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Comparing soil physical properties on robotic and traditionally mown golf course fairways

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Jordens fysiske egenskaper ble studert på to golfbaner der enten små, lette robotklippere eller store, tunge tradisjonelle gressklippere hadde vært brukt i fire til fem år. På begge banene var jorda mindre komprimert der det var brukt robotklippere sammenlignet med der de store maskinene var brukt, men fordi innledende målinger manglet, kan det ikke konkluderes definitivt om forskjellene skyldtes bruk av robotklippere eller tradisjonelle gressklippere.

LAND/COUNTRY:

Norway/Denmark

FYLKE/COUNTY:

Rogaland/Region Aarhus

KOMMUNE/MUNICIPALITY:

Sandnes/Grenå

STED/LOKALITET:

Sandnes/Grenå

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Preface

This report summarizes the results of work package one (WP1) in the 'Fairways4Future'. The goal of WP1 was to investigate the influence of robotic and traditional mowing on golf course fairway soil physical properties. The two different mowing systems were compared after four to five years of robotic or traditional mowing on a golf course in Norway and on a golf course in Denmark.

The two golf courses were involved in the Robogolf-project (2020-2022) investigating turfgrass quality and other issues comparing small light-weight robotic mowers with traditional fairway and rough mowers. Results from field experiments at NIBIO-Landvik indicated less compaction with robotic mowers compared to rotary mowers in rough, and also in fairway this was the impression of the greenkeepers on the golf courses involved in the study.

The overall aim of the project "Fairways4Future" is to investigate mower type (robotic versus traditional), mowing height and fertilizer level, that result in high turfgrass and playing quality with the lowest possible input of energy and fertilizer.

The authors would like to thank David B. Smith and Atle R. Hansen on Sandnes Golf Course, Lasse Nielsen on Grenå Golf Course, and our colleagues Frederik Bø and Jannes Stolte for supporting the project. We would also like to thank Scandinavian Turfgrass and Environment Research Foundation (STERF) for funding this research study.

Grimstad, 20.08.2025

Anne F. Borchert

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1 Introduction

Compacted soils have the potential to limit turfgrass root and shoot growth (Harivandi, 2002). This leads to greater susceptibility to drought and other stresses. In such compacted areas, the soil has less air-filled porosity, lower oxygen levels, and a reduced infiltration rate, which negatively affects turfgrass and playing quality (Bigelow and Soldat, 2013).

Although perennial grasses of most turfgrass systems can normally maintain soil structure by increasing soil organic carbon and producing a network of fine roots associated with fungal hyphae (Soldat and Koch, 2023), abundant traffic with heavy mowers and other maintenance equipment can destroy this soil structure resulting in soil compaction.

Transitioning from heavy reel or rotary mowers to light-weight robotic mowers on golf course fairways and roughs could alleviate soil compaction issues associated with heavy golf course mowers. Observations on a Norwegian golf course using light-weight robotic mowers since 2017 indicate that traffic injuries were decreased (Hansen, 2022). Results from the Robogolf-project (2020 – 2022) also suggest that switching from heavy rotary mowers to light-weight robotic mowers in semi-rough prevents soil compaction and improves water infiltration (Hesselsøe et al. 2022).

Soil compaction is defined as “a form of physical degradation resulting in densification and distortion of the soil where biological activity, porosity and permeability are reduced, strength is increased and soil structure partly destroyed” by the European Soil Data Centre (ESDAC, 2025). Typical parameters for measuring soil compaction, which are all measured in this study, include soil bulk density, total porosity, soil penetrometer resistance, surface hardness, and water infiltration.

The aim of this study was to examine soil physical properties of golf course fairways mown with traditional reel mowers in comparison to golf course fairways mown with light-weight robotic mowers. Soil compaction parameters were investigated at Sandnes Golf Club (Norway) and Grenå Golf Club (Denmark) on fairways that, for four to five years prior to the data collection for this study, had been mown with either traditional or robotic mowers in the Robogolf-project.

2 Materials and Methods

2.1 Location and climate on trial sites

Sandnes Golf Club (Sandnes GC) is located at the southwestern coast of Norway, about 10 km south from Stavanger (Figure 1). The Köppen climate classification is temperate with no dry season and a warm summer (Cfb). The average annual temperature was 8.3 °C and average annual precipitation 1.480 mm from 2020 - 2023.

The 18 hole and 6 short-hole courses were established from 2003-2005. One-fourth of the golf course is covered with a marine clay that was originally excavated from the construction of a dry dock for oil installations, one-fourth is on sandy soil, one-fourth is on peat soil, and one-fourth is on agricultural land (Hansen, 2022). With up to 54.000 rounds of golf played per year, the golf course is one of the busiest in Norway.



Figure 1. Map of Norway and Denmark with Sandnes GC and Grenå GC location marked (www.freeworldmaps.net).

Grenå Golf Club's (Grenå GC's) 18 holes were established in 1981 on an old landfill. The course is situated on the east coast of Jutland in Denmark approximately 60 km east of Aarhus (Figure 1). Average annual temperature is 9.5 °C and average annual precipitation is 732 mm from 2020 – 2024 (DMI, 2025).

2.2 Fairway characteristics and assessment areas at Sandnes GC

At Sandnes GC, the 10th fairway was chosen for the Robo-Golf project in 2020 because it was one of the most difficult fairways to mow traditionally. In periods with heavy rainfall, this fairway was difficult to mow, and in periods with less rain dry patches developed quickly. As such, the greenkeepers wanted to test how the robotic mowers performed compared to the traditional mowers. Before 2020 the whole fairway had been mown traditionally with a Jacobsen 250 reel mower. In 2020

the fairway was split into two areas: one area using the same traditional mower and the other using a robotic mower (Husqvarna 550) (Photo 1; Figure 2 and Figure 3).



Photo 1. Traditional and robotic mowers at Sandnes GC. To the left traditional Jacobsen 250 reel mower and robotic Husqvarna 550. Photo: Sandnes GC.

Traditional mowing was done three times per week at a height of 12 mm while robotic mowing was done daily at the same height in a random mowing pattern. These two mowing practices were continued for almost four years, from spring 2020 to autumn of 2023. On 6 September 2023, field measurements of soil physical properties were completed on both areas. Weather conditions during sampling were sunny and warm (20 °C). The last precipitation (2.2 mm) before sampling was on 3 September. Turfgrass species on the fairway were a mixture of fine fescues, bentgrass, and annual bluegrass. Annual nitrogen fertilization was 50 kg/ha/yr.



