PUTTING GREEN CHARACTERISTICS ASSOCIATED WITH SURFACE DEPRESSIONS CAUSED BY SELECTED FORMS OF TRAFFIC

BY GARY GENTILUCCI

A thesis submitted to the
Graduate School-New Brunswick
Rutgers, The State University of New Jersey
in partial fulfillment of the requirements
for the degree of
Master of Science
Graduate Program in Plant Biology.
Written under the direction of
Dr. James A Murphy
and approved by

Harry J. Motto
Bruce B. Clarke
Richard H. Hurley
James A Murphy

New Brunswick, New Jersey
October, 1997

ABSTRACT OF THE THESIS

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Thesis Director:

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The use of devices that assist a player's mobility during the playing of golf has introduced non-conventional forms of traffic on golf courses; the subsequent effect on playing surface quality is unknown. Objectives of this study were to i) evaluate the depth of depression caused by wheeled and foot traffic on golf putting greens, ii) assess testing procedures that might describe the ability of a golf putting green to bear traffic, and iii) examine edaphic properties of golf putting greens associated with surface depressions and the ability to bear traffic. Putting greens at twelve golf courses located throughout New Jersey were used as testing sites for traffic during 1996. A change in microrelief was used to measure the depth of depression occurring after 30 seconds of static pressure for each form of traffic. A Clegg Impact Soil Tester was used to measure surface hardness and a hand held penetrometer to measure surface strength of putting greens. Wheeled traffic produced greater depths of depression than foot traffic during the 1996 season. Putting greens studied separated into two distinct groups, i) high sand greens with organic matter levels below 2% and gravimetric moisture contents less than 27% at the 0 to 5-cm depth zone below the upper mat layer and ii) topdressed modified native soil greens having organic matter levels above 2% and gravimetric moisture content greater than 27%. The depth of depression caused by traffic on high sand greens was lower when surface hardness and strength were higher. Conversely, the depth of depression caused by each form of traffic on topdressed modified native soil greens did not change significantly over the range of surface hardness and strength measured. Greater depth of the upper mat layer was associated with greater depth of depression caused by traffic on high sand greens. Additionally, greater depth of the upper mat layer was associated with lower surface hardness on high sand greens. Greater surface strength was observed as the organic matter content of the upper mat layer increased. Therefore, the form of traffic as well as the edaphic conditions of the putting green being trafficked influences the amount of depression after a traffic event on golf putting greens.

ACKNOWLEDGMENTS

I wish to thank:

Dr. Bruce Clarke, Dr. Richard Hurley, Dr. Harry Motto for their insight and guidance in completion of my project. Bill Dickson and Joe Clark for their assistance at Horticultural Farm II. Margaret Secks, the other graduate students, and the crew for their help with the field work. Dr. James A. Murphy, my advisor, for four years of encouragement, mentoring, and growth that helped me become a more complete person. My friends and family for the essential part of life away from school and work.

My sincerest gratitude goes toward the United States Golf Association, the Golf Course Superintendents Association of America, and The Professional Golfers Association for their financial support of my graduate studies.

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INTRODUCTION

The game of golf was estimated to be played by twelve percent of people in the United States during 1990 for a total of 25 million active participants and surveys indicate the number of people playing is growing (Balough et al, 1992). The increase in play on golf courses has increased the pressure from stresses associated with traffic of turfgrass. The demand for high quality turfgrass surfaces for the playing of golf is increasing along with the games popularity.

Maintaining healthy turfgrass plants for putting green surfaces is of primary importance to golf course superintendents. The high quality of a putting green is only possible by intensive management. Considerable effort of turfgrass managers is directed towards cultural programs, soil modification, and drainage improvements which reduce the effects of traffic on golf putting greens. Traditionally turfgrass managers have limited the type of traffic allowed on golf putting greens to foot traffic and maintenance equipment. Golf carts are generally not allowed on putting greens and maintenance machinery used on golf putting greens is specifically designed to be light-weight with large contact areas and low contact pressures. Maintenance machinery is not operated on putting greens when conditions such as frost and excessive wetness or dryness make the turf more susceptible to damage

The Americans with Disabilities Act of 1990 was passed to eliminate barriers which limit accessibility to the disabled. The passing of the act increased awareness regarding the play of golf by disabled persons. The use of assistive devices for the playing of golf has introduced non-conventional forms of traffic on golf courses. The effect of assistive devices on playing surface quality, particularly of golf putting greens, is unknown.

The deformation of a putting green surface is potentially the most acute and troublesome form of damage associated with traffic from assistive devices. Wear is also a potentially acute form of damage associated with assistive devices; proper operation of the assistive devices (etiquette) can minimize this type of injury. Soil compaction is likely to be a minor issue considering the current level of traffic from assistive devices. If the use of assistive devices on golf greens increases, however, soil compaction may become an important chronic stress on putting greens.

The bearing strength of a golf green will determine the amount of deformation or rutting resulting from an applied force. The degree of rutting will be increased when bearing strengths are minimal or load pressures are high. The ability to quantify bearing strengths and study factors associated with different bearing strengths will help in understanding the effect of different forms of traffic on golf putting greens.

LITERATURE REVIEW

Turfgrass is used for functional, recreational, and ornamental purposes. Many outdoor sports and recreational activities utilize turfgrass as a playing surface. Injury and loss of turf may result from traffic during sporting activities on turfgrass playing surfaces. Playing surface quality may be reduced as a result of the injury to turfgrass plants from traffic.

Problems associated with traffic on turfgrass are classified into four types; soil compaction, wear, rutting or soil displacement, and divoting (Carrow and Petrovic, 1992). These four types of damage frequently occur in combination, although they can be separately described as follows. Soil compaction is defined as the pressing together of soil particles, resulting in a more dense soil mass with less pore space. Wear is the injury to a turfgrass plant from pressure, scuffing, or tearing directly on turfgrass tissues. Rutting or soil displacement is the displacement of soil particles due to a pressure, which results in a rut or depression. Divots are pieces of turf removed by the action of a golf club or other such object striking the turf.

These four types of damage frequently occur in combination, however at a given time, one type of stress usually represents the primary problem on the turf. The management of traffic related stresses include (i) minimizing or controlling traffic, (ii) increasing the traffic tolerance of the turf, and (iii) alleviating the unavoidable stresses caused by traffic.

Rutting and soil compaction

A rut is the result of a compactive force which physically compresses, displaces, and/or removes soil. Compaction and wear can occur at the same time as rutting, but are not necessarily always readily visible, whereas the major impact of rutting is an uneven turfgrass surface. The development of an uneven surface results from a concentrated pressure on a surface causing surface compaction, shearing deformation, or a combination of the two. The susceptibility of a turf soil to rutting is a function of similar factors affecting compaction: soil texture, soil strength, soil moisture, and the type of traffic (Carrow and Petrovic, 1992).

The prevention of rutting and soil displacement is accomplished by maintaining a firm surface that will adequately bear the expected traffic (Carrow and Petrovic, 1992). The bearing strength of a surface will determine when deformation of the surface will occur. Bearing strength is most often described as the amount of sinkage present after a force is placed on a surface. The forces exerted by vehicular and foot traffic must be met by the bearing strength of a surface to prevent the development of rutting.

Sources of rutting and soil compaction

The two predominant types of traffic on golf putting greens are foot and vehicular traffic. Vehicular traffic is usually restricted to lightweight maintenance equipment designed to reduce the amount of soil compaction or chance of rutting. Compaction of soil may involve soil displacement resulting in footprinting or rutting of the soil by human or wheeled traffic, respectively (Beard, 1973). Turfgrass management practices to maintain turfgrass health and putting surface quality are continually required to relieve the stress placed on turfgrass plants from traffic. Often daily movement of the golf cup is used to control the flow of foot traffic across a putting green. The traffic pattern of maintenance equipment is varied daily to minimize the development of ruts.

Foot traffic. The degree of soil compaction and development of foot printing from foot traffic is influenced by the (i) speed of the traffic event, and (ii) the magnitude of the compacting force (surface contact area and weight) (Carrow and Petrovic, 1992). The pressure exerted by foot traffic is greater under a running or walking athlete compared to pressure exerted under static conditions (van Wijk et al., 1977).

A larger contact area for the same load will reduce the static pressure exerted on a surface. Watson (1961) described a 90-kg person wearing either football shoes or street shoes as an example to demonstrate the effect of surface contact area on pressure exerted on a surface. The football shoes had a contact area of 4.45-cm^2 and a 1-MPa static pressure compared to 109-cm^2 of contact area for the street shoes and 0.04-MPa of static pressure.

The study of foot traffic on golf putting greens has concentrated on putting green surface quality after traffic by different shoe sole designs. In 1958, a newly introduced 'ripple sole' shoe was compared to traditional metal spikes and lug soles (Ferguson, 1958; Ferguson, 1959). Wear damage to the turf surface was measured by turf density ratings and quadrant counts of living turfgrass present for the trafficked areas. Soil compaction was compared by measuring the amount of deformation occurring across the path of travel. The 'ripple sole' shoe did not produce any more damage (wear and compaction) compared to the traditional spike or lug sole.

A more recent study examined several multi-stud spikeless shoe sole designs and conventional spikes. Gibeault et al. (1983) studied the affects of four shoe types under wet and dry playing conditions. Turf damage was assessed through visual ratings of wear and a subjective putting quality rating. They found that under all conditions the greatest and longest lasting damage resulted from the spiked shoe.

Wheeled traffic. Wheeled traffic on turfgrass exerts three primary types of forces on the soil including (i) the vertical force due to the dynamic load of the wheel, (ii) the sheer stress resulting from tire slippage, and (iii) vibration from the engine transmitted through the tire (Soane et al., 1981). The magnitude of these forces depends on interactions between the characteristics of the surface and the wheel involved. Pressure distribution in the soil under tires is a function of the pattern of pressures on the surface and the physical characteristics of the soil (Soehne, 1958).

Air inflated tires follow the general rule that the pressure exerted on the surface is approximately equal to the inflation pressure (Hakansson et al., 1988). A change in either the inflation pressure or load will result in a change of the contact area size. Increasing the vertical load on a pneumatic tire will result in flattening of the tire and contact area will be increased allowing the average surface pressure to remain the same. If the load on the tire is constant and the inflation pressure is reduced, the tire will flatten to increase contact area (Chancellor, 1976).

The complex interactions of surface conditions and tire characteristics can cause actual surface pressures to deviate from the value of inflation pressure. The distribution of surface pressure within the contact area is not always uniform (Soehne, 1958). The stiff wall of an inflated tire will transmit some forces directly to the ground and concentrate surface pressure around the edge of the tire-surface contact area (Gill & Vanderberg, 1967). If a soil is very soft, the soil near the front of the tire-soil contact area does not have enough strength to compress the tire against the inflation pressure and surface pressure in that location will be below inflation pressure (Chancellor, 1976).

Tire tread design will affect surface contact area and the pressure exerted on a surface. Lugged or knobby tires have less contact area than smooth tires of the same diameter and width, and will have increased surface pressure at the lugs compared to inflation pressure. Turf maintenance equipment with smooth "turf type" pneumatic tires generally apply 0.03- to 0.05-MPa static pressure (van Wijk et al., 1977).

Surface pressure applied by rigid wheels is strongly affected by the depth the wheel sinks into a soil; as a wheel presses into a soil more contact area is created to distribute the load (Chancellor, 1976). A firm surface trafficked by a rigid wheel will have a smaller contact area than the same wheel load on a softer surface. If a load is increased, the tendency is for the wheel to sink more deeply, spreading the load over a larger contact area. The pressure distribution is not uniform under a rigid wheel; pressures under the edge of the wheel are less than those under the center (Liston & Martin, 1968).

The pressure exerted on a surface by a traffic event will distribute stresses through the soil profile below. Most pressure distributions resulting from traffic on turfgrass surfaces occur in the upper 8-cm of soil (Beard, 1973). Burton and Lance (1966) studied the affects of golf car traffic on bermudagrass turf, and found that soil physical properties were affected in the upper 10-cm zone. The physical properties in the upper 3-cm of a soil below Kentucky bluegrass was altered by compaction treatment that simulated foot traffic and turf equipment, whereas the 3- to 6-cm zone changed very little (O' Neil and Carrow, 1983).

The pattern of surface pressure determines how the pressure is transferred within a soil (Chancellor, 1976). Pressure distributions in soils under a concentrated load have been described by a set of equations known as the *Boussinesq* equations (Hillel, 1980). The equations are intended for uniform elastic materials and disregard horizontal components of stress placed on a surface.

Chancellor (1976) describes a few interesting principles determined by the *Boussinesq* theory. The contact pressure will be greatest directly at the surface below a tire and gradually decrease with depth. At any given depth, the pressure is maximal directly under the center of the loaded surface area and decreases toward the spreading edges. Pressures applied to an area on a surface affects a much larger area within the soil. Increasing the surface area to which pressure is applied increases pressure within the soil, even though surface pressure is not increased.

Surface pressure can apply forces to a soil which results in the development of a rut. Smith and Dickson (1990) compared compactive efforts on the dimensions of rutting for agricultural tires. They found an increase in ground pressure, achieved by increasing the tire inflation pressure, resulted in an appreciable increase in the rut cross-sectional area and depth. The amount of contact pressure determines the degree of surface compaction, whereas the depth of soil compaction is more dependent on the total load (Porterfield and Carpenter, 1986; Taylor and Burt, 1987). Tire sinkage depth has been used as a measure of the depth at which traffic caused compaction (Adam and Erbach, 1995). They described an equation that related tire sinkage depth with the depth to which bulk density of the soil increased.

The operation of wheeled vehicles influences the pressures exerted on a surface. The compaction of a soil increased as the speed of wheeled traffic decreased (Stafford and Mattos, 1981). They found that shear strain-induced compaction from wheel slip at lower speeds increased the compacting effort. The distribution of a load on a wheel can shift with stopping, starting, and turning of vehicles, concentrating higher pressures on a smaller contact area of the surface. Carrow and Johnson (1989) found that sharpness of turns was more important than tire design on the amount of wear for bermudagrass turf.

Surface and soil conditions affecting compaction and rutting

The degree of surface compaction and rutting is dependent on the magnitude of the forces exerted by the traffic and the conditions of the surface and soil being trafficked. The problems of rutting and soil displacement occurs most often on wet, fine-textured soils (Carrow and Petrovic, 1992). Soil under these conditions is susceptible to compaction that allows a rut to develop and have a low shear strength allowing for soil displacement.

Soil moisture. The resulting compaction of a soil, for a given amount of pressure, is a function of soil moisture content (Hillel, 1980). For a given compacting effort, the attainable bulk density of a soil will increase with increasing soil wetness. As soil wetness increases, the soil will reach a peak called maximum density at a wetness called optimum moisture, beyond which the density achieved from a compactive effort will decrease (Hillel, 1980). Akram and Kemper (1979) compacted a wide variety of soils ranging from silty clays to loamy sands. They found that the soils when compacted at water contents around field capacity, resulted in maximum bulk densities and minimum infiltration rates.

Soil trafficked by smooth pneumatic tires had the greatest increase in density to occur when soil moisture content was highest (Gill & Reaves, 1956). They found a dry soil condition resulted in more compaction at the surface compared to deeper depths. They also found that a dry soil had a higher contact pressure compared to a wet soil, the wet soil increased the contact area therefore reducing the contact pressure compared to the dry soil. Swartz and Kardos (1963) evaluated sand-soil-peat mixtures for the effects of compaction on physical properties. Physical properties including percolation rate and aeration porosity were adversely effected at a high moisture content compared to compaction at lower moisture levels.

