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Root growth dynamics in golf greens with different compression intensities and winter survival

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The aim of this study was to measure root growth dynamics under Nordic putting green conditions in order to estimate the sensitivity of root growth to winter damages and compression. Root numbers of turfgrasses were measured from soil depths of 0–40 cm by minirhizotrons. The minirhizotrons tubes were installed in the most compressed (center) and less walked (edge) parts of putting greens with good or weak winter survival. The highest root numbers were recorded under less walked green edge areas with good winter survival. The lowest root numbers were measured from center areas of greens, especially from areas suffering winter damage in previous years. Morphological parameters of roots were studied by a destructive soil sampling method in midseason 1998. Based on image analysis of washed roots, root length density at soil depths of 0–2.5 cm was 400 cm cm^{-3} in greens of weak winter survival and up to 900 cm cm^{-3} in greens of good winter survival. Our findings emphasize that root growth of turfgrasses is highly dynamic and sensitive to compression despite of non significant effects on soil porosity. Reduced root growth of greens with weak winter survival continued despite of recovery of shoot growth.

Key-words: annual bluegrass, *Poa annua* L., bentgrass, *Agrostis stolonifera* L., rooting, soil structure, turfgrasses, trampling, compression, compaction

Introduction

One of the most severe problems in turfgrass maintenance in cold climates is winter damage to roots and crowns. Roots and crowns situated in the porous thatch layer are subjected to considerable temperature fluctuations that can damage turfgrass crowns and the root system if snow cover is thin. Crown and root damage may result in slow initiation of growth in spring thus shortening the golf season.

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Therefore, operating budgets such as 100 000 USD are used in some golf courses in USA to snow and ice removal and recovery efforts (Skorulski 2002). In Southern Finland the golf season usually starts in late April or early May and in Central Finland in the middle of May. Because of slow recover of greens after winter, season delays typically occur and parts of the golf courses, mainly greens, need to be closed. This is critical for the business and all efforts are made to alleviate winter damages and avoid late opening of golf courses.

Under wetted conditions with excessive thatch accumulation, freezing/thawing cycles, common in Nordic countries, may play a large role in causing winter injury (Beard 1964). Foot and vehicular wear and compaction of greens induce low water infiltration and wetted conditions where winter damage by ice encasement is likely to occur. Comparing to fine textured soils, coarse textured putting greens with 80–85% of sand and 15–20% (v/v) peat (Lagerstedt et al. 1996) are less sensitive to soil compaction (Håkansson 2005). Turfgrasses are, however, subjected to intensive pressure of vehicular and foot traffic and some soil compaction is apparent (Pietola et al. 2005). Although warm season turfgrasses are generally more wear tolerant than cool season turfgrasses (Youngner 1961), short (<10 mm) and frequent (5 times per week) mowing of putting greens (Carrow 1980) as well as wear and compaction generally decrease shoot growth and rooting (Madison 1962, Carrow 1980, O´Neil and Carrow 1982, 1983, Sills and Carrow 1983). Root systems under compacted putting green conditions may also be susceptible to weak aeration (Grable 1966).

Wetted conditions with winter injury followed by excessive trampling may restrict root growth and hence nutrient use efficiency. In addition to avoid winter injuries to prolong the season, a current challenge of managing golf greens is how to use water and nutrients as efficiently as possible. For optimal use of nutrients and water, knowledge of the growth, distribution, and turnover of roots is essential (Barber and Silberbush 1984, Eissenstat 1992). Little information is, however, available regarding root growth dynamics of turfgrasses under Nordic conditions, especially over an entire growing season. Data concerning soil compaction or winter injuries are even scarcer. This information is necessary for improving management practices such as timing of nutrient application, removal of thatch, sanding, aeration and possible traffic control.

In this study, we examined rooting under typical putting green conditions. The objective was to study soil structure and root growth on thriving and winter-damaged greens. Specifically, we attempted to study root growth dynamics on thriving and winter-damaged greens with various foot traffic intensities over one-year period. Additionally, we aimed to measure root biomass and morphological parameters of roots on thriving and winter-damaged greens in the middle of the golf season.

Material and methods

Field site and management practices

Root data was collected from April to September 1998 and from April to May 1999 from 10-year old putting greens, mixture of creeping bentgrass (*Agrostis stolonifera* L., cv. Penncross, 45 %) and annual bluegrass (*Poa annua* L., 55%), in Southern Finland (60°39’N, 24°49’E). Putting greens had been constructed in 1987–88 with sand particle size of 0.1 to 2.0 mm and 20% (v/v) peat to a soil depth of 30 cm (Golf Course Architect Kosti Kuronen, interview in February 2007). Soil pH varied between 6.2 and 7.3. Fertilization rates in the growing season of 1998 were 285 kg ha^{-1} N, 45 kg ha^{-1} P, and 260 kg ha^{-1} K.

