UNIVERSITY OF PISA

Development of Innovative Machines for Turfgrass Management and Turf Quality Control

by

Michel Pirchio

Ph. D. Thesis

Agriculture, Food and Environment

Department of Agriculture, Food and Environment
University of Pisa

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Candidate: Michel Pirchio

Supervisors	Opponents
Prof. Marco Volterrani	Prof. Andrea Peruzzi
Prof. Marco Fontanelli	Dott. Nicola Grossi

Accepted by the Ph.D School
The Coordinator
(Prof. Andrea Cavallini) Date:

Declaration

This thesis is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly with due reference to the literature and acknowledgement of collaborative research and discussions.
This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma.

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Abstract

Turfgrass management and turf quality control are two important aspects regarding sports turfs. Four trials have been carried out to develop and study different machines and solutions for improved turfgrass management and turf quality control:

1) - Autonomous mowers can increase turf quality and reduce local noise and pollution compared with gasoline-powered rotary mowers. However, very little is known about the effects of autonomous mowing on encroaching weeds. The aim of this research was to compare the effects of an autonomous mower and an ordinary gasoline-powered mower on weed development in an artificially infested tall fescue (*Festuca arundinacea* Schreb.) turf with different nitrogen (N) rates. A three-way factor experimental design with three replications was adopted. Factor A consisted of three N rates (0, 75, and 150 kg ha−1), factor B consisted of two mowing systems (autonomous mower vs. walk-behind gasoline rotary mower equipped for mulching), and factor C which consisted of four different transplanted weed species: (a) *Bellis perennis* L., (b) *Trifolium repens* L.; (c) *Trifolium subterraneum* L.; and (d) *Lotus corniculatus* L. Of these, *B. perennis* is a rosette-type plant, while the other three species are creeping-type plants. The interaction between mowing system and transplanted weed species showed that the four transplanted weed species were larger when mowed by the autonomous mower than by the rotary mower. The autonomous mower yielded larger weeds probably because the constant mowing height caused the creeping weed species to grow sideways, since the turfgrass offered no competition for light. N fertilization increased turf quality and mowing quality, and also reduced spontaneous weed infestation. Autonomous mowing increased turf quality, mowing quality, but also the percentage of spontaneous weed cover.

2) - Sports turfs often consist of hard-to-mow warm season turfgrasses, such as zoysiagrass (*Zoysia* sp.) or bermudagrass (*Cynodon* sp.). Although autonomous mowers have several advantages over manually - operated mowers, they are not designed to mow lower than 2.0 cm and are consequently not used on high quality sports turfs. An ordinary autonomous mower was modified to obtain a prototype autonomous mower cutting at a low height. The prototype autonomous mower was tested on a manila grass (*Zoysia matrella* (L.) Merr.) turf, and compared its performance in terms of turf quality and energy consumption with an ordinary autonomous mower and with a gasoline reel

mower. A three-way factor experimental design with three replications was adopted. Factor A consisted of four nitrogen rates (0, 50, 100 and 150 kg·ha-1), factor B consisted of two mowing systems (autonomous mower vs. walk-behind gasoline reel mower with no clipping removal), and factor C consisted of two mowing heights (1.2 and 3.6 cm). Prototype autonomous mower performed mowing at 1.2 cm mowing height while ordinary autonomous mower mowed at 3.6 cm mowing height. The interaction between mowing system and mowing height showed that the turf quality was higher when the turf was mowed by the autonomous mower and at 1.2 cm rather than at 3.6 cm. Autonomous mowing reduced mowing quality but also reduced leaf width. Lower mowing height induced thinner leaves. Nitrogen (N) fertilization increased overall turf quality, reduced weed cover percentage, but also reduced mowing quality. These results show that autonomous mowers can perform low mowing even on tough-to-mow turfgrass species and on high quality sports turfs.

3) - Poor quality in turfgrass mowing is highlighted by the shredded leaf tips with necrotic tissues that give an unsightly brownish colour to the turf and may also lead to turf disease. Mowing quality is also typically assessed by visual rating, thus the score depends on the person doing the assessment. To make the evaluation of mowing quality not subjective, an innovative method was developed. The aim of the trial was to examine the effects of different mowing systems and two different nitrogen rates (100 and 200 kg ha−1) on two turfgrass species in order to test the new mowing quality calculation. Three different mowing systems were used: a battery-powered rotary mower set at 3000 rpm and 5000 rpm respectively and a gasoline-powered rotary mower set at full throttle. The battery-powered mower at low blade rpm produced a poorer mowing quality and turf quality than the gasoline-powered mower and battery-powered mower at high rpm, which produced a similar mowing quality and turf quality. Leaf tip damage level values showed a significant correlation with the results of the visual mowing quality assessment. Lower leaf tip damage level values (slightly above 1) corresponded to higher visual mowing quality scores (around 8).

4) - Warm-season turfgrasses can be grown successfully in the transition zone, but dormancy occurs to some extent during the winter. Overseeding with cool-season turfgrasses is necessary if winter desiccation of warm-season turfgrasses is not tolerated. The increasing availability of zoysiagrass cultivars has enabled this genius to be considered suitable for low-maintenance golf courses. Zoysiagrasses have the most rigid leaves of all turfgrass species so turfgrass mowers need more sharpening. Autonomous mowers have proven to produce a superior turf quality compared with traditional walk-behind rotary mowers, but no autonomous mower has ever been tested at a low mowing height on an overseeded warm season turfgrass. Because of this, the trial was carried out to simulate a golf tee overseeded with cool season turfgrasses, with low input fertilization rates and with one of the most difficult turf species to mow; i.e., manila grass. The trial was carried out in S. Piero a Grado, Pisa (43°40’ N, 10° 19’ E, 6 m. a.s.l.), Italy, from October 2016 to October 2018. After a two-year period the best turf quality was achieved with *Festuca rubra* spp. cultivars. In many cases turf quality increased after manila grass green-up since the combination of both cool season and warm season species gave a higher quality to the turfgrass, especially because of the finer leaf texture and higher shoot density. Overseeding manila grass with some cultivars of *Festuca rubra* spp. could be suitable for golf tees with low-input management, looking forward to the reduction of chemical inputs allowed on turfs by the European regulations.

Acknowledgments

Here we are! This journey is nearly over… If I have reached the end it is only thanks to Prof. Andrea Peruzzi, Prof. Marco Volterrani, Prof. Marco Fontanelli and Dr. Nicola Grossi. Within their different roles, each of them has showed great patience (that is really necessary with me), plenty of motivation and immense knowledge. I could not have imagined to have better mentors and I feel really lucky about this.

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Chapter 1

Introduction

1.1. Turfgrass mowing and mowing quality

Mowing plays a key role in turfgrass management (Howieson and Christians, 2001; Trenholm et al., 2009) and is one of the most frequent and intensive stresses for a turfgrass since it removes part of the photosynthetic leaf area (Howieson and Christians, 2001). Originally, turf mowing required human labour. The height and frequency of mowing were performed in order to respect the “1/3 rule”, which means that mowing does not involve more than one third of the total height of the grass, in order to prevent scalping and physiological stress (Beard, 1973). Mowing is a very important operation for sports turfs, so the specific features of each turfgrass species should be considered for optimal mowing (Trenholm et al., 2009). To have the best turf quality, the blades need to be sharpened so as to perform a clean cut with no shredding (Smith et al., 1981; Howieson and Christians, 2001). The quality of the mowing is reflected in the evenness of cut of the turfgrass leaves (Turgeon, 2012). The mowing quality should always be as high as possible, especially for high quality sports turfs (Howieson and Christians, 2001; Trenholm et al., 2009). Dull mower blades can lead to shredded leaf tips (Smith et al., 1981; Howieson and Christians, 2001; Trenholm et al., 2009). After a few hours, the shredded leaf tips dry out, giving the turf a brownish and unsightly appearance (Smith et al., 1981; Howieson and Christians, 2001). Dull mower blades are also believed to increase the risk of turf disease (Emmons, 1995). However, Ellram et al. (2007) found that *Sclerotinia homoeocarpa* (Dollar Spot) fungal disease incidence was not affected by mower blade sharpness. Leaf shredding can also change how much water the turfgrass consumes. It is commonly believed that leaf shredding due to dull mower blades will increase water consumption, however Steinegger et al. (1983) found that mowing a turf with dull blades reduced water consumption because a shredded turfgrass has a slower recovery and a lower shoot density. The fewer and slower growing plants will absorb less water. Mowing quality is mainly evaluated by a visual assessment (Morris and Shearman, 2010) and depends on the skills of the person observing the tips of the leaves after mowing, thus data collected by different people may vary. Howieson and Christians (2001) studied the effects of four different mower settings (using a reel mower) and of trinexapac-ethyl on the turf quality and mowing quality of creeping bentgrass (*Agrostis stolonifera* L.). The mowing quality was assessed using three different methods: visual assessment, leaf tissue chlorophyll content and ethylene production, measuring the perimeter of the necrotic area 24 h after mowing. The four settings of the reel mower were related to the reel/bedknife contact. The four reel mower settings were: (A) slight contact, sharp blade; (B) no contact, sharp blade; (C) slight contact, dull blade; (D) no contact, dull blade. Mower setting (A) produced the lowest mowing injury and the highest turf quality and chlorophyll content. Mower setting (D) produced the lowest turf quality, chlorophyll content and the highest mowing injury, with the highest number of ragged leaf tips and necrotic tissues. Mower settings (B) and (C) produced an intermediate turf quality, chlorophyll content and mowing injury, however in some cases mower setting (C) produced similar results to mower setting (A). Howieson and Christians (2006) also tested the blade sharpness and mowing injury of a reel mower which had been sharpened in different ways. To assess mowing injury, Howieson and Christians (2006) did not use a visual assessment but measured the length of the necrotic area due to leaf tip shredding. Carbide milling led to the lowest mowing injury and the greatest chlorophyll content, while cylindrical grinding led to the highest mowing injury and lowest chlorophyll content.

1.2. Turfgrass mowers

Typically, turfgrass mowers were divided in three main groups: reel mowers, rotary mowers and flail mowers. Recently, a fourth kind of turfgrass mowers is becoming more and more widespread: autonomous mowers.

1.2.1. Reel mowers

Reel mowers cut the grass with a scissor-like action using a reel cylinder and a bed knife. Reel mowers perform optimal mowing at a short height (below 2.5 cm) and are suitable for tough-to-mow grasses such as zoysiagrass and bermudagrass (Munshaw, 2013). Reel mowers are thus usually chosen for golf courses and sports turfs. Because of their scissor-like cutting action, reel mowers have a higher quality of cut compared to rotary mowers and cause less damage to the leaf blades, producing a better looking turf and up to 65% fewer diseases (Beard and Eaton, 1973).

1.2.2. Rotary mowers

Rotary mowers cut the grass by hitting it with a revolving single blade and are most effective at mowing tall grass and mulching clippings. However, rotary mowers are not suitable for mowing at low heights and often result in scalping (Munshaw, 2013). The most widespread and versatile machines for home lawn maintenance in Italy are electric rotary mowers for small gardens and gasoline-powered rotary mowers for larger gardens (Grossi et al., 2016). Gasoline rotary mowers are usually chosen for larger home lawns, while electric rotary mowers are usually chosen for smaller home lawns. Electric rotary mowers are supplied with electricity using a cord or a battery. In the past, electric rotary mowers working on private lawns in Italy were supplied only with a cord. In fact, battery powered rotary mowers are still not in widespread use since their cost is higher compared to cord-supplied models and the surface they can cover usually ranges from 500 to 1000 m^2 (Grossi et al., 2016). Both gasoline-powered and electric-powered rotary mowers share the same cutting principles and can both be equipped for mulching. Originally, the rpm adjustment of gasoline-powered rotary mowers could not be set precisely. The trend was thus to use gasoline-powered rotary mowers at full throttle. Technologically advanced machines such as battery-powered rotary mowers offer the possibility of precisely setting the revolutions per minute (rpm) value of the cutting blades. Unfortunately, it is still unknown whether battery-powered and gasoline-powered rotary mowers yield a different mowing quality.

1.2.3. Flail mowers

Flail mowers are less common compared to reel mowers and rotary mowers and are usually mounted on large machines such as tractors. Flail mowers cut the grass by hitting it with T-shaped or Y-shaped pivoting blades mounted around a revolving cylinder. The revolving cylinder is always parallel to the surface that needs to be mown. Regarding mowing quality, Trenholm et al. (2009) claim that flail mowers do not equal the mowing quality of rotary or reel mowers, thus their use should be limited to low-maintenance sites that are cut infrequently. Conversely, Parish and Fry (1997) found that a properly sharpened flail mower can yield the same turf quality and mowing quality as a rotary mower. Nevertheless, flail mowers are not used for small gardens and high-quality sports turfs.

