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

Results from 2020

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SAMMENDRAG: (FOR SUMMARY IN ENGLISH, SEE PAGE 6)

Denne rapporten gir resultater fra første år i prosjektet 'ROBO-GOLF: Bedre gresskvalitet, redusert gjødselkostnad og mindre bruk av fossil energi ved bruk av robotklipper på fairway og semi-rough'

I arbeidspakke (WP) 1 ble 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 anlagt på NIBIO Landvik i 2020. Foreløpige resultater fra perioden 11.august - 30.oktober 2020 (etter at grasdekket var etablert) viste bedre helhetsinntrykk med robotklipping enn med manuell klipping på fairway, spesielt i engkvein (*Agrostis capillaris*) som ble mindre angrepet av mikrodochiumflekk. På semi-rough var derimot skuddtettheten mindre og bladbredden større, og engrapp (*Poa pratensis*) ble mer invadert av tunrapp og mer angrepet av rust ved robotklipping enn ved manuell klipping.

I WP2 ble det på Landvik sådd et nytt fairwayområde der vi i 2021 og 2022 skal sammenlikne gjødsel-virkningen av tilbakeføring av avklipp ved robotklipping og manuell klipping av en grasbestand bestående av rødsvingel, engrapp, engkvein og tunrapp. I 2020 ble robotklipping og manuell klipping (begge med tilbake-føring av avklipp) sammenlikna fra 11.august til 30.oktober. Det var ingen forskjell i helhetsinntrykk eller skuddtetthet, men en svak tendens til mer engkvein og tunrapp, men mindre engrapp og rødsvingel, ved robotklipping enn ved manuell klipping med sylinderklipper.

I WP3 ble det i mai 2020 etablert demofelt med robotklipping av fairway og semi-rough på Bærheim GP (Sandnes, Norge), Grenaa GK (Danmark), Ness GK (Island), Jönköpings GK (Sverige) og Ikaalisten GK (Finland). De foreløpige observasjonene fra etableringsåret viste jamt over like god (fairway) eller bedre (semi-rough) kvalitet ved robotklipping sammenliknet med manuell klipping. På fairway gav robotklipping noen ganger bedre kvalitet i mai og like god kvalitet i juni og juli, men dårligere kvalitet fra august til oktober. En rundspørring blant spillere på tre av banene viste positiv eller nøytral holdning til robotklippere hos 90 % av spillerne , men mange spillere etterlyste tilpasning av lokale eller internasjonale regler til bruk av robotklippere på golfbaner.

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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) in January 2020.

The project has three subprojects / 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, Jönköpings GC, Sweden and Ikaalisten GC (in 2020; from January 2021 replaced with Hirsala Golf), 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 Landvik in August 2020, the latter after grow-in of a new experimental area.

This report gives a description of methods used and preliminary results obtained in the three WPs in 2020. The project is scheduled to continue until 1 July 2023.

NIBIO, 21.05.21

Trygve S. Aamlid

(project leader)

Content

Summary

Robotic mowers can contribute to more sustainable use of resources on golf courses. The objective of the project 'ROBO-GOLF 2020-2023' is to generate and disseminate knowledge about implications for turfgrass quality, fertilizer requirements, labor and energy use, and players' satisfaction by going from manual mowing to robotic mowing on fairways semi-roughs. The project consists of three subprojects (work-packages, WP).

In WP1, two three-replicate split plot field trials, both comparing robotic vs. manual mowing on main plots and pure stands of colonial bentgrass (*Agrostis capillaris*), red fescue (*Festuca rubra*) and Kentucky bluegrass (*Poa pratensis*) on 100 m2 subplots in the fairway trial, and perennial ryegrass (*Lolium perenne*), red fescue and Kentucky bluegrass in the semi-rough trial, were established from seed from mid-May to early August 2020 at NIBIO Landvik Research Center, southeast-Norway. Six robotic mowers (Husqvarna 550), one for each replicate on fairway (target mowing height 15 mm) and one for each replicate on semi-rough (target mowing height 35 mm) were installed on 11 August 2020. Turfgrass quality and associated characters on the robotic-mowed plots were observed in comparison with control plots mowed with a triplex cylinder mower (fairway) or a rotary mower (85 cm wide,) semi-rough) from 11 August till 30 October. Preliminary results in the fairway trial showed an overall tendency ($P<0.10$) to a positive impact of robotic vs. manual mowing on turfgrass quality, notably in colonial bentgrass which was significantly less infected with microdochium patch when mowed with robot mowers than with manual cylinder mowers. Red fescue, in contrast, showed lower quality with robotic than with manual mowing during a period with vigorous height growth in early September. In the semi-rough trial, the same high quality was observed with robotic and manual mowing in perennial ryegrass, while Kentucky bluegrass was more invaded with annual bluegrass (*Poa annua*) and had more leaf rust (*Puccinia poae-nemoralis*), thus producing lower quality with robotic than with manual mowing. As in the fairway trial, the quality of robotic-mowed red fescue plots also tended to be behind the corresponding plots with manual mowing.

In WP2, an experimental fairway that will be used to study the fertilizer effect of returning clippings at robotic vs. manual mowing in 2021 and 2022 was established at NIBIO Landvik in 2020. The fairway was established by seeding a traditional 'Scandinavian' fairway seed mixture comprising Kentucky bluegrass, colonial bentgrass and red fescue. Robotic vs. manual mowing was introduced from 11 August 2020. Assessments from August till October and tiller countings at the end of the growing season showed a uniform experimental area with no effect of robotic vs. manual (triplex cylinder) mowing on turfgrass quality or total tiller density, but an insignificant trend to a higher percentage of colonial bentgrass and annul bluegrass and correspondingly less red fescue and Kentucky bluegrass with robotic than with manual mowing.

In WP3, large scale demonstration trials with robotic mowers in comparison with cylinder mowers on fairways and rotary mowers on semi-roughs were laid out in May 2020 on one golf course in each of the five Nordic countries: Bærheim, Norway; Grenå, Denmark; Jönköping, Sweden; Ness, Iceland; and Ikaalisten, Finland (from 2021 Ikaalisten will be replaced by Hirsala). Turfgrass quality, coverage of broadleaved weeds and energy use were recorded monthly from May to October by the course manager on all five courses, and a survey on players' attitudes to robotic mowers conducted on the courses in Norway, Denmark and Sweden (in total 398 respondents). The turfgrass quality of robotic mowed plots was mostly equal to manually mowed control plots on fairways and better that manually mowed control plots on semi-roughs. In the fairway trials, the quality of robotic mowed plots was usually better than manually mowed plots in May and equal to manually mowed plots in June and July, but sometimes inferior to manually mowed plots in autumn. The survey showed that about 90 % of the players were positive or neutral to robotic mowers, but many respondents asked for adaptation of the local rules on the golf course or even of R&A's international rule of golf to the new technology.

All results in this report must be regarded as provisional as the field trials continue in 2021 and 2022.

1 Introduction

The use of light-weight robotic mowers in private and public gardens and parks has escalated during the past decade, but golf courses have mostly been slow in adopting this new technology. Among the reasons for the reluctance to install robotic mowers are that golfers fear that they will interfere with play by damaging balls or altering ball positions, and that greenkeepers perceive robotic mowers as a threat to their jobs. Furthermore, the scientific literature contains very little documentation about the effect of robotic mowing on turfgrass quality. Exceptions to this is are a one-year documentation of the performance of the robotic mower Bigmow from Belrobotics on a football pitch (mowing height 25 mm) at the Sport Turf Research Institute, UK (Ferguson & Newell 2010) and research conducted by an Italian group on a semi-rough seeded with tall fescue (*Festuca arundinacea*) (Grossi et al. 2016, Pirchio et al. 2018a) and on a fairway seeded with manilagrass (*Zoysia matrella*) (Pirchio et al. 2018b). These studies found that plots mowed with robotic mowers had better turfgrass quality, higher tiller density and finer turfgrass leaves compared with control plots maintained with a manual rotary mower in the semi-rough trial and with a manual triplex cylinder (reel) mowers in the trials of fairways and football pitches. The relevance of the Italian research for Nordic conditions is, however, limited as neither tall fescue nor manilagrass is used on Nordic golf courses. To the best of our knowledge, no information is available on the effect of robotic mowers in pure stands or mixtures of red fescue (*Festuca rubra*), Kentucky bluegrass (*Poa pratensis*), perennial ryegrass (*Lolium perenne*), or colonial bentgrass (*Agrostis capillaris*); the species most commonly seeded on roughs or fairways in northern environments.

In order to avoid abrupt changes in turfgrass' photosynthetic capacity and top/root ratio, a general rule of thumb in turfgrass maintenance is never to remove more than 1/3 of turf height at each mowing (e.g. Turgeon 2011). Based on this '1/3 rule', robotic mowers are likely to produce a healthier and more stress-tolerant turf as the average mowing frequency will normally increase from 1-3 times per week to 5-20 times per day (Grossi et al. 2016). However, there is also a risk that robotic mowers will lead to more competition from broadleaved weeds (Pirchio et al. 2016a) and more entry points for foliar diseases (Putman & Kaminski 2011).

Return of clippings has been found to reduce N fertilizer requirements by 30 to 75% in turfgrass field trials (Heckman et al. 2000, Kopp & Guillard 2002, Liu & Hull 2006). The reduction is, however, dependent on to what extent clippings get into contact with the soil and are mineralized (Kauer et al. 2013). Especially at semi-rough mowing height with infrequent mowing and long clippings sticking together under wet conditions, there is a risk for a significant amount of the N in clippings to be lost by volatilization as NH_3 (Whitehead et al. 1988). It may therefore be hypothesized that small clippings reaching the soil surface with the use of robotic mowers will lead to stronger fertilizer savings that return of longer clippings using conventional mowers. Grubbs (2016) documented a higher nitrogen use efficiency of lawn clippings as the mowing frequency was increased from once to twice per week, but it remains to be confirmed if this finding can be extrapolated to higher mowing frequencies with robotic mowing.

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.

2 WP1: Robotic versus manual mowing of turfgrass species on fairways and semi-roughs

2.1 Materials and methods

2.1.1 Experimental site and preparation of experimental area

An experimental area for use in WP1 and WP2 (see next chapter) was seeded 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 May 2020. Precrops in 2018-2019 were timothy seed production on the area used to establish the fairway trials (WP1 and WP2) and perennial ryegrass seed production on the area used to establish the semi-rough trial (WP1). Both seed crops had been sprayed with glyphosate and plowed in the late autumn 2019. Soil samples taken in spring 2020 showed a pH (H_2O) of 5.8, and soil nutrient contents (expressed in mg (kg dry soil)$^{-1}$ after extraction with ammonium lactate): P-AL: 140, K-AL: 89, Mg-AL: 72, Ca-AL: 1100. The ignition loss was 7.0, which for this soil type, after correction for clay content, equals 5.0 % organic matter (Krogstad 2009).

From 15 to 22 April, the experimental area was harrowed, fertilized with 5.0 kg N in Fullgjødsel NPK 22-2-12 (see fertilizer plan, Table 2), and leveled carefully by repeated hand-raking and rolling. It was then left for three weeks to allow emergence of timothy and perennial ryegrass seedlings from the soil seed bank. Roundup (glyphosate, 540 g a.i. ha^{-1}) was sprayed on 11 May to kill the seedlings that had emerged.

The field map for the 86 m x 60 m = 0.516 ha experimental area is shown in Figure 1. 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.

Before seeding the experimental area, the silty loam soil on a 0.5 x 0.5 = 0.25 m^2 subplot in the WP1 fairway trial was replaced with USGA sand to a depth of 30 cm (Photo 1, see also blue dots in the field map in Figure 1). This was done to facilitate later determination of root development on manually mowed vs. robotic mowed plots. The sandy subplots received 5.0 kg N in Fullgjødsel NPK 22-2-12 immediately before seeding to replace the fertilizer that had been given before digging out the subplot (Table 2).

Photo 1. The silty loam soil was replaced with sand to 30 cm depth on 0.25 m2 subplots along a line in the WP1 fairway trial.
Photo: Trygve S. Aamlid

The main plots were seeded under favorable weather conditions between 13 and 20 May 2020 using a drop-seeder (Photo 2). The seed was raked gently into the topsoil before rolling with a small, walk-behind roller. Information about turfgrass varieties / seed mixtures and seeding rates can be found in Table 1. After seeding the last plot on 20 May, the entire trial area was covered with a white, permeable tarp until 8 June to preserve moisture, increase temperature and protect against hard rain and erosion (Photo 3).

