolons). The mat, directly beneath the thatch, is a soil layer with organic matter mixed in it (Emmons, 1995).

Thatch build-up occurs when the production of plant tissue is greater than the decomposition rate. Plant debris is primarily decomposed by soil microorganisms such as fungi, bacteria, and actinomycetes. Earthworms also feed on organic matter and help to break it down (Emmons, 1995). Lignin , the major component of thatch, is most resistant to decay. The lignin content of thatch may vary from 10 to 40 percent, while the cellulose content may be 5-15 percent (Daniel and Freeborg, 1987). Roots are highest in lignin content, but stems, rhizomes, stolons and leaf sheaths also contain substantial quantities. Leaf tissue, which is relatively low in lignin, does not contribute significantly to thatch accumulation because it is decayed rapidly (Emmons, 1995).

2.3.2.2 Causes of Thatch Accumulation

Factors such as grass species and cultivar, soil pH, pesticides, fertilisation and irrigation can contribute to thatch build-up.

Some grass species and cultivars tend to form thatch quicker than others. Grasses with a vigorous growth habit or tissues that resist decomposition are likely to form thatch. For example, vigorously growing Kentucky bluegrass cultivars, such as A-20, Nugget and Birka are noted thatch producers (Shearman *et al.*, 1993). Slow-growing species such as fine fescues can form significant thatch layers because their leaves, crowns and nodes are highly resistant to decomposition (Agnew, 1993).

Thatch development increases as the soil pH decreases. When the pH decreases below 6, two factors influence thatch accumulation. Firstly, more stolon or rhizome growth is evident, providing a higher level of lignified tissue to degrade, and secondly microbial and earthworm activity declines meaning that decomposition rate decreases (Wrigley, 1998).

Various pesticides inhibit thatch decomposition. For example, fungicide use has been linked to increased thatch development (Smiley and Craven, 1978), which could be the result of decreased microbial activity, reduced soil pH and a greater shoot growth rate because of a healthier turfgrass. Several insecticides have been linked to reduced earthworm populations, which may also lead to increased thatch accumulation (Potter, 1991).

Heavy nitrogen fertilisation will promote thatch accumulation by encouraging leaf and stolon growth. While nitrogen will help microbial degraders in thatch degradation (Berndt *et al.*, 1992), applications beyond a certain level have a greater influence upon accumulation of organic matter than the rate of decomposition (Wrigley, 1998). Heavy irrigation can also promote thatch accumulation. Excessive irrigation can cause waterlogged soils that can inhibit microbial activity. It is best to water deeply and infrequently. Allowing soil to dry out between irrigation will ensure that oxygen will be available to soil microbes (Agnew, 1993).

In general, conditions that increase vegetative growth or prolong the life of individual plant parts, which thus become more lignified with maturity, favour thatch. Any combination of factors retarding decay and decomposition also favour thatch (Daniel and Freeborg, 1987). One of the major reasons why thatch forms in sand-based rootzone is believed to be due to the lack of microbial activity (White, 1998).

2.3.2.3 Effects of Thatch

The drawbacks of excessive thatch are related to temperature variation within the thatch, altered water relations, pests infestations, pesticide degradation and fertiliser availability.

Soil temperature will vary greatly within a porous thatch layer. Inordinately high and low temperature fluctuations will occur in the thatch compared to the underlying soil. It is not uncommon for air temperature and thatch temperature to be similar (Agnew, 1993). Shallow rooting is another consequence of heavy thatch accumulation. The roots become confined to the thatch layer. The turf is weakened and more susceptible to drought and other stresses because of the shallow root system (Emmons, 1995).

The low bulk density of thatch coupled with great pore space allows for good water infiltration into the thatch layer. However, this does not always mean that the underlying soil will receive this moisture. In fact, most water will be retained in the thatch rather than moving into the underlying soil. Thatch can dry out very quickly and will not be rewet by the upward movement of water from the underlying soil profile. This results in drought stress injury to roots growing in the thatch layer. Furthermore, dry thatch can become hydrophobic, which in turn can cause slow infiltration rates and increase runoff during irrigation (Agnew, 1993).

A thick thatch provides a good environment for the survival and growth of some insect pests and disease organisms (Shildrick, 1985). Many surface-feeding insects, such as sod webworm larvae and adult bluegrass billbugs, are more likely to inhabit thatch as it can protect them from direct environmental stress and predators (Agnew, 1993). Thatch harbours disease inoculum and retains moisture that favours incubation and infection. Turf diseases such as fusarium, dollar spot, smut, brown path and typhula blight are favoured by excess thatch (Daniel and Freeborg, 1987).

Thatch can suppress the effectiveness of herbicides or pesticides by either degradation or by binding the product so that it does not reach the target pest. For example, DCPA (Dacthal) and benefin (Balan) break down faster in thatch than in soils (Hurto, *et al.*, 1979; cited in Agnew, 1993). This suggests that higher rate or repeat applications of pre-emergence herbicides are necessary for weed control on thatchy turf (Agnew, 1993). Some insecticides are tied up in the thatch. If they are absorbed, even a heavy watering after application may not move them through the layer. Grub control becomes more difficult when the downward movement of insecticides is significantly slowed by a thick layer of thatch (Emmons, 1995).

Fertiliser efficiency is adversely affected by a thatchy turf. Water-soluble nitrogen sources are more likely to be lost to volatilisation from thatchy turf, while non-mobile fertilisers such as phosphorus may not penetrate the thatch barrier (Agnew, 1993).

Thatch is not entirely bad. A thin layer of 8 mm to 12 mm thatch may provide some benefits to the turf environment. In moderation it can insulate the turfgrass against sudden temperature changes and provide a mulching effect reducing water loss via evaporation (Wrigley, 1998). However, the cushioning effect is the greatest value. A common objective for many years has been to establish a 5-8 mm mat layer at the green surface to provide resiliency and shot-holding ability on sand-based greens (Beard, 1982; White, 1998).

2.3.2.4 Control of Thatch

Thatch control can be separated into prevention, biological and mechanical control.

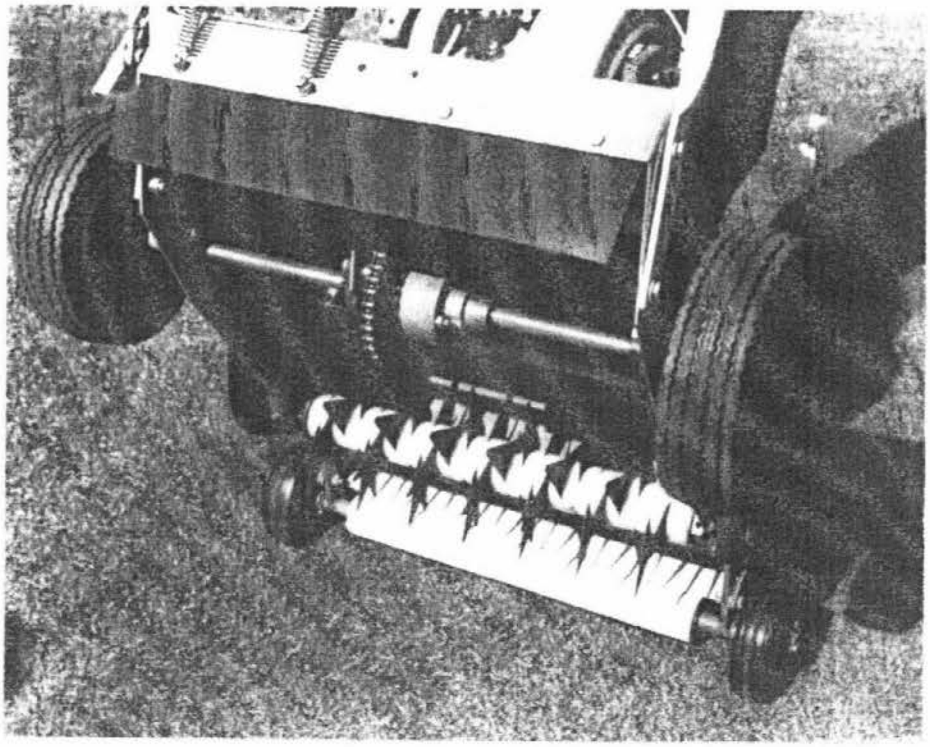
There are several ways to prevent thatch build-up, select a species and/or cultivar which does not grow vigorously, do not over fertiliser, remove clippings if irregular mowing is practised, and avoid excessive irrigation and minimise pesticide usage improving microbiological environment.

Biological control is linked to improving the soil microorganisms that actively decompose thatch. Cultivation by core aeration can improve the soil environment for soil microorganisms. This is especially true on compacted or waterlogged soils. Core aeration mixes soil with thatch, improving soil aeration, water relations and temperature fluctuations. Earthworms and insects naturally control thatch by mixing soil into the thatch layer. Earthworm activity will be greatest during cool, moist weather. Conversely, during droughty years, thatch may accumulate on un-irrigated turf because the earthworm activity is low (Agnew, 1993).

Topdressing improves the biological control of thatch. The periodic addition of a compatible topdressing material will intermingle soil with the thatch and enhance the breakdown of those plant parts that are resistant to decomposition. The amount and rate of topdressing to be used depends upon fertilisation rate, irrigation frequency and species of grass. The more vigorous the growth, the more frequently the topdressing should be applied (Agnew, 1993; Emmons, 1995).

Mechanical control is the only effective means of removing excessive thatch. Vertical mowing can be practiced to remove thatch from turf. The machine has a series of knives mounted on a horizontal shaft (Fig. 9). As the shaft rotates at a high speed the blades slice into the thatch and rip it out of the turf. The blades are spaced 25 to 75 mm apart on the shaft, and can penetrate as deep as 50 mm. The machines can be adjusted to cut into the turf to various depths. The proper depth setting depends upon the thickness of the thatch. The knives should penetrate to the bottom of the thatch layer, and some turf specialists recommend slicing into the surface soil beneath (Emmons, 1995). Decomposition may be encouraged if the blades pull soil up into the thatch. The slits in the soil surface may help to alleviate compaction. Vertical mowing is beneficial because new growth is stimulated when the stolons and rhizomes are severed. This can result in increased turf density and is the major reason why vertical mowing is performed on putting greens. (Emmons, 1995).

Figure 9. Knives on a vertical mower



The frequency of dethatching operations is determined by the rate of thatch accumulation. When thatch layer becomes thicker than 13 mm (8 mm on greens) vertical mowing should be considered. Care should be taken to ensure that the turf is well rooted because this is a very destructive process. It should be done when play is minimal and when subsequent environmental conditions favour rapid growth and recuperation (Beard, 1982). The best time to vertical mowing warm season grasses is in the late spring or early summer. Late summer or early autumn is preferred for cool season grasses (Emmons, 1995). Vertical mowing should be followed by topdressing to protect the exposed plants and light fertilisation to encourage new growth (Agnew, 1993).

Coring, contrary to popular belief does not remove a significant proportion of thatch. Benefits are derived from more extensive rooting and from improving environmental conditions for biological control (Wrigley, 1998).

The bottom line in thatch control is the development of an integrated system that combines prevention, biological control and mechanical removal.

2.4 Playing Quality

Playing quality of golf greens is one of the most important criteria by which players judge the performance of a course. Two main factors that golfers often considered as the playing quality of greens are: the behaviour of the ball on impact following an approach shot and the "speed" of the green during putting (Lodge and Baker, 1991; Baker *et al.*, 1996). Playing quality requirements can be used to set objectives for construction and maintenance work. Playing quality standards are also invaluable in research work, as they provide guidance to the attributes required from the surface, thus giving objective criteria against which experimental treatments can be compared (Hind *et al.*, 1995).

2.4.1Hardness

Surface hardness that control post-impact ball behaviour is influenced by a range of factors: rootzone composition, fertiliser application, irrigation, soil moisture content and thatch.

Baker and Richards (1991) found hardness values were consistently lower on pure sand rootzones compare to the rootzones containing a soil component (soil:sand- 1:1, 1:2 and 1:4). The differences among the three sets of mixes containing soil were relatively small. However, with wetter conditions the pattern of hardness values was reversed, with a consistent decrease as the proportion of soil in the mix increased. Lodge and Baker (1991) reported that pure sand rootzones produce the hardest surface, while the USGA and soil rootzones gave similar softer surfaces.

Lodge and Baker (1991) found increasing nitrogen application decreased hardness on pure sand, USGA and soil rootzones, but the effect was most pronounced in the sand-based rootzones. In the same study they also found the highest rate of irrigation (125% replacement of evapotranspiration losses) produced softer turf on both soil and USGA rootzones, but had no significant effect on the hardness of pure sands. Baker *et al.* (1996) reported that hardness of greens increased as moisture content decreased.

A moderate amount of mat (thatch intermixed with soil) is desirable on greens to provide the cushion needed for resiliency and shot-holding ability. However, excessive thatch will make greens too soft and cause many problems as discussed in previous review. A depth of approximately 5-8 mm is preferred (Beard, 1982).

Baker *et al.* (1996) proposed a limits of hardness value from their survey of 147 greens in the UK using the Clegg Impact Soil Tester, 0.5 kg mass dropped from 300 mm. The preferred range they recommend was 70 to 100 gravities and acceptable range was 55 to 120 gravities.

2.4.2 Green Speed

Ball roll characteristics during putting (green speed) are influenced by a wide range of factors such as rootzone composition, turf species composition and cultivar, fertiliser input, and mowing height.

Lodge and Baker (1991) found pure sand rootzones produced the fastest putting surface, the USGA in the middle, while soil showed the slowest ball roll. They also showed that increasing nitrogen application decreased green speed in all rootzones. In the same study it was reported that faster putting surfaces are characterised by a lower proportion of bent (*Agrostis* spp.) and a high proportion of Fescues (*Festuca* spp.) in the sward. Canaway and Baker (1992) also found green speed was greatest on turf established with *Festuca rubra* ssp. *litoralis* G.F.W. Meyer and *Festuca rubra* ssp. *commutata* Gaud., and slowest on *Poa annua* L. turf.

Mowing practices have greatest influence on green speed. The closer the mowing height, the "faster" the green. Speed increases as the mowing height is lowered because less leaf tissue remains to resist movement of the ball. Topdressing, vertical mowing, and core cultivation also have an effect on green speed (Emmons, 1995).

The USGA Green Section measured green speeds on some fifteen hundred golf courses in thirty-six states during 1976-77 playing season using the Stimpmeter technique. A reference chart has been developed from these observations that can serve as a basis for evaluating green speed (Table 4). Development of this chart should not be interpreted as an attempt to standardise green speeds on golf courses around the USA. The decision as to green speed should be made by the membership of individual clubs depending on local conditions, budget, and standard of play expected. Baker *et al.* (1996) proposed a limits of green speed from their survey of 147 greens under British conditions. The normal range they recommended is 1.6 to 2.8 m and acceptable range is 1.5 to 3.0 m.

Table 1. Reference chart of green speeds calculated by Stimpmeter technique

	Average Length of Roll *	
Relative Green Speed	Regular Play (m)	Tournament Play (m)
Fast	2.6	3.2
Medium fast	2.3	2.9
Medium	2.0	2.6
Medium slow	1.7	2.3
Slow	1.4	2.0

* Reduce length of roll by 15 centimetre for bermudagrass greens.

Playing quality are influenced by many factors such as rootzone type, maintenance practices (aeration, fertiliser application, mowing and rolling), thatch and turf species composition and cultivar. When introducing a new practice, research is needed in order to meet the standard requirement of playing quality.

3. Material and Methods

The trial was conducted at the New Zealand Sports Turf Institute, Palmerston North. The trial construction consisted of a suspended water table design with a 250 mm deep rootzone layer, formed from five different rootzone materials, overlying a 100 mm pea gravel drainage layer. The size of gravel is summarised in Table 1.

Table 2. Particle size distribution of pea gravel

Category	Diameter	Pea gravel
Fine stone	8-16 mm	0.0%
Coarse gravel	4-8 mm	67.7%
Fine gravel	2-4 mm	31.4%
V. coarse sand	1-2 mm	0.6%
Coarse sand and below	< 1 mm	0.3%

3.1 Experimental Design

The trial layout was made up of three randomised blocks. Each block contained five plots of different rootzone materials randomly arranged. The five rootzone materials were partial amended sand; local silt soil; pure sand; full amended sand and partial amended sand with zeolite (main treatment, Fig. 1). The mixing rates of sand/compost and sand/zeolite were 6:1 and 9:1 (by volume) respectively. Selected analysis of the rootzone media is summarised in Table 2. A split plot design was superimposed on the rootzone treatments using different aeration treatments (sub-treatments): untreated control; HydroJect; Verti-drain and scarifying, with all sub-treatments being applied twice per year in spring and autumn (refer to Table 3). This frequency was based upon current New Zealand turf management practices for golf greens. The sub-plot size was 1.8 m by 3.2 m.

Figure 10. Main treatment design

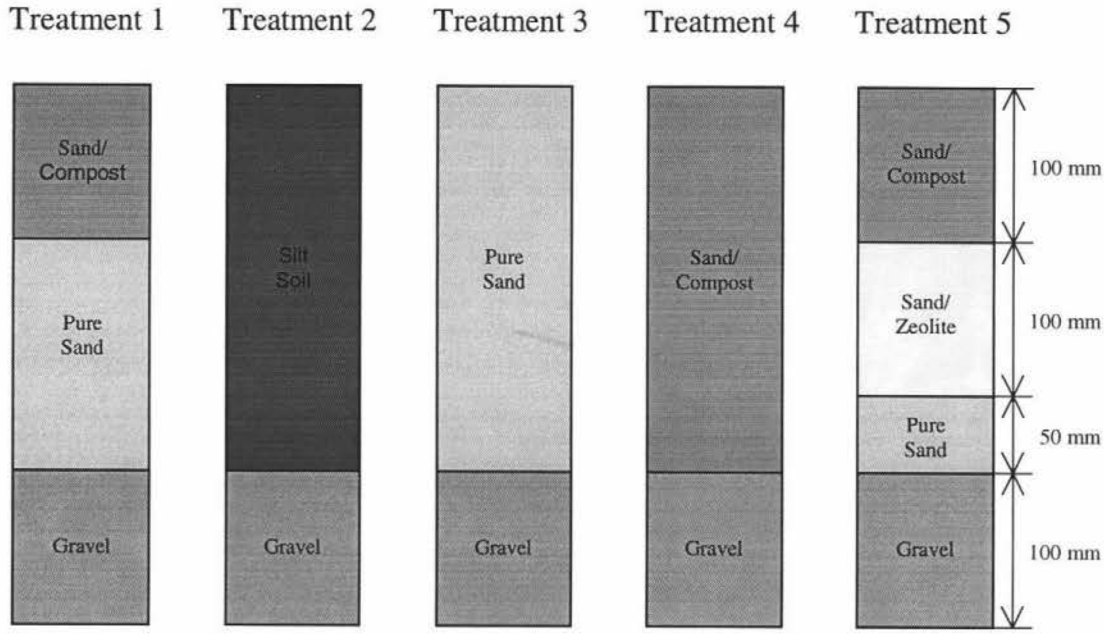


Table 3. Characteristics of the rootzone media

Category	Diameter (mm)	Silt Soil	Pure Sand	Sand/ Compost	Compost	Zeolite
Fine Gravel	2-4	0.0	0.6	0.9	-	0.0
V. Coarse Sand	1-2	0.0	4.2	4.2	-	23.6
Coarse Sand	0.5-1.0	0.1	27.8	27.3	-	56.4
Medium Sand	0.25-0.5	0.5	58.8	54.7	-	14.7
Fine Sand	0.15-0.25	7.4	8.0	8.0	-	1.1
V. Fine Sand	0.05-0.15	40.2	0.4	1.2	-	0.7
Silt	0.002-0.05	46.1	0.1	1.8	-	1.7
Clay	<0.002	5.7	0.1	1.9	-	1.8
					-	
% OM (w/w)		3.3	0.0	2.1	36.0	-
K_{sat} (mm/hr)		-	975	226	-	-
Total Porosity (%)		-	42.4	42.2	-	-
Bulk Density (t/m^3)		-	1.53	1.5	0.52	-
CEC (meq/100g)		11.0	0.0	10.0	-	108
pH		5.4	7.2	7.6	8.5	-

- Not determined

3.2 Establishment, Maintenance and Treatments

The trial was sown on 27 March 1997 with a 10:10:60 mix of colonial bentgrass *(Agrostis capillaris)* "Egmont", "Browntop", and Chewing's fescue *(Festuca rubra* ssp. *commutata* **Gaud.**) "Enjoy" seed mixture (by weight). After sowing, pure sand plots were covered with "Biomac-Woolmulch" to prevent moisture loss and aid grass establishment. Fertiliser application was varied in plots, sand plots received more fertiliser in order to obtain a uniform establishment (refer to Table 4). Following successful establishment after 12 months, the trial was maintained as near golf green turf irrespective of rootzone design. Details of aeration treatments and trail maintenance are given in Tables 3 and 4.