Figure 2. An ariel view of Sandnes Golf Club. The 10th fairway was split into two management zones, which were mown with a robotic mower (green circle) and a traditional reel mower (blue circle). www.norgebilder.no

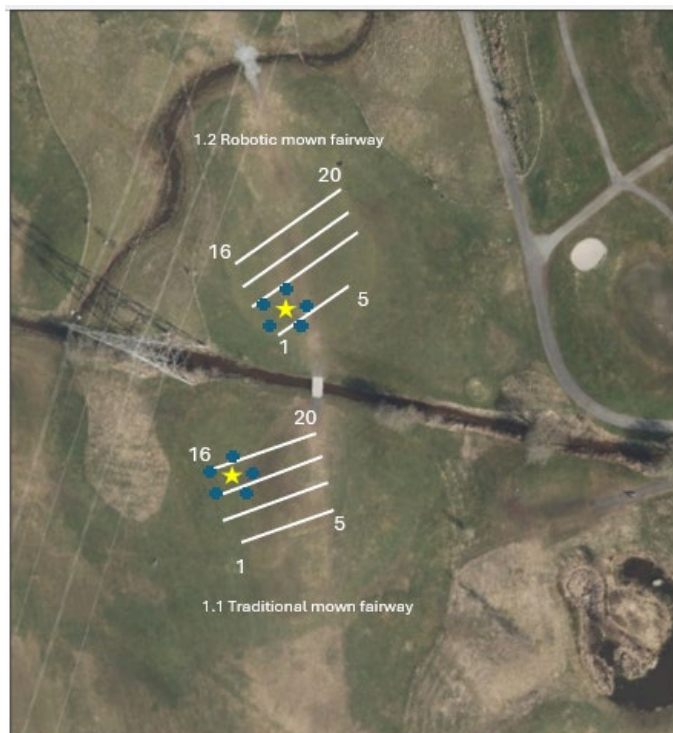


Figure 3. The 10th fairway with the location of registration areas at Sandnes GC. The yellow stars indicate the location of the soil pit where samples for bulk density, porosity, field capacity, and grain size distribution were taken. The blue crosses indicate where soil water content, surface hardness, and penetrometer measurements were taken (n=5). The white lines show where additional penetrometer measurements were taken on four transects (n = 20; 5 measurements along each line; numbers = measurement ID). www.norgebilder.no

2.3 Fairway characteristics and assessment areas at Grenå GC

At Grenå GC, the 5th and the 8th fairways were used in the study (Figure 4). The 5th fairway was mown with a Husqvarna 550 robotic mower from 2020 to 2023 and a Husqvarna Ceora robotic mower in 2024. The 8th fairway was maintained with a traditional fairway mower (Hayder 524) three times per week from 2020 to August 2024. Both mowing systems had a mowing height of 15 mm. Field measurements on Grenå GC were done 26 August 2024, with weather conditions that included sun, rain (3-4 mm), wind and temperatures at 16 °C. Assessment areas are marked in detail in Figure 5. Turfgrass species were a mixture of fine fescues, perennial ryegrass and annual bluegrass. Annual nitrogen fertilizer was 51 kg/ha/year.



Figure 4. An ariel view of Grenå Golf Club. The 5th fairway was mown with a robotic mower (green circle) and the 8th fairway was mown with a traditional mower (blue circle). <https://dataforsyningen.dk/map>



Figure 5. The 5th and 8th fairways with the location of the registration areas at Grenå Golf Club. The yellow stars indicate the location of the soil pit where samples for bulk density, porosity, field capacity, and grain size distribution were taken. The blue crosses indicate where soil water content, surface hardness, and penetrometer measurements were taken (n=5). The white lines show where additional penetrometer measurements were taken on four transects (n = 20; 5 measurements along each line; numbers = measurement ID). <https://dataforsyningen.dk/map>

2.4 Soil physical properties

Assessments of soil physical properties were done at Sandnes and Grenå GC's with the exception that no water infiltration rate was done at Sandnes. Soil physical properties including organic matter percentage, porosity, bulk density, and grain size distribution were all measured within a 1 m² area on the robotically and traditionally mown fairway at each golf course. Within this area a soil pit was dug where three bulk density rings were pounded into the ground at three different depths (5 – 10, 10 – 15, and 15 – 20 cm). A soil sample to measure organic matter percentage was taken by removing soil from the walls of the soil pit at three different depths.

2.4.1 Soil texture and organic matter

For soil texture analysis of three soil depths (5 – 10 cm, 10 – 15 cm, and 15 – 20 cm; n = 1), approximately 250 g soil from each depth on each fairway were sent to the laboratory ALS, Czech Republic. These seven particle sizes were determined according to the method CZ_SOP_Do6_07_120 (BS ISO 11277:2009) using laser diffraction: <0.063 mm, 0.063 - 0,125 mm, 0.125 – 0.25 mm, 0.25 – 0.5 mm, 0.5 – 1.0 mm, 1.0 – 2.0 mm, and > 2.0 mm.

To determine organic matter levels, loss on ignition was conducted for each soil depth (5 – 10 cm, 10 – 15 cm, 15 – 20 cm; n = 1), a 15 g soil subsample was dried at 105 °C for 24 hours, following the method described by Krogstad (1992). Thereafter, the samples were placed in a muffle furnace (HERAEUS camber furnace Type K114, Kendro Laboratory products, Hanau, Germany) at 550 °C for four hours. The weight of mineral soil matter was then determined and organic matter content was calculated by subtracting mineral soil matter from total sample weight (Krogstad, 1992).

2.4.2 Soil bulk density and porosity

Soil cores were divided into three soil depths from 5 – 10, 10 – 15, and 15 – 20 cm to analyze soil bulk density and water retention parameters on each fairway (Figure 3 and Figure 5). For each depth, three subsamples were taken according to the following procedure:

1. The soil surface was laid open at the desired depth scraping it off with a soil scraper. It was ensured that the soil was not disturbed by shovels, augers or other equipment at the sample area.
2. The soil cores were placed randomly on the soil with the sharp edge down towards the soil surface (Photo 2,a). To force the soil corers into the soil, a steel soil bell hammer was used.
3. With a small shovel the soil corers were excavated and carefully removed from the soil by placing the shovel a little below the bottom of the soil corer before lifting them up.
4. The excessive soil was carefully cut off so that the sample was even on both sides and edges before covering the sample with plastic lids on both sides (Photo 2,b).

At the NIBIO soil laboratory in Ås, Norway, soil bulk density and water retention parameters were analyzed for each of the undisturbed soil cores. The pF-determination was done by using an Eijkelkamp sandbox (Royal Eijkelkamp, Giesbeek, the Netherlands) to put on pressures pF 0.0 (saturation), pF 1.0, pF 1.5, and pF 2.0 (-100 hPa; field capacity). With rubber bands, nylon cloths were fastened to the bottoms of each cylinder (100cc). The weight of the soil cores when fully saturated at pF 0.0 was recorded. Next, the soil cores were placed on the sandbox and gently pressed down to ensure good contact between the soil and sand. Weights were measured again after equilibrium was reached at each level of applied suction. After completing the sandbox procedure, the soil samples were dried overnight in an oven set to 105 °C to determine the soil's bulk density (pF 0.0). The volumetric water content was then calculated using the following formula:

$$\theta = \frac{w}{\rho_d}$$

where w represents the gravimetric water content, obtained by dividing the weight of the soil water by the weight of the dry soil, and ρ_d represents the bulk density (g/cm^3), computed by dividing the weight of the dry soil by the volume of the core ring (100 cc).



Photo 2. The soil corers were placed on the soil surface before forcing them into the soil (a) and removed afterwards using a small shovel (b). In the background, the wooden case for transportation is shown (Photos: Anne F. Borchert).

