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Robotic Mowing of Tall Fescue at 90 mm Cutting Height: Random Trajectories vs. Systematic Trajectories

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Abstract: Tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort.) is often managed with a cutting height ranging from 70 to 100 mm in ornamental lawns. Some autonomous mowers have been specifically designed to maintain mowing height in the same range. Generally, autonomous mowers operate by following random trajectories, and substantial overlapping is needed to obtain full coverage of the working area. In the case of tall grass, this may cause lodging of grass plants, which in turn may reduce turf quality. The introduction of a navigation system based on systematic trajectories has the potential to improve the performances of autonomous mowers with respect to machine efficiency and turf quality. With the aim of determining the effects of reduced mowing frequency and systematic navigation systems on turf quality and mower performances in terms of working time, energy consumption and overlapping, the performances of two autonomous mowers working with random and systematic trajectories were tested on a mature tall fescue lawn at 90 mm cutting height. The working efficiency was approximately 80% for the systematic trajectories and approximately 35% for the random trajectories; this was mainly due to the lower overlapping associated with systematic trajectories. Turf quality was slightly higher for the mower working systematically (a score of 8 using a 1–9 score with 1 = poor, 6 = acceptable and 9 = best) compared to the one working randomly (quality of 7 and 6 on a 1–9 scale with 1 = poor and 9 = best). No appreciable lodging was observed in either case. For tall, managed lawns, systematic trajectories may improve autonomous mowers' overall performances.

Keywords: RTK-GPS; mowing pattern planning; turf lodging; energy efficiency

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1. Introduction

Turfgrass is the most common and intensively managed form of vegetation in urban areas [1]. In response to recent trends regarding ecological and economic sustainability, increasing preference is being given to turf species and alternative maintenance strategies that require lower inputs and improve resource allocation [2].

Tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort.) is the predominant turf species in Italy and in the whole Mediterranean area [3,4] for residential lawns and landscape purposes. The species is also popular throughout the central and northern part of the transition zone of the United States [5]. Indeed, due to its tolerance to several abiotic stresses such as shade, salinity, warm temperatures and wear, tall fescue is often preferred over other cool-season species in the transition zone [6–10]. In green spaces, parks and ornamental lawns, tall fescue is often managed with a tall cutting height (ranging from 70 to 100 mm) in order to achieve some benefits such as lower fertilization and irrigation requirements, reduced mowing frequency [11,12] and more efficient light penetration [13]. Dernoeden et al. [14] found that tall fescue managed with a tall cutting height showed greater weed suppression compared to tall fescue mowed at lower cutting height.

However, with a tall cutting height, shoot density decreases and leaf width increases compared to the same turf species mown at a lower cutting height [15]. Low shoot density and high leaf width are two parameters associated with non-optimal traffic tolerance and turf quality [15]. Thus, the overall quality of turf managed with a tall cutting height may be negatively affected, especially under intensive traffic conditions.

With regard to maintenance duties, regular mowing represents one of the most demanding tasks for turfgrass managers and homeowners. As an alternative strategy to conventional mowing methods, autonomous mowers are being adopted more and more frequently, and their market is rapidly expanding [16]. This trend is probably sustained by their low noise emission, safety and ability to reduce management costs [17,18]. Some new models have recently been introduced to extend the range of mowing heights from 50 to 90 mm [19]. Autonomous mowers are battery-powered machines designed to autonomously mow an area of turf and can be recharged when needed. Collection of clippings is not performed; therefore, high mowing frequencies that produce clippings with low biomass and reduced size [20] are best adapted to these types of mowers. Clipping return further contributes to cost reduction, avoiding disposal and recycling of nutrients [21]. Moreover, Pirchio et al. [12] and Grossi et al. [22] observed that a turf managed with autonomous mowers showed a higher quality compared to the same type of turf mown once a week with ordinary rotary mowers.

Autonomous mowers generally operate following random trajectories, and substantial overlapping is needed to completely cover the assigned working area. This results in a low overall efficiency [23] regarding both the time needed to complete a mowing cycle and the relative energy consumption. Furthermore, unnecessary repeated passes may affect turf quality, especially in tall grass which, being less dense and less resilient, is more prone to lodging. To improve the efficiency of autonomous mowers, navigation systems based on "random assisted" patterns [24] or systematic trajectories have been recently introduced [25]. These GNSS navigation solutions not only allow increased efficiency but also decrease the overlapping and the associated traffic, thus reducing the potential for plant lodging. Recent navigation systems and reduced mowing frequency may therefore represent key factors for increasing the adoption of autonomous mowing in turfs maintained at a tall cutting height.

In this trial, a systematic autonomous mower and a random autonomous mower were tested on a mature tall fescue lawn maintained at 90 mm cutting height, with the aim of determining the effects of reduced mowing frequency and systematic navigation systems on turf quality and mower performances in terms of working time, energy consumption and overlapping.