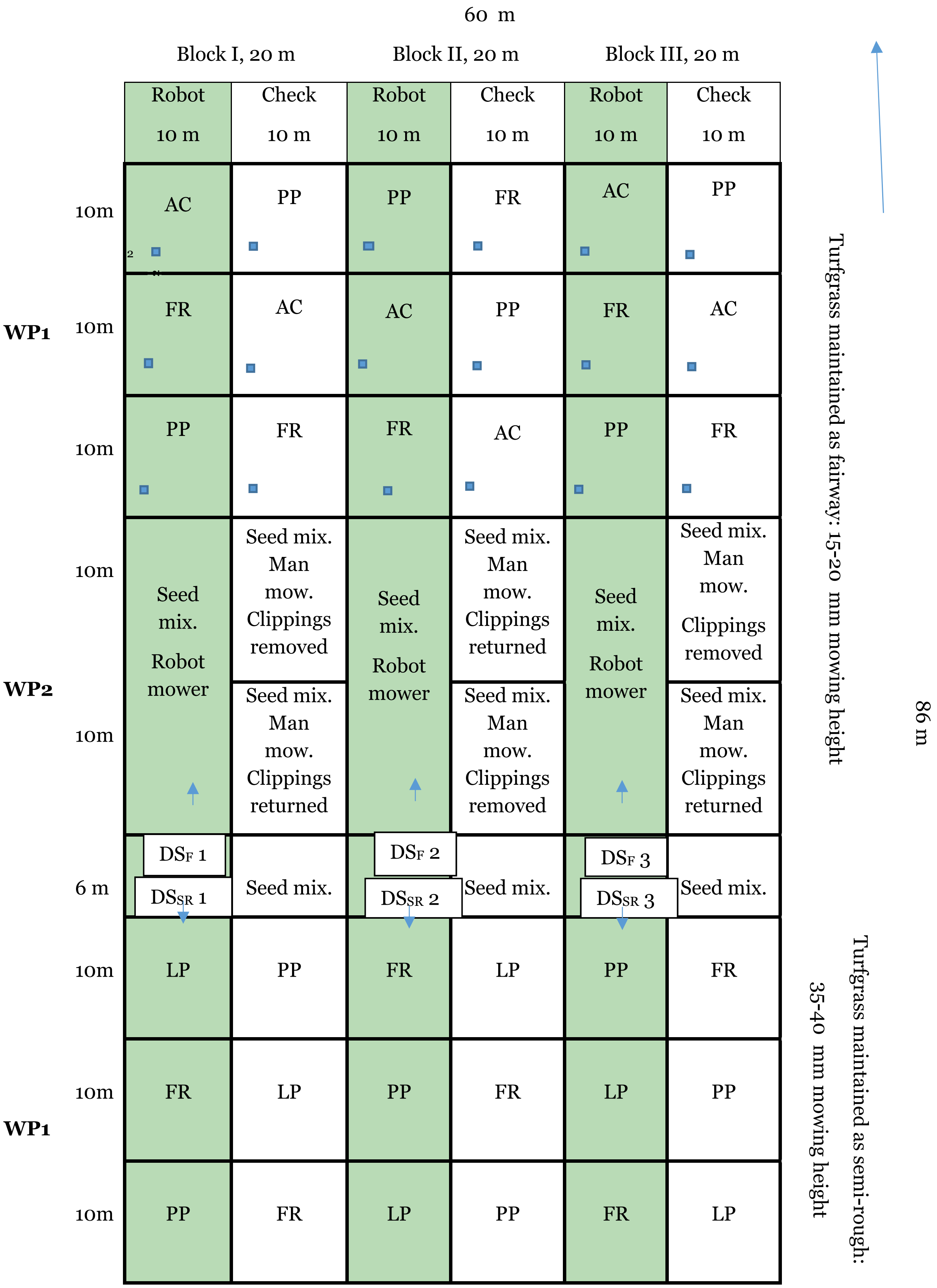

Figure 1. Field map of WP1 and WP2 seeded at Landvik in May 2020. FR: Red fescue (Festuca rubra), PP: Kentucky bluegrass (Poa pratensis), AC: Colonial bentgrass (Agrostis capillaris), LP: Lolium perenne. DS_F: Docking station, fairway mowers, DS_{SR}: Docking station, semi-rough mowers.

Photo 2. Seeding, raking and rolling plots on 14 May 2021. Photo: Trygve S. Aamlid

Table 1. Turfgrass varieties and seed blends under 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*)

Photo 3. Removal of tarp on 8 June 2020. The grasses had emerged nicely, but there were also many broadleaved weeds. Photo: Karin J. Hesselsøe.

Approximately one week after removal of the tarp, on 16 June, the plots seeded with red fescue, colonial bentgrass and Kentucky bluegrass were sprayed with iodsulfuron, 5.0 g a.i. ha^{-1} (commercial product Hussar OD, 50 ml ha^{-1} + the additive Renol rape seed oil, 0.5 L ha^{-1}). This herbicide is sufficiently selective in the aforementioned species and is effective against broadleaved weed and many grasses, including perennial ryegrass and to a lesser extent annual bluegrass (*Poa annua*). On the same day, the semi-rough plots seeded with perennial ryegrass were sprayed with the triple mixture fluoxypyr + clopyralide + MCPA (80, 40 and 400 g a.i. ha^{-1}; commercial product Ariane S, 2 L ha^{-1}) which is effective against broadleaved weeds only.

The experimental area was fertilized as described in Table 2, including five additional applications to the 0.25 m^2 sandy subplots in the WP1 fairway trial. Fertilizer inputs in August and September were reduced considerably because of high growth rates on all seeded plots.

Irrigation of the main trial area was not necessary thanks to a drought resistant soil and regular rainfall (Table 3, Figure 2), but the sandy subplots were irrigated daily in periods without rainfall until the installation of the robotic mowers.

The semi-rough trial was mowed for the first time on 12 June using a rotary mower (John Deere X305, 0.85 m wide and adjusted to 40 mm mowing height. Subsequently, the semi-rough trial was mowed twice a week at 40 mm until the installation of the robotic mowers and start of the experimental period on 11 August. In the fairway trials, the same rotary mowing / mowing height was practiced until 1 July. After that the fairway trials were mowed with a triplex fairway mower (Toro 3250 D; first time at 30 mm height and then with a stepwise reduction in mowing height reaching the targeted 15 mm on 29 July.

Table 2. **Fertilizer applications to WP1 fairway and semi-rough trials and WP2 fairway trial in 2020. Shaded rows indicate extra applications to 0.25 m^2 subplots in the WP 1 fairway trial where the silt loam soil had been replaced by sand.**

			kg ha^{-1}							
Date	**Fertilizer type**	**Fertilizer**	**N**	**P**	**K**	**Mg**	**S**	**Ca**	**Fe**	**Mn**
21 Apr./ 13 May[1]	Fullgjødsel 22-2-12	7250	54.0	4.3	29.0	3.3	6.8	2.0	0.00	0.00
9 June	Everris Proturf 15-5-15	120	18.0	2.6	14.9	1.4	0.0	1.7	0.00	0.00
15 June	Fullgjødsel 12-4-18 Micro	150	17.7	6.0	26.4	2.4	14.3	3.0	0.00	0.45
23 June	Fullgjødsel 12-4-18 Micro	150	17.7	6.0	26.4	2.4	14.3	3.0	0.00	0.45
28 June	Everris Proturf 15-5-15	120	18.0	2.6	14.9	1.4	0.0	1.7	0.00	0.00
7 July	Everris Proturf 15-5-15	120	18.0	2.6	14.9	1.4	0.0	1.7	0.00	0.00
14 July	Everris Proturf 18-0-7	200	36.0	0.0	11.6	3.6	0.0	4.2	0.00	0.00
28 July	Everris Proturf 18-0-7	100	18.0	0.0	5.8	1.8	0.0	2.1	0.00	0.00
4 Aug.	Everris Proturf 18-0-7	100	18.0	0.0	5.8	1.8	0.0	2.1	0.00	0.00
9 Sep.	Everris Proturf 18-0-7	50	9.0	0.0	2.9	0.9	0.0	1.5	0.00	0.00
22 Sep.	Everris Proturf 15-5-15	40	6.0	0.9	5.0	0.5	0.0	0.6	0.00	0.00
15 Oct.	Everris Proturf 15-5-15	30	4.5	0.7	3.7	0.4	0.0	0.4	0.00	0.00
Sum	Main experimental area,WP1 and WP2		153.0	12.2	88.1	12.1	6.8	12.3	0.00	0.00
	Other nutrients relative to N, %		100	8	58	8	4	8	0.0	0.0
Sum	0.25 m2 sandy subplots, WP1 fairway		234.9	24.2	143.8	17.8	35.3	19.3	0.00	0.90
Rel.	Other nutrients relative to N, %		100	10	61	8	15	8	0.00	0.38

[1] Preseeding applications conducted on 21 April on the main experimental area and on 13 May on the sandy 0.25 m^2 subplots in the WP1 fairway trial.

2.1.2 Installation, maintenance and adjustment of mowing time and mowing height

Six professional Robotic Mowers, Husqvarna 550, were installed on 11 August 2020 by Husqvarna's Norwegian representative Oddmund Ihle (Photo 4). Each fairway mower was covering 500 m^2 (WP1 + WP2) and each semi-rough mower was covering 300 m^2 (WP1; Figure 1). The mowing areas were defined by demarcation cables installed on 11 August (Photo 5). The docking stations had energy meters that recorded energy use by each individual mower.

Through Husqvarna's app. downloaded to operators' computers and mobile phones, the mowers were programmed to mow for four hours per day on all days except Sundays in the fairway trials and three hours per day on all days except Sundays in the semi-rough trial. At installation, the daily start times varied from 8 a.m. to 6 p.m., but from 25 August all start times were set to morning hours to avoid interference with the assessments and measurements which were usually carried out after lunch (see later).

Photo 4. Oddmund Ihle, Husqvarna, installed the robotic mowers on 11 Aug. 2020. Photo: Karin J. Hesselsøe.

The robotic mowers installed on fairway were equipped with fairway kits allowing closer mowing. The mowing height was initially adjusted to step 3, corresponding to 18-20 mm mowing height. After two weeks, on 25 Aug., the height was lowered to step 2 (see 'Results and discussion' for realized mowing heights).

The mowing height for the semi-rough mowers was set to step 5 (35 mm) and maintained at this height throughout the trial period except from 12 to 30 Oct. when it was increased to step 6.

All mowers were equipped with brushes to prevent grass clippings from accumulating on the wheels and thus affecting mowing height and leaving lumps of clippings on the turfgrass surface.

Photo 5. Installation of demarcation cables at approximately 5 cm depth around plots to be mown with a robotic mower. Photo: Karin J. Hesselsøe.

The knives on all robotic (fairway and semi-rough) mowers were replaced on 25 August and 17 September (Photo 6). A third replacement on 29 September was limited to the knives on the fairway mowers which tended to wear out more rapidly than the knives on the semi-rough mowers.

Towards the end of the growing season, on 12 October, the mowing frequency of all robotic mowers was reduced from six to three days of mowing per week. On 30 October the mowers, docking stations and energy meters were taken inside for storage until the next growing season. The energy meters were sent to Husqvarna for readings of energy use.

Photo 6. First replacement of knives on robotic mowers, 25 Aug. 2020. The knives on fairway mowers (top left) had more signs of wear than the knives on semi-rough mowers (bottom left). Photos: Anne F. Borchert.

2.1.3 Mowing height and maintenance of manual mowers

During the experimental period 11 August – 30 October 2020, the bench setting of the triplex fairway cylinder mower was initially set to 15 mm, i.e. the same height as at the end of the grow-in period. However, since the measurements of sward height immediately after mowing from 31 August to 4 September showed this setting to result in higher mowing than with the robotic mowers, the triplex aggregates were adjusted to a bench setting of 12.5-14.0 mm from 11 September onwards. Further details about these settings and implications for mowing height can be found in 'Results and discussion'.

The mowing height of the rotary semi-rough mower was adjusted to 35 mm from the start of the experimental period until Monday 7 September and from Monday 29 September until the last mowing for the season. From Friday 11 September until Friday 25 September the mowing height was set to 30 mm.

In the late autumn, the manual mowing frequency for fairway and semi-rough was maintained at three and two times per week until 25 September. In week 40, both fairway and semi-rough were mowed on Monday and Friday, and from week 41 (5 October) on Mondays only. The last manual mowing for the season was on 19 October.

2.1.4 Weather data

The mean temperature for May-October 2020 was slightly higher, while the rainfall was slightly lower compared with the 'normal' values for the reference period 1991-2020 (Table 3). The strongest deviations from temperature 'normal' were recorded in June which was unusually warm and in July which was unusually cold. The maximum temperature for the year, 27.9°C was recorded on 16 June.

Figure 2 gives a more detailed account of temperature and rainfall during the experimental period 11 August – 30 October. Rainfall was regular and growing conditions favorable. Except for 17 October and 19 October which had minimum temperatures of -0.7 °C and -1.3 °C, respectively, the air temperatures were not below freezing during the experimental period.

Table 3. Mean monthly temperature and monthly precipitation May-October 2020 at the Norwegian meteorological Institute's weather station Landvik as compared with the 30 year 'normal' values 1991-2020.

	Mean monthly temperature, °C		Monthly precipitation, mm	
	2020	1991-2020	2020	1991-2020
May	10.2	11.2	44	80
June	17.2	14.8	144	88
July	15.1	16.9	169	89
Aug.	16.8	16.1	68	125
Sep.	13.1	12.6	100	137
Oct.	9.1	8.0	143	175
Mean / sum	13.6	13.3	668	694

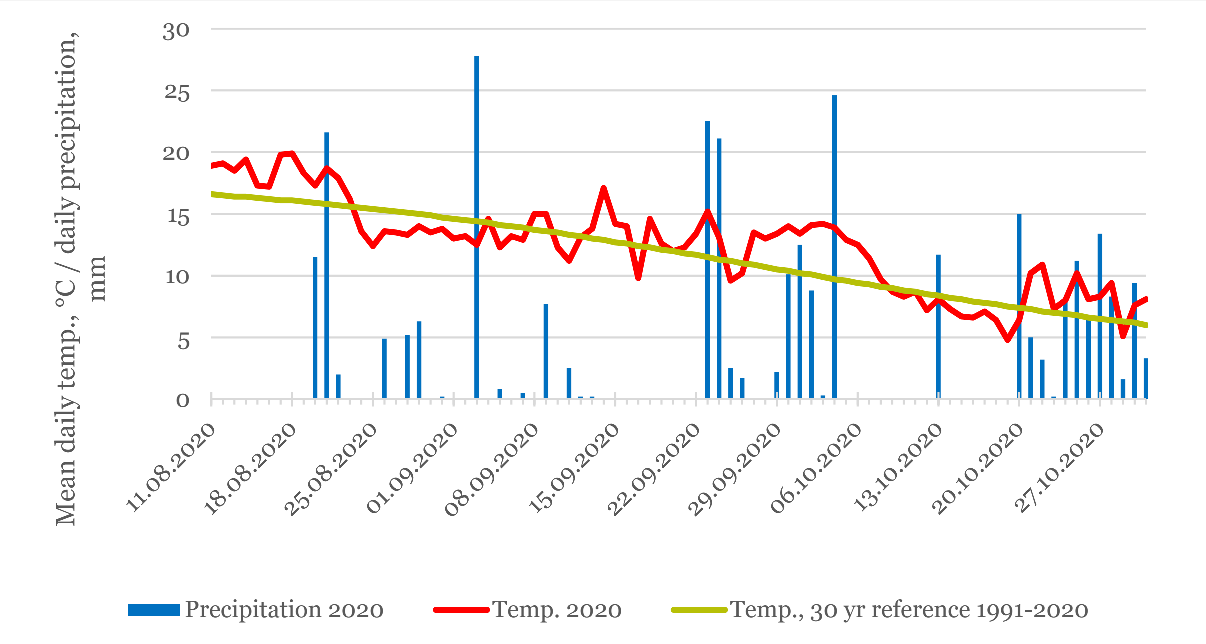

Figure 2. Mean daily temperature and precipitation during the experimental period 11 Aug.-30 Oct. 2020.

2.1.5 Data collection

At the installation of the robotic mowers on 11 August a representative 2 m x 2 m plot to be used for assessments and measurements was identified in the center of each 10 m x 10 m treatment plot (Photo 7, see also Photo 11).