Table 4. Aeration treatments

HydroJect	Carried out on 16/2/98 and 6/11/98, plus WettaSoil @ 2.5L/1300m^2. The spacing was 75 mm square and depth of the holes were varied from 100-200 mm depending on the different rootzones.
Verti-drain	Carried out on 2/3/98, using 16 mm diameter hollow tines to 100 mm depth. Carried out on 17/11/98, using 18 mm diameter solid tines to 150 mm depth. For both treatments the spacing was 90 x 120 mm.
Scarifing	Carried out on 27/2/98 and 18/11/98. The blade width was 3 mm and the blade spacing was 30 mm. The depth of scarifying was 10-15 mm.
Topdressing	After aeration treatments topdressing @ 45L/plot of respective rootzone materials was applied.

Table 5. Trial maintenance during 1997 and 1998

Mowing The trial site was mown at a height of 7 mm irrespective of season.

Irrigation Applied using a pop-up system, and use the pure sand plots as the benchmark for determining watering requirements.

Fertiliser 14 applications were applied to pure sand plots, 13 to sand/ compost and 12 to soil in 1997, make up of the following nutrient inputs:

(kg/ha)

	N	P	K	Mg	S	
Soil Plot	249	98	103	154	126	
Sand/Compost Plot	272	123	103	154	127	
Pure Sand Plot		301	131	153	157	143

During 1998, 12 applications were applied to the plots. Every plot received the same amount, the total input being:

(kg/ha)

N	P	K	Mg	S
282	31	199	15	348

Pesticide Dimilin (ai: Diflubenzuron) @ 50g/ha, was applied on 7/4/98 for treatment of porina moth (*Wiseana spp.*). Thiodan 35 EC (ai: Endosulfan) @ 1.5L/ha, was applied on 17/4/98 and 15/9/98 to control earthworms. Lorsban (ai: Chlorpyrifos) @ 1.5L/ha, was applied for treatment of porina moth and earthworms on 1/8/98.

Fungicides Tilt (ai: Propiconazole) @1.5L/ha, was applied on 8/6/98; Folicur DF (ai: Terbuconazole) @ 750g/ha, was applied on 29/9/98 and BAS 505 (ai: beta-Methoxy-acrylates) @ 1.8L/ha, was applied on 5/11/98 to control the Take-all patch disease.

Herbicides Tordon BK (ai: Picloram/2,4-D) @ 1.5L/ha, was applied on 22/9/98 to control chickweed (*Stellaria* spp.), clover (*Trifolium* spp.), hydrocotyle (*Hydrocotyle* spp.) and onehunga weed (*Soliva* spp.).

Wear Compaction wear was applied using a 1.5 ton cricket roller on 7/4, 17/8, 25/8, 1/9 and 3/11 in 1998. A double pass was used on each occasion.

3.3 Sampling Protocol

Sampling was carried out twice, in early April 1998 and again in late October/early November. Each sub-plot was split into two halves. Destructive samples were taken only from the same half-side throughout the plots, so the other half could be used for non-destructive sampling. The methods used were as follows:

3.3.1 Rootzone Characteristics

Water retention was measured in soil/sand cores (50 mm diameter and 35 mm deep). Cores were extracted from three depths (0-35 mm; 35-70 mm and 70-105 mm). The cores were saturated from the bottom before being placed on a tension table to remove water at 300 mm (-3 kPa) and 400 mm (-4 kPa) of tension. Cores were weighed after each 24-hour equilibrium period, then oven dried for 24 hours at 105°C and weighed again. The water retention was measured as the volumetric moisture content at each tension and air-filled pore space at each tension was obtained by subtracting the volumetric moisture content from the total porosity (Hummel, 1993b; Hind et. al. 1995).

Total porosity was a calculated value based on the bulk density and particle density values of the cores. The equation used was:

Total porosity (%) = 1- (bulk density/particle density) x 100

(Hummel, 1993b)

Saturated hydraulic conductivity was measured on soil cores (100 mm diameter and 77 mm deep) taken from the surface. Cores were placed in a pan of water and allowed to saturate from the bottom before a constant water head of 15 mm was applied on cores. After 30 minutes the water volume passing through the cores were collected in a beaker for 2 minutes. Saturated hydraulic conductivity was calculated using the equation:

$$K_{sat} = QL/hAt, \text{ where}$$

K_{sat}: saturated hydraulic conductivity (mm/hr)

Q : the volume of water (mm^3) passing through the core in a unit of time t

L : the length of sand/soil in the core (mm) h : the hydraulic head (from the bottom of the sample to the water level above the sand/soil) (mm)

A : crosss sectional area of the core (mm^2)

t : time required to collect Q (hr)

(Hummel, 1993b)

Water infiltration rates were measured using a single ring infiltrometer, with a depth of 150 mm and diameter of 300 mm. The ring was hammered into the turf to a depth of approximately 50 mm, then filled with water and maintained in this condition for approximately 10 minutes in order to saturate the ground beneath. Infiltration rate was then recorded by measuring the decrease in water level within the ring over a period of time. Values were standardised to 10°C (Taylor et.al., 1991; Lodge and Baker, 1993).

Oxygen diffusion rate was measured using a Jensen oxygen diffusion rate meter. Ten microelectrodes of 4 mm exposed platinum wire were inserted to a depth of 50 mm and a potential of 650 millivolts was applied. Rates were normalised to field capacity (100 mb) to remove the effect of antecedent moisture conditions on diffusion pathways (Carter, 1993).

Moisture content of the surface layer (0-50 mm) was measured on 25 mm diameter soil cores. Cores, which included their surface vegetation were dried at 105°C for 24 hours to determine the gravimetric moisture content (Baker and Richards, 1993).

3.3.2 Root Development and Organic Matter Content

Root development was measured from two 25 mm diameter and 250 mm deep cores per sub-plot. The cores were sectioned into 50 mm intervals. Contents of each interval were washed on a sieve and the roots isolated. Roots were dried in an oven for 24 hours at 75°C and weighed.

Organic matter accumulation was measured from 25 mm diameter and 50 mm deep cores used for gravimetric moisture content determination. The cores were dried at 105°C for 24 hours and weighed. Organic matter content was calculated following loss on ignition at 400°C for 8 hours (Baker and Richards, 1993).

3.3.3 Playing Quality

The hardness of the turf surface was measured using a Clegg Impact Soil Tester (Baker and Richards, 1991). Two cylindrical hammers were used, 0.5 kg and 2.25 kg. The 0.5 kg hammer was dropped down a guide tube through a height of 300 mm and the 2.25 kg was dropped from 450 mm. An accelerometer in the hammers recorded the deceleration in gravities. Five locations were tested within each sub-plot. The 0.5 kg hammer was dropped four times on each site and only the first and fourth readings were recorded, while the 2.25 kg hammer was dropped only once and this reading was recorded. The two means of five readings from the 0.5 kg hammer (first and fourth reading), and one from the 2.25 kg hammer per sub-plot were used in the analysis.

Green speed was measured using a Stimpmeter. The Stimpmeter is an extruded aluminium bar, 910 mm long with a V-shaped groove extending along its length. The bar has a precisely milled ball-release notch 750 mm from the tapered end (which rests on the ground) that allows the ball to be released with a constant velocity when the bar is raised to an angle approximately 20 degrees from the horizontal (Beard, 1982). Three pairs of measurements were made in opposing directions on each sub-plot. Where the readings in opposing directions differed by more than 20%, the correction suggested by Brede (1991) was used in the calculation of the results.

3.4 Statistical Analysis

Analysis of variance was used to test differences between the treatments of soil/sand physical properties, root development and playing quality. Correlation analysis using Pearson correlation coefficients was employed to analyse the general relationships between variables. A significance level of $p<0.05$ was used in all statistical tests. The infiltration data were transformed as $\log_{10}(x+1)$ to stabilise the variance.

4. Results

4.1 Rootzone Characteristics

4.1.1Rootzone Construction

The physical properties (bulk density, total porosity, volumetric moisture content, air-filled porosity, infiltration rate, oxygen diffusion rate and moisture content) of constructed rootzones were measured 13 months after construction (first measurement). Twenty months after construction (second measurement), infiltration rate, oxygen diffusion rate and moisture content (0-50 mm) were again measured.

Bulk density and total porosity

Bulk density values were lower for all five rootzones for the surface layer (0-35 mm) than for 35-70 mm and 70-105 mm depths. Bulk density of the silt soil rootzone tended to be slightly greater compared with sand rootzones (Fig. 11 (A)). This was significant ($p \leq 0.05$) in the 70-105 mm depth. As would be expected, sand rootzones amended with compost had lower bulk densities compared with the pure sand rootzone. However, these were not significant (refer to Appendix Tables 1-3).

Total porosities were generally higher for the surface layer (0-35 mm) (50.5-52.3 %) than for 35-70 mm (45.5-47.6 %) and 70-105 mm (47.6-49.3 %) depths. Total porosity was lower on the silt soil rootzone compared with sand rootzones (Fig. 11 (B)). However, there were no significant differences between the rootzones (refer to Appendix Tables 1-3).

Volumetric moisture content and air-filled porosity

The individual measurement of constructed rootzones for volumetric moisture contents (VMC) were quite different for each of the three sampling depths. VMC of the rootzones are given in Fig. 12. The silt soil rootzone had the highest VMC, partially amended sand rootzones the second, fully amended sand rootzone the third, and pure sand rootzone the lowest VMC. At 0-35 mm depth, at both –3 kPa and –4 kPa moisture potential, there was a significant difference ($p \leq 0.05$) between silt soil rootzone and sand rootzones (refer to Appendix Table 1). At 35-70 mm depth, at both –3 kPa and –4 kPa moisture potential, there were significant differences ($p \leq 0.05$) between silt soil rootzone, amended sand rootzones, and pure sand rootzone (refer to Appendix Table 2). At 70-105 mm depth, at both –3 kPa and –4 kPa moisture potential, there were significant differences ($p \leq 0.05$) between silt soil rootzone, partially amended sand rootzones, fully amended sand rootzone, and pure sand rootzone (refer to Appendix Table 3).

The trend in values for air-filled porosity was virtually the reverse of those for VMC. Air-filled porosities of constructed rootzones are given in Fig. 13. At 0-35 mm depth, at both –3 kPa and –4 kPa moisture potential, sand rootzone air-filled porosities were significantly greater ($p \leq 0.05$) than silt soil rootzone. The partially amended plus zeolite sand rootzone showed significantly lower air-filled porosity than the pure sand rootzone. (refer to Appendix Table 1). At 35-70 mm depth, at both –3 kPa and –4 kPa moisture potential, the pure sand rootzone had highest air-filled porosity, amended sand rootzones the second, and silt soil rootzone the lowest. These were siginficant ($p \leq 0.05$) (refer to Appendix Table 2). At 70-105 mm, at both –3 kPa and –4 kPa moisture potential, there were significant differences ($p \leq 0.05$) between pure sand rootzone, fully amended sand rootzone, partially amended sand rootzone, and silt soil rootzone (refer to Appendix Table 3).

Infiltration rate and oxygen diffusion rate

Infiltration rates of rootzones are shown in Fig. 14 (A). On the first measurement, the pure sand rootzone had the highest rate of 92.5 mm/hr, silt soil rootzone the lowest of 0.4 mm/hr, and amended sand rootzones were intermediate at 64.6 – 76.9 mm/hr. There were significant differences ($p \leq 0.05$) between these rootzones (refer to Appendix Table 4). On the second measurement, the pure sand rootzone and partially amended sand rootzones had higher rates than the fully amended sand rootzone and silt soil rootzone (refer to Appendix Table 5). There was a notable decrease from 76.7 to 56.9 mm/hr on the fully amended rootzone between the two measurements.

Oxygen diffusion rates of rootzones are given in Fig. 14 (B). On the first measurement, pure sand rootzone tended to be lower than other rootzones. However, there were no significant differences between rootzones (refer to Appendix Table 4). On the second measurement, there was a significant difference between amended sand rootzones and pure sand and silt soil rootzones (refer to Appendix Table 5). There was a significant decrease between the two measurements especially for silt rootzone (more than 100%).

Moisture content and saturated hydraulic conductivity

The responses of rootzones on moisture content (0-50 mm) were very similar for both measurements (Fig. 15 (A)). The silt soil rootzone showed the highest moisture content, pure sand rootzone the lowest, with amended sand rootzones being intermediate. For example, the first measurement showed 28.6% for silt soil rootzone, 9.1% for pure sand rootzone, 13.1% for partially amended sand rootzone, 12.0% for partially amended plus zeolite sand rootzone, and 13.9% for fully amended sand rootzone. There were significant differences between silt soil rootzone, pure sand rootzone, and amended sand rootzones (refer to Appendix Tables 4 and 5).

Saturated hydraulic conductivities (K_{sat}) of rootzones are shown in Fig. 15 (B). Silt soil rootzone had significantly lower K_{sat} compared with sand rootzones (refer to Appendix Table 4). The fully amended sand rootzone K_{sat} tended to be higher than other sand rootzones. However, this was not significant.

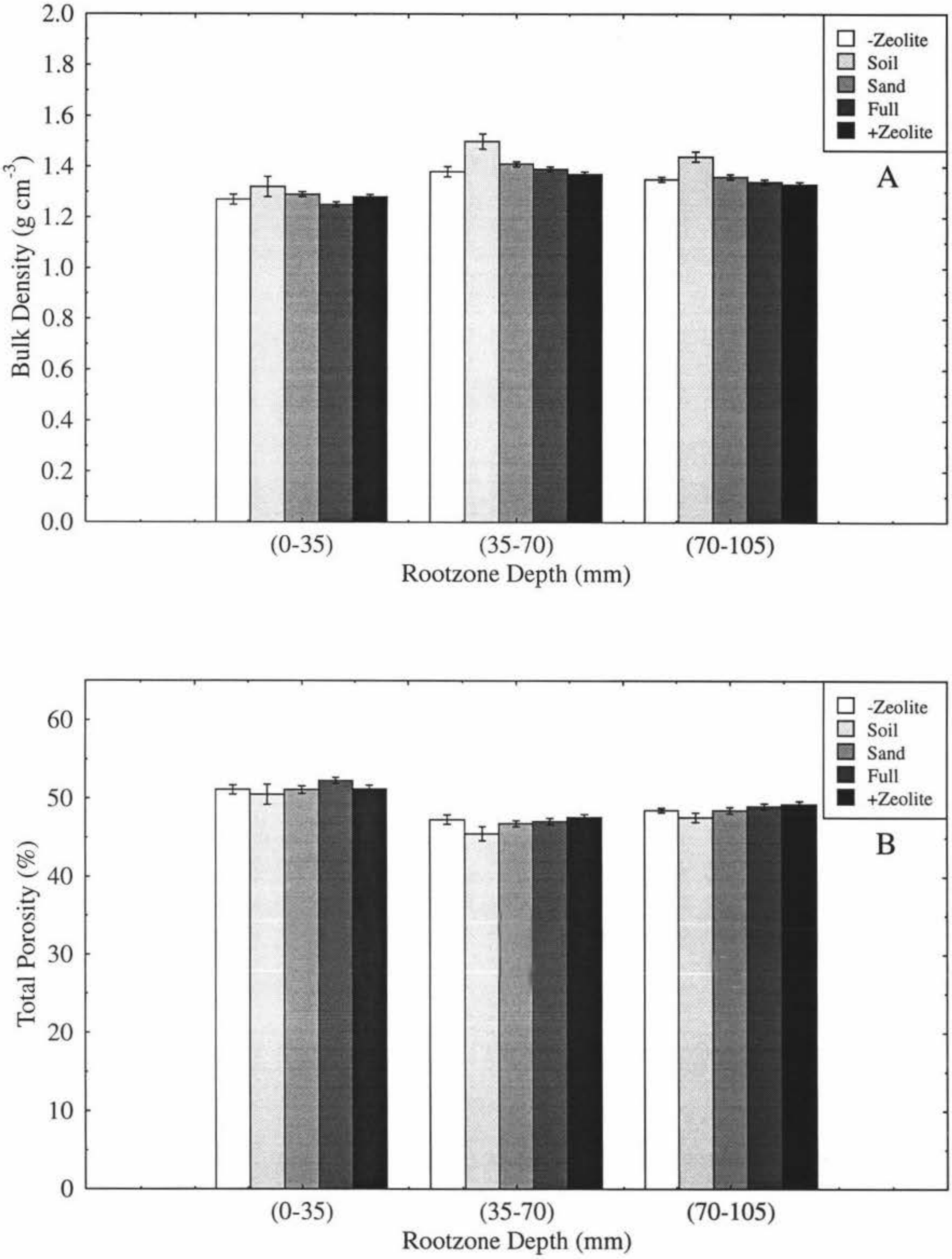
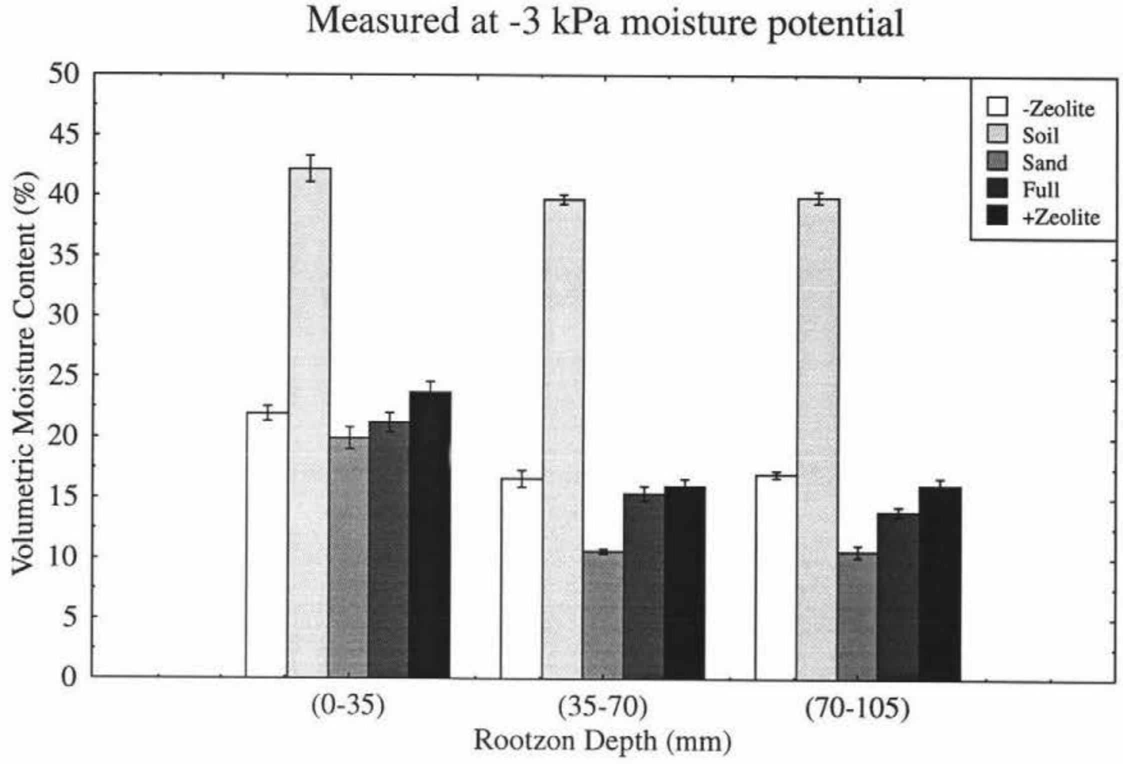


Figure 11. (A) Mean bulk densities of each constructed rootzone measured at 0-35 mm, 35-70 mm and 70-105 mm depths, 13 months after construction. In this and subsequent related graphs, rootzones were constructed as follows: -Zeolite= partially amended sand; Soil= silt soil; Sand= pure sand; Full= fully amended sand and +Zeolite= partially amended sand plus zeolite (refer to Fig. 1 for treatment details). (B) Mean total porosities of each constructed rootzone measured at 0-35 mm, 35-70 mm and 70-105 mm depths, 13 months after construction. (Vertical bars represent the standard error of the mean (n=12)).