1.2.4. Autonomous mowers

Autonomous mowers are machines that operate without the need of an operator and perform turfgrass mowing. The first autonomous mower was produced in 1995 by Husqvarna, a Swedish company, and was powered by solar energy. Current autonomous mowers are battery-powered machines that autonomously perform turfgrass mowing. Autonomous mowers usually move randomly within a precise perimeter for a predetermined period of time. The perimeter is defined by a shallow-buried boundary wire which generates an electro-magnetic field. Once the autonomous mower reaches the boundary wire or an obstacle, it stops and changes direction. Unfortunately, autonomous mowers do not know which areas have or have not been cut. Given a sufficient time interval, the autonomous mower is likely to cut most of the lawn (Chandler, 2003). It is an effective solution to cover areas with many obstacles, but leads to frequent overlapping (Ragonese and Marx, 2015). There are various alternative ways to prevent mowing overlap. Chandler (2003), for example, developed a texture-based vision system to enable the autonomous mower to detect where the grass has already been cut. Another solution is to equip the autonomous mower with a GPS which provides a “random assisted” pattern (Husqvarna, 2018) or with differential GPSs for systematic trajectories (Zucchetti, 2018), but only the largest autonomous mowers use this technology. The working capacity of autonomous mowers designed for private or industrial areas ranges from 400 to 5000 m^2. The largest autonomous mowers can manage up to 30,000 m^2 (Etesia, 2018; Zucchetti, 2018). Autonomous mowers can be equipped with razor-like pivoting blades mounted on a cutting disc (Honda, 2018; Husqvarna, 2018) or with solid blades, with three or four cutting edges (Robomow, 2018; Zucchetti, 2018). Compared to conventional mowers, autonomous mowers have several advantages. Firstly, although autonomous mowers do not replace humans managing turfgrass (professionals or just lawn owners), they help to save a great amount of time. Time saving enables the person managing the turf to have time for other turf management operations or simply for other purposes. Not having to mow the turf also prevents humans from coming into contact with dust, allergens, polluting gasses (if the engine is a gasoline engine), and noise (Hicks and Hall, 2000; Ragonese and Marx, 2015). Secondly, autonomous mowers do not produce polluting gasses or dust. Thirdly, they are so silent that they can perform the mowing even at night. Fourthly, given that autonomous mowers are usually programmed to operate every day, the clippings are very small and are left in place. In fact, autonomous mowers do not collect clippings, which become integrated into the turf and thus recycling nutrients. This process is called “grasscycling”. Grasscycling leads to a higher turf quality, lower weed percentage, lower need for nitrogen fertilization, and does not contribute to the formation of thatch (Brede, 2000). However, there are some differences between the effects of autonomous mower clippings and ordinary mulching rotary mower clippings. Ordinary walk-behind rotary mowers are usually used following the “1/3 rule”. Clippings from ordinary walk-behind rotary mowers are generally larger than clippings from autonomous mowers. Macolino and Ziliotto (2005) observed that ordinary rotary mower clipping release in tall fescue led to a severe reduction of root density and root length, losing up to 45% of total root weight. Ferguson and Newell (2010) observed the effects of the autonomous mower, Bigmow, compared to a reel mower. Turf mowed by Bigmow had a lower disease incidence and lower broad-leaved weed infestation. Autonomous mowers have proven to produce a superior turf quality compared to traditional walk-behind rotary mowers: autonomous mowers (Grossi et al., 2016). However, whether an autonomous mower can equal the quality of cut of a reel mower is not yet clear. A previous trial has been carried out to compare the differences in terms of turf quality and mowing quality between an autonomous mower and a reel mower (Ferguson and Newell, 2010). In terms of overall turf quality, the autonomous mower and the reel mower produced similar results. Labor was significantly reduced by the autonomous mower, with respect to the cylinder mower. The authors suggest that the autonomous mower tested in the trial may be a valid alternative to reel mowers at mowing heights above 2.5 cm. In the scientific literature no autonomous mower has ever been tested at a very low mowing height. Theoretically, autonomous mowers may reach a minimum of 2.0 cm mowing height. In a recent trial, a prototype-autonomous mower cutting at a 1.2 cm mowing height has been tested on a manila grass turf. The authors suggest that the autonomous mower tested in the trial may be a valid alternative to reel mowers at low mowing heights.

1.3. Turfgrass species

Turfgrass species are mainly subdivided in two groups: cool-season species and warm-season species. Cool season species thrive between 10°C and 25°C, while warm-season species thrive between 25°C and 35°C. Warm season turfgrass species can give numerous advantages over cool season species, such as lower water needs, the possibility of irrigating with salty waters and wastewater (Harivandi, 1991; Carrow and Duncan, 1988) and lower susceptibility to fungal diseases (Gullino et al., 2000). To produce the same amount of dry matter, warm-season species require less water, thus are more suitable for Mediterranean climates (Croce et al., 2004; Turgeon, 2012; Volterrani and De Bertoldi, 2012). Warm-season species also have superior recovery and wear resistance compared to cool-season species (Lulli et al., 2012; Volterrani et al., 1997). Considerable advantage would be gained, both from a technical and environmental perspective, by a more widespread utilization of warm-season turfgrasses in the coastal regions of the Mediterranean Basin. This area falls in the turfgrass transition zone, where warm-season turfgrasses can be grown successfully, but dormancy occurs to some extent during the cooler months (Volterrani et al., 1997). Warm-season species usually enter dormancy when temperatures are lower than 10°C. Where winter desiccation of warm-season turfgrasses is not tolerated for technical or aesthetic reasons, overseeding with cool-season turfgrasses is necessary to remedy dormancy. This practice allows to create a temporary, actively growing green cover, when use of turf covers or painting of turfs are considered secondary remedies to warm-season turfgrasses winter dormancy (Volterrani et al., 2003). The most common warm season turfgrasses for golf course fairways and tees in the U.S. are bermudagrass and secondly zoysiagrass (Trappe et al., 2011). Historically, zoysiagrass cultivars were developed for lawn use, however they have a high genetic variability which results in several morphological differences (Anderson, 2000; Magni et al., 2017). Although the use of zoysiagrass on putting greens in the U.S. is very recent (Morris, 2016), the use of zoysiagrass for golf greens, tees and fairways has been encouraging (Engelke et al., 2002a, 2002b; Whereley et al., 2011). The increasing popularity and availability of zoysiagrass cultivars have enabled zoysiagrass to be considered as a suitable turfgrass for sports turfs and golf courses (Patton et al., 2017; Pompeiano et al., 2012, 2014). Moreover, zoysiagrasses have a good tolerance to moisture deficits and shade, produce limited vertical growth requiring minimal mowing, develop a dense mat of vertical and horizontal organs that limit weed invasion, and have a short dormant period, making them potentially suitable also for low-maintenance turfs (Pompeiano et al., 2012; Pompeiano et al., 2014, Whereley et al., 2011). Zoysiagrass has the most rigid leaves of all turfgrass species, followed by bermudagrass and by the other warm season turf species (Turgeon, 2012). Due to their very high plant fiber hemi-cellulose content, zoysiagrass leaves have an improved wear tolerance (Lulli et al., 2012; Shearman and Beard, 1975; Turgeon, 2012). However, the high neutral detergent fiber (NDF) content makes zoysiagrass more difficult to mow. Thus, in order to have a high mowing quality, mowers working constantly on zoysiagrass require more sharpening than mowers working on other grasses (Bevard et al., 2005). Being so hard to mow, manila grass cultivars tend to have a lower quality of cut than japanese lawngrass (*Zoysia japonica* Steud.) cultivars (Patton et al., 2010). The optimal mowing height for zoysiagrasses ranges from 0.3 to 6.4 cm (Patton et al., 2017). Mowing heights ranging from 1.5 cm to 2 cm tend to stimulate a faster greening of zoysiagrass in early spring (Lee and Kim, 2005). In Italy, the most widespread cool-season turfgrass is tall fescue (*Festuca arundinacea* Schreb.) (Volterrani et al., 2004). Tall fescue is noted especially for its wear resistance, weed competition, shade tolerance, and deep root system. Compared to other cool season turfgrass species, tall fescue is the most resistant to drought, high temperatures, and salinity (Huang and Gao, 2000). For sports turf applications, tall fescue is not commonly used, since it has difficulty withstanding low mowing heights (Moore and Christians, 1989) and its leaves tend to partially wither in winter Dernoeden et al., 1993). Burns (1976) revealed how tall fescue is affected by mowing height, showing that the best quality was achieved at heights ranging from 2.5 to 4 cm. In addition, several authors have studied dwarf-type tall fescue cultivars selected to withstand low mowing. Based on the lower growth rate of these cultivars, appropriate levels of fertilization and mowing are required (Miele et al., 2001; Powell and Tapp, 1988; Reicher and Throssel, 1991). Grossi et al. (2004) studied the effects of low mowing height (ranging from 1.0 cm to 2.5 cm) on two cultivars of tall fescue. The highest quality was achieved with the lowest mowing height, proving that tall fescue cultivars selected to withstand low mowing heights are suitable for sports turf applications. Dernoeden et al. (1993) studied the effects of mowing, nitrogen fertilization, and herbicides on the weed management of tall fescue turf. The two main species of weeds found in tall fescue turf were crabgrass (*Digitaria ischaemum* Schreb.)

and white clover (*Trifolium repens* L.). Herbicides were effective in controlling weed populations, irrespective of nitrogen fertilization. High mowing (8.8 cm) was the best cultural management for reducing crabgrass infestation. Mowing at lower heights (3.2 and 5.5 cm) led to higher crabgrass infestation. White clover, on the other hand, was more competitive as the tall fescue height increased. In contrast, Burns (1981) observed a larger infestation of white clover in tall fescue mowed at 4.0 cm compared to tall fescue mowed at 8.0 cm. Burns also found that tall fescue density was higher after three years when mowed at 8.0 cm. In some studies on *Poa pratensis* L. and *F. arundinacea* Schreb. (Griggs and Horst, 1980; Horst et al., 1981; Troll and Hurto, 1981), mulching has increased turf quality compared to mowing with clipping removal. Mulching also improved turf colour in the autumn and winter and did not lead to any variation in thatch thickness. Grossi et al. (2003) compared the effects of mulching and mowing with clipping removal in a tall fescue turf. Turf quality and turf colour were higher when mulching was performed. Thatch was not influenced by the mowing system.
Weed control is an important task in turf management. Weeds can greatly reduce turf quality. Any stress factor that reduces turfgrass cover, such as poor management practices, disease, or extreme environmental conditions, can result in weed infestation. As previously mentioned, weed control in turfgrass over the years has mainly been performed with chemical herbicides. However, the use of chemical herbicides has been increasingly restricted because of their highly negative impact on the environment and on human health. The trend is to find alternative solutions for weed control in turfgrass based on management practices in order to reduce the use of chemical active ingredients.

Chapter 2

Autonomous mower vs. rotary mower: effects on turf quality and weed control in tall fescue lawn

The main purpose of this trial was to compare the effects of an autonomous mower, an ordinary gasoline-powered mower, and nitrogen (N) fertilization rates on weed development in an artificially infested tall fescue (*Festuca arundinacea* Schreb.) turf. To date, very little is known about the effects of autonomous mowers on weed control. The trial was carried out to simulate the spontaneous weed infestation of a cool-season turf with different nitrogen (N) levels, and to evaluate the turf quality and energy consumption of the two mowing systems.

2.1. Materials and methods

2.1.1. The experimental trial. The experimental trial was carried out in S. Piero a Grado, Pisa (43°39′ N 10°21′ E, 5 m a.s.l.) from April to October 2016 on a two-year old stand of *Festuca arundinacea* cv 'Arminda', established in a soil characterized by the following physical-chemical properties: 91% sand, 5% silt, 4% clay, pH 6.6, 1.4 g kg^{-1} of organic matter; EC 0.51 dS m^{-1}. On 23 March 2016, fertilization with 30 kg ha^{-1} of P (superphosphate) and 100 kg ha^{-1} of K (potassium sulphate) was applied. Irrigation was applied as necessary to prevent wilt turf.

The trial started on 20 April 2016. A three-way factor experimental design (A × B × C) was adopted.

- Factor (A) consisted in 3 levels of nitrogen fertilization delivered in one application: (0, 75, and 150 kg ha^{-1} of N (ammonium sulphate 21-0-0).
- Factor (B) consisted in 2 mowing systems: (1) autonomous mowing with a Husqvarna Automower mod. 420 set 8 h day $^{-1}$ working time, and (2) manual mowing (once a week) with a walk-behind gasoline rotary mower Honda mod. HRD 536 HX (Honda France Manufacturing, Ormes, France), equipped for mulching. The six sub-plots were 234 m^2 (18.0 × 13.0 m) each.
- Factor (C) consisted in four different transplanted weed species.

In particular, the four species selected for transplantation were: (a) *Bellis perennis* L., (b) *Trifolium repens* L.; (c) *Trifolium subterraneum* L.; and (d) *Lotus corniculatus* L. *B.*

perennis is a rosette-type plant, while the other three species are creeping-type plants. Young plants were obtained from the local ecotype seeds and raised in peat-filled honeycomb alveoli. Peat volume available for each plant was 5 cm^3. At the time of transplant, plants were 3 to 5 cm high and had never been trimmed down. Plants were manually transplanted (Figure 2.1) in 4 rows of 6 plants m^{-2} (each plant was 0.40 m × 0.25 m apart). Sub-sub-plots were 72. Each sub-sub-plot was 19.5 m^2 (6.0 × 3.25 m). Only one weed species was transplanted on each sub-sub-plot.

Figure 2.1. Manual transplanting of the four weed species. Note the peat-filled honeycomb alveoli.

Both mowers were set at a 3 cm mowing height. The blades of the rotary mower were sharpened every two weeks. The blades of the autonomous mower were replaced every two weeks.