Visual assessments were usually made between noon and 2 p.m. on Tuesdays in the fairway trial and on Wednesdays or Thursdays in the semi-rough trial, i.e. shortly after mowing with the robotic mower and at least 24 hours after manual mowing. The following characters were recorded:

Photo 7. Labeling of 2 x 2 = 4 m² subplots to be used for data collection. Photo: Anne F. Borchert.

Turfgrass quality (overall impression) was recorded on a scale from 1 to 9 where 9 is the best turf and 5 is the lowest acceptable turf. Assessments were made at the start of the experimental period on 11-12 August and subsequently on 8-9 September and 8 October. 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, Photo 8), 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, broadleaved (dicotyledon) weeds, diseases and bare soil.

Turfgrass tiller density was assessed visually on 15 October using a scale from 1 to 9 where 9 is the highest density.

Leaf width of sown species was measured on all plots with colonial bentgrass and Kentucky bluegrass in the fairway trial and on all plots with perennial ryegrass and Kentucky bluegrass in the semi-rough trial after taking samples to the laboratory on 19 October. The width at the center of the youngest fully expanded leaf on ten random tillers was measured under a 20x magnifying lens and the mean value calculated.

Soil penetrometer resistance. Start values for soil penetrometer resistance were recorded on 12 August using an Eijkelkamp soil penetrometer (Eijkelkamp Soil & Water, Giesbeek, Netherlands; Photo 9). 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) was 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.

Water infiltration rate was measured in the fairway trial on 4 September (Photo 10), 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.

Turfgrass height was measured almost daily between 28 August and 4 September and approximately weekly after 11 September. Most measurements were made in the afternoon shortly after mowing with robotic and manual mowers, but in late August/early September there were also a few measurements conducted 24-48 h after the last manual mowing. Three measurements were made per plot using a prism (Turfcheck I) in the fairway trial and a ruler (Turfcheck II) in the semi-rough trial. The means and CVs were calculated.

Photo 8. Anne F. Borchert using the Field Scout chlorophyll meter on 8 Oct. Photo: Karin J. Hesselsøe.

Photo 9. Karin Juul Hesselsøe measuring start values for soil penetrometer resistance on 12 Aug. 2020. Photo: Anne F. Borchert.

Photo 10. Infiltration measurements on 4 Sep. 2020. Photo: Trygve S. Aamlid

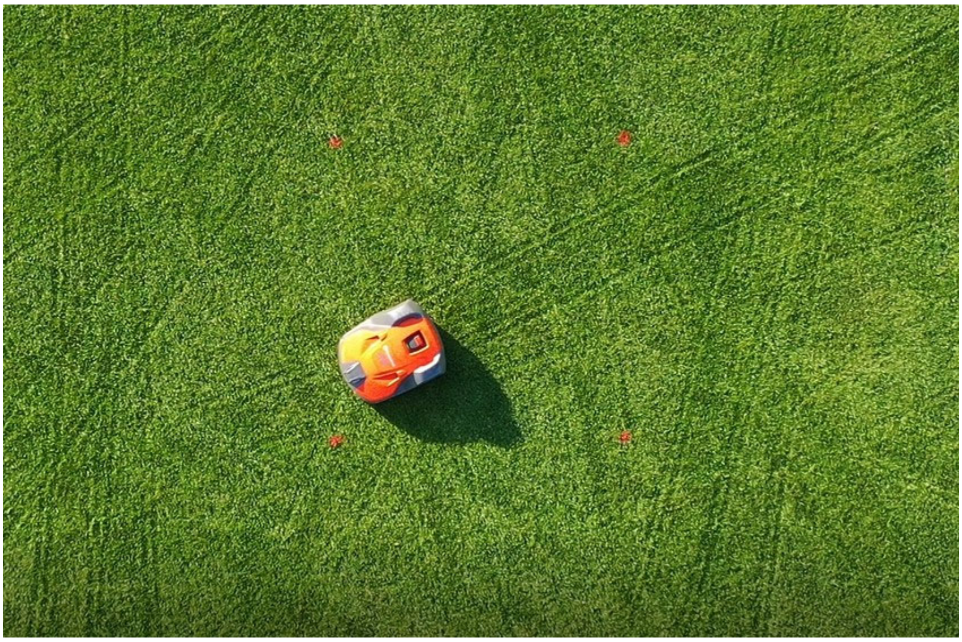

Photo 11. Robotic mower crossing 2 x 2 = 4 m² subplot used for assessments and measurements, 21 Aug. at 10:51. Drone photo: Karin J. Hesselsøe.

2.1.6 Statistical analyses

The experimental data were analyzed using the SAS procedure PROC ANOVA with appropriate test-statements corresponding to the split plot design (PROC ANOVA; SAS Institute, Cary, NC, USA). ANOVAs were performed both individually for each measurement /assessment and on the mean values for different periods. In this report, the term 'significant' always means $P \leq 0.05$, while effects with P-values in the range $0.05 < P \leq 0.10$ are referred to as 'tendencies' or trends'. Significant differences among treatment combinations were identified using Fisher's LSD at $P \leq 0.05$.

2.2 Results: Fairway

2.2.1 Start values

Assessments at the installation of mowers or the day after showed a uniform sward with no significant differences in either turfgrass quality, turfgrass coverage including annual bluegrass and broadleaved weeds, turfgrass chlorophyll index, soil penetration resistance, soil water content or soil infiltration rate between plots allocated to manual vs. robotic mowing (Table 4). A slightly (not significantly) lower turfgrass chlorophyll index on plots subjected to robotic mowing compared with manual mowing probably reflects that the measurements were taken on Wednesday morning after the mowers on robotic-mowed plots had been in operation for one day whilst the plots with manual mowing were unmowed since Monday.

Presumably because of a darker color, and despite more annual bluegrass, a slightly higher score for turfgrass quality was given to plots seeded with Kentucky bluegrass than with colonial bentgrass or red fescue (Table 4). On 4 September there was a tendency (P=0.07) for the infiltration rate to be higher on plots seeded with Kentucky bluegrass than with colonial bentgrass and red fescue, and this may perhaps be due to a more vigorous development of rhizomes which penetrate the upper soil layer under Kentucky bluegrass turf.

The statistical analyses revealed no interaction between manual vs. robotic mowing and turfgrass species at the start of the fairway trial (data not shown in Table 4).

Table 4. Assessments and measurement at the start of the fairway trial. Turfgrass quality and coverage were assessed on Tuesday 11 Aug., just before the installation of the robotic mowers, and turfgrass chlorophyll index, penetration resistance and volumetric soil water content (VSWC) in the morning on Wednesday 12 Aug. (before manual mowing). Infiltration was measured on Friday 4 Sep., after a heavy rainfall.

	Turf-grass quality (1-9)	Coverage, % of plot area				Chlorophyll index (n=5)		Soil penetration resistance (n=5)		VS-WC, %	Infil-tration rate, mm h^{-1}
		Seeded species	Annual bluegr.	Dicot weeds	Bare soil	Mean	CV, %	Mean MPa	CV %		
Manual	6.4	95.3	4.4	0.1	0.2	354	11	3.1	13	28	52
Robot	6.4	96.9	2.7	0.1	0.2	311	8	3.1	16	29	50
***P*-value**	ns[1]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Col. bentgrass	6.3	99.5	0.1	0.1	0.3	299	9	3.0	14	29	24
Red fescue	6.3	98.9	0.8	0.2	0.3	322	10	3.1	14	28	54
Ken. bluegrass	6.6	90.0	9.8	0.1	0.1	377	9	3.3	16	29	75
***P*-value**	ns	*	*	ns	ns	***	ns	ns	ns	ns	(*)
LSD$_{0.05}$	-	6.1	6.1	-	-	23	-	-			-

[1]The significance symbols used in this and the following tables are:
***: $P \leq 0.001$, **: $0.001 < P \leq 0.01$, *: $0.01 < P \leq 0.05$, (*): $0.01 < P \leq 0.05$, ns: not significant

2.2.2 Turfgrass height during the experimental period

No measurements of turfgrass height were made during the first two weeks after installation when the robotic mowers were in 'step 3'. From 25 August to 4 September, after the position had been lowered to step 2 on 25 August, but before the adjustments in the bench setting of the triplex cylinder mower on 14 September, the sward was always lower with robotic mowing than with manual mowing (Table 5). Not surprisingly, this was most evident when the height was measured 24-48 h after the last manual mowing (mean difference 2.8 mm), but the measurements immediately after mowing with both mower types on 31 August, 2 September and 4 September also showed the same trend (mean difference 1.2 mm).

After adjusting the bench setting of the triplex mower, first to 12.5 mm on 14 Sep, and later up and down in the range 13-14 mm, the mowing height of the two mower types became more uniform (mean difference 0.1 mm only, Table 5). Bench settings / mowing heights were discussed in a meeting in the project reference group on 10 Sep., and it was concluded that the height after manual mowing ought be on the same level or slightly lower compared with robotic mowing. Based on this, a bench setting for the triplex mower at 13 mm seems suitable for the experimental seasons 2021 and 2022. A daily variation the average mowing height of ± 1 mm seems unavoidable when leaf wetness and other factors are taken into account. Some of the day-to-day variation in mowing heights in Table 5 can also be explained by different persons doing the measurements. For the remainder of this project, it is important that all measurements of turfgrass height are conducted by the same person.

Significant differences in turfgrass height among the three species were detected only in the measurements conducted 24-48 after manual mowing. The tendency (P=0.08 on average for three observations) was for red fescue to grow more in height than colonial bentgrass, which in turn, had more vigorous height growth than Kentucky bluegrass. A similar, although far less conspicuous, trend was found when measuring height shortly after mowing with both robotic and triplex mowers (Table 5).

Table 5. Turfgrass height measurements (mm) during the experimental period 11 Aug. – 30 Oct. 2021.

	Bench setting, triplex fairway mower, mm												
	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	13.5	14.0	13.0	13.0	13.0
	24-48 h after man. mow.				Shortly after robotic and manual mowing								
	28 Aug.	1 Sep.	3 Sep.	Mean 3 obs.	31 Aug.	2 Sep.	4 Sep.	Mean 3 obs.	18 Sep.	21 Sep.	28 Sep.	5 Oct.	Mean 4 obs.
Manual	23.5	23.5	23.6	23.6	19.6	21.5	20.7	20.6	14.8	15.6	14.8	15.1	15.1
Robot	20.7	19.8	22.1	20.8	18.9	20.7	18.7	19.4	14.7	15.2	15.8	15.2	15.2
	(*)	*	*	*	ns	ns	**	ns	ns	ns	(*)	ns	ns
Col. Bentgr.	22.3	21.2	22.8	22.1	19.0	21.8	19.8	20.2	14.5	15.2	15.3	15.3	15.1
Red fescue	22.7	22.7	23.7	23.1	19.7	20.8	20.1	20.2	14.8	16.1	15.5	15.2	15.4
Ken. bluegr.	21.4	21.1	22.2	21.5	19.0	20.9	19.4	19.7	15.0	15.0	15.1	15.1	15.0
***P*-value**	ns	(*)	*	(*)	ns	ns	ns	ns	ns	ns	ns	ns	ns
$LSD_{0.05}$	-	-	1.2	-	-	-	-	-	-	-	-	-	-

A significant difference between robotic mowing and manual mowing in the variation in turfgrass height among the three individual measurements in each plot was found on 18 September only (data not shown in table). On this date, the CV in turfgrass height on plots mowed with manual and robotic mower were 5.1 and 5.8, respectively (P≤0.05). Otherwise, the CVs were very similar for the two mower types, and this can be taken as an indication that the 4 h working period per day was sufficient to avoid spots from escaping the robotic mowers working in a random pattern. On 21 Sep. and 28 Sep.

the CV in mowing height was significantly or almost significantly (*P*=0.06) higher in red fescue than in colonial bentgrass and Kentucky bluegrass (mean CV 6.3, 4.4 and 4.3, respectively), but one average for all observation dates, there was no significant difference among the three species in mowing uniformity (data not shown in table).

The interactions between mower type and species in turfgrass height or CV among individual measurement were not significant on any observation date.

2.2.3 Turfgrass quality, chlorophyll index, tiller density, leaf width and infestation of weeds and diseases

Neither the main effect of mowing type nor the main effect of species was significant for turfgrass quality assessed on 8 September (Table 6). There was, however, a significant interaction as the manually mowed red fescue plots produced higher quality while the manually mowed colonial bentgrass plots produced lower quality than the other treatment combinations (Figure 3). On 8 October this variable effect of robotic mowing in different species had been replaced by an overall trend for robotic mowing to produce higher turfgrass quality than manual mowing (Table 6, Figure 3).

Table 6. Turfgrass chlorophyll index on three observation dates and turfgrass quality, annual bluegrass encroachment and microdochium patch as affected by mower type and turfgrass species on three observation dates during the experimental period 11 Aug. - 30 Oct. 2020.

	25 August[1]	8 September[2]				8 October[3]			
	Chlorophyll Index	Turfg. quality (1-9)	Chloro-phyll Index	% of plot area		Turfg. quality (1-9)	Chloro-phyll Index	% of plot area	
				Annual bluegr.	Microdoc. patch			Annual bluegr.	Microdoc. patch
Manual	367	6.2	380	3.4	0.5	6.8	396	12.6	0.1
Robot	387	6.3	347	2.1	0.1	7.1	388	9.2	0.0
***P*-value**	ns	ns	*	ns	(*)	(*)	ns	ns	ns
Col. bentgr.	342	5.8	341	0.2	0.9	7.5	393	1.3	0.1
Red fescue	353	6.8	353	0.4	0.0	6.9	394	9.7	0.0
Ken. bluegr.	436	6.3	398	7.7	0.0	6.4	391	21.7	0.0
***P*-value**	***	ns	**	*	***	*	ns	***	ns
$LSD_{0.05}$	20	-	25	5.0	0.3	0.4	-	5.9	-
Interaction	ns	*	ns	ns	**	ns	ns	ns	ns

[1]24 h after manual mowing, bench setting 15 mm and before robotic mowing, position 3
[2]24 h after manual mowing, bench setting 15 mm and after daily robotic mowing, position 2
[2]24 h after manual mowing bench setting 13 mm, after daily robotic mowing, position 2

A major reason for the poor quality of manually mowed colonial bentgrass plots on 8 September was that these plots were more infected by microdochium patch than colonial bentgrass plots subjected to robotic mowing or plots of the other species irrespective of mower type (interaction significant at $P \leq 0.01$, Figure 4). The microdochium patch had, however, mostly disappeared by the assessment on 8 October. Another problem was annual bluegrass which was unaffected by mowing type but far worse in Kentucky bluegrass (Photo 12) than in red fescue, which, in turn, allowed more infestation than colonial bentgrass. Broadleaved weeds, primarily plantains (*Plantago major*) made up an average of 0.25 % of the plot area at the last assessment on 8 October but was not influenced by either mower type or turfgrass species.