2. Materials and Methods

2.1. Experimental Layout

Two trials were carried out from July to December 2020. Trial 1 was conducted from 13 July to 6 September 2020 in a private area in Arena Metato (San Giuliano Terme, Pisa, Italy, 43°46′ N 10°22′ E, 3 m above sea level). The experimental area consisted of two 20 m × 30 m plots (600 m^2 each). The turf was a mature stand (more than 5 years old) and was representative of a standard home lawn, mainly composed of *Schedonorus arundinaceus* (Schreb.) Dumort. cv. Essential (55%), with the rest being mostly *Poa pratensis* cv. Conni (25%) and *Lolium perenne* cv. Clementine (15%). The remaining 5% of ground cover consisted of weed species such as *Paspalum distichum* L., *Cynodon dactylon* (L.) Pers., *Bellis perennis* L., *Poa trivialis* L. and *Trifolium repens* L. As in most home lawns, weeds were tolerated, and no weed control was performed. Fertilization was applied on 27 July 2020 at a rate of 190 kg ha^{-1} of nitrogen from urea. Irrigation was provided as needed to prevent visible moisture stress, with two applications per week for a total of 30 mm per week from June to September. The soil was sandy (sand 79.8%; silt 13.8%; clay 6.4%). Trial 2 was conducted from 21 September to 15 November 2020 at the experimental farm of the Department of Agriculture, Food and Environment of the University of Pisa (San Piero a Grado, Pisa, Italy; 43°40′ N, 10°19′ E, 6 m above sea level). The experimental area consisted of two 20 m $\times$ 25 m plots (500 m^2 each). The turf was a mature stand (more than 5 years old) of *Schedonorus arundinaceus* (Schreb.) Dumort. cv. Inferno. Weeds (below 1% of ground cover) were manually removed when needed. Fertilization was applied monthly at a rate of 60 kg ha^{-1} of nitrogen from ammonium sulfate, from January to September. The soil was silty loam (sand 28%; silt 55%; clay 17%). During this trial session, irrigation was not required. In both trials, each area had a rectangular shape with no obstacles within the area and was mowed by means of two different autonomous mowers. The autonomous mowers employed in the trials were a Husqvarna Automower 450XH (Husqvarna, Stockholm, Sweden) and a prototype of a Husqvarna EPOS Automower (Husqvarna, Stockholm, Sweden). Both autonomous mowers worked at an average speed of 0.46 m s^{-1} with a cutting-disk revolving speed of 2300 rpm. Both autonomous mowers were set to cut at 90 mm cutting height and had a working width of 240 mm (Table 1). The Husqvarna Automower 450XH adopts a random mowing pattern, and the perimeter of its working area is defined by a shallow-buried boundary wire. An electromagnetic signal determines a change in the direction of the mower when the boundary is encountered. The Husqvarna EPOS Automower prototype operates with a systematic mowing pattern. This operating mode is based on real-time kinematic global navigation satellite systems (RTK-GNSS) and allows the autonomous mower to follow parallel contiguous lines within a working area that is defined by the user through the same navigation system.

Table 1. Autonomous mowers' operational characteristics for the two different trials.

Working Width (mm)	Mowing Height (mm)	Trial	Managed Area (m^2)	Mowing Pattern	Working Time (min)
240	90	1	600 m^2	Systematic trajectories	150
				Random trajectories	390
		2	500 m^2	Systematic trajectories	120
				Random trajectories	300

In order to determine the operational working time of the two autonomous mowers, preliminary trials were carried out at both locations. The autonomous mowers were left working until the areas were judged to be totally mown. Table 1 reports the preliminary determination of the working time needed to manage the different working areas.

The working time determined in the preliminary trials was then adopted to maintain the turf for the whole duration of the trials. A mowing frequency of 3 times per week was adopted for both the random and systematic autonomous mowers, in order to reduce equipment traffic while still maintaining a clipping amount and size compatible with its return to the turf.

2.2. Assessments

The autonomous mowers' working data were measured using a remote sensing system consisting of two Emlid Reach RTK devices installed in different cases (base station and rover) [26]. The case containing the base station was positioned on a fixed spot outside the trial area, while the case containing the rover was installed on the autonomous mower. During the autonomous mowers' work, the RTK algorithm evaluated the distance between the base station and the rover (baseline) and was used to precisely determine the rover's position (with an accuracy of $\pm$7 mm). Open-source RTK processing software (RTKLIB 2.4.3) [27] was used to process the recorded data to obtain a POS file containing the relative positions of the rover and the base station. The POS file was further processed with specific custom-built software ("Robot mower tracking data calculator" 1.6, Qprel srl, Pistoia, Italy) in order to obtain autonomous mower trajectories and other operating parameters [23]. The custom-built software selected the POS file points with a variance lower than 5 mm (thus resulting in an accuracy of $\pm$5 mm). Subsequently, trajectories were obtained using the recorded RTK points and the autonomous mower working width. The custom-built software allowed a specific area on the map to be selected and the percentage of the area mowed to be assessed (ratio between the area defined by the trajectories and the entire selected area). In addition to the percentage of the area mowed, the custom-built software allowed several other operating parameters to be calculated (i.e., distance travelled, mean forward speed, intersections and so on) [23] by processing the recorded RTK points every 5 s. In this study, the distance travelled was selected as an operating parameter in order to calculate working efficiency. Working efficiency was calculated as the ratio of the area mowed (obtained by converting the mowed area percentage to m^2) and the area theoretically mowed (obtained by multiplying the distance travelled by the autonomous mower's working width). Four (4) replications were carried out during the two trials for each autonomous mower (for a total of 16 measurements). The mowed area percentage values were extracted from the software at 10 min intervals [28]. To measure the electric energy consumption of the two autonomous mowers, a power consumption meter was used (EL-EPM02HQ; Nedis, MC, 's-Hertogenbosch, The Netherlands). The primary energy requirement of the two autonomous mowers was calculated, considering the efficiency of the Italian National Electric System, as equal to 0.546 [29].

