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ROBO-GOLF: Robotic mowers for better turf quality on golf course fairways and semi-roughs

Results from 2021

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SAMMENDRAG/SUMMARY:

Denne rapporten gir resultater fra andre år (2021) i prosjektet 'ROBO-GOLF: Bedre gresskvalitet, redusert gjødselkostnad og mindre bruk av fossil energi ved bruk av robotklippere på fairway og semi-rough'. Arbeidspakke 1 (WP1) omfatter forsøk med sammenlikning av robotklipper og manuell klipper (sylinder-klipper på fairway, 15 mm klippehøyde; rotorklipper på semi-rough, 35 mm klippehøyde) til ulike grasarter. Resultatene viste forskjeller mellom robotklipping og manuell klipping, som for det meste ble sett på semi-rough når det gjelder sykdommer, ugress (hvitkløver) og jordpakking. En tendens til lavere sykdomsforekomst med robotklipping ble sett spesielt på semi-rough i alle arter på sensommeren/høsten, men også i *Agrostis capillaris* på fairway. Mer hvitkløver på de robotklippede ruter med *Lolium perenne* i semi-rough resulterte i et lavere helhetsinntrykk. I arbeidspakke 2 (WP2) ble nitrogen (N) gjødseleffekten av retur av klipp med robot- vs. manuell klipping studert på fairway etablert i en blanding bestående av *Poa pratensis*, *Agrostis capillaris* og *Festuca rubra*. Årlige N-rater på 0, 30, 60, 90 og 120 kg/ha/år, hver delt inn i 6 like tilførsler, ble brukt over sesongen. Innsamling av klipp én gang per måned viste at tilbakeføring av klipp både for manuell og robotklipping økte gressveksten sammenlignet med når klippet ble fjernet. Samtidig var N-konsentrasjonen i klippet høyere om våren og forsommeren, men ikke på sensommeren og høsten. Helhetsinntrykket av gresset viste samme høye vurdering for robot- og manuell klipp. I WP3 ble demonstrasjonsforsøk med robotklippere sammenlignet med sylinderklippere på fairway og rotorklippere på semi-rough videreført fra 2020 på fem golfbaner i Norden. Helhetsinntrykk, dekning av ugress og sykdommer og energibruk ble registrert månedlig fra mai til september. Helhetsinntrykk i robotklippede ruter var stort sett lik manuelt klippede ruter på fairway og semi-rough. På noen datoer resulterte robotklipping i signifikant høyere helhetsinntrykk enn manuell klipping.

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Preface

The R&D project 'ROBO-GOLF: Robotic mowers for better turf quality, reduced fertilizer cost and less use of fossile energy on golf course fairways and semi-roughs' was initiated by Norwegian Institute for Bioeconomy Research (NIBIO), Husqvarna AB and one golf course in each of the five Nordic countries in 2019. The project received funding from the Scandinavian Turfgrass and Environment Research Foundation (STERF) and Husqvarna in January 2020.

The project has three work packages, two of which (WP1 and WP2) are conducted at NIBIO Landvik, southeast Norway, and the third (WP3) at Ness GC, Iceland, Grenaa GC, Denmark, Bærheim GC, Norway, Jönköping GC, Sweden and Hirsala GC, Finland. The comparison of conventional and robotic mowing started by the installation of robotic mowers on each of the golf courses in May-June 2020 and at NIBIO Landvik in August 2020.

This report is a continuation of the report from 2020 (Aamlid et al., 2021) and gives a description of methods used and preliminary results obtained in the three WPs in 2021. The project is scheduled to continue until 1 July 2023.

In this report only Latin names are used for the following turfgrass species: colonial bentgrass (*Agrostis capillaris*), red fescue (*Festuca rubra*), Kentucky bluegrass (*Poa pratensis*) and perennial ryegrass (*Lolium perenne*).

Landvik, 18.03.22

Karin J. Hesselsøe

Content

Summary

In WP1 field trials comparing robotic and manual mowing of pure stands of *Agrostis capillaris*, *Festuca rubra* and *Poa pratensis* on fairway, and *Lolium perenne*, *Festuca rubra* and *Poa pratensis* on semi-rough, were established at NIBIO Landvik Research Center, southeast-Norway in spring 2020. Robotic mowers (Husqvarna 550) on fairway (mowing height 15 mm) and semi-rough (mowing height 35 mm) were installed in August 2020. Data collections and results from August to October 2020 are described by Aamlid et al. (2021). Despite a winter with little snow cover and deeply frozen soil, the trial area suffered no serious winter damage and none of the plots had to be reseeded in spring 2021. A sub study of the encroachment of broadleaved weeds was established in May 2021, planting in dandelion (*Taraxacum officinale*), white clover (*Trifolium repens*) and broadleaved plantain (*Plantago major*) in both fairway and semi-rough. Turfgrass visual quality and associated characters on the robotic-mown plots were observed in comparison with control plots mown with a cylinder mower on the fairway and a rotary mower on the semi-rough from April to October 2021. Differences between robotic and manual mowing were mostly seen on the semi-rough regarding diseases, encroachment of white clover and soil compaction. A tendency to lower disease incidence with robotic mowing was seen notably on semi-rough in all species in late summer/autumn, but also in *Agrostis capillaris* on fairway. More white clover on the robotic mown plots of *Lolium perenne* on the semi-rough resulted in a lower turfgrass visual quality. In *Poa pratensis* and *Festuca rubra* transplanted and spontaneous white clover also increased significantly on robotic-mown plots in the semi-rough. On the fairway this situation was not seen. Soil compaction was higher on manually mown plots in the semi-rough, but no differences in the fairway. Mowing quality as described by 'leaf tip damage' showed that reel mowing in the fairway was equal or better than robotic mowing. Rotary mowing in the semi-rough tended to give lower mowing quality than the robot. Further investigations are needed especially in *Lolium perenne*: In a thin and weak lawn after winter robotic mowing compared to manual mowing can favor competition from creeping weeds such as white clover. Also, a tendency to stem formation in *Lolium perenne* which increased by robotic mowing has to be investigated further.

In WP2 the nitrogen (N) fertilizer effect of return of clippings with robotic vs. manual mowing was studied on fairway established by seeding a mixture comprising *Poa pratensis*, *Agrostis capillaris* and *Festuca rubra*. Robotic vs. manual mowing was compared from April to October 2021. Annual N rates of 0, 30, 60, 90, and 120 kg/ha/yr, each split into 6 equal inputs, were applied over the season. Collection of clippings once per month showed that a return of clippings both for manual and robotic mowing increased clipping yields compared to when clippings were removed. At the same time the N concentration in clippings was higher in the spring and early summer, but not in the late summer and fall. Turfgrass quality assessments revealed comparably high ratings for robotic and manual mowing.

In WP3, demonstration trials with robotic mowers in comparison with reel mowers on fairway and rotary mowers on semi-rough were continued from 2020 at the golf courses (GC) Bærheim (Norway), Grenå (Denmark), Jönköping (Sweden) and Ness (Iceland). Hirsala GC in Finland was added to the project in 2021. Turfgrass quality, coverage of weeds and diseases and energy use were recorded monthly from May to September by the course manager on all five courses. The turfgrass quality of robotic-mown plots was mostly equal to manually mown plots on fairway and semi-rough. On some dates the robotic mowing resulted in significantly higher turfgrass quality than the manual mowing.

1 Introduction

The objective of the project 'ROBO-GOLF: Robotic mowers for better turf quality on golf course fairways and semi-roughs' (2020-2023) is to generate and disseminate knowledge about implications for turfgrass quality, fertilizer requirement, weed encroachment, susceptibility to various diseases, labor and energy use, CO_2-emissions , soil compaction and players' and greenkeepers' satisfaction of switching from conventional manual mowers to robotic mowers on fairways and semi-roughs with a turf cover of grass species typical for Nordic golf courses.

In addition to the data collections in 2020 (Aamlid et al., 2021) the objective in WP1 in 2021 was to focus on encroachment of broadleaved weeds on robotic versus manual mown plots. Grossi et al (2016) found a lower weed cover with robotic mowing than with manual rotary mowing in a tall fescue (*Festuca arundinacea*) lawn. Two years later Pirchio et al. (2018a) found the opposite situation, when comparing the same type of mowers in the same turfgrass species and investigating the development of transplanted weeds. Pirchio et al. (2018a) concluded that robotic mowers seemed to slightly favour weed infestation – especially this was the case for creeping type weeds such as white clover (*Trifolium repens*). In both Italian experiments mowing with manual rotary mower was done once a week compared to robotic mowing every day at a mowing height at 30 mm. However, in ROBO-GOLF WP1 in 2021 the development of transplanted broadleaved weeds was investigated on both fairway and semi-rough, and three commonly found species of broadleaved weeds in Scandinavian lawns were chosen. Two rosette-type plants: Dandelion (*Taraxacum officinale*) and broadleaved plantain (*Plantago major*) and one creeping-type: White clover (*Trifolium repens*).

A method to estimate mowing quality was described by Pirchio et al. (2018b). The so-called 'leaf tip damage' showed a correlation with visual turfgrass quality when comparing different rotary mowing systems. In ROBO-GOLF WP1 in 2021 the leaf tip damage method was used as a turfgrass quality parameter to compare robotic and manual mowing.

Another hypothesis in the ROBO-GOLF project that was investigated in 2021 was that the small clippings reaching the soil surface with use of robotic mowers would lead to stronger fertilizer savings that return of longer clippings using conventional mowers.

2 WP1 Robotic versus manual mowing on fairways and semi-roughs

2.1 Materials and methods

2.1.1 Experimental site

The experimental area for WP1 and 2 (Figure 1) was established on a silt loam soil (25 % sand, 60 % silt, 15 % clay) at NIBIO Landvik, southeast Norway (58.3°N, 8.5°E, 12 m.a.s.l) in spring 2020. The fairway and semi-rough trials in WP1 were established according to a three-replicate split block design with robot mowing vs. manual mowing on main plots and grass species on subplots. Turfgrass varieties and seed blends in WP1 was established according to Table 1.

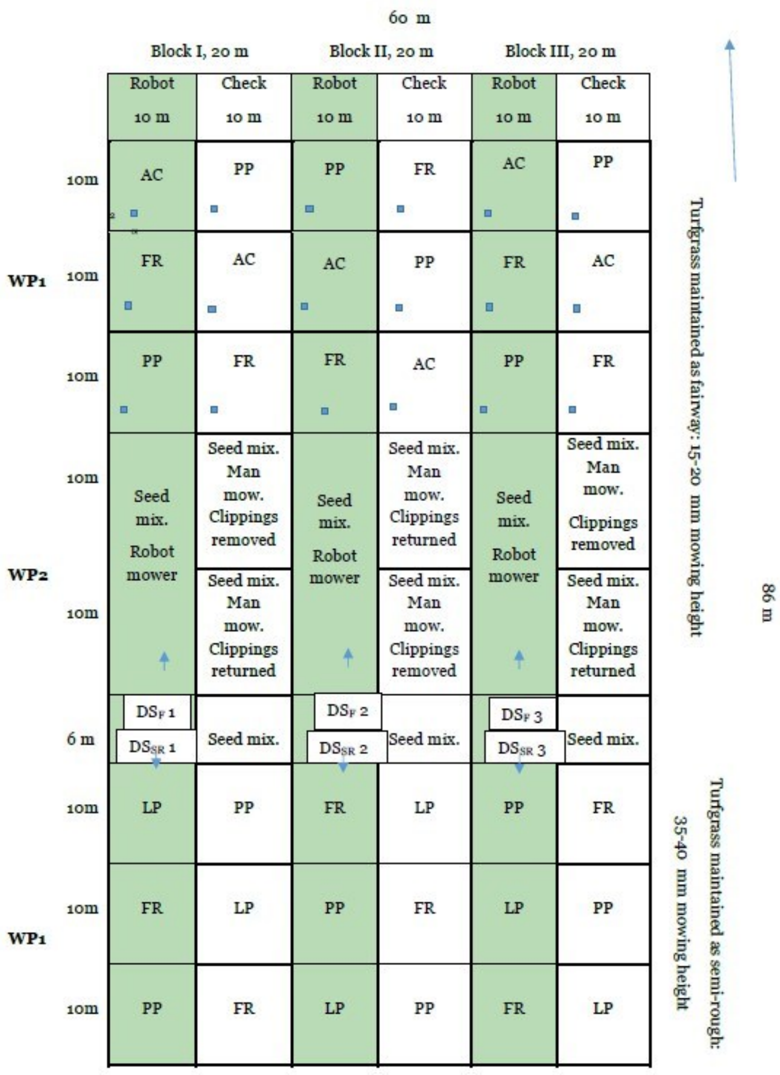

Figure 1: The experimental area for WP1 and 2 established at Landvik in May 2020. FR: Festuca rubra, PP: Poa pratensis, AC: Agrostis capillaris, LP: Lolium perenne. DS$_F$: Docking station, fairway mowers, DS$_{SR}$: Docking station, semi-rough mowers.

Table 1: Turfgrass varieties and seed blends in WP 1 (per cent by weight in seed blends).

Species	Varieties / seed blends	Target seeding rate	Realized seeding rate
		g m^{-2}	
Fairway trial			
Colonial bentgrass	50 % Jorvik, 50 % Leirin	4.2	3.9
Red fescue	20 % Frigg (*Frr*[1]), 20 % Cezanne (*Frl*[2]), 20 % Lystig (*Frc*[3]), 20 % Musica (*Frc*[3]), 20 % Barlienus (*Frc*[3])	15.0	14.9
Kentucky bluegrass	33 % Julius, 33 % (Lincolnshire, 34 % Marcus	12.0	11.0
Semi-rough trial			
Perennial ryegrass	33 % Fabian(4x)[4], 33 % Stolawn, 34 % Clementine	18.0	19.7
Red fescue	25 % Frigg (*Frr*[1]), 25 % Lystig (*Frc*[3]), 25 % Musica (*Frc*[3]), 25 % Barlienus (*Frc*[3])	15.0	13.4
Kentucky bluegrass	33 % Julius, 33 % (Lincolnshire, 34 % Marcus	12.0	10.0

[1] *Frr*: Strong creeping red fescue (*Festuca rubra* ssp. *rubra*),
[2] *Frl*: Slender creeping red fescue (*F. rubra* ssp. *littoralis*)
[3] *Frc*: Chewings fescue (*F. rubra* ssp. *commutata*)

2.1.2 Weather data 2021

January and February 2021 were cold compared with the 30-year reference period (Table 2). The lowest temperature recorded was -17.7°C on 12 February. Snow covered the trials from approx. 10. January to 25. February. March was warmer, but low precipitation in both March and April reduced spring growth, notably of *Lolium perenne* which was weak after the winter.

