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Article

Trampling Analysis of Autonomous Mowers: Implications on Garden Designs

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Abstract: Several trials have been carried out by various authors concerning autonomous mowers, which are battery-powered machines. The effects of these machines on turfgrass quality and energy consumption have been thoroughly investigated. However, there are still some aspects that have not been studied. Among these, random trajectory overlapping is one of the most important. To investigate these aspects, two RTK-GPS devices along with the custom-built software used for previous trials has been upgraded in order to precisely calculate how many times the mower drives over the same spot using random trajectories. This parameter, the number of passages in the same position, was hypothesized to explain the autonomous mower's overlapping and trampling action. The trial has been carried out testing a commercial autonomous mower on three areas with different levels of complexity to assess its performances. The following variables were examined: the percentage of mowed area, the distance travelled, the number of intersections, the number of passages, and the autonomous mower's work efficiency. The average percentage of area mown (average value for the three areas) was 54.64% after one hour and 80.15% after two hours of work. Percentage of area mown was 15% higher for the area with no obstacles after two hours of work. The number of passages was slightly different among the three garden designs. The garden with no obstacles obtained the highest number of passages with an average of 37 passages. The highest working efficiency was obtained in the garden with an intermediate number of obstacles with a value of 0.40 after two hours of work. The estimated energy consumption resulted 0.31 Wh m^{-2} after one hour and 0.42 Wh m^{-2} after two hours of working. These results highlight how the correct settings of cutting time may be crucial to consistently save energy during the long period and may be useful for a complete automation of the maintenance of green areas.

Keywords: turfgrass; RTK; GNSS; precision agriculture; cutting system; path planning; maps; autonomous mower

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1. Introduction

Precision turfgrass management (PTM) is an extension of precise agriculture and has only recently been taken into account as a way to precisely manage pests, fertilization, salinity, cultivation, and irrigation [1,2]. Managers of complex turfgrass sites currently follow precise management procedures for different areas (i.e., golf course greens, tees, fairways, and roughs), which require specific operations. PTM progress is based on acquiring detailed site information and is moving towards a greater precision and efficiency of input management [3]. Specific field applications are targeted for irrigation, fertilizer dispensation, cultivation, and salinity management procedures [4]. Technological innovations have given a significant contribution in agriculture and management of green areas. The adoption of specific techniques or machines provides for working time and cost reduction [5]. Urban environment improvements are provided by greenspaces through different ecosystems services (i.e., reduction of radiation intensity and heat island effects, carbon sequestration, and so on) [6–8]. Among the variety of operations involved in greenspaces maintenance, turfgrass mowing is the most expensive, energy-consuming, and time-consuming [9,10]. Despite mowing the fact that is mandatory in order to fully exploit turfgrass functionality [11], low-maintenance lawns are required more and more [12]. For instance, autonomous mowers represent a technological innovation that may fill this gap. In Italy, autonomous lawn mowers are appreciated for their time and physical effort saving by allowing people to avoid tedious lawn care. The employment of such machines has shown to improve management sustainability by means of no local pollution, very low noise emissions, and by keeping humans away from allergens [13,14]. Assigning turf maintenance to an autonomous mower may prevent people from developing health issues (i.e., hand-arm vibration syndrome [15]). Moreover, Pirchio et al. [16] highlighted how autonomous mowers gave superior results in terms of energy efficiency compared to gasoline-powered machinery. Autonomous mowers are fully automated, because they can be programmed beforehand to operate every day to obtain optimal turf maintenance and a high percentage of mown area [17,18]. Recently, Global Navigation Satellite System (GNSS) technology has been used to study the performances of autonomous mowers and to try to improve their efficiency. Real-Time Kinematic (RTK) Global Position System (GPS) has shown to provide an accuracy of one centimeter [19,20]. These levels of accuracy provided for localization and mapping derive from multiple sensors data fusion [21]. Thanks to this high positioning accuracy, autonomous vehicles are becoming more and more reliable [22]. Sun et al. [23] used RTK systems to track vehicle movement trajectories and to process many other spatial information, highlighting the potential of this system for these types of operations. RTK-GNSS systems could be applied in many contexts such as residential and urban areas to optimize turfgrass mowing through an improved navigation system. Indeed, Sportelli et al. [24] compared the performances of two autonomous mowers operating with random trajectories and systematic trajectories based on RTK navigation systems. The comparison resulted in a significantly higher performance of the autonomous mower working with systematic trajectories in terms of working efficiency, energy efficiency, and time saving. Remote sensing technologies may be applied to perform a thorough analysis of machines' operative characteristics so as to optimize urban greenspaces management [25]. In this regard, Martelloni et al. [26] studied the random trajectories of an autonomous mower to improve the cutting efficiency in different regular shapes of turfgrass areas, highlighting that a regular design of the working area may help to improve the smooth functioning of robot mowers. Sportelli et al. [27] studied the performances of six autonomous mowers of different sizes in areas with higher or lesser obstacle density. The study highlighted how a larger size of the autonomous mowers and a higher number of obstacles negatively affected the performances of the autonomous mowers in terms of working efficiency. Despite the fact that random trajectories may be a valid solution for areas with a reduced number of obstacles and a regular shape, the frequent overlapping may cause some issues and lead to undesirable drawbacks on turfgrass. Trampling damage, deriving from both direct and indirect mechanical stress, and consequent soil structure damage caused by compaction, are very challenging aspects of turfgrass maintenance [28]. As a result, conducting studies on autonomous mowers' trajectories appears to be highly beneficial in order to optimize turf quality and minimize plant stress. Performing trajectory analysis in terms of compaction resistance may help to define long-term maintenance planning and to assess the specific carrying capacity of the studied turf. The custom-built software allowed to calculate the percentage of area mown, the average forward speed, the average working time, the total distance travelled, and the trajectory intersections. Different trials have been carried out to study the parameters related to the trajectory intersections to evaluate autonomous mowers' overlapping and trampling; however, such parameters are often overestimated and difficult to study among different areas. Thus, an additional function has been provided in this new version of the software to calculate the precise number of passages performed by the autonomous mower in the same spot. The aim of this trial was to test the new version of the custom-built software mentioned in [26] in three different garden designs to have even more precise information concerning autonomous mower operational data. In particular, an analysis of the percentage of area mowed, number of intersections, distance travelled, work efficiency, and number of passages of the autonomous mower was carried out to test the new version of the software. Moreover, the parameters considered allowed to give suggestions for green area design improvements in case of long-term automated maintenance.