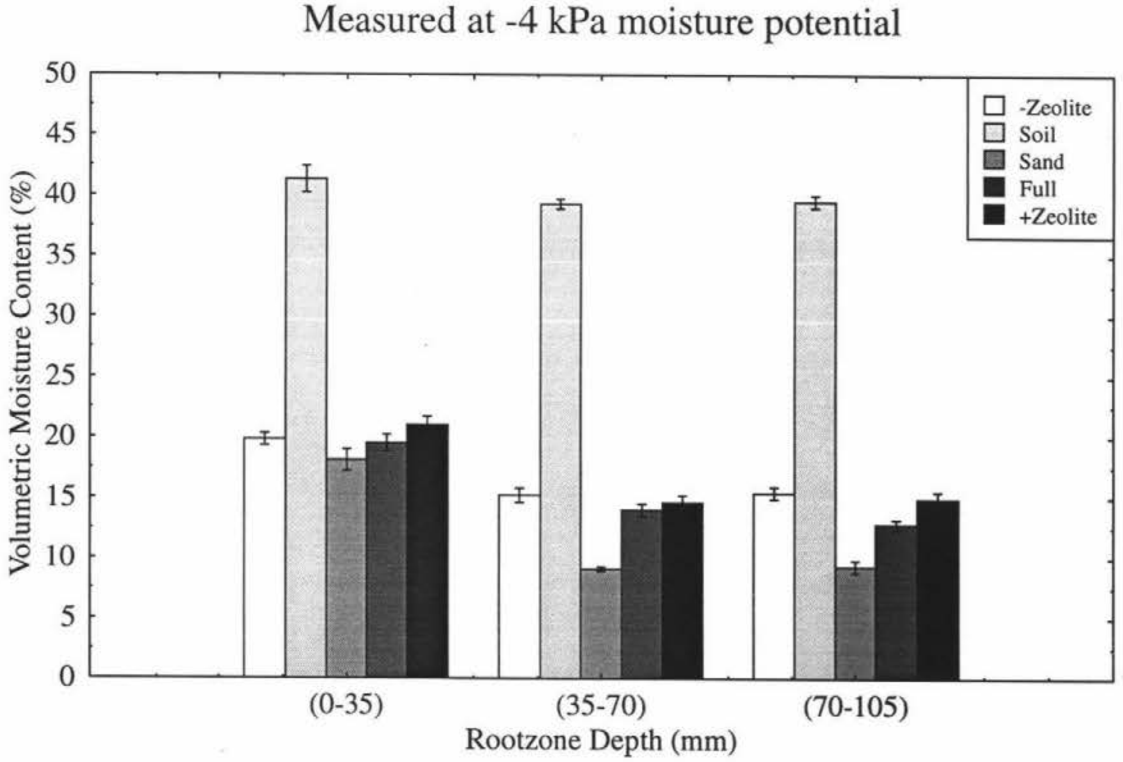
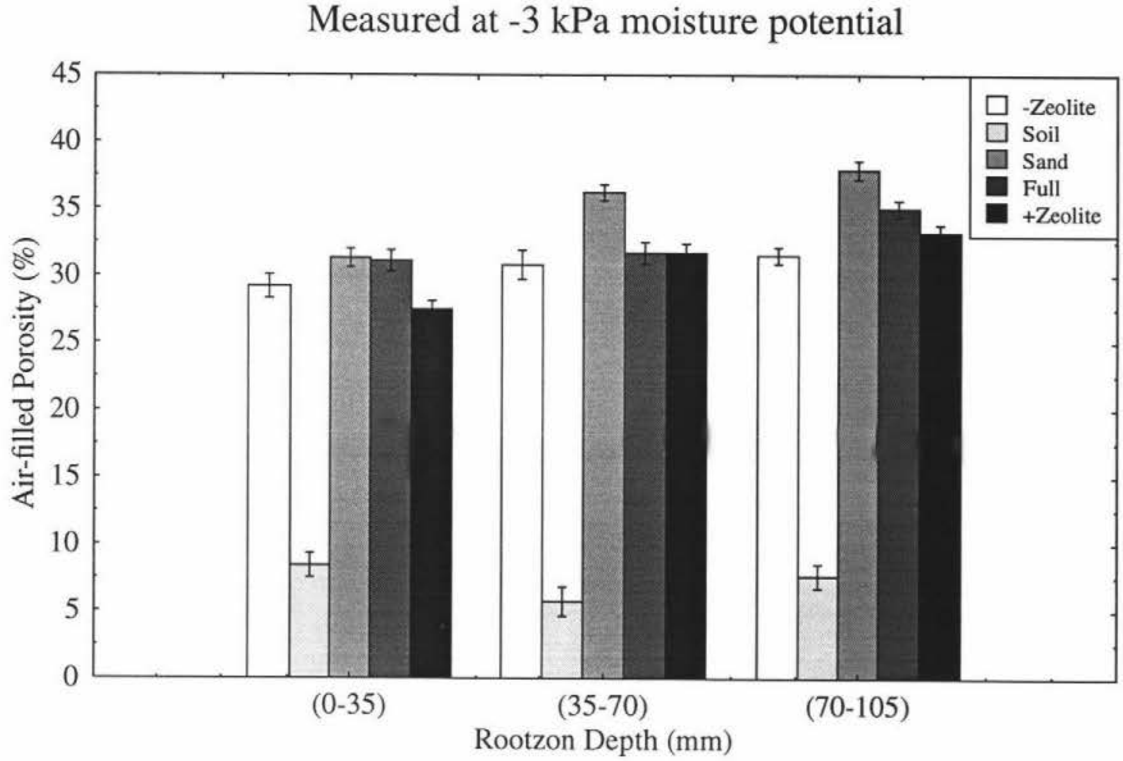


Figure 12. Mean volumetric moisture contents of each constructed rootzone measured at 0-35 mm, 35-70 mm and 70-105 mm depths, 13 months after construction. (Vertical bars represent the standard error of the mean (n=12)).



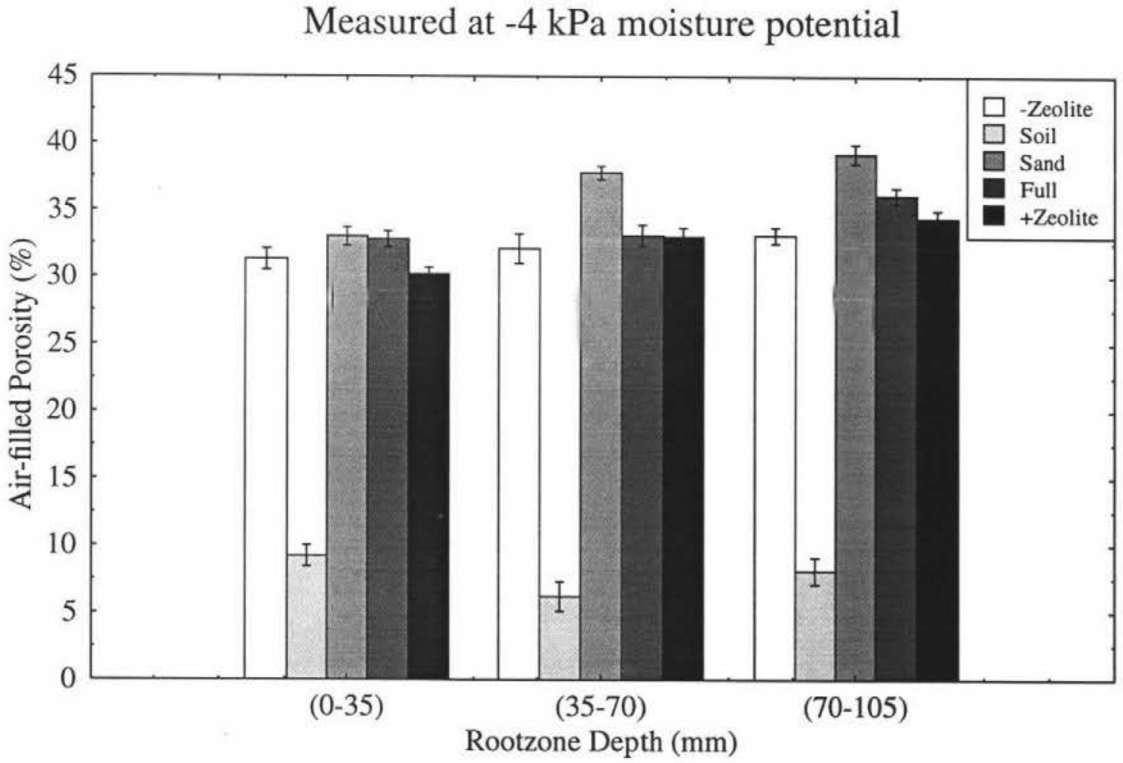


Figure 13. Mean air-filled porosities of each constructed rootzone measured at 0-35 mm, 35-70 mm and 70-105 mm depths, 13 months after construction. (Vertical bars represent the standard error of the mean (n=12)).

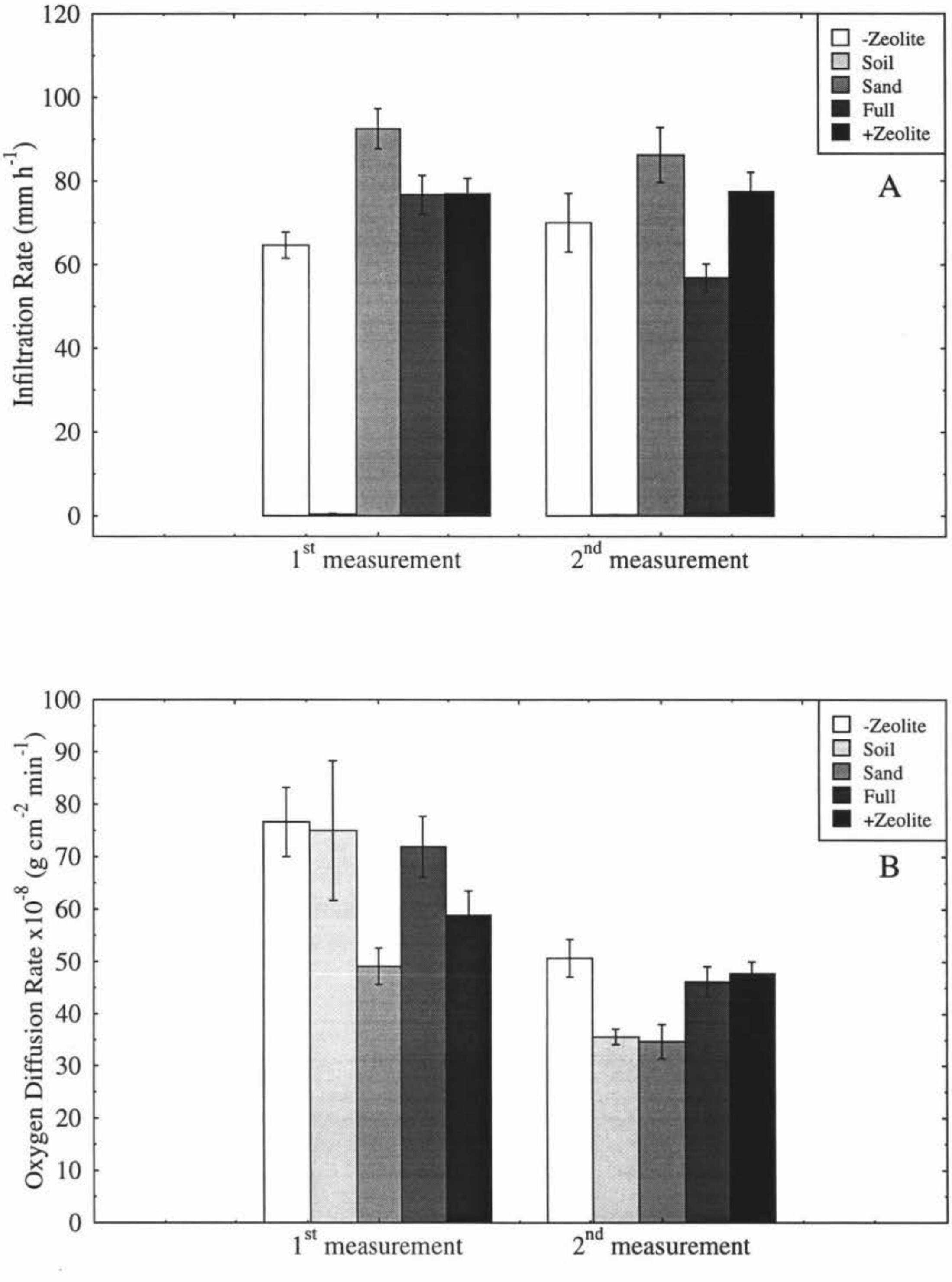


Figure 14. (A) Mean infiltration rates of each constructed rootzone. (B) Mean oxygen diffusion rates of each constructed rootzone. 1st measurement- taken 13 months after construction; 2nd measurement- taken 20 months after construction. (Vertical bars represent the standard error of the mean (n=12)).

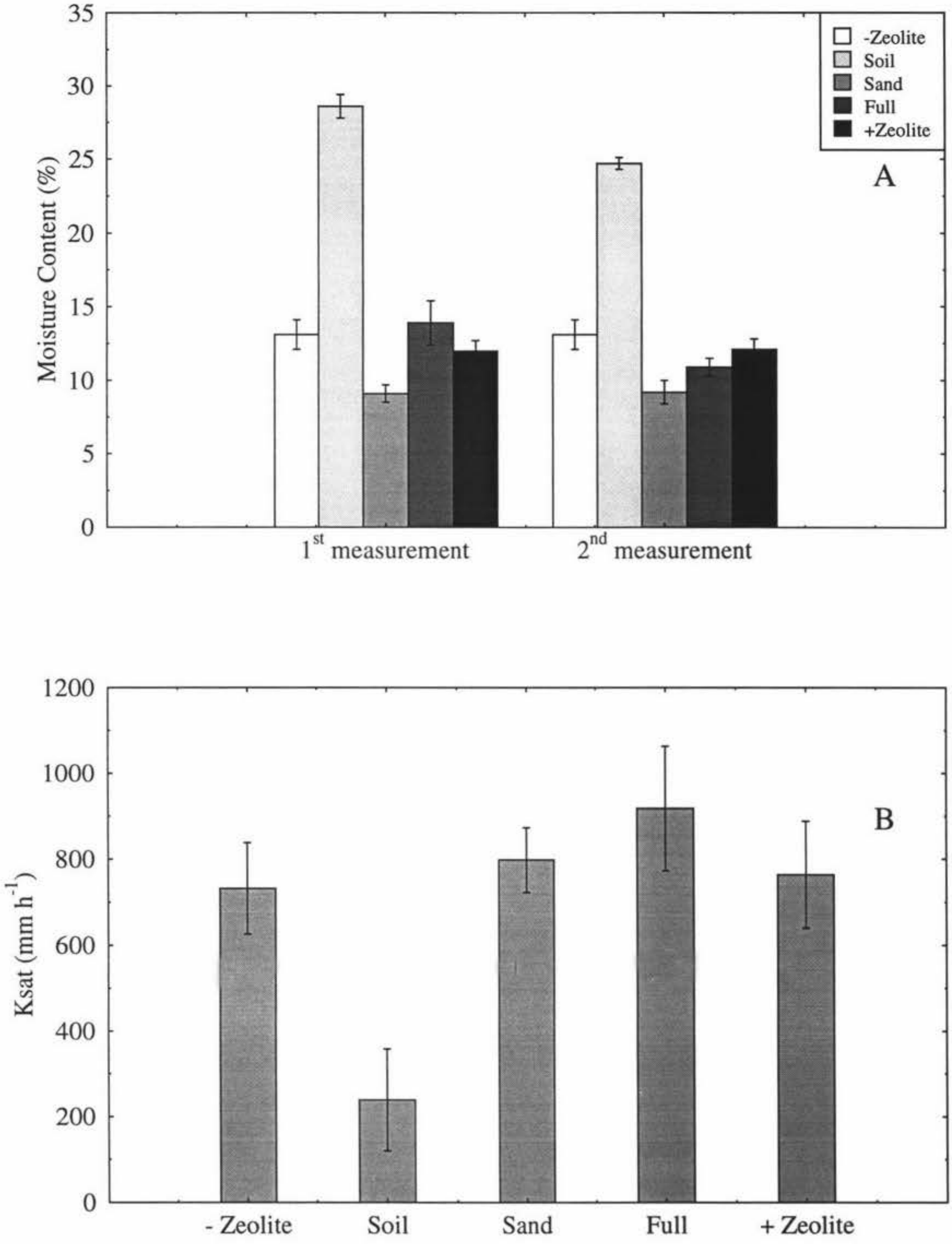
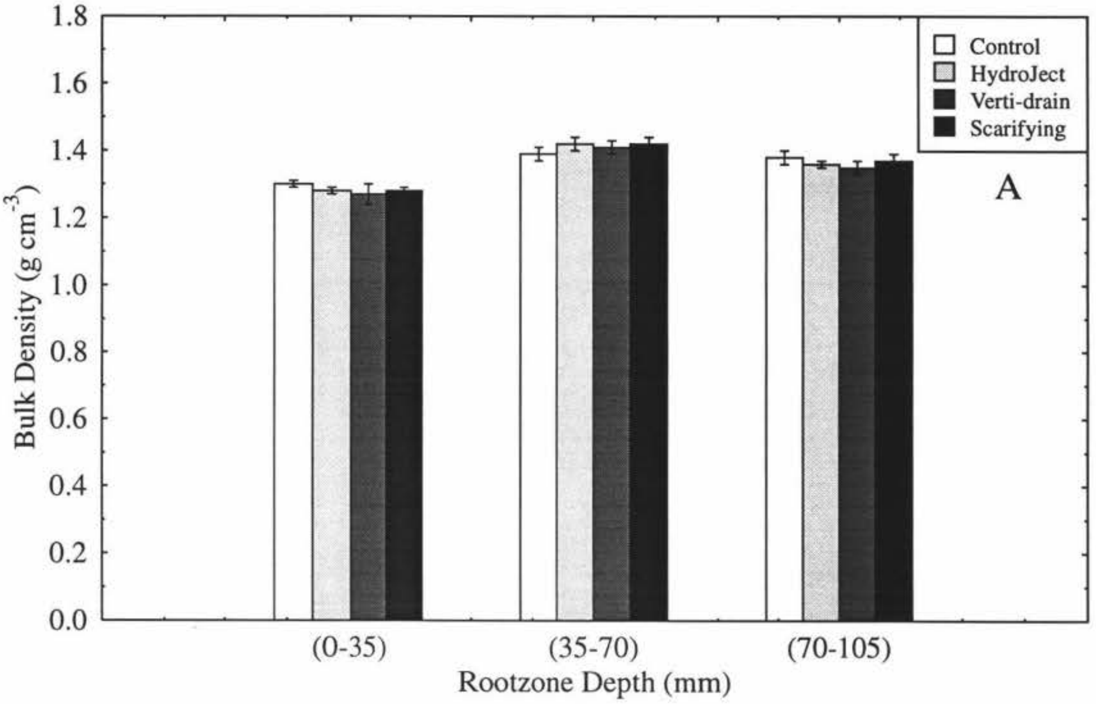


Figure 15. (A) Mean moisture contents (0-50 mm, including sward) of each constructed rootzone. 1st measurement- taken 13 months after construction; 2nd measurement- taken 20 months after construction. (B) Mean saturated hydraulic conductivities of each constructed rootzone, measured 13 months after construction. (Vertical bars represent the standard error of the mean (n=12)).

4.1.2 Aeration Treatment

The physical properties (bulk density, total porosity, volumetric moisture content, air-filled porosity, infiltration rate, oxygen diffusion rate and moisture content) of aeration treatment were measured 1 month after application (first measurement). Eight months after application of aeration treatments (second measurement), infiltration rate, oxygen diffusion rate and moisture content (0-50 mm) were again measured.

The effects of aeration treatments on soil physical properties are given in Figs. 16-20. The aeration treatments incorporated into the trial had no significant effects on any of the features measured (refer to Appendix Tables 6-10). However, the first measurement on infiltration rate for Verti-draining and HydroJecting showed higher rates and Verti-draining also had higher saturated hydraulic conductivity, although these differences were not significant.