Table 2: Mean monthly temperature and precipitation during 2021 at the Norwegian meteorological Institute's weather station Landvik as compared with the 30-year reference period 1991-2020.

Month	Mean monthly temperature °C		Monthly precipitation mm	
	2021	1991 – 2020	2021	1991 – 2020
Jan.	-2.2	0.1	89	144
Feb.	-1.9	0.1	110	97
Mar.	3.9	2.4	63	91
Apr.	6.0	6.4	13	69
May	10.2	11.2	197	80
Jun.	16.3	14.8	50	88
Jul.	19.1	16.9	61	89
Aug.	15.9	16.1	39	125
Sep.	14.2	12.6	70	137
Oct.	10.1	8.0	138	175
Nov.	5.1	4.2	115	169
Dec.	-1.1	1.1	150	147
Mean / sum	8.0	7.8	1093	1411

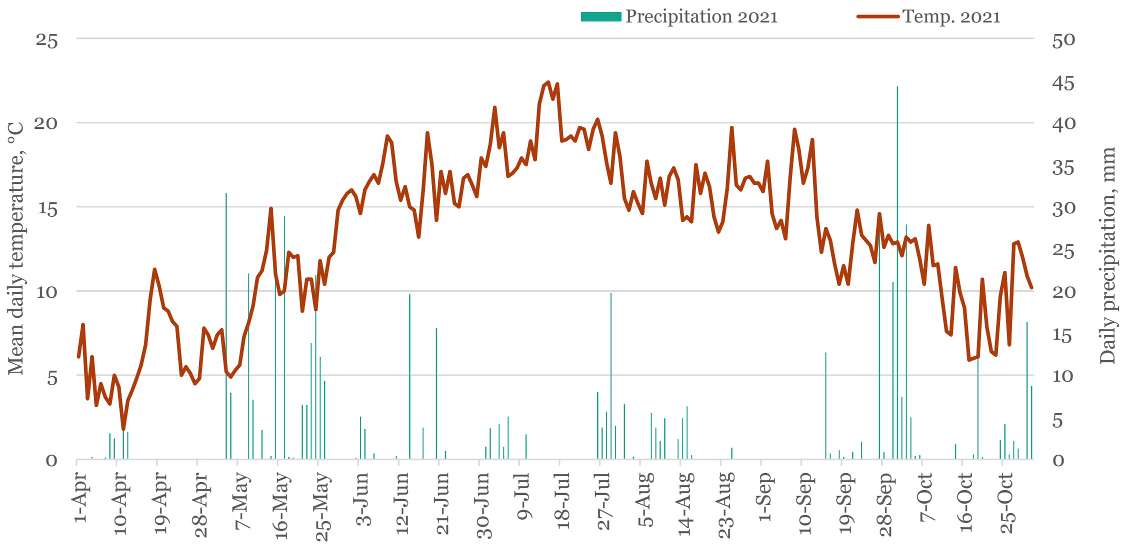

Figure 2: Mean daily temperature and precipitation during the growing season 2021.

2.1.3 Overwintering of the experimental site

The experimental area overwintered very well, and none of the grass species had to be reseeded. Only the *Lolium perenne* was weak and had a slow green-up, but there was no difference between the species in winter-survival.

As seen in the drone photo from 30 March green-up was faster on the fairway compared to the semi-rough, because of higher coverage, but there was no visible difference between green-up on robotic and manually mown plots. On 8 April green-up had improved, but *Lolium perenne* was still behind *Poa pratensis* and *Festuca rubra* on the semi-rough.

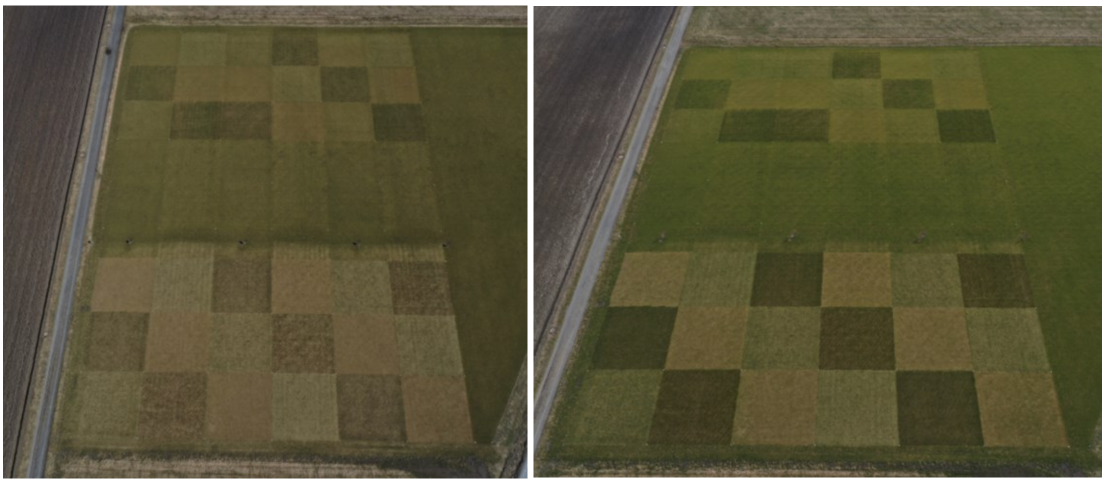

Photo 1 a,b: Drone photos of the experimental area on 30 March (left) and 8 April (right) before start-up of robots and manual mowing. Light colour of the Lolium perenne plots indicates reduced tiller density and slow green-up.

Photos: Ove Hetland.

2.1.4 Maintenance during the season

Start-up of robots on fairway and semi-rough, and first manual mowing on fairway was done on 21. April at 15 mm. First manual mowing on semi-rough was on 23 April at 35 mm. Continuing throughout the season the robots mowed the plots every day for 3 hours/day on the fairway (Position 2) and for 2 hours/day on the semi-rough (Position 5). Manual mowing on the fairway was done on Monday, Wednesday, and Friday at 15 mm with a John Deere triplex mower, and on Monday and Friday at 35 mm with a rotary mower in semi-rough. Knives on the robotic mowers were replaced every 4 weeks and the triplex mower was back-lapped every 2 weeks.

The first application of fertilizer was done on 23 April on both fairway and semi-rough according to the fertilizer plan (Table 3).

Table 3: Fertilization plan (except fertilizer trial in WP2)

Date	Fertilizer type	Fertilizer	N	P	K	Mg	S	Ca	Fe	Mn
						kg ha^{-1}				
23 Apr.	Fullgjødsel 12-4-18 Micro	70	8.3	2.8	12.3	1.1	6.7	1.4	0.0	0.2
19 May	Everris Proturf 18-0-7	70	12.6	0.0	4.9	0.0	0.0	0.0	0.0	0.0
10 Jun.	Everris Proturf 21-5-6	60	12.6	3.0	3.6	1.5	0.0	1.5	0.0	0.0
6 Jul. / 9 Jul.	Everris Proturf 18-0-7	50	9.0	0.0	3.5	0.0	0.0	0.0	0.0	0.0
2 Aug.	Everris Proturf 21-5-6	32	6.7	1.6	1.9	0.8	0.0	0.8	0.0	0.0
1 Sep.	Everris Proturf 18-0-7	34	6.1	0.0	2.4	0.0	0.0	0.0	0.0	0.0
5 Oct. / 6 Oct.	Fullgjødsel 12-4-18 Micro	40	4.7	1.6	7.0	0.6	3.8	0.8	0.0	0.1
Sum			60.0	9.0	35.7	4.1	10.5	4.5	0.0	0.3
Other nutrients relative to N, %			100.0	15.0	59.4	6.8	17.4	7.5	0.0	0.5

From 21 May a new front-mounted rotary mower mounted on an Iseki light-weight tractor (***Photo 3***) was in use to make the mowing in the semi-rough control plots more comparable to average golf course mowing conditions.

Photo 2: Drone photo of the experimental area on 7 May approx. two weeks after first mowing. Photo: Ove Hetland.

Photo 3: New manual mower in the semi-rough plots in use from 21 May.
Photo: Trygve Aamlid.

To simulate wear from golfers the fairway was exposed to wear from a friction wear drum approx. once a week from June to September.

On 27 September robotic mowing was decreased to every second day, and a month later on 27 October, both robotic and manual mowing was cancelled.

2.1.5 Competition from broadleaved weeds

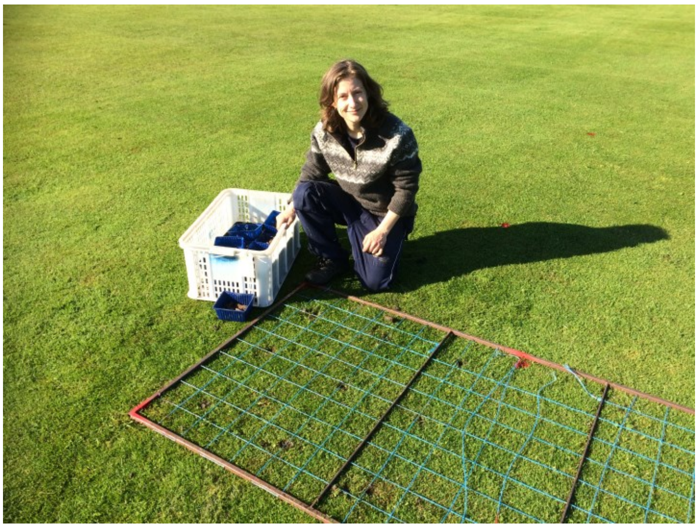


Photo 4: Planting in broadleaved weeds in subplots of WP1 fairway and semi-rough on 28 May.
Photo: Trygve Aamlid.

To investigate the differences between robotic and manual mowing with regard to competition between sown species of turfgrass and broadleaved weeds three subplots of each 1 m2 were established in each treatment plot of WP1 in the last week of May 2021. Subplots with transplanted broadleaved weeds was placed 1 m from the assessment plots for turfgrass quality etc. Nine plants of broadleaved plantain (*Plantago major*), nine plants of white clover (*Trifolium repens*) and nine root pieces of dandelion (*Taraxacum officinale*) were planted on 1 m2 subplots with a plant spacing of 33 cm in both directions (***Photo 4***). First assessments in the subplots were done one month after planting. Unfortunately, only very few of the transplanted root pieces of dandelion developed to living plants, so assessments of this species were cancelled. Broadleaved plantain and white clover survived the transplanting very well and developed vital weed populations with only a few plants needed to be replanted (***Photo 5***).

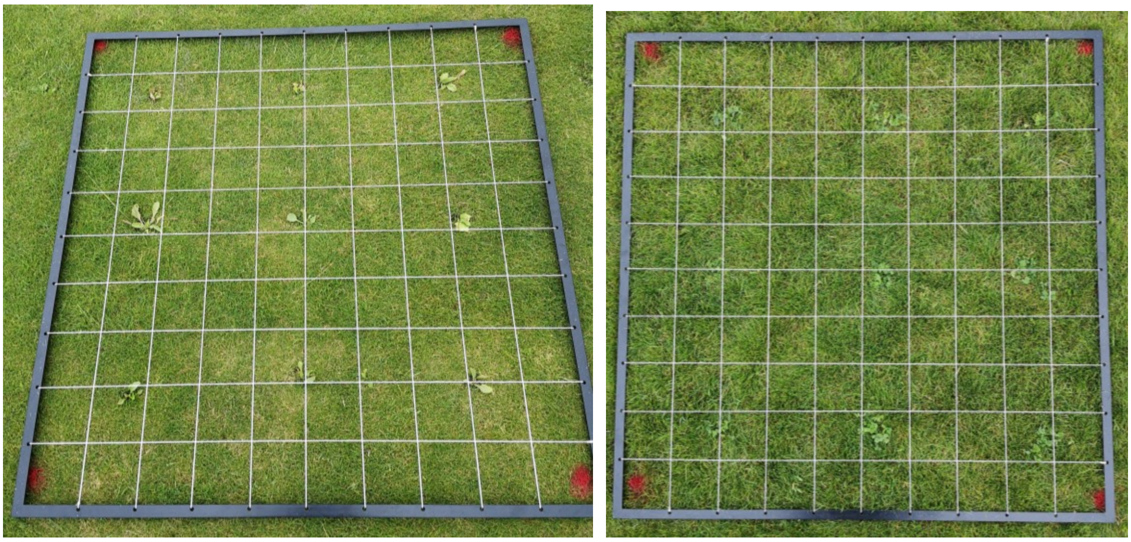

Photo 5: Broadleaved plantain (Plantago major) to the left and white clover (Trifolium repens) to the right planted in 1 m2 subplots on fairway in the end of May.

Photo (end of June): Karin J. Hesselsøe.

2.1.6 Cleanness of cut (Leaf tip damage)

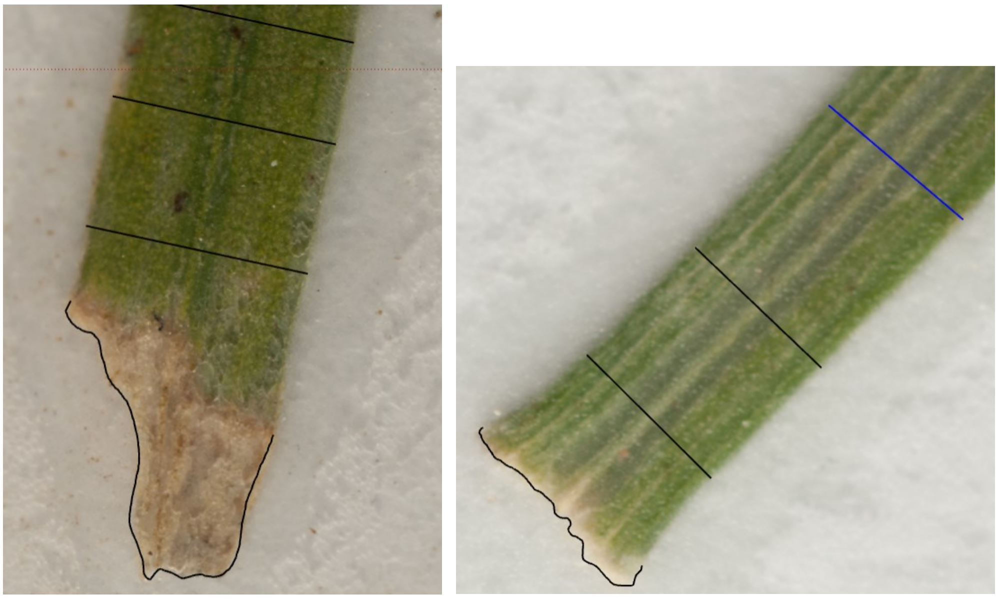

Photo 6: Examples of measuring cleanness of cut (leaf tip damage) in Poa pratensis from one of the fairway plots. The drawn free-hand line indicates the length of the actual cut LE and the straight lines the length of the ideal cut LI.