2. Materials and Methods

The trial was carried out from April 2021 to May 2021 at the Centre for Research on Turfgrass for Environment and Sports (CeRTES) 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 a. s. l.). The trial was performed on a mature cool-season turfgrass stand of tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort.). The area chosen for the trial was an open area with no buildings or trees close to it, so as not to compromise the data collection. The turfgrass was established on a plot of calcaric fluvisol, which had a coarse silty texture (mixed, thermic, typic xerofluvents with a pH of 7.8 and 2.2% of organic matter). During the trial period, irrigation and fertilization were applied as necessary and no weed or pest control was performed.

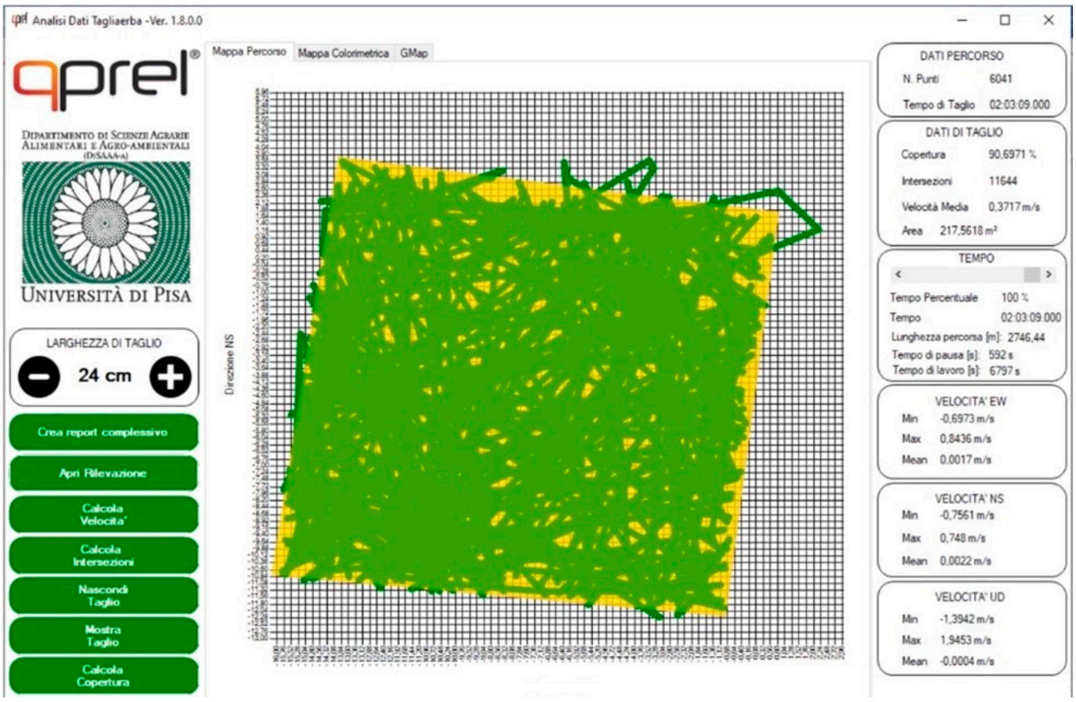
2.1. Remote Sensing System and Software

The remote sensing system consisted of two Emlid Reach RTK (Emlid Tech Kft., Budapest, Hungary) devices mounted inside two custom-made cases (the base station and the rover; Figure 1). The main components of this system are extensively described in [26]. The rover was installed on the studied autonomous mower, while the base station was positioned at the edge of the studied area and in the same point during the whole trial. The algorithm used by the RTK precisely calculated the distance between the base station and the rover, called "baseline", with an accuracy of ±7 mm on a horizontal surface.

(**a**) (**b**)

Figure 1. Details of the remote sensing system consisting of the two RTK-GPS devices: (**a**) the base station on the side of the studied area; (**b**) the rover installed on the autonomous mower.

Two software packages were used to help extract and display the data. One of the two software packages used for collecting the data was RTKLIB (version 2.4.3), an open-source RTK processing software written by Takasu, (Tokyo, Japan). This software allowed to extract and process the data collected by both devices. The RTKLIB off-line processing generated a .pos file that showed the trajectories carried out by the autonomous mower during the entire work session. The other software package used for data collection was a custom-built software "Robot mower tracking data calculator" (Qprel srl, Pistoia, Italy). This software was used to extract operational data form the spatial data measured during the autonomous mower's work. A brief description of the previous version of the custom-built software is provided hereafter, while a more detailed one can be found in [26]. The custom-built software displayed a two-dimensional map showing the recorded points with an accuracy of 0.05 m and allowed to select a specific area on the map (e.g., the studied area) and the cutting width of the different autonomous mowers. With those settings, the software processed the data in order to retrieve several operational parameters such as: percentage of area mown, number of intersections, distance travelled, total working time, total break time, minimum, maximum, and average forward speed values. In this study, the custom-built software was updated to version 1.8.0.0 and provided some innovation. The first innovation allowed operators to change the cutting width (by steps of 1 cm), which significantly affected the different models of the autonomous mower's paths. Another useful function was the possibility to further process the trajectories' intersections in order to compute the number of times the autonomous mower passed on the same position within the selected area. This last parameter was used to assess the autonomous mower trampling effect on the studied area. Figure 2 shows two of the main functions of the updated version of the software. Figure 2a represents an example of a computation of percentage of area mown. The autonomous mowers trajectories (green lines) are visualized inside the map as the results of recorded coordinates and cutting width of the autonomous mower. The yellow area is directly selected from the map and represents the area of interest. Figure 2b, instead, shows an example of the autonomous mower trampling on the selected area. The software processes the trajectories' intersections to obtain the number of passages in the same position. Those processed data are depicted on a color-scaled map to improve the visual rendering, while a histogram below shows the number of pixels correlated with the number of passages (Figure 2b).