Turf quality, wheel marks, lodging, clippings and actual turf height were determined every other week, with a total of four (4) measurements for each trial. Turf quality was visually assessed and scored on a scale from 1 to 9 (1 = poor; 6 = acceptable; 9 = best) [30]. Wheel marks were scored on a 1–9 scale (1 = no wheel marks; 6 = acceptable incidence of marks; 9 = marks over the entire area). Lodging evaluation consisted of a visual assessment of permanent leaf and stem inclination and was scored on a scale from 1 to 9 (1 = no lodging; 6 = acceptable lodging; 9 = lodging over the entire area). Clippings were visually assessed as plant residues on top of the turf and were reported on a 1–9 scale (1 = no clippings; 6 = acceptable presence of clippings; 9 = full clipping cover). Actual turf height was measured with a rising disk turf height meter with 400 g m^{-2} specific density. Average daily growth was determined by measuring turf height weekly within undisturbed growth spots where mowing was not performed.

2.3. Statistical Analysis

The autonomous mowers' working data were analyzed using the statistical software R [31] (R Foundation for Statistical Computing, Vienna, Austria). For the autonomous mower with the systematic navigation system, a linear regression was used to model the mowed area percentage as a function of time (Equation (1)):

$$f(x) = ax + b \tag{1}$$

where a is the slope of the line and b is the intercept on the y axis. For the autonomous mower with the random navigation system, the extension package 'drc' (dose–response curve) of R [32] was used to analyze the mowed area percentage as a function of time with a two stage meta-analysis dose–response model. The non-linear function corresponded to a two-parameter asymptotic regression (Equation (2)):

$$f(x) = d\ (1 - \exp\left(-\frac{x}{e}\right) \tag{2}$$

The parameters d (the upper limit of the function as x approaches infinity) and e (the steepness of the increase of the function) [33] were estimated from the model. The autonomous mowers' data and turf data were subjected to analysis of variance (ANOVA). Where necessary, data were subjected to angular transformation in order to respect the normality assumption. The normality and homoscedasticity of residuals were checked using the Shapiro–Wilk test and the Breusch–Pagan test, respectively. The ANOVA was carried out separately for the two trials, considering the mowing patterns of the two autonomous mowers as a factor. In both trials lodging did not occur, and clippings were not detected; thus, data relative to these parameters were not included in the analysis of variance.

3. Results

The left box in Figure 1 shows the average increase over time of the area mowed by the autonomous mower operating with systematic trajectories. The recorded data fitted the linear regression model well (adjusted R^2 = 0.9953). The right box in Figure 1 reports the relative working path at different time intervals during the assessment of 27 July 2020 in trial 1.