The chlorophyll index was not affected by manual vs. robotic mowing on 25 August, i.e. before robotic mowing height was lowered from step 3 to step 2, or on 8 October when the bench setting of the triplex mower was 13 mm. At the intermediate measurement on 8 September (step 2 for the robotic mower and bench setting 15 mm for the triplex cylinder mower), the chlorophyll index was significantly lower with robotic mowing than with manual mowing. Like the start values on 12 August (Table 4), the chlorophyll index was higher in Kentucky bluegrass than in red fescue and colonial bentgrass on 25 August and 8 September, but this difference between species had disappeared by the last measurement on 8 October (Table 6).

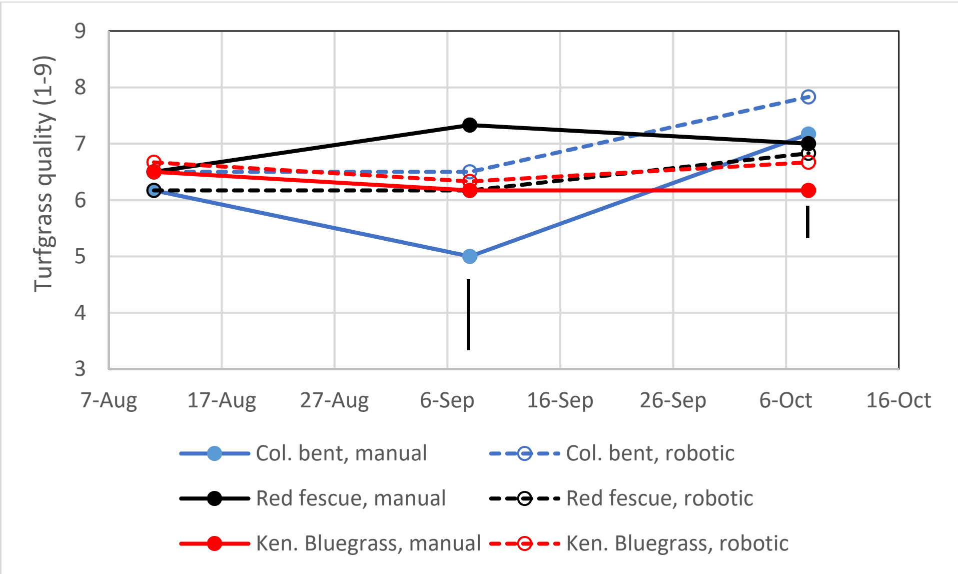

Figure 3. Turfgrass quality in the fairway trial on 11 Aug., 8 Sep. and 8 Oct. as affected by mower type, turfgrass species and their interaction. Vertical bars indicate $LSD_{0.05}$.

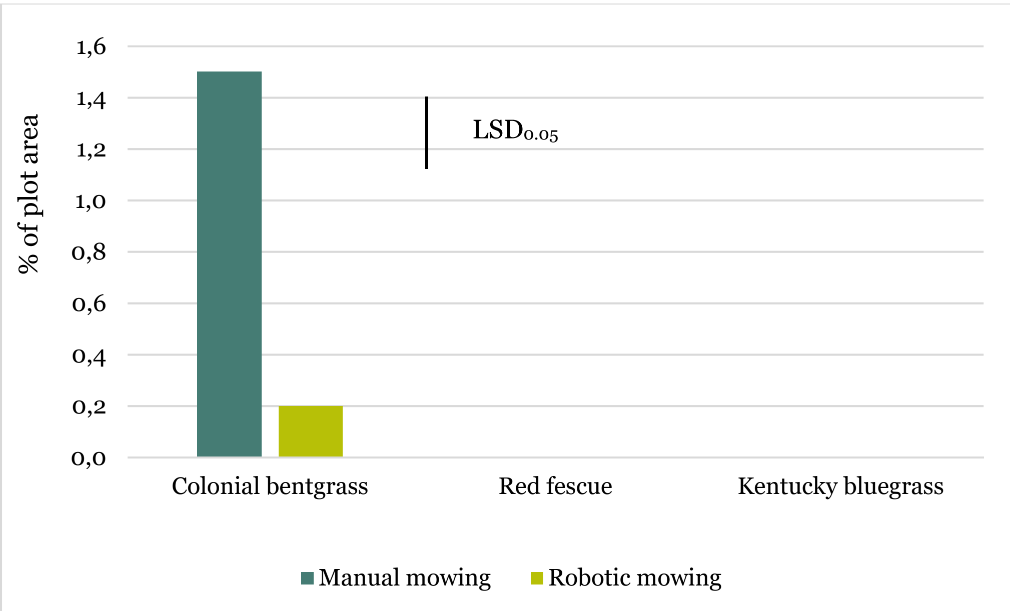

Figure 4. Microdochium patch in colonial bentgrass on 8 Sep. Neither red fescue nor Kentucky bluegrass showed any symptoms of this disease.

The assessment of tiller density on 15 Oct. showed an interaction as the density decreased with robotic mowing in Kentucky bluegrass but was unaffected by mower type in colonial bentgrass and increased insignificantly with robotic mowing in red fescue (Figure 5). Leaves were wider in Kentucky bluegrass than in colonial bentgrass (mean values 1.57 and 0.96 mm, respectively) but unaffected by mower type in both species (data not shown in table or figure).

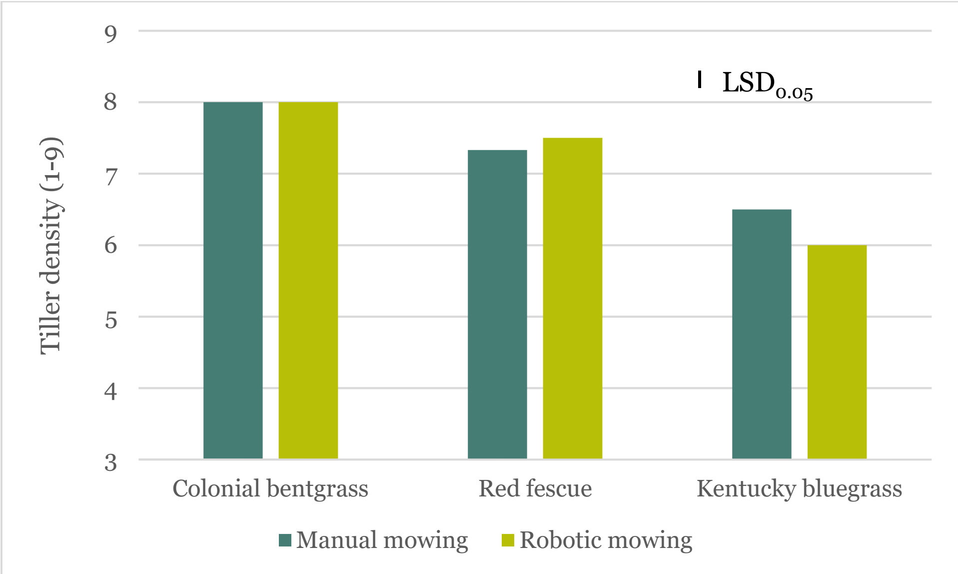

Figure 5. Tiller density on 15 Oct. as affected by mower type, turfgrass species and their interaction.

Photo 12. Kentucky bluegrass plots at fairway mowing height were severely invaded by annual bluegrass towards the end of the growing season. Photo: Trygve S. Aamlid.

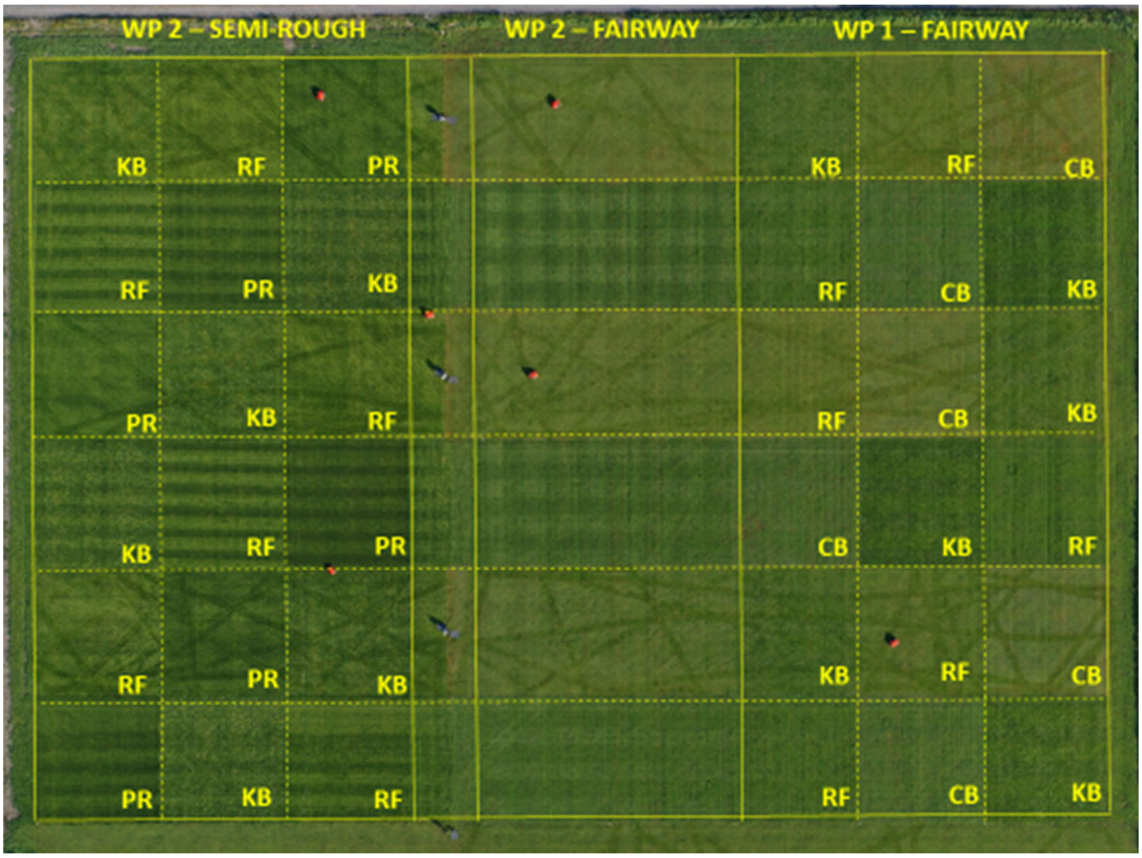

Photo 13. Drone photos of WP1 and WP2 trials on Friday 14 Aug. at 09:03 (top) and Tuesday 22 Sep. at 08:23 (bottom). Lower photo was taken about 20 h after mowing with the rotary mower at 30 mm and robotic mower in position 5 in the semi-rough trial. CB= Colonial bentgrass, RF=red fescue, KB = Kentucky bluegrass, PR= perennial ryegrass. Photos: Karin Juul Hesselsøe.

2.3 Results: Semi-rough

2.3.1 Start values

Photo 14: Robotic mower in operation in semi-rough trial on 18 Aug., i.e. one week into the experimental period. Photo: Karin J. Hesselsøe

The start assessment on 12 August showed almost significantly (P=0.06) higher turfgrass quality on plots assigned to robotic mowing than to manual mowing (Table 7). Although this trend occurred in all species, it was most likely an artefact since the assessment was made on after the robotic mowers had been in operation for one day. Otherwise, it is hard to explain this difference as there was no difference in related characters such as coverage or chlorophyll index. The only other character that showed an almost significant (P=0.06) main effect of mower type was the CV for soil penetrometer resistance which reflected more variable soil compaction levels on plots to be used for robotic mowing than on plots to be used for manual mowing. Again, it is hard to explain this as an effect of robotic vs. manual mowing since the robotic mowers had been in operation for only one day.

Table 7. Start assessments and measurements on 12 Aug. 2020, one day after the start of the semi-rough trial.

	Turf-grass quality (1-9)	Coverage, % of plot area				Chlorophyll index (n=5)		Soil penetro-meter resist-ance (n=5)		Vol. soil water content %
		Seeded species	Annual bluegr.	Dicot weeds	Bare soil	Mean	CV, %	Mean MPa	CV %	
Manual	6.8	97.4	2.2	0.4	0.0	491	10	3.5	11	23
Robot	7.0	97.8	1.8	0.4	0.0	481	11	3.5	14	23
***P*-value**	(*)	ns	ns	ns	ns	ns	ns	ns	(*)	ns
Per. ryegrass	7.3	99.6	0.1	0.3	0.0	500	11	3.5	13	24
Red fescue	6.8	98.3	1.3	0.5	0.0	466	7	3.4	14	22
Ken. bluegrass	6.6	94.9	4.7	0.4	0.0	491	13	3.5	12	23
***P*-value**	***	***	***	ns	ns	(*)	*	ns	ns	ns
$LSD_{0.05}$	0.4	1.8	1.5	-	-	-	4	-	-	-

As for turfgrass species, the start assessments showed a higher turfgrass quality in perennial ryegrass than in red fescue and Kentucky bluegrass. Perennial ryegrass also had the highest chlorophyll index and the least infestation of annual bluegrass. Color uniformity was, in contrast, higher in red fescue than in the two other species.

The mower type x species interactions were not significant for any of the characters.

As compared with the start values in the fairway trial (Table 4), the semi-rough trial had a lower soil water content (23 vs. 29 %) and a high penetrometer resistance (3.5 vs. 3.1 MPa). The red fescue and Kentucky bluegrass plots had more broadleaved (dicot) weeds, notably plantains, but the Kentucky bluegrass plots were less contaminated with annual bluegrass in the semi-rough than in the fairway trial. As compared with the same species in the fairway trial, the chlorophyll index on plots mowed at semi-rough height was 144 units higher in red fescue and 114 units higher in Kentucky bluegrass (Table 4 vs. Table 7).