LARGHEZZA DI TAGLIO
24 cm

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Tempo di Taglio 02:03:09.000

DATI DI TAGLIO
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Velocità Media 0,3717 m/s
Area 217,5618 m²

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Lunghezza percorsa [m]: 2746,44
Tempo di pausa [s]: 592 s
Tempo di lavoro [s]: 6797 s

VELOCITA' EW
Min -0,6973 m/s
Max 0,8436 m/s
Mean 0,0017 m/s

VELOCITA' NS
Min -0,7561 m/s
Max 0,748 m/s
Mean 0,0022 m/s

VELOCITA' UD
Min -1,3942 m/s
Max 1,9453 m/s
Mean -0,0004 m/s

(**a**)

Figure 2. *Cont.*

LARGHEZZA DI TAGLIO
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(**b**)

Figure 2. Software functionality: (**a**) calculation of the percentage of area mown on a square obstacle-free area; (**b**) trampling calculation and visualization on a square obstacle-free area.

2.2. Experimental Field Trials

The experimental plot consisted of a 210 m^2 (15 × 14 m) area and was managed with a Husqvarna Automower® 450X (Husqvarna, Stockholm, Sweden), which moved following straight lines and turned once it intercepted the boundary wire or hit an obstacle (random trajectories). The autonomous mower worked at an average speed of 0.46 m s^{-1} and with a cutting-disk revolving speed of 2300 rpm. The height of cut was set at 3.5 cm, and working width was 24 cm. The area was delimited by a boundary wire that generated an electromagnetic field perceived by the autonomous mower as the edge of the garden. In this trial, in addition to the boundary wire, a guide wire was also used. The guide wire is designed to help the mower to easily find the charging station. The boundary and guide wires were positioned and fixed to the surface with stakes supplied by the manufacturer. The base station remained in the same position during each survey. Obstacles were placed to ensure enough space in each area for the robot to follow the guide wire. In order to avoid interfering with the autonomous mower's movements, it was necessary to leave a clear space of about 1.5 m from the boundary wire. Various garden features (obstacles for the mower) were simulated using wooden poles instead of using the boundary wire to prevent the mower from getting inside such areas. In order to achieve three levels of complexity, some obstacles that simulated common design features were added in the studied area. The obstacles aimed to hinder the autonomous mower so as to better study its performances. The level of complexity changed according to the number and shape of the obstacles. The dimensions of the obstacles were chosen based on product data sheets [29].

The three different garden designs are described hereafter:

- Garden A (Figure 3a) consisted of a 210 m^2 area with no obstacles.
- Garden B (Figure 3b) consisted of a 210 m^2 area with a low level of complexity. To achieve this slight complexity, three obstacles were simulated using wooden poles. The three obstacles were supposed to be a circular bench (diameter 4 m), a 25 m^2 (5 m × 5 m) barbecue area and a rectangular bench (length 2 m × width 0.50 m). In the upper right corner, a circular bench (diameter 0.45 m, thickness 0.50 m and height

0.60 m) and a *Lagerstroemia indica* (L.) tree are placed in the middle (diameter 0.90 m for the roots) and 2 *Delosperma cooperi* (Hook.f.) L. pots (0.70 m^2 and height 0. 60 m).

- Garden C (Figure 3c) consisted of a 210 m^2 area containing all the features of Garden 2 and, in addition, 3 shrubs of *Forsythia* spp. (Vahl) spaced at 1.20 m from each other, a swing of 3 m × 2 m placed close to a slide (length 3.10 m and width 0.40 m) and a lake of approximately 2.30 m^2 of total width.

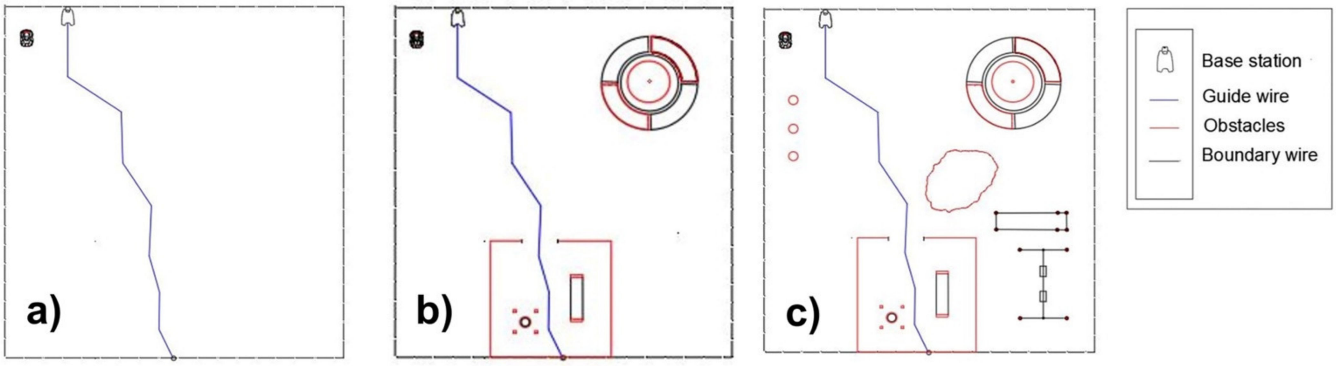


Figure 3. Garden designs scheme studied: (**a**) Garden A, without obstacles; (**b**) Garden B with a circular bench with a *Lagerstroemia indica* L. tree in centre and 2 pots with *Delosperma cooperi* flowers, a barbecue area with a bench, a barbecue, and a shed; (**c**) Garden C with a circular bench with a *Lagerstroemia indica* tree in the centre and 2 pots with *Delosperma cooperi* flowers, a barbecue area with a bench, a barbecue and a shed, 3 plants of *Forsythia* spp., a swing and a slide, 0.40 m wide parts not accessible by the robot, and a small lake.