Photo: Ove Hetland.

Ten fully expanded leaves per plot of *Lolium perenne* and *Poa pratensis* in the semi-rough, and *Agrostis capillaris* and *Poa pratensis* in the fairway were collected on 21 September, 24 h after being cut to compare cleanness of cut between robotic and manual mown leaves. The leaves were attached with transparent tape to a white A4 sheet. Digital pictures were taken using a digital camera (Nikon D40X, extension tube, lens 38 mm 1:2.96 Zukio lens and flash) mounted on a stand. Using Sketchup Free software, the pictures of the leaves were enlarged and measured using the 'leaf tip damage' method as described by Pirchio et al. (2018b). Examples are shown in (***Photo 6***) where the drawn free-hand line indicates the actual cut (LE), and the straight lines indicates the ideal cut (LI). The 'leaf tip damage' level was calculated as the ratio between the length of LE (with possible shredded tips) and length of the LI (with no shredding at all) Leaf tip damage level = LE/LI. When the leaf tip damage level is 1, the mowing quality is excellent (no shredding at all, perfect cut). As the leaf tip damage level values increases, mowing quality decreases.

2.1.7 Data collection

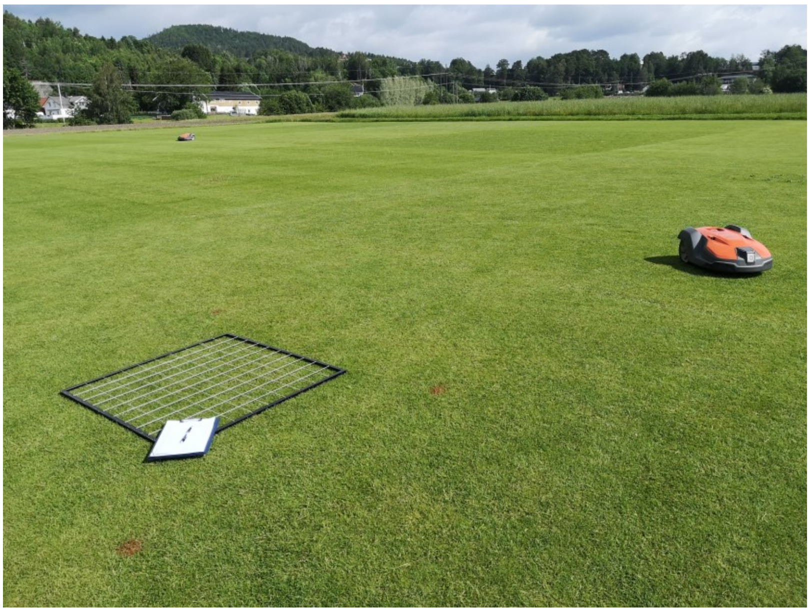

Photo 7: A 2 x 2 m plot in the middle of each 10 x 10 m treatment plot was used for assessments.
Photo: Karin J. Hesselsøe.

As in 2020 a representative 2 m x 2 m plot in the center of each 10 m x 10 m treatment plot was used for assessments and measurements (***Photo 7***). Visual assessments were usually made between noon and 2 p.m. on Tuesdays in the fairway trial and on Wednesdays in the semi-rough trial, shortly after mowing with the robotic mower and at least 24 hours after manual mowing. Start assessments were made on 19 April two days before startup of the robotic and manual mowing and continued until the end of October. The following characters were recorded every four weeks:

Turfgrass visual quality was recorded on a scale from 1 to 9 where 9 is the best turf and 5 is the lowest acceptable turf. Turfgrass quality is an overall score for live turf cover, uniformity, greenness, leaf fineness, disease resistance, freedom of weeds and shoot density.

Turfgrass color (greenness) was determined using a Field Scout CM 1000 chlorophyll meter (Spectrum Technologies, Aurora, IL, USA), mostly on the same days as assessing turfgrass quality. Five readings were taken per plot and the mean and coefficient of variation (CV) calculated, the latter as an expression for uniformity in turfgrass color.

Coverage was recorded as percent of the 2 m x 2 m subplot area that was covered with turf of the sown species, annual bluegrass (*Poa annua*), broadleaved weeds, diseases and bare soil.

Turfgrass height was measured on Mondays or Wednesdays shortly after mowing with robotic and manual mowers. Five measurements were made per plot using a prism (Turfcheck I). The means and CVs were calculated.

Coverage in percent of the **transplanted broadleaved weeds** was registered with a grid frame four weeks after transplanting and subsequently every four weeks until October (***Photo 8***).

Photo 8: Registration of transplanted white clover in the subplots in August.

Photo: Karin J. Hesselsøe.

As in 2020 soil compaction was measured in August both in the fairway and the semi-rough trial. The following characters were recorded:

Soil penetrometer resistance. Using an Eijkelkamp soil penetrometer (Eijkelkamp Soil & Water, Giesbeek, Netherlands). Five measurements were taken per plot to 150 mm depth and the mean value and CV calculated. On the same day, five measurements of volumetric soil water content (VSWC) were conducted using a Time Domain Reflectometer (TDR) instrument (Field Scout 300, Spectrum Technologies, Aurora, IL, USA) with 15 cm long probes. The mean value and CV for VSWC was calculated.

Photo 9: Soil compaction (left) was measured in August on both fairway and semi-rough. A double ring infiltrometer (right) was knocked into the turfgrass surface before filling with water to measure infiltration rate.

Photos: Anne F. Borchert.

As in 2020 water infiltration rate was measured only in the fairway trial:

Water infiltration rate was measured in the fairway trial on 11. August, just after a heavy rainfall had brought the VSWC to field capacity. Infiltration was measured at two sites per 2 m x 2 m plot using a double ring infiltrometer with an outer ring diameter of 128.5 mm and an inner ring diameter of 45 mm. Both rings were filled with 80 mm water and the water level in the inner ring measured after three minutes.

Statistical analyses

The experimental data were analyzed using Microsoft Excel and R version 4.1.2 (R CORE TEAM 2013). Corresponding to the split plot design, ANOVAs were performed for each assessment/measurement date and on the average values for different periods. Mowing systems were considered as main plots and species as subplots. The function "lmer" in package "car" was used taken into account: $lmer\ (Response \sim \text{BLK} + \text{Mowing system} * \text{Species} + (1|\text{BLK:Mowing system})),$ $type="II", test.statistic="F")$ with the arguments Response = parameters; type II = provided p-values in type II anova; test.statistic: F = F-tests (Freedman 2006; Long and Ervin 2000; White 1980). To denote significant differences, contrasts were calculated for pairwise comparison at 5 % level adjusted by "Tukey" performing the function "cld/emmeans" in the package "multcomp" according to Piepho (2004).

2.2 Results Fairway

2.2.1 Turfgrass height

The manually mown fairway was lower in the beginning of the season, with a significant difference of 2 mm in August. In September and October there were no differences in turfgrass height.

Table 4: Turfgrass height in robotic and manual mown fairway measured every 4 weeks.

Treatment	Turfgrass height mm				
	2 Jun.	28 Jul.	25 Aug.	24 Sep.	25 Oct.
MANUAL	14	12	15 a	16	15
ROBOT	16	13	17 b	16	15
P-value	**0.093**	**0.206**	**0.042**	**0.157**	**0.321**
A. capillaris	15	13	16	16	15
F. rubra	15	12	16	16	15
P. pratensis	15	12	16	16	15
P-value	**0.226**	**0.483**	**0.816**	**0.568**	**1.000**

Turfgrass visual quality

Turfgrass visual quality ratings on the fairway plots varied from 5.0 to 8.5 – all assessments with an acceptable turfgrass quality (5 or higher). In the beginning of the season no differences between robotic and manual mowing in the three species were found, but from the end of June and the rest of the season robotic mowing in *Poa pratensis* and *Agrostis capillaris* was better than manual mowing. Significant differences between robotic and manual mowing were found in *Poa pratensis* in June, and in *Agrostis capillaris* in July.

In *Festuca rubra* robotic mowing was slightly better at some assessment dates and manual mowing at other dates, but no trend was found here.

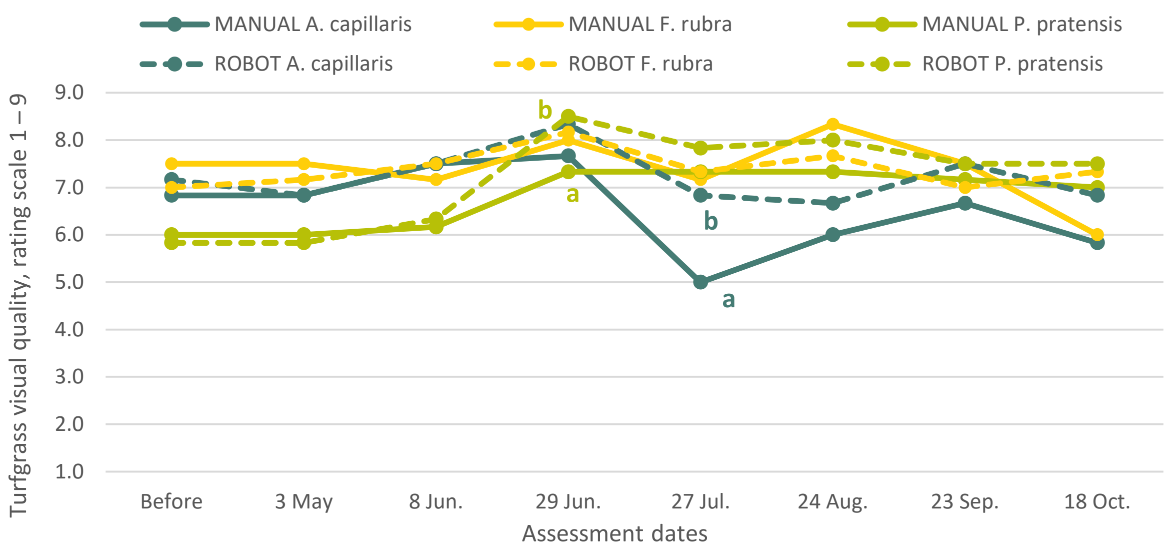

Figure 3: Turfgrass visual quality on fairway in robotic and manual mowing from April to October in Agrostis capillaris, Festuca rubra and Poa pratensis. Rating values 5 or above are acceptable. Different letters (a and b) indicate significant differences.

2.2.2 Diseases

Photo 10: Diseases in the Agrostis capillaris plots on the fairway were take-all-patch and antracnose.

Photo: Anne F. Borchert.

Until July no diseases were found, but from the end of July to October 2-3.5% of disease was found in *Agrostis capillaris*. The diseases were take-all-patch (*Gaeumannomyces graminis*) and antracnose (*Colletotrichum graminicola*) (Photo 10). The disease incidence in *Agrostis capillaris* was significantly higher than in *Festuca rubra* and *Poa pratensis* (Figure 4). In *Festuca rubra* less than 0.5% of disease was found in July-September, but in October 2.5% of the plot area was infected with red thread (*Laetisaria fuciformis*). A trend for lower disease incidence with robotic mowing compared to manual mowing was found from July and the rest of the season, but the difference was not significant.

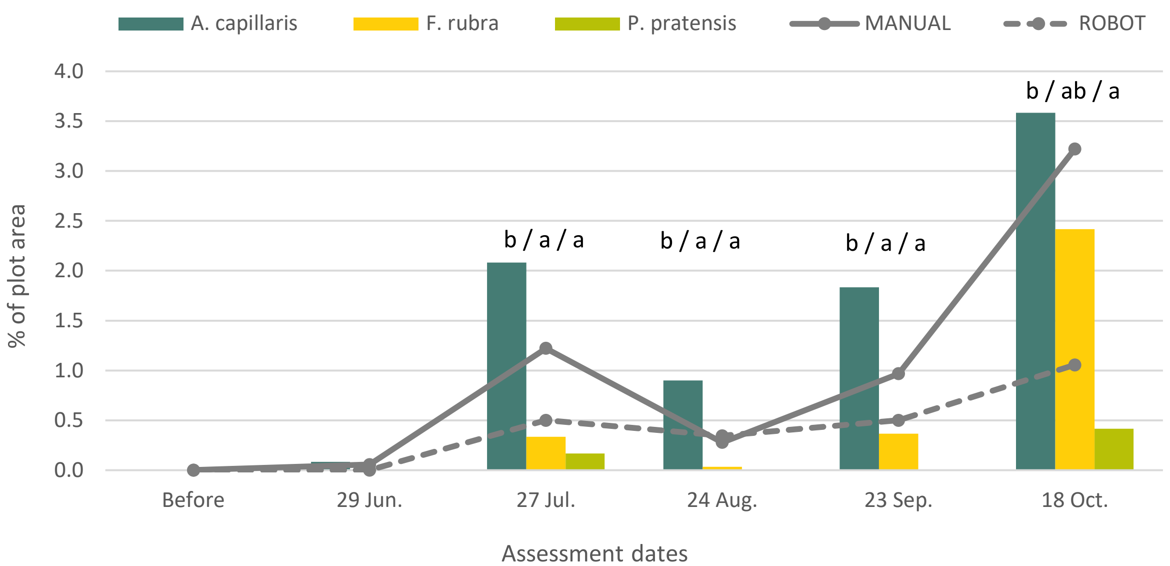

Figure 4: Development of diseases between robotic and manual mowing (grey lines) and difference in disease incidence between the species: Agrostis capillaris, Festuca rubra and Poa pratensis. Different letters (a and b) indicate significant differences between the species.