2.1.2. Description of the machines.

Autonomous mower. The Husqvarna Automower 420 is equipped with two pivoting front wheels and two course treaded rear driving wheels. Automower 420 has a 24 cm-wide cutting disc with three small pivoting blades mounted on the disc for easy changing. Cutting height ranges from 2.0 cm to 6.0 cm. Each rear wheel is powered by a brushless electric motor, and a third brushless electric motor drives the cutting disc. Maximum working capacity is 2200 m^2 for a 24 h d^{-1} working time.

Rotary mower. The Honda HRD 536 HX is a self-propelled rotary mower. It is equipped with mulching blades and with a hydrostatic drive for speed variation from 0 to 4.7 km h^{-1}. The working width is 53 cm. Cutting height ranges from 1.4 cm to 7.6 cm. The power is generated by a 2.7 kW single cylinder gasoline four stroke combustion engine with an overhead camshaft. Engine displacement is 160 cm^3.

2.1.3. Experimental field and data collection.

The entire area was 1404 m^2 (54 × 26 m) subdivided in three randomized blocks of 468 m^2 (18.0 × 26.0 m) each.

For a 32-week period from 20 April to 24 November, the following parameters were assessed weekly:

- turf quality: (1 = poor; 9 = excellent), 6 = acceptable (Morris and Shearman, 2010);
- mowing quality: (1 = unevenly cut edge of leaf blade; 9 = perfectly cut edge of leaf blade), 6 = acceptable;
- disease: (1 = 100% injury; 9 = 0% injury) (Morris and Shearman, 2010);
- weed cover (%): expressed as weed percentage of total ground cover;
- transplanted weed size: measured maximum diameter of each weed with ruler and data reported as cm;
- rotary mower fuel consumption and Automower electricity consumption.

At 32 WAT, a single 50 cm^2 core sample per plot was collected and the following parameters were determined in relation to the tall fescue:

- leaf width: 20 fully expanded leaves per plot were measured with a precision Vernier caliper and data reported in millimetres;
- shoot density: direct counting with data reported as shoots cm^{-2}.

During the whole trial, working speed, working time, turning time, working capacity, power requirement, electrical energy requirement, and gasoline consumption were assessed. A power consumption meter (EL-EPM02HQ; Nedis, MC's-Hertogenbosch, The Netherlands) was used to assess the electrical energy requirement. The gasoline tank was filled just before mowing. Gasoline consumption was measured by refuelling the tank after mowing. The following conversion factors were used to estimate primary energy consumption: 9.2 kWh/L of gasoline (Gupta, 2014) and 0.46 as efficiency of the Italian National Electric System (European Union, 2014). The cost of both machines was estimated by referring to the study area for a comparison. Both fixed costs (purchase and depreciation) and variable costs (labor and consumption due to the use of the machines) were estimated. Machine life for both machines was estimated to be 10 years. The purchase cost of the Automower 420 was 2721 euros. The purchase cost of the Honda HRD 536 HX was 1538 euros. Gasoline cost was 1.50 euros/L. Labor cost was 25 euros/h. The total working period per year was calculated as 210 days.

2.1.4. Statistical analysis. Statistical analysis of biometric data was carried out with COSTAT 6.400 software (CoHort Software, Monterey, CA, USA). All data were analysed by three-way ANOVA. Before being analysed, percentage data was transformed using angular transformation (arcsine of the square root). An all-pairwise Fisher’s least significant difference (LSD) test at the probability level of 0.05 was used to detect the differences between means.

2.2. Results

There was no significant 3-order interaction between factors, however, there was a significant interaction between mowing system and transplanted weed species. For the other parameters, the effects of N fertilization and mowing system (except for turf disease) were statistically significant ($p < 0.05$) (Table 2.1).

The interaction between mowing system and transplanted weed species at 8 weeks after treatment (WAT) showed that the mean diameter values of the four transplanted weed species were significantly larger when mowed by the autonomous mower rather than by the rotary mower (Table 2.2). At 16 WAT, diameter values of the four weed species mowed by the autonomous mower were still significantly larger than diameter values of the same weed species mowed by the rotary mower (Table 2.2). At 24 WAT, weed diameter values continued to be significantly larger when mowed by the autonomous mower than by the rotary mower (Table 2.2). *T. repens* reached a diameter of 12.5 cm when mowed by the autonomous mower vs. 6.8 cm when mowed by the rotary mower. At 32 WAT, weed diameter values were significantly larger when mowed by the autonomous mower than by the rotary mower (Table 2.2). *T. repens* reached a diameter of 24.0 cm when mowed by the autonomous mower vs. 7.0 cm when mowed by the rotary mower. *L. corniculatus* reached a diameter of 14.2 cm when mowed by the autonomous mower vs. 8.3 cm when mowed by the rotary mower.

Table 2.1. Results of analysis of variance testing the effects of N rates, Mowing system, Transplanted weed species, and their interactions on Turf quality (8, 16, 24, and 32 weeks after treatment (WAT)), Mowing quality (8, 16, 24, and 32 WAT), Turf disease (8, 16, 24, and 32 WAT), Spontaneous weed cover percentage (8, 16, 24, and 32 WAT), Transplanted weed size (8, 16, 24, and 32 WAT), Leaf width (32 WAT) and Shoot density (32 WAT).

Parameter	N Rates (A)	Mowing System (B)	Transplanted Weed Species (C)	(A) × (B)	(B) × (C)	(A) × (B) × (C)
Turf quality (8 WAT)	*	*	ns	ns	ns	ns
Turf quality (16 WAT)	*	*	ns	ns	ns	ns
Turf quality (24 WAT)	*	*	ns	ns	ns	ns
Turf quality (32 WAT)	*	*	ns	ns	ns	ns
Mowing quality (8 WAT)	*	*	ns	ns	ns	ns
Mowing quality (16 WAT)	*	*	ns	ns	ns	ns
Mowing quality (24 WAT)	*	*	ns	ns	ns	ns
Mowing quality (32 WAT)	*	*	ns	ns	ns	ns
Disease (8 WAT)	ns	ns	ns	ns	ns	ns
Disease (16 WAT)	*	ns	ns	ns	ns	ns
Disease (24 WAT)	*	ns	ns	ns	ns	ns
Disease (32 WAT)	ns	ns	ns	ns	ns	ns
Weed cover (8 WAT)	*	*	ns	ns	ns	ns
Weed cover (16 WAT)	*	*	ns	ns	ns	ns
Weed cover (24 WAT)	*	*	ns	ns	ns	ns
Weed cover (32 WAT)	*	*	ns	ns	ns	ns
Transplanted weed size (8 WAT)	ns	*	*	ns	*	ns
Transplanted weed size (16 WAT)	ns	*	*	ns	*	ns
Transplanted weed size (24 WAT)	ns	*	*	ns	*	ns
Transplanted weed size (32 WAT)	ns	*	*	ns	*	ns
Leaf width (32 WAT)	*	*	ns	ns	ns	ns
Shoot density (32 WAT)	*	*	ns	ns	ns	ns

* = $p < 0.05$. ns = not significant.

Table 2.2. Mowing system and transplanted weed species interaction effect on weed diameter (cm) after 8, 16, 24, and 32 weeks of treatment. LSD, least significant difference.

8 Weeks after Treatment				
Weed diameter (cm)	Bellis perennis	Trifolium repens	Trifolium subterraneum	Lotus corniculatus
Autonomous mower	4.7	7.4	11.0	6.4
Rotary mower	3.7	5.1	7.9	4.4
LSD 0.05		0.7		
16 weeks after treatment				
Weed diameter (cm)	Bellis perennis	Trifolium repens	Trifolium subterraneum	Lotus corniculatus
Autonomous mower	5.4	10.0	9.4	8.7
Rotary mower	4.0	5.5	5.9	4.6
LSD 0.05		0.8		
24 weeks after treatment				
Weed diameter (cm)	Bellis perennis	Trifolium repens	Trifolium subterraneum	Lotus corniculatus
Autonomous mower	5.9	12.5	8.0	10.1
Rotary mower	4.2	6.8	4.9	5.7
LSD 0.05		1.0		
32 weeks after treatment				
Weed diameter (cm)	Bellis perennis	Trifolium repens	Trifolium subterraneum	Lotus corniculatus
Autonomous mower	6.6	24.0	7.3	14.2
Rotary mower	4.3	7.0	4.8	8.3
LSD 0.05		2.2		

At 8 WAT, all doses of N fertilization improved turf quality values, compared to the unacceptable control value (4.7) (Table 2.3). Mowing quality was improved only with the higher dose of N. Turf disease was not affected by N fertilization. Spontaneous weed cover percentage decreased with higher N doses (5.0%) vs. the control (9.7%).

Table 2.3. Nitrogen fertilization mean effect on tall fescue turf quality (1 = poor, 9 = excellent), mowing quality (1 = poor, 9 = excellent), turf disease (1 = 100% injury; 9 = 0 % injury), and weed cover (%) after 8, 16, 24, and 32 weeks of treatment.

8 Weeks after Treatment				
N fertilization (kg ha^{-1})	Turf quality (1–9 scale)	Mowing quality (1–9 scale)	Turf disease (1–9 scale)	Weed cover (%)
0	4.7	7.2	9.0	9.7
75	5.8	7.1	9.0	7.2
150	6.6	7.5	9.0	5.0
LSD 0.05	0.4	0.2	ns	1.2
16 weeks after treatment				
N fertilization (kg ha^{-1})	Turf quality (1–9 scale)	Mowing quality (1–9 scale)	Turf disease (1–9 scale)	Weed cover (%)
0	5.5	7.0	7.8	15.2
75	6.9	7.0	8.5	8.7
150	7.5	7.1	8.8	6.3
LSD 0.05	0.4	0.1	0.3	2.2
24 weeks after treatment				
N fertilization (kg ha^{-1})	Turf quality (1–9 scale)	Mowing quality (1–9 scale)	Turf disease (1–9 scale)	Weed cover (%)
0	5.4	6.1	8.7	20.0
75	6.8	6.5	9.0	13.5
150	7.8	6.5	9.0	9.0
LSD 0.05	0.3	0.2	0.2	3.7
32 weeks after treatment				
N fertilization (kg ha^{-1})	Turf quality (1–9 scale)	Mowing quality (1–9 scale)	Turf disease (1–9 scale)	Weed cover (%)
0	5.4	6.5	8.5	15.7
75	6.6	6.8	9.0	9.3
150	7.4	6.8	9.0	4.3
LSD 0.05	0.4	0.2	ns	2.4

At 8 WAT, differences between the two mowing systems were also observed (Table 2.4). Turf quality and especially mowing quality were higher for the autonomous mower (5.8 and 7.6, respectively) compared to the rotary mower (5.5 and 6.9, respectively). Spontaneous weed cover percentage increased with the autonomous mower (8.4%) compared to the rotary mower (6.1%).

Table 2.4. Mowing system mean effect on tall fescue turf quality (1 = poor, 9 = excellent), mowing quality (1 = poor, 9 = excellent), and weed cover (%) after 8, 16, 24, and 32 weeks of treatment.

8 Weeks after Treatment			
Mowing system	Turf quality (1–9 scale)	Mowing quality (1–9 scale)	Weed cover (%)
Autonomous mower	5.8	7.6	8.4
Rotary mower	5.5	6.9	6.1
LSD 0.05	0.3	0.3	1.0
16 weeks after treatment			
Mowing system	Turf quality (1–9 scale)	Mowing quality (1–9 scale)	Weed cover (%)
Autonomous mower	6.6	7.3	11.1
Rotary mower	6.5	6.7	9.0
LSD 0.05	0.1	0.2	1.8
24 weeks after treatment			
Mowing system	Turf quality (1–9 scale)	Mowing quality (1–9 scale)	Weed cover (%)
Autonomous mower	6.9	6.9	16.8
Rotary mower	6.4	5.8	11.6
LSD 0.05	0.2	0.1	3.1
32 weeks after treatment			
Mowing system	Turf quality (1–9 scale)	Mowing quality (1–9 scale)	Weed cover (%)
Autonomous mower	6.6	7.2	11.7
Rotary mower	6.3	6.2	7.9
LSD 0.05	0.2	0.1	2.0

At 16 WAT, the turf quality control value was still unacceptable (5.5), but all doses of N increased turf quality values (Table 2.3). Mowing quality slightly increased only with the higher N dose, while turf disease decreased for all N doses. Spontaneous weed cover percentage decreased (ranging from 15.2% to 6.3%) as N dose increased. Mowing systems also led to different results (Table 2.4). Turf and mowing quality were higher for the autonomous mower (6.6 and 7.3, respectively) compared to the rotary mower (6.5 and 6.7, respectively). Spontaneous weed cover percentage was lower for the rotary mower (9%) compared to the autonomous mower (11.1%). At 24 WAT, the turf quality

control value continued to be unacceptable (5.4), however, turf quality greatly increased with N fertilization (Table 2.3). Mowing quality also increased with the N fertilization. Disease was slightly higher for the control (8.7) than for the N fertilized turf (9.0). Spontaneous weed cover percentage was very high for control plots (20.0%), but decreased as the N dose increased (9.0%). Mowing system showed some effects on turf quality since the autonomous mower increased the turf quality value compared to the rotary mower (6.9 vs. 6.4, respectively) (Table 2.4). Mowing quality increased with the autonomous mower vs. the rotary mower (6.9 vs. 5.8). Rotary mower reduced spontaneous weed cover percentage (11.6%) compared to the autonomous mower (16.8%). At 32 WAT, N fertilization increased turf quality, compared to the unacceptable control value (5.4) (Table 2.3). N fertilization also improved mowing quality (6.8) compared to the control value (6.5). Spontaneous weed cover percentage decreased greatly with increasing N doses (4.3%), although the control was slightly lower compared to 24 WAT (15.7% vs. 20.0%). Autonomous mowing improved turf quality (6.6) vs. rotary mowing (6.3) (Table 2.4). Mowing quality also improved with the autonomous mower (7.2) vs. the rotary mower (6.2). Spontaneous weed cover percentage was slightly lower than 24 WAT, however, rotary mowing resulted in a lower weed cover percentage (7.9%) than autonomous mowing (11.7%).