Putting greens during the growing season of 1998 were maintained at a height of 0.4–1.0 cm. In spring 1999 the height of cut was maintained at 1.0 cm. In 1998 mowing was performed 6–7 times per week, vertical mowing three times and sand topdressing two times in a season, aeration with solid tines to a soil depth of 15.0 cm once (on 20 July) and slicing five times in a season. In spring 1999 slicing was performed once (on 5 May). The typical Southern Finland weather data is given in Table 1.

Table 1. Average mean temperatures per month (°C) and monthly rainfall (mm) at the experimental site.

Year	Month	Temperature (°C)	Rainfall (mm)
1998	Apr	3.0	23
	May	10.1	44
	June	14.0	109
	July	16.6	155
	Aug	14.2	91
	Sept	11.9	17
1999	Apr	5.6	48
	May	8.3	8

Treatments

The study included eight greens: four separate putting green sites with either good winter survival (thriving greens) or weak winter survival (winter-damaged greens) were selected based on visual observations of turf growth after winter in previous years. Plant and soil parameters were measured in 1998–1999 from two locations on each of these sites, which were subjected to similar maintenance practices but different foot traffic: green edge area with low foot traffic (edge) and green center area with high foot traffic (center).

Root measurements: minirhizotrons

In September 1997 three cellulose acetate butyrate minirhizotron (MR) tubes (inside diameter 5.0 cm) were installed into holes made by soil probes for each of the eight putting greens (Bartz Technology Co., Santa Barbara, CA, USA), at 45° angles to the soil surface. Two MR tubes of length of 93 cm were installed parallel to each other and 0.50 m apart at the green edge area, and one MR tube of length of 63 cm at the green center area. The entry ports of the tubes faced north. Minirhizotron tubes in green edge areas extended above the soil surface (25 cm). The entry ports were first painted black and then white to exclude light and thermal radiation (Ferguson and Smucker 1989). To facilitate low mowing in the green center area, the entry port of the center tube was a few millimeters below the turf surface and covered with slice of turf, which was removed during video recording. Roots intersecting MR tubes were observed using a BTC-2 type camera (Bartz Technology Co.). An extension MR tube (25 cm) was used in center tubes when MR microvideo camera system (Upchurch and Ritchie 1984), equipped with index handles (Ferguson and Smucker 1989), was inserted into the tubes.

Each of the MR tubes were imaged 14 times from 21 April to 23 September in 1998, from day of year (DOY) 111 to 266. Last two recordings were made on 26 April and 25 May in 1999. The microvideo camera was inserted to a depth where roots were observed and the tube number, date, and starting depth were recorded. The camera was manually withdrawn from the MR at 1.4 cm intervals with images being recorded for 4 seconds at each position. Each recorded root frame at the upper surfaces of the transparent MR tubes was 2.43 cm^2. Summations of three successive frames were used to calculate the total number of roots for each 3.0 cm soil layer; this will be referred to as the MR root count (number of roots per square centimeter of tube face). Means of summations of two tubes in edges areas were counted for each green. The living root numbers on videotapes were counted manually. Living active roots were considered to be white roots with distinctly sharp edges and no signs of decomposition.

Root measurements: washed roots analysis

For the image analysis of washed roots core samples (diameter 5.05 cm) were taken at 2.5 cm increments to a depth of 20 cm on 17 June in 1998. Three subsamples per a green (two edge, one center area) per soil layer were taken and combined for a total sample volume of 150 cm^3 per soil layer. Root samples were frozen (−20°C) in plastic bags until separated from soil using a hydropneumatic elutriation system (Smucker et al. 1982). Before subsampling and image analyses, the washed roots were stored at 4°C in 15% (v/v) ethanol. Subsampling of roots was then performed because of huge amount of fine material per a sample as follows: roots were rinsed with water on a nylon screen and placed uniformly on a clear glass tray (18 × 28 cm) covered with 3 mm of water. A metal core sampler (diameter 7.1 cm) was used to take subsamples (5–10% of roots) from the roots. The rest of the roots were dried (at 70°C for 48 h) and weighed. Subsamples were manually cleaned from non-root debris and the dry weight of the debris was determined. Root subsamples were dyed with Malachite green oxalate for 1–2 days before scanning by injecting 0.15–0.30 ml of 1% dye into the plastic storage container containing 15% (v/v) ethanol. After scanning the roots by Simojoki (2000), roots were dried (at 70°C for 48 h) and weighed. The scanned images of roots were analysed by using ROOTEDGE image analysis program (Ewing and Kaspar 1995), which measured lengths and widths of roots in binary images. In the image analysis, materials with length-to width ratios of <3:1 were deemed non-root debris and discarded. Root length and weight densities were calculated on a soil volume basis for the whole sample (150 cm^3). Prior to the calculations the amount of the debris was subtracted from the amount of the rest of the roots.