2.2.3 Transplanted weeds

Coverage of the transplanted weeds developed differently in the different grass species, and between robotic and manual mowing. Coverage of broadleaved plantain increased only slightly from the initial value of 0.5-1% of plot area with no difference between robotic and manual mowing (data not shown). White clover covered approx. 1% of plot area from June to August and increased to 4-5.5% in September and October with a trend to lesser white clover in robotic-mown plots – though no significant differences were found between the two mowing systems (Figure 5).

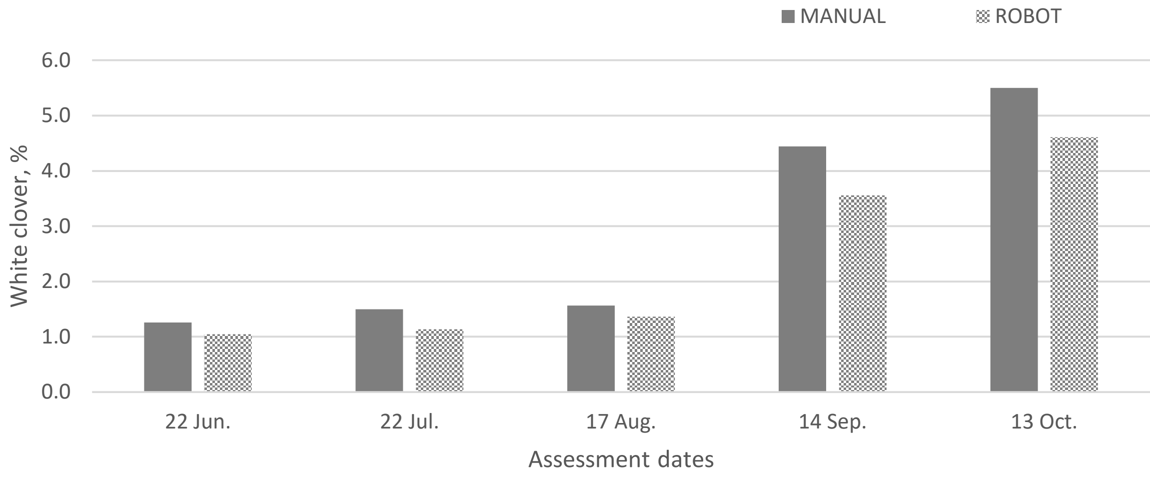

Figure 5: Coverage of transplanted white clover in the subplots between robotic and manual mowing.

The trend to increased coverage of white clover during the season was seen in all turfgrass species (Figure 6), but differences were not significant on any assessment date.

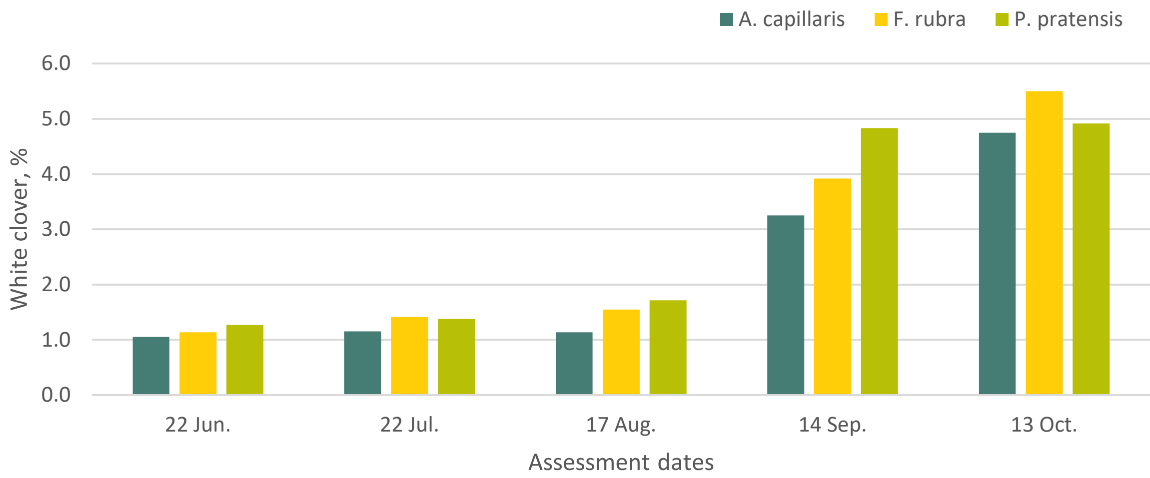

Figure 6: Coverage of transplanted white clover in the subplots between the three species: Agrostis capillaris, Festuca rubra and Poa pratensis.

2.2.4 Water infiltration and soil compaction

On average there were no significant differences in soil compaction and infiltration rate between robotic and manual mowing though a trend to lower soil compaction with robotic mowing was found (Table 5).

Table 5: Soil compaction and water infiltration rate on fairway in August.

Treatment	Water content	Infiltration rate	Soil compaction	
	Vol.-%	mm/h	MPa	CV %
MANUAL *A. capillaris*	27.8	137	4.7	15
MANUAL *F. rubra*	30.8	200	4.2	12
MANUAL *P. pratensis*	30.9	183	4.4	15
ROBOT *A. capillaris*	26.6	147	4.3	17
ROBOT *F. rubra*	28.9	117	4.1	11
ROBOT *P. pratensis*	28.5	283	4.0	12
P-value	**0.903**	**0.248**	**0.634**	
MANUAL	29.8	173	4.4	14
ROBOT	28.0	182	4.2	14
P-value	**0.266**	**0.848**	**0.202**	
A. capillaris	27.2	142	4.5	16
F. rubra	29.9	158	4.1	12
P. pratensis	29.7	233	4.2	14
P-value	**0.178**	**0.212**	**0.118**	

2.2.5 Cleanness of cut (Leaf tip damage)

Cleanness of cut was higher with robotic mowing in the fairway plots, but the opposite was found in the semi-rough plots. A significantly higher leaf tip damage was found in robotic mown *P. pratensis* in the fairway plots. A trend to higher leaf tip damage was found in the manual mown *L. perenne*.

Table 6: Cleanness of cut as described as leaf tip damage of Agrostis capillaris and Poa pratensis on fairway and Lolium perenne and Poa pratensis on semi-rough.

Treatment	**Leaf tip damage**				
	Fairway			**Semirough**	
	A. capillaris	*P. pratensis*		*L. perenne*	*P. pratensis*
MANUAL	1.8	1.6	a	2.6	2.7
ROBOT	2.3	2.3	b	1.6	2.1
P-value	**0.3**	**0.02**		**0.08**	**0.400**

2.3 Discussion

The manually mown fairway was measured to be 1-2 mm lower in June-August. In September and October there were found no difference. It was decided on reference group meeting in autumn 2020 that the robots should be cutting 1-1.5 mm higher than the triplex, which is confirmed by the 2021 assessments.

Only few differences were found in turfgrass visual quality between robotic and manual mown fairway plots. In late July a significantly higher turfgrass visual quality in robotic mown *Agrostis capillaris* could be explained by less disease compared to the manual mown plots (Figure 4). The higher disease incidence in manual mown *Agrostis capillaris* compared to robotic can be explained by the daily dew removal by the robotic mowers (Photo 11).


Photo 11: (Left photo) Treatment plot of Agrostis capillaris – robotic mown to the left and manual mown to the right with visible patches of take-all-patch. (Right photo) Dew removal from daily robotic mowing can explain the lower disease incidence in the robotic mown Agrostis capillaris plots.

An increase in the coverage of transplanted white clover was observed in late summer – especially in *Poa pratensis* in September with a trend to more white clover in manual mown than robotic mown plots, but no significant differences was found so far.

Measurements of soil compaction and water infiltration showed no differences between robotic and manual mowing on the fairway so far.

Mowing quality as described by 'leaf tip damage' showed that reel mowing in the fairway was equal or better than robotic mowing. Rotary mowing in the semi-rough tended to give lower mowing quality than the robot.

2.4 Results semi-rough

2.4.1 Turfgrass height

No differences in turfgrass height were found between robotic and manual mowing except on 28 June when the manually mown plots were significantly lower (29 mm) than the robotic mown plots (36 mm).

Table 7: Turfgrass height in manual and robotic mown semi-rough.

Treatment	Turfgrass height mm					
	4 Jun.	28 Jun.	26 Jul.	23 Aug.	23 Sep.	15 Oct.
MANUAL	36	29 a	34	34	32	31
ROBOT	36	36 b	33	34	32	31
P-value	**0.547**	**0.009**	**0.517**	**0.184**	**0.660**	**0.588**

2.4.2 Turfgrass visual quality

Turfgrass visual quality ratings on the semi-rough plots varied from 4.0 to 8.0 – all assessments with an acceptable turfgrass quality except for robotic mown *Lolium perenne* in August-October (Figure 7). In April-May there were no differences between robotic and manual mowing in the three species, but from June some differences appeared. Robotic mown *Lolium perenne* had a significantly higher turfgrass visual quality in the beginning of June, but from July and the rest of the season it was opposite and the turfgrass visual quality was significantly lower than the manual mown plots in August to October.

In *Festuca rubra* turfgrass visual quality was higher with robotic mowing in June, but the opposite happened from July through September with higher turfgrass visual quality in manual mowing. Significant differences between robotic and manual mowing in *Festuca rubra* were found in the beginning of June, August and September.

In *Poa pratensis* turfgrass visual quality differed only slightly between robotic and manual mowing.

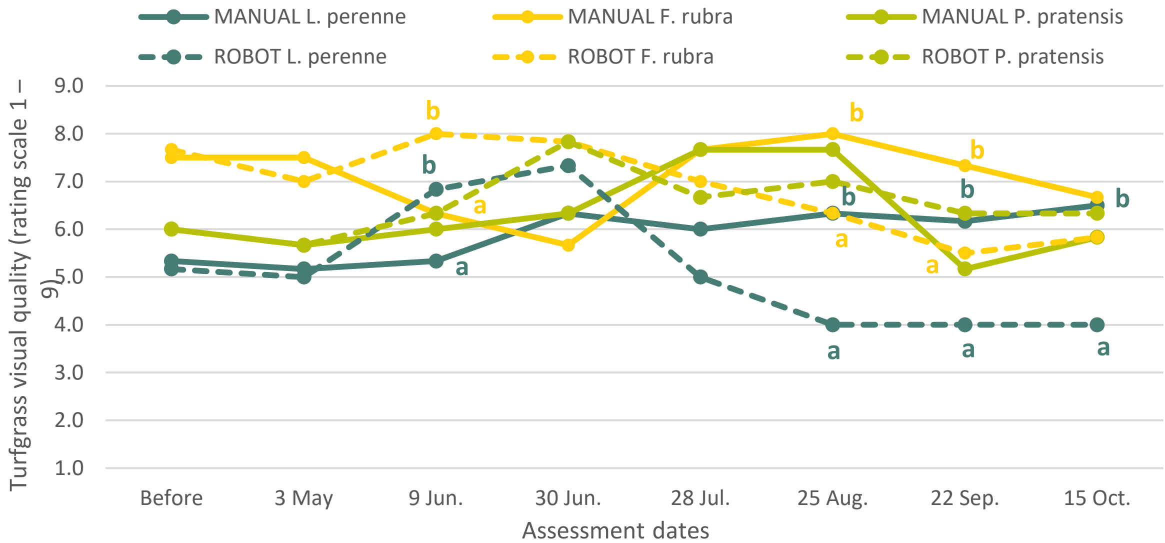

Figure 7: Turfgrass visual quality on semi-rough in robotic and manual mowing from April to October in Lolium perenne, Festuca rubra and Poa pratensis. Rating values 5 or above are acceptable. Different letters (a and b) indicate significant differences between the two mowing systems.

2.4.3 Diseases

Diseases were found in all three species from late summer. In August red thread (*Laetisaria fuciformis*) was found in *Lolium perenne* and in September rust (*Puccinia spp.*) in *Poa pratensis* and red thread in *Festuca rubra*. Disease incidence differed from 2-4% of red thread in *Festuca rubra* to 5-7% in *Lolium perenne*, and up to 20% of rust in *Poa pratensis* (Figure 8). Plot area covered with diseases was significantly lower in robotic than manual mown plots in September and October.

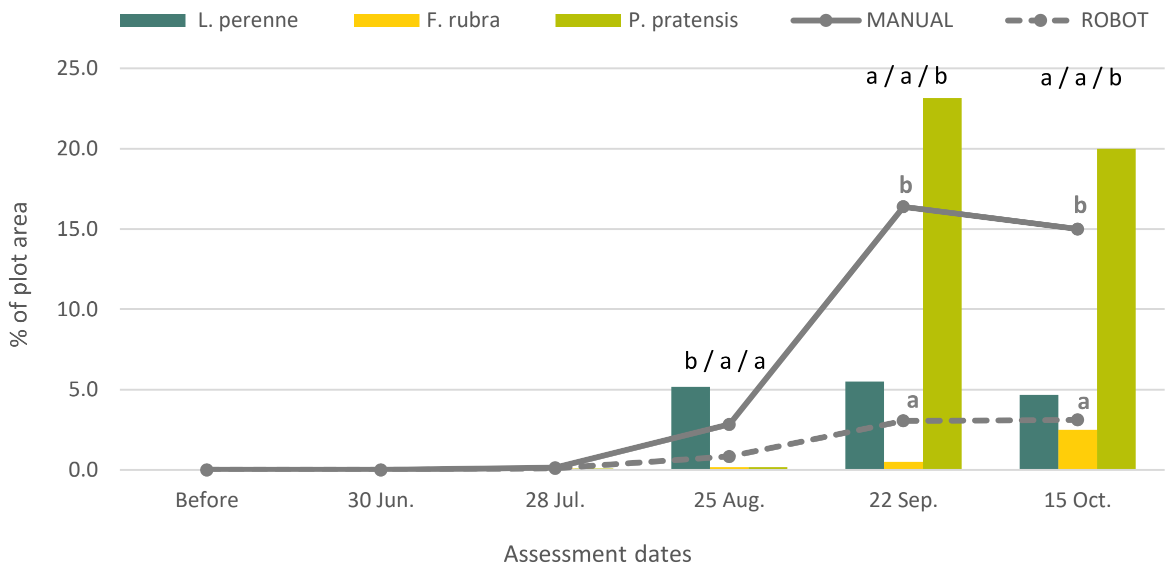

Figure 8: Diseases in the different turfgrass species and between robotic and manual mowing. Different letters (a and b in grey) indicate significant differences between the two mowing systems. Different letters (a and b in black above bars) indicate significant differences between the turfgrass species.