At the end of the trial (32 WAT), leaf width and shoot density were measured for each plot. N fertilization had significant effects on leaf width (Table 2.5). Leaves were significantly wider after an N dose of 150 kg ha^{-1} (0.22 cm) compared to the control (0.18 cm) and an N dose 75 kg ha^{-1} (0.19 cm).

Table 2.5. Nitrogen fertilization mean effect on tall fescue leaf width (cm), and shoot density (shoots cm^{-2}) after 32 weeks of treatment.

N Fertilization (kg ha^{-1})	Leaf Width (cm)	Shoot Density (n° cm^{-2})
0	0.18	2.6
75	0.19	2.9
150	0.22	3.2
LSD 0.05	0.03	0.4

Leaf width was significantly thinner when the turf was mowed by the autonomous mower (0.16 cm) compared to turfgrass mowed with the rotary mower (0.23 cm) (Table 2.6).

Table 2.6. Mowing system mean effect on tall fescue leaf width (cm), and shoot density (n° cm^{-2}) after 32 weeks of treatment.

Mowing System	Leaf Width (cm)	Shoot Density (n° cm^{-2})
Autonomous mower	0.16	3.6
Rotary mower	0.23	2.2
LSD 0.05	0.02	0.3

N fertilization also had significant effects on shoot density (Table 2.5). Shoot density was significantly higher where an N dose of 150 kg ha^{-1} was applied (3.2 shoots cm^{-2}) compared with the control (2.6 shoots cm^{-2}). No significant difference was observed comparing the N dose of 75 kg ha^{-1} with the control. Shoot density was higher when turfgrass was mowed by the autonomous mower (3.6 shoots cm^{-2}) compared to turfgrass mowed with the rotary mower (2.2 shoots cm^{-2}) (Table 2.6).

2.2.1. Energy consumption and estimated costs of the mowing systems

The energy consumption and estimated costs of the autonomous mower and rotary mower are shown in Table 2.7. The autonomous mower's operational time was set at 8 h day^{-1}, including both mowing time and charging time. Overall mowing time was 5.3 h d^{-1} (37.1 h/week) and charging time was 2.7 h day^{-1} (18.9 h/week). Electric energy consumption was 1.37 kWh per week, which corresponds to 2.98 kWh of primary energy (energy from primary sources transformed into electric energy). The power requirement to operate the mowing disc was approximately 30 W. The power required for the boundary wire was 96 Wh day^{-1}. The boundary wire was operative for 24 h day^{-1}.

Table 2.7. Energy consumption and estimated costs of the autonomous mower and the rotary mower working on a surface of 702 m^2 at a 3.0 cm mowing height.

Parameter	Unit	Value
Autonomous mower		
Set daily working time (mowing and recharging)	h day^{-1}	8.00
Daily mowing time (no recharging)	h day^{-1}	5.30
Electric energy consumption per week	kWh/week	1.37
Primary energy consumption per week	kWh/week	2.98
Cost per week	euros/week	14.37
Rotary mower		
Working speed	km h^{-1}	3.00
Total operative time	h/week	0.63
Gasoline consumption	L/week	0.50
Primary energy consumption	kWh/week	4.64
Cost per week (including labor cost, 25 euros/h)	euros/week	20.23

The Honda walk-behind mulching rotary mower, manually operated once per week, covered the same area (702 m^2) in 0.63 h. The average working speed was 3 km h^{-1}. Gasoline consumption was 0.50 L/week. Primary energy consumption was 4.64 kWh (Table 2.7). Comparing the weekly management of the tall fescue turf with the two mowing systems, the autonomous mower required a longer mowing time than the rotary mower (37.1 vs. 0.63 h/week). However, the autonomous mower had a lower energy consumption (2.98 vs. 4.64 kWh/week). As for the estimated costs, the autonomous mower was cheaper than the rotary mower considering the ordinary labour cost in Italy (14.37 vs. 20.23 euros/week) (Table 2.7).

2.3. Discussion

Throughout the trial period, turf quality, mowing quality, disease, shoot density, and tall fescue leaf width were improved when the autonomous mower was used. This could be due to the high cutting frequency of the autonomous mower which led to a constant and lower average turf height throughout compared with the rotary mower. Grossi et al. (2004) observed that tall fescue responded to a lower mowing height by increasing shoot density and reducing leaf width. N fertilization was effective in controlling the spontaneous weed cover (Table 2.1). A healthy turf with a higher density is more competitive against weed encroaching. Because of the shallow sandy soil, the non-fertilized plots showed an unacceptable turf quality and the turf was not competitive against weeds. A similar study was carried out by Dernoeden et al. (1993), who found that N fertilization in tall fescue reduced the crabgrass cover percentage. However, the lower average turf height probably led to a higher spontaneous weed cover in plots mown by the autonomous mower. Dernoeden et al. (1993) found that higher mowing was the best to control crabgrass infestation. Burns (1981) also observed a higher cover percentage of white clover when tall fescue was mown at 4.0 cm compared to an 8.0 cm mowing height. In our study, three of the four species of weeds artificially transplanted were creeping species (*T. repens* L., *T. subterraneum* L., *L. corniculatus* L.). Artificially transplanted weeds were also larger when turf was managed by autonomous mower. This could also be due to the lower average turf height compared to the turf mown with the rotary mower, as observed by other authors (Burns, 1981; Dernoeden et al., 1993). In fact, apart from *B. perennis*, these creeping dicots were able to expand sideways below the mowing height without competing for light from the tall fescue turf, since turf height was kept constant by the autonomous mower. The transplanted weeds adapted their growth at a low height in order not to be cut by the autonomous mower. Where the turf was mown once a week by the rotary mower, weeds had to grow taller to compete for light with tall fescue because the turf height would increase after mowing. Thus, some of the weeds would grow above the mowing height and get cut by the rotary mower. To withstand weed expansion, the turf needs to be properly fertilized in order to be more competitive. In fact, when the N fertilization was higher and the autonomous mower was used, the weed cover percentage did not affect the turf quality, since scores were very high. A lawn that is mown once a week (as commonly happens with rotary mowers) looks neat and tidy after mowing, but not over the following days. Thus, despite possibly having a slightly larger creeping weed species, a lawn mowed by an autonomous mower will always have the optimal quality and appearance if properly fertilized. The lower power requirement of the autonomous mower could depend on the very low power needed to perform mowing (average power required by the machine during mowing is 30 W). In addition, the autonomous mower does not have to cut large amounts of grass because by working every day, it only cuts small clippings. Comparing the number of working hours and the power requirement, the autonomous mower was shown to be a more efficient machine. Brushless electric motors have an efficiency of 90%. A small ordinary gasoline engine has an efficiency ranging from 20% to 25%, although it uses primary energy, while the efficiency of the Italian National Electric System is 46%. However, the primary energy consumption measured in this trial differs from that measured by Grossi et al. (2016), who compared an Automower 330X and a John Deere walk-behind mulching rotary mower. The Automower required 4.80 kWh/week of primary energy to cover 1296 m^2, while the John Deere required 12.60 kWh/week. In our trial, the Automower 420 required 2.98 kWh/week of primary energy vs. 4.64 for the Honda HRD rotary mower. The smaller gap in primary energy requirement is probably due to the higher efficiency of the Honda HRD compared to the John Deere JS63, and to a lower efficiency of the Automower 420 compared to the Automower 330X. The Honda HRD is a recent model, while the John Deere JS63 has been on the market for considerably longer. The higher fuel consumption of the John Deere JS63 is also due to its larger and much more powerful engine compared to the Honda (5.0 vs. 2.7 kW). The Automower 330X has a greater battery capacity than the Automower 420 (5.2 vs. 3.2 Ah). This means that the Automower 330X can be recharged less frequently (every 135 vs. 105 min for Automower 420). Whenever the autonomous mower needs to be recharged, it spends time and energy moving around searching for a signal to guide it to the charging station. The battery charging also has its own efficiency. Thus, a greater number of recharges leads to a slightly less efficient machine. Although the Honda HRD is cheaper than the Automower 420 (1538 vs. 2515 euros), the cost per week of the rotary mower is higher because of its higher energy consumption and requirement for human labour.

Chapter 3

Autonomous rotary mower vs. ordinary reel mower - effects of cutting height and nitrogen rate on manila grass turf quality

The aim of this trial was to develop and test a prototype autonomous mower cutting at a low height on a manila grass turf, and to compare its performance in terms of turf quality and energetic aspects with an ordinary autonomous mower and with a gasoline reel mower. The trial was carried out to simulate a golf tee and a golf rough, with different mowing heights, different fertilization rates, and with one of the most difficult turf species to mow, i.e., manila grass.

3.1. Materials and methods

3.1.1. The experimental trial. The experimental trial was carried out at the Centre for Research on Turfgrass for Environment and Sports (CeRTES) of the Department of Agriculture, Food and Environment of Pisa University, Pisa, Italy (lat. 43°40'N, long. 10°19'E, elevation 6 m) from Apr. to Oct. 2016 on a mature stand of 'Zeon' manila grass. The stand was established on a soil characterized by the following physical-chemical properties: silt-loam (Calcaric Fluvisol, 30% sand, 51% silt and 19% clay) with a pH of 7.7 and 22 g·kg-1 organic matter. From 18 Apr. 2016 manual mowing was carried out once per week at 2.0 cm to help the turf adapt to the future mowing heights. Irrigation was applied as necessary to avoid wilt turf. On 27 June 2016 a three-way factor experimental design (AxBxC) with three replications was adopted.

- Factor A consisted of four levels of nitrogen fertilization applied: 0, 50, 100 and 150 kg·ha-1 of N (ammonium sulphate 21N-0P-0K).
- Factor B consisted of two mowing systems: 1) autonomous mowing with an ordinary autonomous mower and with a prototype autonomous mower; 2) manual mowing with a walk-behind gasoline reel mower with no clipping removal.
- Factor C consisted in two mowing heights: 1.2 or 3.6 cm.

In particular, the prototype autonomous mower was set at 1.2 cm mowing height and the ordinary autonomous mower was set at 3.6 cm mowing height. The reel mower was set at 1.2 cm or at 3.6 cm mowing height depending on which plot needed to be mown. The cutting frequency of the reel mower was once a week at 3.6 cm mowing height and twice per week at 1.2 cm mowing height. Both the ordinary autonomous mower and the prototype autonomous mower operated every day, and were set at 7.2 h·d-1 working time. Both autonomous mowers used the same cutting blades. All autonomous mowers in this trial were set in “ECO” mode. This means that the boundary wires consumed energy only when the autonomous mowers were out of the charging stations. The blades of the reel mower were lapped weekly before each mowing and the blades of both autonomous mowers were replaced every 2 weeks.

3.1.2. Description of the machines.

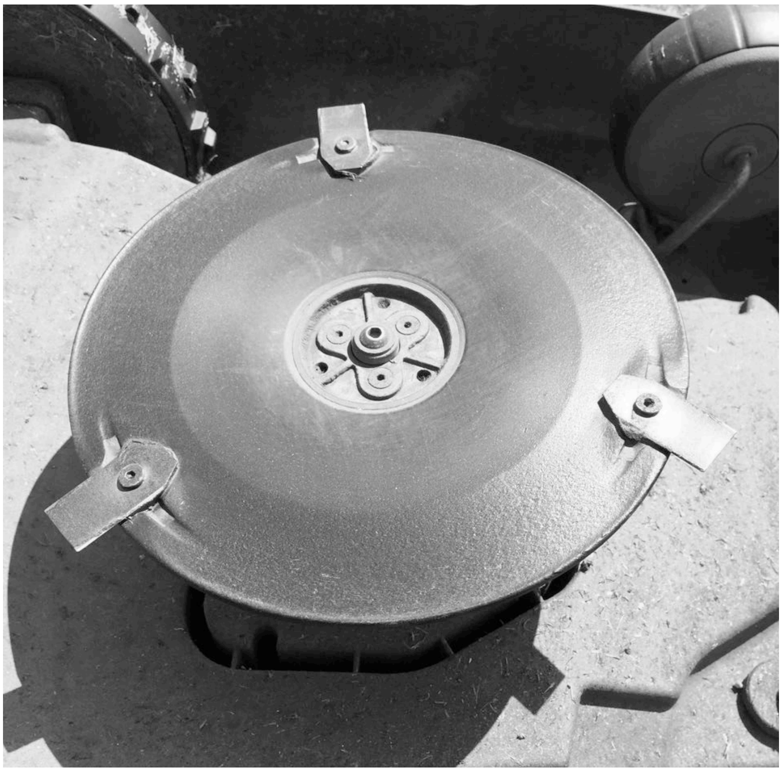
Reel mower. A self-propelled reel mower (20-3.5 RP-7; McLane; Paramount, CA) was used in this trial. The working width is 50 cm. It is equipped with a seven-blade reel and with a single-cylinder gasoline engine (Briggs & Stratton, Wauwatosa, WI) with an output of 2.6 kW. It has a belt drive with no speed variation. Engine displacement is 148 cm3. Mowing height can be adjusted from 0.6 to 3.8 cm.