Soil physical parameters

For calculations of dry bulk density, volumetric water content and macroporosity, soil core samples (inside diameter 7.1 cm, height 5.0 cm) were taken with the aid of a golf hole cutter on 4 October in 1998. Two cores from each sampling position (edge and center) on both thriving and winter-damaged sites were taken from soil depths of 0–5.0 and 10.0–15.0 cm. The volume of macropores (pore diameter > 300 µm and > 30 µm) was measured to calculate soil volumetric water contents between saturation and water potentials of –1, and –10 kPa (Pietola et al. 2005). For measurements of soil dry bulk density and volumetric water content cores were dried at 105°C for 24 h. The averages given by two corings were calculated to represent each sampling position and depth. The texture of each green was analyzed by dry sieving, from sample size of 1 dm^3, at soil depth of 0–15 cm.

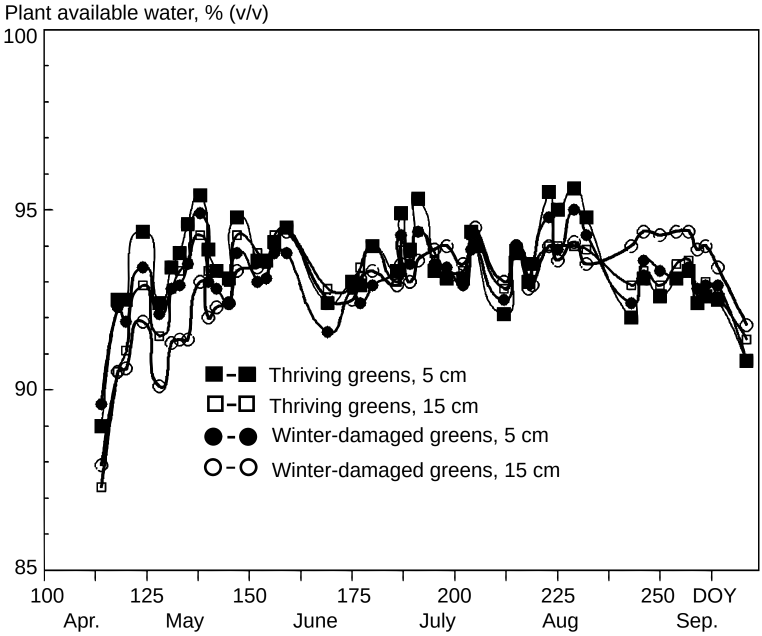

Fig. 1. Plant available soil moisture during the growing season 1998 in 5.0- and 15.0-cm soil depths. Standard error <0.1 (n = 4).

Table 2. Particle size distribution (%) of the golf greens at soil depth of 0–15 cm.

	Particle size (mm)				
	>2	0.6–2	0.2–0.6	0.06–0.2	<0.06
Thriving greens					
I	5.1	40.1	43.3	9.6	1.8
II	5.3	32.6	50	11	1.2
III	5.8	30.1	45.2	16.8	2
IV	0	26.9	49.7	21.7	1.8
average	4.1	32.4	47.1	14.8	1.7
Winter-damaged					
I	4.1	16.3	44.4	31.3	3.9
II	2.7	19.1	48.4	26.1	3.8
III	1.8	22.5	46.9	25.6	3.3
IV	5.6	25.6	47	19.2	2.7
average	3.6	20.9	46.7	25.6	3.4

A cone penetrometer (30° angle), as described by Anderson et al. (1980) was used to measure mechanical impedance to a subsoil at 3.5 cm intervals on 2 October in 1998, when soil was at field capacity. The cone index of each sampling position (edge and center) was measured with four replications at both thriving and winter-damaged sites at a distance of 50 cm from MR tube. The records shown by the penetrometer were converted into pressure units, pascals (Pa), with the coefficient 76.2 (maximum cone diameter 1.28 cm). The medians of four measurements at each depth zone were calculated. Volumetric soil water content was recorded within two days of the measurement of mechanical impedance by method described above.