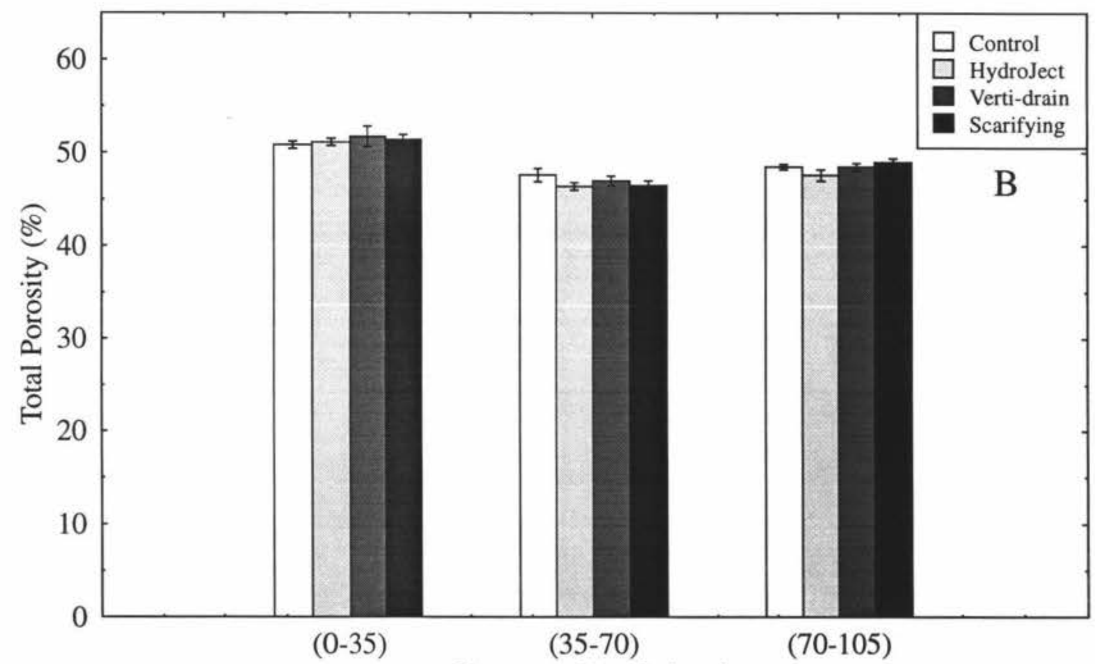
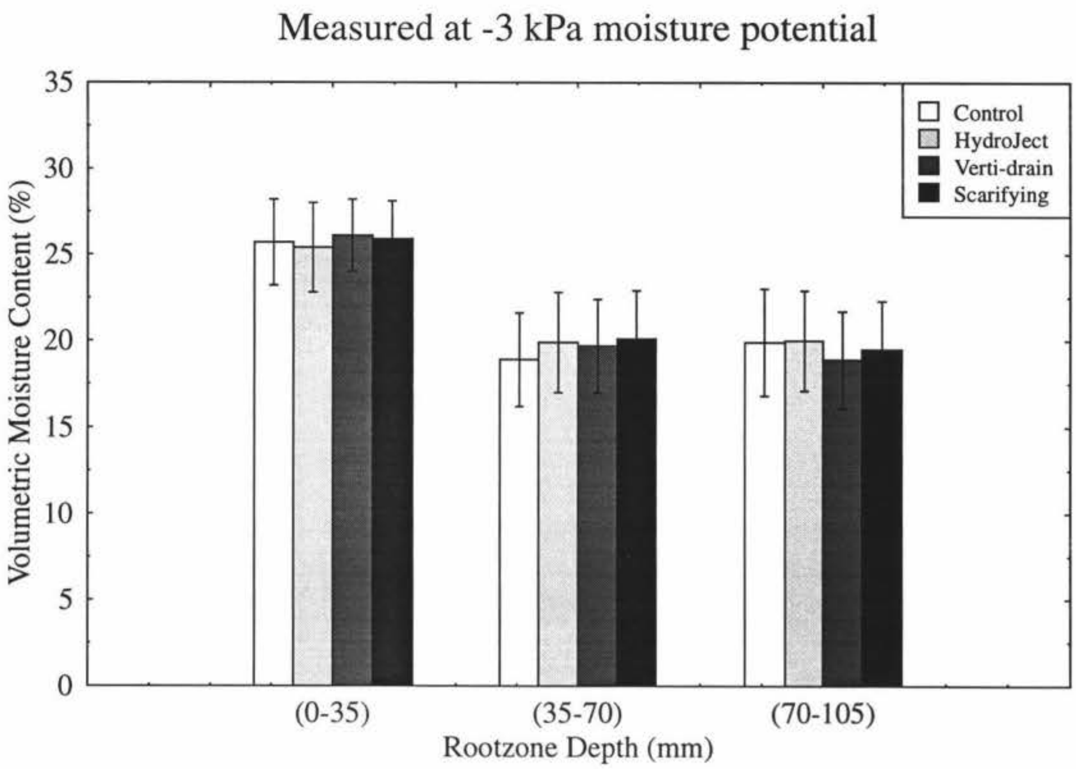


Figure 16. (A) Mean bulk densities of each aeration treatment measured at 0-35 mm, 35-70 mm and 70-105 mm depths, 1 month after aeration. (B) Mean total porosities of each aeration treatment measured at 0-35 mm, 35- 70 mm and 70-105 mm depths, 1 month after aeration. (Vertical bars represent the standard error of the mean (n=15)).



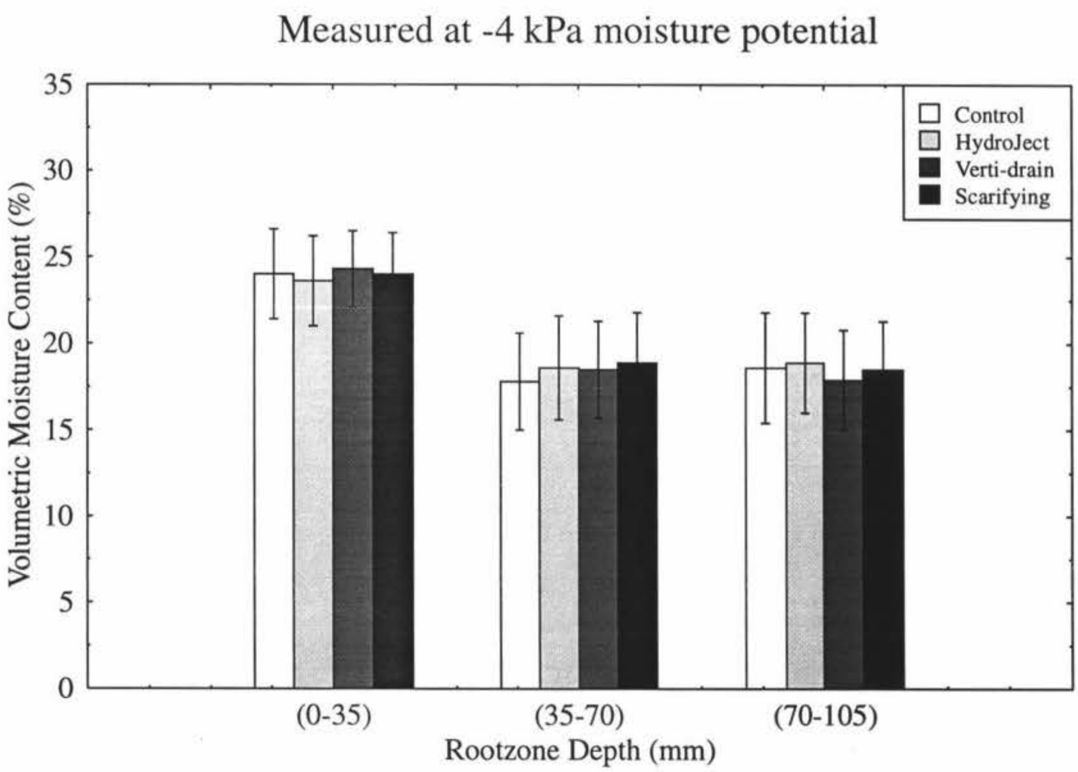
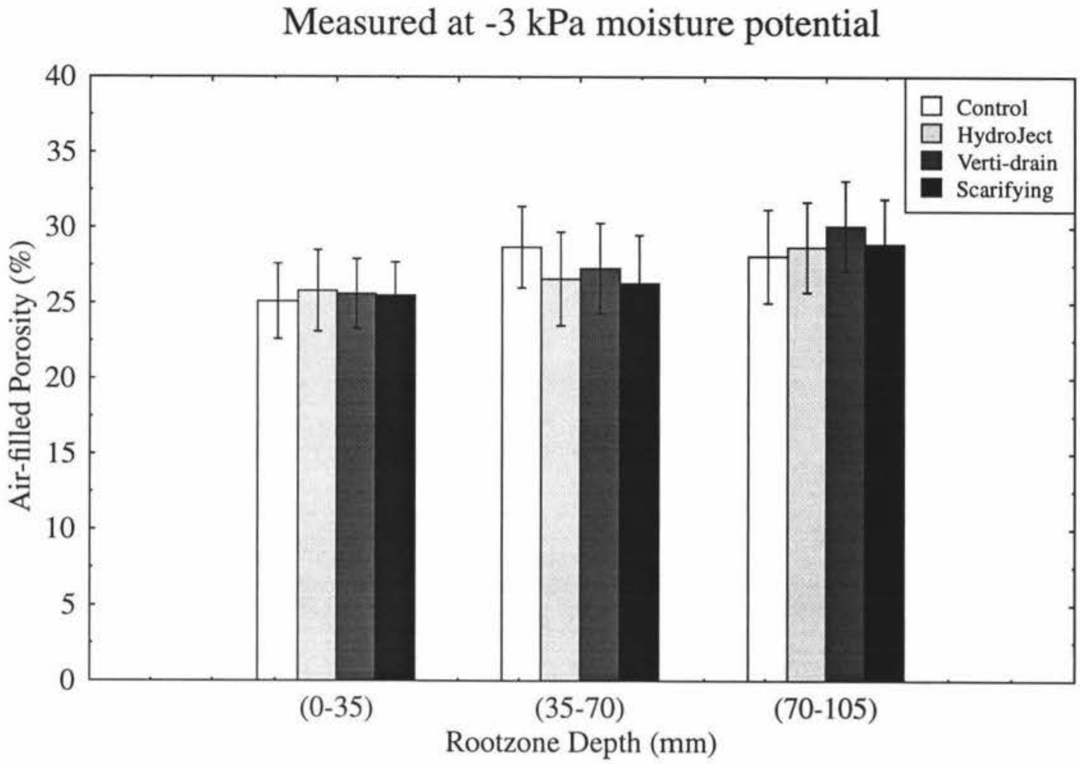


Figure 17. Mean volumetric moisture contents of each aeration treatment measured at 0-35 mm, 35-70 mm and 70-105 mm depths, 1 month after aeration (Vertical bars represent the standard error of the mean (n=15)).



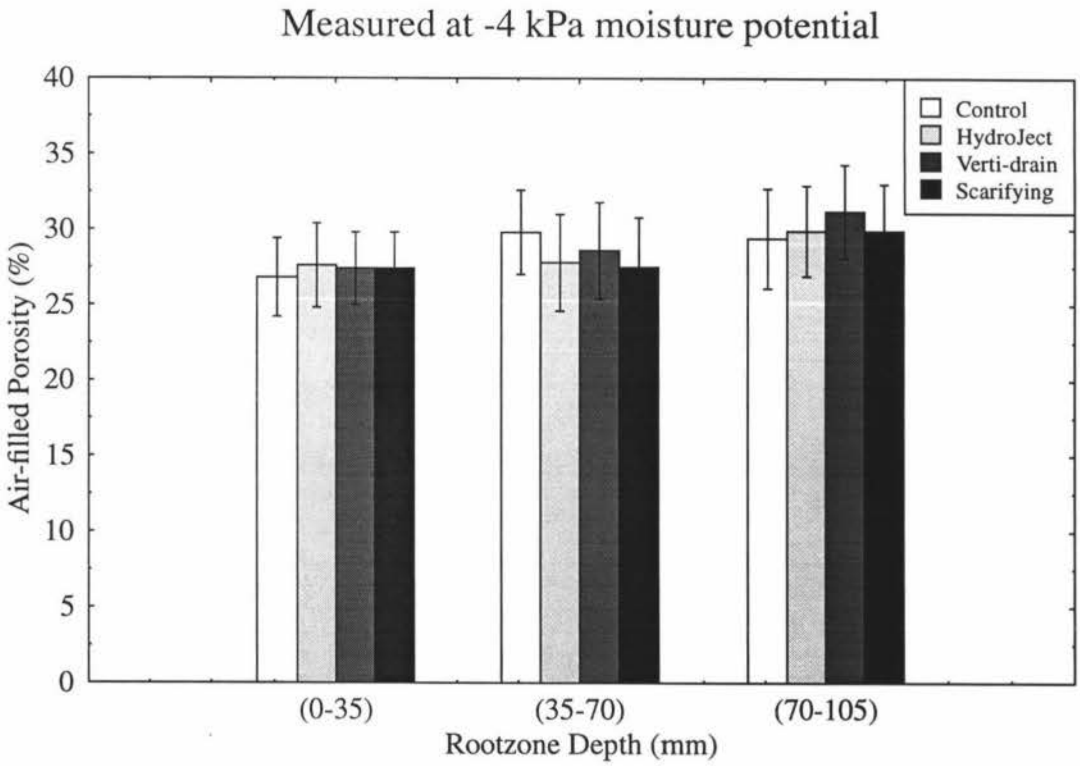
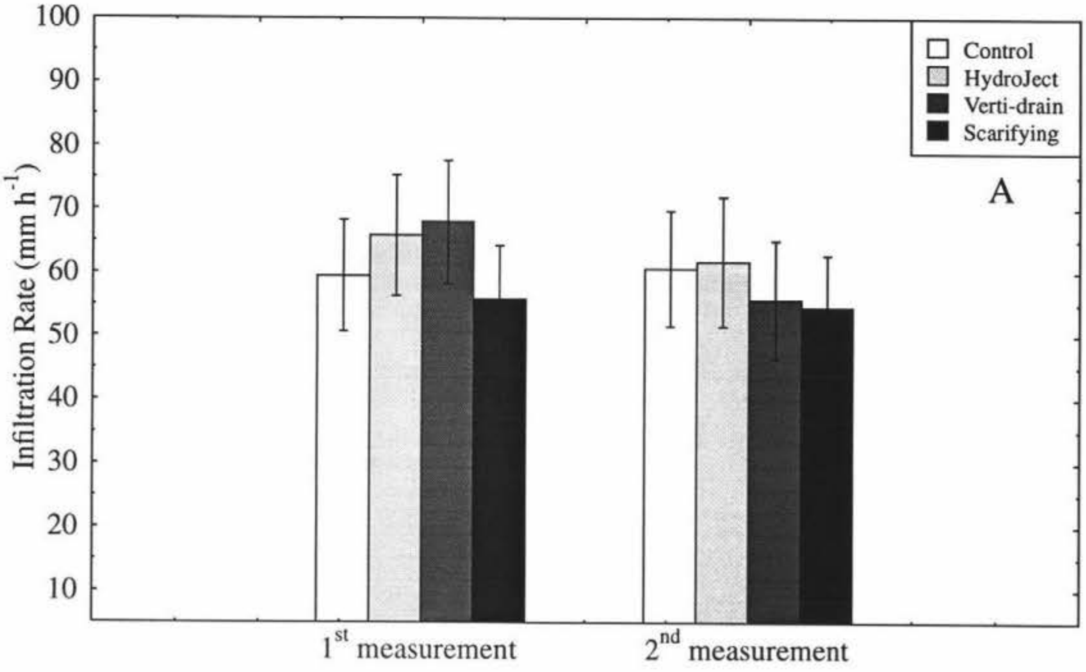


Figure 18. Mean air-filled porosities of each aeration treatment measured at 0-35 mm, 35-70 mm and 70-105 mm depths, 1 month after aeration. (Vertical bars represent the standard error of the mean (n=15)).



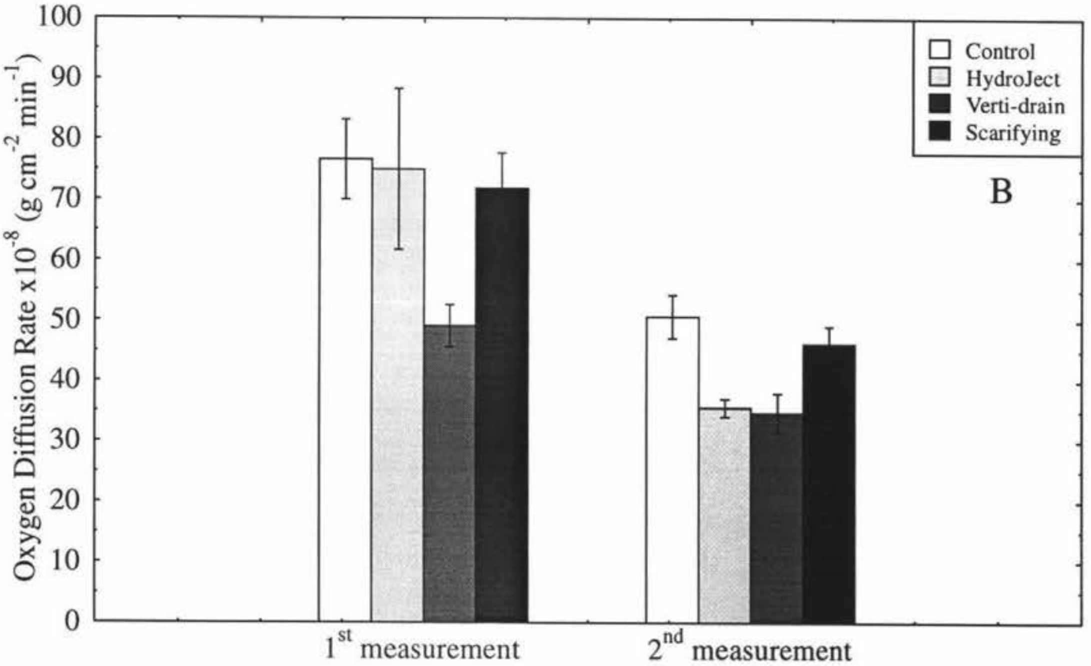
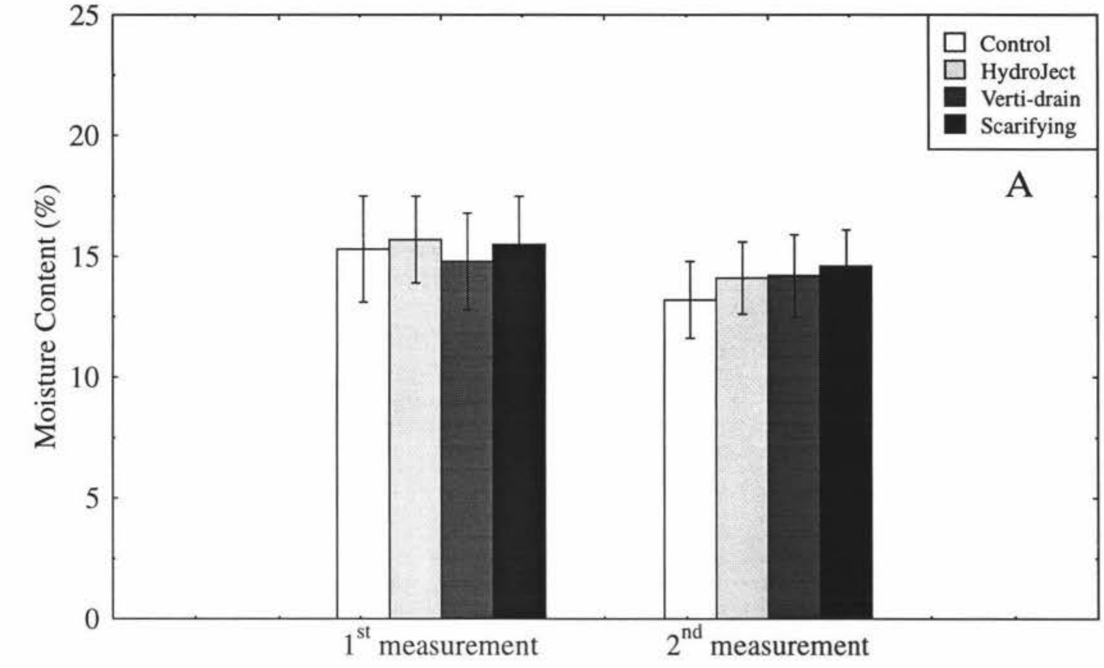


Figure 19. (A) Mean infiltration rates of each aeration treatment. (B) Mean oxygen diffusion rates of each aeration treatment. 1st measurement- taken 1 month after aeration; 2nd measurement- taken 8 months after aeration. (Vertical bars represent the standard error of the mean (n=15)).



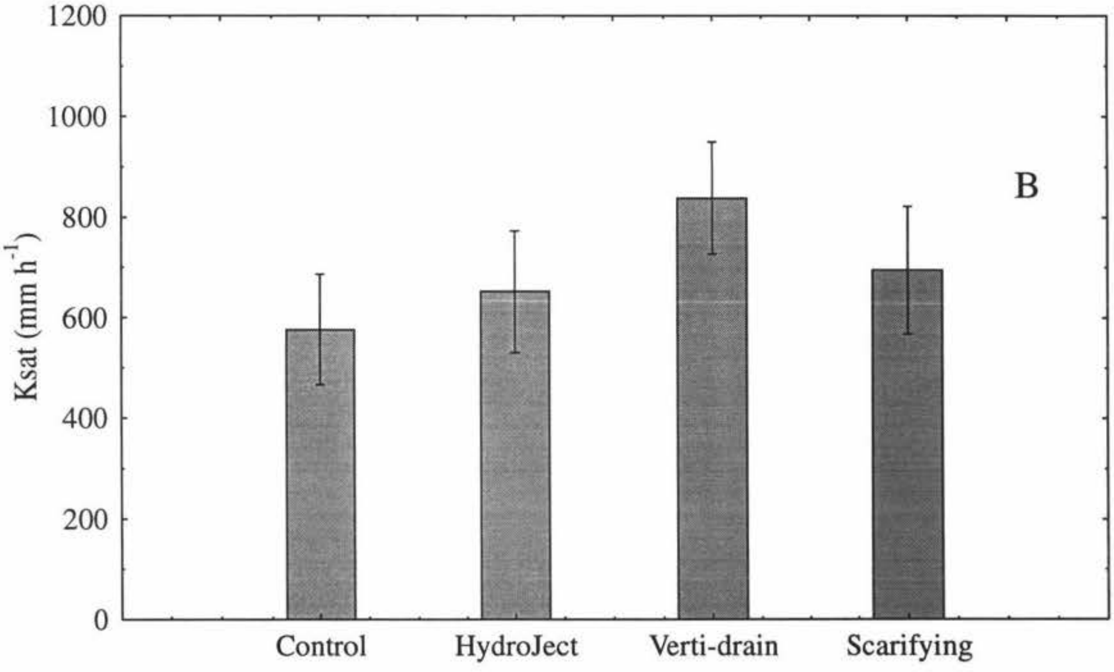


Figure 20. (A) Mean moisture contents (0-50 mm, including sward) of each aeration treatment. 1st measurement- taken 1 month after aeration; 2nd measurement- taken 8 months after aeration. (B) Mean saturated hydraulic conductivities of each aeration treatment measured 1 month after aeration. (Vertical bars represent the standard error of the mean (n=15)).

4.2 Root Development and Organic Matter Content

4.2.1Rootzone Construction

The root developments of constructed rootzones were measured 13 months (first measurement) and 20 months (second measurement) after sowing. Organic matter contents of constructed rootzones were measured 13 months after construction.