Ordinary autonomous mower. An autonomous mower (Automower 310; Husqvarna, Stockholm, Sweden) was used in this trial. It is a small autonomous mower equipped with two front pivoting wheels and two rear course treaded driving wheels. It has three small pivoting blades mounted on a 22-cm-wide cutting disc. Mowing height is adjusted manually and ranges from 2.0 cm to 6.0 cm. The cutting disc and the driving wheels are powered by brushless electric motors. Maximum working capacity is 1000 m2 for a 24 h·d-1 working time.

Prototype autonomous mower. The prototype autonomous mower was obtained by modifying a second Husqvarna Automower 310 in order to achieve lower mowing heights, ranging from 0.3 cm to 4.0 cm (Fifs. 3.1 and 3.2). Due to its manual mowing height adjustment, this autonomous mower was the most appropriate machine to start with to obtain the low mowing prototype. In fact, manual adjustment enables the mowing height to be changed with a continuous variation, allowing even for the slightest adjustment. The first modification was to build a 2 cm spacer to lower the cutting disc. The spacer was placed between the shaft coming from the cutting disc engine and the cutting disc itself. The spacer was built from a piece of alloy and lathed to obtain a lightweight and reliable component. The second modification was to remove the loose stainless steel disc placed under the cutting disc. The purpose of the loose disc was to save energy by preventing the grass from coming into contact with the revolving cutting disc. After the spacer was mounted, the loose disc became an obstacle to low mowing as it touched the ground before the cutting disc, thus the cutting disc could not get lower than 1.1 cm. Removing the loose disc allowed the cutting disc to almost reach ground level, and thus to cut at (theoretically) 0.3 cm. The third modification was to stop the three small blades from pivoting by changing the type of screws used to mount them on the cutting disc. The need to stop the blades from pivoting was because very low turfgrass offered more resistance to mowing, thus the pivoting blades ended up being constantly retracted and did not perform a proper cutting.

Figure 3.1. Cutting disc of the ordinary autonomous mower. Note the stainless loose disc and the pivoting cutting blades underneath.

Figure 3.2. Cutting disc of the prototype autonomous mower. The cutting disc has been custom modified by removing the loose disc and securing the three cutting blades to stop them from pivoting.



3.1.3. Experimental field and data collection.

The entire area was 1200 m2 (60 x 20 m) with 48 experimental plots, each of 25 m2 (5x5 m).

At 4, 8, 12 and 16 weeks after treatment (WAT), the following parameters were assessed on the turf:

- turf quality: (1 = poor; 9 = excellent), 6 = acceptable (Morris and Shearman, 2010);
- mowing quality: (1 = unevenly cut edge of leaf blade; 9 = perfectly cut edge of leaf blade), 6 = acceptable;
- disease: (1 = 100% injury; 9 = 0% injury) (Morris and Shearman, 2010);
- weed cover (%): expressed as weed percentage of total ground cover;

At 16 WAT, a 50 cm2 core sample per plot was collected, and the following parameters were determined: Leaf width: 20 fully expanded leaves per plot were collected and attached on a sheet of paper. Digital imagery was acquired using a scanner. Enlarged pictures of the leaves were printed and measured, data were reported as millimeters; Shoot density: direct counting with data reported as shoot cm2.

From 27 June to 17 Oct., working speed, working time, turning time, working capacity, power requirement, electrical energy requirement and gasoline consumption were assessed. A power consumption meter (EL-EPM02HQ; Nedis,'s-Hertogenbosch, The Netherlands) was used to assess the electrical energy requirement. The gasoline tank was filled just before mowing. Gasoline consumption was measured by refueling the tank after mowing.

3.1.4. Statistical analysis. Statistical analyses were carried out with COSTAT software (version 6.400; CoHort Software, Monterey, CA). All data were analyzed by three-way analysis of variance, and an all pairwise Fisher's least significant difference test at the probability level of 0.05.

3.2. Results

There was no significant three-way interaction between factors. However, there was a significant interaction between mowing system (factor B) and mowing height (factor C). N fertilization rate had a significant effect on turf quality, mowing quality, weed cover percentage, leaf width and shoot density. Mowing system had a significant effect on mowing quality and on leaf width but did not affect weed cover percentage. Mowing height had a significant effect on leaf width. Turf disease was not significantly affected by any of the treatments performed.

The interaction between mowing system and mowing height at 4, 8 and 12 WAT showed that turf quality was higher when the turf was mowed by the autonomous mower and also when the turf was mowed at 1.2 cm rather than at 3.6 cm (Table 3.1).

Table 3.1. Mowing system and mowing height interaction effect on manila grass turf quality (1 = poor, 9 = excellent) after 4, 8, 12 and 16 weeks of treatment.

Turf quality

(1-9 scale)

4 weeks after treatment

	Mowing ht (cm)	
Mowing system	1.2	3.6
Autonomous mower	7.1	6.5
Reel mower	6.8	6.3
LSD 0.05	0.2	

8 weeks after treatment

	Mowing ht (cm)	
Mowing system	1.2	3.6
Autonomous mower	7.2	6.2
Reel mower	6.7	5.8
LSD 0.05	0.2	

12 weeks after treatment

	Mowing ht (cm)	
Mowing system	1.2	3.6
Autonomous mower	7.3	6.8
Reel mower	6.9	6.7
LSD 0.05	0.1	

16 weeks after treatment

	Mowing ht (cm)	
Mowing system	1.2	3.6
Autonomous mower	6.9	6.7
Reel mower	6.3	6.6
LSD 0.05	0.1	

The interaction between mowing system and mowing height also showed that the increase in turf quality due to the use of the autonomous mower was higher at 1.2 cm rather than at 3.6 cm (Table 3.1). At 16 WAT, the reel mower has the opposite effect on turf quality than at 4, 8 and 12 WAT. In fact, turf quality was higher at a 3.6 cm than at

1.2 cm mowing height (6.6 vs. 6.3, respectively) (Table 3.1). At 16 WAT, the autonomous mower produced higher turf quality values compared to the reel mower. The autonomous mower also produced superior turf quality at the 1.2 cm mowing height (6.9 vs. 6.7, respectively), in line with the results obtained at 4, 8 and 12 WAT (Table 3.1). Shoot density (Table 3.2) was higher when the turf was mowed at 1.2 cm with both the reel mower and the autonomous mower.

Table 3.2. Mowing system and mowing height interaction effect on manila grass shoot density (shoots/cm2) after 16 weeks of treatment.

	Mowing ht (cm)	
	Shoot density	**(shoots/cm2)**
Mowing system	1.2	3.6
Autonomous mower	12.9	6.4
Reel mower	9.6	5.8
LSD 0.05	0.7	

In addition, the autonomous mower produced a higher shoot density compared to the reel mower when the turf was mowed at 1.2 cm. Moreover, the increase in shoot density due to the use of the autonomous mower vs. the reel mower was higher and significant only at a 1.2 cm mowing height (Table 3.2). All rates of N fertilization improved turf quality at 4, 8, 12 and 16 WAT compared to the control (Table 3.3).

Table 3.3. Nitrogen fertilization mean effect on manila grass turf quality (1 = poor, 9 = excellent), mowing quality (1 = poor, 9 = excellent) and weed cover (%) after 4, 8, 12 and 16 weeks of treatment.

4 weeks after treatment			
Nitrogen fertilization (kg·ha-1)z	**Turf quality (1-9 scale)**	**Mowing quality (1-9 scale)**	**Weed cover (%)**
0	5.8	7.4	3.3
50	6.6	7.2	0.7
100	7.1	6.9	0.3
150	7.4	6.7	0.0
LSD 0.05	0.3	0.2	0.7

8 weeks after treatment			
Nitrogen fertilization (kg·ha-1)z	**Turf quality (1-9 scale)**	**Mowing quality (1-9 scale)**	**Weed cover (%)**
0	5.6	7.3	3.7
50	6.3	7.2	1.0
100	6.8	7.2	0.3
150	7.3	6.9	0.0
LSD 0.05	0.2	0.1	0.4

12 weeks after treatment			
Nitrogen fertilization (kg·ha-1)z	**Turf quality (1-9 scale)**	**Mowing quality (1-9 scale)**	**Weed cover (%)**
0	6.2	7.3	4.0
50	6.8	7.3	1.3
100	7.2	7.3	0.7
150	7.7	7.1	0.0
LSD 0.05	0.2	0.1	0.8

16 weeks after treatment			
Nitrogen fertilization (kg·ha-1)z	**Turf quality (1-9 scale)**	**Mowing quality (1-9 scale)**	**Weed cover (%)**
0	5.9	7.3	6.3
50	6.5	7.3	1.7
100	7.0	7.1	1.0
150	7.3	6.9	0.3
LSD 0.05	0.3	0.2	1.2

Mowing quality behaved inversely in response to N fertilization compared to turf quality at 4, 8, 12 and 16 WAT (Table 3.3). In fact, higher rates of N fertilization decreased mowing quality (Table 3.3). N fertilization also strongly reduced weed cover at 4, 8, 12 and 16 WAT if compared to the control (Table 3.3).

Mean effect of mowing system (Table 3.4) showed that mowing quality was increased by the reel mower if compared to the autonomous mower at 4, 8, 12 and 16 WAT.

Table 3.4. Mowing system mean effect on manila grass mowing quality (1 = poor, 9 = excellent) after 4, 8, 12 and 16 weeks of treatment.

		Mowing quality (1-9 scale)		
Mowing system	**4 weeks after treatment**	**8 weeks after treatment**	**12 weeks after treatment**	**16 weeks after treatment**
Autonomous mower	6.8	6.8	6.8	6.6
Reel mower	7.3	7.5	7.6	7.6
LSD 0.05	0.1	0.2	0.2	0.2

At the end of the trial (16 WAT), all rates of N fertilization produced significantly wider leaves (up to 1.0 mm) compared to the control (0.7 mm) (Table 3.5).

Table 3.5. Nitrogen fertilization mean effect on manila grass leaf width (mm) and shoot density (shoots/cm2) after 16 weeks of treatment.

Nitrogen fertilization (kg·ha-1)	Leaf width (mm)	Shoot density (shoots/cm2)
0	0.7	7.7
50	0.9	8.3
100	0.9	9.3
150	1.0	9.6
LSD 0.05	0.1	1.0

At 16 WAT, shoot density was also significantly increased by N fertilization compared to the control (Table 3.5). When the turf was mowed by the autonomous mower, leaves were significantly thinner compared to the leaves of the turf mowed by the reel mower (Table 3.6).

Table 3.6. Mowing system mean effect on manila grass leaf width (mm) after 16 weeks of treatment.

Mowing system	Leaf width (mm)
Autonomous mower	0.8
Reel mower	1.0
LSD 0.05	0.1

Turf mowed at 1.2 cm mowing height had thinner leaves compared to turf mowed at 3.6 cm mowing height (Table 3.7).

Table 3.7. Mowing height mean effect on manila grass leaf width (mm) after 16 weeks of treatment.

Mowing ht (cm)	Leaf width (mm)
1.2	0.7
3.6	1.0
LSD 0.05	0.1

3.2.1. Operational characteristics of the mowing systems.

The operational characteristics of the reel mower and of both autonomous mowers are shown in Table 3.8.

Table 3.8. Operational characteristics, energy consumption and estimated costs of: ordinary autonomous mower, prototype autonomous mower and reel mower set at 1.2 cm and at 3.6 cm mowing heights. All machines worked on a surface of 300 m^2.