2.4.4 Transplanted and spontaneous weeds

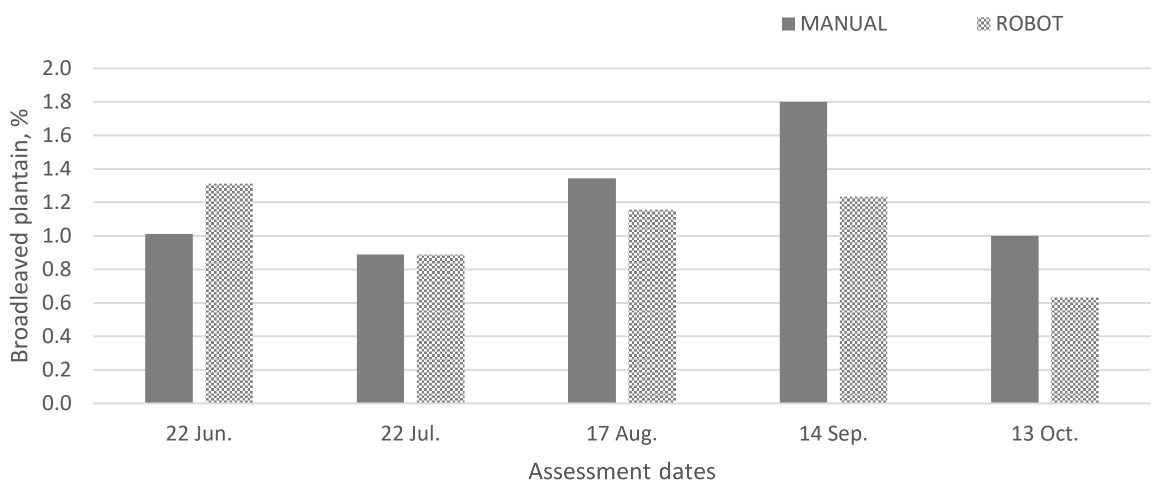

Figure 9: Coverage of transplanted broadleaved plantain in subplots on semi-rough mown by robotic and manual mowers.

Coverage of the transplanted weeds developed differently in the different species, and between robotic and manual mowing. Coverage of transplanted broadleaved plantain (Figure 9) increased only slightly to 1-2% in some subplots. No differences were found between robotic and manual mowing systems. For transplanted white clover the situation was different (Figure 10) and it covered up to 20% of the subplots in the robotic mown plots with significant differences to manual mown plots in June, July and August. At the same time spontaneous white clover developed in the semi-rough – notably in some of the *L. perenne* plots.

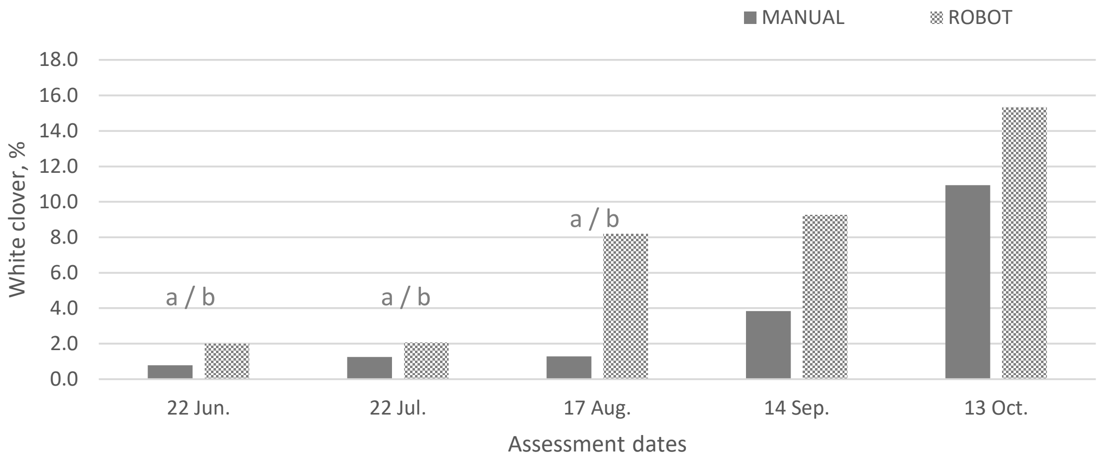

Figure 10: Coverage of white clover in semi-rough (subplots with transplanted white clover) mown by robotic and manual mowers. Different letters (a and b) indicate significant differences between the two mowing systems.

2.4.5 Soil compaction

On average for the three species there was a significant difference in soil compaction between robotic and manual mowing in the semi-rough trial (Table 8). The highest soil compaction was found in manual mown *Lolium perenne and Festuca rubra*.

Table 8: Soil compaction measured in the three turfgrass species at robotic and manual mowing. Different letters (a and b) indicate significant differences between the two mowing systems.

Treatment	Water content	Soil compaction		
	Vol.-%	MPa		CV %
MANUAL *L. perenne*	26.6	4.5		13
MANUAL *F. rubra*	27.3	4.6		11
MANUAL *P. pratensis*	27.8	4.2		17
ROBOT *L. perenne*	26.4	3.1		15
ROBOT *F. rubra*	24.6	3.5		16
ROBOT *P. pratensis*	25.0	3.5		11
P-value	**0.220**	**0.147**		
MANUAL	27.2	4.4	b	14
ROBOT	25.3	3.4	a	15
P-value	**0.09**	**0.015**		
L. perenne	26.5	3.8		23
F. rubra	26.0	4.0		19
P. pratensis	26.4	3.9		17
P-value	**0.763**	**0.147**		

2.5 Discussion

No differences in turfgrass height were found between robotic and manual mowing except on 28. June where the manual mown plots were 7 mm lower than the robotic mown plots due to start-up problems with the new manual rotary mower (Photo 12). These technical problems with scalping in some of the plots were solved quickly but could explain the lower turfgrass quality that was observed in all three species in the manual mown plots in June (Figure 7).

Photo 12: Some start-up problems with the new semi-rough mower led to a significantly lower turfgrass height and quality in manual mown plots in June.

Photo: Trygve Aamlid.

There were great variations in turfgrass visual quality between the turfgrass species and mowing systems in the semi-rough trial. In *Lolium perenne* some changes happened with the turfgrass visual quality, as it was higher in robotic mown plots in June and fell to very low quality (under acceptable) from July and further on. The variations could be explained by an invasion of spontaneous white clover which spread most aggressively in *Lolium perenne* compared to *Festuca rubra* and *Poa pratensis* (Photo 13, Photo 14, Photo 15). The reason for the increasing coverage of white clover can be that *Lolium perenne* was weaker after the winter and had less density in the spring compared to the two other species. At the start assessments in April *Lolium perenne* was rated 5.0 compared to *Poa pratensis* (6.0) and *Festuca rubra* (7.5) (Figure 7). An additional reason could be that the N-rate of 60 kg N/ha was too low for the *Lolium perenne* to develop a dense and strong sward to compete with the white clover.

Photo 13: Drone photo from the semi-rough 28. July. Very few green patches (spontaneous white clover) can be seen in the robotic mown plots with Lolium perenne.

Photo: Karin J. Hesselsøe.

Photo 14: Drone photo from the semi-rough 11 August. More green patches (spontaneous white clover) can be seen in the robotic mown plots with Lolium perenne.

Photo: Karin J. Hesselsøe.

Photo 15: Drone photo from the semi-rough 3 September. Much more green patches (spontaneous white clover) can be seen in the robotic mown plots with Lolium perenne.

Photo: Karin J. Hesselsøe.

Another reason for the lower turfgrass visual quality in the robotic mown *Lolium perenne* was observed as an increased tendency to stem formation observed in a dry period in July and August (Photo 16). Stem formation in *Lolium perenne* can be a stress reaction induced by warm and dry weather conditions, and some varieties are more genetic predisposed to stem formation than others. The reason why the robotic mown plots had more stems than the manual mown plots is not clear, and further investigations are needed here.

Photo 16: Stem formation in robotic mown Lolium perenne was higher than in manual mown plots.

Photo: Karin J. Hesselsøe, September 2021.

In *Festuca rubra* turfgrass visual quality was higher with robotic mowing in June, but the opposite happened from July to September with higher turfgrass visual quality in manual mowing. The reason for the lower ratings of the robotic mown *Festuca rubra* in late summer and autumn was due to an unusual mowing pattern observed in the robotic mown plots compared to the manual mown plots (Photo 17) where the mowing was much more even. The uneven mowing pattern was only observed in *Festuca rubra*, and it developed over time from July to September. The unusual mowing pattern and the reason for it was discussed at the reference group meetings at Grenå GC in September 2021 and on teams meeting in March 2022. At Bærheim in Norway they have sometimes seen a similar mowing pattern by some of the robots, but they thought it was due to a single robot that mowed in a special pattern (Photo 18). Nevertheless, we are not able to explain this phenomenon, and further investigations are needed.

Photo 17: Robotic mown plot with Festuca rubra in September (to the left) and manual mown plot with Festuca rubra (to the right).

Photo: Karin J. Hesselsøe.

Photo 18: Unusual mowing pattern from Bærheim GC (left side of the photo) like the pattern observed in the Festuca rubra plots on the WP1 semi-rough at Landvik.

Photo: David B. Smith.

Diseases were found in all three turfgrass species from late summer according to Figure 8. More red thread in manual mown plots of *Lolium perenne* and *Festuca rubra* and more rust in manual mown *Poa pratensis* could explain the significant differences between the two mowing systems. But the lower disease incidence in the robotic mown plots could not be seen in the turfgrass visual quality ratings for *Lolium perenne* and *Festuca rubra*, because other factors such as white clover infestation in *Lolium perenne* and the unusual mowing pattern in *Festuca rubra* overruled the quality ratings here. Only in *Poa pratensis* the disease incidence (from rust) could explain the lower turfgrass quality ratings in manual mown plots in September and October which could also be seen on Photo 19.

Photo 19: Drone photo of the semi-rough area in late September. Manual mown plots with Poa pratensis is much paler and brownish than robotic mown plots with Poa pratensis due to rust. Transplanted white clover can also be distinguished in robotic mown Lolium perenne plots (repetition 2 and 3).

Photo: Karin J. Hesselsøe.

Transplanted white clover increased significantly in the robotic mown plots compared to the manual mown plots especially in *Lolium perenne* which can be seen on Photo 19. The explanation for this increase is the same as for the spontaneous white clover. In Pirchio (2018a) weed infestation was correlated with N-rate, which can explain the higher invasion in our trial with *Lolium perenne*. A hypothesis from these findings can be that a weak lawn with a too low N-rate is more susceptible to weed infestation when robotic mown compared to manual mown.

On average for the three turfgrass species there was a significant difference in soil compaction between robotic and manual mowing in the semi-rough trial (Table 8). This significant difference was not seen in the fairway trial and can be explained by the heavier semi-rough mower.

3 WP2 Impact of robotic mowing and return of clippings on fertilizer requirements

3.1 Materials and methods

The experimental area for WP2 is placed in between WP1 fairway and WP1 semi-rough experimental area with main plots for robotic mowing of 10 m x 20 m and for manual mowing of 10 m x 10 m (Figure 11).

3.1.1 Experimental design

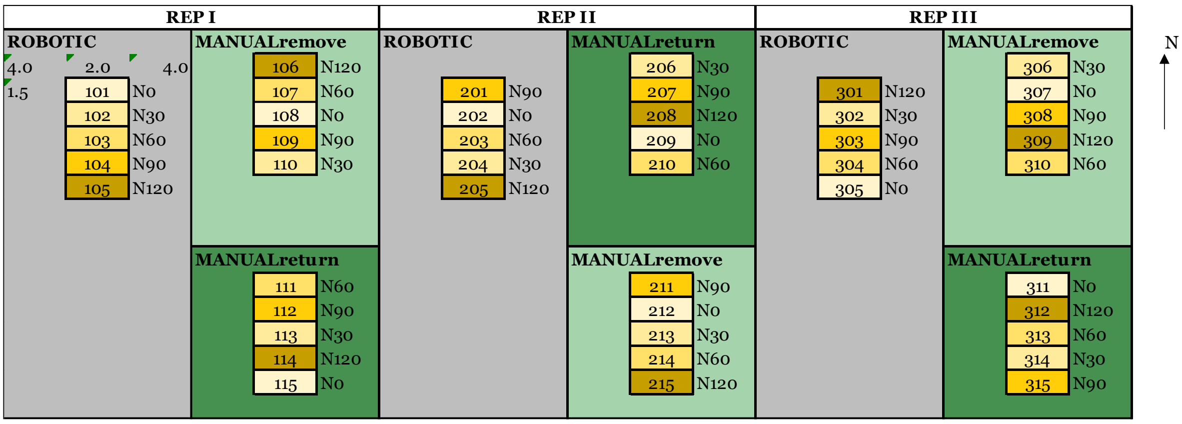

Figure 11: Detailed plan of the WP2 experimental site.

The split plot experimental design of WP2 with three replicates was set up with main plots as: Robotic mowing every day with return of clippings (ROBOTIC), manual triplex mowing Monday, Wednesday, and Friday with return of clippings (MANUALreturn) and manual triplex mowing Monday, Wednesday and Friday with clippings bagged off (MANUALremove). The mowing height was the same as in WP1. Subplots of 1.4 m x 2.0 m were established in the main plots with annual fertilizer application of: 0, 30, 60, 90 and 120 kg N/ha split into 6 equal applications monthly from April to September. The fertilizer type used in the subplots was Wallco complete 5-1-4 liquid (Table 9). Main plots outside the subplots were fertilized as in WP1 (Table 3).