Additionally, soil moisture was measured throughout the growing season 1998 (from 11 April to 30 October) by the gypsum block method (Soil Moisture Co., AZ, USA) (Bouyoucos 1954) from soil depths of 5.0 and 15.0 cm. The continuous soil moisture recording for plant available water content was performed 2–3 times a week.

The accumulation of thatch was measured on 29 April and 17 August in 1998 by inserting soil core sampler into the surface soil in the proximity of the MR tubes. Thickness of thatch layer was measured by using a metric ruler (Callahan et al. 1997).

The significance of differences between group means was tested by analysis of variance by completely randomized plot design with four replicates at each depth zone. Comparisons of means were made using Tukey´s Honestly Significant Difference (HSD) test to determine significant ($P \leq 0.05$) differences (Steel and Torrie 1980).

Results and discussion

Soil physical condition

At soil depths of 0–15 cm, soil texture was slightly coarser in thriving greens, with 32% sand particles (diameter 0.6–2.0 mm), compared to 21% in winter-damaged greens (Table 2). Therefore, reduced soil macroporosity at soil depths of 0–5 cm and 10–15 cm was recorded for winter-damaged greens (Table 3). Because of rainy season 1998 and irrigation, soil moisture was high through the season with no significant differences in plant available water content between thriving and winter-damaged greens (Fig. 1). The present data from the growing season did not show any water logging. Some thatch accumulation was, however, recorded in the soil surface (0–5 cm) of winter-damaged greens, explaining higher volumes of macropores (diameter > 30 µm) than under thriving green conditions (Table 3): thickness of thatch in April 1998 was 16 mm for thriving and 13 mm for damaged greens and corresponding values in August 1998 were 18 and 20 mm, respectively. It is possible that organic matter from thatch coated air-filled pores and hindered air and water flow in the rooting medium

(Chong et al. 2003). On the other hand the lower volumes of macropores in thriving greens than in winter-damaged greens in the soil surface layer can result in accumulation of roots and decaying plant parts to air-filled pores, because of excess root and shoot growth (Carrow 2004). Although trampling did not significantly affect total porosity or bulk density (Table 3), intensive foot traffic and wear tore the cells of turfgrasses, and apparently closed macropores of thatchy soil surface.

The results of soil volume and mass relationships indicate that the putting green mixture of sand and peat restricted soil compaction, thus agreeing with Swartz and Kardos (1963) or Brown and Duble (1975). Soil compaction was, although slightly, recorded by increased soil mechanical impedance (Fig. 2). Cone penetrometer resistance exceeded 4.0 MPa in center areas of the winter-damaged greens at a soil depth of 20 cm. In thriving greens, penetrometer resistance exceeded 4.0 MPa much deeper in soil (30 cm). Lagerstedt et al. (1996) suggested that soil penetrometer resistance of 1.4–4.0 MPa does not restrict the growth of turfgrass roots. For field crops on less coarse soils, 3 MPa is a general limit of too high penetration resistance to impede root growth (Håkansson 2005). In all likelihood, lower mechanical impedance in greens with good winter survival allowed more space for roots to penetrate deeper into the soil to exploit nutrients and water. This, for one, promoted good winter survival, as deep root system and large surface area shelter from the negative effects of cold weather, for example frost heaving.

Root growth dynamics

After MR-tube installation in September 1997, no root growth was observed in the surface of the tube before May 1998. Numbers of roots observed from MR increased from 5 May to 24 June (125–175 DOY) in green edge areas, but in green center areas root numbers increased later from 24 June to 2 October (175–275 DOY) (Fig. 3). Root growth of green center areas later in summer is apparently a sign of reduced root development under foot traffic.

The recorded accelerating root growth rate (Fig. 3) is typical under Nordic conditions, and found also for annual ryegrass in field conditions in Southern Finland (Pietola and Alakukku 2005). Based on botanical analyses of the present study, thriving greens had 47.5% annual bluegrass and 52.5% creeping bentgrass and winter-damaged greens 40.9% and 59.1%, respectively. Annual bluegrass initiates growth slowly in the spring (Paatela

Table 3. Macropore volume, total porosity, and dry bulk density in compressed and less walked parts of golf greens of thriving and winter-damaged sites on 7 October 1998.