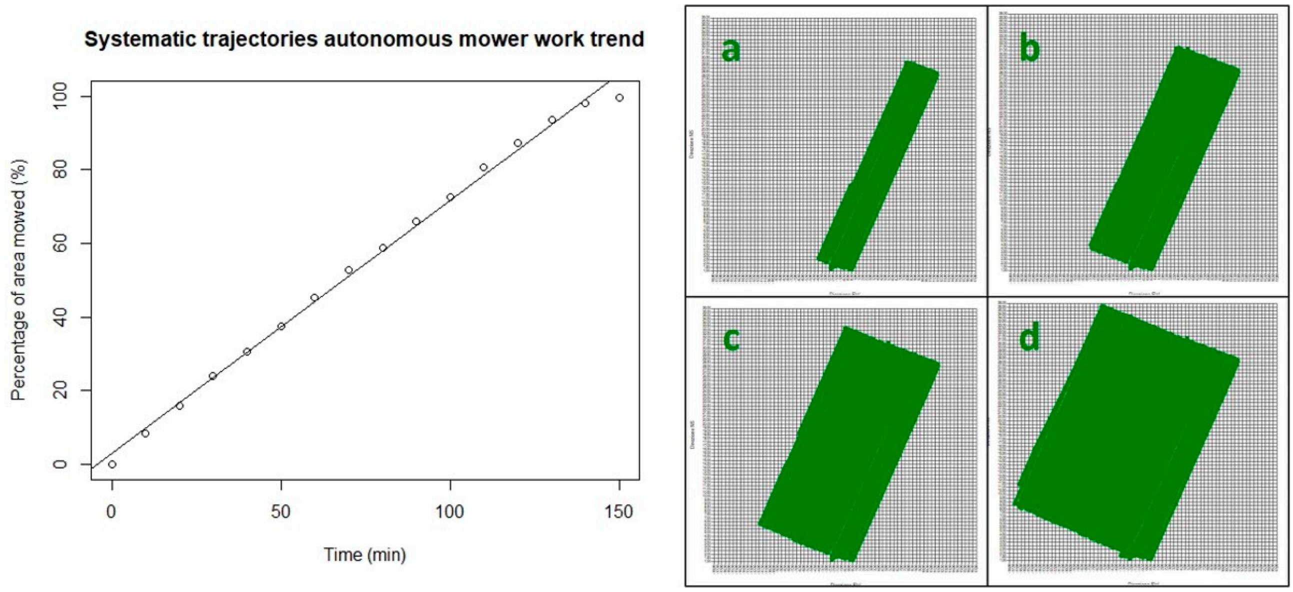

Figure 1. (**Left**) Data trend of mowed area percentage as a function of time (min) for the autonomous mower with systematic trajectories working on 600 m^2: observed values averaged across 4 replications (dots) and regression line (solid line). (**Right**) Custom-built software showing the mowed area on 27 July 2020 at different time intervals: (**a**) 30 min; (**b**) 60 min; (**c**) 90 min; (**d**) 150 min.

The percentage of area mown as a function of time for an autonomous mower working with systematic trajectories on an area of 600 m^2 showed a linear distribution in accordance with Equation (3):

$$f(x) = 0.6875x + 2.945 \tag{3}$$

The left box in Figure 2 shows the average increase over time of the area mowed by the randomly operating autonomous mower. The recorded data fitted the asymptotic regression model well (lack-of-fit test: p = 0.970). The right box in Figure 2 shows the relative working path at different time intervals during the assessment on 2 September 2020 in trial 1.

The percentage of area mown as a function of time for an autonomous mower working with random trajectories on an area of 600 m^2 showed a non-linear asymptotic distribution in accordance with Equation (4):

$$f(x) = 100.93(1 - \exp\left(-\frac{x}{90.73}\right)) \tag{4}$$

The left box in Figure 3 shows the average increase over time of the area mowed by the autonomous mower operating with systematic trajectories. The recorded data fitted the linear regression model well (adjusted R^2 = 0.9962). The right box of Figure 3 shows the relative working path at different time intervals during the assessment of 5 October 2020 in trial 2.

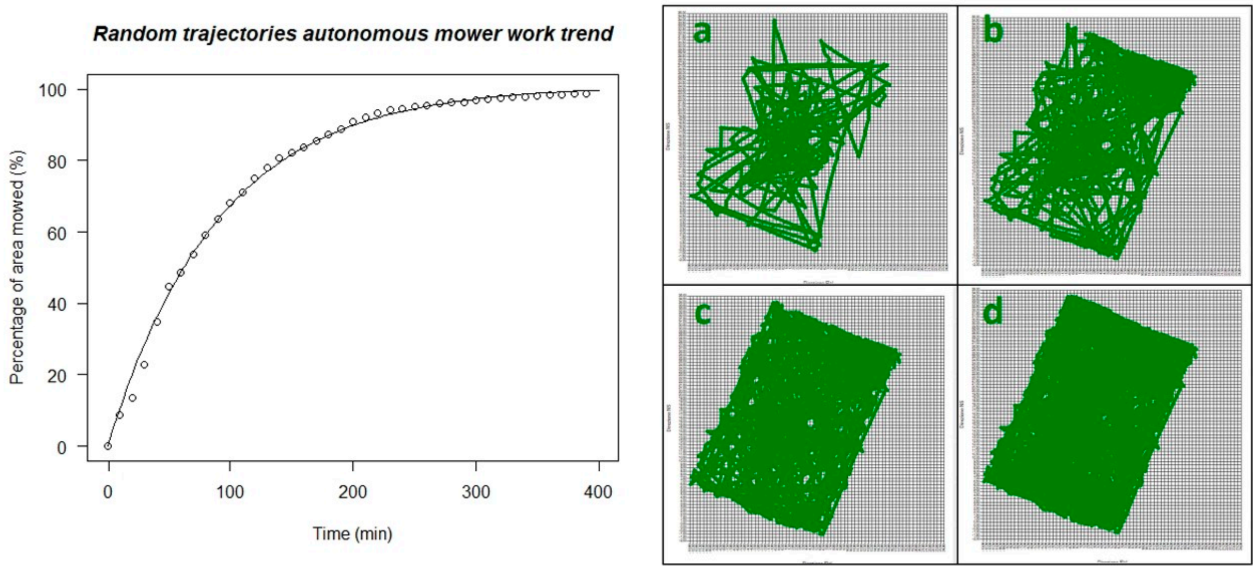

Figure 2. (**Left**) Data trend of mowed area percentage as a function of time (min) for the autonomous mower with random trajectories working on 600 m^2: observed values averaged across 4 replications (dots) and regression curve (solid line). (**Right**) Custom-built software showing the mowed area on 2 September 2020 at different time intervals: (**a**) 60 min; (**b**) 150 min; (**c**) 240 min; (**d**) 390 min.