Moist soil can exhibit relatively unstable structure, which under pressure may result in structural degradation and shearing deformation (Chancellor, 1976). Shear resistance decreases with increasing soil moisture content for a sand amended with organic matter ranging from 0.4 to 8.6% by weight (van Wijk and Beauving, 1980). Lowest amounts of compaction for the sand mixtures occurred when shear resistance of the sand mixtures was greatest and moisture content were the least. They concluded that water was acting as a lubricant enabling particles to pack more closely together at higher moisture contents.

Soil texture. The ability of a soil to compact depends greatly on its texture (Beard, 1973). Course textured soils are high in sand content, while fine textured soils have a relatively high amount of particles in the silt and clay size fraction. The adverse effects of compaction on soil physical properties are less evident on sands than fine textured soils (Beard, 1973). Coarse textured soils (sands) may compact but the bridging between hard sand particles prevents the elimination of many of the larger pores (Carrow and Petrovic, 1992). As sand content increased from 69 to 93% for soil mixtures with varying proportions of soil and organic matter, the degree of compaction was reduced (Taylor & Blake, 1981). They attributed the decrease in compaction to sufficient amount of sand present for bridging between sand particles forming a rigid matrix resistant to compaction.

The particle size distribution of a soil affects the degree of compaction for the soil. Particle size distribution curves indicate the accumulated percentage of soil particles over a range of diameter sizes. The shape of the curve indicates the distribution of particles present in a sample. Poorly graded soils contain the majority of particles in one or several distinct sizes, which results in a step-like curve. Well graded soils have a uniform distribution of sizes with near equal amounts of particles indicated by a smooth curve. A narrow particle size distribution has the majority of particle separates fall within a small range, resulting in a steep curve. A wide particle size distribution will have a more flattened curve indicating a broad range of particle sizes.

A narrow particle size distribution can minimize soil compaction (Taylor and Blake, 1979; 1981). A wide range of particle size allows for the spaces between particle and aggregates to be filled with smaller particles, which results in a high bulk density. Particle size distribution curves are often developed for the sand fraction of soils, but curves can be built to include the silt and clay fractions. Soils with low sand content, < 50%, exhibit the same increases of densities with wider particle size distributions as those found with high sand content (Chancellor, 1971). A wide particle size distribution will have more contact between particles than a narrow distribution, therefore the resistance to shear will be greater for a wide particle size distribution compared to a narrow size distribution (Harris, 1971).

The organic matter content of a sand is important in the development of rutting and soil displacement. An increase in organic matter content of a sand increased the penetration resistance found with a cone penetrometer (van Wijk and Beuving, 1980). They also found that a compactive effort to increase soil strength was more effective in sands that had a higher organic matter content. They concluded that increased levels of organic matter for sands increased the strength measured by penetration resistance, and less rutting and soil displacement were associated with the increased strength.

Turfgrass presence. Turfgrass root systems contribute to soil strength and, thus, influence the tendency of rutting and soil displacement (van Wijk and Beuving, 1980). They found that sands with turfgrass root systems increased the penetration resistance compared to bare sands, especially when organic matter content was low. The increased penetration resistance was attributed to the root system hindering the lateral displacement of the sand.

Gibbs et al. (1989) found surface stability on sand rootzones could be accounted for by changes in root organic matter. Surface stability was estimated by traction measurements made with a studded disc torque wrench. An increase in root organic matter was accompanied by an increase in traction, the lack of cohesion of sand in the absence of roots resulted in lower traction. Traction values on sand without roots were affected by moisture content. Increased traction values were found as the matric potential of a sand increased from - 40 to 0 kPa.

The above ground parts of turfgrass plants can dissipate part of the forces placed on a surface (Beard, 1973). Surface hardness measured by peak deceleration was lower for turf covered soil mixtures compared to bare soil mixtures (Henderson et al., 1990).

Climatic conditions. Climate conditions can cause a turfgrass surface to be susceptible to surface compaction and lateral shearing. A weak, wet surface layer often results during times of high rainfall (Boekel, 1980). When precipitation exceeds evaporation from a soil, increased levels of moisture occur in the soil. The stability of the surface is low and development of a rut is more likely during these wet conditions. Partially frozen soils where the soil surface is thawed and the soil below is frozen are highly susceptible to damage from traffic (Beard, 1973).

Surface characterization of turfgrass surfaces

Research studying turfgrass surfaces has been dominated by measurements of turfgrass plant and rootzone characteristics (Bell and Homes, 1988). Turfgrass plant factors studied include species, cultivar, biomass, density, ground cover, height of cut, and root biomass. Rootzones of sport surfaces have been characterized through measurements of moisture content, infiltration rate, and porosity. While these measurements are critical for understanding turfgrass surface characteristics they are not of direct importance to a player (Bell et al., 1985).

Playing quality is the main factor by which athletes judge sports turf surfaces. The playing quality of a sports surface is controlled by the physical properties of both the immediate surface layer and the underlying material (Bell et al., 1985). Playing quality has many components which can fall into two broad groups: (i) interactions between the ball and the surface and (ii) interactions between the participant and the surface (Bell et al., 1985).

Objective measurement of the interactions between the ball and a playing surface can be accomplished through ball rebound and ball roll measurements (Canaway and Baker, 1993). The measurements of surface hardness and traction can quantitatively characterize the interactions between a player and the surface (Canaway and Baker, 1993). These objective assessments should be correlated to players' opinions for a meaningful interpretation (Baker and Canaway, 1993).

The playability of a field determines when surface conditions are suitable for participation in a particular sporting activity. Quantitative methods for determining the playability of a field (especially soccer) has been studied by the Sports Turf Research Institute (Carrow and Weicko, 1989). The research has been directed toward developing a series of reproducible measures to assess the suitability of a playing surface for a given sport. Previously mentioned testing procedures including ball bounce, ball roll, traction, and impact severity were used to determine if a field was acceptable for play. The suitability of a playing surface depends on the sport being played and the level of competition (Carrow and Weicko, 1989).

Surface hardness. Surface hardness is a measurement of the shock-absorbing properties of a surface. Impact resistance or impact absorption characteristics are measured to determine surface hardness. Impact absorption has been assessed by measuring the peak deceleration of a moving body as it comes in contact with a surface (Clegg, 1976).

A portable device, known as the Clegg Impact Soil Tester (CIT), was developed to measure the hardness of road surfaces in Western Australia by Clegg (1976). The device provides a rapid measurement of the peak deceleration, in gravity units, when an impact hammer is dropped on a surface from a known height. Different hammer weights are available to approximate the type of impact being studied. This device has been used to measure and compare the hardness of turfgrass surfaces (Lush, 1985; Bell and Homes, 1988; and Rogers et al., 1988).

Turfgrass cricket pitches were assessed for surface hardness using the Clegg Impact Soil Tester (Lush, 1985). The 0.5-kg weight hammer was dropped from a height of 0.3-m and hardness values were compared to the rebound heights of cricket balls dropped from 4.6-m above the pitch. Correlation between impact values and ball rebound heights were statistically significant on both new and old cricket balls having coefficients of determination (r^2) of 0.75 and 0.85, respectively.

Performance criteria was developed based on surface hardness for soccer fields in England (Bell and Homes, 1988). Playing quality was determined through surveys of opinions by athlete following soccer games. The playing quality was then compared to quantitative tests including surface hardness. Surface hardness was measured by peak resistance values of the CIT with a 0.5-kg hammer when dropped from a height of 0.3-m. The surface hardness values were found to relate well to players' perceptions of playing quality. Surface hardness values between 10- and 100-g had responses indicating that hardness was acceptable, with values of 20- to 80-g being preferred.

High school athletic fields in Pennsylvania were evaluated for relationships between surface hardness, soil properties, and maintenance practices (Rogers et al., 1988). Surface hardness values were taken using the

CIT dropped from a height of 0.46-m. They found factors affecting surface hardness included soil moisture, bulk density, and turf cover. They also compared surface hardness values of the 0.5-kg hammer with values obtained using the 2.25-kg hammer. Impact values for the 0.5-kg hammer followed the same pattern as those for the 2.25-kg hammer, but the 0.5-kg hammer had higher impact values compared to the 2.25-kg hammer. The higher values for the lighter hammer were associated with a faster stopping time (greater deceleration) when compared to the heavier weight hammer.

Turfed racing tracks for horses were monitored for surface hardness using the 0.5-kg CIT (Sifer and Beard, 1992). They built a set of performance criteria relating peak deceleration with turf-soil status. Acceptable racing conditions were associated with values between 30- to 110-g, while good racing conditions with low injury potential had values fall between 50- and 90-g. Unacceptable conditions with high injury potential were associated with soft values below 30-g and excessively firm conditions with values above 110-g.

Root zones of golf greens were measured for surface hardness with the CIT by Baker and Richards (1991). They found different compositions of sand type and mixing ratio affected surface hardness when measured with the 0.5-kg hammer dropped from 0.3-m. They found that under dry conditions a pure sand mix had consistently lower hardness values compared to mixtures of sand and soil. Hardness patterns were reversed under wet conditions; the pure sand green had the highest hardness values, whereas hardness decreased as the proportion of soil in the mix increased. A wide range of sand particle size caused inter-packing of particles resulting in greater hardness values in the sand.

Soil strength. Soil strength is the ability of a soil to resist an applied force, or the capacity of a soil to withstand deformation. Soil strength is often measured as the resistance which must be overcome to cause physical deformation of a soil. A cone penetrometer is one instrument used to measure soil strength. A cone penetrometer measures the force required to penetrate a soil with a cone shaped probe.

The penetration resistance was measured for the upper 2- to 3-cm of a turf surface with a cone penetrometer (van Wijk and Beuving, 1980). They assessed the quality of sports fields by measuring the bearing strength of the surfaces. The bearing strength was determined by pressing a heel into the surface and judging the resulting damage. They determined that penetration resistance was a measurable and reproducible criterion for determining the playing conditions of grass sports fields in the Netherlands. A penetration resistance above 13 kg cm^{-2} measured by a cone penetrometer for the upper 2- to 3-cm of a turfgrass surface was correlated with the ability to withstand intensive play without serious deformation.

Field et al. (1993) described an impact penetrometer technique for assessing the playability of turfgrass horse racing tracks. The impact penetrometer drops a 1-kg weight from a height of 1-m and the depth of penetration is recorded. Racetimes for a particular class of horse were compared to penetrometer readings for several racetracks in New Zealand. They found that penetrometer readings correlated well with racetimes for individual racetracks, but varied between racetracks. A method was described to allow individual racetrack penetrometer readings to be adjusted to a universal scale.

Ball roll. The measurement of ball travel has been used to quantify the playing quality of turfgrass surfaces. The United States Golf Association developed the stimpmeter to measure the 'speed' of putting greens (Radko, 1980). The stimpmeter quantifies putting green speed by measuring the distance traveled by a golf ball.

Footprints of several different shoe types were found to not interfere with golf ball travel across golf greens (Ferguson, 1958). Ferguson (1958) noted that to attain uniformity in direction and distance of roll, the ball must be released in the same manner. An unpredictable path of travel would result if side spin occurred during release of the ball.

A method for measuring ball roll on small plots for research was developed by Gaussoin et al. (1995). Three stimpmeters were fabricated identically to the USGA stimpmeter, except for the location of the ball release notch. The modified stimpmeters had ball release notches located 57-, 38-, and 19-cm, rather than at 76-cm from the beveled end. They found the shortened stimpmeters were effective in measuring golf ball rolling distances.

Microrelief measurements of surfaces

Surface relief measurements of agricultural fields have been made using various techniques. Early measurements to quantify surface roughness in erosion studies and soil physical characteristics in tillage studies included point gauge methods (Kuipers, 1957; Burwell et al., 1963). The point gauge instrument aligns and lowers pins to contact a surface. A scale board behind the pins is used to measure the relative heights of the pins. Kuipers (1957) measured the height of needles as they fell across a recently tilled soil and used the standard deviation of the heights as an indicator of the roughness of the soil surface.

More recently laser techniques have been developed to measure surface roughness (Romkens et al., 1986; Huang et al., 1988). The micro-reliefmeter is a laser probe which is moved along a transect by a microprocessor-based motion control device. Data acquisition involves computer hardware that determines the vertical and horizontal coordinates by measuring the voltage output of the laser instrument.

The main objective of both of these techniques is to have an accurate and reproducible method for determining the contour of a surface. These techniques have their limitations. Point gauge measurements can damage the surface being measured as the probes often penetrate into soft soil surfaces (Romken et al., 1986) Laser measurements of microreliefs often require considerable setup time and expensive equipment.

Thatch / mat characteristics

Thatch is defined as a tightly intermingled layer of dead and living stems, leaves, and roots that accumulate between the green vegetation and the soil surface (Beard, 1973). Mat is defined as partially decayed thatch with intermixed sand or soil as a result of topdressing, cultivation, and the activity of soil flora and fauna (Beard, 1973). Mat usually occurs directly below the thatch and immediately above the original soil surface. Thatch results from an imbalance between accumulating and decomposing processes acting on surface organic (plant) debris that develops as a turf grows (Beard, 1973).

Thatch and mat layers have been quantified through several different techniques. Thatch and mat thickness was determined by measuring the distance from the mat and soil interface to the green vegetation (White & Dickens, 1984). The demarcation between thatch and mat layers were made visually; when the separation between layers was not readily visible, physical separation of the two layers was accomplished by teasing the friable mat layer from the core. The thatch was identified as the tightly intermingled layer of living and dead grass tissues that remained after pressing the sample together between the thumb and forefinger . They found that the rate of thatch development varied for different cultivars of bermudagrass, while cultural treatments affected thatch accumulation similarly for all cultivars.

The amount of accumulated thatch and mat was reported as percent organic matter content by Carrow et al. (1987) for bermudagrass turf. Roots and soil beneath the thatch/mat layer and shoot material above the thatch were removed, the difference between dry weight at 100° C and ash weight at 600° C for the sample was determined to be total organic matter content. Sand topdressing reduced thatch by 44 and 62% for one and two yearly applications, respectively.

The amount of compression has been measured to characterize thatch presence on turfgrass surfaces. A device called a "thatchmeter" was designed to rapidly determine the compression of thatch from bermudagrass greens under two different bearing pressures, 7.3 g cm^{-2} and 570 g cm^{-2} (Volk, 1972). Volk (1972) found significant and positive regression for the amount of compressibility (mm) with both measured thickness and weight of thatch. Compression measurements were taken in a similar fashion for a creeping bentgrass putting green constructed to USGA specifications to determine the accumulation of thatch and organic matter (Callahan et al., 1997). They found compression measurements correlated positively with thatch thickness measurements and were appropriate for measuring the build up of organic matter at the surface of turf.

Summary

Wheeled and foot traffic exert pressures onto a surface and the pressure is distributed through the soil below. The pressure exerted on the surface by traffic may cause deformation of the surface. The measurement of microrelief on a golf putting green would allow the evaluation of the amount of depression caused by different forms of traffic. Surface hardness and soil strength can characterize a putting green surface. The characteristics of hardness and strength could be related to the degree of depression. Furthermore, edaphic properties can be determined for different putting greens and related to the amount of depression and quantified surface characteristics.

The objectives of this thesis were to 1) evaluate the depth of depression on golf putting greens for different forms of traffic, 2) assess testing procedures for describing the ability of a golf putting green to bear traffic, and 3) examine edaphic properties of golf putting greens associated with the ability to bear traffic.

MATERIALS AND METHODS

Putting greens at twelve golf courses located throughout New Jersey were used as testing sites from March through October 1996. Superintendents at each golf course were asked to identify one putting green to represent the putting green construction type located at their golf course. Additional greens were used at one golf course, if more than one green construction type was available. A relatively flat area approximately 35 m^2 of each green was selected and used for study on subsequent evaluation dates.