2.4.3 Soil compaction and surface hardness

To determine soil compaction (kPa), penetrometer measurements were done from 0 - 30 cm depth using the Field Scout SC900 Soil Compaction Meter (Spectrum Technologies Inc., Illinois, USA; Photo 3). Five measurements were done in a circle close to the soil pit and additional 20 measurements on four transects distributed over a larger area of each fairway (see Figure 3 and Figure 5). The cone tip on the penetrometer was 13 mm (1/2 inch) in diameter.



Photo 3. Penetrometer measurements using the Field Scout SC900 Soil Compaction Meter at Grenå GC (Photo: Karin J. Hesselstøe).

Surface hardness was determined with a Clegg Soil Impact Tester (SD Instrumentation LTD, Trowbridge, United Kingdom) at five measurement points with five strokes close to the soil cylinder samplings (Photo 4). The load of Clegg was 2.25 kg.



Photo 4. Measuring surface hardness with the Clegg Soil Impact Tester at Grenå GC (Photo: Karin J. Hesselstøe).

2.4.4 Water content and infiltration

Soil volumetric water content (VWC %) was measured with the Field Scout TDR 100 Soil Moisture Meter with a rod length of 7.6 cm, 12.2 cm and 20.0 cm depth (Photo 5). Five measurements of each depth were done in a circle close to the soil cylinder samplings on each fairway (see Figure 3 and Figure 5).



Photo 5. Soil water content measurements with Field Scout TDR 100 Soil Moisture Meter at Grenå GC (Photo: Karin J. Hesselstøe).

On each fairway, six water infiltration measurements were done using the double-ring infiltrometer method. Of the six measurements, three were conducted close to the soil cylinder samplings and three randomly distributed on the fairway. The double-ring infiltrometer had an inner ring of 4.7 cm in diameter and an outer ring with a 12.2 cm diameter. For measuring infiltration, both rings were forced into the soil, approximately 0.5 cm below the turfgrass, using a plank and a hammer. Both rings were filled with water up to the edge and after 3 minutes it was measured by using a caliper, how deep the water had sunk in the inner ring (mm). Water infiltration rate was measured at Grenå GC only.

2.5 Statistics

Calculations and statistics were conducted by using the software Microsoft Excel and Minitab (Version 20.2). Two-sample tests (t-test) for independent samples were performed for soil compaction, soil water content, soil bulk density, total porosity, field capacity, soil hardness and infiltration measurements to compare the means of the two independent groups/treatments: Traditional mown fairway (TRAD) and Robotic mown fairway (ROBO). The means were significantly different when the p-value was <0.05 . Loss on ignition data had no replicates and was therefore shown without t-test calculation. Soil textures were visualized in a particle size distribution curve, which illustrates the seven particle size fractions with their accumulated percentage. To describe the relationship between soil bulk density and total porosity (pF 0.0) or field capacity (pF 2.0) a Pearson correlation coefficient was calculated using data collected on traditionally and robotic mown fairway for each location.

3 Results

3.1 Sandnes GC

3.1.1 Soil texture and organic matter

With visual examination, the traditional mown fairway revealed a 5 cm organic matter layer below the turfgrass surface, and from 10 – 15 cm a soil layer rich in roots (Photo 6,a). The robotic mown fairway had no visible organic matter layer but did have a higher content of coarse fragments (Photo 6,b).



Photo 6. Soil profile at 0 – 20 cm depth on traditional mown fairway (a) and robotic mown fairway at Sandnes GC (b); Photos: Anne F. Borchert.

Due to higher organic matter levels in the 5 – 10 cm depth, soil samples were not analyzed for particle size distribution. While on the robotic fairway both depths revealed similar distribution curves, the traditional fairway had finer material in the depth of 15 – 20 cm compared to 10 – 15 cm (Figure 6).

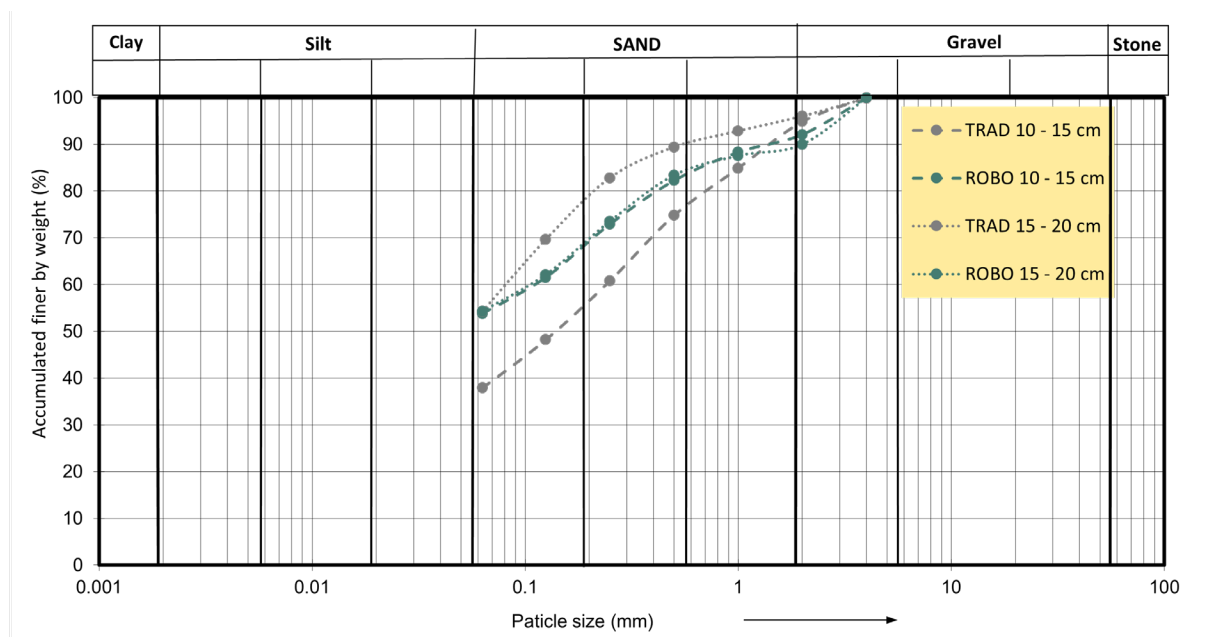


Figure 6. Soil particle size distribution for soil depth of 10 – 15 cm and 15 – 20 cm on both traditional and robotic mown fairways at Sandnes GC (n = 1).

On the robotic mown fairway, soil organic matter was similar in all three depths and ranged from 27 to 30% (Figure 7). For the traditional mown fairway organic matter was higher in 5-10 cm (44%) and in 10-15 cm (63%) compared to 15-20 cm (35%;). Due to only one sample, significant differences could not be determined for each depth, but on average of all depths organic matter content was less on the robotic mown fairway (29%) compared to the traditional mown (47%). However, those differences were insignificant ($p = 0.163$; t-test).