2.3.2 Turfgrass height during the experimental period

The measurement of turfgrass height using the Turfcheck II ruler in the semi-rough trial was less precise and more dependent on the operator than the use of the Turfcheck I prism in the fairway trial. In the semi-rough trial, the robotic mower and rotary (manual) mower were initially set to, in turn, position 5 with mowing six days a week, and 35 mm height with mowing two days a week. Not surprisingly, these mowing procedures resulted in a higher sward when measured 72-96 h after manual mowing vs. 2-4 h after robotic mowing (Table 8). More importantly, on average for 31 August and 4 September these settings resulted in a turfgrass height close to 38 mm shortly after mowing with both mower types. While the differences between species were not significant, on 31 August there was a significant interaction as robotic mowing at position 5 resulted in a higher sward than rotary mowing at 35 mm in Kentucky bluegrass and red fescue, but not in perennial ryegrass (Figure 6).

A reduction in the setting of the rotary mower from 35 to 30 mm in between 11 September and 25 September resulted in an, on average for three observation dates, 3.5 mm lower sward just after mowing compared with robotic mowing (Table 8). The drone photo taken on 22 September (Photo 13, bottom) shows that this reduction resulted in a lighter (perennial ryegrass and red fescue) or more brownish (Kentucky bluegrass) color compared with the plots mowed with the robotic mowers. After adjusting the rotary mower back to 35 mm on 28 September the turfgrass heights were again very similar with the two mower types although lower than at the same setting in August and the first week of September. This difference between the two observation periods was most likely due to different persons doing the measurements.

Table 8: Results from turfgrass height measurements (mm) during the period 11 Aug. – 12 Oct. in the semi-rough trial. The robotic mower was in height-position 5 throughout this period, and was not raised to position 6 until 12 Oct.

	Rotary mower set to 35 mm					Rotary mower set to 30 mm				Rotary mower set to 35 mm		
	28 Aug.	**3 Sep.**	**31 Aug.**	**4 Sep.**	**Mean 2 obs**	**11 Sep.**	**18 Sep**	**21 Sep.**	**Mean 3 obs**	**28 Sep.**	**5 Oct.**	**Mean 2 obs.**
	72-96 h after man. mowing		**Measurements shortly after robotic and manual mowing on Mondays or Fridays**									
Manual	40.0	43.0	35.9	39.1	37.5	31.6	30.9	25.2	29.2	34.0	34.6	34.3
Robot	37.8	40.3	37.8	38.7	38.2	36.1	33.8	28.0	32.7	34.3	35.4	34.8
	**	ns	*	ns	ns	(*)	(*)	(*)	**	ns	ns	ns
Per. ryegrass	38.7	43.5	37.7	38.7	38.2	33.4	32.0	26.8	30.8	34.1	34.8	34.4
Red fescue	39.7	41.0	36.4	39.0	37.7	34.1	32.6	25.8	30.7	34.1	34.7	34.4
Ken. bluegr.	38.4	40.5	36.5	39.0	37.8	34.1	32.6	27.3	31.3	34.2	35.6	34.9
***P*-value**	ns	ns	ns	ns	ns	ns	(*)	ns	ns	ns	*	ns
$LSD_{0.05}$	-	-	-	-	-	-	-	-	-	-	0.6	-
Interaction	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns

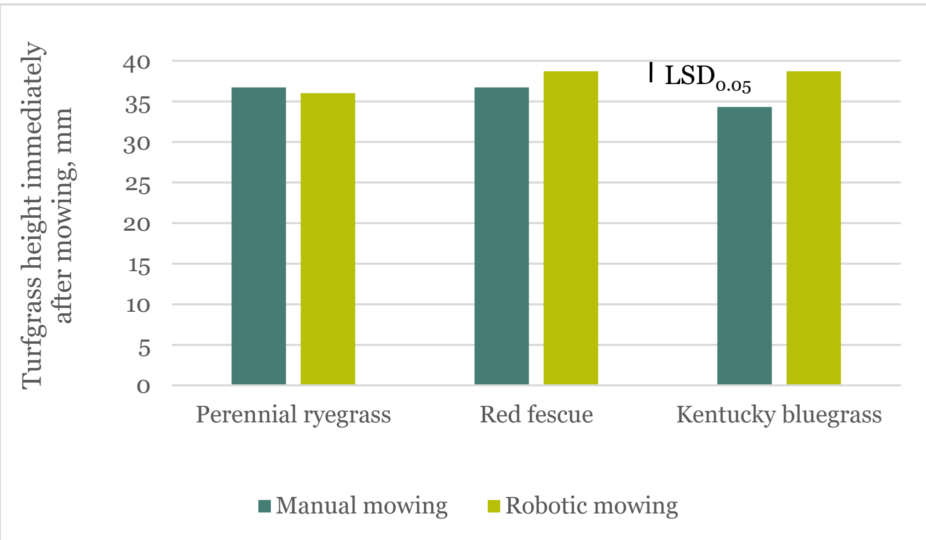

Figure 6: Results from turfgrass height measurements immediately after mowing with rotary mower (set to 35 mm) and robotic mower (set to position 5) on Monday 31 Aug. in the semi-rough trial.

On average for seven observations taken shortly after mowing with both mower types, the CV among the three individual height measurements was 4.8 with robotic mowing vs. 4.1 with rotary mowing (data not shown in table). The fact that neither this difference in mean value nor the difference in CV on any observation date was statistically significant suggests that a mowing period of 3 hours per day was sufficient for the robotic mowers to provide full coverage of the 300 m² mowing area.

The bluegrass sward was significantly higher than the fescue and ryegrass sward after mowing on 5 October and showed a similar tendency on 18 September (Table 8). This may perhaps be taken as an indication that it was easier for Kentucky bluegrass than for the more upright perennial ryegrass and red fescue leaves to escape the horizontal knives on both mower types. On 18 September and 28 September, this was also confirmed by an almost significantly (P=0.08 and P=0.06, respectively) higher CV among the three individual measurements in Kentucky bluegrass than in red fescue and perennial ryegrass (data not shown).

All in all, the data in Table 8 suggest that height position 5 on the robotic mower and a setting of 35 mm on the rotary mower will result in approximately the same mowing height and thus a fair comparison of turfgrass quality and associated characters in 2021 and 2022. However, even with these settings, we have to be prepared for a daily variation of ± 2-3 mm in the semi-rough trial, i.e. more than in the fairway trial.

2.3.3 Turfgrass quality, chlorophyll index, weed and rust infestation during the experimental period

Despite the fact that the measurements were conducted less than 4 hours after robotic mowing but 24-72 after manual mowing, the chlorophyll index was significantly higher with robotic mowing than with manual mowing on 25 August and showed a similar tendency (P=0.09) on 9 September (Table 9). However, neither in September nor in October were these chlorophyll indices reflected in the scores for turfgrass quality which were generally lower with robotic than with manual mowing (Table 9). Turfgrass quality seemed to be more correlated with the occurrence of annual bluegrass, broadleaved weeds and – in Kentucky bluegrass – rust disease (*Puccinia poae-nemoralis*, Photo 15) than with the chlorophyll index. At the end of the growing season, the visual score for tiller density was also lower with manual than with robotic mowing (Table 9).

As for turfgrass species, the higher turfgrass quality and chlorophyll index in perennial ryegrass than in red fescue and Kentucky bluegrass at the start of the trial was confirmed by the assessments and measurements in September and October. As in the fairway trial, the quality of the Kentucky bluegrass faded markedly in October, mostly because of increasing contamination with annual bluegrass and increasing infestation with rust which were both more severe on plots mowed with the robotic than with the manual mowers (Figure 7). Consequently, there also tended to be an interaction with the robotic mowing producing approximately the same quality as manual mowing in perennial ryegrass and red fescue, but reduced quality in Kentucky bluegrass (Figure 8).

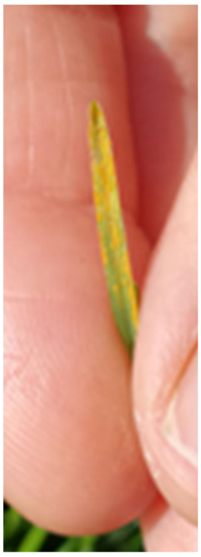

Photo 15. Starting attack of leaf rust in Kentucky bluegrass. Photo: Karin J. Hesselsøe

A almost significant interaction (P=0.06) between mower type and species was evident even for tiller density; in this case red fescue was more negatively affected by robotic mowing than Kentucky bluegrass, while there was no effect of mower type in perennial ryegrass (Figure 9).

For Kentucky bluegrass and perennial ryegrass there was also a strong tendency (P=0.07) to a negative effect of robotic mowing on leaf width in the samples taken to the laboratory (Table 9). Theses samples were, however, taken as late as 19 October, after the frequency of both manual and robotic mowing had been reduced and after the mowing height of the robotic mower had been increased to position 6 on 12 Oct. It is therefore uncertain to what the extent the results on leaf width can be regarded as representative for the entire experimental period.

Table 9. Assessments and measurements of turfgrass quality and associated characters in the semi-rough trial from 25 Aug. to 15 Oct.

	25 Aug[1].	9 Sep[2].					8 Oct[3].				Mean for Sep. & Oct., Turfgr. quality (1-9)	15 Oct. Tiller den-sity (1-9)	15 Oct. Leaf width, mm
	Chlo-ro-phyll Index	Turf-grass qual. (1-9)	Chlo-ro-phyll index	% of plot area: Annual bluegr.	% of plot area: Ru-st	Turf-grass qual. (1-9)	Chloro-phyll Index	% of plot area: Annual bluegr.	% of plot area: Ru-st	% of plot area: Dicot. weeds			
Manual	382	6.7	375	1.4	0.0	7.3	455	3.2	1.1	0.3	7.0	6.8	1.76
Robot	437	6.2	428	1.3	0.9	6.9	478	6.8	2.8	0.6	6.6	6.5	2.03
***P*-value**	**	*	(*)	ns	ns	ns	ns	ns	ns	ns	**	***	(*)
Per. rye.	430	7.4	413	0.1	0.0	8.4	523	0.1	0.0	0.4	8.0	6.5	1.94
Red fesc.	391	6.8	406	0.8	0.0	7.2	472	2.3	0.0	0.4	7.0	7.2	-
Ken.blue.	407	5.1	386	3.2	1.4	5.9	406	12.7	5.8	0.7	5.5	6.4	1.86
***P*-value**	*	***	*	*	*	***	**	*	ns	ns	***	***	ns
$LSD_{0.05}$	26	0.4	22	2.5	1.1	0.4	35	10.4	-	-	0.4	0.3	ns
Interact.	ns	ns	(*)	ns	*	ns	ns	ns	ns	ns	ns	(*)	-

[1]24 h after rotary mowing at 35 mm and shortly after robotic mowing, position 5
[2]48 h after rotary mowing at 35 mm and shortly after robotic mowing, position 5
[2]72 h after rotary mowing at 35 mm and shortly after robotic mowing, position 5

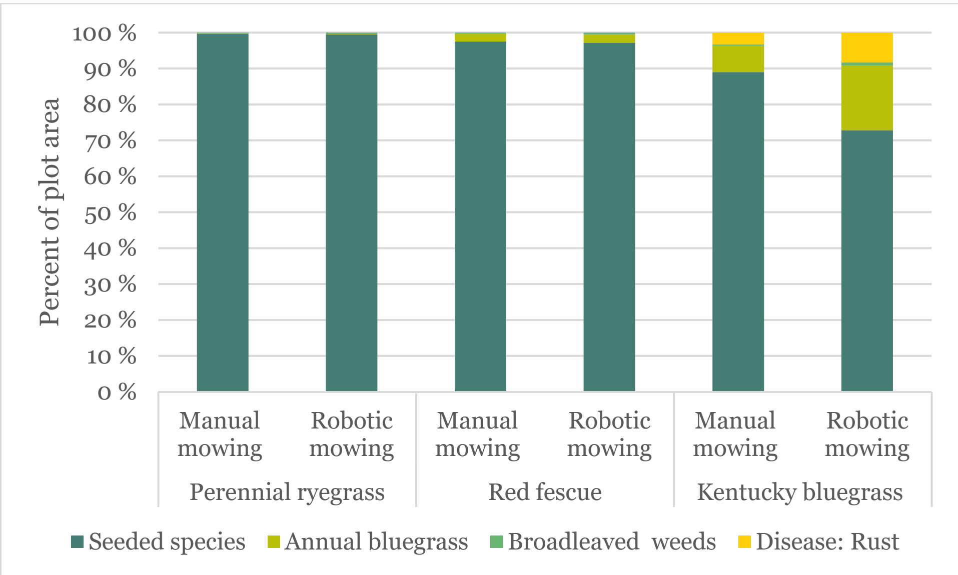

Figure 7. Coverage of seeded species, annual bluegrass, broadleaved weeds and diseased turf in the semi-rough trial on 8 Oct. 2020 as affected by turfgrass species and mower type.

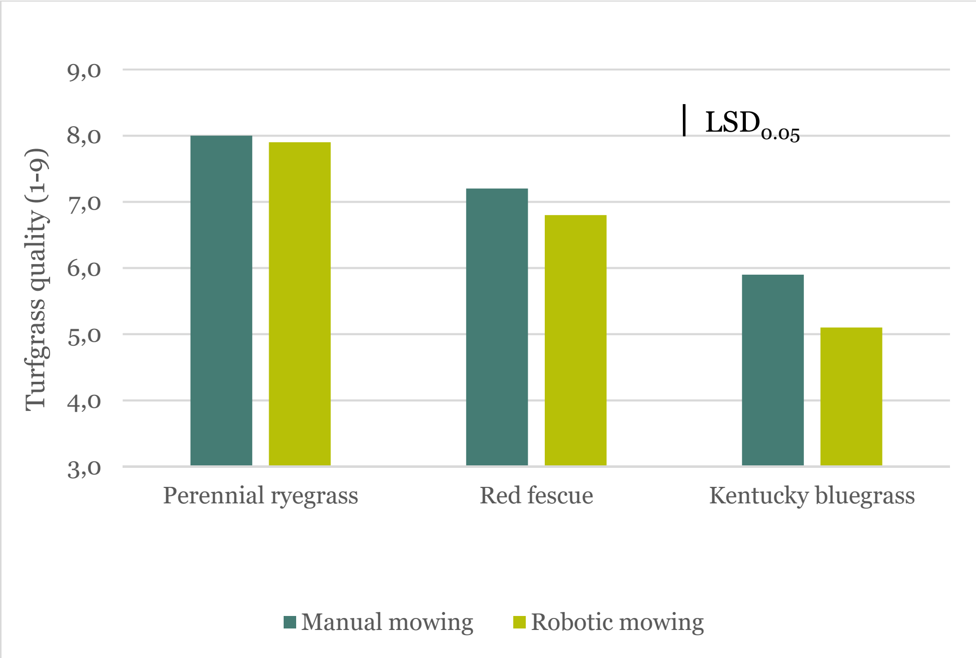

Figure 8. Turfgrass quality as affected by turfgrass species and mower type in the semi-rough trial. Mean of observations on 8 Sep. and 8 Oct.