Table 9: Fertilizer type, fertilizer and nutrient rates (kg/ha^{-1} y) for each subplot factor

Treatment[1]	Fertilizer type	Fertilizer	N	P	K	Mg	S	Ca	Fe	Mn
					kg ha^{-1} y					
N0	No fertilizer	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N30	Wallco 5-1-4	588	30.0	5.9	25.3	2.4	2.4	2.4	0.1	0.1
N60	Wallco 5-1-4	1176	60.0	11.8	50.6	4.7	4.7	4.7	0.2	0.2
N90	Wallco 5-1-4	1765	90.0	17.6	75.9	7.1	7.1	7.1	0.3	0.4
N120	Wallco 5-1-4	2353	120.0	23.5	101.2	9.4	9.4	9.4	0.4	0.5

[1] Annual fertilizer rate was split in 6 equal applications.

3.1.2 Maintenance during the season

The subplots in WP2 were fertilized first time on 19 April and irrigated with 3 mm irrigation water. Start-up of robots at position 2 and first manual mowing at 15 mm was done on 21 April continuing as in WP1 through the season until October.

3.1.3 Collection of clippings

Both fertilization and collection of clippings in the subplots were done monthly on Mondays. First collection of clippings (Photo 20) was done on 3 May, two weeks after fertilization. To ensure a uniform starting point before collection of clippings, robotic mowing was cancelled from Thursday morning and those plots were mown with the manual fairway mower with return of clippings on the day after (Friday morning). The collection of clippings was done with walk-behind greens mower mowing height 15 mm. Clippings from each subplot were collected in paper bags (Photo 20) and dried for dry matter weight. Two pooled samples of the plant material (one with clippings from May - June and one with clippings from July - October) were analyzed for N concentration (TDC thermal conductivity detector) at ALS-laboratory.

Photo 20: Clippings in the WP2 subplots were collected with a John Deere walk-behind mower. The samples were analysed for dry matter weight and N concentration.

Photo: Trygve Aamlid.

3.1.4 Data collection

Before the trial started, soil samples (0 – 20 cm depth) for loss on ignition, pH, P-AL, K-AL, Mg-AL, Ca-AL, Na-AL, and mineral N analyses were collected on each main plot for ROBOTIC and MANUALreturn. Soil bulk density was also determined.

Start registrations were done on 11 April. Thereafter monthly registrations were done on Thursdays, ten days after fertilizer applications and just before robotic mowing was cancelled for the weekend. The following parameters were assessed: Turfgrass visual quality (scale 1 — 9) where 1 is poor, 9 is excellent, and 5 is the lowest acceptable quality; Turfgrass color using a Field Scout CM 1000 chlorophyll meter (Spectrum Technologies, Aurora, IL, USA). Five measurements were taken per plot for mean value and coefficient of variation calculation; Tiller density (scale 1 — 9), where 9 expresses the highest turf density; Coverage of *Poa annua,* broadleaved weeds, and turfgrass diseases as percent of plot area.

Botanical composition was done at the end of the season. Tillers of the seeded species and of *Poa annua* were counted in 5 random core samples (diameter 18 mm) taken from the main plots MANUALreturn and ROBOT.

3.1.5 Statistical analyses

The experimental data was analyzed using Microsoft Excel and R version 4.1.2 (R CORE TEAM 2013). Corresponding to the split plot design, ANOVAs were performed for each assessment/measurement date and on the average values for different periods. Mowing systems were considered as mainplots and fertilizer rate as subplots. The function "lmer" in package "car" was used taken into account: $lmer$ ($Response$ ~ BLK + Mowing system ∗ Fertilizer rate + (1|BLK:Mowing system)), $type$="II",$test.statistic$="F") with the arguments Response = parameters; type II = provided p-values in type II anova; test.statistic: F = F-tests (FREEDMAN 2006; LONG and ERVIN 2000; WHITE 1980). To denote significant differences, contrasts were calculated for pairwise comparison at 5 % level adjusted by "Tukey" performing the function "cld/emmeans" in the package "multcomp" according to PIEPHO (2004).

3.2 Results WP2

3.2.1 Soil physical and chemical parameters

Before the trial started, manual or robotic mown main plots did not show any differences in soil physical or chemical properties (Table 10).

Table 10: Soil physical and chemical properties before trial.

Treatment	Soil bulk density	Loss on ignition	pH	N_{min}	NO_3-N	NH_4-N	P-AL	K-AL	Mg-AL	Ca-AL	Na-AL
	kg/l	%		kg/ha			mg/100 g air-dried soil				
MANUAL	1.2	6.4	5.9	4.1	0.4	3.7	16.7	10.4	7.2	95	2.9
ROBOT	1.2	6.3	6.0	4.6	0.6	4.0	17.3	9.8	7.3	94	3.0
P-value	0.423	0.423	0.423	0.716	0.401	0.821	0.802	0.452	0.828	0.300	0.907

3.2.2 Turfgrass visual quality

For all mowing systems, turfgrass visual quality showed acceptable ratings above 5, even without fertilizer application. On N0 level, robotic mown plots revealed significantly higher turfgrass quality ratings compared to MANUALremove (p = 0.082) but not compared to MANUALreturn. This response could not be found at any other N level. Higher N rates (30 to 120 kg N/ha/yr) slightly increased turfgrass visual quality ratings by max. 1 unit on the scale. For MANUALremove, the fertilizer rates 30, 60, and 120 kg N/ha/yr resulted in significantly higher ratings compared to no fertilizer application. ROBOTIC and MANUALreturn plots showed significantly higher ratings at N120 level compared to N0 level but not compared to any other N level. In general, there were no significant differences in turfgrass visual quality ratings between MANUALreturn and ROBOT treatment.

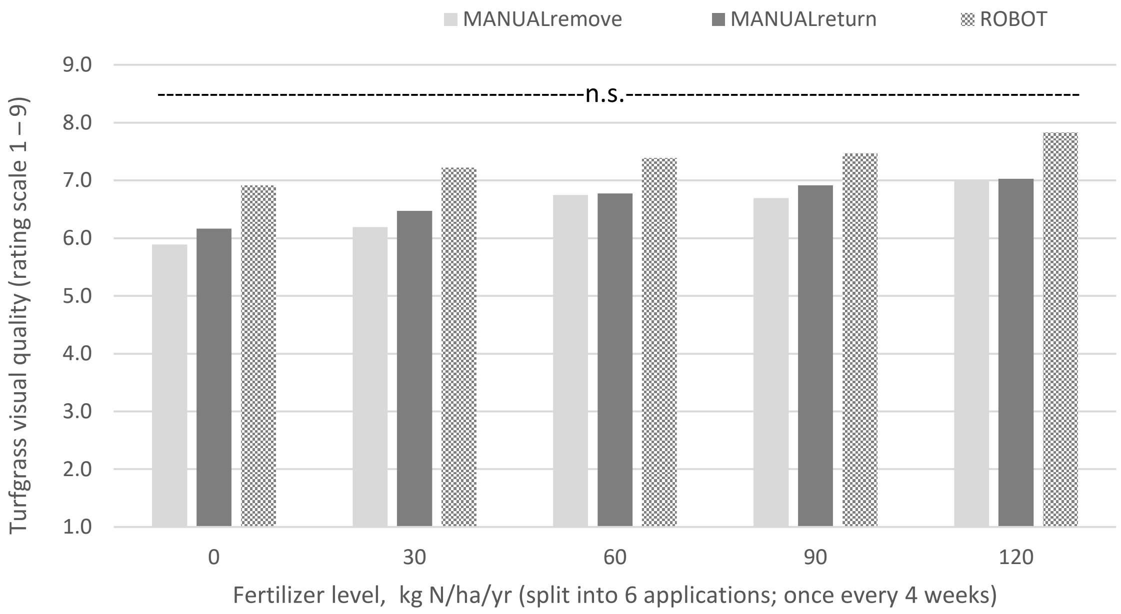

Figure 12: Turfgrass visual quality at N rates of 0 to 120 kg N/ha for the three mowing systems: MANUALremove, MANUALreturn, and ROBOT. n.s. = Not significant.

3.2.3 Clippings collected

Across all assessment dates, clipping yields did not show significant differences between robotic and manual mowing but between MANUALremove with the lowest yield and MANUALreturn with the highest yield. During the vegetation period, clipping yields varied between assessment dates regardless of mowing system and N level (Figure 13). Clipping yield was highest in late May and late June with up to almost 5.5 $g/m^2/d$. At the end of May ROBOTIC and MANUALreturn plots revealed significantly higher yields than MANUALremove plots. Differences between robotic and manual return mowing were insignificant. At the end of June, contrary results were found, showing significantly higher yields for MANUALreturn compared to ROBOTIC or MANUALremove. Additionally on these two assessment dates, increasing fertilizer application had the strongest impact on clipping yield for all mowing systems. Nevertheless, no interactions could be found.

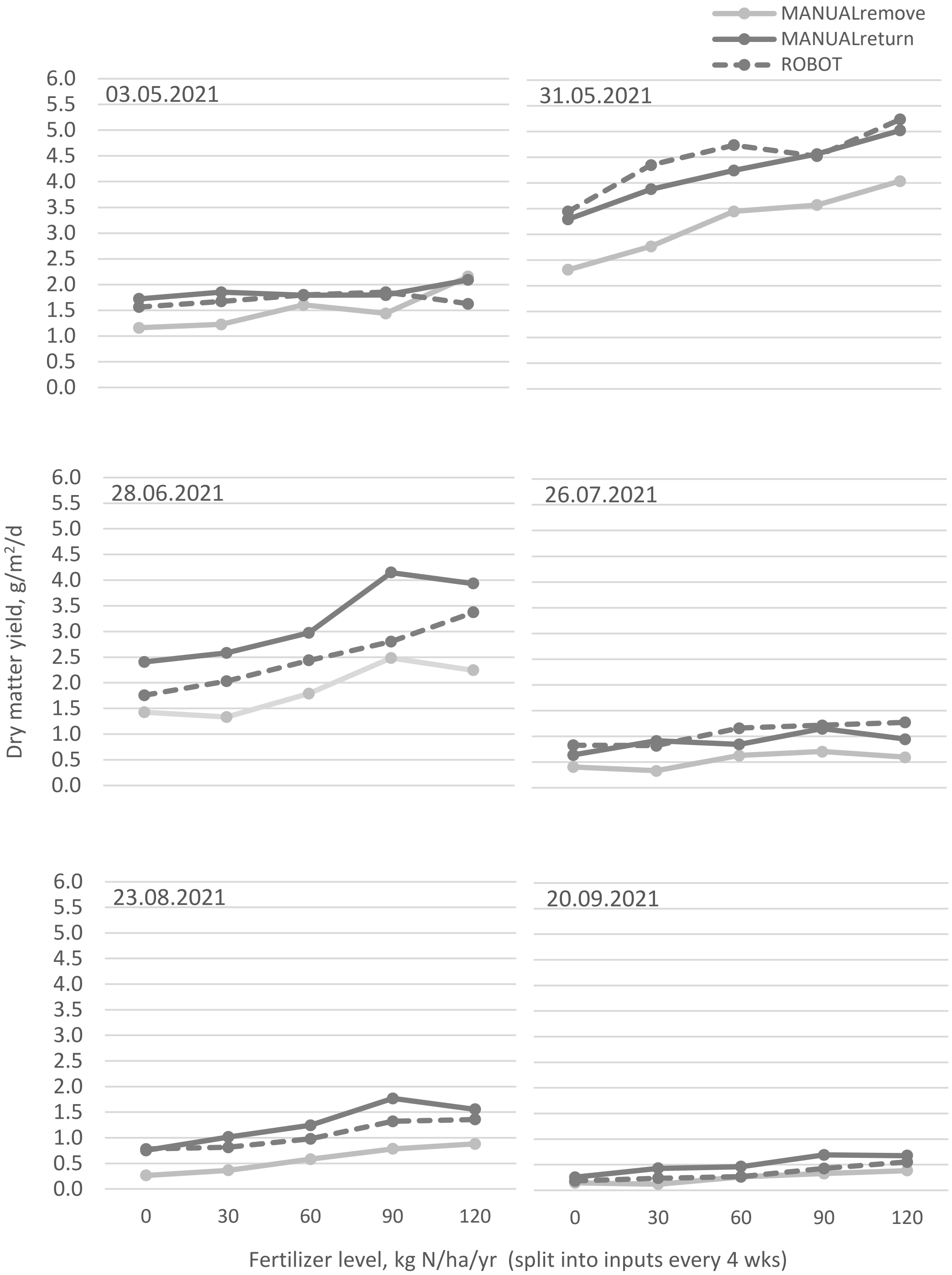

Figure 13: Dry matter yield in response to the three mowing systems: MANUALremove, MANUALreturn and ROBOT for each date of clippings collection.

3.2.4 N concentration in clippings

In spring, N concentration in clippings ranged between 3.0 and 4.0 % regardless of mowing system and N level. In summer/fall the N concentrations were lower, ranging between 2.5 and 3.5 %. Neither in spring nor in summer/fall N concentrations differed significantly between the three mowing systems ($p= 0.061$ and 0.126, respectively). Interactions between mowing systems and fertilizer levels could not be found either.

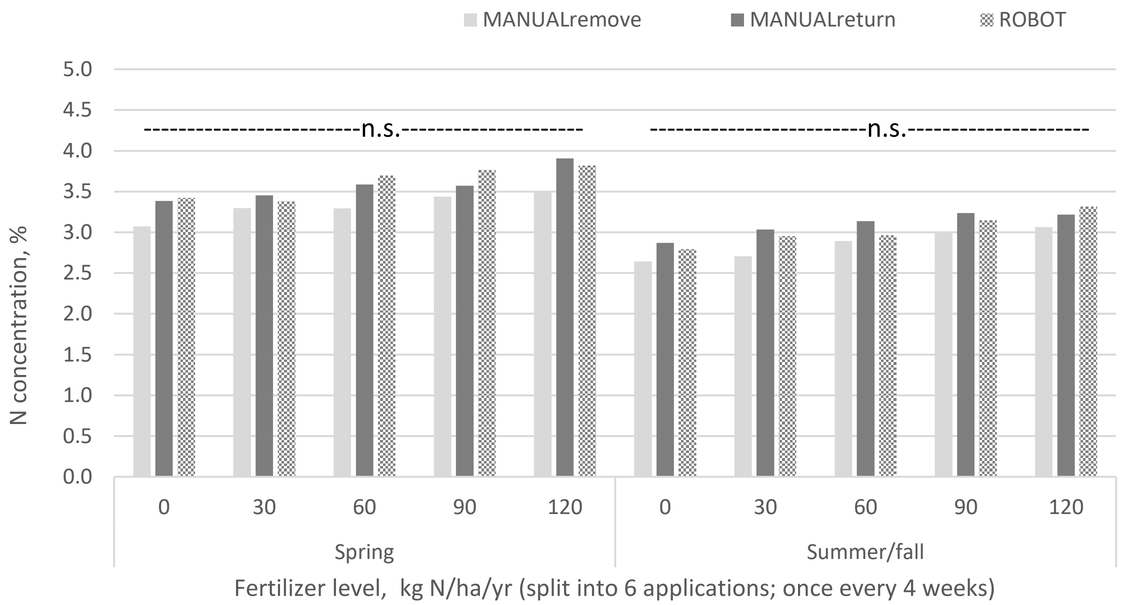

Figure 14: N concentration in the clippings of the three mowing systems: MANUALremove, MANUALreturn, and ROBOT.