Root development

Root distributions of constructed rootzones are given in Fig. 21. On the first measurement, 0-50 mm depth, the pure sand rootzone root development was significantly ($p \leq 0.05$) greater than other rootzones. At 50-100 mm depth, silt soil rootzone root development was significantly less than for other rootzones. At 100-150 mm and 150-200 mm depths, silt soil rootzone showed less roots than other rootzones. However these were not significant. At 200-250 mm depth, pure sand rootzone root development was significantly greater than silt soil rootzone (refer to Appendix Table 11).

On the second measurement, 0-50 mm depth, pure sand rootzone root development was significantly greater ($p \leq 0.05$) than other rootzones. At 50-100 mm depth, silt soil rootzone root development was significantly less than other rootzones, and pure sand rootzone root development was significantly greater than amended sand rootzones. At 100-150 mm depth, silt soil rootzone root development was significantly less than other rootzones. At 150-200 mm depth, there were no significant differences between rootzones, although root development for the silt soil rootzone tended to be less. At 200-250 mm depth, pure sand rootzone root development was significantly greater than the partially amended plus zeolite sand rootzone (refer to Appendix Table 12).

Total root weights of constructed rootzones are shown in fig. 22 (A). Pure sand rootzone root weight was significantly greater than other rootzones in both measurements (refer to Appendix Tables 11 and 12).

Organic matter content

Organic matter content was strongly influenced by rootzone materials (Fig. 22 (B) and Appendix Table 13). The silt soil rootzone tended to have higher organic matter content at all depths. The difference of organic matter content in rootzones can be explained best by the nature of rootzone material.

4.2.2 Aeration Treatment

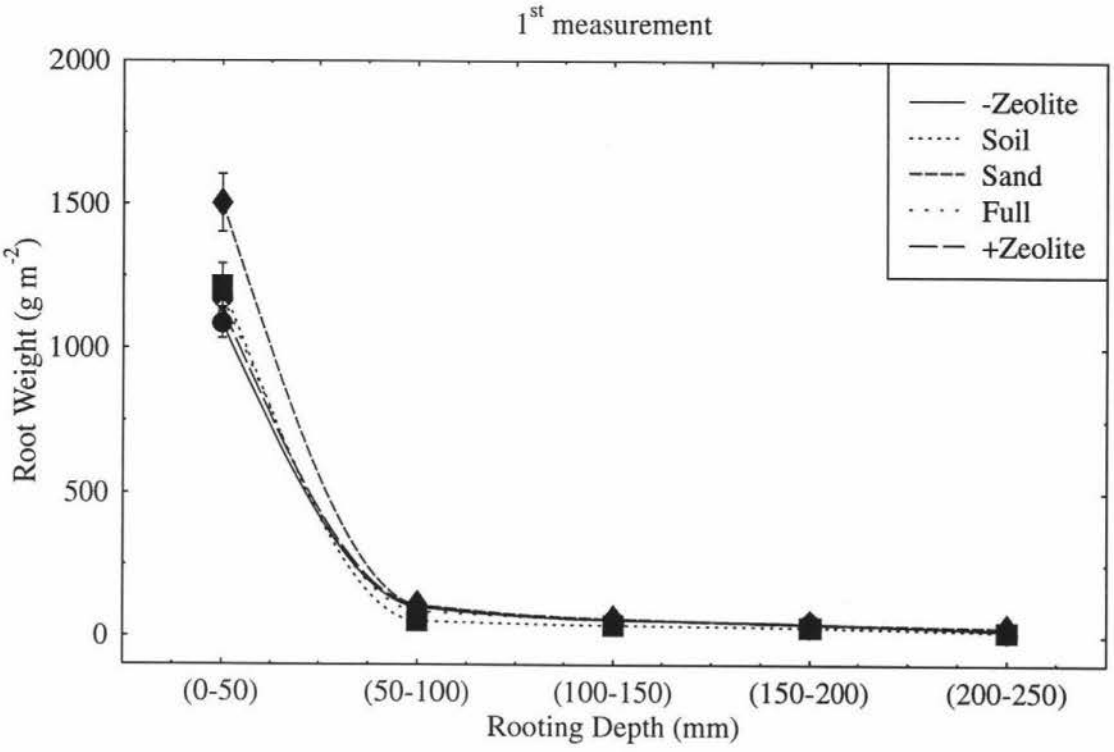
The effects of aeration treatments on root development were measured 1 month (first measurement) and 8 months (second measurement) after aeration. Effects of aeration treatments on organic matter contents were measured 1 month after aeration.

Root development

Effects of aeration treatments on root development are given in Fig. 23. On the first measurement, Verti-draining showed slightly greater root development than other aeration treatments at 0-50 mm depth, although this was not significant. However, it was significantly greater compared to the untreated control at 100-150 mm depth (refer to Appendix Table 14). On the second measurement, HydroJecting showed greater root development than other aeration treatments at 0-50 mm depth, although this was not significant. However, Verti-draining showed greater root development at other depths. Again this was not significant (refer to Appendix Table 15). The effects of aeration treatments on total root weight are shown in Fig. 24 (A). Verti-draining and HydroJecting treatments tended to have greater root development, however, the differences were not significant (refer to Appendix Tables 14 and 15).

Organic matter content

The effects of aeration treatments on organic matter content are given in Fig. 24 (B). There were no significant differences between aeration treatments (refer to Appendix Table 16).



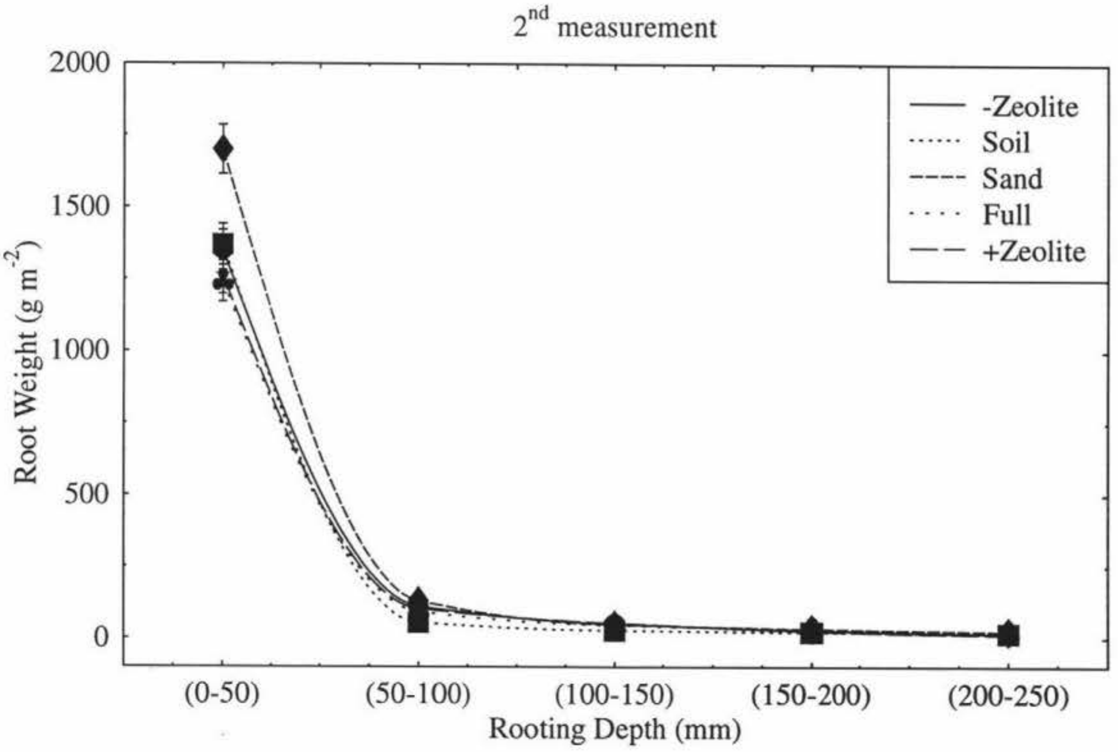


Figure 21. Root dry weight in relation to rooting depth and rootzone construction. 1st measurement- taken 13 months after sowing; 2nd measurement- taken 20 months after sowing. (Vertical bars represent the standard error of the mean (n=12)).

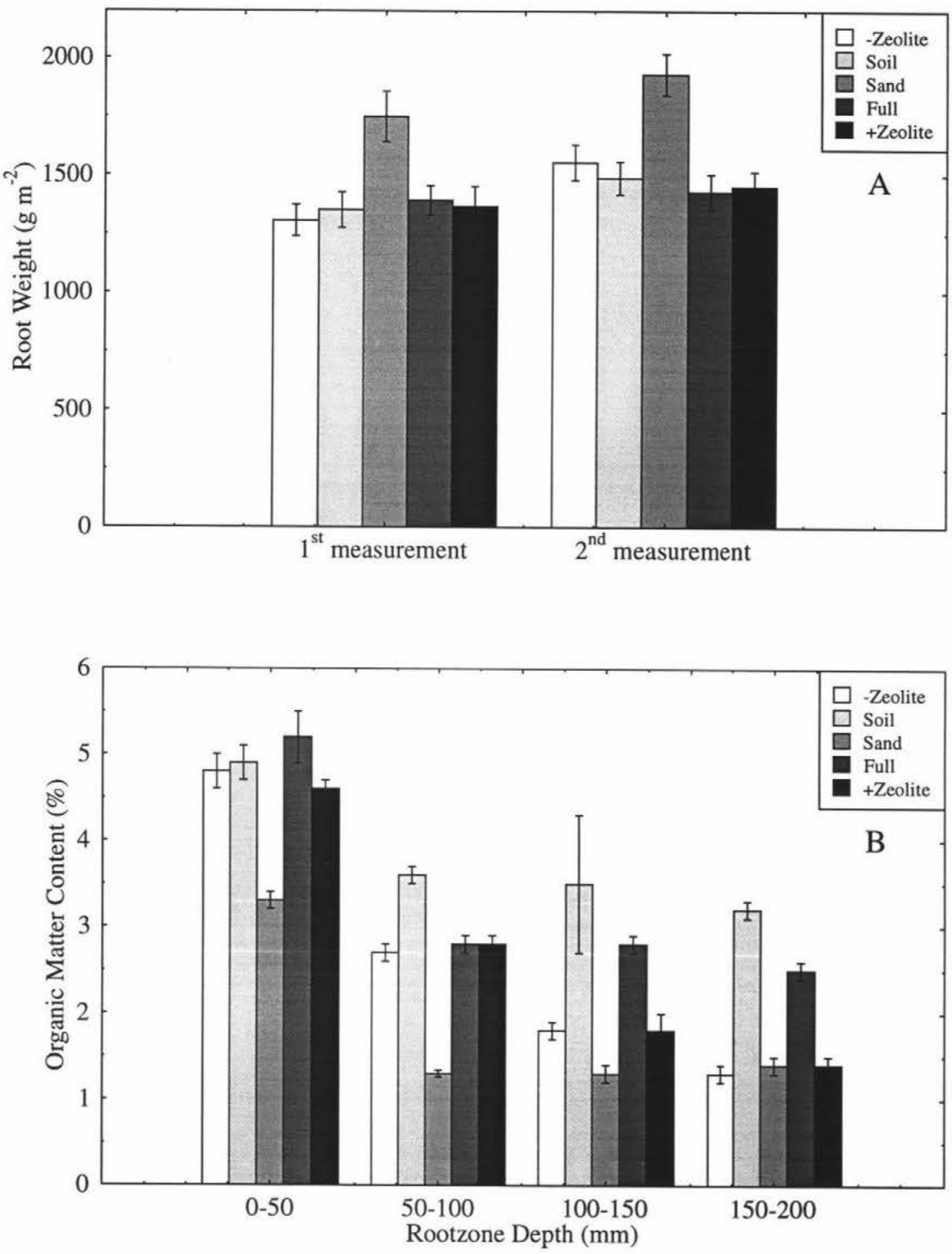
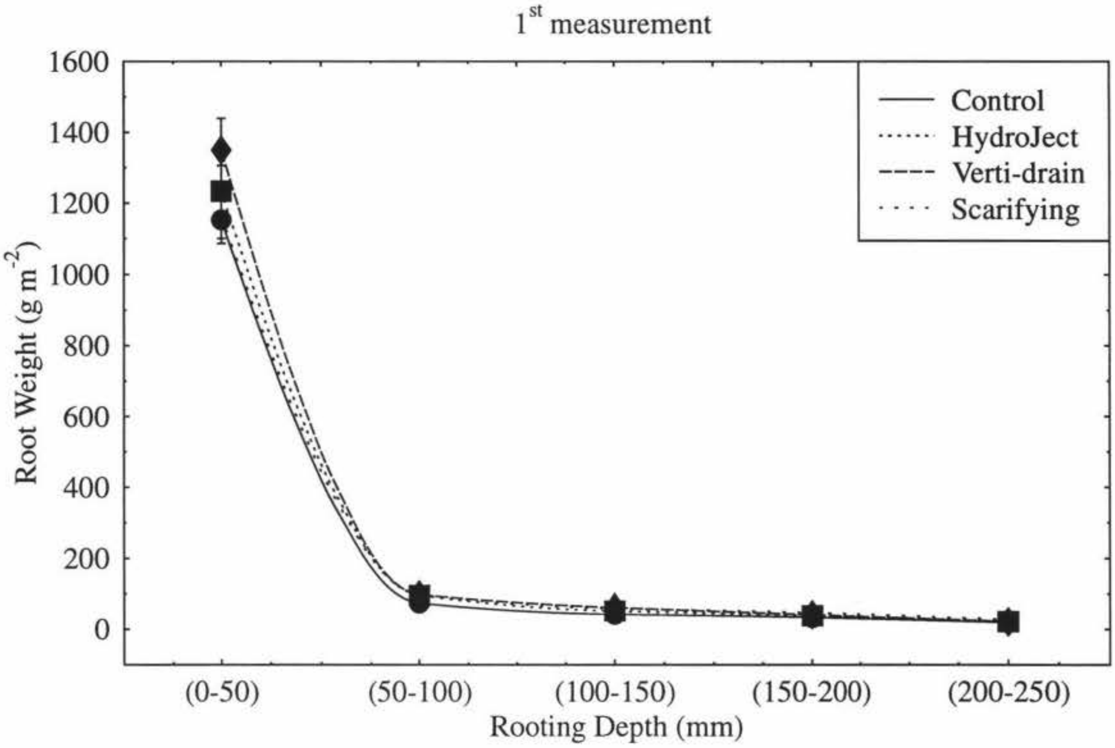


Figure 22. (A) Mean total root dry weight of each constructed rootzone. 1st measurement- taken 13 months after sowing; 2nd measurement- taken 20 months after sowing. (B) Mean organic matter contents (0-50 mm, 50-100 mm, 100-150 mm and 150-200 mm) of each constructed rootzone measured 13 months after construction. (Vertical bars represent the standard error of the mean (n=12)).



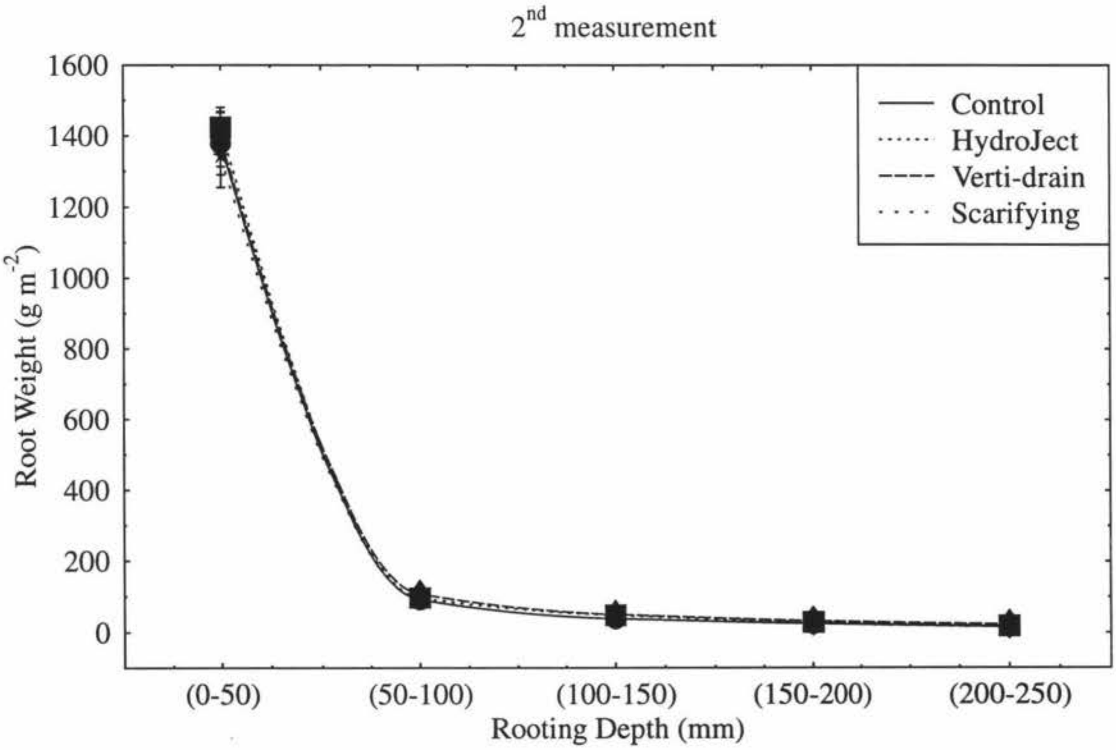


Figure 23. Root dry weight in relation to rooting depth and aeration treatment. 1st measurement- taken 1 month after aeration; 2nd measurement- taken 8 months after aeration. (Vertical bars represent the standard error of the mean (n=15)).

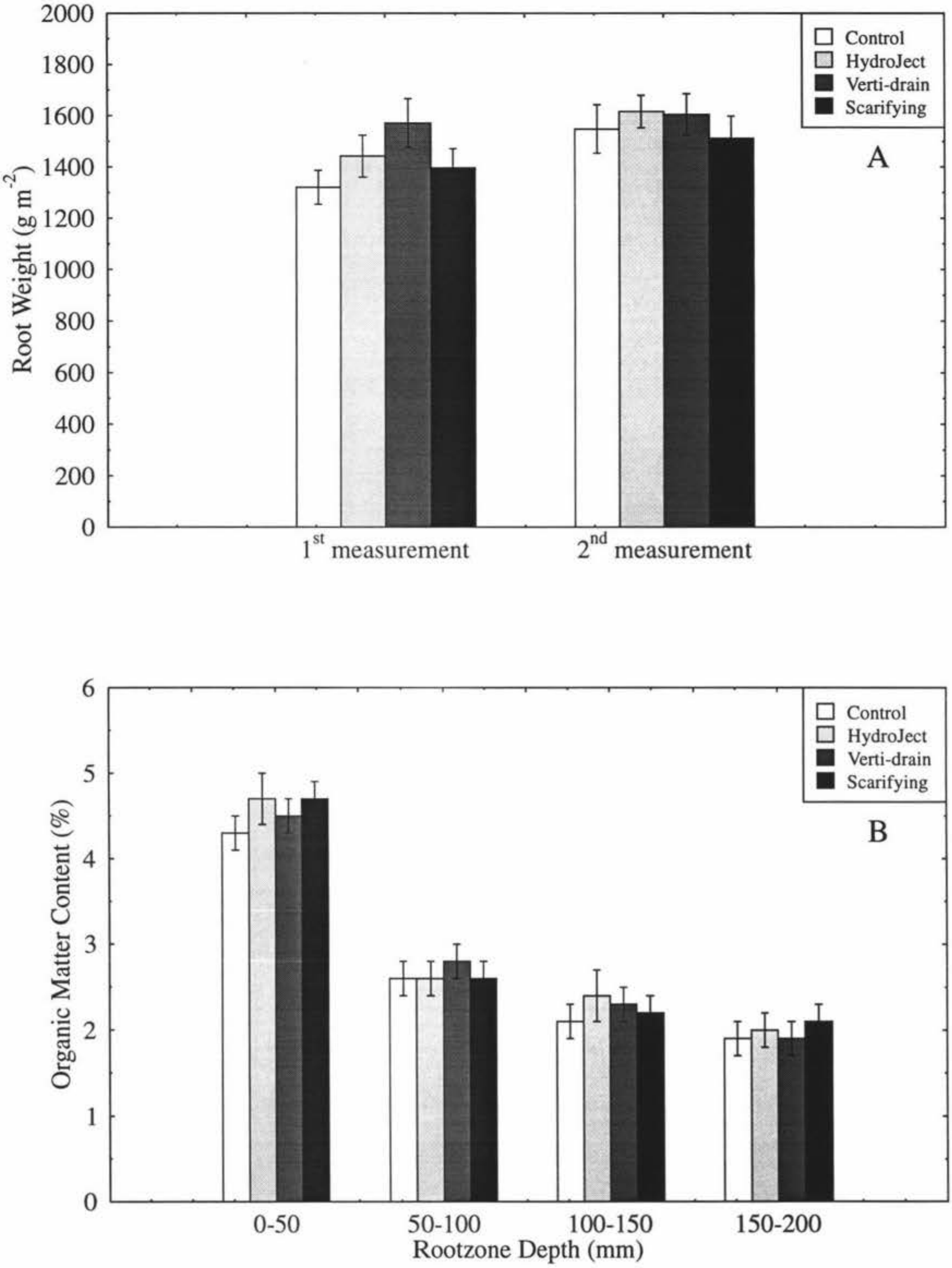


Figure 24. (A) Mean total root dry weight of each aeration treatment. 1st measurement- taken 1 month after aeration; 2nd measurement- taken 8 months after aeration. (B) Mean organic matter contents (0-50 mm, 50- 100 mm, 100-150 mm and 150-200 mm) of each aeration treatment measured 1 month after aeration. (Vertical bars represent the standard error of the mean (n=15)).