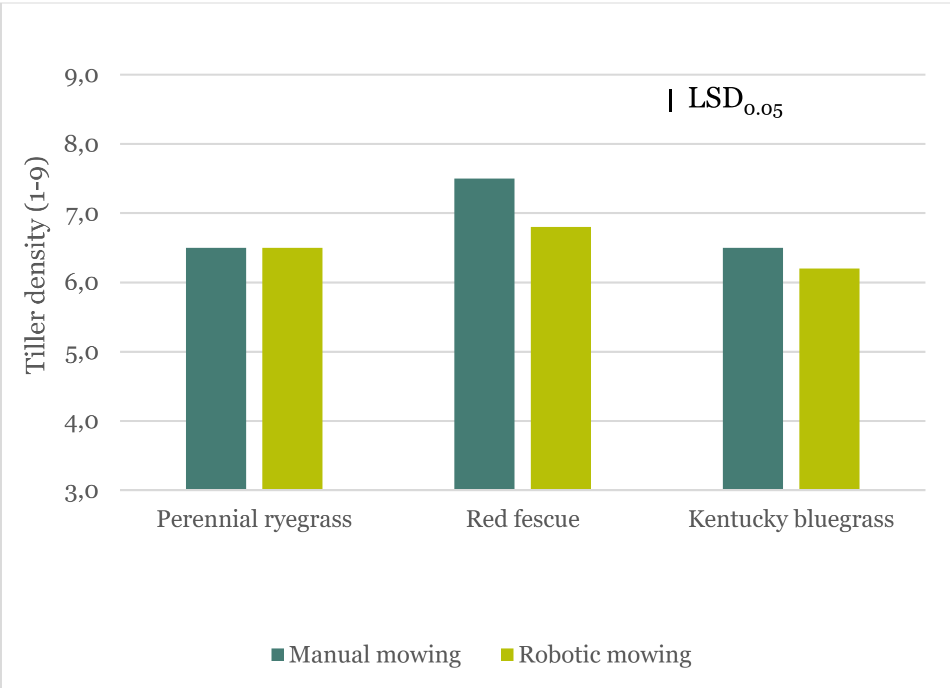

Figure 9. Turfgrass tiller density as affected by turfgrass species and mower type in the semi-rough trial. Observations taken on 15 Oct.

2.4 Discussion WP1

2.4.1 Turfgrass establishment and start values

From April to August, WP1 had a good start with the establishment of a new and uniform experimental area. All turfgrass species emerged evenly and there were hardly any significant differences between plots to be used for robotic vs. manual mowing when the robotic mowers were installed on 11 August. An exception was the trend for main plots to be mowed with robotic mowers to have higher start values for turfgrass quality than the corresponding plots to be mowed with the rotary mower in the semi-rough trial (Table 7), but it is unsure to what extent these results were affected by the fact that this assessement was made after the mower had been in operation for one day. The start assessments should have been made before installation, and for the rest of the project it is important to make a correct start assessment of all plots before the mowing starts in spring.

2.4.2 Effect of robotic vs. manual mowing on turfgrass quality and associated characters

The assessments showed no or a slightly positive effect of robotic vs. manual mowing on turfgrass quality in the fairway trial, but a negative effect in the semi-rough trial. While this is in contrary to opinion by most greenkeepers participating in WP3 of this project, that robotic mowers have greater advantages over manual mowing on semi-rough than on fairways (see later in this chapter), our results are partly supported by Pirchio et al. (2018) who in their trial with manila grass found a stronger increase in turfgrass quality by switching from a cylinder mower to a robotic mower at 12 mm (mower equipped with fairway-kit) than at 36 mm mowing height.

In our trial, the reason for higher turfgrass quality with manual than with robotic mowing in the semirough may partly have been that the systematic mowing back and forth in the north-south direction gave a tidier impression than the random mowing pattern of the robotic mower (Photo 13 top). In addition to this, turfgrass quality was influenced by less infestation of leaf rust, less encroachment by annual bluegrass, higher tiller density and finer leaves in Kentucky bluegrass and perennial ryegrass. Despite a possible effect of assessment time, the fact that start values for turfgrass quality tended to be higher on plots assigned to robotic than to manual mowing was another indication of the relatively poor performance of the robotic semi-rough mowers during this first experimental period. It may, however, be argued that our comparison of rotary and robotic mowing on semi-rough does not have top relevance for golf courses as the low-weight, 0.85 m wide rotary mower was probably more precise and left a better impression than much larger semi-rough mowers commonly used on golf courses. For 2021 and 2022 NIBIO has therefore purchased a new 1.8 m wide rotary mower to be used on the control plots in the semi-rough trial. Even with this new mower, it must also be kept in mind that the experimental semi-rough at Landvik are flatter, more uniform and perhaps better drained than the more rugged semi-roughs on many golf courses.

Among most interesting findings from this first experimental period was the trend to different performance of robotic vs. manual mowing in the various turfgrass species. In the fairway trial, robotic mowing showed a clear advantage in colonial bentgrass by minimizing microdochium patch, but was indifferent in Kentucky bluegrass and negative when red fescue was still growing vigorously in height in early September. The effect of robotic mowing on various turfgrass diseases will be interesting to see during the following two growing seasons as our preliminary data show contrasting effects on microdochium patch in colonial bentgrass on fairway and on leaf rust in Kentucky bluegrass on semi-rough. By comparion, Ferguson & Newell (2010) reported less red thread (*Laetisaria fuciformis*) after mowing predominately ryegrass turf with a robotic than with a manual cylinder mower at 25 mm mowing height. As for strongly positive effect of manual mowing on turfgrass quality of red fescue in

September, it may well be that the precise mowing of the upright and narrow leaves of this species were especially more favored by front roller mounted on the cylinder mower.

In the semi-rough trial the turfgrass quality of perennial ryegrass was virtually unaffected by mower type, while it was mostly reduced in Kentucky bluegrass. These grasses differ in leaf angle, improved varieties of Kentucky bluegrass having almost horizontal leaves when they are fully expanded (Sheffer et al. 1978). Our measurements of turfgrass height after mowing suggest that a higher proportion of these horizontal leaves escaped the knives on the robotic than on the more powerful rotary mower which perhaps brought them more upright before mowing due to air flow. If this speculation is correct, it may also help to explain why leaves were wider and why there was a trend to more rust disease with robotic than with rotary mowing.

2.4.3 Experimental procedures and directions for 2021-2022

An important target for the first experimental period 11 August – 30 October 2020 was to standardize and fine-tune our procedures for turfgrass maintenance and data collection in 2021 and 2022. To this end, we paid special attention to mowing heights / bench settings in order to facilitate a fair and objective comparison of robotic vs. manual mowing. This worked out well, and we soon realized how important it is that all visual assessments within one trial are conducted by the same, experienced evaluator. Equally important is that all assessments are done on the same weekday and at the same time of the day relative to the mowing schedule for robotic and manual mowers. For 2021 and 2022 we have now decided that all assessments in the fairway trials (WP1 and WP2) shall be conducted on Tuesdays after lunch, i.e. 25-32 h after mowing control plots with the triplex cylinder mower, and after the daily period with robotic mowing. In the semi-rough trial, all assessments will be conducted by the same person after lunch on Wednesdays, 49-56 hours into the mowing interval for the rotary mower.

Our preliminary data suggest that mowing heights may have an effect on visual turfgrass quality and especially on turfgrass color as expressed by the chlorophyll index. As in the study by Ferguson & Newell (2010) it is, however, likely that the turf will adapt to mower type and that day-to-day fluctuations in color and other visual characters, over time, will become less apparent with robotic than with manual mowing. In a reference group meeting on 10 September 2020 it was discussed whether robotic and manual mowers should be adjusted to mow at the same height or whether a daily height growth of 0.5-1.0 mm (depending on turfgrass species) should be taken into account, thus aiming for the same average height over the 2-3 day and 3-4 day intervals for manual mowing on fairways and semi-roughs, respectively. To some extent, this is perhaps a theoretical discussion as the realized mowing height will also vary with soil moisture (and thus surface firmness), leaf wetness and other factors. According to Husqvarna's representatives, it is impossible to avoid a certain variation among individual mowers, even of the same model and adjusted to the same position. Most likely this variation will be at least ± 1 mm on fairway and even more on semi-rough.

The reference group's conclusion was to follow the procedures used by Ferguson & Newell (2010), Grossi et al. (2016) and Pirchio et al. (2018a,b), thus targeting the same mowing height with the robotic and manual mowers, but at the same time ensuring that the manual mowers never leave a higher cut than the robotic mowers. For the 2021 and 2022 growing season, this will be ensured by (1) maintaining the robotic mowers constantly in position 2 and 5 on fairway and semi-rough, respectively; (2) keeping the bench setting of the triplex cylinder mower at 13 mm corresponding to a realized mowing height of approximately 15 mm, and (3) adjusting the semi-rough rotary mower to 35 mm. Height measurements will be conducted after mowing on Mondays preceding the monthly visual assessments on Tuesdays in the fairway trial and on Wednesdays in the semi-rough trial. The knives on the robotic mowers will be replaced monthly (always two weeks before assessments), the mowing aggregates on the fairway cylinder mower will be back-lapped every two weeks (always one week before assessments) and the new and wider rotary mower will come with new knives in spring 2021.

3 WP2: Preparation for fertilizer trial to start in 2021

The objective of this work-package is to quantify and compare the fertilizer effect of returning clippings on fairways with daily robotic mowing and mowing three times a week with a cylinder mower. A fertilizer trial is scheduled to start in 2021 and our task in 2020 was to ensure the establishment of a uniform experimental area.

3.1 Materials and methods

Seedbed preparation, seeding, turfgrass grow-in and the installation of robotic mowers followed the same procedures as outlined for the fairway part of WP1 in the previous chapter. The experimental area was seeded on 20 May 2020 with the following fairway mixture commonly used on Norwegian golf courses (percent by weight)

- Chewings fescue (*F. rubra* ssp. *commutata)* 'Musica': 15 %
- Chewings fescue (*F. rubra* ssp. *commutata)* 'Greensleeves': 20 %
- Strong creeping red fescue (*F. rubra* ssp. *rubra*) 'Frigg': 15 %
- Kentucky bluegrass (*Poa pratensis*) 'Mercury': 25 %
- Kentucky bluegrass (*Poa pratensis*) 'Marcus': 20 %
- Colonial bentgrass (*Agrostis capillaris*) 'Leirin': 5%

In the establishment year 2020, the trial area received fertilizer as WP1 (Table 2). It was subjected to a simplified registration program to ensure a uniform starting point for the fertilizer trial to be conducted in 2021 and 2022. At the end of the growing season on Monday 12 October, five cylinder samples, 95 mm in diameter, were taken from each plot and the tiller number of each of the seeded species plus annual bluegrass determined under a binocular lens in the laboratory.

3.2 Results and discussion

The establishment of the trial area was uniform (Table 10). Assessments and measurements after the installation of the robotic mowers on 11 August showed only small and insignificant differences in turfgrass quality and coverage. The only exception was the chlorophyll index which on 8 September, 2 hours after robotic mowing at position 2 and 24 hours after manual mowing with the cylinder aggregates set to 15 mm, showed a significantly higher value with manual than with robotic mowing. This corresponds with the findings in WP1 on the same date (Table 6).

Table 10. Assessments in WP2 after the installation of robotic mowers on 11 August.

	25 Aug.	8 Sep.		8 October 2020				
						% of plot area		
	Turfgrass quality (1-9)	Turfgrass quality (1-9)	Chloro-phyll index	Turfgr. quality (1-9)	Chloro-phyll index	Seeded mixture	Annual bluegr.	Dicot. weeds
Manual	6.5	6.7	371	7.6	396	98.6	1.4	0.0
Robot	6.3	6.7	338	7.6	382	98.2	1.7	0.1
P-value	ns	ns	**	ns	ns	ns	ns	ns

The samples taken to the laboratory on 12 October showed no significant difference in the tiller numbers / botanical composition between plots that had been subjected to robotic mowing or cylinder mowing since 11 August (Figure 10). Both treatments had colonial bentgrass as the predominant grass species, followed by red fescue. The trend to more annual bluegrass tillers with robotic than with manual mowing is in line with the visual assessments on 8 October (Table 10).

All in all, we consider this part of the experimental area as well suited for the fertilizer trial to start in 2021.

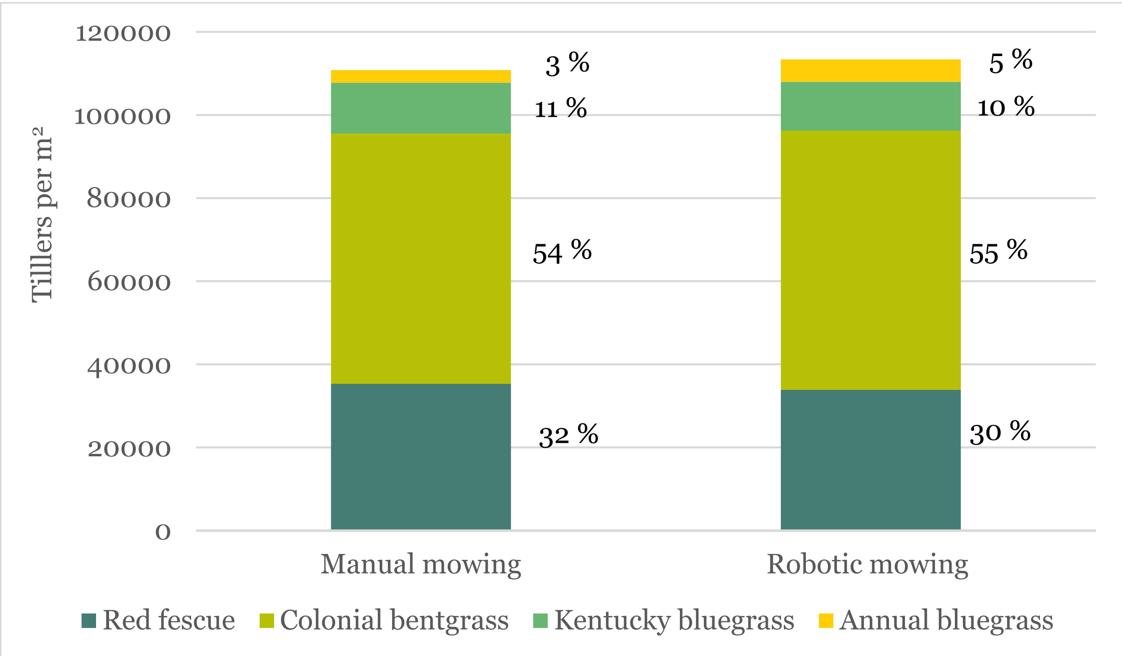

Figure 10. Botanical composition of the fairway to be used for the fertilizer trial in WP2 as determined by tiller density of the three seeded species plus annual bluegrass on 12 Oct. 2020. Per cent of total tiller number belonging to various species has been indicated.