3.2.5 Botanical analyses

The botanical composition showed no differences in *F. rubra* coverage with 44 % for both mowing systems ROBOTIC and MANUALreturn. *A. capillaris* coverage was 5 % lower (39 %) on robotic mown plots than on MANUALreturn plots (44 %). For *P. pratensis*, the situation was the other way round. Robotic mown plots had more *P. pratensis* (17 %) than MANUALreturn plots (11 %).

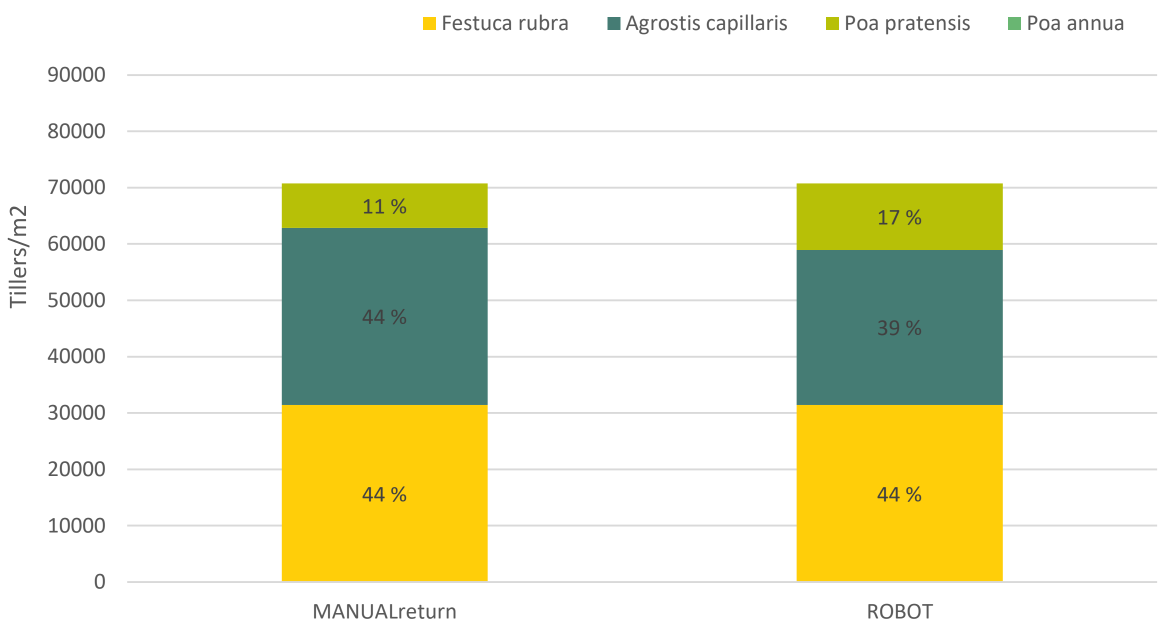

Figure 15: Botanical composition of the mowing systems MANUALreturn and ROBOT.

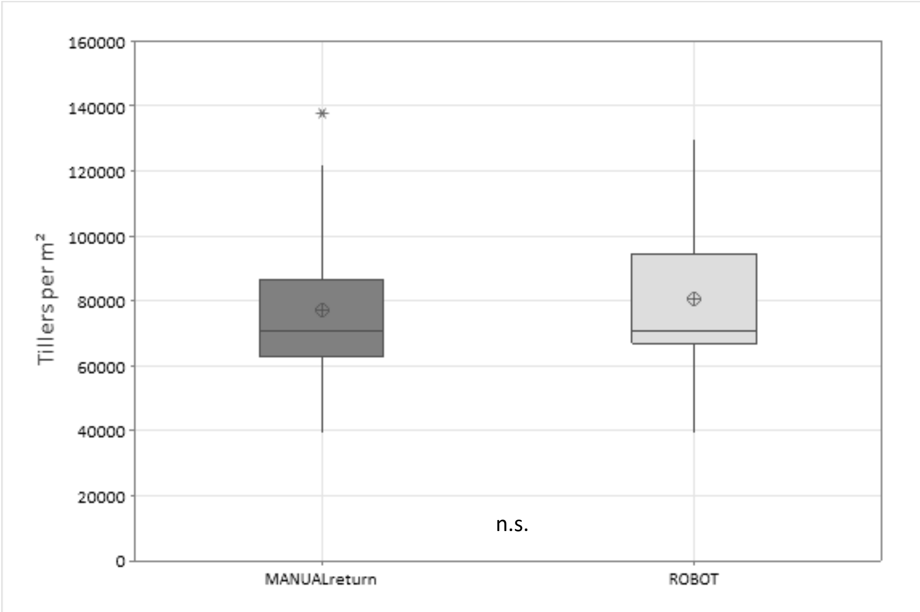

Figure 16: Tillers pr. m² counted in the two mowing systems MANUALreturn and ROBOT.

3.3 Discussion

Before the trial started, soil physical and chemical properties were comparable for all plots (Table 10). Thus, the experimental area was suited for the fertilizer trial. Regardless of mowing system or N level, mean turfgrass visual quality was acceptable with ratings above 5.0. For MANUALremove, the fertilizer rates of 30, 60, and 120 kg N/ha/yr resulted in significantly higher ratings compared to no fertilizer application. ROBOTIC and MANUALreturn plots showed significantly higher ratings at N120 level compared to N0 level but not compared to any other N level. It can be concluded that on manual mown fairways with clippings removed the fertilizer rate has a higher impact on turfgrass visual quality than on manual mown fairways with clippings returned or on those mown by a robot. At the same time, the current results indicate that an N rate > 30 kg/ha/yr might not be necessary for MANUALreturn or ROBOTIC mown turfgrass swards as turfgrass visual quality could not be increased significantly. In general, there were no significant differences in turfgrass visual quality ratings between MANUALreturn and ROBOT treatment. This might indicate that switching from manual mowing with clippings returned to robotic mowing does not worsen turfgrass visual quality. It was expected that clipping yields would increase due to robotic mowing compared to MANUALreturn as the robots were mowing the sward every day leaving smaller turfgrass pieces. However, this was not the case (Figure 13). There were no significant differences in clipping yields. In fact, MANUALreturn treatment resulted in highest clipping yields. Especially in June, apparently sufficient soil moisture and warm temperatures after a wet May (197 mm) led to a fast mineralization of the returned clippings. Why clipping yields were higher on MANUALreturn plots compared to ROBOTIC mown plots in June, cannot be answered yet. One reason might be higher volatile N losses on ROBOTIC mown plots. However, lower clipping yields might be an advantage for robotic mowing in case of energy use. The trial also indicates that a return of clippings in manual mowing systems can reduce fertilizer rate up to 66 %. N concentrations in clippings did not show any considerable differences between mowing systems and revealed a turfgrass sufficient level (Figure 14).

No clear differences in the botanical composition between the two mowing systems were found in 2021. A reason for this might have been the high variability between the 15 subsamples for each treatment. More subsamples should be taken in 2022. The same analyses in 2020 (Aamlid et al., 2021) showed more *Agrostis capillaris* and less *Festuca rubra*. Due to daily robotic mowing, it was expected that these plots would show a higher tiller density. This was not the case (Figure 16).

4 WP3 Demonstration trials on golf courses

Photo 21: The robotic mowers on fairway and semi-rough at the experimental area in Grenå September 2021.

Photo: Karin J. Hesselsøe.

Demonstration trials on four golf courses: Bærheim (Norway), Grenå (Denmark), Jönköping (Sweden) and Ness (Iceland) were continued using the same plots on fairway and semi-rough for assessments as in 2020. For baseline information on soil type, turf age, grass species, fertilization and maintenance on the four golf courses see (Aamlid et al., 2021). In December 2020 the Finnish golf course Ikaalisten was replaced with Hirsala (se info below). On each of the golf courses, two neighbour fairways and semi-rough areas of similar size, shape and soil type were used – one area for robotic mowing and one area for manual mowing, and two robotic mowers (model 550), one for the designated fairway and one for the designated semi-rough were used (Photo 21).

4.1 Materials and methods

4.1.1 Baseline info from Hirsala

Photo 22: Hole 16 at Hirsala Golf.

Photo: Janne Lehto.

Hirsala Golf is 18-holes woodlands/heathland type golf course and is located about 25 km west of Helsinki. The golf course comprises 65 ha of diverse woodlands. The golf course is designed by David Jones and today is a shared ownership public golf course. Greens are creeping bentgrass (originally A4/G1/L93 mix) and the rest of the maintained turf areas mix of Fescues and *Poa pratensis*.

Course manager Janne Lehto is managing the golf course together with a staff of six full time greenkeepers and seasonal staff of on average five greenkeepers. The assessments were done by Janne Lehto and mechanic Ari-Pekka Marjatsalo. At Hirsala Golf they use Husqvarna robotic mowers on all greens surrounds covering 3000 m2 of semi-rough. They also mow three fairways with robotic mowers as a trial and intend to increase the fleet during 2022.

Table 11: Baseline info from Hirsala.

	Fairway	Semi-rough
Soil type	Sand cap on top of clay	Sand cap on top of clay
Turf age	15 years	15 years
Grass species	Fescue/ Poa pratensis/ Poa annua	Fescue/ Poa pratensis/ Poa annua
Fertilisation	60kg N/ha	0kgN/ha
Mowing height/frequence	12 mm, 2 times/week	42 mm, 1 times/week
Manual mower type	Toro Reelmaster 5510	Toro Groundsmaster 4300 Rotary mower

4.1.2 Data collection and weather

As in the first year of the project three representative 1 m2 plots on robotic and three on manual mown fairway and the same on semi-rough were used for assessments which were reported from the course managers to project leader via the app Socrative. Visual assessments were done every four weeks approx. from April to September.

The first mowing's on fairway and semi-rough were done with manual mowers and after that start assessments were done before the robotic mowers were started. Next assessments were done in the beginning of the month after start-up assessments. The following characters were recorded every four weeks:

Turfgrass visual quality was recorded on a scale from 1 to 9 where 9 is the best turf and 5 is the lowest acceptable turf. Turfgrass visual quality is an overall score for live turf cover, uniformity, greenness, leaf fineness, disease resistance, freedom of weeds and shoot density.

Coverage of weeds and diseases: Recordings of plot area (in percent) with the weed species: Annual bluegrass (*Poa annua*), dandelion (*Taraxacum officinale*), daisies (*Bellis perennis*), broadleaved plantain (*Plantago major*) and clover (*Trifolium sp.*). Coverage of plot area (in percent) with diseases in total.

Energy and labour use: To calculate the consumption of electricity an energy logger was installed at the docking station for each robotic mower as in the first year. Labour use and the consumption of diesel/gasoline by the manual cylinder and rotary mowers was estimated by the course managers in June.

At all the experimental sites spring 2021 was cold and dry, so growth was limited though a lot of golf rounds were played, because of the Corona-lock-down. At Grenå in Denmark first assessments were done in the middle of April. In Norway, Sweden, and Finland first assessments were done in the beginning of May, and in Iceland in late May. First assessments recording robotic versus manual mowing at all sites was in June. Unfortunately, there were technical problems with the robotic semi-rough mower in Iceland, so no data from here were collected from semi-rough in July. In Finland a very dry summer decreased the turfgrass quality ratings on the fairway in July.

4.1.3 Statistical analyses

The experimental data from WP3 were analyzed using Microsoft Excel and Minitab 20.2. Stat ANOVA Mixed Effects Model, Tukey pairwise comparisons and 95% confidence.

4.2 Results

Data on turfgrass visual quality and coverage of weeds are shown below for each golf course. Only very few diseases were found.