		Autonomous mower	
		prototype	**ordinary**
Parameter	**Unit**	**1.2 cm**	**3.6 cm**
Working width	cm	22.00	22.00
Set daily working time (mowing and recharging)	h·d-1	7.20	7.20
Daily mowing time (no recharging)	h·d-1	3.60	3.80
Electric energy consumption per week	kWh/week	0.86	0.82
Primary energy consumption per week	kWh/week	1.86	1.79
Cost per week	euros/week	11.04y	11.03

		Reel mower	
Parameter	**Unit**	**1.2 cm**	**3.6 cm**
Engine power	kW	2.60	2.60
Working speed	km·h-1	1.50	2.00
Working width	cm	50.00	50.00
Total operative time	h/week	0.80	0.30
Gasoline consumption	L/week	0.58	0.25
Primary energy consumption	kWh/week	5.37	2.32
Cost per week (including labor cost, 25 euros/h)	euros/week	29.70	11.53

The ordinary autonomous mower operational time was 7.2 h·d-1 (50.4 h/week) for a 300 m2 working area (Table 3.8). Total charging time was 3.8 h·d-1 (26.6 h/week), and total mowing time was 3.4 h·d-1 (23.8 h per week). The total energy consumption (boundary wire and battery charging) of the ordinary autonomous mower was 0.82 kWh/week, which corresponds to 1.79 kWh of primary energy (energy from primary sources transformed into electric energy). The power requirement of the boundary wire (which was in ECO mode) was 0.11 kWh per week, since the boundary wire was operative only during mowing and had an average consumption of 4 W. The electric energy consumption required for the battery charging was 0.72 kWh per week. The ordinary autonomous mower had an average power consumption of 27 W during mowing. The walk-behind reel mower set at a 3.6 cm mowing height, was manually operated once per week and covered a working area of 300 m2 in 0.3 h. The average working speed was 2 km·h-1. The walk-behind reel mower was equipped with a gasoline which had a fuel consumption of 0.25 L/week. Primary energy consumption was 2.32 kWh (Table 3.8). The prototype autonomous mower operational time was set at 7.2 h·d-1 (50.4 h per week) for a 300 m2 working area, considering both charging time and mowing time (Table 3.8). Total charging time was 3.6 h·d-1 (25.2 h per week) and total mowing time was 3.6 h·d-1 (25.2 h per week). The total energy consumption (boundary wire and battery charging) of the prototype autonomous mower was 0.86 kWh per week, which corresponds to 1.86 kWh of primary energy (energy from primary sources transformed into electric energy). The power requirement of the boundary wire (which was in ECO mode) was 0.10 kWh per week, since the boundary wire was operative only during mowing and had an average consumption of 4 W. The electric energy consumption required for the battery charging was 0.76 kWh per week. The prototype autonomous mower had an average power consumption of 30 W during mowing. The walk-behind reel mower set at a 1.2 cm mowing height, was manually operated twice a week and covered the working area of 300 m2 in 0.4 h. The average working speed was 1.5 km·h-1. The walk-behind reel mower was equipped with a gasoline engine which had a fuel consumption of 0.58 L/week. Primary energy consumption was 2.73 kWh (Table 3.8). Comparing the weekly management of the two mowing systems (autonomous mowing and manual reel mowing) at both heights, it appears that both autonomous mowers required a much longer mowing time than the reel mower. Both autonomous mowers had a lower energy consumption than the reel mower set at the two mowing heights. Looking at the estimated costs, both autonomous mowers were slightly cheaper than the reel mower (Table 3.8).

3.3. Discussion

For the entire duration of the trial, autonomous mowing produced a superior turf quality compared to the reel mower at both 1.2 and 3.6 cm mowing heights. Conversely, Ferguson and Newell (2010) observed a higher turf quality produced by the Belrobotics (Wavre, Belgium) mod. Bigmow autonomous mower, vs. the reel mower only 6 months after their trial had started. Ferguson and Newell (2010) also found that the autonomous mower produced a lower weed encroachment compared to the reel mower throughout the trial. Conversely, in the previous trial, the autonomous mower produced a slightly higher weed encroachment for creeping types of weeds, which may adapt to a constant mowing height and grow sideways. Typically, N fertilization tends to help improve mowing quality since leaf blades are more turgid and become less difficult to cut (Gibeault and Hanson, 1980). However, in this trial mowing quality was reduced by higher rates of N fertilization. Since manila grass leaves are so rigid (Patton et al., 2017) and more difficult to cut than all other turfgrass species (Turgeon, 2012), the increase in turf biomass produced by higher N fertilization rates required a higher power in order to perform high quality mowing. For this reason, mowing quality was higher when the manila grass turf was mowed with the reel mower, since both autonomous mowers had a less powerful mowing system. Moreover, on a hard-to-mow turfgrass species, the scissor-like action of the reel mower is more effective than the revolving blades of a rotary mower. At a 3.6 cm mowing height, operating the reel mower once a week was enough to respect the one-third rule (meaning that no more than one third of the grass height should be removed in a single mowing) (Turgeon, 2012), but the average turf height throughout the whole week was obviously higher with respect to the turf mower by the ordinary autonomous mower. Grossi et al. (2016) and the authors of the previous trial also observed that the daily mowing carried out by the autonomous mowers on tall fescue (*Festuca arundinacea* Schreb.) kept the average turf height lower if compared to the turf mowed with the rotary mower. However, at 3.6 cm mowing height manila grass showed to be less sensitive to mowing frequency since there was a smaller difference in turf quality between the reel and autonomous mowers compared to the 1.2 cm mowing height. Moreover, 1.2 cm mowing height resulted in a higher turf quality compared to 3.6 cm. This may encourage the use of selected cultivars of manila grass such as ‘Zeon’ for sports turf applications and even golf tees, in line with other authors (Engelke et al., 2002a, 2002b).

Regarding energy consumption, in the previous trial the authors found a much lower primary energy requirement for the autonomous mower compared to a walk-behind gasoline rotary mower (2.98 vs. 4.64 kWh/week). In our trial the autonomous mowers still required less primary energy compared to the reel mower, but the difference in energy requirement was much smaller when mowing was performed at 3.6 cm (1.79 vs. 2.32 kWh/week). Comparing the economic costs of the machines, the prototype autonomous mower was considerably cheaper than the reel mower cutting at 1.2 cm, but the ordinary autonomous mower was just slightly cheaper than the reel mower cutting at 3.6 cm (Table 3.8). The small difference between the cost of the ordinary autonomous mower and the cost of the reel mower is due to the low mowing frequency of the reel mower (once a week). With a higher mowing frequency (as performed for a 1.2 cm mowing height and as performed by our prototype), the ordinary autonomous mower would be considerably cheaper than the reel mower.

Chapter 4

Comparison between different rotary mowing systems: testing a new method to calculate turfgrass mowing quality

In scientific literature, a trial to evaluate mower sharpness has not been carried out using rotary mowers. The aim of this study was to compare the effects of three different turfgrass mowing systems and two different nitrogen rates in order to test a new method developed at the University of Pisa to assess objective turfgrass mowing quality.

4.1. Materials and methods

4.1.1. The experimental trial. The experimental trial was carried out in S. Piero a Grado, Pisa (43°39′ N 10°21′ E, 5 m a.s.l.) in 2017 from May to November on a 14-month-old bermudagrass hybrid (*Cynodon dactylon* [L.] Pers. x *Cynodon. transvaalensis* Burtt-Davy) cv Patriot stand and on a two-year-old tall fescue (*Festuca arundinacea* Schreb.) cv Grande stand. The stands were established on a soil with the following properties: 91% sand, 5% silt, 4% clay, pH 6.5, 1.3 g kg^{-1} of organic matter; EC 0.46 dS m^{-1}, water availability 3.45% *w*/*w*.

On May 22, a two-way randomized block experimental design (A × B) with three replications was carried out. Factor (A) consisted in two nitrogen rates (100 and 200 kg ha^{-1}) applied on May 22 and on August 30 with a rotary spreader using ammonium sulphate (21-0-0). Factor (B) consisted in three different walk-behind mowing systems: (1) gasoline rotary mower with a blade revolving speed of 2800 rpm (GM); (2) battery powered electric mower revving at 3000 rpm (BMS); (3) battery powered electric mower revving at 5000 rpm (BMF). The experimental area of each turf species was 216 m^2, subdivided into three blocks, each of 72 m^2 (6 × 12 m). The single plot was 12 m^2 (3 × 4 m). Working speed was 3 km h^{-1}. All mowers were equipped for clipping removal. The blades of all mowers were sharpened before every assessment with an angle grinder.

4.1.2. Description of the machines.

Gasoline-powered mower. The gasoline-powered mower used in this trial was a Honda mod. HRD 536 HX (Honda France Manufacturing, Ormes, France). The mower was a self-propelled walk-behind rotary mower that can be equipped with mulching blades. The drive is hydrostatic, allowing a speed variation from 0 to 4.7 km h^{-1}. The working width was 53 cm. Cutting height was adjustable from 1.4 to 7.6 cm. The power generator was a four-stroke gasoline engine with an output of 2.7 kW, with an overhead camshaft and a displacement of 160 cm^3.

Battery-powered mower. The battery-powered mower used was a Pellenc mod. Rasion Smart (Pellenc, Pertuis, France), which was a battery-powered self-propelled walk-behind rotary mower. This machine had two counter-revolving cutting blades, for a total working width of 60 cm. The machine was powered by three brushless electric motors, one for the cutting blades and two for the rear driving wheels. Each rear driving wheel was powered by a single electric motor, allowing each driving wheel to move independently from the others. The cutting height could be adjusted from 2.5 to 7.5 cm in increments of 1.0 cm with an electronic device. The speed of the electric drive could be electronically adjusted from 1 to 5 km h^{-1} in increments of 1 km h^{-1}. The revolving speed of the cutting blades could also be electronically adjusted, ranging from 3000 to 5000 rpm. The battery capacity was 1100 Ah.

4.1.3. Experimental field and data collection. Plots were mowed once per week. Mowing height was 3.5 cm. Irrigation was applied as necessary to avoid wilt.

Every three weeks, starting on May 17 for the tall fescue stand and on June 7 for the bermudagrass stand, the following parameters were assessed and determined:

- turf quality with visual rating: (1 = poor; 9 = excellent), 6 considered acceptable (Morris and Shearman, 2010);
- subjective mowing quality assessed with visual rating: (1 = uneven cut edge of leaf; 9 = perfect cut edge of leaf);
- leaf tip damage level (1 = excellent cut, no shredding at all; a greater value of leaf tip damage level indicates more leaf shredding).

To determine the level of leaf tip damage, 12 fully expanded leaves per plot were collected 24 h after being cut with freshly sharpened blades (first mowing since sharpening). Leaves were attached to an A4 sheet. Digital imagery was acquired using a scanner (Epson mod. Stylus Photo RX585) at 4800 dpi resolution. Using Sketchup® software, the pictures of the leaves were enlarged 50 times for measuring (Figures 4.1 and 4.2). The leaf tip damage level was calculated as the ratio between the length (mm) of the actual cut "LE" (with possible shredded tips) and length of the ideal cut "LI" (with no shredding at all) tangential to the edge of the leaf after the cut:

$$\text{Leaf tip damage level} = LE/LI\ [\text{mm/mm}] \qquad (1)$$

When the leaf tip damage level is 1, the mowing quality is excellent (no shredding at all, perfect cut). As leaf tip damage level values increase mowing quality decreases.

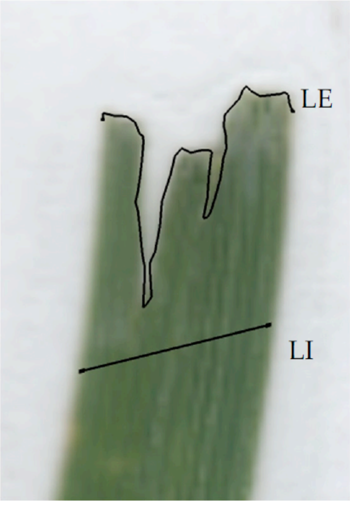


Figure 4.1. Leaf tip damage level = 3.50.

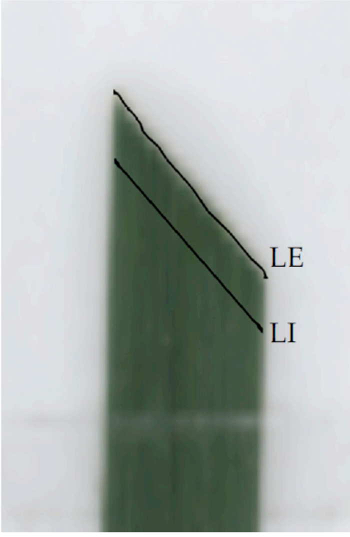


Figure 4.2. Leaf tip damage level = 1.07.

4.1.4. Statistical analysis. Statistical analysis of biometric data was carried out with COSTAT 6.400 (CoHort Software, Monterey, CA, USA). All data were analysed by two-way analysis of variance (ANOVA) and an all pairwise Fisher's least significant difference test (LSD) at the probability level of 0.05.

Leaf tip damage level data and subjective mowing quality data were analysed with a linear correlation and the Pearson correlation coefficient was determined.

4.2. Results

There was no significant interaction between the nitrogen rates and mowing system. The single effects of nitrogen rates and mowing system were statistically significant ($p < 0.05$) for both bermudagrass and tall fescue (Table 4.1).

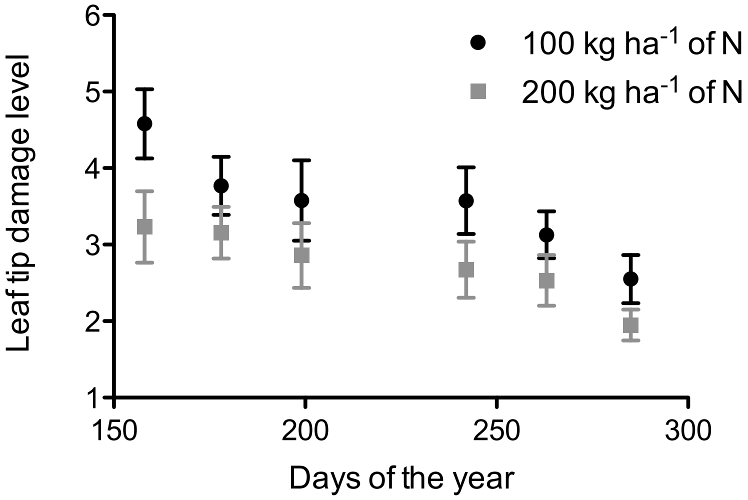
Table 4.1. Results of analysis of variance testing the effects of nitrogen rates, mowing system and their interaction on turf quality, subjective mowing quality and leaf tip damage level. The two species were analysed separately.