Initial evaluation of each putting green included identification of turfgrass species present, height of cut, and age (Table 1). Topdressing material at each location was sampled and analyzed for organic matter content by the wet combustion technique (Walkley and Black, 1934). Sand particle size distribution at 2000, 1000, 500, 250, 106, 53 µm, and pan was determined for topdressing materials using a sieve shaker. Fineness modulus and a uniformity coefficient was determined for each topdressing material based on particle size distribution curves (Blake, 1980).

Edaphic features associated with each green of study were sampled during October 1996. Ten 2-cm diameter samples were taken from the 0- to 15-cm depth. The shoot tissue was removed from the sample by cutting the plants at the base of the crown. The profile was separated into upper mat, lower mat, and a base layer using visual techniques similar to Ledeboer and Skogley (1967). The upper mat was considered the layer containing less decomposed,

Table 1. Characteristics of golf course putting greens and topdressing material used on the putting greens monitored through the 1996 growing season for surface hardness, surface strength, and ability to bear traffic.

Construction Type and Location	Green	Age	Height of cut	Turfgrass Species	Current Topdressing		
					OM†	C_u‡	FM§
		yrs	mm		%		
High Sand Greens							
Canoe Brook CC	11th	2	4.0	Bentgrass	0.0	2.6	1.8
Fiddlers Elbow Golf & CC	Practice	8	4.8	Bent/Poa	0.0	2.8	1.4
Montclair GC	5th	3	3.2	Bentgrass	0.5	2.5	1.6
Metedeconk National GC	19th	10	4.0	Bentgrass	0.5	2.8	2.0
Woodbury CC	1st	4	3.8	Bentgrass	0.0	1.7	2.0
Galloway National GC	17th	2	4.0	Bentgrass	0.5	2.4	1.8
Galloway National GC	18th	2	4.0	Bentgrass	0.5	2.4	1.8
Blue Heron Pines GC	1st	4	3.8	Bentgrass	0.5	2.0	1.9
Topdressed Modified Native Soil Greens							
Canoe Brook CC	13th	75	4.0	Bent/Poa	0.0	2.6	1.8
Fiddler's Elbow Golf & CC	12th	23	4.8	Bent/Poa	1.0	2.1	1.7
Montclair GC	18th	60	3.2	Bent/Poa	0.5	2.5	1.6
Plainfield CC	5th	45	3.2	Bent/Poa	0.0	2.4	1.4
Springdale GC	12th	75	4.0	Bent/Poa	2.5	2.5	2.0
Tavistock CC	4th	25	4.0	Bent/Poa	0.5	2.4	1.8
Ramblewood CC	9th	25	4.0	Bent/Poa	3.5	2.1	2.0
Pine Valley GC	12th	80	3.2	Bent/Poa	0.8	1.6	1.8

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† Percent organic matter determined by the Wakely-Black procedure.

‡ Coefficient of uniformity.

§ Fineness modulus of particle size distribution.

more fibrous plant material mixed with topdressing. The lower mat was the zone of more highly decomposed and less fibrous plant material combined with topdressing. The upper level of the base layer was identified as the point where the rootzone material used in the original green surface construction was first observed.

Upper mat samples were measured for thickness (three measurements per samples) under compression with a 100-g mass. Upper mat samples were dried at 105° C, weighed, and ashed at 600° C to determined organic matter content (Table 2). Soil textural analysis was determined by the hydrometer method on a bulk 0- to 5-cm sample below the upper mat layer (Gee and Bauder, 1986) (Table 2).

Golf putting green surface characteristics

Evaluation of surface hardness and strength for each putting green took place from April to September 1996 on approximately a monthly basis. The Clegg Impact Soil Tester (2.5-kg hammer dropped from a 46 cm height) was used to measure surface hardness at twelve positions on each green and averaged for a daily reading (Clegg, 1976). Surface strength was measured with an Eijkelkamp 6.06 type IB hand penetrometer using a 100 N compression spring and 1/4-cm^2 cone base area. The resistance to penetration was recorded for the 0- to 2.5-cm depth at 12 locations on each green and averaged.

Immediately after measurements of surface hardness and strength, six 0.95 cm diameter samples were taken from the 0- to 5-cm depth below the turf

Table 2. Edaphic characteristics of golf course putting greens monitored through the 1996 growing season for surface hardness, surface strength, and the ability to bear traffic.

Construction Type and Location	Upper Mat Layer Depth	BD†	OM‡	0 to 5 cm Depth Below Upper Mat Sand	Silt	Clay	OM	Depth to Base§
	mm	g m^{-3}	%	--------- % --------				mm
High Sand Greens								
Canoe Brook CC	18	0.86	7.3	98	0	2	0.8	18
Fiddlers Elbow Golf & CC	13	1.10	5.4	100	0	0	1.9	28
Montclair GC	13	0.89	9.3	100	0	0	0.4	14
Metedeconk National GC	11	0.92	6.7	96	3	1	1.2	41
Woodbury CC	8	1.08	6.6	97	0	3	1.4	15
Galloway National GC	11	0.74	13.9	100	0	0	1.6	21
Galloway National GC	12	0.76	13.9	100	0	0	1.1	20
Blue Heron Pines GC	11	0.80	7.7	97	2	1	1.0	34
Topdressed Modified Native Soil Greens								
Canoe Brook CC	10	0.94	9.2	84	12	4	6.2	80
Fiddler's Elbow Golf & CC	11	1.03	7.4	89	8	3	5.4	63
Montclair GC	9	0.67	18.0	87	12	1	4.7	100+
Plainfield CC	10	1.21	5.0	88	10	2	4.5	76
Springdale GC	9	1.01	11.7	83	12	5	7.3	100+
Tavistock CC	16	0.84	11.9	93	4	3	7.9	100+
Ramblewood CC	9	0.94	15.6	84	12	4	6.8	90
Pine Valley GC	-	-	-	93	4	3	3.8	-

† Bulk density.

‡ Percent organic matter determined by the Walkley-Black procedure.

§ Distance from putting green surface to the material used to construct original green rootzone.

\- Sample not taken

surface and dried for 24-h at 105° C to determine gravimetric moisture content. Soil temperature was recorded for the 5 cm depth of each green using a ReoTemp soil thermometer with a range of -4 to 71° C.

Evaluation of traffic and disruption of golf putting green

Microrelief measurements. The depth of depression and degree of rebound caused by traffic was determined by measurements of microrelief. Microrelief measurements were made using a depth dial gauge micrometer. Two wooden blocks (4 x 4 x 2 cm) were fixed to the turf surface and provided the base for an aluminum bracket that held a depth dial gauge (Fig. 1). The two wooden blocks were fixed to the turf surface by 6 cm long spikes driven through the blocks. Both spikes extended 1 cm above the top of the blocks. The spikes secured the blocks to the turf surface and created a peg to fix the position of the aluminum bracket. The bracket was made from 90 degree angled aluminum with 3 cm sides and a 4 mm thickness. A series of 6 mm diameter holes was drilled at 1 cm intervals on center of one side of the aluminum bracket (61-cm length) over a length of 46 cm. The 90 degree angle was used to eliminate flexing of the bracket. At each end of the bracket a 6-mm diameter hole was drilled so the peg of the wooden block would secure the aluminum bracket. Thus, the aluminum bracket could be removed while the wooden blocks remained fixed to the turf surface which provided the ability to repeat measurements at the same position after traffic.

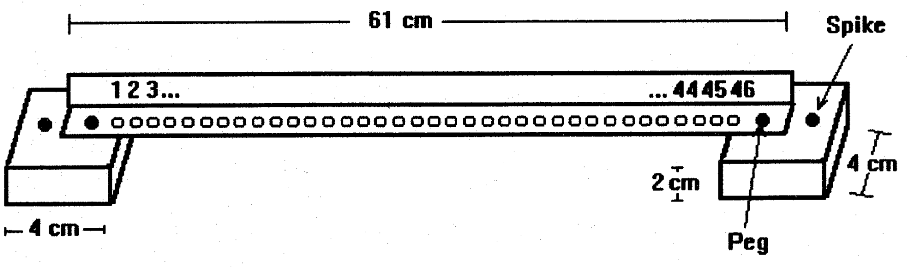

Figure 1. Diagram of the wooden blocks and aluminum bracket to hold depth dial micrometer.

Measurement of microrelief was accomplished by placing the base of a depth dial gauge micrometer onto the aluminum bracket and inserting the 6 mm diameter pin of the dial gauge through a hole at the position being measured. A constant force spring moved the depth measuring pin down into contact with the turf surface. The 'depth' at the respective hole position along the aluminum bracket was recorded. A series of measurements at selected hole positions provided a set of depths that 'mapped' the contour for that surface transit. Depths were taken at the same hole position after traffic was applied to determine relative changes of surface contour.

Traffic evaluation. The depth of depression after traffic on the putting greens was evaluated on eleven of the twelve golf courses. Traffic was applied as 30 seconds of static (stationary) pressure on the putting green surface. The 30 second time period was used to represent the approximate time of putting and waiting for fellow competitors to play out a putt. Forms of traffic evaluated included the 8.0-cm wide heel of a sneaker, 7.5-cm wide heel of a golf shoe, rear tire of a wheelchair with a 61-cm diameter and 2.5-cm wide rigid rubber tire (Everest and Jennings Inc.), rear tire of the Quickie GPS wheelchair with a 61-cm diameter and 3.5-cm wide pneumatic tire inflated to 0.3 MPa (Quickie Designs Inc., Fresno, CA), rear tire of the Golf Express single rider cart with a 33-cm diameter and 16.5-cm wide pneumatic tire inflated to 0.08 MPa (Electric Mobility, Sewell, NJ), and rear wheel of the Lone Rider single rider cart with a 33-cm diameter and 12.7-cm wide pneumatic tire inflated to 0.08 MPa (Lone

Rider, Weston, Ontario Canada). The weight and contact area for the different forms of traffic is presented in Table 3.

On a day of evaluation for the depth of depression for a form of traffic, a level location within the 35 m^2 was selected for microrelief measurements. Dial gauge measurements were taken at 10 positions along a transit perpendicular to the line of traffic and included positions that were trafficked and non-trafficked. Surface contour was measured before and after traffic; therefore, changes in contour indicated a change due to traffic. Positions that did not receive traffic provided reference 'depths' that ensured errors due to bracket and gauge positioning were minimized. Additionally, depth measurements were taken three times at each transit position to enhance accuracy and repeatability. The measurement for depth of depression was an average of the hole positions which were trafficked, the number of the positions used for the average was constant for each form of traffic (Table 3).

Rebound of the putting green surface after traffic was assessed using microrelief measurements one-half hour after traffic to gauge the relative amount of rebound for the green.

Ball roll deflection measurements The interference of ball roll by traffic was evaluated on four of the twelve golf courses during 1996. Ball roll was accomplished using a stimpmeter. A stand was used to hold the stimpmeter in an elevated position to ensure consistency in direction and length of ball roll across the green. Prior to traffic, the final resting point of the ball was recorded

Table 3. Description of the forms of traffic evaluated and the number of positions for depth of depression during 1996.

Form of Traffic	Total Weight †	Contact Area ‡	Calculated Contact Pressure	Width of Traffic	# of Positions §	Actual Measured Width
	kg	cm^2	MPa	mm		mm
Heel of sneaker	80	230	0.03	8.0	4	6
Heel of golf spike	80	63	0.12	7.5	4	6
Rigid tire of wheelchair	98	26	0.40	2.5	2	1
Pneumatic tire of wheelchair	90	72	0.12	3.5	2	1
Pneumatic tire of Golf Express	215	290	0.05	16.5	4	12
Pneumatic tire of Lone Rider	148	225	0.06	15.2	4	12

† Total weight of 80 kg person and assistive device.

‡ Contact area for foot traffic includes total contact area for two shoes. The golf spike contact area was determined by the shoulder of spike. Wheeled traffic contact area was determined by contact area of rear wheel measured for depth of depression and multiplied by four for total number of wheels in contact with surface.

§ The number of hole positions on bracket measured with the depth micrometer to quantify the depth of depression.

by measuring the forward (x) and lateral (y) distance positions relative to the end of the stimpmeter and initial line of travel (Fig. 2). After traffic, ball roll measurements were repeated to determine the deviation of ball roll caused by traffic. Eight golf balls were rolled both before and after traffic at a 30° angle across the line of traffic. Ball roll crossed the line of traffic in the last 0.9 m of ball travel. Trials in 1995 indicated the 30° angle and 0.9 m distance was effective in measuring ball roll interference.

Ball roll deflection measurements were taken 21 and 28 May and 4 June 1997 on the nursery green at Metedeconk National Golf Club. On each day of evaluation the form of traffic being evaluated included the heel of a golf shoe, 2.5-cm wide rigid tire wheelchair, and 3.5-cm wide pneumatic tire wheelchair. All forms of traffic had three ruts with a different depth of depression and a check (no depression) evaluated on each day of ball roll deflection measurements. The same procedure was used as in 1996 except six balls, instead of eight, were rolled both before and after traffic events.

Data analysis

All depth of depression measurements taken during the 1996 season for the heel of a sneaker, heel of a golf shoe, 2.5-cm wide rigid rubber tire wheelchair, and 3.5-cm wide pneumatic tire wheelchair were subjected to an ANOVA in PCSAS (SAS Institute, 1985) and means were separated with Fisher's protected LSD, $\alpha = 0.05$. Data taken on 11 and 18 September and 2 and 28 October 1996 were used to evaluate depth of depression caused by the

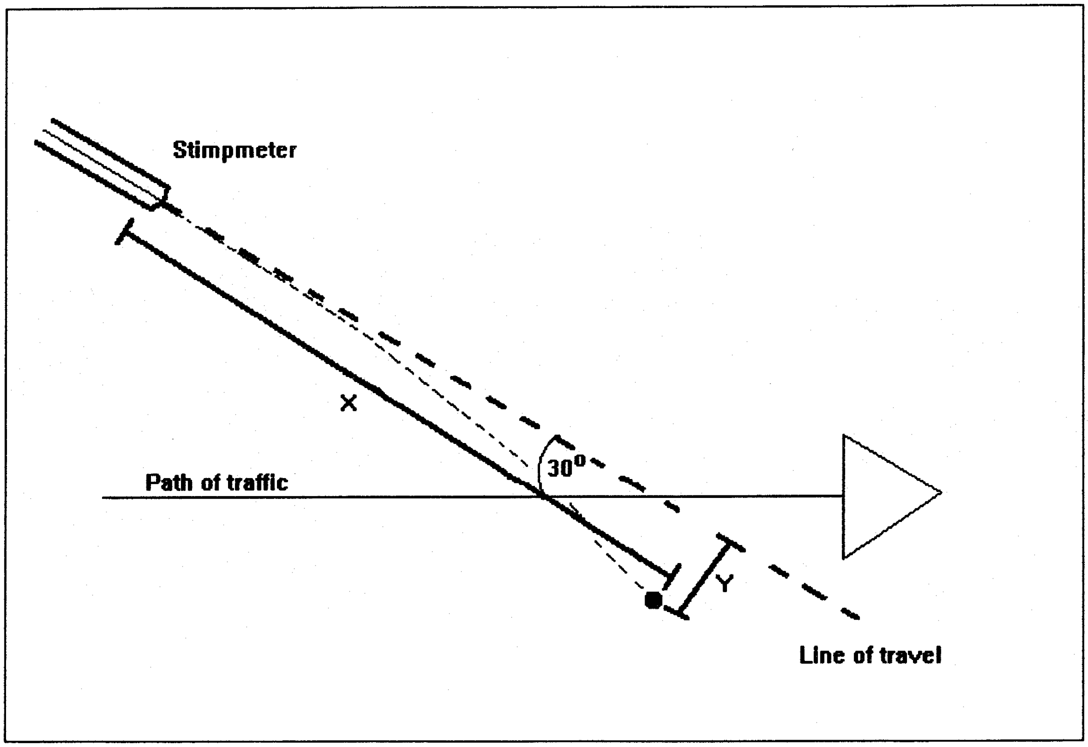

Figure 2. Diagram of an overhead view of ball roll deflection measurements. The forward (x) and lateral (y) positions are relative to the end of the stimpmeter and initial line of travel, respectively.

heel of a sneaker, heel of a golf shoe, 2.5-cm wide rigid rubber tire wheelchair, 3.5-cm wide pneumatic tire wheelchair, and pneumatic tires of the single rider carts (both the Lone Rider and Golf Express combined). The data was subjected to an ANOVA in PCSAS and means were separated with Fisher's protected LSD, $\alpha = 0.05$.