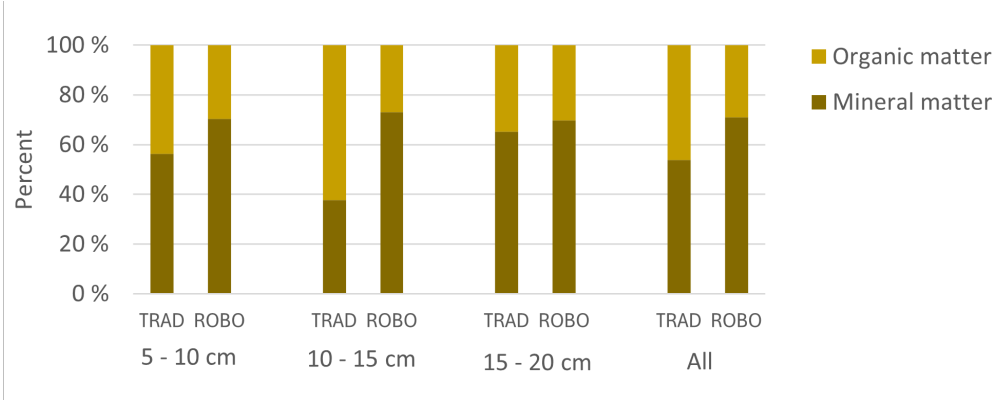


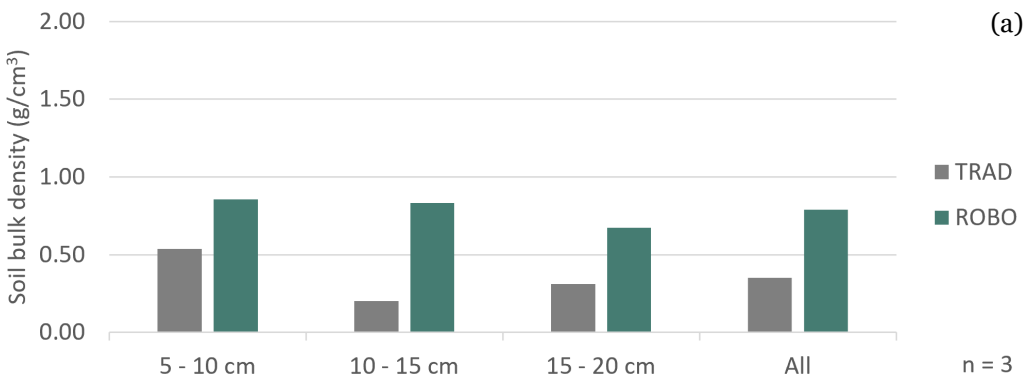
Figure 7. Soil organic and mineral matter (n = 1).

3.1.2 Bulk density and porosity

Bulk density was generally higher on the robotic mown fairway compared to traditionally mown fairway (Figure 8,a). The differences were significant in the 10 – 15 cm and 15 – 20 cm depths, but not in the 5 – 10 cm soil depth. Average bulk density across all soil depths was 0.8 g/cm³ on the robotic mown fairway and 0.4 g/cm³ on the traditional mown fairway.

Total porosity was lower on the robotic mown fairway, but only significantly in the soil depth of 15 – 20 cm and across all soil depths (Figure 8,b). The average porosity was 51% for the robotic mown fairway and 66% for the traditional mown fairway.

Field capacity on the robotic mown fairway was significantly lower with 37% compared to 46% for the traditional mown fairway (Figure 8,c). When differentiating by depth, there were no significant differences in field capacity.



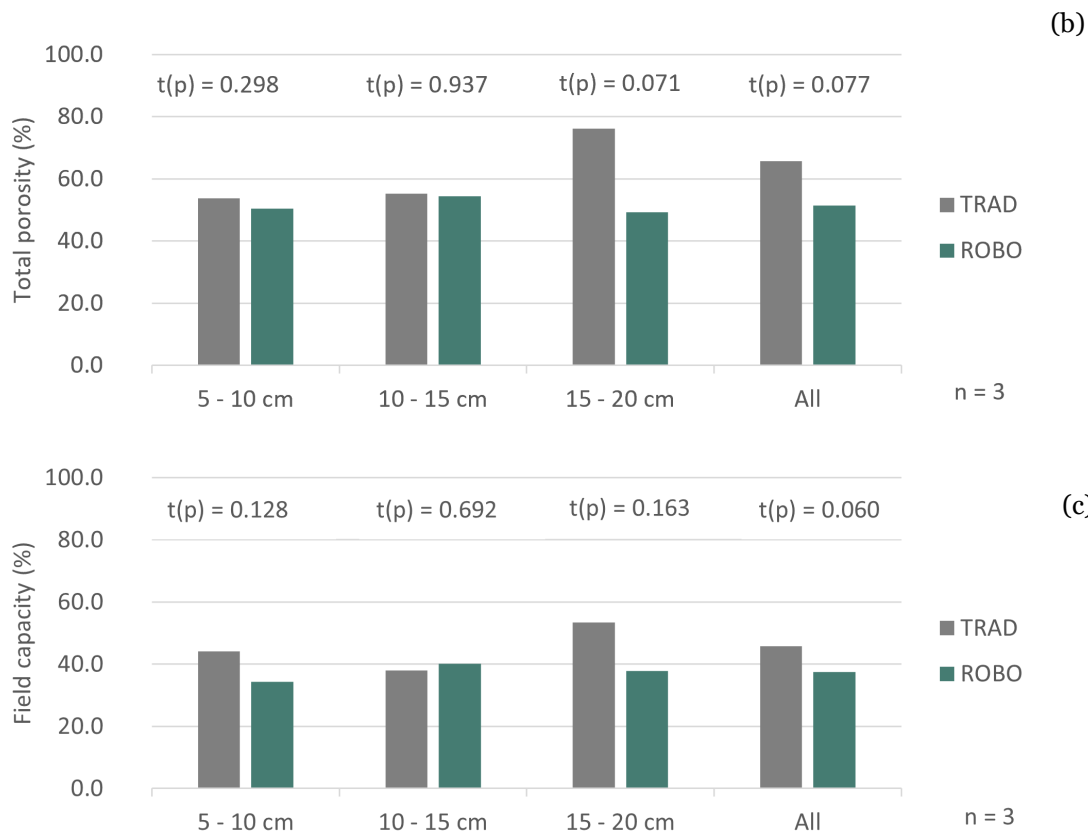


Figure 8. Soil bulk density (a), total porosity (b) and field capacity (c) for soil depth of 5 – 10 cm, 10 – 15 cm, 15 – 20 cm and all samples at traditional and robotic mown fairway at Sandnes GC.

Figure 9 shows the difference in bulk density between the robotically and traditionally mown fairway. There was a weak correlation between porosity and bulk density under traditional mowing but no correlation under robotic mowing at saturation. The weak correlation under traditional mowing gives an indication that some of the soil cores were compacted, while the lack of correlation indicates less compaction in the robotically mown fairway. At field capacity there was no correlation between porosity and bulk density.