2.3. Assessements and Statistical Analysis

Each measurement carried out using the remote sensing system lasted two hours. Three runs were carried out for each of the three gardens (for a total of nine runs). Each run was considered a replication for the statistical analysis. Since this research only focused on the operative performance of the autonomous mower and the new functionality of the software, different physical plots were not needed. Before the measurements were performed, the autonomous mower was fully recharged so to obtain an uninterrupted data collection without overestimating the operational data. All the measurements started from the charging station. In this study, the percentage of area mown, the number of passages, the number of intersections, the distance travelled, and the working efficiency were evaluated in function of time. Time was used as a factor with 8 levels (15 min for each time interval). The distance travelled was selected as an operating parameter in order to calculate the working efficiency as indicated by Equation (1):

$$\text{Work Efficiency} = \text{Actual Cut Surface}/\text{Theoretical Cut Surface} \tag{1}$$

where the Actual Cut Surface was obtained by converting the percentage of area mown calculated by the software to its value in m^2. The Theoretical Cut Surface was obtained by multiplying the distance travelled by the autonomous mower with its working width. The percentage of area mown, the number of passages, the number of intersections, and the values of the working efficiency were extracted from the software at intervals of 15 min [30]. The autonomous mowers data were subjected to analysis of variance (ANOVA) using the statistical software R (R Core team, Vienna, Austria). When necessary, data were transformed in order to respect the normality assumption. The values of the percentage of area mown were subjected to angular transformation, while the number of passages, the number of intersections, and the distance travelled were square root transformed. The Shapiro–Wilk test and the Levene's test (package "car") [31] were carried out in order to assess data normality and residual homoscedasticity, respectively. A factorial two-way ANOVA with Garden and Time as independent variables was performed to test the significance ($p < 0.05$) of different garden typologies on the percentage of area mown, on the number of passages, on the number of intersections and on the working efficiency at intervals of 15 min. The ANOVA analysis was followed by post hoc LSD test at the 0.05 probability level provided by the package ("agricolae") [32]. Moreover, an association analysis was carried out in order to evaluate significant positive correlations among the parameters.

3. Results and Discussion

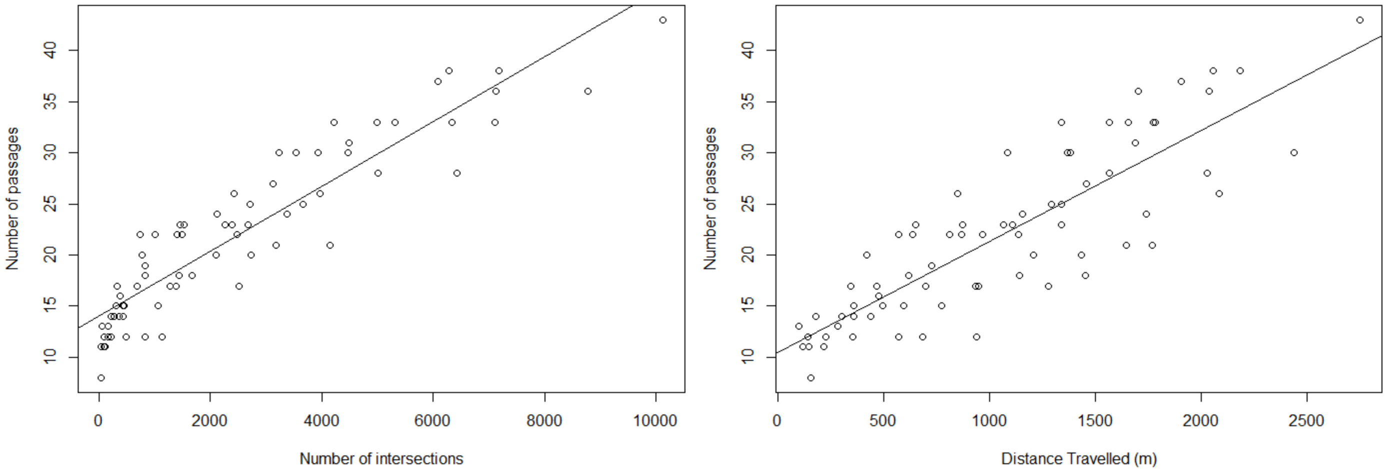
The analysis of variance revealed that the interaction between garden typology and time intervals had a significant effect on the number of intersections, the distance travelled, the number of passages, and the working efficiency (Table 1). The interaction was not statistically significant on the percentage of area mowed.

Table 1. Results of ANOVA testing the effects of garden typology (Garden), time intervals (Time), and their interaction on the percentage of area mowed (Area mowed), the number of intersections (Intersections), the distance travelled (Distance), the number of passages (Passages), and the working efficiency (Efficiency).

Source	Area Mowed (%)	Number of Intersections	Distance Travelled (m)	Number of Passages	Work Efficiency
Garden	***	***	***	***	***
Time	***	***	***	**	NS
Garden × Time	NS	***	**	***	***

***, **, significant at 0.001 and 0.01 probability level, respectively. NS, not significant at 0.05 probability level.

The association analysis revealed that the number of passages was strongly correlated with the number of intersections and the distance travelled producing Pearson's correlation coefficients (r) of 0.921, and 0.856, respectively (Figure 4).