A *F* test for homogeneity of the variances of ball roll data measured before and after traffic was performed for each date of evaluation. Student's *t* test was used to compare ball roll positions before and after traffic.

The regression procedure of PCSAS was used to evaluate the relationship of the depth of depression caused by each form of traffic and the gravimetric moisture content of the 0- to 5-cm depth below the turf surface. The relationship of surface hardness and strength with the gravimetric moisture content of the 0- to 5-cm depth below the turf surface was also evaluated with the regression procedure of PCSAS. The regression procedure of PCSAS was then used to evaluate the relationship between the depth of depression caused by each form of traffic and surface hardness and strength measurements.

Multiple regression analysis was performed on depth of depression and percent rebound of each form of traffic and surface hardness and strength to identify edaphic features associated with the measurements. The forms of traffic evaluated included the heel of a sneaker and golf shoe combined, 2.5-cm wide rigid tire wheelchair, and 3.5-cm wide pneumatic tire wheelchair. The regression model used a complete linear model: $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5$

$+\beta_6 X_6 + \beta_7 X_7$, where Y = depth of depression, percent rebound, surface hardness, or surface strength, X_1 = height of turfgrass cut, X_2 = depth of upper mat layer, X_3 = percent organic matter of the upper mat layer, X_4 = organic matter content of the 0- to 5-cm depth below the upper mat layer, X_5 = organic matter content of topdressing material, X_6 = soil temperature at the 5-cm depth, and X_7 = gravimetric moisture content of the 0- to 5-cm depth below the turf surface. Variables were deleted from the model if the parameter estimate (β) was not significant ($\alpha = 0.05$), if the variable increased the mean square error (σ^2), or if the deletion of a variable did not decrease the R^2 of the model (Weisberg, 1985).

Single determination regression was performed to evaluate the relative importance of all variables used in the multiple regression equations. The best single determination regression (lowest α) was presented to express the amount of variation for the individual variable.

Multiple regression analysis was performed on surface hardness and strength measurements at four narrow ranges of gravimetric moisture content of the 0- to 5-cm depth below the surface to identify edaphic features other than moisture associated with the measurements. Regression analysis used a complete linear model: $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6$, where Y = surface hardness or surface strength, X_1 = height of turfgrass cut, X_2 = depth of upper mat layer, X_3 = percent organic matter of the upper mat layer, X_4 = organic matter content of the 0- to 5-cm depth below the upper mat layer, X_5 =

organic matter content of topdressing material, and X_6 = soil temperature at the 5-cm depth. Components were deleted from the model as previously discussed for surface hardness and strength.

RESULTS AND DISCUSSION

Evaluation of traffic and disruption of golf putting green

Microrelief measurements. The average depth of depression for the heel of a sneaker, heel of a golf shoe, 2.5-cm wide rigid tire wheelchair, and 3.5-cm wide pneumatic tire wheelchair for all putting greens throughout 1996 is shown in Table 4. The lack of significant differences in measurements of surface hardness, surface strength, and gravimetric moisture content for the 0- to 5-cm depth below the turf surface for each form of traffic indicated that the measurements of depression were collected randomly and not biased by conditions.

The heel of a golf shoe and sneaker did not differ in the depth of depression caused after applying 30 seconds of static pressure. As expected, the greatest depth of depression occurred with the 2.5-cm rigid tire wheelchair. The 3.5-cm wide pneumatic tire wheelchair caused less depression than the 2.5-cm rigid tire, however, depressions caused by the 3.5-cm wide pneumatic wheelchair were greater than the heel of either shoe (Table 4).

The pneumatic tires of single rider carts were not measured on enough occasions to compare with the other forms of traffic over the entire season. Sufficient data were collected on 11 and 18 September and 2 and 28 October 1996 to evaluate the depth of depression caused by the heel of a sneaker and golf shoe combined and the 16.5- and 15.2-cm wide pneumatic tire of the Golf Express and Lone Rider cart, respectively. The average depth of depression for

Table 4. Depth of depression, percent rebound, surface hardness, surface strength, and gravimetric moisture content of the 0- to 5-cm depth zone below the turf surface measured for each form of traffic averaged over all putting greens measured in 1996.

Form of Traffic	n†	Depth of Depression	Rebound ‡	Surface Hardness §	Surface Strength ¶	Moisture Content #
		mm	%	g	kg cm^{-3}	%
Heel of golf shoe	19	0.4	17	68	15.6	26.6
Heel of sneaker	23	0.5	24	64	14.8	27.8
2.5-cm wide rigid tire wheelchair	35	1.8	19	66	15.0	27.5
3.5-cm wide pneumatic tire wheelchair	33	1.2	18	68	15.3	25.5
LSD *(0.05)*		0.2 ***	NS	NS	NS	NS
CV; %		39	8	13	16	47

*** Significant at the 0.001 probability level.

† Number of observations.

‡ Percent rebound of depth of depression after 30 minutes; the number of observations for percent rebound data was 18, 20, 31, and 32 for the heel of a sneaker, shoe, 2.5- wide rigid tire, and 3.5-cm wide pneumatic tire wheelchair, respectively.

§ Surface hardness, maximum deceleration measured in gravities.

¶ Surface strength measured at the 0-to 2.5-cm depth zone.

\# Gravimetric moisture content of the 0- to 5-cm depth zone below the turf surface.

the pneumatic tires of the single rider carts was greater than the heel of the shoes (Table 5).

The amount of rebound of the putting green 30 minutes after traffic was not statistically different for each of the forms of traffic (Table 4 and 5). Thus, the depth of depression initially caused by wheeled traffic would remain as deeper depressions 30 minutes after traffic compared to the depression caused by foot traffic.

Ball roll deflection. Deflection of golf ball roll was evaluated for traffic with the 2.5-cm wide rigid tire wheelchair in 1996. As evidenced by the data, ball roll over the path traveled by wheel traffic was altered, however, results were variable. Results indicated that the lateral position of golf ball roll was significantly altered 20% of the time when the depth of depression was 1.5 mm or less after traffic (Table 6). The lateral position of golf ball roll was significantly altered 60% of the time when the depth of depression was greater than 1.5 mm after traffic.

The homogeneity of the variances of the forward and lateral positions was only significant three times during ball roll evaluation in 1996 and did not appear to be a useful determination of ball roll deflection. The change in lateral position appears to be the best indicator of ball roll deflection.

The forward position measurement was significantly different after traffic on seven out of sixteen dates during 1996. The forward position measurement was not strongly associated with depth of depression caused by wheel traffic.

Table 5. Depth of depression, percent rebound, surface hardness, surface strength, and gravimetric moisture content of the 0- to 5-cm depth zone below the turf surface measured for foot traffic and single rider carts averaged over all putting greens measured on 11 and 18 Sept. and 2 and 28 Oct. 1996.

Form of Traffic	n†	Depth of Depression	Rebound‡	Surface Hardness§	Surface Strength¶	Moisture Content#
		mm	%	g	kg cm^{-3}	%
Heel of sneaker and golf shoe	6	0.7	27	57	12.8	27.2
16.5 and 15.2 cm wide pneumatic tire single rider carts	8	1.1	26	57	12.4	28.7
LSD $_{(0.05)}$		0.4*	NS	NS	NS	NS
CV; %		34	57	7	10	53

* Significant at the 0.05 probability level.

† Number of observations.

‡ Percent rebound of depth of depression after 30 minutes.

§ Surface hardness maximum deceleration measured in gravities.

¶ Surface strength measured at the 0- to 2.5-cm depth zone.

Gravimetric moisture content of the 0- to 5-cm depth zone below the turf surface.

Table 6. The final resting lateral and forward position of eight golf ball rolls across a putting green at four locations before and after traffic with a 2.5-cm rigid tire wheelchair in 1996. Ball roll intersected traffic at 30^0 angle and within the last 0.9 m of the final resting spot.

			Lateral Position				Forward Position			
Location	Date	Depth †	Before	After	Var‡	T test§	Before	After	Var	T test
		mm	---------- cm ----------				------------- cm ----------			
Plainfield										
	10 June	0.8	17 ± 10	23 ± 5	NS	NS	394 ± 12	391 ± 17	NS	NS
	22 July	1.3	26 ± 5	31 ± 7	NS	NS	249 ± 4	256 ± 15	**	NS
	16 Sept	1.1 pneumatic ¶	16 ± 2	17 ± 4	NS	NS	264 ± 5	273 ± 3	NS	**
		1.9	1 ± 7	8 ± 1	***	**	442 ± 26	479 ± 25	NS	*
Tavistock										
	20 June	0.5	52 ± 8	61 ± 6	NS	*	336 ± 8	351 ± 9	NS	***
Fiddlers										
	13 June	1.0	52 ± 6	61 ± 6	NS	*	352 ± 9	382 ± 12	NS	***
	10 July	1.0	28 ± 7	25 ± 7	NS	NS	279 ± 8	280 ± 7	NS	NS
Metedeconk										
	6 June	0.8	1 ± 4	2 ± 5	NS	NS	313 ± 9	329 ± 7	NS	**
		0.8	-1 ± 7	-2 ± 10	NS	NS	338 ± 14	359 ± 9	NS	**
	11 July	1.2	23 ± 1	22 ± 3	**	NS	406 ± 14	419 ± 14	NS	NS
	14 Aug	1.4	9 ± 5	8 ± 6	NS	NS	468 ± 14	473 ± 26	NS	NS
		2.6	9 ± 5	19 ± 9	NS	**	468 ± 14	470 ± 27	NS	NS
		3.8	9 ± 5	26 ± 8	NS	***	468 ± 14	464 ± 18	NS	NS
		0.0 (check)	12 ± 9	14 ± 6	NS	NS	396 ± 16	408 ± 17	NS	NS
		2.2	12 ± 9	12 ± 9	NS	NS	396 ± 16	391 ± 12	NS	NS
		3.4	12 ± 9	8 ± 9	NS	NS	396 ± 16	381 ± 8	NS	*

*, **, ***, Significant at the 0.05, 0.01, and 0.001 probability levels, respectively. NS Not significant.

† Depth of depression immediately after traffic, 0.0 = no traffic.

‡ *F* test for homogeneity of the variances.

§ Probability of a greater *t*-value.

¶ Depression made with 3.5 cm wide pneumatic tire wheelchair.

When differences were observed, the change in forward position resulted in an increased length of ball roll eight out of nine times. This increase in ball roll length could be caused by the repeated ball rolls lying down turfgrass blades along the path of ball travel.

Ball roll deflection was evaluated in 1997 for the heel of a golf shoe, 2.5-cm wide rigid tire wheelchair, and 3.5-cm wide pneumatic tire wheelchair (Tables 7, 8, and 9). No traffic (0.0 mm of depression) altered lateral position of ball roll only once (11% of the time) in 1997. The heel of the golf shoe altered the lateral position of the golf ball roll 50% of the time (Table 7). The depth of depression caused by the heel of a golf shoe ranged from 0.4 to 0.9 mm.

Depressions from wheeled traffic in 1997 produced similar results as in 1996. The 2.5- and 3.5-cm wide wheeled traffic altered ball roll 22% of the time when depth of depression was 2.0 mm or less (Table 8 and 9). When the depth of depression caused by wheeled traffic was greater than 2.0 mm, the lateral position of ball roll was altered 33% of the time.

Relationship of gravimetric moisture content with depth of depression, surface hardness, and surface strength

The depth of depression caused by the heel of a golf shoe and sneaker changed very little over the range of gravimetric moisture content for the 0- to 5-cm depth below the turf surface on high sand greens and topdressed modified native soil greens (Figure 3). Conversely, the depth of depression for the 2.5-cm wide rigid tire wheelchair and 3.5-cm wide pneumatic tire wheelchair increased

Table 7. The final resting lateral and forward position of six golf ball rolls across a putting green before and after traffic with the heel of a golf shoe on the Metedeconk National Golf Club nursery green during 1997. Ball roll intersected traffic at 30^0 angle and within the last 0.9 m of the final resting spot.

		Lateral Position				Forward Position			
Date	Depth †	Before	After	Var ‡	T test §	Before	After	Var	T test
	mm	--------- cm --------				--------- cm ----------			
21 May									
	0.0	26 ± 6	24 ± 4	NS	NS	228 ± 8	227 ± 6	NS	NS
	0.4	17 ± 2	15 ± 1	NS	*	232± 11	225 ± 8	NS	NS
	0.9	13 ± 2	14 ± 3	NS	NS	227 ± 8	231 ± 7	NS	NS
28 May									
	0.0	18 ± 2	12 ± 4	NS	**	236± 10	236 ± 7	NS	NS
	0.8	29 ± 3	23 ± 3	NS	**	198± 12	191 ± 8	NS	NS
	0.9	23 ± 2	21 ± 3	NS	NS	215 ± 8	214 ± 8	NS	NS
	0.9	17 ± 1	9 ± 6	**	**	255 ± 5	248± 10	NS	NS
4 June									
	0.0	17 ± 2	17 ± 1	NS	NS	248± 12	254 ± 4	*	NS
	0.4	24 ± 2	25 ± 3	NS	NS	248 ± 7	255 ± 6	NS	NS
	0.6	22 ± 4	19 ± 2	*	NS	266± 22	274± 21	NS	NS
	0.8	19 ± 5	14 ± 2	NS	*	274± 15	284± 10	NS	NS

*, **, ***, Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

NS Not significant.

† Depth of depression immediately after traffic, 0.0 = no traffic.

‡ *F* test for homogeneity of the variances.

§ Probability of a greater *t*-value.

Table 8. The final resting lateral and forward position of six golf ball rolls across putting green before and after traffic with a 2.5-cm wide rigid tire wheelchair on the Metedeconk National Golf Club nursery green during 1997. Ball roll intersects traffic at 30^0 angle and within the last 0.9 m of final resting spot.

		------------ Lateral Position ------------				------------ Forward Position ------------			
Date	Depth †	Before	After	Var ‡	T test §	Before	After	Var	T test
	mm	--------- cm --------				--------- cm ----------			
21 May									
	0.0	17 ± 4	15 ± 4	NS	NS	226± 13	230± 10	NS	NS
	1.7	24 ± 2	21 ± 2	NS	*	263± 11	263± 13	NS	NS
	1.8	18 ± 3	19 ± 3	NS	NS	271 ± 9	275± 11	NS	NS
	3.2	14 ± 5	8 ± 3	NS	*	268 ± 9	264 ± 9	NS	NS
28 May									
	0.0	12 ± 1	12 ± 1	NS	NS	272± 14	285± 10	NS	*
	2.0	8 ± 6	4 ± 3	NS	NS	272± 14	265± 11	NS	NS
	2.6	12 ± 4	9 ± 2	NS	NS	253 ± 6	248 ± 9	NS	NS
	4.5	35 ± 7	22 ± 4	NS	**	252 ± 7	245± 10	NS	NS
4 June									
	0.0	11 ± 5	9 ± 5	NS	NS	256± 14	255± 14	NS	NS
	2.4	22 ± 3	23 ± 2	NS	NS	222± 15	229± 11	NS	NS
	2.5	24 ± 2	23 ± 3	NS	NS	297± 13	290 ± 7	NS	NS
	2.8	18 ± 2	16 ± 5	*	NS	282± 27	284± 23	NS	NS

*, **, ***, Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

NS Not significant.