4.3 Playing Quality

4.3.1Rootzone Construction

The effects of constructed rootzones on playing quality were measured 13 months (first measurement) and 20 months (second measurement) after construction.

Hardness

Effects of constructed rootzones on surface hardness are shown in Figs. 25 and 26 (A). On the first measurement, the pure sand rootzone tended to be harder than other rootzones, with the silt soil rootzone being the softest. For example, 121 gravities for pure sand rootzone, 113-118 gravities for amended sand rootzones, and 109 for silt soil rootzone were obtained at the first drop of 0.5 kg Clegg Impact Hammer measurement. There were no significant differences between rootzones on 0.5 kg Clegg Impact Hammer measurements, but there was a significant difference between pure sand rootzone and silt soil rootzone for 2.25 kg Clegg Impact Hammer measurement (refer to Appendix Table 17).

On the second measurement, the pure sand rootzone was found to produce the hardest surface, silt soil the softest and amended sand rootzones intermediate hardness. For example, 121 gravities for pure sand rootzone, 108-110 gravities for amended sand rootzones, and 96 gravities for silt soil rootzone were obtained at the first drop of 0.5 kg Clegg Impact Hammer measurement. There were significant differences between pure sand rootzone, amended sand rootzones and silt soil rootzone for both 0.5 kg and 2.25 kg Clegg Impact Hammer measurements (refer to Appendix Table 18).

Green speed

Green speeds of constructed rootzones are given in Fig. 26 (B). The rootzones had no significant effects on green speed on both measurements (refer to Appendix Tables 17 and 18).

4.3.2 Aeration Treatment

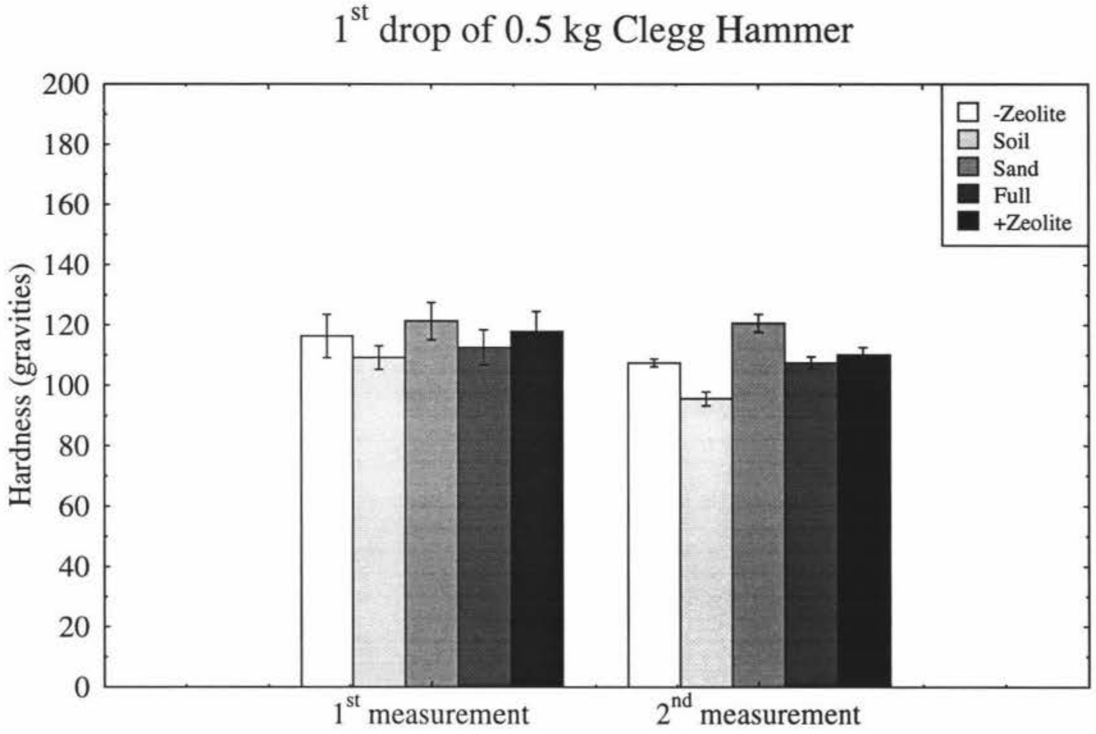
The effects of aeration treatments on playing quality were measured 1 month (first measurement) and 8 months (second measurement) after aeration.

Hardness

Effects of aeration treatments on hardness are shown in Fig. 27 and 28 (A). Verti-draining tended to produce softest surface, the HydroJecting the second, scarifying third and untreated control the hardest surface. On the first measurement, Verti-draining was found to have a significantly softer surface than untreated control and scarifying aeration for both 0.5 kg and 2.25 kg Clegg Impact Hammer measurements (refer to Appendix Table 19). However, there were no significant differences between aeration treatments on the second measurement (refer to Appendix Table 20).

Green speed

Effects of aeration treatments on green speed are shown in Fig. 28 (B). There were no significant differences between aeration treatments on both measurements (refer to Appendix Tables 19 and 20).



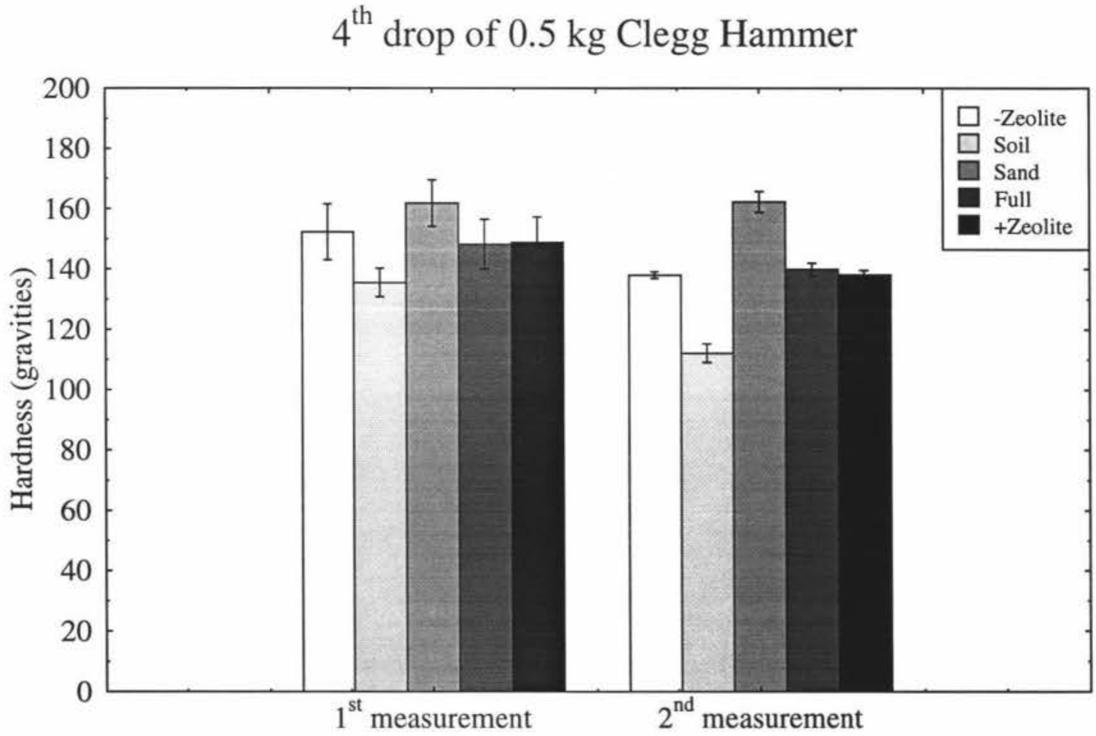
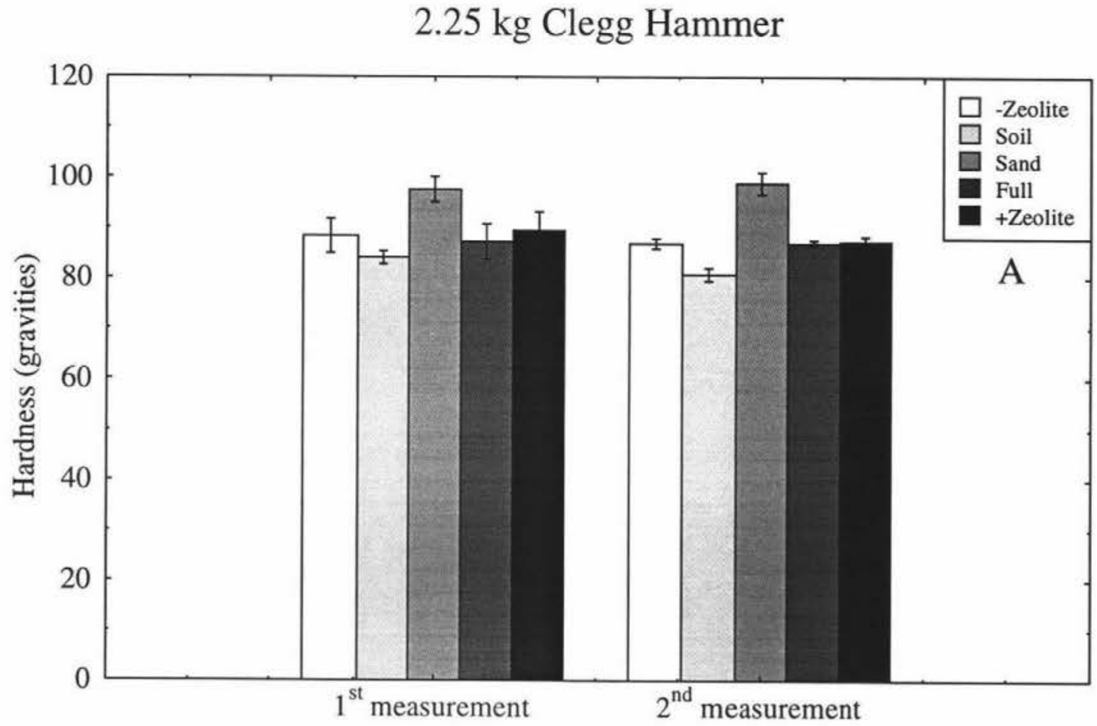


Figure 25. Mean surface hardness of each constructed rootzone . 1st measurement- taken 13 months after construction; 2nd measurement- taken 20 months after construction. (Vertical bars represent the standard error of the mean (n=12)).



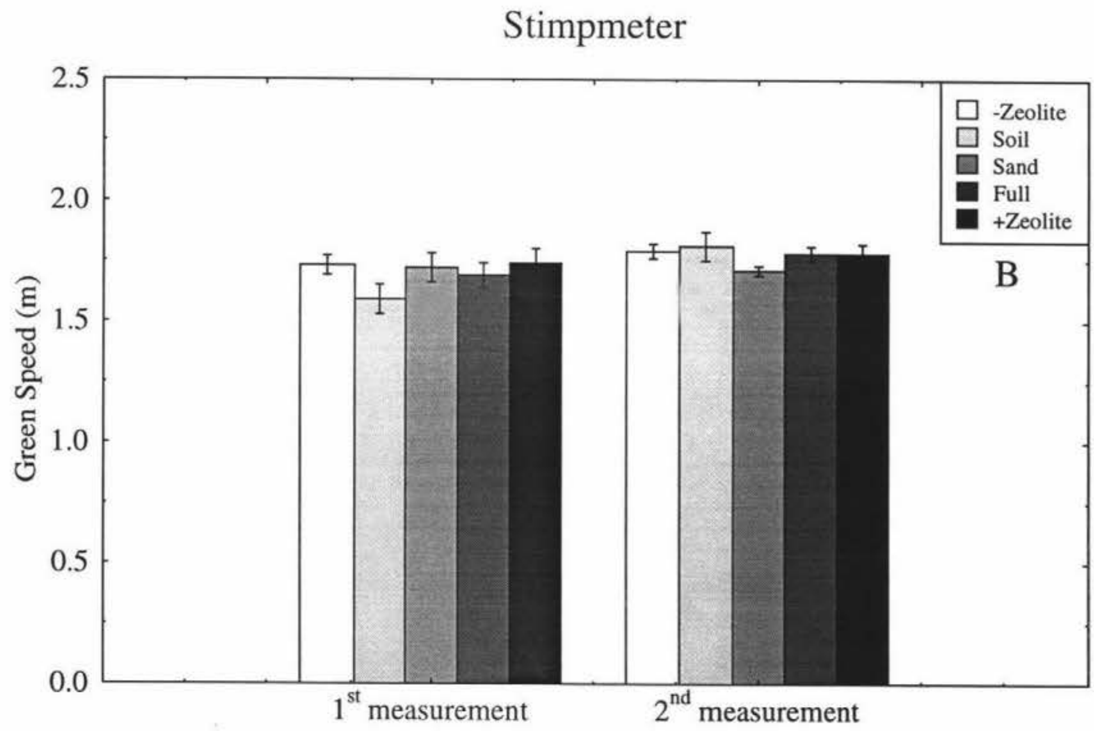
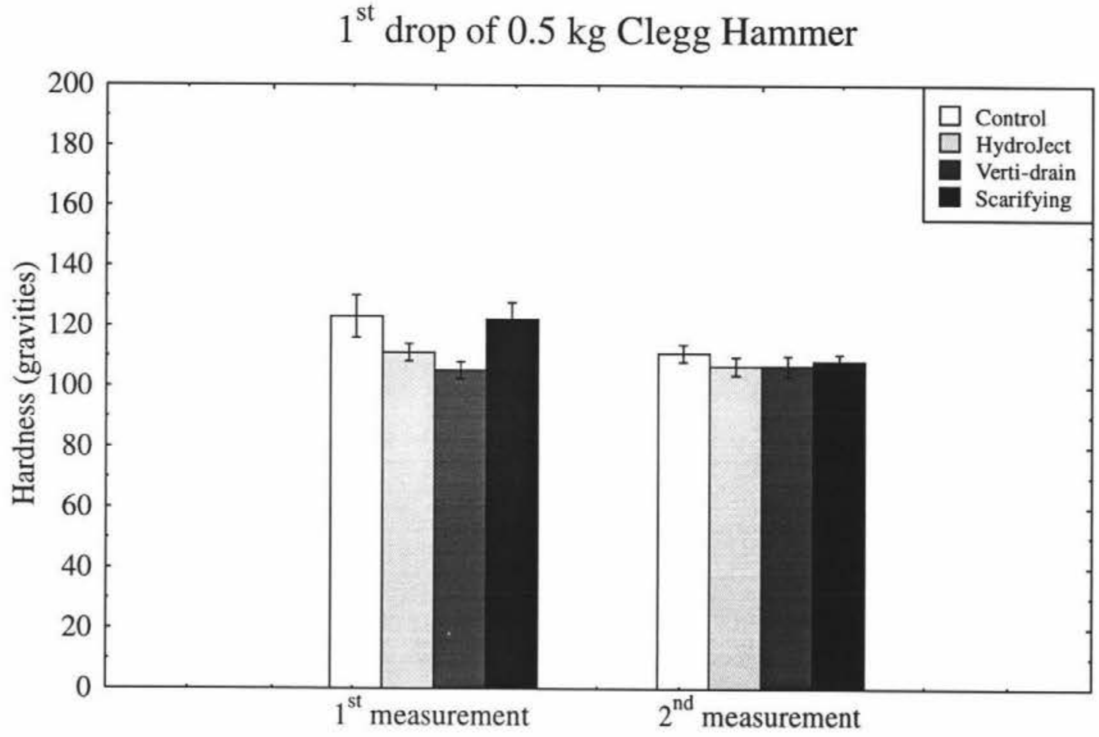


Figure 26. (A) Mean surface hardness of each constructed rootzone. (B) Mean green speeds of each constructed rootzone. 1st measurement- taken 13 months after construction; 2nd measurement- taken 20 months after construction. (Vertical bars represent the standard error of the mean (n=12)).



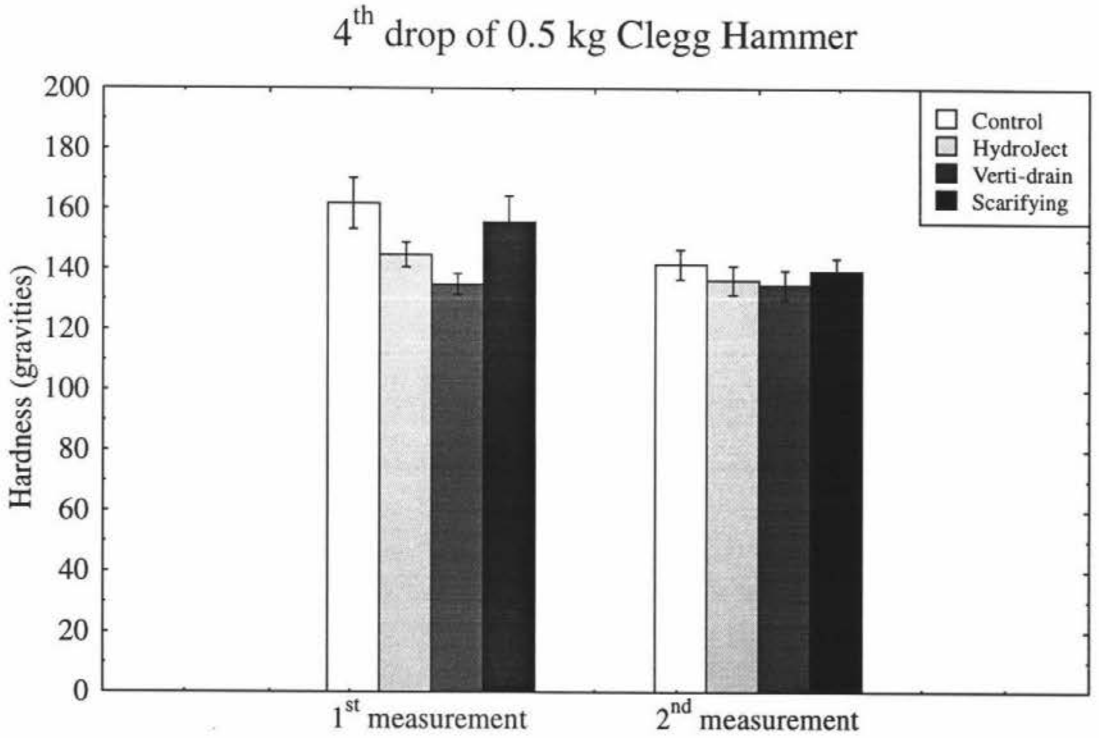


Figure 27. Mean surface hardness of each aeration treatment. 1st measurement- taken 1 month after aeration; 2nd measurement- taken 8 months after aeration. (Vertical bars represent the standard error of the mean (n=15)).