Parameter	Nitrogen Rates (A)	Mowing System (B)	(A) × (B)
(a) Bermudagrass hybrid			
Turf quality (June 7)	*	*	ns
(June 27)	*	*	ns
(July 18)	*	*	ns
(August 30)	*	*	ns
(September 20)	*	*	ns
(October 12)	*	*	ns
Subjective mowing quality (June 7)	*	*	ns
(June 27)	*	*	ns
(July 18)	*	*	ns
(August 30)	*	*	ns
(September 20)	*	*	ns
(October 12)	*	*	ns
Leaf tip damage level (June 7)	*	*	ns
(June 27)	*	*	ns
(July 18)	*	*	ns
(August 30)	*	*	ns
(September 20)	*	*	ns
(October 12)	*	*	ns
(b) Tall fescue			
Turf quality (May 17)	*	*	ns
(June 7)	*	*	ns
(June 27)	*	*	ns
(July 18)	*	*	ns
(August 30)	*	*	ns
(September 20)	*	*	ns
(October 12)	*	*	ns
(November 2)	*	*	ns
Subjective mowing quality (May 17)	*	*	ns
(June 7)	*	*	ns
(June 27)	*	*	ns
(July 18)	*	*	ns

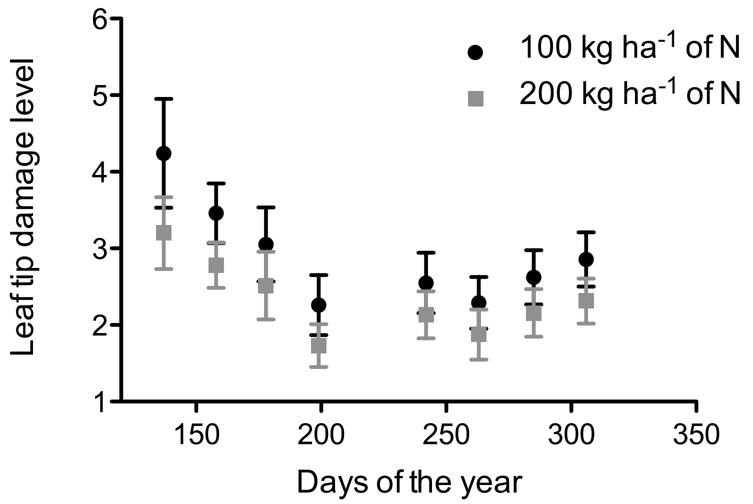
(August 30)	*	*	ns
(September 20)	*	*	ns
(October 12)	*	*	ns
(November 2)	*	*	ns
Leaf tip damage level (May 17)	*	*	ns
(June 7)	*	*	ns
(June 27)	*	*	ns
(July 18)	*	*	ns
(August 30)	*	*	ns
(September 20)	*	*	ns
(October 12)	*	*	ns
(November 2)	*	*	ns

* = $p < 0.05$; ns = not significant.

As expected, higher nitrogen rates increased turf quality for both turf species (data are not shown). Nitrogen rates had an effect on both bermudagrass and tall fescue leaf tip damage levels (Graph 4.1 and Graph 4.2). Regardless of species, leaf tip damage level was higher when 100 kg ha^{-1} nitrogen rate was applied.



Graph 4.1. Effects of nitrogen rates on bermudagrass leaf tip damage level (Equation (1)) on June 7, June 27, July 18, August 30, September 20 and October 12. For each assessment date, leaf tip damage level values were statistically different at $p < 0.05$ when nitrogen rate 100 and 200 kg ha^{-1} were applied.



Graph 4.2. Effects of nitrogen rates on tall fescue leaf tip damage level (Equation (1)) on May 17, June 7, June 27, July 18, August 30, September 20, October 12 and November 2. For each assessment date, leaf tip damage level values were statistically different at $p < 0.05$ when nitrogen rate 100 and 200 kg ha^{-1} were applied.

When the turf was mown with the battery-powered mower revving at 3000 rpm, the turf quality of both turf species was often lower with respect to the turf mown by the gasoline-powered mower and the battery-powered mower revving at 5000 rpm (Table 4.2). Gasoline-powered mower and the battery-powered mower revving at 5000 rpm often produced similar turf quality values.

Table 4.2. Mowing system mean effect on bermudagrass and tall fescue turf quality (1 = poor, 9 = excellent), where BMS = battery-powered mower revving at 3000 rpm, BMF = battery-powered mower revving at 5000 rpm and GM = gasoline-powered mower.

	Turf Species							
	Bermudagrass				**Tall Fescue**			
Mowing system	May 17	June 27	August 30	November 2	June 7	July 18	August 30	October 12
BMS	6.2	6.3	6.3	6.6	7.3	7.1	6.8	6.4
BMF	6.9	6.8	6.8	7.7	8.0	7.8	7.6	7.0
GM	6.9	6.7	6.9	7.4	7.9	7.8	7.7	7.2
LSD *	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

* LSD = least significant difference at $p < 0.05$.

The mowing system also had an effect on the bermudagrass and tall fescue subjective mowing quality (Table 4.3), in particular the battery-powered mower revving at 3000 rpm often produced a lower subjective mowing quality values on both bermudagrass and tall fescue. Conversely, the gasoline-powered mower and battery-powered mower revving at 5000 rpm produced a higher mowing quality on either of the turf species.

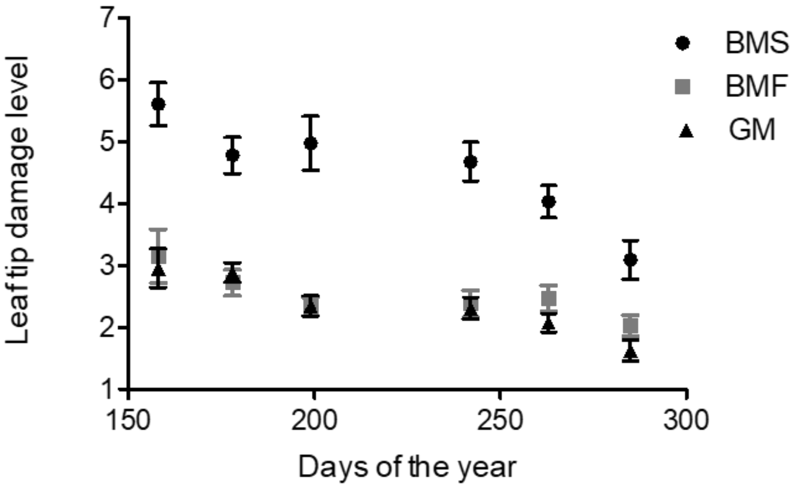
Table 4.3. Mowing system mean effect on bermudagrass and tall fescue subjective mowing quality (1 = poor, 9 = excellent), where BMS = battery-powered mower revving at 3000 rpm, BMF = battery-powered mower revving at 5000 rpm and GM = gasoline-powered mower.

	Turf Species							
	Bermudagrass				**Tall Fescue**			
Mowing system	May 17	June 27	August 30	November 2	June 7	July 18	August 30	October 12
BMS	6.5	6.5	6.7	6.5	6.6	6.5	6.6	6.9
BMF	7.4	7.3	7.3	7.4	7.1	7.3	7.3	7.4
GM	7.3	7.4	7.5	7.4	7.0	7.3	7.3	7.6
LSD *	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

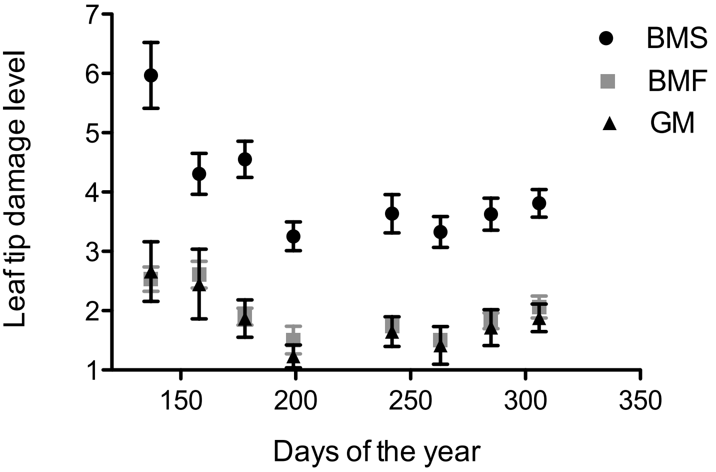
* LSD = least significant difference at $p < 0.05$.

The mowing system also had an effect on the bermudagrass leaf tip damage level (Graph 4.3) and tall fescue leaf tip damage level (Graph 4.4). The leaf tip damage level of both turf species was higher when the turf was mown with the battery-powered mower revving at 3000 rpm.

The gasoline-powered mower and battery-powered mower revving at 5000 rpm produced similar leaf tip damage on both turf species.



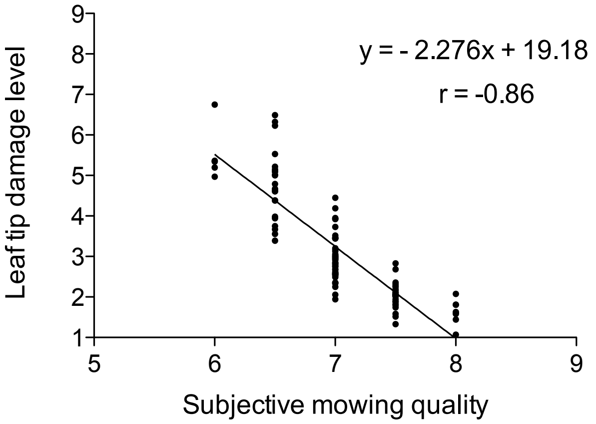
Graph 4.3. Mowing system effect on bermudagrass leaf tip damage level (Equation (1)) on June 7, June 27, July 18, August 30, September 20 and October 12. BMS = battery-powered mower revving at 3000 rpm, BMF = battery-powered mower revving at 5000 rpm and GM = gasoline-powered mower. Letters "a" and "b" indicate statistically different values at $p < 0.05$ for each assessment date.



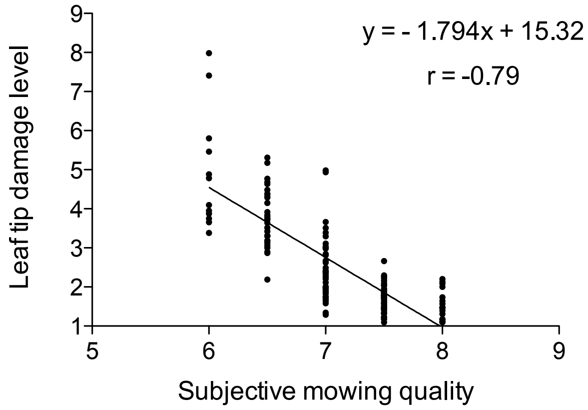
Graph 4.4. Mowing system effect on tall fescue leaf tip damage level (Equation (1)) on May 17, June 7, June 27, July 18, August 30, September 20, October 12 and November 2. BMS = battery-powered mower revving at 3000 rpm, BMF = battery-powered mower revving at 5000 rpm and GM = gasoline-powered mower. Letters "a" and "b" indicate statistically different values at $p < 0.05$ for each assessment date.

Bermudagrass and tall fescue leaf tip damage level values resulted in a significant correlation (r = −0.86 and −0.79, respectively) with subjective mowing quality values

(Graph 4.5 and Graph 4.6, respectively). Lower leaf tip damage level values led to a greater subjective mowing quality for both turf species.



Graph 4.5. Bermudagrass leaf tip damage level (Equation (1)) and subjective mowing quality (1 = poor, 9 = excellent) correlation and Pearson's correlation coefficient (r). All replicates are reported.



Graph 4.6. Tall fescue leaf tip damage level (Equation (1)) and subjective mowing quality (1 = poor, 9 = excellent) correlation and Pearson's correlation coefficient (r). All replicates are reported.

4.3. Discussion

As expected, nitrogen fertilization increased the turf quality and mowing quality of both bermudagrass and tall fescue throughout the whole trial. As observed by Gibeault and Hanson (1980) on perennial ryegrass, nitrogen fertilization helps keep leaf tissues more turgid and less stringy, thus reducing leaf shredding during mowing. Regarding the mowing quality of rotary mowers, a higher revolving speed of the cutting blade usually results in a better mowing quality since this increases the impact on the grass leaves. However, in the present research, the differences in leaf tip damage level showed that the battery-powered mower revving at 3000 rpm produced more leaf shredding than the gasoline-powered mower revving at 2800 rpm on both bermudagrass and tall fescue. In addition, on bermudagrass and tall fescue, the battery-powered mower revving at 5000 rpm and the gasoline-powered mower revving at 2800 rpm showed the same leaf tip damage levels. This is probably because the battery-powered mower had two 30 cm blades, while the gasoline-powered mower had a single 53 cm blade. The same angular mower blade speed corresponds to different peripheral speeds. A higher peripheral speed produces a stronger impact on the grass leaves leading to a higher mowing quality. Setting the gasoline-powered mower at a lower power output in order to reduce power consumption also means slowing down the mower blade speed, thus decreasing the mowing quality and turf quality. Although battery-powered mower revving at 3000 rpm produced an acceptable turf quality, in order to have the best turf quality it is preferable to use the battery-powered mower revving at 5000 rpm or the gasoline-powered mower at full throttle.