(**a**) (**b**)

Figure 4. Positive correlation plots between number of passages and other studied parameters: (**a**) Correlation plot showing positive correlation between number of passages and number of intersections. (**b**) Correlation plot showing positive correlation between number of passages and distance travelled.

Analysis of variance and mean separation tests for the number of intersections and the distance travelled gave similar results to those obtained from the number of passages. Therefore, data concerning the number of intersections and the distance travelled will not be presented and discussed in detail. Figure 5 depicts the percentages of area mowed in function of garden typology and time intervals. Such results were analyzed separately since the interaction between garden typology and time intervals was not significant.

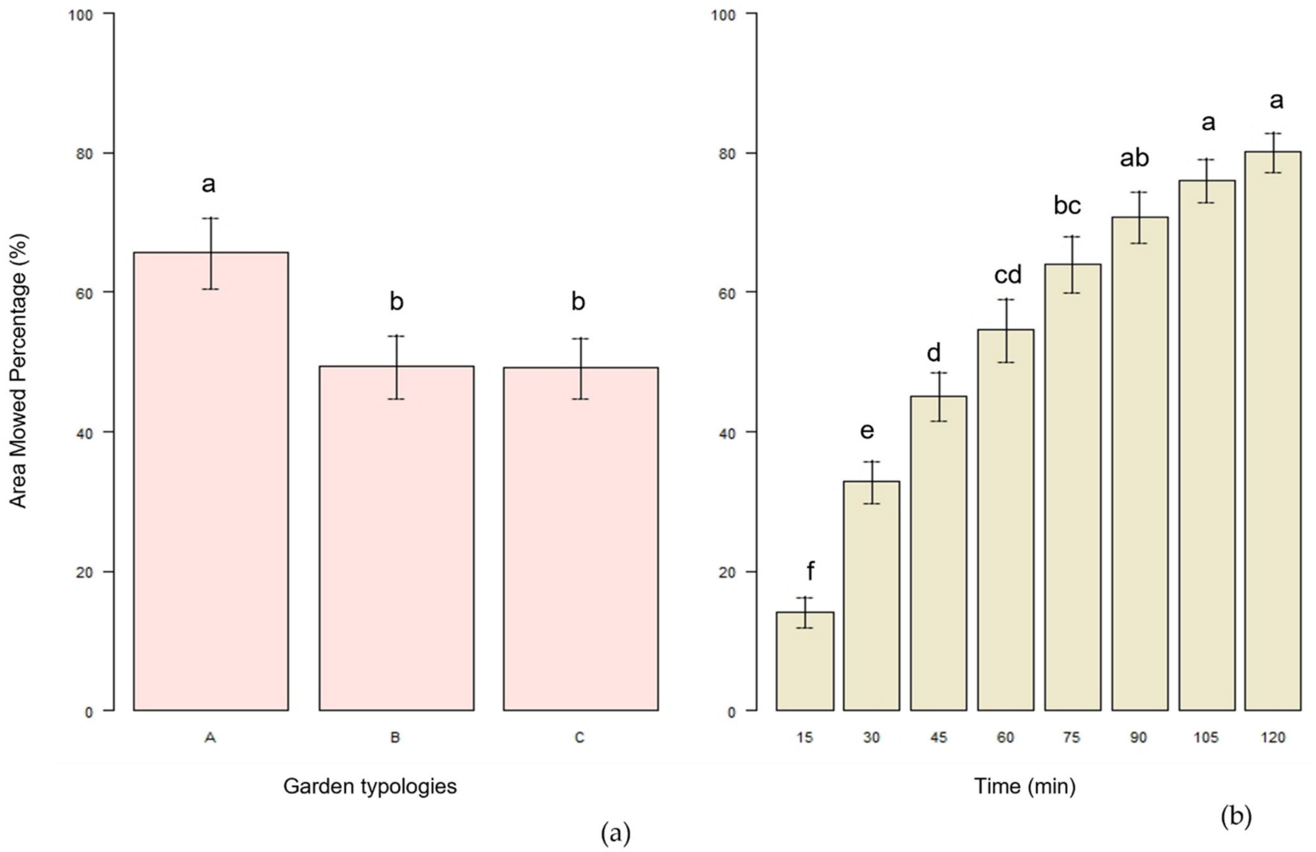


Figure 5. Mean percentage of area mowed for garden typology (**a**) and time intervals. (**b**) Vertical bars represent the standard errors. Different letters on the same plot indicate significant difference at $p < 0.05$ (LSD test).

Mean percentage of area mowed for Garden A was significantly higher compared to the mean percentage of area mowed for the other two gardens with a mean value of 65.67% of the area mowed after two hours of mower activity. No significant differences were observed between the mean percentages of area mowed for the other two garden typologies with an average of 49.34% of the area mowed for garden B and 49.24% for garden C (Figure 5a). Garden A represented an obstacle-free garden, while the other two gardens were arranged with different design features to provide variable garden complexity. Values of the percentage of area mowed after two hours of cutting in obstacle-free gardens with different shapes obtained by [26] were not different, indicating that autonomous mower performances are higher when operating in areas with no obstacles. Such results are in accordance with what has been observed by Sportelli et al. [33]. Authors evaluated the working performances of an autonomous mower working in a vegetable field (with 150 plants established) and compared them with the working performances obtained in a vegetable-free area. The autonomous mower working in the area with the obstacles required an increase of working time of approximately +290% compared to the autonomous mower working in the obstacle-free area. However, in the present trial, the analysis of the percentage of area mowed in function of time intervals revealed that the autonomous mower was able to mow approximately 54.64% of the assigned area after one hour of work and 80.15% of the assigned area after two hours of work (Figure 5b). Figure 6 shows the results concerning the maximum number of passages in function of time intervals and garden typologies (Figure 6).