† Depth of depression immediately after traffic, 0.0 = no traffic.

‡ *F* test for homogeneity of the variances.

§ Probability of a greater *t*-value.

Table 9. The final resting lateral and forward position of six golf ball rolls across putting green before and after traffic with a 3.5-cm wide pneumatic tire wheelchair on the Metedeconk National Golf Club nursery green during 1997. Ball roll intersects traffic at 30^0 angle and within the last 0.9 m of final resting spot.

Date	Depth †	Lateral Position				Forward Position			
		Before	After	Var ‡	T test §	Before	After	Var	T test
	mm	cm				cm			
21 May									
	0.0	15 ± 5	19 ± 6	NS	NS	233 ± 9	237± 14	NS	NS
	1.0	11 ± 1	15 ± 4	*	*	233 ± 4	232± 10	NS	NS
	1.5	15 ± 3	13 ± 2	NS	NS	237 ± 9	236± 11	NS	NS
	2.5	23 ± 2	21 ± 1	NS	*	244± 10	246± 11	NS	NS
28 May									
	0.0	16 ± 2	15 ± 1	NS	NS	217 ± 7	213 ± 7	NS	NS
	1.6	13 ± 2	11 ± 5	NS	NS	201± 10	188 ± 9	NS	*
	2.5	15 ± 8	15 ± 3	NS	NS	220 ± 5	223± 17	*	NS
	2.6	12 ± 2	10 ± 3	NS	NS	224± 11	225± 10	NS	NS
4 June									
	0.0	12 ± 5	9 ± 1	**	NS	277± 17	287 ± 9	NS	NS
	0.6	10 ± 2	11 ± 3	NS	NS	263± 11	266± 15	NS	NS
	1.0	33 ± 5	35 ± 5	NS	NS	250 ± 8	255 ± 7	NS	NS
	1.6	18 ± 5	15 ± 5	NS	NS	279± 26	284± 26	NS	NS

*, **, ***, Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

NS Not significant.

† Depth of depression immediately after traffic, 0.0 = no traffic.

‡ *F* test for homogeneity of the variances.

§ Probability of a greater *t*-value.

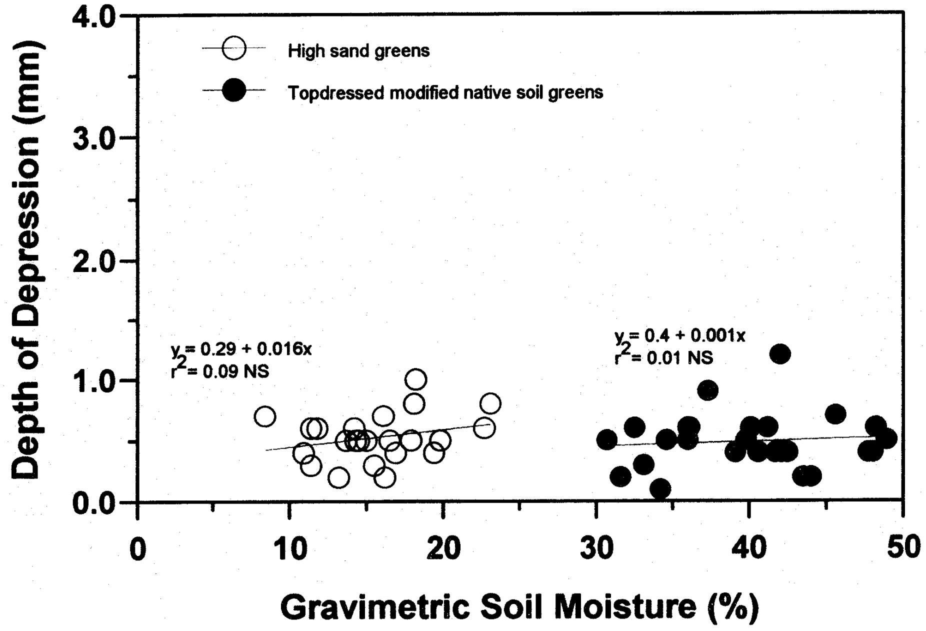

Figure 3. Relationship between gravimetric moisture content of the 0- to 5-cm depth zone below the turf surface and depth of depression for the heel of a golf shoe after 30 seconds of static pressure on rootzones of high sand and topdressed modified native soil.
NS = Not significant.

as the gravimetric moisture content for the 0- to 5-cm depth below the turf surface increased on high sand greens (Figures 4 and 5). The depth of depression caused by the tire of wheelchairs on topdressed modified native soil greens did not exhibit a clear relationship with the gravimetric moisture content of the 0- to 5-cm depth below the turf surface (Figures 4 and 5).

Surface hardness measurements increased as the gravimetric moisture content for the 0- to 5-cm depth below the turf surface decreased (Figure 6). It was also apparent that two distinct groupings existed within the data which described the relationship between gravimetric moisture content of the 0- to 5-cm layer below the turf surface and surface hardness. The two groups were also described well by the organic matter content at the 0-to 5-cm soil depth below the upper mat layer. One group of data had gravimetric moisture contents below 27% and organic matter contents below 2.0% and will be referred to as high sand greens (Table 1). The other group typically had moisture contents greater than 27% and organic matter contents above 2.0% and will be referred to as topdressed modified native soil greens.

The relationship between gravimetric moisture content for the 0-to 5-cm depth and surface strength is shown in Figure 7. Surface strength did not exhibit a significant relationship with gravimetric moisture content of the 0- to 5-cm depth.

The most obvious deviation from these two groupings was the 12th green at Pine Valley Golf Club. Although the organic matter level for the 0- to 5-cm

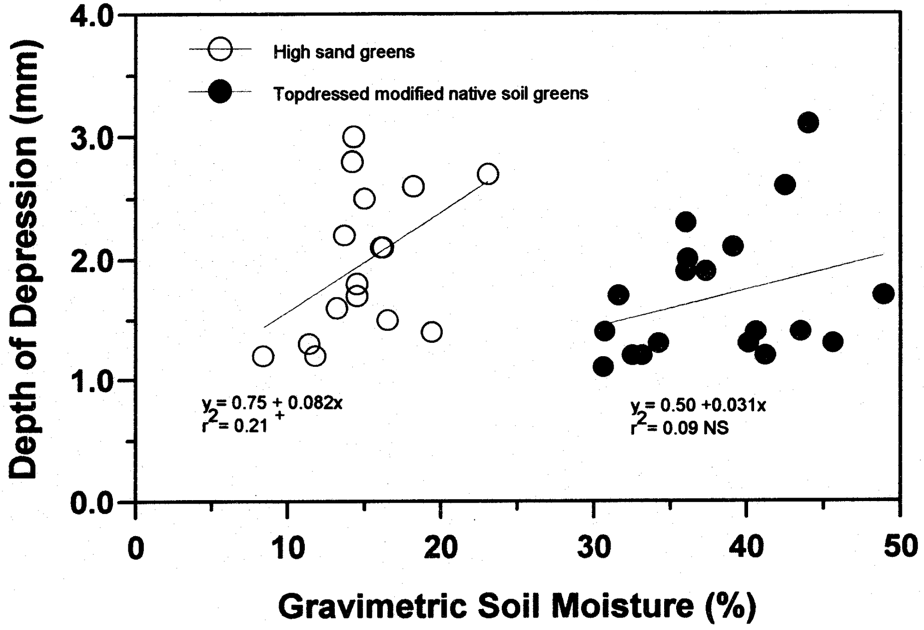

Figure 4. Relationship between gravimetric moisture content of the 0- to 5-cm depth zone below the turf surface and depth of depression for 2.5-cm wide rigid tire wheelchair after 30 seconds of static pressure on rootzones of high sand and topdressed modified native soil. NS = Not significant. $^{+}$ Significant at the 0.07 probability level.

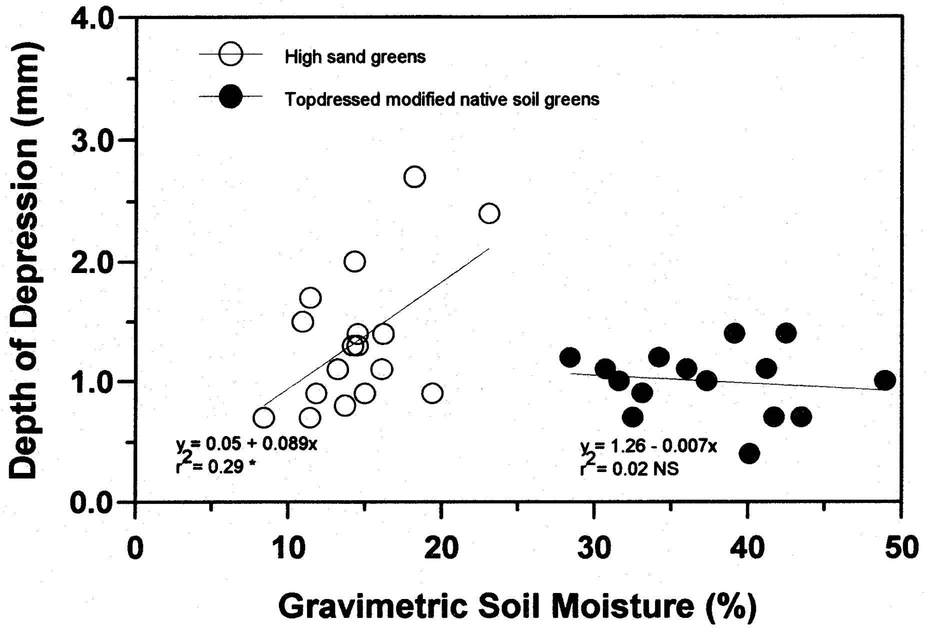

Figure 5. Relationship between gravimetric moisture content of the 0- to 5-cm depth zone below the turf surface and depth of depression for 3.5-cm wide pnuematic tire wheelchair after 30 seconds of static pressure on rootzones of high sand and topdressed modified native soil. NS = Not significant. * Significant at the 0.05 probability level.

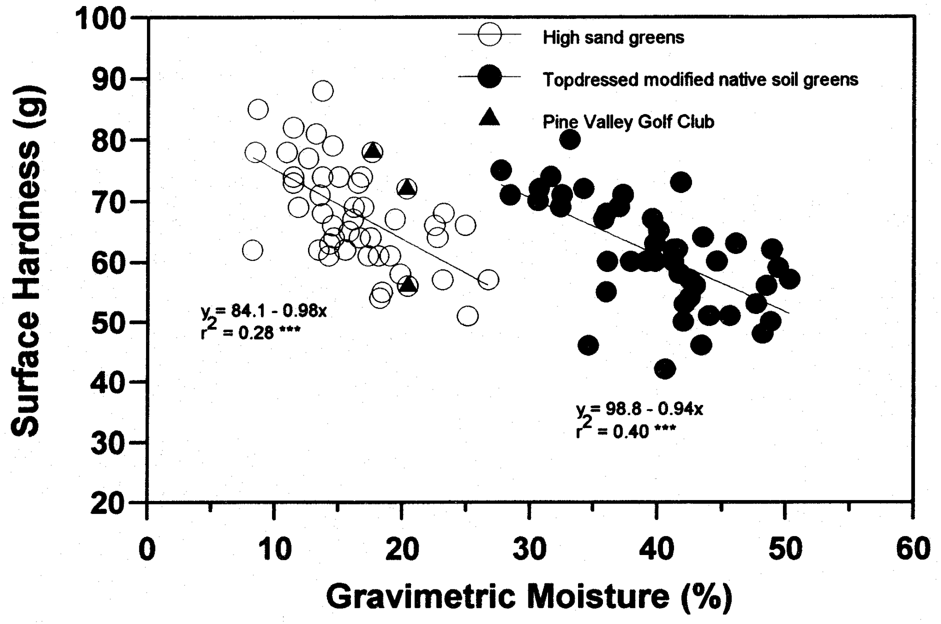

Figure 6. Relationship between gravimetric moisture content of the 0- to 5-cm depth zone below the turf surface and surface hardness (maximum deceleration measured in gravities) for rootzones of high sand and topdressed modified native soil.
*** Significant at the 0.001 probability level.

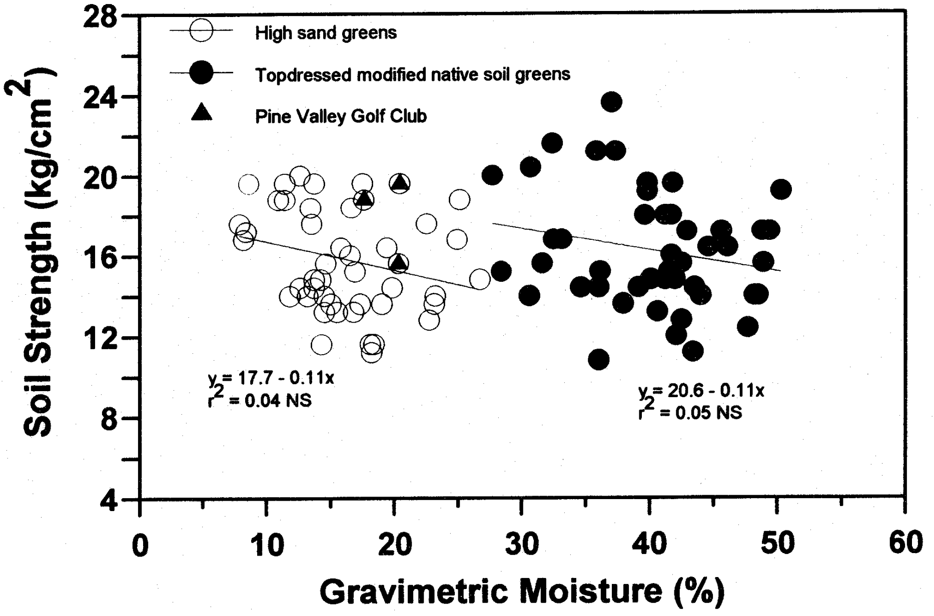

Figure 7. Relationship between gravimetric moisture content of the 0- to 5-cm depth zone below the turf surface and surface strength measured for the 0- to 2.5-cm depth zone for rootzones of high sand and topdressed modified native soil.
NS = Not significant.

depth below the upper mat layer at Pine Valley was above 2.0%, its values for gravimetric moisture content of the 0- to 5-cm layer below the turf surface are similar to high sand greens. The 0- to 5-cm depth below the upper mat layer at Pine Valley was high in sand content and low in organic matter content compared to the other topdressed modified native soil greens (Table 2) and may be responsible for moisture values being similar to greens built using high sand root zone mixes.

Test methods for determining bearing strength of golf greens

Surface hardness and surface strength measurements were compared to depth of depression measurements to evaluate if these quantitative tests could describe the bearing strength of golf greens. The organic matter content at the 0- to 5-cm soil depth below the upper mat layer was strongly correlated with surface hardness, surface strength, and depth of depression data. Therefore, surface hardness and strength measurements were regressed separately with depth of depression measurements on high sand and topdressed modified native soil greens.