Soil depth (cm)			Porosity (%, v/v)			Dry bulk density
			Ø>300 µm	Ø>30 µm	all pores	(g cm^{-3})
0–5	Thriving greens	Less walked	1.6	12.4	43.6	1.32
		Compressed	1.8	12.5	45.5	1.31
	Winter-damaged	Less walked	1.4	15.4	42.8	1.31
		Compressed	1.4	16.2	42.7	1.29
	HSD$_{0.05}$		ns	3.2	ns	ns
10–15	Thriving greens	Less walked	1.7	20.1	41.1	1.52
		Compressed	1.7	22.1	41.5	1.48
	Winter-damaged	Less walked	1.2	14.9	39.5	1.45
		Compressed	1.3	13.4	42.3	1.42
	HSD$_{0.05}$		ns	4.0	ns	ns

HSD$_{0.05}$ = honestly significant difference at 5% level. ns = not significant at 5% risk level

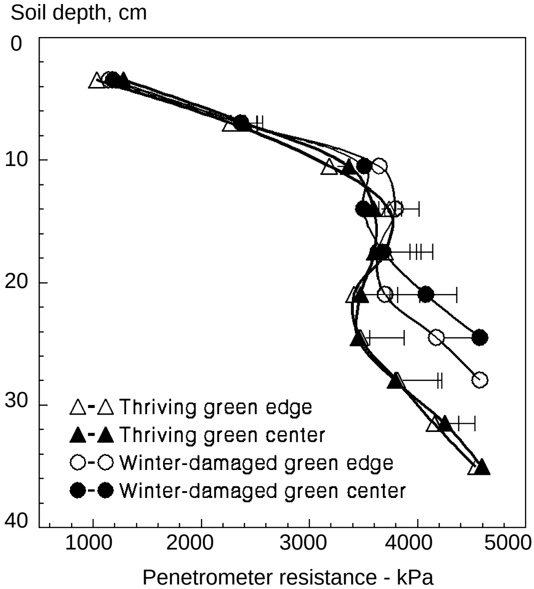

Fig. 2. Penetrometer resistance on 2 October 1998 in compressed (center) and less walked (edge) parts of golf greens of thriving and winter-damaged sites. Error bar = 1 × standard error. (n = 4)

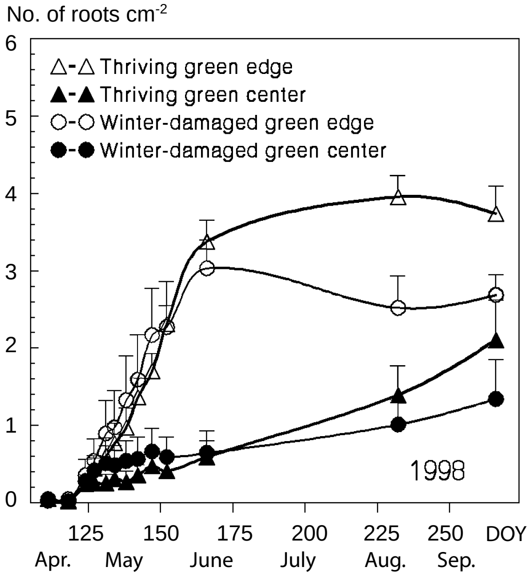

Fig. 3. Average root numbers during the 1998 growing season on a minirhizotron tube surface in 0- to 40-cm soil layers of turfgrass species *Agrostis stolonifera* L. and *Poa annua* L. in compressed (center) and less walked (edge) parts of golf greens of thriving and winter-damaged sites. Error bar = 1 × standard error. (n = 4)

and Järvinen 1994). Despite of higher amount of annual bluegrass in thriving greens, total number of roots increased faster than those of winter-damaged greens (Fig. 3).

The negative effect of traffic and wear was reflected by lower root numbers in center areas of putting greens, especially in winter-damaged areas of less favourable soil physical conditions. Intensive foot traffic hindered root growth even more than winter damage alone in winter-damaged greens. Obviously, the wear tore the cells of turfgrasses and closed macropores which, in turn, affected rooting (Figs. 3–5).

Greatest root numbers were recorded from soil depths of 0–6 cm, in agreement with observations by Murphy et al. (1994) who reported that creeping bentgrass and annual bluegrass maintain root system at soil depths of 0–2.5 cm. In June 1998 56–57% of roots were located at this surface (0–6 cm) layer, (Fig. 4). Number of roots in the surface layer declined to 44–54% in August, indicating penetration of roots deeper into the soil (Fig. 5). The deepest rooting was observed in August, at the soil depth of 30–36 cm. Deep rooting was also found in May 1999 (Fig. 6) in thriving greens from soil layers where soil mechanical impedance was low (Fig. 2). Therefore, total number of roots within the 0 to 39-cm region of the soil profile increased most under the less compressed parts of green edge areas. These numbers of roots, that were significantly ($P < 0.05$) higher than in green center areas, were recorded on 20 August to 23 September in 1998 (DOY 232–266) and on 26 April to 25 May in 1999 (DOY 116–145) (Figs. 3, 7).