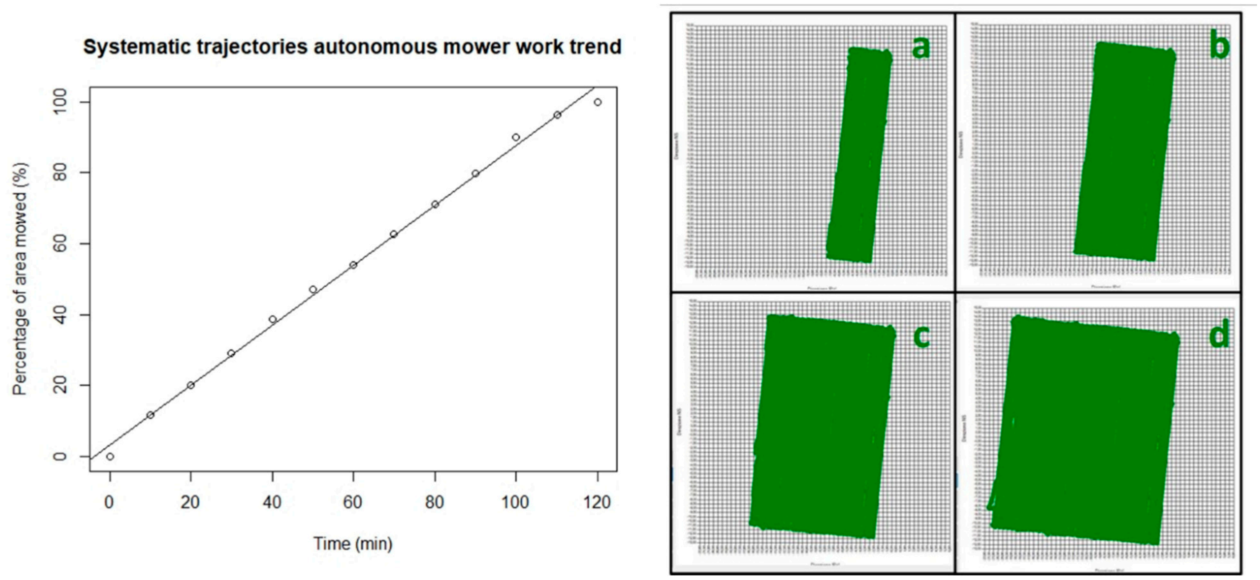

Figure 3. (**Left**) Data trend of mowed area percentage as a function of time (min) for autonomous mower with systematic trajectories working on 500 m^2: observed values averaged across 4 replications (dots) and regression line (solid line). (**Right**) Custom-built software showing the mowed area on 5 October 2020 at different time intervals: (**a**) 30 min; (**b**) 60 min; (**c**) 90 min; (**d**) 120 min.

The percentage of area mown as a function of time for an autonomous mower working with systematic trajectories on an area of 500 m^2 showed a linear distribution in accordance with Equation (5):

$$f(x) = 0.8427x + 3.309 \tag{5}$$

The right box in Figure 4 shows the area mowed by the random operating autonomous mower over time and the relative working path during the assessment of 2 November 2020 in trial 2. The recorded data fitted the asymptotic regression model well (lack-of-fit test: $p = 0.894$).