Surface hardness and strength were more strongly correlated to depth of depression on high sand greens than topdressed modified native soil greens over all forms of traffic (Table 10 and 11). The depth of depression caused by the heel of the golf shoe and sneaker changed very little over the range of surface hardness and strength measurements on high sand greens (Figures 8 and 9). However, the depth of depression created by the tires of the wheelchairs

Table 10. Coefficient of determination (r^2), model significance ($P > F$), and number of observations (n) for simple linear regression of the depth of depression of the forms of traffic with surface hardness and strength values on high sand greens.

Form of Traffic	Variable †	n	r^2	P > F
Heel of golf shoe and sneaker	Hardness $_L$	21	0.39	0.003
	Hardness $_Q$		0.50	0.002
	Strength $_L$	19	0.21	0.05
	Strength $_Q$		0.29	0.06
2.5 cm wide rigid tire wheelchair	Hardness $_L$	16	0.44	0.005
	Hardness $_Q$		0.46	0.02
	Strength $_L$	14	0.43	0.01
	Strength $_Q$		0.46	0.03
3.5 cm wide pneumatic tire wheelchair	Hardness $_L$	17	0.40	0.006
	Hardness $_Q$		0.67	0.001
	Strength $_L$	15	0.22	0.07
	Strength $_Q$		0.50	0.01
16.5 and 12.7 cm wide pneumatic tire single rider carts	Hardness $_L$	6	0.23	0.34
	Hardness $_Q$		0.77	0.11
	Strength $_L$	6	0.00	0.97
	Strength $_Q$		0.24	0.65

† L = linear equation and Q = quadratic equation.

Table 11. Coefficient of determination (r^2), model significance ($P > F$), and number of observations (n) for simple linear regression of the depth of depression of the forms of traffic with surface hardness and strength values on topdressed modified native soil greens.

Form of Traffic	Variable †	n	r^2	$P > F$
Heel of golf shoe and sneaker	Hardness $_L$	21	0.01	0.67
	Hardness $_Q$		0.07	0.50
	Strength $_L$	20	0.15	0.09
	Strength $_Q$		0.27	0.07
2.5 cm wide rigid tire wheelchair	Hardness $_L$	19	0.18	0.07
	Hardness $_Q$		0.23	0.12
	Strength $_L$	18	0.11	0.17
	Strength $_Q$		0.23	0.13
3.5 cm wide pneumatic tire wheelchair	Hardness $_L$	16	0.03	0.52
	Hardness $_Q$		0.09	0.53
	Strength $_L$	15	0.03	0.55
	Strength $_Q$		0.12	0.47
16.5 and 12.7 cm wide pneumatic tire single rider carts	Hardness $_L$	3	-	-
	Hardness $_Q$		-	-
	Strength $_L$	3	0.75	0.33
	Strength $_Q$		-	-

† L = linear equation and Q = quadratic equation.

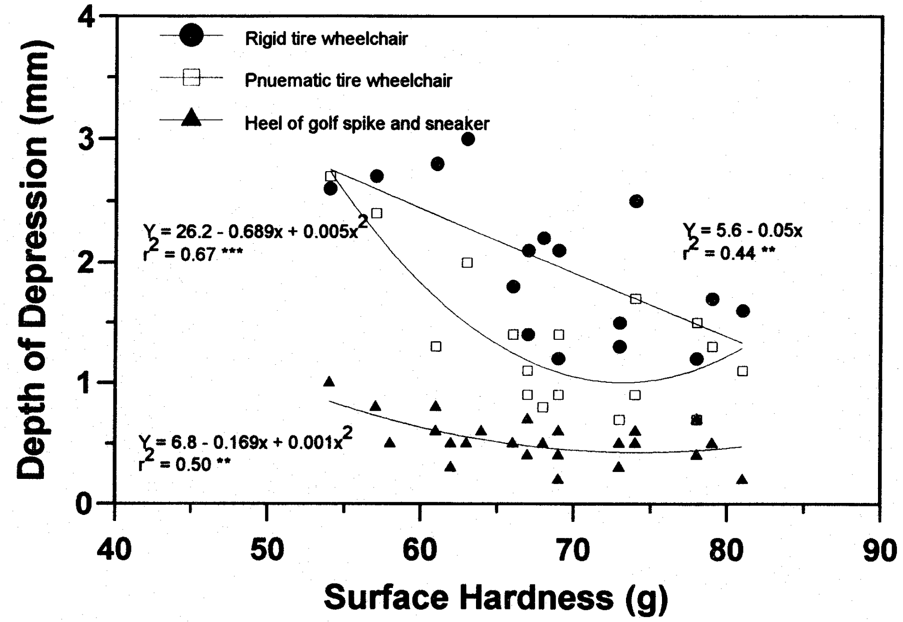

Figure 8. Relationship between surface hardness (maximum deceleration measured in gravities) and the depth of depression caused by 30 seconds of static pressure from the heel of a sneaker and golf shoe, 2.5-cm wide rigid tire wheelchair, and 3.5-cm wide pnuematic tire wheelchair on high sand greens located in New Jersey during 1996. **, *** Significant at the 0.01 and 0.001 probability levels, respectively.

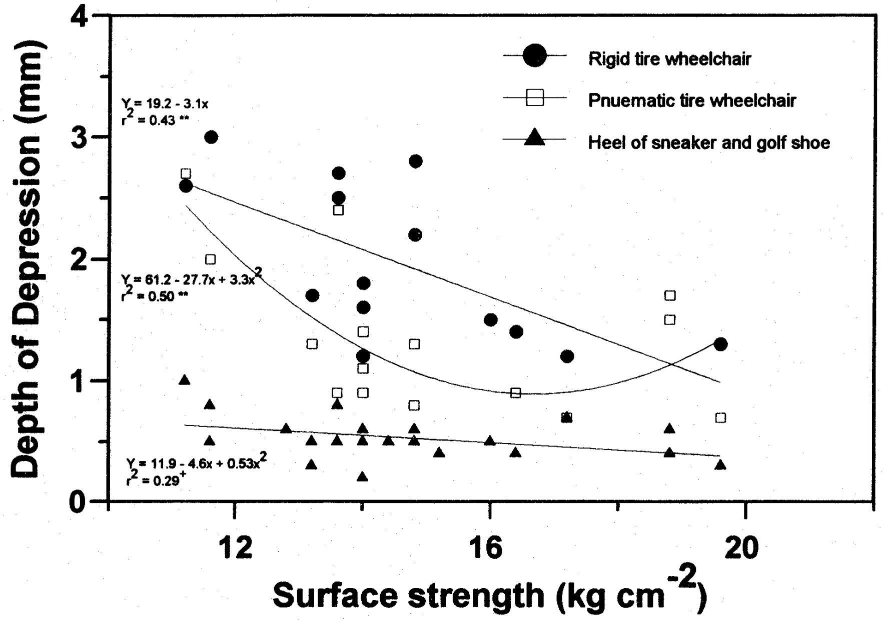

Figure 9. Relationship between surface strength measured for the 0- to 2.5-cm depth zone and the depth of depression caused by 30 seconds of static pressure from the heel of a sneaker and golf shoe, 2.5-cm wide rigid tire wheelchair, and 3.5-cm wide pnuematic tire wheelchair on high sand greens located in New Jersey during 1996.
$^{+}$, ** Significant at the 0.06 and 0.01 probability level, respectively.

varied with surface hardness or strength values of high sand greens. Higher surface hardness and strength measurements were associated with reduced depths of depressions, whereas lower surface hardness and strength were associated with greater depth of depression.

The depth of depression created by all forms of traffic was not significantly correlated to surface hardness and strength measured on topdressed modified native soil greens (Table 11). The depth of depression created by a given form of traffic was similar across all measured values of surface hardness and strength (Figures 10 and 11). It is apparent from the data that topdressed modified native soil greens bear traffic differently than high sand greens. Further evaluation is necessary to determine if surface hardness and strength values for topdressed modified native soil greens represent the complete range of possible conditions.

Edaphic properties associated depth of depression and percent rebound

The association of edaphic properties with the depth of depression and percent rebound for foot traffic, the 2.5-cm wide rigid tire wheelchair, and the 3.5-cm wide pneumatic tire wheelchair was evaluated to provide a better understanding of the factors affecting the bearing strength of putting greens. The depth of depression and rebound data was combined for the heel of a golf shoe and sneaker because there was no difference between the two and will be referred to as foot traffic.

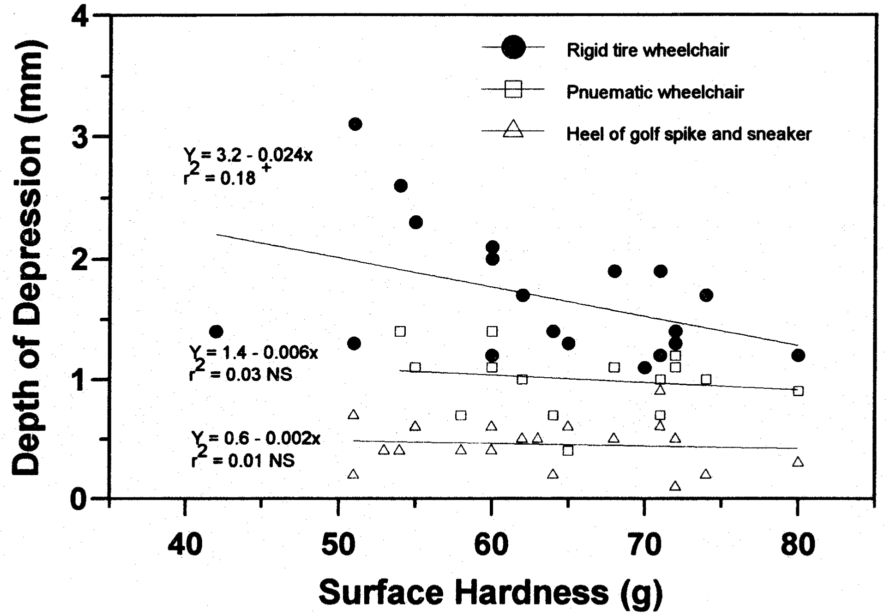

Figure 10. Relationship between surface hardness (maximum deceleration measured in gravities) and the depth of depression caused by 30 seconds of static pressure from the heel of a sneaker and golf shoe, 2.5-cm wide rigid tire wheelchair, and 3.5-cm wide pnuematic tire wheelchair on topdressed modified native soil greens located in New Jersey during 1996. NS = Not significant. + Significant at the 0.07 probability level.

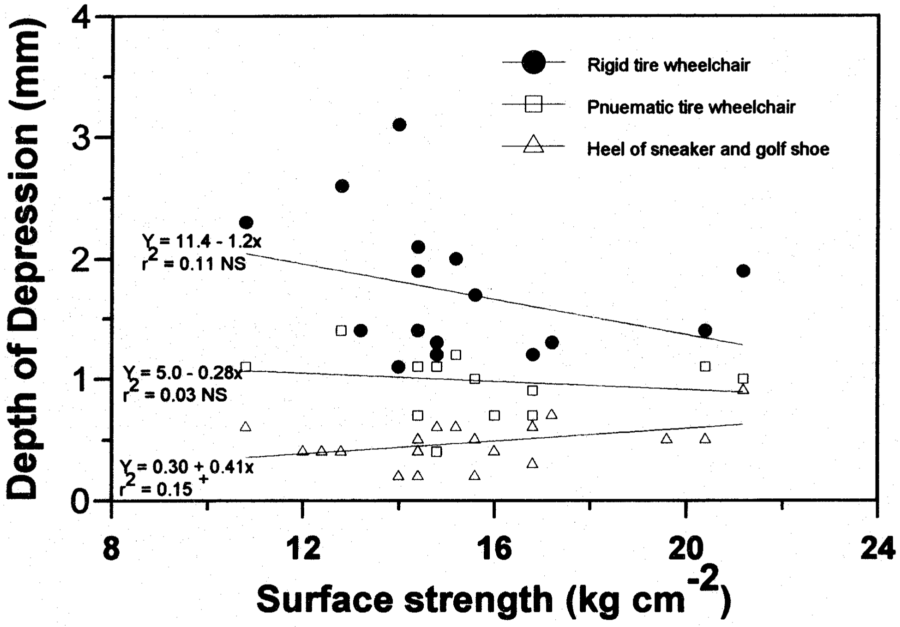

Figure 11. Relationship between surface strength for the 0- to 2.5-cm depth zone and depth of depression caused by 30 seconds of static pressure from the heel of a sneaker and golf shoe, 2.5-cm wide rigid tire wheelchair, and 3.5-cm wide pnuematic tire wheelchair on topdressed modified native soil greens located in New Jersey during 1996. NS = Not significant. $^+$ Significant at the 0.09 probability level, respectively.

The depth of depression caused by the different forms of traffic on high sand greens was associated with the factors of depth and organic matter content of the upper mat layer and organic matter content of the topdressing material (Table 12). The depth and organic matter content of the upper mat layer were contained in the best single variable equations. The depth and organic matter content of the upper mat layer was negatively correlated to the bulk density of the upper mat layer (data not shown). The compactibility of a soil depends on the initial compactness of the soil (Hakansson et. al., 1988), therefore, the depth and organic matter content of the upper mat layer may indicate the compactibility of the turf surface and associated to the depth of depression caused by traffic.

Equations describing depth of depression on the topdressed modified native soil greens did not have a single unique edaphic property that remained in the best fit models for all forms of traffic. Depth of depression did not vary with surface hardness and strength values on topdressed modified native soil greens (Figures 10 and 11). The topdressed modified native soil greens may have rootzones with a great amount of variation and the depth of depression caused by traffic can not be accurately described by any one edaphic property or surface measurement. Apparently the bearing strength or 'resiliency' of topdressed modified native soil greens was similar over a broad range of conditions.

The organic matter content of the upper mat layer remained in all three best single variable equations that were significantly associated with the percent

Table 12. Regression equations, coefficient of multiple determination (R^2), model significance ($P > F$), coefficient of simple determination (r^2) of best single variable model, and number of observations (n) for edaphic properties of golf putting greens associated with the depth of depression (Y) of the forms of traffic on high sand greens and topdressed modified native soil greens.

Construction Type and Form of Traffic ‡	Best Multiple Variable Equation §	n	R^2	$P > F$	Best Single Variable Equation §	r^2	$P > F$
High Sand:							
2.5 cm tire	$Y = 2.9 - 0.11{*}X_3$	16	0.21	0.07†	$Y = 2.9 - 0.11{*}X_3$	0.21	0.07
3.5 cm tire	$Y = 0.1 + 0.14{*}X_2 - 1.13{*}X_5$	17	0.63	0.001*	$Y = -0.3 + 0.14{*}X_2$	0.40	0.006
heel of shoe	$Y = 0.2 + 0.03{*}X_2$	21	0.16	0.07†	$Y = 0.2 + 0.03{*}X_2$	0.16	0.07
Topdressed Modified Native Soil:							
2.5 cm tire	$Y= -3.8 + 0.06{*}X_6 + 0.04{*}X_7$	19	0.44	0.001*	$Y = -1.9 + 0.05{*}X_6$	0.30	0.01
3.5 cm tire	$Y= 1.1 - 0.10{*}X_5$	16	0.22	0.06†	$Y = 1.1 - 0.10{*}X_5$	0.22	0.06
heel of shoe	$Y= -0.02 + 0.04{*}X_2$	21	0.30	0.009**	$Y = -0.02 + 0.04{*}X_2$	0.30	0.009

† * ** All variables in the model significant at the 0.10, 0.05 and 0.01 level, respectively.