4 WP3: Demonstration trials on five golf courses

Demonstration trials were established in spring 2020 on the five golf courses: Bærheim (Norway), Grenå (Denmark), Jönköping (Sweden), Ness (Iceland) and Ikaalisten (Finland). On each course, two neighbor fairways and semi-rough areas of similar size, shape and soil type were selected – one area for robotic mowing and one area for manual mowing (control). On each golf course Husqvarna installed two robotic mowers (model 550), one for the designated fairway and one for the designated semi-rough.

4.1 Materials and methods

Baseline information on soil type, turf age, grass species, fertilization and maintenance were recorded for each golf course.

Bærheim, Norway

Bærheim Golf Park is situated 10 km south of Stavanger on the southwestern coast of Norway. The golf park was established in 2005 on an old farmland/linksland/landfill. The golf course was designed by Atle Revheim Hansen and build by Atle Revheim Hansen/Golfmanagement A/S.

Bærheim GP is owned by Golfmanagement and comprises 54 hectares land including a 18 hole golf course and a 6 short-hole course. Today, Bærheim GP is the host for Sandnes Golf Club.

Photo 16. The greenkeepers team at Bærheim, March 2021.

The southwestern part of Norway is known for its windy and wet climate. Bærheim GP is one of the busiest golf courses in Norway with up to 54000 rounds played 365 days a year. The average for the last 5 years is around 45000 rounds. To be able to run a golf course of a certain standard with such a playing pressure and in such a climate, and to meet the requirements and demands of the customers, it's crucial that drainage and overall management are suitable. The course has over 1000 catch basins spread all over the course that compensates for the wet weather and enables daily maintenance without too many interruptions.

On Bærheim it has been a revolution going from old conventional mowing with big and heavy equipment to robotic mowers. In 2017 64 robotic mowers were bought from Husqvarna to implement robotic mowing on the 23 ha of semi-rough. Today the course has 75 robotic mowers, including a few on fairways.

The fairway used in in the control treatment in ROBO-GOLF was cut 3 times pr. week at 12 mm using a Jacobsen 250 cylinder mower (Table 11). The semi-rough was cut 2 times pr. week at 30 mm using a Jacobsen AR 250 rotary mower. Both robotic mowers were set to work for 24 h a day, 7 days a week.

Course manager Atle R. Hansen and greenkeeper David B. Smith did the assessments for ROBO-GOLF.

Table 11. Baseline info about the demo-trial at Bærheim GP.

	Fairway	Semi-rough
Soil type	Peat/ sand	Peat / sand
Turf age	15 years	15 Years
Grass species	Fescue/bentgrass/ annual bluegrass	Fescue/bentgrass/ annual bluegrass
Fertilisation per year	50 kg N/ha	None
Mowing height/frequency (control treatment)	12 mm/ 3 times per week	30 mm/ 2 times per week
Manual mower type (control treatment)	Jacobsen 250 (Cylinder mower)	Jacobsen AR 250 (Rotary mower)

Grenå, Denmark

Grenå's 18-holes park course is located on the west coast of Jutland, Denmark. In addition, there is a 12-hole Pay & Play par-3 course. The golf course comprises 80 hectares of land and was established in 1981 on an old landfill. The golf course is designed by Frederik Dreyer and Lars Sommer and hosts Grenå Golf Club with 505 members. The greens have a turf cover of red fescue, colonial bentgrass and annual bluegrass, while the fairways and semi-roughs have a diverse grass composition comprising perennial ryegrass, red fescue and annual bluegrass.

At Grenå they have used robotic mowers for surroundings and the driving range for 3 years. In addition to the mowers used for ROBO-GOLF project they have 8 Husqvarna robotic mowers. Course manager Lars Henrik (Lasse) Nielsen is managing the golf course together with 3 greenkeepers.

In the ROBO-GOLF project the fairway was cut 3 times pr. week at 15 mm with a Hayder 524 cylinder mower, while the semi-rough was cut 2 times pr. week at 42 mm with a Toro Grandmaster 4700 rotary mower (Table 12). Both mowers worked for 24 h, 7 days a week. The assessments for ROBO-Golf were done by Lasse Nielsen and greenkeeper trainee Jack Christensen.

Photo 17. Course manager Lasse Nielsen at Grenå. Photo: Karin J. Hesselsøe.

Table 12. Baseline info about the demo trial at Grenå GC.

	Fairway	Semi-rough
Soil type	A diverse topsoil on top of old landfill	A diverse topsoil on top of old landfill
Turf age	35-45 years	35-45 years
Grass species	Perennial ryegrass/ red fescue/ annual bluegrass	Perennial ryegrass/red fescue/annual bluegrass
Fertilisation	51 kg N/ha	51 kg N/ha
Mowing height/frequency (control treatment)	15 mm, 3 times/week	42 mm, 3 times/week
Manual mower type (control treatment)	Hayder 524 (5 aggregates) (Cylinder mower)	Toro Grandmaster 4700 (Rotary mower)

Jönköping, Sweden

Jönköpings GC is situated at the southern point of lake Vättern, 150 km east of Gotenburg. The golf course was established in 1938 on an old farmland that used to be an agricultural school from 1892 to 1929. The golf course was designed by Frank Dyer (first 9 holes in 1938) and Nils Sköld (last 9 holes in 1942). Jönköping GC is owned by its members and comprises 56 hectares of land including a 18 holes golf course, a 6 hole Par 3/training course and a driving range. The greens have a turf cover of almost 100 % annual bluegrass. Course manager Markus Rehnström is managing the golf course together with four greenkeepers.

In the ROBO-GOLF project the control fairway was cut 3 times pr. week at 13 mm using a Toro 5010-H cylinder mower. The robotic mower on the fairway mowed for 24 h a day, 7 days a week. The control semi-rough was cut once a week at 50 mm using a Toro 4700 rotary mower. The robotic mower on the semi-rough mowed for 24 h a day, 7 days a week at 50 mm (Table 13). Course manager Markus Rehnström did the assessments for ROBO-GOLF.

Photo 18. Robotic mower on the fairway at Jönköping GC, July 2020. Photo: Marcus Rehnström.

Table 13. Baseline info about the demo-trial at Jönköpings GC.

	Fairway	Semi-rough
Soil type	Sand based	Sand based
Turf age	83 years	83 years
Grass species	Annual bluegrass	Annual bluegrass
Fertilisation	3 times/year	None
Mowing height/frequency (control treatment)	13mm 3 times/week	50mm 1 time/week
Manual mower type (control treatment)	Toro 5010-H (Cylinder mower)	Toro 4700 (Rotary mower)

Ness, Iceland

Ness GC is located on the Seltjarnarnes peninsula, about 10 minutes' drive from Reykjavik city center. It is a 9-hole golf course established in 1964. The course comprises 24 hectares. Ness is a non-for-profit members' club, run as a sports club, like almost all other golf clubs in Iceland.

Greens are of different age and construction. The oldest greens are "push up" greens with a high content of organic matter, while the latest greens (10 years old) were constructed using sand. The turf is a mixture of annual bluegrass, red fescue and colonial bentgrass. Course manager Bjarni Hannesson is in a full time position at the course and did the assessments for ROBO-Golf. In addition to Bjarni one assistant greenkeeper is hired on a 6 month contract (usually a newly graduated greenkeeper from US/International). During the height of the season, 8 workers aged 17-24 (high school/university students working in the summer) are provided by the local municipality for 3 months.

In the ROBO-GOLF project the control fairway was cut at 15 mm three times pr. week using a Jacobsen LF3400 cylinder mower. The semi-rough was cut at 45 mm twice per week using a Jacobsen AR3 rotary mower. Both robotic mowers worked for 24 h a day, 7 days a week (Table 14).

Photo 19. Robotic-mowed fairway at Ness, August 2020. Photo: Bjarni Hannesson.

Table 14. Baseline info about Ness.

	Fairway	Semi-rough
Soil type	Push-up, high in organic matter, no clay but high in silt.	Push-up, sandier than on the fariway, but high in organic matter
Turf age	+50 years	15 years
Grass species	Annual bluegrass, colonial bentgrass	Annual bluegrass, fescue, colonial bentgrass, perennial ryegrass
Fertilisation	UREA 40 kg N/ha	None
Mowing height/ frequency (control treatment)	Bench setting at 14 mm 3 times per week (gives 15 mm mowing height as with the robotic mower)	45 mm, 2 times per week
Manual mower type (control treatment)	Jacobsen LF3400 (Cylinder mower)	Jacobsen AR3 (Rotary mower)

4.1.1 Visual assessments

To evaluate differences between robotic and manually mowed areas the turfgrass quality and the percentage of weeds and diseases were recorded monthly. The course managers selected six permanent registration plots on the experimental fairway and six on the experimental semi-rough (Photo 20). Three plots were placed in the robotic mowed area and three plots in the manually mowed area. Each plot was 1.0 m².

Turfgrass quality was assessed as an overall score for live ground cover, uniformity, greenness, fineness of leaves, disease resistance and shoot density on a scale from 1-9 where 9 is the best turf. Percent of plot area covered with broadleaved weeds and diseases were also recorded monthly. The lowest figure used was 0.1 % of plot area (3.2 cm x 3.2 cm = 10 cm² in 1 m²).

Photo 20. An illustration on how the course managers were advised to place the three registration plots on each experimental area. Example from Grenå, June 2020. Photo: Karin J. Hesselsøe.

Assessments were done monthly from June to October using an app (Socrative). Via this app the assessments were reported online from the course managers' cell phones directly to the WP leader Karin J. Hesselsøe. A text message ('Now it is time for ROBO-Golf recordings') was sent from the WP leader in the beginning of each month. A reminder was sent if the recordings did not show up during the first week of the month. The app worked very well to promote communication between the course managers /evaluators and the WP-leader, and it saved a lot of time in data collection. Instructions for assessments (Photo 21) were given in the protocol and a short instruction video (in Danish) was also disseminated.

Photo 21. Example from protocol (and video) to facilitate recordings by the course managers. Plot area was 1 m2. On this plot, the turfgrass quality was assessed to 6 (scale from 1 to 9, where 9 is best), dicot weeds (dandilion) covered 1 % (10x10 cm) and diseases were 0 %.
Photo: Karin J. Hesselsøe

4.1.2 Labor and energy use

To calculate the consumption of electricity an energy logger was installed at the docking station for each robotic mower. For comparison the course managers measured the consumption of diesel/gasoline by the manual cylinder and rotary mowers. Time spent on manual mowing (labor use) was also measured and reported via the app. The energy and labor data from the experimental areas will be extrapolated and recalculated to show economic and environmental consequences of switching from manual mowers to robotic mowers on the entire golf course.

4.1.3 Survey

In autumn 2020 a web-based survey was conducted among the players on the golf courses in Norway, Denmark and Sweden. The goal of the survey was to monitor players' perceptions and attitudes to the robotic mowers. The survey was completed using Google Survey.

4.2 Results

4.2.1 Turfgrass quality

Bærheim, Norway

The results from the fairway (Table 15) showed a turfgrass quality between 7 and 9, but no significant differences between robotic and cylinder-mowed plots.

The results from the semi-rough (Table 15) showed a slightly higher turfgrass quality on the robotic mowed plots. In May the robotic mowed plots were significantly better than the rotary mowed plots, and in August the difference was almost significant.

Photo 22. Robotic-mowed fairway plot at Bærheim. Left: Beginning of June, Right: End of July. Photos: Atle R. Hansen.

Table 15. Turfgrass quality on robotic and cylinder mowed plots on fairway and robotic and rotary mowed plots on semi-rough at Bærheim, Norway. Means of three permanent plots used for assessments.

	Turfgrass quality, scale 1-9					
	May	**June**	**July**	**Aug.**	**Sep.**	**Oct.**
Fairway						
Robotic mower	9.0	8.3	8.0	8.0	8.0	7.3
Cylinder mower	8.7	8.3	7.7	8.0	8.0	7.7
***P*-value**	ns	ns	ns	ns	ns	ns
Semi-rough						
Robotic mower	8.0	8.0	7.6	8.0	7.6	7.3
Rotary mower	5.6	8.0	7.3	6.6	7.0	7.0
***P*-value**	*	ns	ns	(*)	ns	ns

[1]The significance symbols used in this and the following tables are:
***: *P*≤0.001, **:0.001<*P*≤0.01, *: 0.01<*P*≤0.05, (*): 0.01<*P*≤0.05 (‘tendency’) , ns: not significant

Photo 23: Registration plot on rotary-mown semi-rough at Bærheim, Sep. 2020. Photo: Atle R. Hansen.

Grenå, Denmark

The turfgrass quality on the fairway was slightly higher with robotic than with manual mowing during most of the season. In May the robotic mowed plots were significantly better than the cylinder-mowed plots (Table 16).

The turfgrass quality on the robotic mowed semi-rough tended to be higher that on the rotary-mowed semi-rough in the beginning and at the end of the season, but there were no differences in the middle of the season.

Table 16. Turfgrass quality on robotic- and cylinder- mowed plots on fairway and robotic- and rotary mowed plots on semi-rough at Grenå, Denmark. Means of three permanent plots used for assessments.