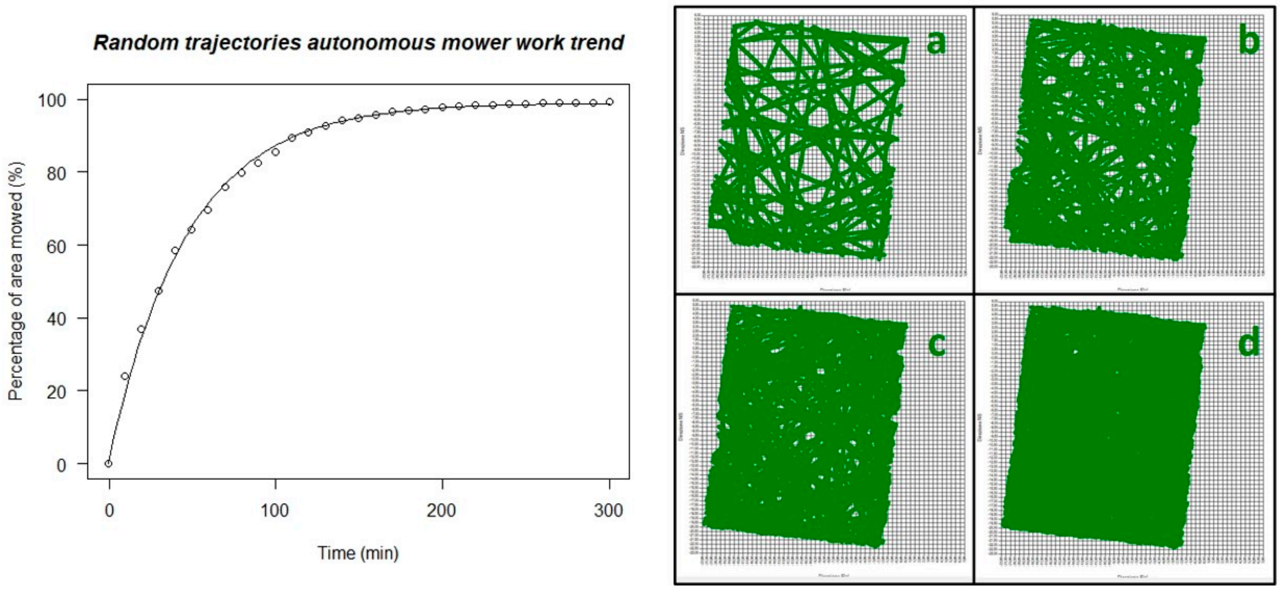

Figure 4. (**Left**) Data trend of mowed area percentage as a function of time (min) for the autonomous mower with random trajectories working on 500 m^2: observed values averaged across 4 replications (dots) and regression curve (solid line). (**Right**) Custom-built software showing the mowed area on 2 November 2020 at different time intervals: (**a**) 60 min; (**b**) 120 min; (**c**) 180 min; (**d**) 300 min.

The percentage of area mown as a function of time for an autonomous mower working with random trajectories on an area of 500 m^2 showed a non-linear asymptotic distribution in accordance with Equation (6):

$$f(x) = 98.93(1 - \exp\left(-\frac{x}{46.90}\right)) \tag{6}$$

Analysis of variance revealed that in both trials, the autonomous mowers' distance travelled, theoretical mowed area and efficiency were significantly affected by the mowing pattern. Wheel marks were significantly affected by the mowing pattern, while turf quality was significantly affected only in trial 1 (Table 2).

Table 2. Results of analysis of variance testing the effect of mowing patterns on the mowed area percentage, actual mowed area, distance travelled, theoretical mowed area, efficiency, turf quality, wheel marks and turf height. The analysis of variance was carried out separately for the two trials.

Source	Trial	Percentage of Area Mowed (%)	Actual Mowed Area (m^2)	Distance Travelled (m)	Theoretical Mowed Area (m^2)	Efficiency	Turf Quality	Wheel Marks	Turf Height (mm)
Mowing pattern	1	ns	ns	***	***	***	*	***	ns
	2	ns	ns	***	***	***	ns	*	ns

*, *** Significant at the 0.05, and 0.001 probability level, respectively; ns, not significant at the 0.05 probability level.

Table 3 shows the results for the autonomous mowers' parameters. Once correctly set, both work systems allowed the autonomous mowers to mow about 99% of the area in both trials (Table 3). When following systematic trajectories, autonomous mowers travelled lower distances (3142.16 m for trial 1 and 2403.95 m for trial 2) compared to when following random trajectories (6960.35 m for trial 1 and 6541.45 m for trial 2). Consequently, the autonomous mowers with systematic trajectories showed higher working efficiency (0.79 for trial 1 and 0.86 for trial 2) compared to autonomous mowers operating with random trajectories (0.35 for trial 1 and 0.32 for trial 2).

Table 3. Results for autonomous mowers' parameters. Data were pooled over the 4 replications.

Trial	Mowing Pattern	Percentage of Area Mowed (%)	Actual Mowed Area (m^2)	Distance Travelled (m)	Theoretical Mowed area (m^2)	Work Efficiency
1	Systematic Trajectories [1]	99.61	597.66	3142.16	754.12	0.79
	Random trajectories [2]	98.68	592.06	6960.35	1670.48	0.35
2	Systematic Trajectories [3]	99.79	498.95	2406.95	577.67	0.86
	Random trajectories [4]	99.26	496.30	6541.45	1569.95	0.32

[1] Parameters after 150 min of work. [2] Parameters after 390 min of work. [3] Parameters after 120 min of work. [4] Parameters after 300 min of work.

Table 4 shows the results for the turf data obtained during the two trials. Values were averaged over the four repetitions for each trial. In trial 1, turf quality was higher when the autonomous mowers followed systematic trajectories compared to random trajectories (6.9 and 6.1 respectively). In trial 2, however, no differences in turf quality were found between the two mowing patterns, with an average score of 8.1. Turf height did not show significant differences between mowing patterns, at 108 mm for systematic trajectories and 105 mm for random trajectories in trial 1. In trial 2, turf height was 94 mm for systematic trajectories and 90 mm for random trajectories.

Table 4. Results for turf parameters evaluated during the two trials. Data were pooled over the 4 replications.

Trial	Mowing Pattern	Quality	Wheel Marks	Actual Turf Height (mm)
1	Systematic Trajectories	6.9	6.8	108
	Random trajectories	6.1	1.3	105
2	Systematic Trajectories	8.1	6.4	94
	Random trajectories	8.1	3.9	90

Wheel-mark values were higher when the autonomous mowers followed systematic trajectories (6.8 for trial 1 and 6.4 for trial 2) compared to the autonomous mowers operating with random trajectories (1.3 for trial 1 and 3.9 for trial 2). However, permanent lodging did not occur in any of the trials (Table 4). In Figure 5, the visual effects of the two different operating patterns are shown.