Intensive wear has been demonstrated to tear and scuff cells of turfgrasses, especially in low mowing, causing deterioration of growth (Youngner 1962, Carroll and Petrovic 1991). Our study also showed that root growth is disturbed by intensive wear and foot traffic. The effect was most clear at soil surface to a 10 cm soil depth (Figs. 4–6). While the result may be partly due to somewhat different

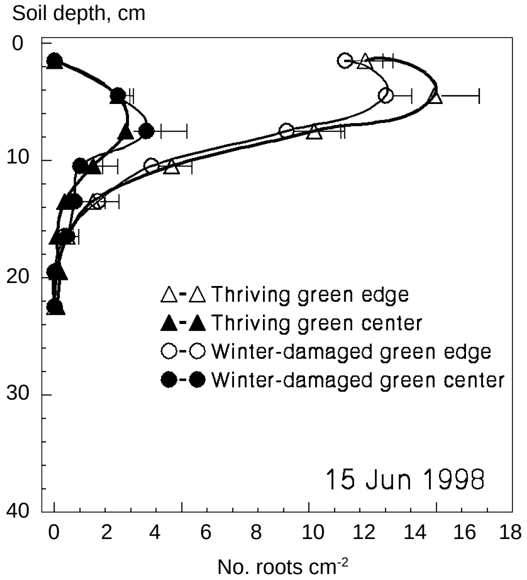

Fig. 4. Root distribution of turfgrass species *Agrostis stolonifera* L. and *Poa annua* L. on 15 June 1998 in compressed (center) and less walked (edge) parts of golf greens of thriving and winter-damaged sites. Error bar = 1 × standard error. (n = 4)

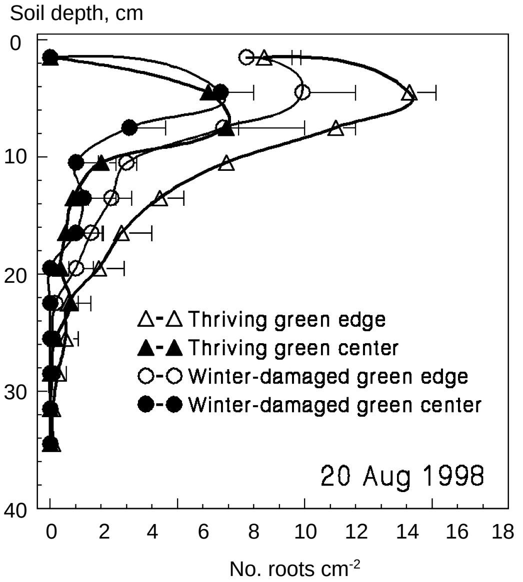

Fig. 5. Root distribution of turfgrass species *Agrostis stolonifera* L. and *Poa annua* L. on 20 August 1998 in compressed (center) and less walked (edge) parts of golf greens of thriving and winter-damaged sites. Error bar = 1 × standard error. (n=4

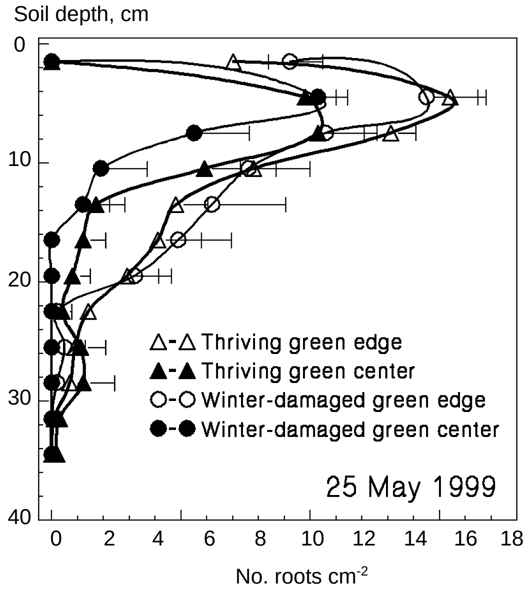

Fig. 6. Root distribution of turfgrass species *Agrostis stolonifera* L. and *Poa annua* L. on 25 May 1998 in compressed (center) and less walked (edge) parts of golf greens of thriving and winter-damaged sites. Error bar = 1 × standard error. (n = 4)