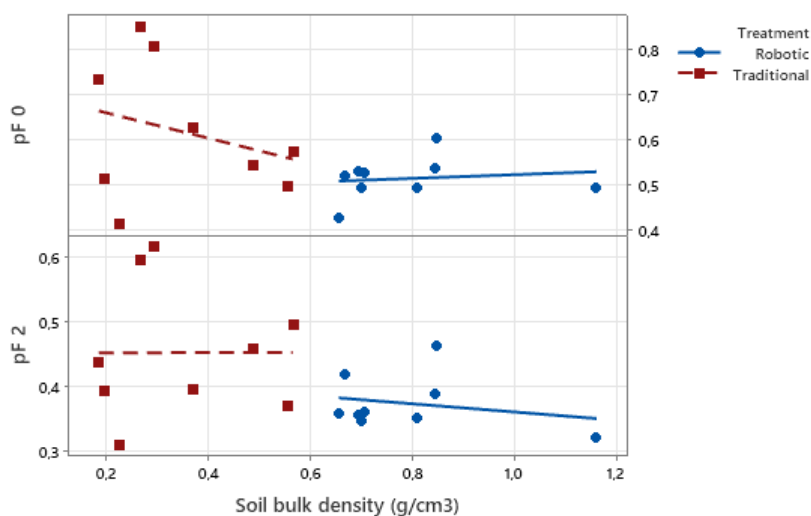


Figure 9. Correlation between soil bulk density and porosity at pF 0.0 (saturation) and pF 2 (field capacity) for traditional and robotic mown fairway at Sandnes GC.

3.1.3 Soil compaction and surface hardness

Soil compaction measured with the penetrometer on the four transects found that the traditionally mown fairway had consistency higher penetrometer values than on the robotically mown fairway (Figure 10).

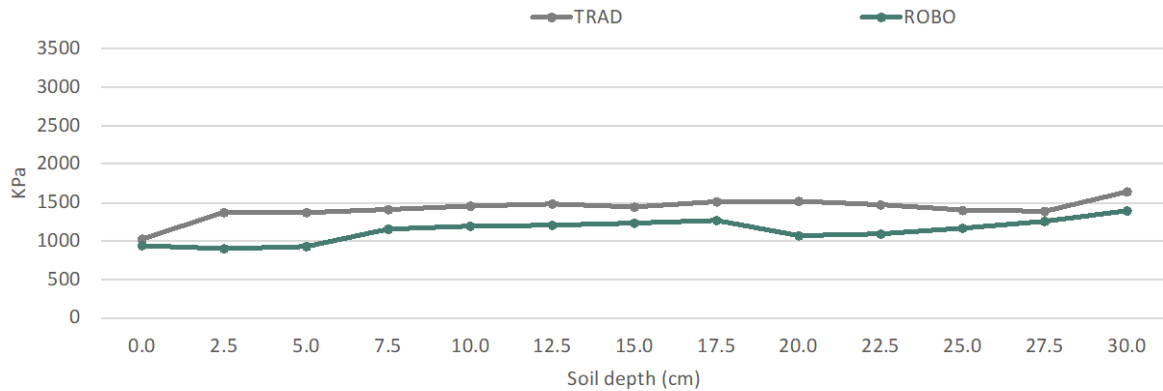


Figure 10. Average penetrometer measurements (kPa) for traditional (TRAD) and robotic (ROBO) mowing from 0 to 30 cm on Sandes GC fairway (n=20).

Surface hardness, as measured by the Clegg Soil Impact Tester, was significantly lower on the robotic mown (36 Gm) than on the traditional mown (40 Gm) fairway on the first stroke, but not for strokes 2 – 5 (Table 1). Surface hardness increased from first to fifth stroke with the instrument.

Penetrometer measurements were significantly lower on robotic mown areas than on traditional mown areas (Table 1). In addition, penetrometer values measured close to where the soil core was taken on the robotic mown fairway compared to those taken on the larger area were noticeably lower (< 750 kPa and 1153 kPa, respectively).

Table 1. Surface hardness (Gm) measured with Clegg Soil Impact Tester (load 2.5 kg) and average soil compaction (kPa) measurements taken with the penetrometer on the traditional (TRAD) and robotic (ROBO) mown fairways in the different depth at Sandnes GC.

Treatment	Surface hardness (Gm)					Soil compaction (kPa)				
	1	2	3	4	5	0 – 30 cm	0 – 30 cm	5 – 10 cm	10 – 15 cm	15 – 20 cm
	n=5					n=20		n = 5		
TRAD	40	44	45	46	46	1453	1458	1617	1497	1359
ROBO	36	41	43	45	44	1153	693	586	749	749
t-Test (p)	0.076	0.257	0.537	0.730	0.682	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

3.1.4 Water content and infiltration

At soil depths 0-7.6 cm and 0-12.2 cm, the average soil volumetric water content was above 50% on both traditional and robotic mown areas. However, at soil depths from 0-20 cm the soil water content was significantly lower for robotic mowing compared to traditional mowing (Table 2). Data for infiltration rate was not collected.

Table 2. Average soil water content (%) and infiltration rate (mm/h) for each treatment at Sandnes GC.

Treatment	Soil water content ^a			Infiltration rate ^b	
	0.0 - 7.6 cm	0.0 - 12.2 cm	0.0 - 20.0 cm	Close to soil core	Randomly chosen
	%			mm/h	
TRAD	51.3	56.3	47.8	-	-
ROBO	51.5	54.1	43.4	-	-
t-Test (p)	0.948	0.393	0.033	-	-

^a Soil volumetric water content measurement using Time-Domain-Reflectometry-instrument (TDR). n = 5 for each depth.

^b Double-ring-infiltrometer method. n = 3 for assessment area and for randomly chosen.

3.2 Grenå GC

3.2.1 Soil texture and organic matter

Visual examinations revealed that the traditionally mown fairway had a 2 cm thatch layer on the top and a sand enriched soil from 15 cm to 20 cm below the surface (Photo 7,a). The robotic mown fairway had a slightly thicker thatch layer of 3 cm, and the soil included both smaller and larger stones (Photo 7,b).



Photo 7. Soil profile at 0 – 20 cm depth on traditional mown fairway (a) and robotic mown fairway (b) at Grenå GC; Photos: Anne F. Borchert.

Soil particle size distribution was very similar on both fairways and in all three soil depths (Figure 11). Except for the layer of 15 – 20 cm on the traditional mown fairway where the soil layer had coarser material.