‡ 2.5 cm tire = 2.5 cm wide rigid tire wheelchair, 3.5 cm tire = 3.5 cm wide pneumatic tire wheelchair, and heel = heel of sneaker and golf shoe for 30 seconds of stationary pressure.

§ X_1 = height of cut, X_2 = depth of upper mat layer, X_3 = organic matter content of the upper mat layer, X_4 = organic matter content of the 0 to 5 cm depth below the upper mat layer, X_5 = organic matter content of the topdressing material, X_6 = soil temperature at the 5-cm depth, and X_7 = gravimetric moisture content of the 0 to 5 cm depth below the green surface.

rebound of a depression 30 minutes after traffic with the 2.5- and 3.5-cm wide tire wheelchairs (Table 13). Thomas and Guerin (1981) developed a method to measure the elasticity of sports turf, elasticity measurements were time intervals required for the compacted area to closely return to its original state. They observed differences in elasticity for growing media of different soil textures. The organic matter content of the upper mat layer, like soil texture, may affect the elasticity or rebound of a depression by wheeled traffic.

The percent rebound of a depression 30 minutes after foot traffic did not show a strong association with any of the edaphic features studied (Table 13). Although the percent rebound of a depression for foot traffic is similar to rebound for wheeled traffic, the depth of depression was greater for the wheeled traffic. The depth of depression for foot traffic may be to small to observe an association of edaphic properties with the percent rebound of a depression.

Edaphic properties associated with surface hardness and strength

Multiple regression analysis for edaphic properties associated with surface hardness and strength was performed over all green types (high sand and topdressed modified native soil greens combined). The organic matter content of the 0- to 5-cm depth below the upper mat layer and the gravimetric moisture content of the 0- to 5-cm depth below the surface remained in the best multiple variable equation for both surface hardness and strength (Table 14). The height of cut and organic matter content of the upper mat layer also remained in the best multiple variable equation for surface hardness and surface

Table 13. Regression equations, coefficient of determination (R^2), model significance ($P > F$), coefficient of simple determination (r^2) of best single variable model, and number of observations (n) for edaphic properties of golf putting greens associated with the percent of rebound of a depression (Y) 30 minutes after different forms of traffic on high sand and topdressed modified native soil greens.

Construction Type and Form of Traffic ‡	Best Multiple Variable Equation §	n	R^2	$P > F$	Best Single Variable Equation §	r^2	$P > F$
High Sand:							
2.5 cm tire	$Y = -0.4 + 2.2*X_3$	16	0.28	0.03	$Y = -0.4 + 2.2*X_3$	0.28	0.03
3.5 cm tire	No significant model	17	-	-	No significant model	-	-
heel	$Y = -10.3 + 1.9*X_7$	21	0.14	0.08†	$Y = -10.3 + 1.9*X_7$	0.14	0.08
Topdressed Modified Native Soil:							
2.5 cm tire	$Y = 1.6 + 1.9*X_3$	16	0.40	0.008**	$Y = 1.6 + 1.9*X_3$	0.40	0.008
3.5 cm tire	$Y = -1.5 + 2.2*X_3$	14	0.38	0.01*	$Y = -1.5 + 2.2*X_3$	0.38	0.01
heel	No significant model	18	-	-	No significant model	-	-

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†*** All variables in the model significant at the 0.10, 0.05, 0.01 level.

‡ 2.5 cm tire = 2.5 cm wide rigid tire wheelchair, 3.5 cm tire = 3.5 cm wide pneumatic tire wheelchair, and heel = heel of sneaker and golf shoe for 30 seconds of stationary pressure.

§ X_1 = height of cut, X_2 = depth of upper mat layer, X_3 = organic matter content of the upper mat layer, X_4 = organic matter content of the 0 to 5 cm depth below the upper mat layer, X_5 = organic matter content of the topdressing material, X_6 = soil temperature at the 5-cm depth, and X_7 = gravimetric moisture content of the 0 to 5 cm depth below the turf surface.

Table 14. Regression equations, coefficient of determination (R^2), model significance ($P > F$), coefficient of simple determination (r^2) of best single variable model, and number of observations (n) for edaphic properties of golf putting greens associated with surface hardness and strength (Y).

Surface Measurement	Best Multiple Variable Equation †	n	R^2	P > F	Best Single Variable Equation †	r^2	P > F
Surface Hardness							
	$Y = 103 + -5.9{*}X_1 + 2.5{*}X_4 - 0.9{*}X_7$	99	0.52	0.001*	$Y = 76 - 0.41{*}X_7$	0.33	0.001
Surface Strength							
	$Y = 13.5 + 0.46{*}X_3 + 0.58{*}X_4 - 0.15{*}X_7$	94	0.44	0.001*	$Y = 11.7 + 0.43{*}X_3$	0.34	0.001

*** All variables in the model significant at the 0.05 level.**

† X_1 = height of cut, X_2 = depth of upper mat layer, X_3 = organic matter content of the upper mat layer, X_4 = organic matter content of the 0 to 5 cm depth below the upper mat layer, X_5 = organic matter content of the topdressing material, X_6 = soil temperature at the 5-cm depth, and X_7 = gravimetric moisture content of the 0 to 5 cm depth below the green surface.

strength, respectively. The association of the height of cut and organic matter content of the upper layer with surface hardness and strength will be discussed later with the analysis at specific gravimetric moisture levels.

As discussed previously, surface hardness and strength were separated into two groups based on gravimetric moisture content of the 0- to 5-cm depth below the turf surface (Figures 6 and 7) and organic matter content of the 0- to 5-cm depth below the upper mat layer (Table 2). The factors of gravimetric moisture content of the 0- to 5-cm depth below the turf surface and organic matter content of the 0- to 5-cm depth below the upper mat layer separated the rootzones into high sand and topdressed modified native soil greens. Thus the type of root zone was consistently associated with surface hardness and strength and is an important consideration when evaluating the bearing strength of putting greens.

The examination of the relationship between surface hardness and edaphic properties at specific gravimetric moisture levels was performed to identify edaphic characteristics other than gravimetric moisture which influenced surface hardness measurements. Surface hardness measurements were grouped into four levels of gravimetric moisture content: 10 to 15, 15 to 20, 35 to 40, and 40 to 45%. The 10 to 15% and 15 to 20% levels of gravimetric moisture consisted of high sand greens and the 35 to 40% and 40 to 45% were topdressed modified native soil greens.

The best single variable model associated with surface hardness at the 10- to 15- and 15- to 20-% levels of gravimetric moisture content of the 0-to 5-cm depth below the turf surface included the variable of depth of the upper mat layer (Table 15). Rogers et al. (1988) found that lack of turf cover inside the hashmarks of high school athletic fields contributed to higher surface hardness measurements. The depth of mat layer could provide a cushioning effect similar to turf cover for surface hardness measurements on high sand greens.

At the 35 to 40% gravimetric moisture range, the height of cut remained in the best fit single variable model accounting for the largest percentage of the variation of surface hardness (Table 15). While the relative change in the height of cut between putting greens does not appear to be large enough to change readings of surface hardness, the factor of height of cut is likely associated with other management practices (i.e., rolling, topdressing, irrigation, etc.) which influence surface hardness.

The organic matter content of the upper mat layer was in the best single variable equation of surface hardness at the 40 to 45 % range of gravimetric moisture content. Surface hardness would be expected to decrease as the organic matter content of the upper mat layer increased, increased organic matter content would reduce bulk density and lower surface hardness values (Rogers et. al., 1988). However, the equation indicates a positive relationship, that as organic matter content increases, surface hardness increases. Possibly,

Table 15. Regression equations, coefficient of determination (R^2), model significance ($P > F$), coefficient of simple determination (r^2) of best single variable model, and number of observations (n) for edaphic properties of golf putting greens associated with surface hardness and strength (Y) at four distinct moisture ranges.

Surface Measurement and Moisture Content ‡	Best Multiple Variable Equation §	n	R^2	$P > F$	Best Single Variable Model	r^2	$P > F$
Surface Hardness:							
---- % ----							
10 to 15	$Y = 109 - 2.5*X_2 + 1.4*X_3 - 12.5*X_4 - 17.9*X_5$	20	0.53	0.02*	$Y = 87.7 - 1.28*X_2$	0.24	0.03
15 to 20	$Y = 103 - 2.0*X_2 - 9.5*X_4 - 10.8*X_5$	19	0.47	0.02†	$Y = 77.3 - 0.97*X_2$	0.26	0.03
35 to 40	$Y = 72 - 7.5*X_1 + 1.7*X_2 + 3.3*X_5$	11	0.70	0.03†	$Y = 79.2 - 4.05*X_1$	0.32	0.07
40 to 45	$Y = 8 + 1.6*X_3 + 4.6*X_4$	17	0.77	0.001**	$Y = 36.9 + 1.79*X_3$	0.46	0.03
Surface Strength:							
---- % ----							
10 to 15	$Y = 6.2 + 0.42*X_3 + 0.09*X_6$	19	0.53	0.003*	$Y = 11.0 + 0.56*X_3$	0.41	0.002
15 to 20	$Y = 9.7 + 0.60*X_3$	13	0.37	0.009**	$Y = 9.7 + 0.60*X_3$	0.37	0.009
35 to 40	$Y = 9.6 + 0.65*X_3$	11	0.70	0.001***	$Y = 9.6 + 0.65*X_3$	0.70	0.001
40 to 45	$Y = 3.4 + 0.41*X_2 + 0.66*X_3$	17	0.76	0.001**	$Y = 8.2 + 0.60*X_3$	0.60	0.001

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† * ** *** All variables in the model significant at the 0.10, 0.05, 0.01, and 0.001 levels, respectively.

‡ Gravimetric moisture content for the 0- to 5-cm depth below the turf surface.

§ X_1 = height of cut, X_2 = depth of upper mat layer, X_3 = organic matter content of the upper mat layer, X_4 = organic matter content of the 0 to 5 cm depth below the upper mat layer, X_5 = organic matter content of the topdressing material, and X_6 = soil temperature at the 5-cm depth.

when upper mat layers are at high moisture contents, increased organic matter content of that layer may increase surface hardness.

Factors associated with surface strength other than gravimetric moisture content of the 0- to 5-cm depth below the turf surface were determined using best fit multiple regression models similar to surface hardness (Table 15). The organic matter content of the upper mat layer was in all best fit multiple and single variable models for the four narrow moisture ranges. Penetration resistance increased as percentage of organic matter in the soil mixture and amount of rooting increased (van Wijk and Beuving, 1980). The organic matter content of the mat layer was measured by loss on ignition, this loss can be associated with either plant debris or organic humus, an increase in either of these would be expected to be associated with increased surface strength.

SUMMARY

A traffic event exerts a force on a surface that results in pressures being distributed to the surface and down through the soil below. The magnitude of the forces exerted and the condition of the surface being trafficked will determine the amount of deformation of the surface after a traffic event.

The amount of depression was measured immediately after 30 seconds of static pressure from the heel of a shoe, a 2.5-cm wide rigid tire wheelchair, and a 3.5-cm pneumatic tire wheelchair on golf putting greens. A change in microrelief was used to measure the depth of depression occurring after 30 seconds of static pressure for each form of traffic. The depth of depression was different for the forms of traffic evaluated; the wheeled traffic was associated with greater depth of depression compared to foot traffic.

The 0- to 5-cm depth zone below the upper mat layer is composed of material used during construction and/or topdressing of a putting green. The organic matter content and gravimetric moisture content of the 0- to 5-cm depth zone below the upper mat layer characterized two distinct group of the putting greens studied. One group, designated as high sand greens, had organic matter levels below 2% and gravimetric moisture contents less than 27%. The other, referred to as topdressed modified native soil greens, had organic matter levels above 2% and gravimetric moisture content greater than 27%.

Surface hardness and surface strength measurements were used to characterize putting green surfaces. Surface hardness was measured with the

Clegg Impact Soil Tester. Surface strength was measured for the 0- to 2.5-cm depth of putting greens with a hand held penetrometer.

The depth of depression caused by traffic on high sand greens was lower when surface hardness was higher. The depth of depression for the heel of a shoe, 2.5-cm wide rigid tire wheelchair, and 3.5-cm wide pneumatic tire wheelchair averaged 0.7, 2.8, and 2.1 mm, respectively, when surface hardness values were below 65 gravities. Depths of 0.5, 1.5, and 1.2 mm were measured for a heel of a shoe, 2.5-cm wide rigid tire wheelchair, and 3.5-cm wide pneumatic tire wheelchair, respectively, when surface hardness values were above 75 gravities.

Surface strength measurements showed similar relationship with the depth of depression on high sand greens. The depth of depression for a heel of a shoe, 2.5-cm wide rigid tire wheelchair, and 3.5-cm wide pneumatic tire wheelchair averaged 0.7, 2.8, and 2.4 mm, respectively, at surface strength values below 13.0 kg cm^{-2} and depths of 0.5, 1.4, and 1.1 mm, respectively, when surface strength measurements were above 16.0 kg cm^{-2}. This is in close agreement with Van wijk and Beauving (1980) who found that the top layer of soccer fields withstand intensive play without serious deformation if the penetration resistance of the upper 2 to 3 cm of the top layer is about 13 to 14 kg cm^{-2}.

The depth of depression caused by for each form of traffic on topdressed modified native soil greens did not change significantly over the range of conditions measured. The average depth of depression for topdressed modified native soil greens across all measured values of surface hardness and strength was 0.5, 1.7, and 1.0 mm for the heel of a shoe, 2.5-cm wide rigid tire wheelchair, and 3.5-cm wide pneumatic tire wheelchair, respectively.

Ball roll lateral distance was altered 60% of the time when depth of depression was greater than 1.5 mm for the 2.5-cm wide rigid tire wheelchair in 1996. The traffic of golf putting greens with a 2.5-cm wide rigid tire of a wheelchair at surface hardness below 65 gravities or surface strength values below 13 kg cm^{-2} would be associated with depth of depressions large enough to cause ball roll deflection 60% of the time. Surface hardness values above 75 gravities and surface strength values above 16 kg cm^{-2} on high sand greens would be associated with depth of depression measurements that altered ball roll lateral distance 20% of the time in 1996.

Ball roll deflection data in 1997 support these results with a larger percent of ball roll altered at greater depths of depression. Wheeled traffic altered ball roll lateral distance 38% of the time when depth of depression was greater than 2.0 mm. Wheeled traffic on golf putting greens at surface hardness below 65 gravities or surface strength values below 13 kg cm^{-2} would be associated with depth of depressions large enough to cause ball roll deflection 38% of the time. Surface hardness values above 75 gravities and surface strength values above 16 kg cm^{-2} on high sand greens would be associated with depth of depression measurements that altered ball roll lateral distance 22% of the time in 1997.

Edaphic properties of putting greens were examined for relationships with depth of depression and percent rebound of a depression. Multiple regression best fit equations indicated that the depth of the upper mat layer was an important factor associated with the depth of depression on high sand putting greens. Greater rebound of a depression 30 minutes after traffic was associated with higher organic matter content of the upper mat layer on high sand and topdressed modified native soil greens.

Surface hardness measurements decreased with increasing gravimetric moisture for both green construction types. Rogers and Waddington (1990) similarly found impact absorption decreased with increased gravimetric moisture for high school athletic fields. Multiple regression analysis was used to help identify the most important variables controlling surface hardness at narrow ranges of gravimetric moisture. The depth of the upper mat layer was included in the best fit models of surface hardness at the selected moisture ranges of high sand greens.

Surface strength measurements were evaluated at different moisture ranges similarly to surface hardness. The organic matter content of the upper mat layer remained in the best single variable equation for edaphic features associated with surface strength at all four narrow gravimetric moisture ranges evaluated.