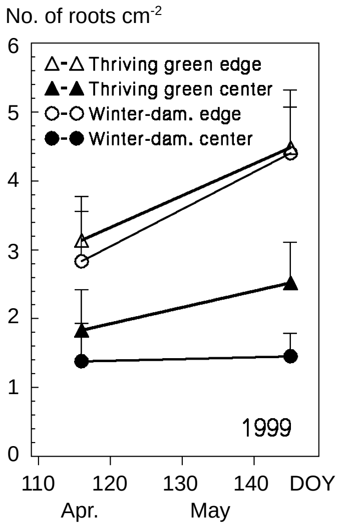

Fig. 7. Average root numbers during the 1999 early season on a minirhizotron tube surface in 0- to 40-cm soil layer of turf grass species *Agrostis stolonifera* L. and *Poa annua* L. in compressed (center) and less walked (edge) parts of golf greens of thriving and winter-damaged sites. Error bar = 1 × standard error. (n = 4)

Table 4. Root length densities, root diameter, and dry weight of thriving and winter-damaged greens on 17 June 1998.

Soil depth (cm)		Root		
		length density (cm cm^{-3})	diameter (mm)	dry weight (mg $^{-3}$)
0–2.5	Thriving	899	0.30	39.9
	Winter-damaged	412	0.32	21.9
	HSD$_{0.05}$	386	ns 1)	15.0
2.5–5	Thriving	506	0.30	14.6
	Winter-damaged	432	0.28	10.7
	HSD$_{0.05}$	ns	ns	ns
5–7.5	Thriving	15.0	0.21	0.33
	Winter-damaged	39.0	0.24	0.93
	HSD$_{0.05}$	ns	ns	ns
7.5–10	Thriving	11.5	0.21	0.23
	Winter-damaged	11.1	0.21	0.26
	HSD$_{0.05}$	ns	ns	ns
10–12.5	Thriving	6.4	0.18	0.13
	Winter-damaged	4.2	0.18	0.18
	HSD$_{0.05}$	ns	ns	ns
12.5–15	Thriving	2.4	0.17	0.05
	Winter-damaged	1.2	0.19	0.03
	HSD$_{0.05}$	ns	ns	ns
15–17.5	Thriving	0.4	0.34	0.01
	Winter-damaged	0.1	0.20	0.01
	HSD$_{0.05}$	ns	ns	ns
17.5–20	Thriving	0.4	0.17	0.01
	Winter-damaged	0.1	0.18	0.01
	HSD$_{0.05}$	ns	ns	ns

HSD$_{0.05}$ = honestly significant difference at 5% level. ns = not significant at 5% risk level

heights of cut between the green edge and center areas, it is probably mostly due to plant and soil compression under foot traffic (Madison 1962).

Minirhizotron root counts from August 1998 to May 1999 continued to show significantly lower root numbers in winter-damaged greens (Figs. 3, 7), although shoot growth had recovered. This result is in accord with Qian et al. (2001), who reported that root regrowth of buffalograss (native to the short-grass prairie region of North America) was reduced by freezing temperatures to a greater extent than shoot regrowth.

Root biomass and lengths

The washed root data from midseason verified the negative effect of winter injuries, specifically on rooting in the soil surface, where MR analysis could not record roots as efficiently. Root diameter varied (0.18–0.30 mm) at different soil layers, but was similar in thriving and winter-damaged greens (Table 4).

Up to 98% of root lengths of thriving greens were recorded at depths of 0–5 cm. The corresponding figure for winter-damaged greens was 94%. Root length density (RLD) at soil depths of 0–2.5 cm was 900 cm cm^{-3} in thriving greens, but only 410 cm cm^{-3} in winter- damaged greens. This result is in agreement with the 414 cm cm^{-3} observed by Murphy et al. (1994). The impact of winter damage was reflected by MR root counts at soil depths of 0–24 cm, averaging 6.4 roots cm^{-2} for thriving greens and 6.0 roots cm^{-2} for winter-damaged greens. These MR root counts are only slightly higher than those reported by Murphy et al. (1994).

Comparing to RLD data, the MR data indicated relatively small negative effect of winter damage on rooting. This can be due to the difficulties to record all roots on soil surface by MR-technique as the contact between MR tube and soil is weak, and the whole viewing frame was full of roots at soil depths of 0–2.5 cm, where most roots were recorded by the RLD data. Despite of elimination of short non-root residue by the computer image analysis, RLD data may also have been overestimated in the soil surface due to extensive amount of long and hardly visible non-root residues in the sample.

Conclusions

Although trampling did not significantly affect soil volume and mass relationships, root growth was restricted by foot traffic. Therefore, intensively used parts of golf greens demand site-specific management practices to optimize rooting.