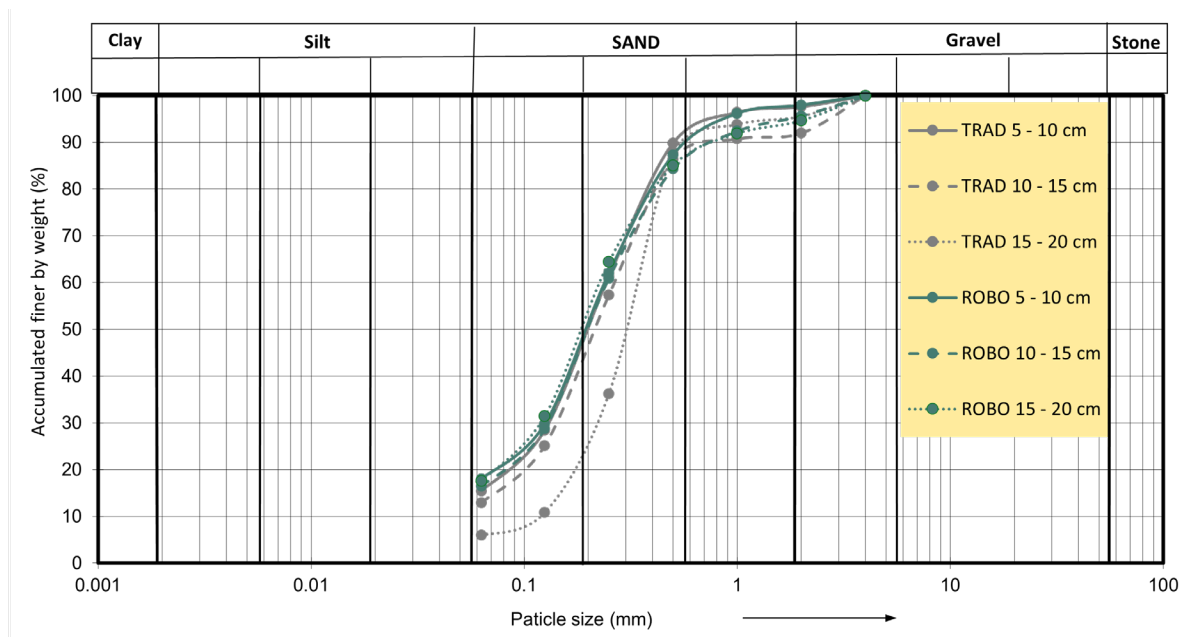


Figure 11. Soil particle size distribution for soil depth of 5 – 10, 10 – 15 and 15 – 20 cm on both traditional and robotic mown fairways at Grenå GC.

On both fairways, soil mineral and organic matter composition was similar ($p = 0.163$; t-test) (Figure 12). Soil organic matter ranged for the robotic mown fairway from 3.7% to 5.8%, on the traditional mown fairway from 1.3% to 5.0%.

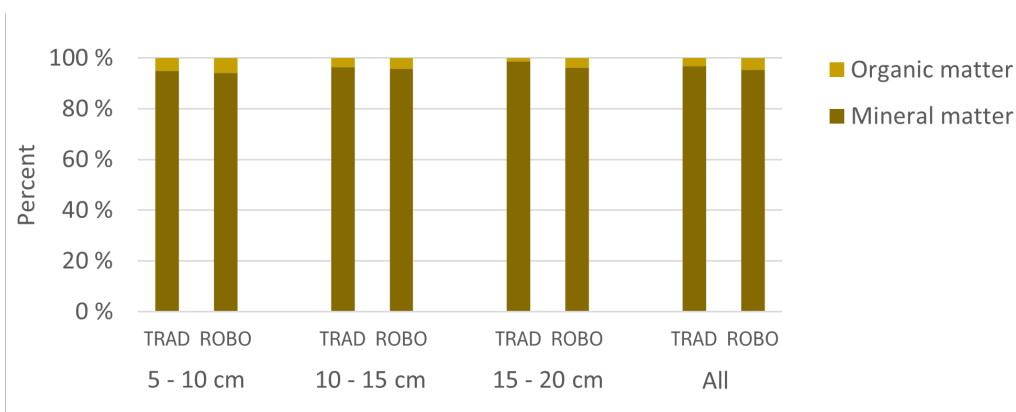


Figure 12. Average soil organic and mineral matter ($n = 1$).

3.2.2 Soil bulk density and porosity

Even though soil bulk density was slightly lower on the robotic mown fairway across all soil depths and for 10 – 15 cm as well as for 15 – 20 cm, no significant differences were determined (Figure 13,a). The average bulk density across all depths was 1.3 g/cm³ on the robotic mown fairway and 1.4 g/cm³ on the other fairway.

Total porosity was comparable on both fairways, except when measured in the soil depths of 15 – 20 cm, in which it was significantly higher on the robotic mown fairway (Figure 13,b). In this soil layer the robotic mown fairway had a porosity of 47% and the traditional fairway had a porosity of 43%.

Field capacity was significantly higher on the robotic mown fairway compared to the traditional mown, except at the soil depth of 10 – 15 cm (Figure 13,c). The average field capacity across all soil depths was 31% for the robotic mown fairway and 22% for the traditional mown fairway.