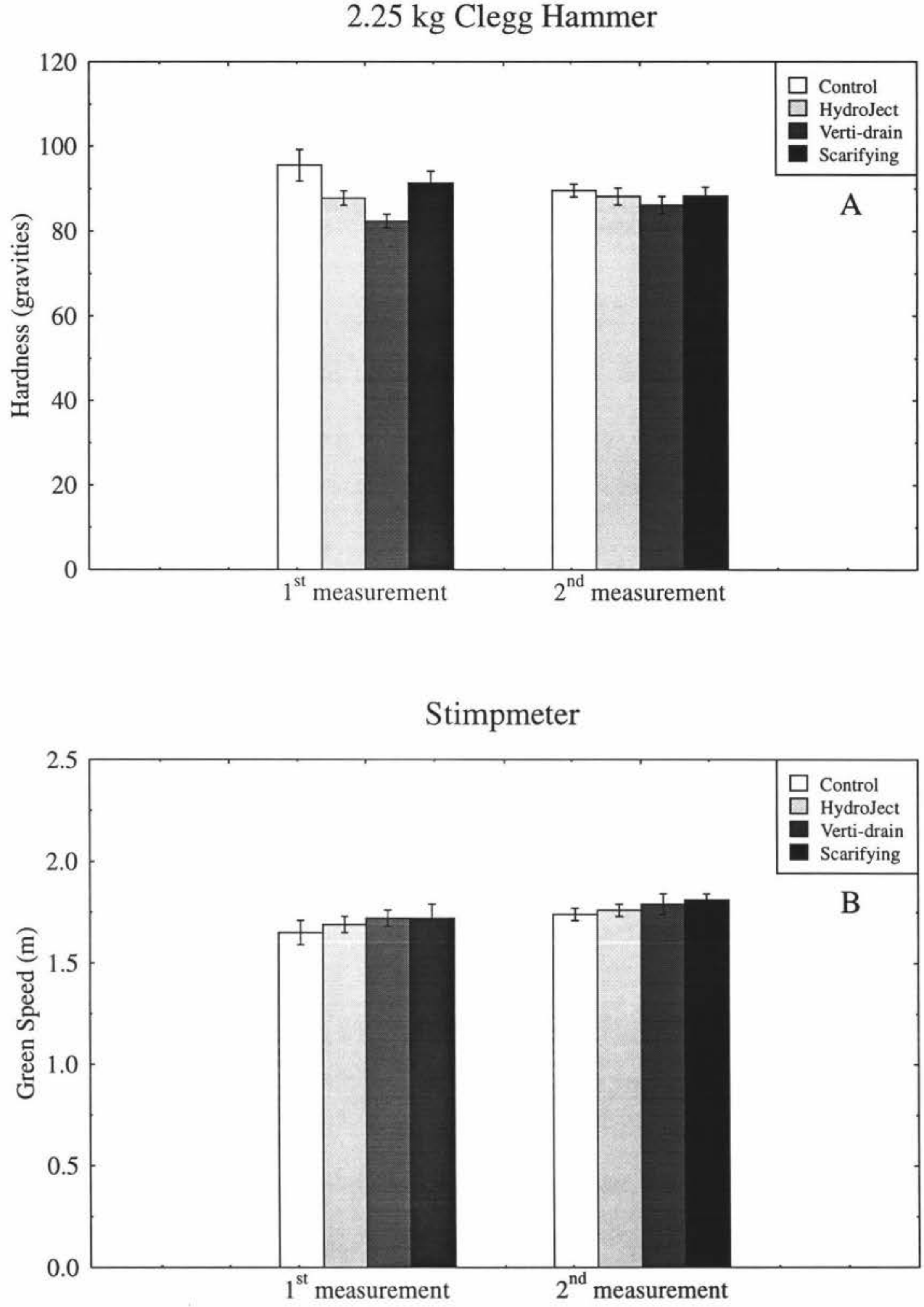


Figure 28. (A) Mean surface hardness of each aeration treatment. (B) Mean green speeds of each aeration treatment. 1st measurement- taken 1 month after aeration; 2nd measurement- taken 8 months after aeration. (Vertical bars represent the standard error of the mean (n=15)).

5. Discussion

5.1 Rootzone Characteristic

5.1.1 Rootzone Construction

There is relativity little published work that defines the optimum soil physical conditions for golf rootzones under field conditions. However, for laboratory compacted cores performance requirements are well documented. USGA Green Section Staff (1993) recommended that laboratory materials should have a bulk density of 1.2-1.6 g/cm^3, a total porosity of 35-55 %, a capillary porosity at –3 kPa moisture potential of 15-25 %, an air-filled porosity at –3 kPa of 15-30 % and under most conditions a saturated hydraulic conductivity of 150-600 mm/hr.

For golf green turf in the USA, Waddington *et al.* (1974) (cited in Hind *et al.*, 1995) suggested that a 25 mm/hr field infiltration rate should be regarded as a minimum acceptable value. In the UK, Gibbs and Baker (1989) reviewed infiltration requirements. They suggested values should be above 20 mm/hr to cope with periods of intensive rainfall, while 10 mm/hr was a minimum requirement for areas of good quality turf.

The range of mean bulk densities (1.25-1.50 g/cm^3) and total porosities of five rootzones all fell within the acceptable range (35-55%). However, the bulk density values of the silt soil rootzone tended to be higher (at 35-70 mm depth, 1.5 g/cm^3 was recorded). In the future, this would be likely to cause problem in terms of compaction. Although prior studies showed rootzone type would have an effect on bulk density (Cook and Baker, 1998), it did not occur in this study.

Volumetric moisture content at a moisture potential of –3 kPa was above 15% for all sand rootzones at 0-35 mm depth. However, for the 35-70 mm and 70-105 mm depths, the pure sand rootzone fell below 15% (approximately 10%), this is supported by finding of Baker and Richards (1993). In terms of irrigation management, the pure sand rootzone would be the most demanding. The fully amended sand rootzone was also fell below 15% at 70-105 mm depth. The lower VMC of fully amended sand rootzone at 70-105 mm depth compared with partially amended sand rootzones is an unexpected result, likely not to be of practical significance. The results of subsequent measurements for VMC need to be analysed prior to making any firm conclusions. For silt soil rootzone there was a very high VMC at all depths (approximately 40%). This resulted in a very low air-filled porosity in this rootzone, and is considered detrimental to healthy turf growth.

Air- filled porosities at a moisture potential of –3 kPa were relatively high (above 30%) for sand rootzones, especially for pure sand rootzone (38% at 70-105 mm depth). This result is different with prior studies (Baker and Richard, 1993) that found sand rootzones had lower air-filled porosity (below 30%). These values fell outside of the recommended range and are considered to be unacceptable, as the rootzones a lower than desirable VMC. The higher air-filled porosity of fully amended sand rootzone at 70-105 mm compared with partially amended sand rootzones is also an unexpected result. Again, it is important to observe the influence of rootzone construction over a period of time to see if this result remains consistent. For silt soil rootzone the air-filled porosity (below 10%) was well below the suggested acceptable threshold of 15%. This implies roots in this rootzone will have an inadequate oxygen supply to sustain adequate root growth. This was supported by this study.

Infiltration rates of all sand rootzones were well above the minimum acceptable values (Waddington *et al.*, 1974; cited in Hind *et al.*; Gibbs and Baker, 1989), especially the pure sand rootzone. Similar results of high infiltration rate in the sand rootzone were also found in other studies (Lodge and Baker, 1993). For the silt soil rootzone, the infiltration rate was very low (0.4, 0.2 mm/hr for first and second measurement respectively). These values are well below the USGA and UK minimum requirements. A silt soil rootzone is therefore likely to produce ponding during heavy rainfall. The notable decrease of infiltration rate for the fully amended sand rootzone between the two measurements (7 months apart) may have been contributed to by a higher level of settling than would occur in the fully amended sand rootzone. As this decrease occurred only over a 7 month period, a long term assessment of this feature should applied to this rootzone construction.

Saturated hydraulic conductivities of all sand rootzones were relatively high (above 700 mm/hr), especially the fully amended sand rootzone (above 900 mm/hr). The higher K_{sat} of fully amended sand rootzone is supported by prior studies, although there were some opposite results (Hummel, 1993a). The higher K_{sat} is unlikely to have any detrimental impacts upon root development and growth of the turf plant. The silt soil rootzone (239 mm/hr) fell within the range of the USGA recommend range. However, it is unlikely that a sustainable high K_{sat} for this rootzone will exist long term. This study's result was possibly a reflection of the lack of consolidation.

Oxygen diffusion rate of five rootzones all met the adequate requirement (0.4 $\mu g/cm^2/min$, refer to section 2.1.2.4) in the first measurement. However, by the second measurement, only amended sand rootzones met the requirement. The higher oxygen diffusion rate in amended sand rootzones was expected as these rootzones would not be compacted as hard as pure sand and silt soil rootzones. The difference between the two measurements was possibly influenced by the lack of consolidation that had occurred at the time of the first measurement.

5.1.2 Aeration Treatment

The failure of aeration treatments to induce any notable response in soil physical properties was probably due to the timing of measurements. In one study, McAuliffe *et al.* (1993) measured soil physical properties shortly after aeration (2 weeks). They found Verti-drain and HydroJect treatments significantly increase infiltration rate and saturated hydraulic conductivity. However, there was no significant difference between treated or untreated control 8 months later. As described in the literature review, in the USA aeration is frequently undertaken at biweekly or monthly intervals, suggesting that there is an expectation that aeration would only have a short period of effect. In order to ascertain significant results, measurements may have to be taken closer to the time aeration is applied shortly after aeration applied.

5.2 Root Development and Organic Matter Content

5.2.1 Rootzone Construction

Greater root development within pure sand was probably due to a combination effects, firstly, the rootzone received more fertiliser during the first year of establishment; secondly, lack of significant cation exchange capacity in the pure sand rootzone may have encouraged roots to search out more nutrients. However, the greater root development of pure sand rootzone mostly occurred at the 0-50 mm depth. This will be a detrimental impact upon turf growth as more organic matter (living or dead) accumulates in the top 50 mm (refer to section 2.3.2.3). The lower root development at 200-250 mm within partially amended plus zeolite sand rootzone may have been influenced by the effect of zeolite at the 100-200 mm. The silt soil rootzone had fewer roots developed at some depths. This was probably due to less favourable soil conditions, for example, the very low air-filled porosities (6-9 %) at the 35-105 mm rootzone inhibiting the root growth.

The different organic matter content in the rootzones was due to the nature of rootzone material, so it will not be described in this thesis. However these data are valuable, as in the future they can be used to determine the rate of accumulation of organic matter in the rootzones. As stated in the introduction, accumulation of organic matter in the top 50 mm of the rootzone is adverse for turf growth. For this reason, it is considered important to study the influence of rootzone construction on organic matter accumulation.

5.2.2 Aeration Treatment

Verti-drain and HydroJect treatments tended to have greater root development. However, this was only significant for the Verti-drain treatment compared to the untreated control at 100-150 mm (first measurement). Similar results were found in other studies (McAuliffe *et al.*, 1993), none of the aeration treatments (HydroJect, Verti-drain and Vibramole) significantly increased root mass. As the measurements of root development were carried out only after once of aeration treatments applied.

Presumably with time and continued aeration treatment, more significant result would be expected.

Although this study did not provide similar results to prior studies, that some aeration (core cultivation and scarifying) treatments will limit organic accumulation (Vavrek, 1992), this may be a function of sward age and current state of development. With time and further aeration applications, a significant result could be expected in the top rootzone layer measurement.

5.3 Playing Quality

5.3.1 Rootzone Construction

The pure sand rootzone was found to produce the hardest surface, while the silt soil rootzone gave softest. This is supported by Lodge and Baker (1991). Values of hardness for pure sand rootzone were slightly higher (121 gravities) than the UK recommend range (55-120 gravities) (Baker *et al.*, 1996), while other rootzones met the acceptable range. The harder surface of pure sand rootzone was due to it having the least amount of organic matter, meaning there was less compressible matter to absorb some of the energy as impact tester hit the surface.

Green speeds measured from five rootzones were very similar, and showed no significant difference. The results of the measurements overall mean was 1.65-1.81 m and would be classified as being medium slow for regular membership play, according to the criteria given by the USGA Green Section. Although prior studies showed rootzone type would have an effect on green speed (Lodge and Baker, 1991), it did not occur in this study. This may have been contributed to by the maintenance of the trail. As green speed is rather sensitive to cutting height (Engel *et al.*, 1980), measuring at a different height may have influenced the result for rootzone responses. For the study that indicated there was an effect of rootzone type on green speed, was measured at 5-6 mm height of turf. However, in this study the sward was maintained at 7 mm. A further possibility for the difference in result is that turf species composition has a great effect on green speed (Lodge and Baker, 1991; Canaway and Baker, 1992). In later years green speed may become more evident due to changes in species composition associated with different rootzone materials.

5.3.2 Aeration Treatment

The Verti-drain and HydroJect treatments produced softer surfaces as expected, due to the loosening of the rootzones. Some significant differences in the first measurement did not appear in the second measurement. This was probably due to the aeration treatments only having a short period of effect. However, in the long term aeration treatments may produce a harder surface as some of aeration treatments can contribute to a breakdown the thatch through enhancing decomposition, which has a great influence on hardness (Anon., 1992).

There was no significant difference between aeration treatments for green speed, again, probably due to the short period effect of aeration. To observe significant results, it may be necessary to measure parameters shortly after aeration treatments are applied.

5.4 Correlation analysis

Hardness was weakly and negatively correlated (R^2= -0.20, $p < 0.001$) with green speed. Same results were also found in other studies (Lodge and Baker, 1993; Baker *et al.*, 1996). This may indicate that either the Clegg Impact Hammer did not measure hardness at the level of interaction of the rolling ball, or that general turf hardness did not greatly influence green speed.

Hardness was found to be correlated with moisture content (R^2= -0.80). Hardness increased moisture content decreased. There was also a negative correlation between moisture content and infiltration rate (R^2= -0.80). Other than these, there was no correlation between the variables measured.

There was no interaction between the two treatments (constructed rootzone and aeration) in this study.

6. Conclusions

6.1 Rootzone Construction

On the basis of the results from the soil physical propertities, root development and playing quality the following recommendation can be made:

(a) Partially amended sand rootzone construction is recommended as it meets most requirements of green construction. There exists potential to modify the compost percentage composition in the rootzone construction. Both higher (20% by volume) and lower (5 and 10 % by volume) percentages of compost should be assessed to ascertain what influences they have upon the properties measured in this experiment.

(b) Partially amended plus zeolite sand rootzone construction is also recommended as it appears to have similar properties and performance of the partially amended sand rootzone construction. However, this type of construction is likely to incur a higher cost.

(c) Fully amended sand rootzone construction is an acceptable rootzone construction. However, as the partially amended sand rootzone construction appears to provide suitable performance characteristics at a lower cost the additional costs of fully amended sand rootzone construction are not warranted.

(d) Pure sand rootzone construction is not recommended as poor soil physical properties and a harder surface make it unsuitable. Drawbacks of this rootzone construction can be overcome by installation of an efficient irrigation system combined with aeration treatments. However, the greater root development at the top 50 mm within this construction will result a detrimental impact for turf growth as a thatch problem.

(e) Silt soil rootzone construction is unsuitable for green construction as soil physical properties are very poor and exhibit less root development. It is difficult to modify the poor soil physical properties of this rootzone construction.

Investigation of rootzone construction in this study is incomplete. It is important to continue making measurements of soil physical properties and root development to ascertain if trends develop. While evident that amendments have positively contributed to rootzone characteristics questions such as the appropriate ratio of sand to amendment, placement of amendment within the profile and optimal depth of amendment remain unresolved.

6.2 Aeration Treatment

There were no significant results in aeration treatments from this study to enable making any recommendations. However, Verti-drain and HydroJect treatments did show some positive effect on soil physical properties and root development. These were not significant at this point in time and should be monitored over time to see if any significant trend emerges.

Failure of aeration treatments to exhibit significant differences in this study may be due to the timing of measurements. I order to ascertain the effect of aeration treatment, it is recommended that they be taken closer to the time aeration treatment is applied as aeration treatments may only have a short period of effect. Currently, there is very little published information to evaluate the effectual period of aeration treatments, necessitating further experimental work in this area.

As this study is based on a four-year project, any recommendation given in this paper should be reviewed with later results in order to observe trends that may develop. Only under this condition can definite recommendations be proposed.

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APPENDIX

Table 1. Effect of rootzone construction on soil physical properties at 0-35 mm. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Rootzone	Bulk Density (g/cm^3)		Total Porosity (%)		Moisture Content -3 kPa (%)	
1	1.276±0.015 (1.20-1.36)	a*	51.10±0.55 (48.0-53.9)	a	21.94±0.57 (18.9-25.5)	a
2	1.322±0.039 (1.18-1.68)	a	50.51±1.28 (39.0-55.6)	a	42.17±1.10 (31.7-47.0)	b
3	1.286±0.014 (1.17-1.35)	a	51.14±0.53 (48.7-55.4)	a	19.86±0.93 (14.9-24.2)	a
4	1.247±0.011 (1.17-1.30)	a	52.27±0.40 (50.4-55.1)	a	21.22±0.80 (17.4-26.4)	a
5	1.277±0.013 (1.18-1.33)	a	51.16±0.47 (49.1-54.8)	a	23.73±0.85 (19.0-28.4)	a

Rootzone	Moisture Content - 4 kPa (%)		Air-filled Porosity -3 kPa (%)		Air-filled Porosity -4 kPa (%)	
1	19.78±0.49 (17.2-22.4)	a	29.17±0.94 (23.2-32.7)	ac	31.3±0.779 (25.6-34.4)	ac
2	41.34±1.12 (30.2-46.2)	b	8.35±0.86 (5.3-14.1)	b	9.18±0.80 (5.8-14.5)	b
3	18.13±0.85 (13.3-22.6)	a	31.31±0.74 (27.3-35.8)	a	33.03±0.67 (30.1-37.3)	a
4	19.47±0.73 (15.3-23.8)	a	31.06±0.76 (25.8-34.4)	a	32.79±0.64 (28.3-35.4)	ac
5	20.98±0.68 (17.5-25.1)	a	27.46±0.64 (23.0-30.4)	c	30.18±0.47 (26.3-31.9)	c

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 2. Effect of rootzone construction on soil physical properties at 35-70 mm. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Rootzone	Bulk Density (g/cm^3)		Total Porosity (%)		Moisture Content -3 kPa (%)	
1	1.382±0.016 (1.28-1.48)	a*	47.34±0.56 (43.8-50.9)	a	16.56±0.65 (12.6-22.0)	a
2	1.498±0.025 (1.26-1.61)	a	45.47±0.91 (41.3-54.0)	a	39.72±0.38 (36.8-42.1)	b
3	1.406±0.012 (1.34-1.47)	a	46.83±0.43 (44.6-49.1)	a	10.60±0.21 (9.0-12.2)	c
4	1.388±0.012 (1.34-1.46)	a	47.12±0.44 (44.6-49.0)	a	15.43±0.55 (11.6-18.4)	a
5	1.373±0.011 (1.32-1.45)	a	47.63±0.41 (44.7-49.4)	a	15.96±0.57 (11.8-18.3)	a

Rootzone	Moisture Content -4 kPa (%)		Air-filled Porosity -3 kPa (%)		Air-filled Porosity -4 kPa (%)	
1	15.18±0.63 (12.0-20.6)	a	30.78±1.11 (22.5-38.3)	a	32.14±1.07 (23.9-38.9)	a
2	39.29±0.36 (36.6-41.5)	b	5.74±1.14 (2.8-17.2)	b	6.15±1.13 (3.3-17.4)	b
3	9.07±0.18 (7.8-10.3)	c	36.23±0.58 (32.4-39.0)	c	37.75±0.54 (34.2-40.2)	c
4	14.03±0.53 (10.2-16.9)	a	31.71±0.83 (27.4-37.0)	a	33.11±0.80 (28.9-38.4)	a
5	14.64±0.58 (10.7-17.0)	a	31.68±0.70 (28.2-37.5)	a	32.99±0.67 (30.4-38.2)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 3. Effect of rootzone construction on soil physical properties at 70-105 mm. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Rootzone	Bulk Density (g/cm^3)		Total Porosity (%)		Moisture Content -3 kPa (%)	
1	1.350±0.010 (1.29-1.41)	a*	48.49±0.34 (46.4-50.5)	a	16.95±0.33 (15.4-19.8)	a
2	1.443±0.016 (1.31-1.51)	b	47.55±0.60 (44.9-52.5)	a	39.93±0.50 (35.4-42.5)	b
3	1.358±0.010 (1.31-1.43)	a	48.50±0.38 (45.8-50.2)	a	10.57±0.52 (9.5-16.1)	c
4	1.337±0.011 (1.28-1.40)	a	48.95±0.39 (46.8-51.0)	a	13.9±0.37 (11.9-15.5)	d
5	1.330±0.011 (1.26-1.38)	a	49.28±0.42 (47.3-51.9)	a	16.11±0.62 (13.4-19.4)	a

Rootzone	Moisture Content -4 kPa (%)		Air-filled Porosity -3 kPa (%)		Air-filled Porosity -4 kPa (%)	
1	15.36±0.48 (11.8-18.7)	a	31.53±0.59 (26.6-34.2)	a	33.14±0.64 (27.6-35.5)	a
2	39.47±0.53 (34.8-42.0)	b	7.63±0.94 (4.0-17.1)	b	8.08±0.97 (4.0-17.7)	b
3	9.29±0.54 (8.2-15.1)	c	37.93±0.70 (31.9-40.1)	c	39.2±0.69 (33.0-41.3)	c
4	12.83±0.39 (10.4-14.8)	d	35.03±0.61 (31.6-37.7)	d	36.13±0.63 (32.7-38.5)	d
5	14.86±0.56 (12.3-18.4)	a	33.18±0.62 (27.9-35.2)	ad	34.42±0.57 (28.9-36.2)	ad

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 4. Effect of rootzone construction on soil physical properties. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Rootzone	Infiltration Rate (mm/hr)		ODR x 10^{-8} ($g/cm^2/min$)		Moisture Content 0-50 mm (%)		K_{sat} (mm/hr)	
1	64.57±3.12 (46.0-80.3)	a*	76.60±6.59 (54.3-122.4)	a	13.12±1.01 (8.48-18.35)	a	732±106 (296-1450)	a
2	0.429±0.219 (0.06-2.79)	b	75.0±13.30 (30.9-148.3)	a	28.57±0.82 (25.11-35.35)	b	239±119 (9-1372)	b
3	92.52±4.84 (68.9-116.3)	c	49.14±3.47 (36.6-69.2)	a	9.06±0.59 (5.93-12.14)	c	798±75 (377-1162)	a
4	76.71±4.60 (55.5-103.2)	a	71.94±5.78 (48.5-118.4)	a	13.94±1.52 (7.47-24.45)	a	918±145 (354-2083)	a
5	76.93±3.73 (53.4-99.3)	a	58.86±4.63 (38.8-90.3)	a	11.95±0.67 (7.75-14.66)	a	764±124 (210-1558)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 5. Effect of rootzone construction on soil physical properties. Values shown are the mean plus or minus one standard error with the range in brackets (2nd measurement).