Finer soil texture caused reduced macrospore volumes and increased mechanical impedance in winter-damaged greens, where reduced root growth was observed even the following year and in spite of the recovery of shoot growth.

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SELOSTUS

Golfnurmien juuriston kasvun vaihtelut runsaasti tallatuilla viheriöiden keskiosilla ja vähän tallatuilla reunoilla

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Maan tiivistyminen vaikeuttaa juuriston kasvua sekä edelleen kasvien veden ja ravinteiden ottoa. Golfviheriöillä pelaamisesta aiheutuvan tallauksen tiedetään vahingoittavan kasvustoa, mutta tallauksen vaikutuksista juuristoon on vähän tietoa. Varsinkin huonosti talvehtineilla viheriöillä kasvuston on todettu olevan erityisen arka pelaamisesta aiheutuvalle kulutukselle. Tämän tutkimuksen tavoitteena oli mitata pelaamisesta aiheutuvan tallauksen vaikutuksia viheriöiden nurmikkoheinien juuriston kasvuun kasvukauden eri aikoina. Juuriston kasvua mitattiin sekä hyvin että heikosti talvehtineilla viheriöillä.

Tutkimus toteutettiin 1997–1999 Hyvinkäällä Hyvigolfin kentällä, jonka viheriöillä kasvoi kylänurmikkaa ja rönsyrölliä. Tutkimusmenetelminä käytettiin miniritsotronitekniikkaa ja maasta erikseen pestyjen juurien kuva-analyysiä. Miniritsotronit eli läpinäkyvät muoviputket (halkaisija 5 cm, pituus 60 cm) sijoitettiin syksyllä 1997 viheriöiden laidoille ja keskiosiin 45 asteen kulmaan maanpintaan nähden. Seuraavina vuosina juurikuvia tallennettiin putkien sisältä videokameralla 0–40 cm:n syvyyksissä. Juurikuvat (2,43 cm^2) tallennettiin putkien yläpinnasta, ja kuvaus kohdennettiin samoihin kuva-alueisiin jokaisella 14 mittauskerralla. Kesällä 1998 otettiin lisäksi maanäytteitä, joista juuret eroteltiin vesi- ja ilmavirran avulla hydropneumaattisella elutrointi-laitteella. Juuret värjättiin ja skannattiin vesipatjan päällä lasitarjottimella. Skannatusta digitaalisesta kuva-aineistosta määritettiin juurien pituus ja paksuus kuva-analyysin avulla.

Tulosten mukaan viheriöiden nurmikkoheinien juurten määrä vaihteli suuresti kasvukauden eri aikoina. Keväällä juuriston kasvu oli nopeaa, mutta videokuvista lasketut juurien ja juurten haarojen lukumäärät tasaantuivat keskikesällä. Tallatuilla viheriöiden keskiosilla juuria havaittiin huomattavasti vähemmän kuin viheriöiden reunoilla. Hyvin talvehtineilla ja vähän tallatuilla viheriöiden osilla juurien lukumäärät olivat suurimmat. Suurin osa juuristosta kasvoi 0–5 cm:n kerroksessa. Kuva-analyysin perusteella juuritiheys (= pituus maatilavuudessa) oli 20 cm:n syvyydessä keskimäärin 180 cm/cm^3 hyvin talvehtineilla ja 110 cm/cm^3 huonosti talvehtineilla viheriöillä (n = 4). Maan pinnassa (0–2,5 cm) vastaavat juuritiheydet olivat jopa 900 ja 400 cm/cm^3, joka vastaa ulkomailla mitattuja golfnurmikkoheinien tiheyksiä.

Tallausvaikutus oli suurin pintamaassa. Penetrometrillä mitattu maan mekaaninen vastus tai huokostilavuus ei kuitenkaan muuttunut merkittävästi 0–10 cm:n syvyydessä. Tulos viittaa siihen, että tallaus vaikutti juuristoon kuluttamalla maan päällistä kasvustoa, painamalla kuitukerrosta kasaan ja tuhoamalla maan huokosten jatkuvuutta. Kuitukerroksen painuminen kasaan hidastaa kaasujen vaihtoa, ja huokosten jatkuvuuden tuhoutuminen hidastaa veden johtavuutta kasvualustassa. Nämä muutokset saattavat aiheuttaa talvivaurioita lisäämällä jään muodostusta. Tutkimuksen mukaan huonosti talvehtineilla viheriöillä juuriston kasvu oli heikentynyt vielä kaksi vuotta talvivaurioiden toteamisen jälkeen, vaikka maanpäällinen kasvusto oli jo elpynyt.