Figure 5. Visual effect of different autonomous mower operating patterns on tall fescue turf trial 2 on 10 October 2020. (**Left**) systematic trajectories operating pattern. (**Right**) random trajectories operating pattern.

Table 5 shows the operating characteristics and the primary energy consumption estimation for the two autonomous mowers studied in these trials working with random or systematic trajectories. The values shown in Table 5 represent the average values of the two trials. The primary energy estimation showed a difference of about 500 kWh per year between the two operational modes.

Table 5. Operating characteristics and energy consumption estimation according to different autonomous mowers' mowing patterns in the two trials.

Parameter	Unit	Systematic Trajectories	Random Trajectories
Hourly electric energy consumption *	kWh h^{-1}	0.12	0.08
Estimated work capacity	h ha^{-1}	40	83
Electric energy consumption per hectare	kWh ha^{-1}	4.75	6.63
Electric energy consumption per year	kWh $year^{-1}$ ha^{-1}	684.00	954.72
Primary energy consumption	kWh $year^{-1}$	1252.75	1748.57

* Electric consumption data of the two trials were pooled and averaged over the two trials.

4. Discussion

4.1. Autonomous Mowers' Operating Patterns

The aim of this study was to evaluate the effects of two different autonomous mowers (working with systematic and random trajectories) on a tall fescue turf managed at 90 mm cutting height. Both autonomous mowers were set to work for long enough to mow 99% of the trial area. As expected, in both trials, autonomous mowers working with random trajectories required a significantly longer time to mow the entire area, compared to the autonomous mowers working with systematic trajectories (2.6 and 2.5 times higher in trial 1 and trial 2, respectively). The autonomous mowers' operating patterns (random vs. systematic) significantly affected the distance travelled and consequently the mowers efficiency (Table 2). In both trials, the randomly operating autonomous mowers travelled more than 6500 m (6960.35 and 6541.45 m in trial 1 and trial 2, respectively). Generally, the random operating pattern of the autonomous mowers led to more work overall to mow a given area, due to frequent overlapping. Furthermore, the higher distance travelled, together with the higher time, significantly decreased the working efficiency. Martelloni et al. [23] found that the efficiency of randomly operating autonomous mowers was close to 30% after 120 min of working on a surface with a rectangular shape with no obstacles. The results obtained in both trials showed similar work efficiency values (35% after 390 min of working in trial 1 and 32% after 300 min of working in trial 2). Conversely, systematic operating patterns for autonomous mowers ensured approximately 80% work efficiency in both trials (79% after 150 min of working in trial 1 and 86% after 120 min of working in trial 2). Wang et al. [34] support these results and report several advantages of coverage path planning. Bosse et al. [35] obtained a higher mowed area percentage using an autonomous mower with a 2 m working width operating with a spiral inward or a spiral shift path planning algorithm. With these settings, it was possible to mow 95% of a 321 m^2 turf area in 15 min. These findings suggest that further improvements of autonomous mowers' working efficiency may be achieved with a larger working width. Furthermore, lower primary energy consumption occurred in both trials when the autonomous mowers were operating with systematic trajectories, even though they showed a higher hourly energy consumption. This higher energy consumption may be attributable to the greater technological complexity of the systematically operating autonomous mowers. However, the lower amount of time needed to perform complete management of the studied area provided for a significant primary energy saving. Primary energy consumption may be further decreased using electric energy generated by solar panels installed on the mowers [36]. These results confirm the findings of [37], suggesting that a more precise application of these machines leads to considerable economic savings. Furthermore, automated machines may provide for multitasking performance. Kang et al. [38] showed that multifunctional lawnmowers may be more efficient than conventional lawnmowers in terms of costs, multifunctionality and requirement for non-renewable resources.

The results obtained for the random operating patterns are supported by findings obtained by [39,40]. Random operating patterns in these trials were compared with conventional gasoline-powered machines and showed a lower energy consumption. Hubbard et al. [41] evaluated the performance of a randomly operating autonomous mower in managing airport green spaces, confirming that these machines have a great potential for enhancing sustainability. However, the higher energy consumption required by randomly operating autonomous mowers compared with systematically operating autonomous mowers is mainly due to the higher operating time resulting from the substantial overlapping in random trajectories. Bechar and Vinegult [42] suggested using small autonomous machines as they not only have a lower energy consumption, but also exert lower ground pressure. This aspect is crucial for tall fescue turfgrass management [43].

4.2. Turfgrass Parameters

In general, in both trials, turf quality was acceptable regardless of the autonomous mowers' mowing pattern (Table 4). In trial 1, turf quality obtained a slightly higher score with systematic trajectories compared to random trajectories (6.9 and 6.1, respectively). This result can be attributed to the lower uniformity of the turf yielded by the randomly operating autonomous mower. Random unmown spots contributed to an uneven turf surface. In trial 2, turf quality did not show any difference between the two types of autonomous mowers' operating patterns, with an average score of 8.1.