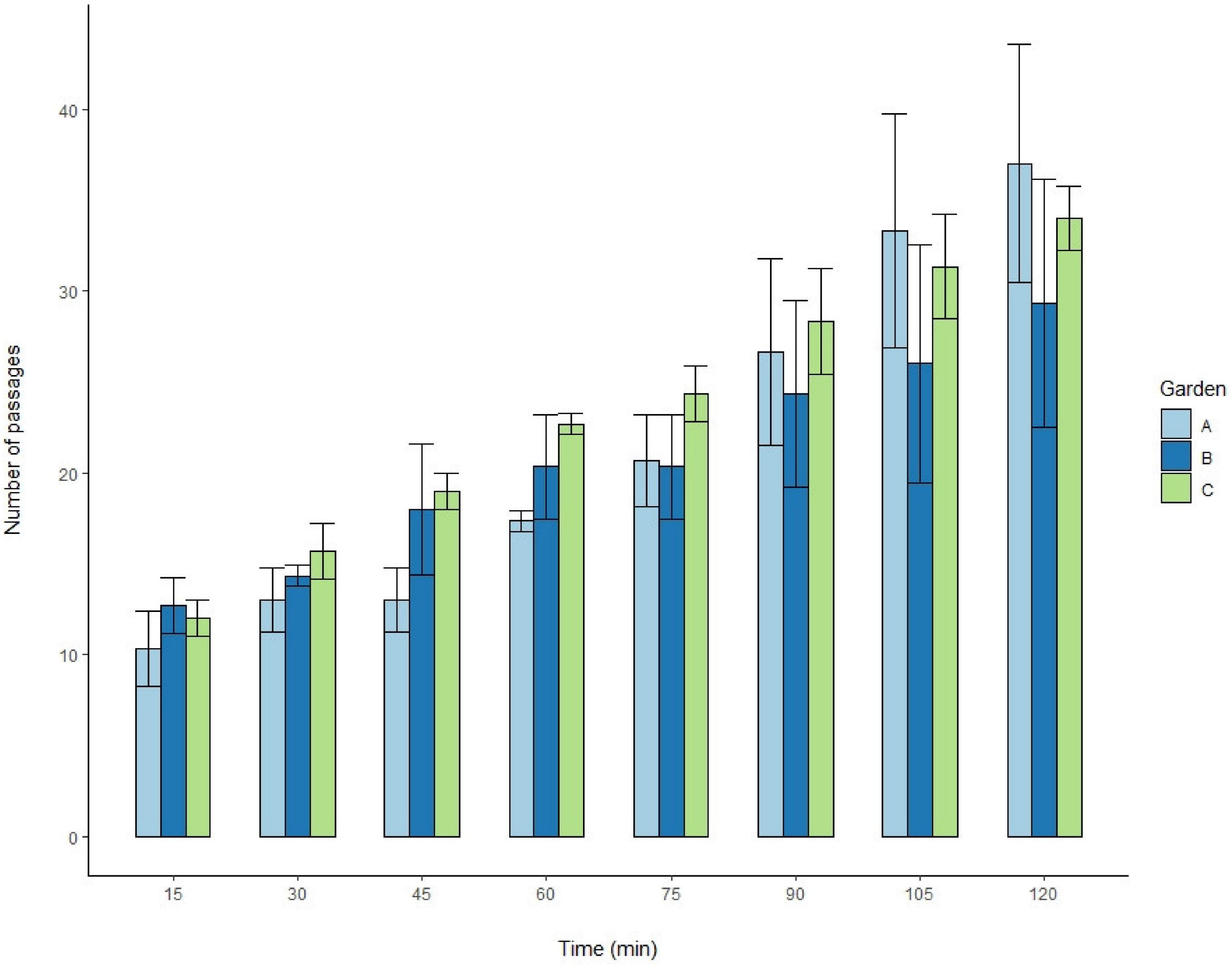


Figure 6. Back-transformed maximum number of passages in function of garden typologies and time intervals. Vertical bars represent the standard errors (A = no obstacles, B = low level of complexity, C = high level of complexity).

After one hour of work, the autonomous mower reached a higher number of passages in Garden C compared to Garden A with an average of 22.67 and 17.33, respectively, while no significant difference was observed compared to the number of passages obtained in Garden B (average value of 20.33). After two hours of work, instead, the higher number of passages resulted from the autonomous mower working in garden A (with an average value of 37). The number of passages measured in Garden B and Garden C after two hours of work did not show significant differences (with an average value of 29.33 and 34, respectively). In general, greater numbers of passages were observed in correspondence with the areas where obstacles were present or with the edges of the gardens (close to the edge, the mower performs more maneuvers since it stops, turns, and departs after changing direction). Figure A1 (in Appendix A) depicts the spatial distributions of the maximum number of passages in the studied areas. Moreover, areas with a high number of passages happen to be not randomly distributed among the different garden types studied. Indeed, a similar trend has been observed in the central areas of garden B and garden C. The reason for this higher number of passages is that, due to its random operating pattern, the mower got stuck in the delimited area and performed a very high number of maneuvers (turning and departing with another direction) before getting out of the area. Moreover, during the mower's first working hour, the mean number of passages observed in Garden A resulted always lower than the number of passages observed in the other two gardens (Figure 6). After the first working hour, the number of passages observed in Garden A started to increase, reaching the highest value after the second working hour. Despite the fact that autonomous mowers are forced to stop and change direction where obstacles are present, overlapping in obstacle-free areas significantly increased over time. The autonomous mower worked more in the areas with no obstacles due to the higher movement capacity, as confirmed by the results of the total distance traveled (data not shown). The distance traveled by the autonomous mower was affected by garden typology. After two hours of work, the distance traveled was significantly lower in Garden B and Garden C compared to Garden A (data not shown). In this regard, as the number of obstacles increases, the area in which the mower can work decreases, leading to shorter paths and an overall lower surface managed. Figure 7 reports the values of working efficiency in function of time intervals and garden typologies.