The depth and organic matter content of the upper mat layer was associated with the depth of depression, percent rebound of a depression, surface harness, and surface strength. These edaphic characteristics along with gravimetric moisture content of the 0- to 5-cm depth zone below the turf surface and organic matter content of the 0- to 5-cm depth zone below the upper mat layer are important factors affecting the bearing strength of putting greens.

The results indicate that the depth of depression after traffic with a 2.5- and 3.5 cm wide tire wheelchairs was dependent on surface conditions (hardness and strength) for high sand greens, whereas the depth of depression caused by foot traffic did not change under varying surface conditions. The edaphic properties associated with depth of depression, surface hardness, and surface strength were depth and organic matter content of the upper mat layer. The evaluation of depth and organic matter content of the upper mat layer in designed replicated experiments would provide a better understanding of the effect these factors have on the depth of depression after traffic events.

Ball roll deflection needs further study if depth of depression measurements are to be clearly interpreted for acceptable limits of depression and interference with play. Further investigation is necessary to determine if values of surface hardness and strength represent the entire range of surface conditions found on topdressed modified native soil greens.

Future work might also include the following. The evaluation of different width pneumatic tires (6.4, 7.6, 10.1 cm) for depth of depression and ball roll deflection. The examination of surface hardness between 65 and 75 gravities and surface strength values between 13 and 16 kg cm^{-2} for depth of depression of different forms of traffic and associated edaphic features. The evaluation of traffic on putting greens with different grass species including bermudagrass (*Cynodon dactylon*), overseeded perennial ryegrass (*Lolium perenne*) and rough bluegrass (*Poa trivialis*).

Appendix 1. Date of evaluation, surface hardness, surface strength, gravimetric moisture content of the 0- to 5-cm depth below the turf surface, and soil temperature at the 5-cm depth of high sand greens evaluated during 1996.

Putting Green Location	1996	Surface Hardness†	Surface Strength‡	Gravimetric Moisture	Temp
		g	kg cm^{-2}	%	°C
Canoebrook 11th	May 13	64	18.4	16.6	19
	May 23	62	18.4	13.4	24
	Jun 24	73	16.0	16.5	26
	Aug 6	54	11.2	18.2	22
	Aug 26	63	11.6	14.3	18
	Oct 2	55	11.6	18.4	14
	Oct 28	61	11.6	18.1	14
	Nov 25	61	13.6	17.3	7
Fiddler's Elbow practice	May 1	51	18.8	25.1	16
	Jun 13	66	16.8	24.9	21
	Jul 10	57	14.8	26.7	21
	Aug 22	61	13.6	19.0	-
	Sept 18	57	13.6	23.1	19
	Oct 15	68	14	23.2	8
Montclair 5th	May 14	85	19.6	8.6	13
	Jun 17	82	18.8	11.4	21
	Jul 16	68	14.8	13.7	22
	Aug 12	69	-	16.2	19
	Sept 24	69	15.2	16.9	10
	Nov 20	77	14.4	12.6	2
Metedeconk 19th	May 2	58	14.4	19.8	-
	Jun 6	62	13.2	15.5	18
	Jul 11	69	14	11.8	22
	Aug 14	67	-	16.1	22
	Sept 11	61	14.8	14.2	22
	Oct 16	66	14	14.5	11
Woodbury 1st	Apr 22	62	16.8	8.2	22
	May 15	-	17.6	7.9	20
	Jun 19	74	13.2	16.8	21
	Jul 25	74	13.6	15.0	21
	Aug 29	81	14.0	13.2	20
	Sept 27	79	13.2	14.5	14
	Oct 30	88	14.4	13.7	12

Appendix 1 (continued).

Putting Green Location	1996	Surface Hardness	Surface Strength	Gravimetric Moisture	Temp
		g	kg cm^{-2}	%	°C
Galloway 17th	Jun 4	77	20.0	12.6	24
	Jul 9	78	17.2	8.4	28
	Aug 6	78	18.8	10.9	25
	Oct 1	64	15.6	14.6	18
Galloway 18th	Jun 4	64	19.6	17.5	24
	Jul 9	73	19.6	11.4	28
	Aug 6	74	18.8	11.4	27
	Oct 1	65	16.4	15.8	17
Blue Heron Pines 1st	Apr 30	74	19.6	13.7	20
	Jun 4	66	17.6	22.5	26
	Jul 9	67	16.4	19.4	27
	Aug 6	71	17.6	13.5	27
	Oct 1	64	12.8	22.7	-
Pine Valley 12th	Apr 22	56	19.6	20.4	-
	Jul 29	72	15.6	20.3	24
	Oct 7	78	18.8	24.9	13

† Surface hardness is maximum deceleration measured in gravities.
‡ Surface strength measured at the 0- to 2.5-cm depth zone.
- Measurement not taken.

Appendix 2. Date of evaluation, surface hardness, surface strength, gravimetric moisture content of the 0- to 5-cm depth below the turf surface, and soil temperature at the 5-cm depth of topdressed modified native soil greens evaluated during 1996.

Putting Green Location	1996	Surface Hardness†	Surface Strength‡	Gravimetric Moisture	Temp
		g	kg cm^{-2}	%	°C
Canoebrook 13th	Apr 4	50	14.8	42.0	16
	May 13	50	17.2	48.8	14
	May 23	48	14.0	48.2	18
	Jun 24	51	14.0	44.0	24
	Aug 6	54	12.8	42.5	27
	Aug 26	60	14.4	39.1	23
	Oct 2	53	12.0	42.1	14
	Oct 28	53	12.4	47.7	13
	Nov 25	56	14.0	48.5	6
Fiddler's Elbow 12th	May 1	42	13.2	40.6	20
	Jun 13	60	15.2	36.1	22
	Jul 10	55	10.8	36.0	22
	Aug 22	71	15.2	28.4	24
	Sept 18	46	11.2	43.4	18
	Oct 15	60	13.6	37.9	7
Montclair 18th	May 14	69	23.6	37.0	13
	Jun 17	67	21.3	35.8	22
	Jul 16	56	17.2	42.9	25
	Aug 12	72	-	34.2	19
	Sept 24	63	19.6	39.8	11
	Nov 20	60	19.2	39.8	2
Plainfield 5th	Apr 15	46	14.4	34.6	16
	Jun 10	70	14	30.6	22
	Jul 22	71	16.8	32.5	20
	Aug 19	74	15.6	31.6	22
	Sept 16	68	14.4	36.0	23
	Oct 17	80	16.8	33.1	14
Springdale 12th	Apr 18	62	15.2	41.5	11
	May 15	67	18.0	39.6	9
	Jun 19	57	15.6	42.5	18
	Jul 18	65	14.8	40.1	23
	Aug 20	64	14.4	43.5	19
	Sept 30	60	14.8	41.2	18
	Oct 29	58	16.0	41.7	-

Appendix 2 (continued).

Putting Green Location	1996	Surface Hardness	Surface Strength	Gravimetric Moisture	Temp
		g	kg cm^{-2}	%	°C
Tavistock 5th	Apr 17	58	18.0	41.7	11
	May 15	69	21.6	32.4	17
	Jun 20	51	17.2	45.6	20
	Jul 24	71	21.2	37.3	20
	Aug 28	72	20.4	30.7	22
	Nov 18	62	18.0	41.2	5
	Nov 18	75	20.0	27.7	5
Ramblewood 9th	May 15	57	19.2	50.3	15
	Jun 20	59	17.2	49.4	25
	Jul 25	73	19.6	41.8	26
	Aug 29	60	16.4	44.6	24
	Sept 25	62	15.6	48.9	14
	Oct 30	63	16.4	46.1	13

† Surface hardness is maximum deceleration measured in gravities.
‡ Surface strength measured at the 0- to 2.5-cm depth zone.
- Measurement not taken.

Appendix 3 Number of averaged positions, measured depth of depression, and percent rebound of a depression for the heel of a sneaker, heel of a golf shoe, 2.5-cm wide rigid tire wheelchair, 3.5-cm wide pneumatic tire chair, and 15-cm wide pneumatic tire single rider cart measured on high sand greens during 1996.

Putting Green Location	1996	Rigid Tire Wheelchair			Pneumatic Tire Wheelchair			Heel of Sneaker			Heel of Golf Shoe			Pneumatic Single Rider		
		n†	Dep‡	Reb§	n†	Dep‡	Reb§	n†	Dep‡	Reb§	n†	Dep‡	Reb§	n†	Dep‡	Reb§
			mm	-%-		mm	%		mm	%		mm	%		mm	%
Canoebrook 11th	Jun 24	1	1.5	25	-	-	-	3	0.5	40	-	-	-	-	-	-
	Aug 6	1	2.6	8	1	2.7	0	1	1.0	20	-	-	-	-	-	-
	Aug 26	2	3.0	20	2	2.0	25	1	0.5	20	-	-	-	-	-	-
	Oct 2	-	-	-	-	-	-	-	-	-	2	1.1	27	2	1.5	27
	Oct 28	-	-	-	-	-	-	2	0.8	38	-	-	-	2	1.3	23
	Oct 28	-	-	-	-	-	-	-	-	-	-	-	-	2	1.0	40¶
Fiddler's Elbow Practice	Sep 18	2	2.7	22	2	2.4	21	-	-	-	2	1.7	23	2	2.8	21
Montclair 5th	July 16	1	2.2	36	1	0.8	38	1	0.5	40	-	-	-	-	-	-
	Aug 12	1	2.1	19	2	1.4	14	-	-	-	1	0.2	0	-	-	-
	Sep 24	-	-	-	-	-	-	-	-	-	2	0.4	25	-	-	-
Metedeconk 19th	July 11	1	1.2	8	1	0.9	11	1	0.6	0	-	-	-	-	-	-
	Aug 14	1	2.1	5	2	1.1	9	1	0.7	0	-	-	-	-		-
	Sep 11	2	2.8	11	2	1.3	8	-	-	-	1	0.6	0	2	0.6	0
	Oct 16	2	1.8	16	2	1.4	7	-	-	-	2	0.5	0	-	-	-
Woodbury 1st	July 25	1	2.5	8	1	0.9	22	1	0.5	40	-	-	-	-	-	-
	Aug 29	2	1.6	13	2	1.1	18	-	-	-	1	0.2	0	-	-	-
	Sep 27	2	1.7	12	2	1.3	15	-	-	-	2	0.5	20	-	-	-
Galloway 17th	Jul 9	1	1.2	17	1	0.7	14	1	0.7	29	-	-	-	-	-	-
	Aug 6	-	-	-	1	1.5	20	-	-	-	1	0.4	0	-	-	-

Appendix 3 (continued).

putting Green Location	1996	Rigid Tire Wheelchair			Pneumatic Tire Wheelchair			Heel of Sneaker			Heel of Golf Shoe			Pneumatic Single Rider		
		n†	Dep‡	Reb§	n†	Dep‡	Reb§	n†	Dep‡	Reb§	n†	Dep‡	Reb§	n†	Dep‡	Reb§
			mm	%		mm	%		mm	%		mm	%		mm	%
Galloway 18th	Jul 9	1	1.3	38	1	0.7	29	1	0.3	0	-	-	-	-	-	-
	Aug 6	-	-	-	1	1.7	18	-	-	-	1	0.6	0	-	-	-
Blue Heron Pines 1st	Jul 9	1	1.4	29	1	0.9	11	1	0.4	50	-	-	-	-	-	-
	Oct 1	-	-	-	-	-	-	-	-	-	2	0.6	-	-	-	-

† Number of observations.
‡ Depth of depression.
§ Percent rebound of depression 30 minutes after traffic.
¶ Pneumatic tire of 16.5 cm wide pneumatic tire single rider cart.

Appendix 4. Number of averaged positions, measured depth of depression, and percent rebound of a depression for the heel of a sneaker, heel of a golf shoe, 2.5-cm wide rigid tire wheelchair, 3.5-cm wide pneumatic tire chair, and 15-cm wide pneumatic tire single rider cart measured on topdressed modified native soil greens during 1996.

Putting Green Location	1996	Rigid Tire Wheelchair			Pneumatic Tire Wheelchair			Heel of Sneaker			Heel of Golf Shoe			Pneumatic Single Rider		
		n†	Dep‡	Reb§	n†	Dep‡	Reb§	n†	Dep‡	Reb§	n†	Dep‡	Reb§	n†	Dep‡	Reb§
			mm	-%-		mm	%		mm	%		mm	%		mm	%
Canoebrook 13th	Jun 24	1	3.1	16	-	-	-	3	0.2	0	-	-	-	-	-	-
	Aug 6	1	2.6	12	1	1.4	-	1	0.4	-	-	-	-	-	-	-
	Aug 26	2	2.1	24	2	1.4	29	1	0.4	50	-	-	-	-	-	-
	Oct 2	-	-	-	-	-	-	-	-	-	2	0.4	50	2	0.7	43
	Oct 28	-	-	-	-	-	-	2	0.4	25	-	-	-	2	1.1	33
	Oct 28	-	-	-	-	-	-	-	-	-	-	-	-	2	0.9	36¶
Fiddler's Elbow 12th	May 1	1	1.4	-	-	-	-	-	-	-	-	-	-	-	-	-
	Jun 13	1	2.0	20	-	-	-	1	0.6	33	-	-	-	-	-	-
	Jul 10	2	2.3	4	1	1.1	18	1	0.6	0	-	-	-	-	-	-
	Aug 22	-	-	-	2	1.2	8	-	-	-	-	-	-	-	-	-
Montclair 18th	Aug 12	1	1.3	38	1	1.2	42	-	-	-	1	0.1	0	-	-	-
	Sep 24	-	-	-	-	-	-	-	-	-	2	0.5	20	-	-	-
Plainfield 5th	Jun 10	1	1.1	-	-	-	-	-	-	-	-	-	-	-	-	-
	July 22	1	1.2	8	1	0.7	14	1	0.6	33	-	-	-	-	-	-
	Aug 19	1	1.7	23	2	1.0	0	1	0.2	0	-	-	-	-	-	-
	Sep 16	2	1.9	21	2	1.1	9	-	-	-	1	0.5	20	-	-	-
	Oct 17	2	1.2	17	2	0.9	22	-	-	-	2	0.3	0	-	-	-
Springdale 12th	July 18	1	1.3	23	1	0.4	0	1	0.6	50	-	-	-	-	-	-
	Aug 20	1	1.4	7	1	0.7	14	1	0.2	-	-	-	-	-	-	-
	Sep 30	2	1.2	33	2	1.1	36	-	-	-	2	0.6	17	-	-	-
	Oct 29	-	-	-	2	0.7	14	-	-	-	2	0.4	25		-	-

Appendix 4. (continued).

Putting Green Location	1996	Rigid Tire Wheelchair			Pneumatic Tire Wheelchair			Heel of Sneaker			Heel of Golf Shoe			Pneumatic Single Rider		
		n†	Dep‡	Reb§	n†	Dep‡	Reb§	n†	Dep‡	Reb§	n†	Dep‡	Reb§	n†	Dep‡	Reb§
			mm	-%-		mm	%		mm	%		mm	%		mm	%
Tavistock 5th	Jun 20	1	1.3	-	-	-	-	1	0.7	-	-	-	-	-	-	-
	July 24	1	1.9	-	1	1.0	20	1	0.9	22	-	-	-	-	-	-
	Aug 28	2	1.4	14	2	1.1	45	-	-	-	1	0.5	40	-	-	-
Ramblewood 9th	Sep 25	2	1.7	41	2	1.0	40	-	-	-	2	0.5	40	-	-	-

† Number of observations.
‡ Depth of depression.
§ Percent rebound of depression 30 minutes after traffic.
¶ Pneumatic tire of 16.5 cm wide pneumatic tire single rider cart.