Rootzone	Infiltration Rate (mm/hr)		ODR x 10^{-8} ($g/cm^2/min$)		Moisture Content 0-50 mm (%)	
1	69.99±6.95 (43.4-109.9)	acd*	50.68±3.56 (31.7-67.3)	ad	13.08±0.96 (7.4-17.9)	a
2	0.218±0.036 (0.060-0.402)	b	35.63±1.53 (27.4-42.3)	bc	24.67±0.37 (22.2-26.7)	b
3	86.18±6.60 (52.8-127.3)	c	34.65±3.32 (13.4-51.2)	c	9.23±0.77 (4.4-13.1)	c
4	56.87±3.26 (43.4-84.9)	d	46.20±2.92 (31.1-62.4)	bd	10.93±0.60 (8.5-15.6)	a
5	77.38±4.57 (52.4-104.3)	ac	47.73±2.27 (34.3-64.6)	d	12.13±0.71 (8.2-16.0)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 6. Effect of aeration treatment on soil physical properties at 0-35 mm. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Aeration	Bulk Density (g/cm^3)		Total Porosity (%)		Moisture Content -3 kPa (%)	
1	1.296±0.014 (1.21-1.41)	a*	50.77±0.43 (48.0-53.5)	a	25.71±2.45 (16.6-43.3)	a
2	1.282±0.013 (1.20-1.39)	a	51.14±0.43 (47.4-53.9)	a	25.40±2.57 (16.8-46.4)	a
3	1.272±0.032 (1.17-1.68)	a	51.67±1.05 (39.0-55.6)	a	26.13±2.12 (19.0-47.0)	a
4	1.275±0.013 (1.18-1.38)	a	51.36±0.47 (48.1-55.4)	a	25.89±2.22 (14.9-41.5)	a

Aeration	Moisture Content -4 kPa (%)		Air-filled Porosity -3 kPa (%)		Air-filled Porosity -4 kPa (%)	
1	23.95±2.55 (15.3-43.0)	a	25.06±2.47 (5.6-34.1)	a	26.82±2.56 (5.8-35.3)	a
2	23.57±2.62 (14.7-44.7)	a	25.75±2.69 (5.3-34.4)	a	27.55±2.75 (6.5-35.7)	a
3	24.29±2.19 (17.6-46.2)	a	25.58±2.28 (6.3-33.0)	a	27.39±2.36 (7.1-35.2)	a
4	23.95±2.38 (13.3-42.2)	a	25.49±2.21 (6.6-35.8)	a	27.41±2.35 (7.5-37.3)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 7. Effect of aeration treatment on soil physical properties at 35-70 mm. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Aeration	Bulk Density (g/cm^3)		Total Porosity (%)		Moisture Content -3 kPa (%)	
1	1.390±0.020 (1.26-1.54)	a*	47.59±0.68 (44.2-54.0)	a	18.92±2.74 (10.6-40.5)	a
2	1.422±0.017 (1.33-1.56)	a	46.41±0.44 (43.2-49.3)	a	19.85±2.87 (10.3-42.1)	a
3	1.405±0.020 (1.33-1.61)	a	47.03±0.53 (41.3-49.2)	a	19.69±2.65 (10.4-40.0)	a
4	1.421±0.017 (1.34-1.57)	a	46.47±0.47 (42.8-49.1)	a	20.14±2.82 (9.0-40.5)	a

Aeration	Moisture Content -4 kPa (%)		Air-filled Porosity -3 kPa (%)		Air-filled Porosity -4 kPa (%)	
1	17.75±2.84 (8.8-40.0)	a	28.67±2.70 (3.7-38.3)	a	29.83±2.78 (4.1-38.9)	a
2	18.63±2.96 (8.6-41.5)	a	26.57±3.14 (3.4-37.5)	a	27.79±3.23 (3.7-39.4)	a
3	18.46±2.77 (9.1-39.5)	a	27.34±3.03 (3.2-37.8)	a	28.55±3.15 (3.6-39.1)	a
4	18.93±2.93 (7.8-40.2)	a	26.33±3.16 (2.8-39.0)	a	27.54±3.26 (3.3-40.2)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 8. Effect of aeration treatment on soil physical properties at 70-105 mm. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Aeration	Bulk Density (g/cm^3)		Total Porosity (%)		Moisture Content -3 kPa (%)	
1	1.378±0.017 (1.26-1.50)	a*	48.04±0.49 (45.3-51.9)	a	19.95±3.06 (9.8-40.9)	a
2	1.361±0.013 (1.28-1.46)	a	48.69±0.30 (46.8-51.0)	a	19.99±2.85 (9.6-42.5)	a
3	1.352±0.016 (1.28-1.50)	a	48.99±0.46 (45.3-52.5)	a	18.88±2.81 (9.5-41.3)	a
4	1.366±0.015 (1.29-1.51)	a	48.43±0.37 (44.9-50.6)	a	19.54±2.76 (9.7-39.8)	a

Aeration	Moisture Content -4 kPa (%)		Air-filled Porosity -3 kPa (%)		Air-filled Porosity -4 kPa (%)	
1	18.61±3.21 (8.6-40.7)	a	28.09±3.13 (5.8-38.2)	a	29.41±3.27 (6.4-38.9)	a
2	18.85±2.90 (8.7-42.0)	a	28.69±2.97 (6.3-40.1)	a	29.85±3.03 (6.8-41.0)	a
3	17.85±2.89 (8.2-41.3)	a	30.11±3.01 (4.0-40.0)	a	31.15±3.09 (4.0-41.3)	a
4	18.51±2.83 (8.6-39.5)	a	28.89±2.99 (5.7-39.7)	a	29.91±3.07 (6.3-41.3)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 9. Effect of aeration treatment on soil physical properties. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Aeration	Infiltration Rate (mm/hr)		ODR x 10^{-8} ($g/cm^2/min$)		Moisture Content 0-50 mm (%)		K_{sat} (mm/hr)	
1	59.44±8.81 (0.07-113.6)	a*	70.41±6.87 (36.6-125.0)	a	15.27±2.23 (5.93-32.34)	a	576±110 (22-1450)	a
2	65.83±9.53 (0.11-116.3)	a	62.87±7.18 (30.9-138.9)	a	15.69±1.80 (7.75-29.63)	a	652±121 (9-1475)	a
3	67.91±9.66 (0.13-116.0.)	a	72.56±8.55 (34.8-148.3)	a	14.80±1.99 (7.35-27.70)	a	838±112 (116-1622)	a
4	55.75±8.36 (0.06-104.0)	a	59.41±5.70 (35.1-115.9)	a	15.53±2.03 (7.53-35.35)	a	695±127 (15-2083)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 10. Effect of aeration treatment on soil physical properties. Values shown are the mean plus or minus one standard error with the range in brackets (2nd measurement).

Aeration	Infiltration Rate (mm/hr)		ODR x 10^{-8} ($g/cm^2/min$)		Moisture Content 0-50 mm (%)	
1	60.61±9.10 (0.15-105.1)	a*	41.82±3.41 (13.4-67.0)	a	13.19±1.60 (5.7-25.0)	a
2	61.70±10.20 (0.10-123.0)	a	43.55±2.91 (28.4-67.3)	a	14.06±1.51 (8.1-26.1)	a
3	55.66±9.26 (0.08-127.3)	a	43.19±3.15 (22.8-65.5)	a	14.23±1.70 (4.4-26.7)	a
4	54.53±8.23 (0.06-95.9)	a	43.35±2.69 (30.3-65.7)	a	14.57±1.53 (8.2-25.4)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 11. Effect of rootzone construction on root weight at various depths. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Rootzone	0-50 mm (g/m^2)		50-100 mm (g/m^2)		100-150 mm (g/m^2)	
1	1085.5±51.9 (872.9-1376.0)	a*	101.08±9.15 (64.6-169.2)	a	55.56±4.62 (34.0-90.6)	a
2	1215.8±76.9 (932.0-1732.4)	a	52.12±4.00 (29.5-68.6)	b	37.66±4.39 (16.9-63.5)	a
3	1503.8±101 (716.9-1903.3)	b	109.79±8.09 (67.8-147.3)	a	60.20±4.77 (32.2-88.2)	a
4	1184.1±57.0 (953.8-1698.6)	a	87.53±5.44 (53.6-113.8)	a	56.46±8.29 (29.3-136.7)	a
5	1137.9±75.0 (781.3-1556.4)	a	106.50±8.96 (39.3-154.2)	a	56.97±5.42 (22.2-95.3)	a

Rootzone	150-200 mm (g/m^2)		200-250 mm (g/m^2)		0-250 mm (g/m^2)	
1	43.70±4.57 (22.2-67.6)	a	19.37±2.71 (10.4-39.1)	ab	1305.2±67.0 (1030.1-1684.1)	a
2	30.33±5.42 (12.8-72.3)	a	15.39±1.74 (9.6-33.6)	b	1351.2±75.6 (1055.4-1843.4)	a
3	42.71±3.03 (28.3-63.1)	a	31.31±3.84 (9.2-51.1)	a	1747.8±108 (861.9-2199.0)	b
4	41.97±3.69 (22.2-65.8)	a	21.47±1.96 (12.6-37.3)	ab	1391.5±61.6 (1150.9-1970.9)	a
5	40.64±5.16 (17.9-78.2)	a	24.54±4.49 (8.6-65.0)	ab	1366.5±85.1 (975.8-1759.9)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 12. Effect of rootzone construction on root weight at various depths. Values shown are the mean plus or minus one standard error with the range in brackets (2nd measurement).

Rootzone	0-50 mm (g/m^2)		50-100 mm (g/m^2)		100-150 mm (g/m^2)	
1	1350.8±69.3 (1000.2-1636.0)	a*	110.43±6.44 (74.9-143.4)	ac	49.43±4.03 (29.1-66.4)	a
2	1369.2±72.0 (1078.2-1796.3)	a	53.36±3.59 (25.9-67.0)	b	27.12±1.82 (10.8-34.8)	b
3	1698.7±85.4 (1189.6-2119.6)	b	128.78±9.00 (80.0-181.3)	c	46.71±5.24 (31.6-84.1)	a
4	1241.0±71.5 (816.7-1801.4)	a	90.93±4.61 (68.6-122.0)	a	44.20±4.26 (19.6-71.7)	a
5	1260.5±63.6 (877.8-1642.0)	a	101.62±8.56 (47.7-152.7)	a	51.66±4.65 (32.2-88.2)	a

Rootzone	150-200 mm (g/m^2)		200-250 mm (g/m^2)		0-250 mm (g/m^2)	
1	27.47±2.76 (12.4-40.1)	ab	15.64±2.78 (3.3-38.9)	ab	1553.8±75.6 (1171.9-1906.5)	a
2	21.22±2.09 (12.2-39.7)	a**	16.96±1.81 (7.9-27.5)	ab	1487.8±69.9 (1214.9-1920.6)	a
3	32.23±4.39 (11.4-64.6)	b**	23.14±3.16 (8.6-47.7)	a	1929.5±88.3 (1441.3-2343.8)	b
4	30.99±2.91 (9.2-42.6)	ab	21.35±2.38 (4.5-34.6)	ab	1428.5±76.2 (919.3-2003.5)	a
5	25.33±2.45 (13.2-41.3)	ab	12.61±1.56 (5.5-23.0)	b	1451.7±63.8 (1062.5-1795.3)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

** Significant different at the 0.1 level of probability.

Table 13. Organic matter content at various depths in relation to rootzone construction. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Rootzone	0-50 mm (%)		50-100 mm (%)		100-150 mm (%)		150-200 mm (%)	
1	4.81±0.18 (4.08-5.96)	a*	2.72±0.14 (1.99-3.92)	a	1.78±0.09 (1.36-2.41)	a	1.26±0.09 (0.55-1.56)	a
2	4.89±0.17 (3.96-5.94)	a	3.63±0.05 (3.38-3.82)	b	3.46±0.81 (3.03-4.05)	b	3.23±0.10 (2.75-3.68)	b
3	3.33±0.09 (2.95-4.15)	b	1.32±0.04 (1.08-1.50)	c	1.34±0.05 (1.01-1.61)	c	1.36±0.07 (0.98-1.72)	a
4	5.18±0.25 (3.85-6.95)	a	2.76±0.07 (2.52-3.36)	a	2.82±0.14 (2.03-3.92)	d	2.50±0.08 (1.98-2.84)	c
5	4.59±0.14 (3.79-5.29)	a	2.80±0.09 (2.25-3.41)	a	1.79±0.15 (1.08-2.76)	a	1.42±0.06 (0.84-1.66)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 14. Effect of aeration treatment on root weight at various depths. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Aeration	0-50 mm (g/m^2)		50-100 mm (g/m^2)		100-150 mm (g/m^2)	
1	1152.4±66.0 (716.9-1657.8)	a*	73.57±6.94 (32.6-115.7)	a	42.01±3.37 (16.9-58.0)	a
2	1233.4±71.6 (913.8-1776.8)	a	95.74±7.01 (39.3-147.3)	a	51.63±4.37 (29.3-81.9)	ab
3	1349.8±89.2 (781.3-1889.8)	a	97.69±8.43 (58.5-149.5)	a	61.32±7.28 (26.1-136.7)	b
4	1166.0±65.4 (872.9-1903.3)	a	98.6±10.0 (29.5-169.2)	a	58.51±4.53 (28.5-95.3)	ab

Aeration	150-200 mm (g/m^2)		200-250 mm (g/m^2)		0-250 mm (g/m^2)	
1	33.05±3.30 (15.7-60.9)	a	19.39±2.53 (8.6-40.3)	a	1320.4±66.3 (861.9-1841.3)	a
2	38.53±4.10 (17.9-65.4)	a	22.15±4.07 (8.8-65.0)	a	1441.5±82.2 (1066.8-2003.7)	a
3	40.86±3.96 (12.8-67.0)	a	21.25±1.88 (13.6-39.1)	a	1570.9±94.9 (1016.5-2199.0)	a
4	47.03±4.34 (18.3-78.2)	a	26.89±3.22 (12.2-51.1)	a	1397.1±74.2 (1030.1-2125.1)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 15. Effect of aeration treatment on root weight at various depths. Values shown are the mean plus or minus one standard error with the range in brackets (2nd measurement).

Aeration	0-50 mm (g/m^2)		50-100 mm (g/m^2)		100-150 mm (g/m^2)	
1	1377.9±87.5 (816.7-2088.0)	a*	91.45±9.25 (41.3-152.7)	a	38.43±3.40 (19.6-65.8)	a
2	1425.0±55.4 (1032.0-1754.2)	a	96.77±9.51 (41.8-181.3)	a	48.05±5.35 (24.2-88.2)	a
3	1391.2±77.2 (1052.7-2119.6)	a	107.6±8.44 (52.7-153.0)	a	50.29±4.01 (27.1-80.2)	a
4	1342.0±86.4 (877.8-2099.0)	a	92.27±8.10 (25.9-164.0)	a	38.51±3.42 (10.8-63.3)	a

Aeration	150-200 mm (g/m^2)		200-250 mm (g/m^2)		0-250 mm (g/m^2)	
1	24.8±3.17 (9.2-47.9)	a	15.85±2.20 (3.3-32.4)	a	1548.4±94.8 (919.3-2343.8)	a
2	28.38±3.34 (13.2-64.6)	a	18.07±2.60 (8.6-47.7)	a	1616.3±62.7 (1237.9-2131.8)	a
3	32.12±2.47 (13.4-44.8)	a	22.72±2.27 (9.0-38.9)	a	1603.9±81.4 (1214.9-2340.5)	a
4	24.49±1.76 (12.2-38.7)	a	15.12±1.79 (6.5-26.7)	a	1512.4±86.3 (1062.5-2315.5)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 16. Organic matter content at various depths in relation to aeration treatment. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Aeration	0-50 mm (%)		50-100 mm (%)		100-150 mm (%)		150-200 mm (%)	
1	4.32±0.17 (3.39-5.48)	a*	2.59±0.22 (1.15-3.82)	a	2.09±0.21 (1.01-3.52)	a	1.92±0.21 (0.98-3.52)	a
2	4.74±0.28 (2.95-6.95)	a	2.61±0.20 (1.40-3.81)	a	2.41±0.25 (1.35-4.05)	a	1.97±0.22 (0.84-3.56)	a
3	4.51±0.23 (3.14-5.96)	a	2.78±0.23 (1.08-3.92)	a	2.26±0.22 (1.17-3.64)	a	1.87±0.23 (0.55-3.68)	a
4	4.66±0.22 (3.20-6.43)	a	2.61±0.20 (1.25-3.82)	a	2.20±0.23 (1.13-3.75)	a	2.06±0.22 (1.03-3.65)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 17. Effect of rootzone construction on playing quality. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Rootzone	Clegg 0.5 kg 1st (gravities)		Clegg 0.5 kg 4th (gravities)		Clegg 2.25 kg (gravities)		Stimpmeter (m)	
1	116.3±7.2 (94.8-153.2)	a*	152.3±9.2 (132-200)	a	88.3±3.4 (77.8-108)	ab	1.73±0.04 (1.53-1.92)	a
2	109.2±3.9 (92.4-128.4)	a	135.5±4.7 (116-162)	a	84.0±1.3 (79.4-90.4)	b	1.59±0.06 (1.38-1.84)	a
3	121.3±6.2 (100-154.0)	a	161.8±7.7 (140-204)	a	97.5±2.5 (85.6-107)	a	1.72±0.06 (1.54-1.99)	a
4	112.6±5.8 (89.0-143)	a	148.2±8.3 (124-192)	a	87.2±3.5 (78.8-109)	ab	1.69±0.05 (1.46-1.95)	a
5	117.8±6.7 (96.6-154)	a	148.9±8.4 (116-193)	a	89.4±3.7 (75.4-109)	ab	1.74±0.06 (1.41-1.94)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 18. Effect of rootzone construction on playing quality. Values shown are the mean plus or minus one standard error with the range in brackets (2nd measurement).

Rootzone	Clegg 0.5 kg 1st (gravities)		Clegg 0.5 kg 4th (gravities)		Clegg 2.25 kg (gravities)		Stimpmeter (m)	
1	107.5±1.3 (101-113)	a*	138.0±1.1 (133-143)	a	86.8±1.0 (82.4-93.8)	a	1.79±0.03 (1.67-2.03)	a
2	95.6±2.3 (81.2-103)	b	112.2±3.1 (93.6-124)	b	80.7±1.3 (73.2-84.8)	b	1.81±0.06 (1.59-2.24)	a
3	120.6±3.0 (102-137)	c	162.2±3.5 (142-186)	c	98.8±2.2 (87.8-110)	c	1.71±0.02 (1.59-1.85)	a
4	107.5±2.0 (99.4-120)	a	139.9±2.1 (127-153)	a	86.9±0.6 (83.4-90.2)	a	1.78±0.03 (1.62-1.99)	a
5	110.1±2.5 (99.6-134)	a	138.1±1.5 (130-145)	a	87.2±1.0 (82.2-94.8)	a	1.78±0.04 (1.61-2.01)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

Table 19. Effect of aeration treatment on playing quality. Values shown are the mean plus or minus one standard error with the range in brackets (1st measurement).

Aeration	Clegg 0.5 kg 1st (gravities)		Clegg 0.5 kg 4th (gravities)		Clegg 2.25 kg (gravities)		Stimpmeter (m)	
1	123.1±7.1 (92.4-154)	a*	161.8±8.4 (135-200)	a	95.5±3.7 (80-109)	a	1.65±0.06 (1.41-1.99)	a
2	111.1±2.9 (94.8-126)	ac	144.8±4.1 (131-171)	a	87.8±1.7 (81.2-97)	ab	1.69±0.04 (1.42-1.85)	a
3	105.3±2.8 (89.0-120)	bc	135.0±3.5 (116-153)	b	82.4±1.6 (75.4-94)	b**	1.72±0.04 (1.51-1.91)	a
4	122.2±5.5 (103-154)	a	155.7±8.7 (116-204)	a	91.3±2.8 (79.4-107)	a**	1.72±0.07 (1.38-1.95)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.

** Significant different at the 0.1 level of probability.

Table 20. Effect of aeration treatment on playing quality. Values shown are the mean plus or minus one standard error with the range in brackets (2nd measurement).

Aeration	Clegg 0.5 kg 1st (gravities)		Clegg 0.5 kg 4th (gravities)		Clegg 2.25 kg (gravities)		Stimpmeter (m)	
1	111.0±2.9 (91.4-137)	a*	141.7±4.9 (106-186)	a	89.6±1.5 (82.6-105)	a	1.74±0.03 (1.60-2.03)	a
2	106.7±3.0 (81.4-130)	a	136.4±4.8 (93.6-172)	a	88.2±2.0 (73.8-108)	a	1.76±0.03 (1.67-2.12)	a
3	106.8±3.4 (81.2-134)	a	134.9±4.8 (93.8-168)	a	86.2±2.0 (73.2-104)	a	1.79±0.05 (1.59-2.24)	a
4	108.4±2.2 (93.8-127)	a	139.4±4.3 (112-169)	a	88.3±2.1 (77.8-110)	a	1.81±0.03 (1.66-2.01)	a

* Within each column, numbers with the same letter are not significantly different at the 0.05 level of probability.