4.2.1 Turfgrass quality and weeds

Norway

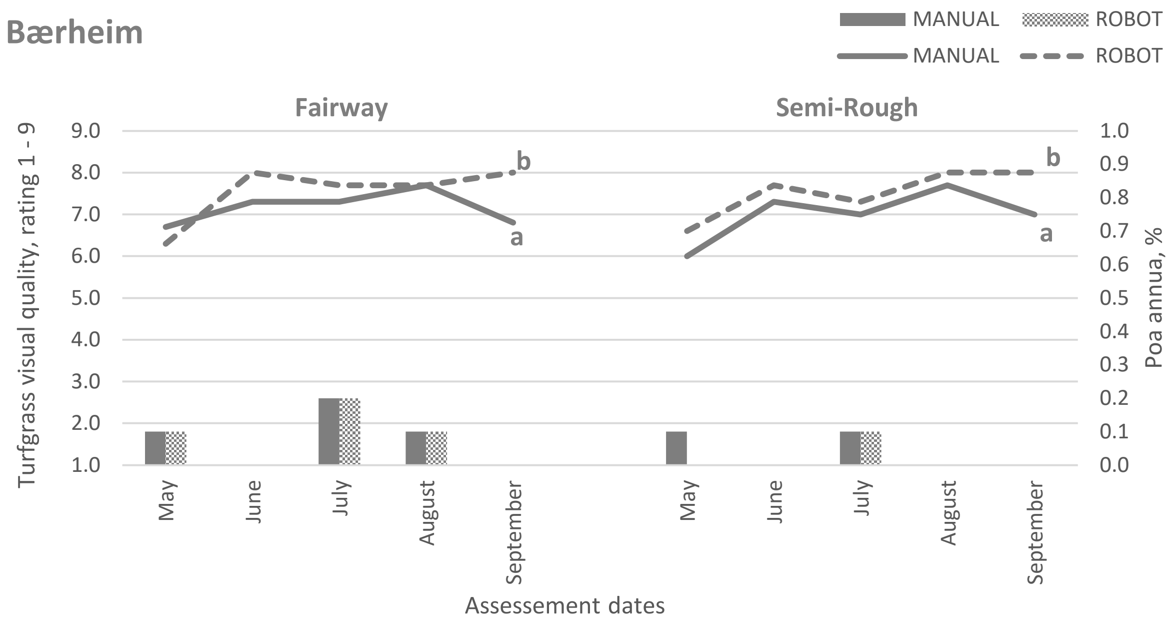

Figure 17: **Turfgrass visual quality on fairway and semi-rough in robotic and manual mowing (lines) at Bærheim. Coverage of Poa annua in percent of plot area in robotic and manual mowing (bars). Different letters (a and b) indicate significant differences.**

Denmark

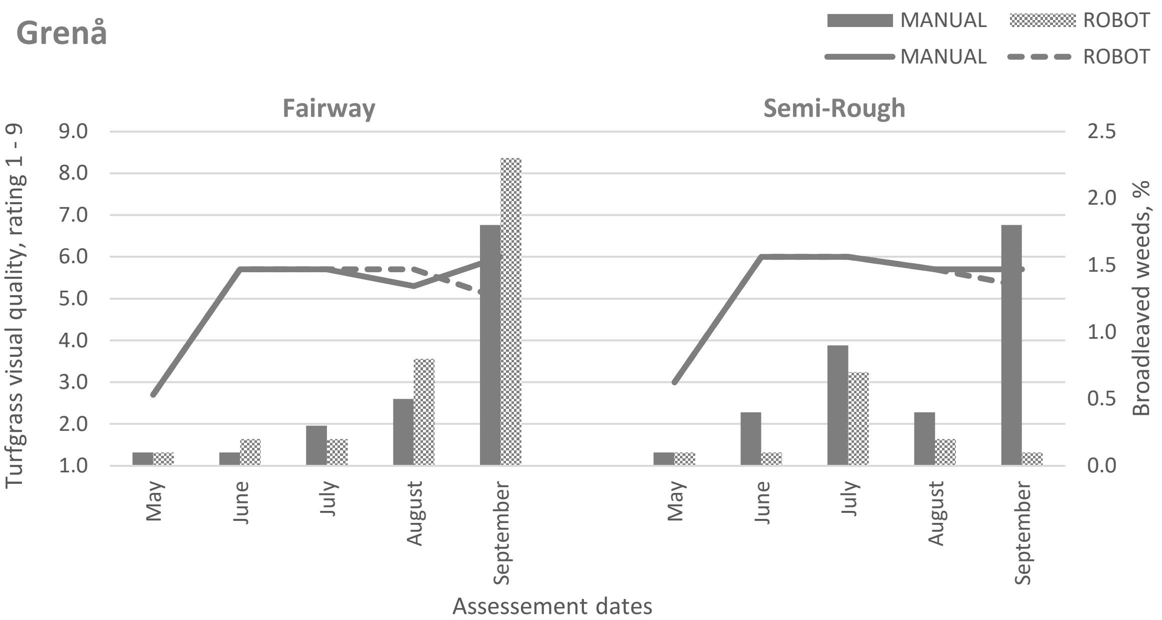

Figure 18: Turfgrass visual quality on fairway and semi-rough in robotic and manual mowing (lines) at Grenå. Coverage of broadleaved weeds in percent of plot area in robotic and manual mowing (bars).

Iceland

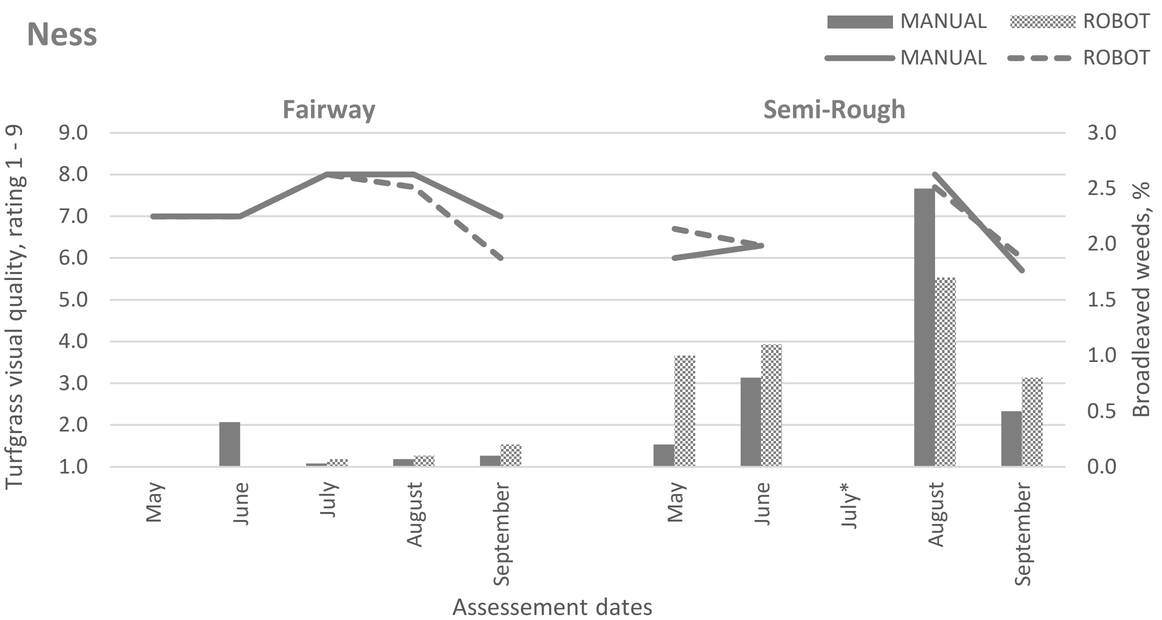

Figure 19: Turfgrass visual quality on fairway and semi-rough in robotic and manual mowing (lines) at Ness. Coverage of broadleaved weeds in percent of plot area in robotic and manual mowing (bars). *: No data from semi-rough in July due to robot break-down.

Photo 23: Fairway at Ness, Iceland in July. Robotic mown to the right, manual to the left.

Photo: Bjarni Hannesson.

Sweden

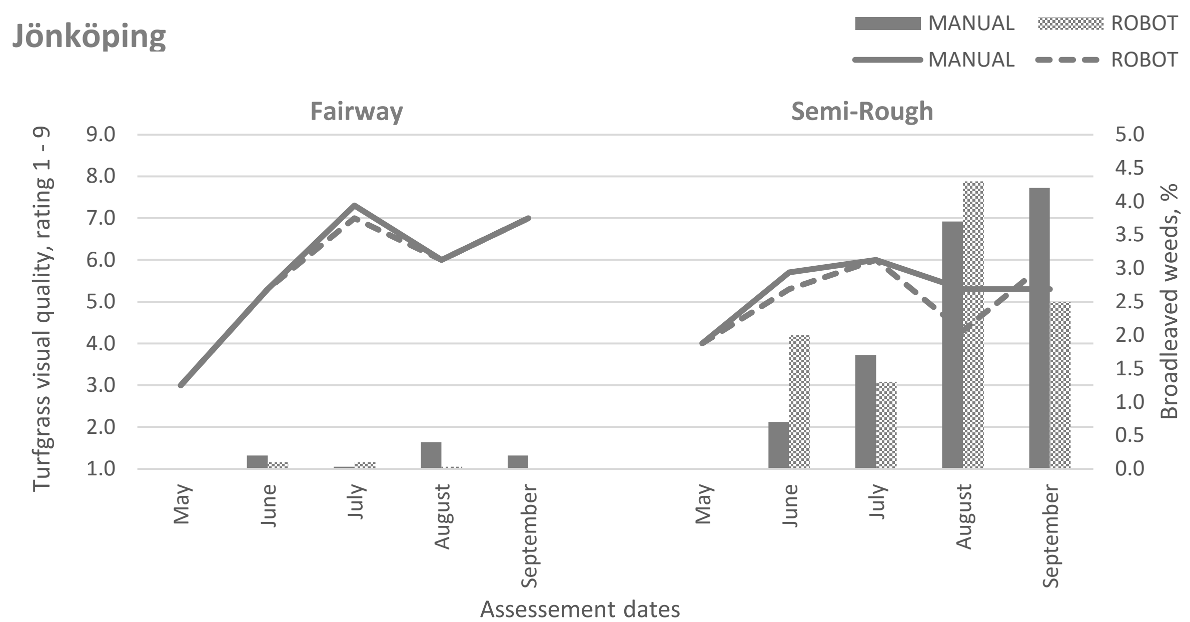

Figure 20: Turfgrass visual quality on fairway and semi-rough in robotic and manual mowing (lines) at Jönköping. Coverage of broadleaved weeds in percent of plot area in robotic and manual mowing (bars).

Finland

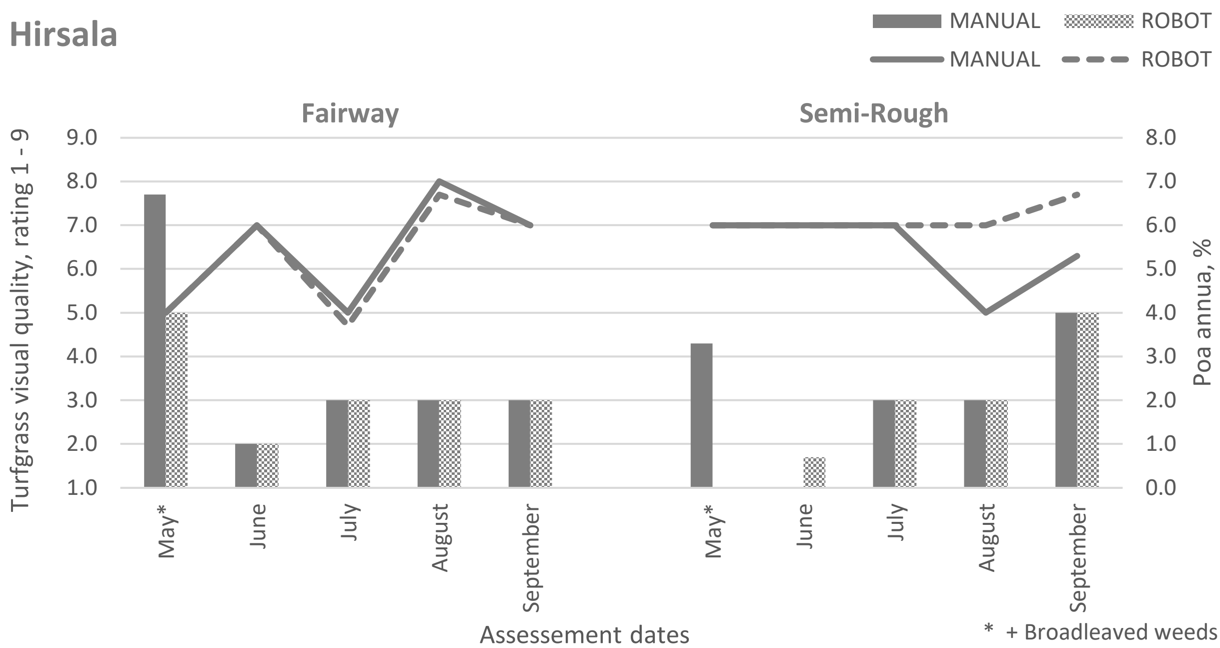

Figure 21: Turfgrass visual quality on fairway and semi-rough in robotic and manual mowing (lines) at Hirsala. Coverage of Poa annua and broadleaved weeds in percent of plot area in robotic and manual mowing (bars).

4.2.2 Energy and labour use

The course managers estimations showed large variations in the diesel consumption and time spend on manual mowing of the fairway and semi-rough (Table 12 and Table 13). Data from the energy loggers will be provided by Husqvarna.

Table 12: Estimated diesel consumption and labour use for mowing the fairways at the golf courses.

	Area for manual mowing? m2	Diesel used on mowing this fairway area? L	Diesel consumption on fairway L/ha	Time spend on mowing exp. fairway area? Min	Time used, fairway Min/ha
Bærheim/Norway	1061	0.9	8.5	3.1	29.2
Ness/Iceland	600	0.5	8.3	5	83.3
Grenå/Denmark	3500	1.5	4.3	7	20.0
Hirsala/Finland	4000	3.5	8.8	18	45.0
Jönköping/Sweden	3500	1.1	3.1	17.5	50.0

Table 13: Estimated diesel consumption and labour use for mowing the semi-rough at the golf courses.

	Area for manual mowing? m2	Diesel used on mowing this semi-rough? L	Diesel consumption on semi-rough L/ha	Time spend on mowing ? Min	Time used, semi Min/ha
Bærheim/Norway	1000	1.4	14	4	40
Ness/Iceland	1000	0.4	4	6	60
Grenå/Denmark	2000	2	10	10	50
Hirsala/Finland	2000	2	10	9	45
Jönköping/Sweden	1000	0.35	3.5	5	50

4.3 Discussion

Turfgrass visual quality of robotic mown plots was mostly equal to manually mown plots on the five golf courses. Only at Bærheim (Norway) robotic mowing both on fairway and semi-rough was significantly better at the assessments in September. The difference could be due to high rainfall at Bærheim in the autumn where the robots caused less wear on the turf compared to the manual mowers. At Ness (Iceland) reduced quality of robotic mown plots on fairway was seen in autumn (not significant). An explanation could be that the robots mowed too often when the temperature decreased on a relatively small fairway area. Weather-timers (that can stop the robots in wet and cold weather) were not installed on the experimental mowers. In 2020 observations were done that showed less seeds heads of *Poa annua* in robotic mown fairway compared to manual mown. These observations were not confirmed in 2021. At Jönköping (Sweden) the fairway had high quality with few weeds compared to the semi-rough with many dandelion and white clover, but no differences between robotic and manual mowing. The increase of white clover observed in some of the robotic mown semi-rough plots at Landvik in WP1 cannot be confirmed at any of the golf courses. At Hirsala (Finland) a spraying against broadleaved weeds was done in spring which can explain the decrease of coverage from Many to June. In August and September turfgrass visual quality on semi-rough was lower in manual compared to robotic mowing (not significant). An explanation for this could be increased growth in that period, and the manual mowers could not keep up with growth in that period.

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