	Turfgrass quality, scale 1-9					
	May	**June**	**July**	**Aug.**	**Sep.**	**Oct.**
Fairway						
Robotic mower	5.0	4.3	4.3	4.0	4.7	4.3
Cylinder mower	3.3	3.0	4.7	3.0	3.3	3.3
***P*-value**	*	ns	ns	(*)	(*)	(*)
Semi-rough						
Robotic mower	4.7	4.7	5.7	3.7	4.3	4.7
Rotary mower	3.7	3.7	5.7	3.7	4.0	3.3
***P*-value**	(*)	(*)	ns	ns	ns	(*)

Jönköping, Sweden

The results from the fairways at Jönköpings GK showed robotic and cylinder mowing to produce very similar turfgrass quality except for the observation in August when the quality of the cylinder mowed fairway was better (Table 17).

On the semi-rough the turfgrass quality was significantly better with robotic than with rotary mowing during most of the season.

Table 17. Turfgrass quality on robotic- and cylinder mowed plots on fairway and robotic- and rotary mowed plots on semi-rough at Jönköping, Sweden. Means of three permanent plots used for assessments.

	Turfgrass quality, scale 1-9					
	May	**June**	**July**	**Aug.**	**Sep.**	**Oct.**
Fairway						
Robotic mower	6.0	7.0	7.0	7.0	7.0	7.0
Cylinder mower	6.0	7.0	7.0	8.0	7.0	7.0
***P*-value**	ns	ns	ns	*	ns	ns
Semi-rough						
Robotic mower	5.0	5.3	5.0	5.0	4.3	4.7
Rotary mower	4.0	3.3	4.0	3.7	3.0	3.3
***P*-value**	*	*	*	(*)	(*)	(*)

Ness, Iceland

The results from the fairway showed a tendency to better quality on the robotic mowed areas in the beginning of the season and the opposite situation towards the end of the season. In July there were no registrations, because the course manager was in Covid-19-quarantine.

On the semi-rough there were only two registrations (May and June) showing slightly higher quality on robotic mowed plots, but no significant differences. The robotic mower broke down in the middle of the summer and there was no possibility for technical support in Iceland.

Table 18. Turfgrass quality on robotic- and cylinder mowed plots on fairway and robotic- and rotary mowed plots on semi-rough at Ness, Iceland. Means of three permanent plots used for assessments.

	Turfgrass quality, scale 1-9					
	May	**June**	**July**	**Aug.**	**Sep.**	**Oct.**
Fairway						
Robotic mower	8.0 a	8.0	X	8.0	6.0 b	5.0 b
Cylinder mower	7.0 b	7.3	X	8.0	7.0 a	7.0 a
***P*-value**	*	ns	-	ns	*	*
Semi-rough						
Robotic mower	5.7	5.7	X	XX	XX	XX
Rotary mower	5.3	5.3	X	XX	XX	XX
***P*-value**	ns	ns	-	-	-	-

X: Missing values due to Covid-19 quarantine XX: Missing values due to robotic mower breakdown

Ikaalisten, Finland

At Ikaalisten the score for turfgrass quality were mostly higher with robotic than with manual mowing on both fairway and semi-rough. However, none of the differences were statistically significant.

Table 19. Turfgrass quality on robotic- and cylinder mowed plots on fairway and robotic- and rotary mowed plots on semi-rough at Ikaalisten, Finland. Means of three permanent plots used for assessments.

	Turfgrass quality, scale 1-9					
	May	**June**	**July**	**Aug.**	**Sep.**	**Oct.**
Fairway						
Robotic mower	3.3	X	4.3	5.7	4.0	X
Cylinder mower	2.7	X	3.3	4.3	3.3	X
***P*-value**	ns	-	ns	ns	ns	-
Semi-rough						
Robotic mower	2.7	X	3.3	4.0	3.3	X
Rotary mower	2.0	X	3.0	3.7	3.3	X
***P*-value**	ns	-	ns	ns	ns	-
X: Missing values						

4.2.2 Broadleaved weeds

Results on the percentage of broadleaved weeds found in the plots are shown in Table 20 for Denmark, Iceland and Sweden as an average of assessments from May to October (Table 20). Results from Norway and Finland are not shown, because almost no dicot weeds were recorded there.

The results showed no significant differences between robotic and manually mowed plots. The mean values for semi-rough plots nonetheless suggest a trend to more broadleaved weed with robotic mowing that will be interesting to follow in 2021 and 2022.

Table 20. Percent broadleaved weeds on plots with robotic and manual mowing on fairway and semi-rough in Denmark, Iceland and Sweden. Means of monthly assessments.

	Broadleaved weeds (% of plot area)		
Fairway	**Denmark**	**Iceland**	**Sweden**
Robotic mower	0.33	0.16	0.04
Cylinder mower	0.35	0.13	0.03
***P*-value**	ns	ns	ns
Semi-rough			
Robotic mower	0.51	X	0.2
Rotary mower	0.28	X	0.1
***P*-value**	ns	ns	ns
X: Missing values			

4.2.3 Energy and labor use

The use of diesel and time spent for manual mowing was recorded three times in the season (June, July and September, Table 21).

Table 21. Energy and labor use for manual mowing of control fairway and semi-rough at the five courses.

Fairway	Norway	Denmark	Iceland	Sweden	Finland
Time spent (minutes)	8.7	11.3	8	15 ($3000 m^2$)	13
Fuel consumption (liters)	1.3	1.5	0.45	0.5-1	X
Semirough					
Time spent (minutes)	7.8	13.3	$8000 m^2/h$	5 ($500 m^2$)	X
Fuel consumption (liters)	1.8	2	4L/h	X	1

X: Missing values

4.2.4 Players' attitudes to robotic mowers

The survey of players' attitudes to robotic mowers was completed at Bærheim, Grenå and Jönköping GC. The majority of answers (80-99 %) came from golf club members and only a few from green-fee players (Table 22). Most of the respondents had been playing golf for 6 years or more. At Jönköping the players were asked about their golf handicap, and it was on average 19.4.

Photo 24: Players and robotic mowers in action at Bærheim GC. Photo: Atle R. Hansen.

Photo 25. Robotic mower among players on the fairway at Jönköping. Photo: Marcus Rehnström.

The survey showed an overall positive or neutral attitude to robotic mowers (87-93%, Table 22), but many players asked for implications of the new technology on the rules of the game. Good communication with the players is therefore important before introducing robotic mowers.

Table 22. Results from the survey among players at Bærheim, Grenå and Jönköpings GC.

	Number of res-pondents	Members/ greenfee %	Male/ female %	Age: 45+, %	Positive or neutral to robotic mowers on the course, %	Negative experiences with the robotic mowers on the course, %
Bærheim	31	97/3	87/13	83	90	9.5
Grenå	91	78/22	66/34	95	87	7
Jönköping	276	99/1	74/26	85	93	11

Some of the comments from players having positive attitudes to the robotic mowers were (answers from Bærheim, Grenå and Jönköping):

- The robotic mowers make the grass more even and dense
- The ball can lay on top of the grass
- The fairway is always mown very nicely and without clippings
- You don't need to wait for the greenkeepers to finish their job
- No noise
- The semi-rough feels newly mown every day
- Less dew in the grass
- Good for environment and economy
- Gives time for the greenkeepers to do other jobs than mowing

Among players having negative attitudes to the robotic mowers, comments were (answers from both Bærheim, Grenå and Jönköping):

- The robotic mowers hit my ball
- Concerned about implications of robotic mowers on hedgehog cubs
- Some players miss the 'cuttinglines'
- Some players are afraid of hitting the robotic mowers with their ball/or that they may be hit by the robotic mowers
- It is annoying when the robotic mower is mowing in the 'landing area'
- Prefer that robotic mowers mow at nighttime
- Need local rules for hitting the robotic mowers

4.3 Discussion WP3

4.3.1 Turfgrass quality on fairway

Results from the first year showed few differences in turfgrass quality between robotic-mowed and manually mowed fairways on the five courses.

At Ness, and to a lesser extent at Bærheim, there was a 'tendency' to better turfgrass quality on fairway with robotic mowing in the beginning of the season, but the opposite situation at the end of the season. The lower ratings on the robotic-mowed plots in October was commented by the course manager at Ness:

"*I don't know if it was because my mower went out under frosty conditions, or that it has been working too much once the grass growth slowed down... or both. But it was evident that the automown area looked a lot more worn out than the reel mowed area that was being mowed once a week at the time of the latest rating. We have now stopped mowing".*

At Grenå and Ikaalisten the robotic mown plots were slightly better than the manually mowed plots most of the season, but hardly any significant differences were found. At Jönköping there were no differences, except for the observation in August where the cylinder-mowed fairway plots were better. This could be explained by the missing 'cutting lines' on the robotic mowed fairway.

Another observation from the course manager at Jönköping was that the robotic mowed turfgrass is 'standing up' more than the cylinder mowed turfgrass where the rollers on the cylinder mower 'lay down' the grass. When the grass is 'standing up' the ball has a tendency to 'lay in' the grass instead of 'laying on' the grass. This can be a disadvantage especially for low handicap players who take advantage of no grass between the club and the ball. The mowing height is also an important factor as the mowing height on the fairway varied from 12 to 15 mm on the different courses.

Though there were hardly any differences in turfgrass quality between the robotic and the manully mowed fairway plots, the course manager at Ness stated: *"There isn't much quality difference, but I just love how consistent the fairway looks on the robomow side*".

4.3.2 Turfgrass quality on semi-rough

Results from the first year showed differences in turfgrass quality between robotic and manually mowed semi-rough on the five courses. The overall trend was for robotic mowed plots to have higher turfgrass quality than the manually mowed plots.

At Bærheim the robotic mowed semi-rough was better in May and August, and was altogether more consistent in turfgrass quality than the rotary mowed control area. The robotic mowed semi-rough at Jönköping showed a significantly better turfgrass quality than the manually mowed semi-rough during most of the season, and the same tendency was seen even at Grenå and Ikaalisten. At Ness the robotic mower in the semi-rough trial broke down in July.

In a reference group meeting in March 2021 the course managers agreed that the advantage of robotic relative to manual mowing was bigger on semi-rough than on fairway. While the three assessment plots in each experimental area may have been too small or too few to show this difference, it was a general impression that the robotic mowers produced less wear on the grass than the heavy rotary mowers, especially under wet conditions in the autumn. Less grass clippings compared to rotary mowing was another observation that was not reflected by the plot assessments.

4.3.3 Weeds

Broadleaved weeds were found in the plots at Grenå, Ness and Jönköping. The results from these three courses showed no differences between robotic and manually mowed plots on fairway, and only an insignificant trend on semi-rough.

In the beginning of July the course manager at Ness observed that the robotic mowed fairway had less seed heads of annual bluegrass than the cylinder-mowed fairway (Photo). This observation has to be confirmed in 2021 and 2022.

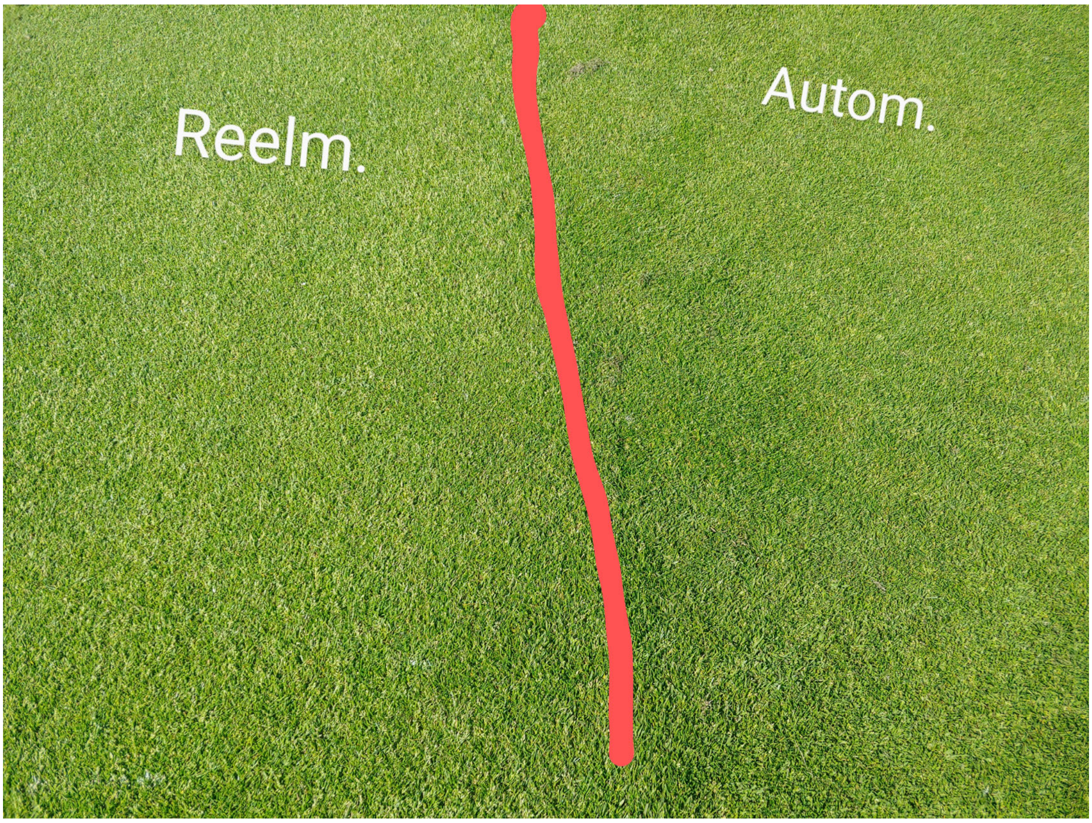

Photo 26. An observation from Ness GC, Iceland, of less seed heads of annual bluegrass on the robotic mowed fairway (to the right) compared to the cylinder- mowed fairway (to the left). Photo: Bjarni Hannesson, July 2020.

4.3.4 Energy consumption

The use of diesel and time spent for manual mowing was recorded three times (June, July and September) at the five courses. Intentionally, these data should have been compared with data from the energy loggers at the docking stations for the robotic mowers, but that has not possible due to a mistake when programming the loggers at Husqvarna.

4.3.5 Survey among players

The survey showed an overall positive or neutral attitude to the robotic mowers, but many players asked for implications of the new technology on the rules of the game. Golf courses switching to robotic mowing will therefore need local rules for particular situations, e.g. when a player hits the robotic mower or the robotic mower moves the ball. Good communication with players is obviously important before introducing this new technology.

One of the course managers asked for general rules from R&A for robotic mowing.

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