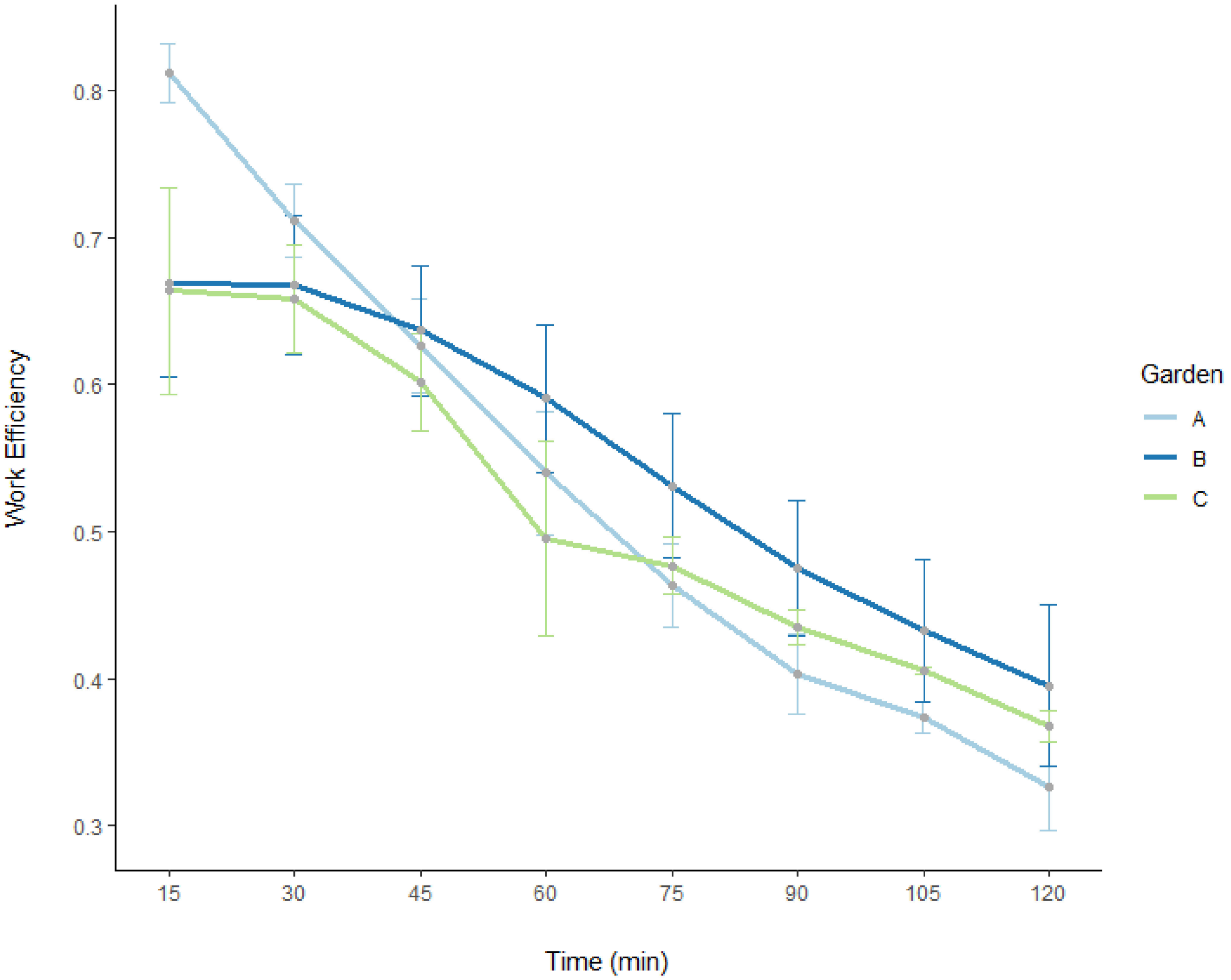


Figure 7. Back-transformed values of working efficiency in function of garden typologies and time intervals. Vertical bars represent the standard errors (A = no obstacles, B = low level of complexity, C = high level of complexity).