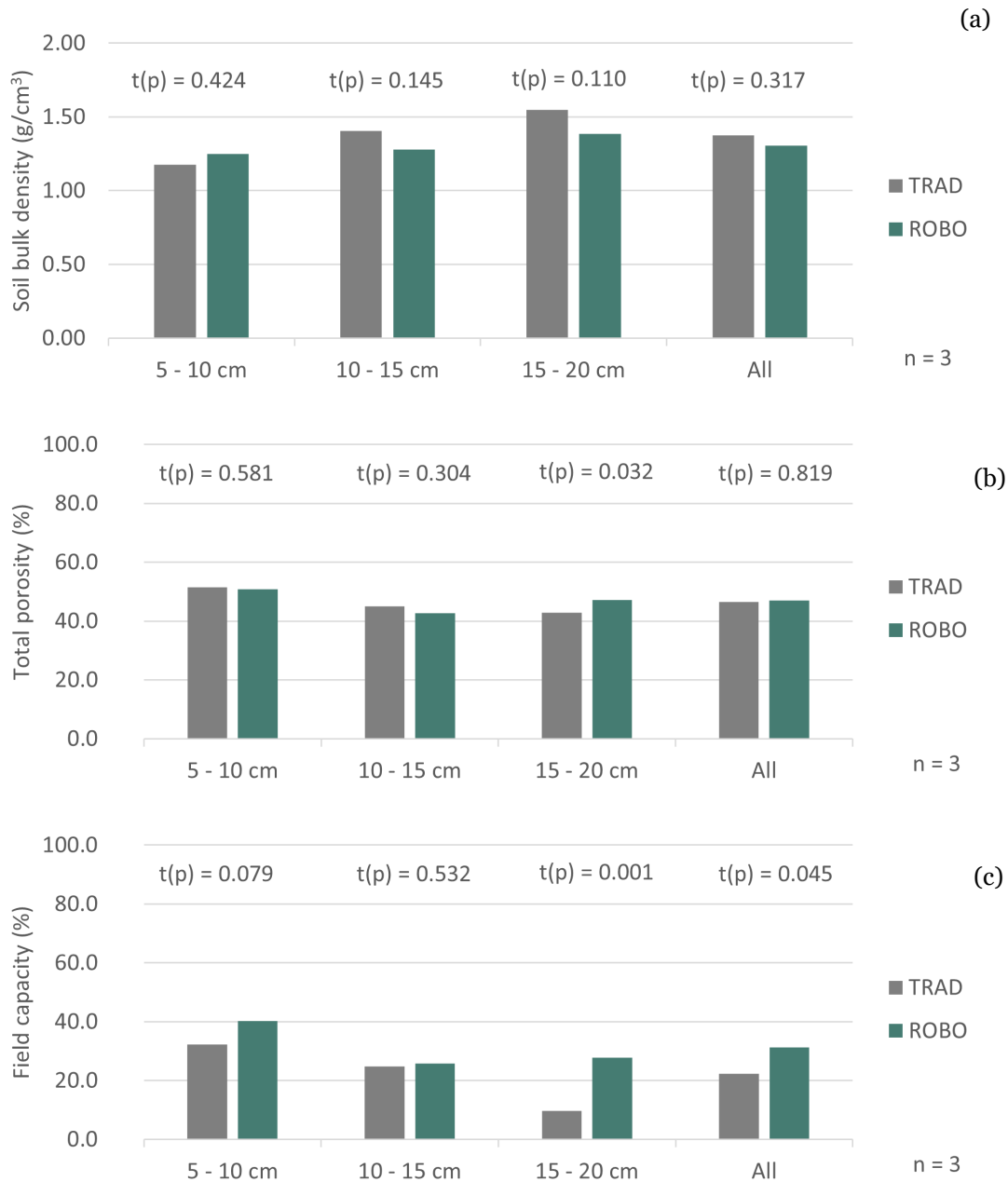


Figure 13. Soil bulk density (a), total porosity (b) and field capacity (c) for soil depth of 5 – 10, 10 – 15, 15 – 20 cm and all samples together on traditional and robotic mown fairways at Grenå GC.

There was no relationship between porosity at saturation and field capacity and bulk density on the robotic mown fairway (Figure 14). On the traditionally mown fairway there was a negative correlation between porosity and bulk density. Taken together, these results indicate a higher degree of soil compaction in the traditionally mown fairway than on the robotically mown fairway.

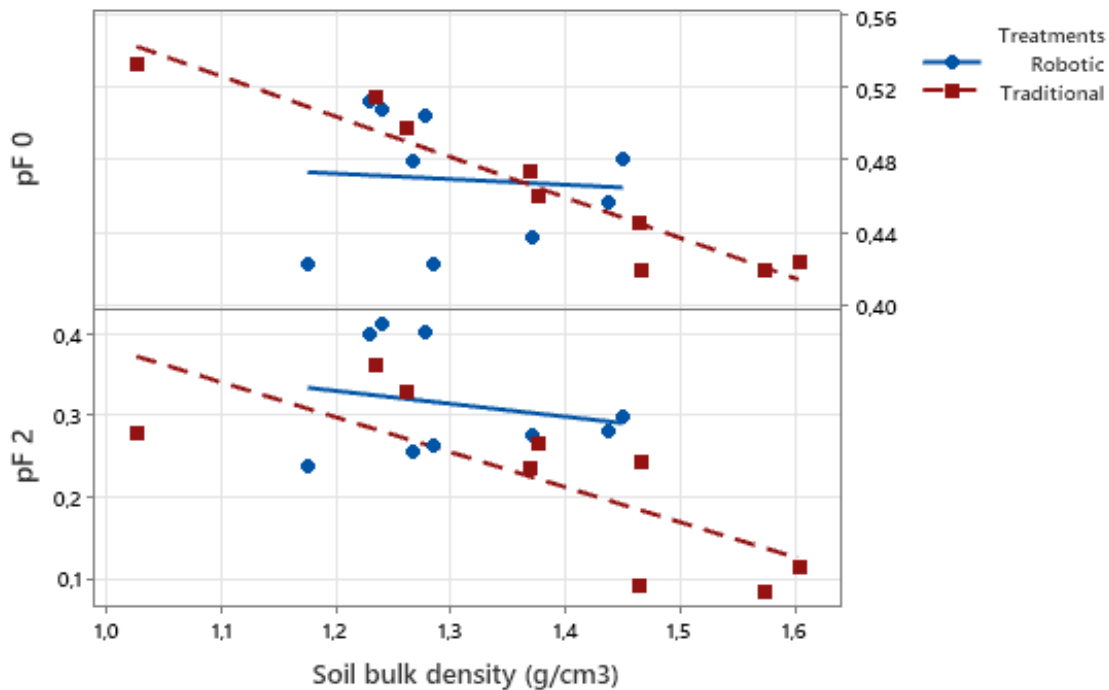


Figure 14. Correlation between soil bulk density and porosity at pF 0.0 (saturation) or pF 2 (field capacity) for traditional and robotic mown fairway at Grenå GC.

3.2.3 Soil compaction and surface hardness

For both mowing systems soil compaction increased from the soil surface down to 27.5 cm depth. At 30.0 cm the soil was too hard to measure with the penetrometer. Soil compaction measured with the penetrometer was less on the robotic mown fairway across all soil depths (Figure 15).

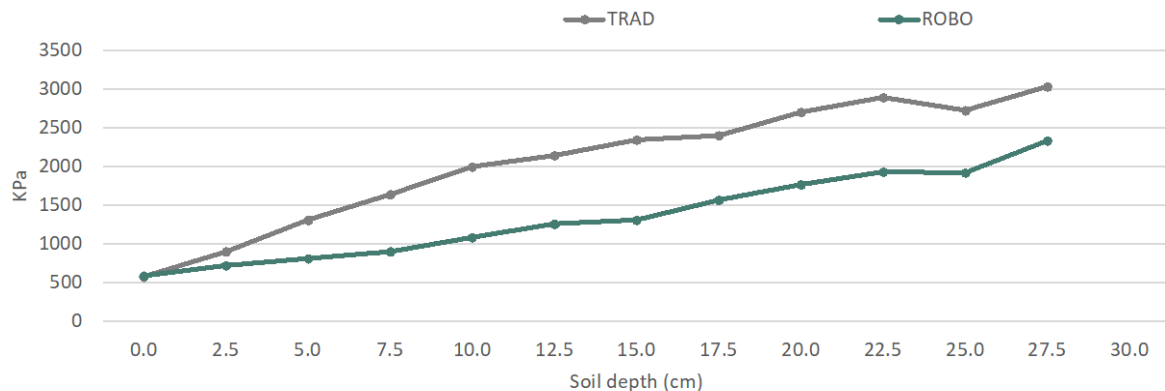


Figure 15. Average penetrometer measurements (kPa) for traditional and robotic mowing in 13 decreasing soil depths from 0 to 30 cm (n=20) on Grenå GC fairways.

Significantly less soil compaction was found for the robotic mown fairway compared to the traditional mown fairway across all soil depths (Table 3). They were also significantly lower when taken close to the soil core at the depths of 10 – 15 cm and 15 – 20 cm, but not in the upper layer from 5 – 10 cm.

There were also differences in Clegg Soil Impact Tester values, showing significantly less surface hardness for the robotic mown fairway (stroke 2 – 5; Table 3). For the first stroke with the Clegg Soil Impact Tester, no significant differences between mowing systems were found, but the values were on average slightly lower for the robotic mown fairway (44 Gm) compared to the traditional mown

fairway (47 Gm). For both fairways, Clegg Soil Impact Tester values increased from the first to the fifth stroke, thereby less on the robotic mown fairway.

Table 3. Surface hardness (Gm) with Clegg Soil Impact Tester (load 2.25 kg) and average soil compaction (kPa) measurements taken with the penetrometer on the traditional (TRAD) and robotic (ROBO) mown fairways in different depths at Grenå GC.