Differences in turf quality scores between the two trials can be attributed to the different maintenance regimens adopted at the two locations (experimental plots and residential lawn, respectively) and to the different soils and climatic conditions [44]. Temperatures and amounts of precipitation are reported in the Appendix A. In both trials, wheel marks were not persistent in the turf plots managed with the random patterns, while they persisted for several days in the plots mown with the systematic patterns. The persistence of wheel marks associated with the systematic trajectories is probably due to the repeated trampling of the wheels within narrow bands. Despite being visible and receiving scores that may appear to be over the acceptable threshold, the wheel marks revealed an accurate mowing pattern and the effect on turf appearance may be considered positive (Figure 5). Lodging was not observed for any mower in either trial (data not shown). Even in case of wheel marks due to repeated trampling produced by the systematic trajectories, plants were not permanently lodged, with leaves and shoots recovering their upright position over time. Sun and Liddle [45] demonstrated how turf age is positively correlated with leaf tensile strength. Furthermore, as age increases, leaves accumulate higher amounts of cell wall components such as cellulose and lignin [46,47]. In both trials the turf consisted of a mature tall fescue lawn and the age may be the main cause of the absence of lodging in these trials. Clippings were not observed for either mower in either trial (data not shown). Turf canopy architecture characterized by long leaves and stems and a low density may have enhanced clipping incorporation, preventing its permanent retention on the surface of the turf.

Among turfgrasses, tall fescue is considered a highly traffic-tolerant species due to its wear resistance [6]. However, it is relevant to mention that both trials were carried out on extremely simplified areas. Most gardens and parks are characterized by a more complex arrangement of features, which generally leads to high overlapping. In these conditions, the random behavior of the autonomous mower may lead to higher lodging of the turf, especially in boundary zones and narrow spaces. The actual cutting height was consistently more than 10 mm over the set value (90 mm) in trial 1. These results may be explained by the very dense and actively growing turf. Indeed, the average daily growth during the observation period of trial 1 was 5 mm per day (data not shown), and this represents a substantially high value. In trial 2, the actual cutting height remained close to the set height of 90 mm for both the operating patterns. The average daily growth was around 1 mm per day (0.7 mm) in trial 2, and this low growth rate can be reasonably expected during the fall

(Figure A1 in Appendix A). In general, autonomous mowers have proven to be a reliable solution for maintaining a constant turf height [48], and these trials confirm these results.

5. Conclusions

In these trials, a systematic autonomous mower and a random autonomous mower were tested on a mature tall fescue lawn maintained at 90 mm cutting height, with the aim of assessing the implications of the two working patterns on turf quality and the mowers' operating performance. The results obtained from these trials highlighted the fact that autonomous mowers can successfully manage a tall fescue lawn at a tall cutting height whether operating with random or systematic patterns, provided that mowing frequency is conveniently adapted to reduce traffic. A mowing frequency of three times per week gave an acceptable balance between clipping size and trampling in tall grass. In general, systematic patterns provided for higher working efficiency and lower working time, and may be preferred for tall, managed turfgrasses. Furthermore, the autonomous mowers operating with systematic trajectories created an accurate mowing pattern with an aesthetically pleasing, orderly motif. For this reason, systematically operating autonomous mowers may be considered more promising for managing parks and ornamental turfgrass areas. However, future trials aimed at assessing turf lodging and overlapping in more complex scenarios are needed.

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Appendix A

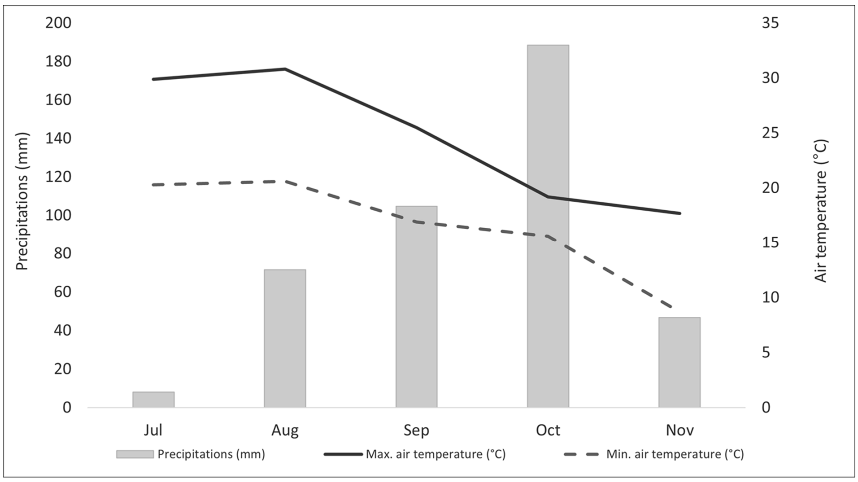

Figure A1. Diagram of precipitation and air temperature between July and November 2020.

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