The highest working efficiency was observed in Garden A after 15 min of work (0.81). No differences among working efficiency values were observed in the three garden typologies during the first hour of work (values ranging between 0.71 and 0.63). After the first working hour, a significantly higher working efficiency was observed in Garden B compared to Garden C (0.59 and 0.50, respectively). During the second working hour, working efficiency observed in Garden A was always lower compared to the working efficiency observed in Garden B and Garden C (Figure 7). During the second working hour, no significant differences were observed between working efficiency values of the three different garden typologies (values ranging from 0.53 to 0.33). At the end of the second working hour, the autonomous mower's working efficiency was higher for Garden B (0.40) compared to Garden C (0.37) and Garden A (0.33). According to the autonomous mower operator's manual, the studied autonomous mower requires an average power consumption during mowing of 35 W (±20%). The energy consumption per unit area (m^2) was estimated and resulted 0.31 Wh m^{-2} after one hour of working and 0.42 Wh m^{-2} after two hours of working. These values were averaged over the replications and the garden typology. This is in line with the efficiency trends that showed how the overall work performances of autonomous mowers operating with random trajectories decrease during the time. These results highlight how the correct settings of cutting time may be crucial to consistently save energy during the long period, especially for random operating autonomous mowers. Indeed, it is well known that random operating autonomous mowers require more work to manage a given area, due to the frequent overlapping, compared to autonomous mowers' working following systematic trajectories. Working efficiency values observed in Garden A after two hours of work were similar to those obtained by [26], who found that the efficiency of randomly operating autonomous mowers working in an obstacle-free square area was close to 30% after two hours of work. Similarly, Sportelli et al. [24] obtained working efficiency values ranging from 0.32 to 0.35 for a random operating autonomous mower after five hours of work in an obstacle-free rectangular area. In the present trial, Garden B showed the most interesting findings. Indeed, after two hours of continuous work on Garden B, the autonomous mower achieved the highest working efficiency compared to Garden A and Garden C. Garden B represented an intermediate level of complexity between an obstacle-free area and an area with a great number of obstacles. These results highlight that the arrangements of the garden features within an area significantly affected the mower's working efficiency since the autonomous mower operated with the same settings throughout the trial. In this light, Sportelli et al. [25] proposed several design suggestions in order to maximize the efficiency of the autonomous mowers managing green areas and demonstrated how a smart planning can lead to consistent economic savings. In scientific literature, it has been demonstrated that a correct arrangement of garden features may also provide fr environmental benefits. Liu et al. [9] studied the energy consumption and the GHG emission levels deriving from the annual maintenance of an urban greenspace. Such emission levels can be divided into low, average, and high according to the change in plant structure combinations. The emission levels can be useful to help assess the environmental impact of the maintenance of a specific green area. Masoudi et al. [7] studied the effects of urban green spaces composition and configuration on urban heat islands. The authors developed a method to help the correct addressing of greening priorities so as to obtain higher cooling effects. Managing green spaces less intensively has also shown beneficial effects. For example, performing maintenance only on specific areas and not on the total surface may help to reduce mowing operations, energy consumption, and labor costs [34]. This type of management has shown to have beneficial effects on biodiversity and environment. However, in urban areas a more extensive management is usually required, so as to avoid unpleasant aesthetical effects of long vegetation (wild-looking areas). Many attempts have also been made to further maximize the autonomous mowers' efficiency: path planning and systematic trajectories [35]. For instance, Sportelli et al. [24] compared an autonomous mower operating with random trajectories with an autonomous mower operating with systematic trajectories. The trial was carried out on two identical rectangular areas with no obstacles. The working efficiency of the autonomous mower working with systematic trajectories resulted approximately 80%, while the working efficiency of the autonomous mower working with random trajectories ranged from 30% to 35%, approximately. Bosse et al. [36] tested the working efficiency of a large prototype autonomous mower that had a working width of 2 m on an area of 321 m^2. Testing showed that by using a spiral inward operating algorithm (near the perimeter) and a spiral shift operating algorithm (in the inner area), the mower managed to cover 95%

of the area in 15 min. However, this was a very large machine compared to commercial autonomous mowers designed for private gardens such as the one chosen for the present trial, characterized by a working width of 0.24 m. The large working width contributed to reduce the time needed to cover the entire turfgrass area. Another strategy could be to manage green spaces less intensively; for instance, reducing mowing operations, energy consumption, and labor costs by performing maintenance only on specific areas and not on the total surface (i.e., mown paths) [37].

4. Conclusions

The present trial highlighted the potential that the tracking software upgrade might have in terms of green area management. In fact, the upgrade enabled to map the points in the selected green areas and to track the progress of the autonomous mower in three different gardens. The accuracy of the RTK-GPS system and the potential of the software package produced useful data for green area management. Data were gathered both from the percentage of area mowed and from the distance travelled. The results were consistent and in line with predictions after two hours of continuous work. The areas close to the garden features and to the edge of the garden were characterized by a higher number of passages and a higher overlapping fulfilled by the autonomous mower. The results of this trial may be useful to gather data for a complete automation of the maintenance of green areas. However, some limitations of this method should be considered. This kind of garden maintenance is suited for areas far from buildings, vegetation, or other obstacles, so as to ensure that the accuracy of receivers and the data collection is not compromised. Another important issue is the spatial distribution of the obstacles within the area managed by the autonomous mower. When placing an obstacle, the minimum distance from the boundary wire and the guide wire should always be considered so as to allow the machine to move freely. Furthermore, the presence of tight passages should be considered when using an autonomous mower, since these machines have a minimum working width, so as to prevent possible manual operations by the user. The estimated energy consumption highlighted how the correct settings of cutting time may be crucial to consistently save energy during the long period and increase the overall sustainability of green areas management. To conclude, it would be of great interest to carry out a similar study using a robotic lawnmower with a systematic mowing pattern. Probably, using systematic trajectories it may be possible to achieve an easier and more satisfactory level of design and management in terms of relationship between area mown and working time.

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Appendix A

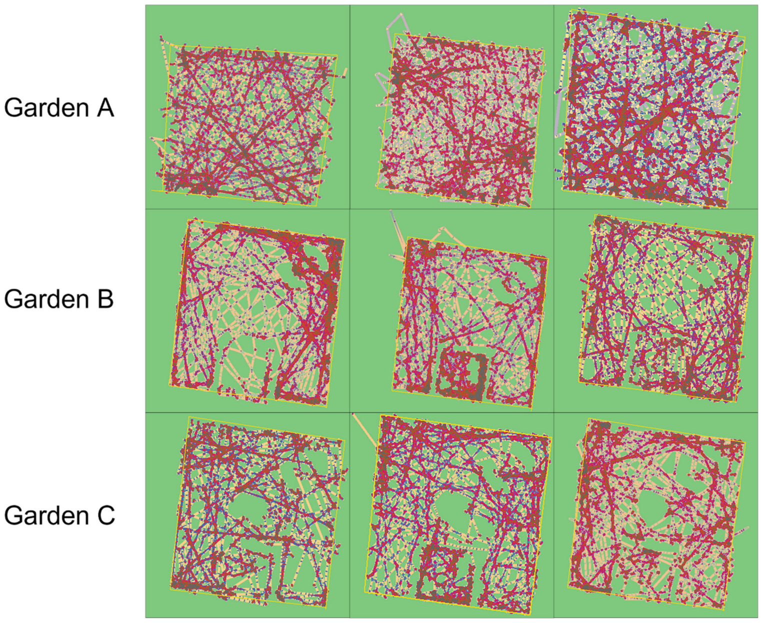

Figure A1. Trampling analysis output from the custom-built software showing colorimetric maps of the three garden designs studied in this trial.

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