Treatment	Surface hardness (Gm)					Soil compaction (kPa)				
	1	2	3	4	5	0 – 30 cm	0 – 30 cm	5 – 10 cm	10 – 15 cm	15 – 20 cm
	Gm					n = 20	n = 5			
TRAD	47	55	58	60	61	1798	1625	1021	1891	2751
ROBO	44	49	52	52	53	1231	1350	897	1335	1652
t-Test (p)	0.205	0.014	0.022	0.008	0.003	< 0.001	0.101	0.271	0.003	0.001

3.2.4 Water content and infiltration

Average soil volumetric water content differed between mowing systems in all measured soil depths, but only significantly at 0.0 – 12.2 cm and 0.0 – 20.0 cm (Table 4). In those depths, soil water content was higher on the robotic mown fairway compared to the traditional mown fairway. Infiltration rate was not significantly different on both fairways but was 4 times lower on the robotic mown fairway, when measured close to the cylinder samples, compared to the traditional mown fairway.

Table 4. Average soil water content (%), surface hardness (Gm), and infiltration rate (mm/h) for each treatment at Grenå GC.

Treatments	Soil water content ^a			Infiltration rate ^b	
	0.0 - 7.6 cm	0.0 - 12.2 cm	0.0 - 20.0 cm	Close to soil soil cores	Randomly chosen
	%			mm/h	
TRAD	31.2	29.7	21.4	687	207
ROBO	36.6	44.6	35.3	160	233
t-Test (p)	0.276	< 0.001	< 0.001	0.242	0.873

^a Soil volumetric water content measurement using Time-Domain-Reflectometry-instrument (TDR). n = 5 for each depth.

^b Double-ring-infiltrometer method. n = 3 for assessment area and for randomly chosen.

4 Discussion

Due to their low weight, light-weight robotic mowers are assumed to have a positive effect on physical soil properties, such as compaction and water balance. This was also the impression of the greenkeepers on the golf courses at Sandnes in Norway and Grenå in Denmark (Hesselsøe et al. 2022). The present study was meant to test the greenkeepers' impressions with objectively assessed data but has limitations as no soil physical properties were assessed at the start of the project. This study is therefore limited to evaluate the differences between the robotic and the traditional mown fairways at the end of the study.

In addition, at Sandnes Golf Club, the organic matter content and soil texture of the two fairways differed. The higher percentage of organic matter in the soil cores taken from the traditional mown fairway is likely responsible for the observed differences in the bulk density, porosity and field capacity in comparison to the soil cores taken in the robotically mown fairway. Because soil organic matter, bulk density, and porosity were all measured within a 1 m² area it is hard to determine how comparable the two fairways are in terms of their soil physical properties.

However, soil compaction as measured by the penetrometer over four transects that covered a much larger area of both fairways than all other measurements taken in the study, indicated consistently lower soil compaction in the robotically mown fairway as compared to the traditionally mown fairway. In addition, though they were taken over a smaller area, the surface hardness readings and penetrometer readings taken surrounding the soil pit also indicated that the robotically mown fairway had a lower surface hardness and a lower penetrometer resistance.

At Grenå Golf Club, the organic matter and soil texture as measured at the soil pit in each fairway were very similar, meaning that the two fairways are likely more comparable to one another than at Sandnes Golf Club. Soil compaction as measured across the four transects indicated that the traditionally mown fairway had a consistently higher penetrometer resistance across all soil depths. The surface hardness readings and penetrometer readings taken around the soil pit on the robotically mown fairway also consistently indicated that the robotically mown fairways were softer and had lower levels of soil compaction. The soil water content on the robotically mown fairway was slightly higher, but there were no consistent differences between the water infiltration rates, though this was only measured in two locations.

Ferguson and Newell (2010) compared robotic mowing (Bigmow Belrobotics S.A.) with traditional cylinder mowing in a one-year experiment on British sports fields. They experienced by the end of the trial period that the robotic mown plots were significantly firmer measured with the Clegg Soil Impact Tester (68.3 Gm) than the cylinder mower plots (58.4 Gm). They hypothesized that the difference could be explained by the fact that the cylinder mower returned large amounts of clippings to the plots on a weekly basis, which failed to break down and thus increased the thatch layer at the base of the sward, while the robotic mower is mowing more frequently, returning small amounts of clippings to the plot on a regular basis which should break down quicker. Macolino et al. (2025) also found that when mowing turfgrass at lawn height with an autonomous mower led to a thinner thatch layer than when mowing with a traditional mower. In this study the thatch layer was not measured outside of the soil pit making it not possible to adequately compare thatch layer thickness between the two mowing treatments. However, there was little difference in Clegg Soil Impact measurements between the robotically and traditionally mown fairways. As such, in this study, it appears that the robotically mown fairways had lower soil compaction but did not develop a firmer soil surface as was reported by Ferguson and Newell (2010).

At Sandnes, the penetrometer values reached a maximum of 2000 kPa and at Grenå a maximum of 3500 kPa. Thus, there was a risk of inhibited root growth on both golf courses according to Passioura (2002), who mentions values of > 1000 kPa as critical soil compaction leading to slower root growth.

The mowing system was not the only reason for differences in soil physical properties between the fairways. Soil heterogeneity at the sites was also important. Sandnes is a site that has a variety of soils including sandy, peat, and mineral soils. The two fairway areas, as tested by the samples taken in the soil pits, had organic matter contents that are so high that they nearly qualify as organic soils, however to what extent organic matter contents across the entire fairway was not measured. The fairways tested at Sandnes are likely a combination of organic and mineral soils.

The soils at Grenå are mineral soils but given that the site is an old landfill soil properties across the site are likely highly variable. Water infiltration rates measured with double ring infiltrometer should be > 60 mm/h according to the DIN 18035-4 for the requested infiltration rate on sports turf areas (DIN, 2018). At Grenå they were more than 10 times higher for the traditional mown fairway close to the cylinder sample area. This variation may be due to the heterogeneity of the engineered soils that are capping the landfill.

5 Conclusions

Taken together, the results from both Sandnes and Grenå, though limited by the lack of data at the start of the study and the low spatial coverage of soil physical property data at the end of the study, do begin to suggest that robotic mowing may lead to measurable decreases in soil compaction in comparison to traditional mowing.

Robotic mowers have a wide range of benefits, including lower labor costs, lower carbon emissions, and an increasing amount of evidence indicates that robotic mowers lead to a thinner thatch layer. Robotic mowers might also have the effect of decreasing soil compaction, as the results of this study suggest.

The Fairway4Future project will continue until the end of 2026 investigating the effect of robotic mowing on turfgrass quality and weed encroachment. Based on the results from Robogolf (Hesselsøe et al., 2022) our hypothesis is, that robotic mowing will increase encroachment of broadleaf weeds at rough mowing heights (35 mm). At fairway mowing heights (15 mm) robotic mowing will decrease encroachment of broadleaf weeds such as white clover (*Trifolium repens*) (Hesselsøe et al., 2024). Experiments at NIBIO-Landvik and at golf courses in Finland, Denmark and Germany will further clarify these findings and hopefully lead to recommendations on how to manage high quality fairways and roughs with low input of energy and fertilizer.

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