Although mowing dates were not considered as a factor, being irrigation only applied to avoid wilt, we observed the trend of bermudagrass and tall fescue leaf tip damage level during the period of the trial. Interestingly, the bermudagrass leaf tip damage levels tended to decrease from the beginning of the trial until the end (from summer to autumn), the tall fescue leaf tip damage levels first decreased (from spring to summer) and then increased until the end of the trial (from summer to autumn), following the turfgrass growth rate shown by Turgeon (2012). Graph 4.5 and Graph 4.6 also show a correlation between the leaf tip damage levels and subjective mowing quality values. A high leaf tip damage level corresponds to a lower subjective mowing quality. However, even if there is a correlation between leaf tip damage level and visual assessment, leaf tip damage level is totally independent from the person that does the assessment and gives more realistic information of the mowing machine performances. Visual assessment may be influenced by the colour of the turf or by the intensity of light, while leaf tip damage level, being calculated from measured data, is not influenced by external factors. Moreover, leaf tip damage level can be applied to any turf species since the shape and the colour of the leaves do not affect the measurements of the leaf tip. Howieson and Christians (2001) also found that a higher mowing injury corresponded to lower visual assessment mowing quality values. However, Howieson and Christians (2001, 2006) only measured the perimeter of necrotic leaf areas without considering the width of the leaf and thus did not develop a fully objective method to assess mowing quality. In fact, two leaves with the same percentage of necrotic area (similar shredding) but with different leaf widths will give different perimeter values despite the similar shredding indicating a similar mowing quality. Howieson and Christians (2001, 2006) found that ragged turf leaves contain less chlorophyll than optimally cut turf leaves. The chlorophyll content is important both for turf health and for optimal turf quality. More chlorophyll leads to a higher turf quality. In fact, in this trial when the mowing quality was lower, the turf colour was often not optimal, resulting in a lower overall turf quality.

Chapter 5

Manila grass overseeding with cool season turfgrasses: effects on ground cover and quality produced by an autonomous mower modified for low mowing height

The aim of this trial was to compare the performance of different cool season turfgrasses overseeded on a manila grass turf over a 2-year period, evaluating their persistence as ground cover, overall quality, turf color and shoot density, mowed with a prototype-autonomous rotary mower cutting at 1.0 cm. In scientific literature, no autonomous mower has ever been tested at a low mowing height on an overseeded warm season turfgrass. The trial was carried out to simulate a golf tee, overseeded with cool season turfgrasses, in low input fertilization rates and with one of the most difficult turf species to mow; i.e., manila grass.

5.1. Materials and methods

5.1.1. The experimental trial. The trial was carried out in the experimental station “Rottaia” of Centre for Research on Turfgrass for Environment and Sports (CeRTES), Department of Agriculture Food and Environment, University of Pisa, located at S. Piero a Grado, Pisa (43°40’ N, 10° 19’ E, 6 m. a.s.l.), Italy, from October 2016 to October 2018. A mature stand of manila grass (*Zoysia matrella* cv Zeon), established on silt-loam soil (Calcaric Fluvisol, 28% sand, 55% silt and 17% clay) with a pH of 7.8 and 18 g kg−1 organic matter, was scalped and verticut on October 2, 2016. A top-dressing with 5 mm of silica-sand was carried out afterwards.

5.1.2. Experimental field and data collection. On October 20, 2016, 11 different cool season turfgrasses and a dwarf white clover (*Trifolium repens* cv Microclover) were overseeded manually (Table 5.1), arranged in a randomized block experimental design with 4 replications. Plots had a 1.5 m^2 (1.0 x 1.5 m) surface area.

Table 5.1. List of species overseeded on manila grass.

Species	Cultivar	Seed rates (g m^{-2})
Agrostis stolonifera	L93	5
Festuca arundinacea	Essential	50
Festuca rubra commutata	Greenmile	25
Festuca rubra rubra	Heidrun	25
Festuca rubra tricophylla	Valdora	25
Lolium multiflorum	Axcella	50
Lolium perenne	Berlioz	50
Lolium perenne	Columbine	50
Poa pratensis	Yvette	15
Poa supina	Supreme	15
Poa trivialis	Sabrena	15
Trifolium repens	Microclover	20

To encourage seed germination, the entire trial area was covered with Edilfloor Thermofelt geotextile (30 g m^{-2} specific weight) for 20 days after seeding and irrigated daily.

At sowing date 50 kg ha^{-1} of N, 92 kg ha^{-1} of P and 50 kg ha^{-1} of K were distributed. In 2017 and 2018, 50 kg ha^{-1} of P, 100 kg ha^{-1} of N and 50 kg ha^{-1} of K were distributed each year, splitted in two applications. First mowing was carried out on December 20, 2016, with a rotary mower (Honda mod. HRD 536 C; Honda France manufacturing; Ormes, France) set at 6.0 cm mowing height, while following mowings were carried out with a reel mower (McLane mod. 20-3.5 RP-7; McLane; Paramount, CA) once a week, with mowing height being gradually reduced to 1.0 cm.

Figure 5.1. Overseeded cool season turf species on manila grass before the installation of the autonomous mower.

From February 13, 2017, automatic mowing was performed with an autonomous mower (Husqvarna mod. Automower 310; Husqvarna; Stockholm, Sweden) custom modified to cut from 0.5 to 2.5 cm. Mowing height was set at 1.0 cm and mowing time was set at 7 h d^{-1}.

Every month, from February 2017 to October 2018, the following parameters were visually assessed:

- Ground cover (%): as the percentage of ground covered by the overseeded species and by manila grass.
- Weed cover (%):as the percentage of ground covered by weeds;
- Turf quality: (1 = poor; 9 = excellent), with 6 considered acceptable (Morris and Shearman, 2018).
- Turf color: (1 = straw brown, 6 = light green and 9 = dark green). (Morris and Shearman, 2018).

On May 25, 2017, and on May 16, 2018 one 50 cm^2 core sample per plot was collected and shoot density was determined by direct counting with data reported as number of shoots per square centimeter.

5.1.3. Statistical analysis. Statistical analysis was carried out with a COSTAT 6.400 software (CoHort Software, Monterey, CA, USA). All data were analyzed by one-way ANOVA, and an all pairwise Fisher's Least Significant Difference (LSD) test at the probability level of 0.05.

5.2. Results

5.2.1. Weed cover

Weed cover percentage resulted lower than 1% during all the trial period (data not shown) probably due to the extreme competition exerted by manila grass against weeds.

5.2.2. Ground cover

During the first year *Lolium* entries showed a very high ground cover at the beginning of the trial (from 69% to 84%), but at the end of the summer their ground cover strongly decreased (Table 5.2), and nil differences were found between *Lolium perenne* cultivars. *Poa* entries and *Festuca arundinacea* ground cover also strongly decreased during summer, while *Agrostis stolonifera* increased its ground cover throughout the summer (from 61% to 78%). *Trifolium repens* ground cover increased during all the first year (from 36% to 99%) (Table 5.2).

Table 5.2. Cool season species and *Zoysia matrella* ground cover percentages during the first year of the trial (2017) on February 20, April 3, June 7 and September 2.

SPECIES	CULTIVAR	20-Feb		3-Apr		7-Jun		2-Sep	
		Cool Species (%)	*Zoysia matrella* (%)	Cool Species (%)	*Zoysia matrella* (%)	Cool Species (%)	*Zoysia matrella* (%)	Cool Species (%)	*Zoysia matrel* (%)
Agrostis stolonifera	L93	40	*	62	38	61	39	78	22
Festuca arundinacea	Essential	55	*	45	55	46	54	4	96
Festuca rubra commutata	Green mile	40	*	57	43	55	45	61	39
Festuca rubra rubra	Heidrum	35	*	61	39	58	42	52	48
Festuca rubra tricophylla	Valdora	49	*	47	53	51	49	65	35
Lolium multiflorum	Axcella	69	*	43	57	10	90	0	100
Lolium perenne	Berlioz	81	*	61	39	47	53	11	89
Lolium perenne	Columbine	84	*	72	28	52	48	17	83
Poa pratensis	Yvette	36	*	47	53	29	71	19	81
Poa supina	Supreme	30	*	44	56	39	61	4	96
Poa trivialis	Sabrema	55	*	80	20	7	93	32	68
Trifolium repens	Microclover	36	*	61	39	89	11	99	1
LSD $P \leq 0.05$		*16*	*	*21*	*21*	*18*	*18*	*15*	*15*

* = Dormant

Zoysia matrella green up started on March 10.

After the green-up *Zoysia matrella* ground cover ranged from 20% to 57%, filling up the empty spaces formerly covered by the cool season species. *Zoysia matrella* ground cover progressively increased during summer as most of the cool season species ground cover decreased apart from *Trifolium repens*, *Agrostis stolonifera*, *Festuca rubra tricophylla*. *Trifolium repens* did not allow *Zoysia matrella* to expand, as only 1% of *Zoysia* was left after the summer (Table 5.2). At the beginning of the second year of the trial *Lolium* entries showed a ground cover ranging from 20% to 41% (Table 5.3), but at the end of the trial *Lolium* entries ground cover was close to 0. *Poa* entries had a slightly higher ground cover at the beginning of the second year (ranging from 47% to 48%), but at the end of the trial ground cover was also close to 0 (Table 5.3).

Table 5.3. Cool season species and *Zoysia matrella* ground cover percentages during the second year of the trial (2018) on February 9, April 6, June 1 and October 3.

SPECIES	CULTIVAR	9-Feb		6-Apr		1-Jun		3-Oct	
		Cool Species (%)	*Zoysia matrella* (%)	Cool Species (%)	*Zoysia matrella* (%)	Cool Species (%)	*Zoysia matrella* (%)	Cool Species (%)	*Zoysia matrella* (%)
Agrostis stolonifera	L93	67	*	66	34	31	69	33	67
Festuca arundinacea	Essential	10	*	11	89	3	97	5	95
Festuca rubra commutata	Greenmile	80	*	79	21	30	70	26	74
Festuca rubra rubra	Heidrun	80	*	79	21	26	74	19	81
Festuca rubra tricophylla	Valdora	86	*	85	15	35	65	30	70
Lolium multiflorum	Axcella	20	*	20	80	5	95	0	100
Lolium perenne	Berlioz	35	*	35	65	8	92	3	97
Lolium perenne	Columbine	41	*	41	59	10	90	3	97
Poa pratensis	Yvette	47	*	45	55	16	84	3	97
Poa supina	Supreme	48	*	40	60	11	89	0	100
Poa trivialis	Sabrena	47	*	45	55	5	95	0	100
Trifolium repens	Microclover	91	*	69	31	71	29	55	45
LSD $P \leq 0.05$		*19*	*	*21*	*21*	*11*	*11*	*14*	*14*

* = Dormant

Zoysia matrella green up started on March 7.

Festuca arundinacea had a very low ground cover during all the second year, while the ground cover of *Festuca rubra* cultivars was very high at the beginning of the second year (ranging from 80% to 86%) and decreased during summer. *Agrostis stolonifera* ground cover also decreased during the summer (from 67% to 33%), showing a major competition of manila grass. *Trifolium repens* showed a very high ground cover at the beginning of the second year while decreased at the end of the summer. After the green-up *Zoysia matrella* ground cover ranged from 15% to 89% and progressively increased since all cool season species decreased their ground cover during summer (Table 5.3). At the end of both years *Trifolium repens* had the highest ground cover, followed by *Agrostis stolonifera* and by *Festuca rubra* cultivars (Table 5.2, Table 5.3).

5.2.3. Turf quality

During the first year of the trial turf quality of most cool season species increased from February to September, with the exception of *Poa supina*, *Lolium multiflorum* and *Festuca arundinacea*, since their ground cover was lower than 5%. At the beginning of the trial, only *Lolium perenne* cultivars and *Festuca rubra* cultivars had an acceptable turf quality. *Trifolium repens* had the lowest turf quality while *Lolium perenne* cultivars had the highest (Table 5.4).

Table 5.4. Cool season species turf quality (1 = poor, 9 = excellent) during the first year (2017) on February 20, April 3 and September 2 and during the second year (2018) on February 9, April 6 and October 3.

		2017			2018		
SPECIES	CULTIVAR	20-Feb	3-Apr	2-Sep	9-Feb	6-Apr	3-Oct
		Quality (1-9)			Quality (1-9)		
Agrostis stolonifera	L93	5.5	6.3	7.0	5.4	5.4	5.6
Festuca arundinacea	Essential	5.4	4.8	*	5.3	6.0	*
Festuca rubra commutata	Greenmile	6.2	6.3	7.3	7.0	6.8	7.6
Festuca rubra rubra	Heidrun	6.4	6.8	7.5	6.8	6.1	7.5
Festuca rubra tricophylla	Valdora	6.4	6.6	7.4	6.8	6.4	7.5
Lolium multiflorum	Axcella	4.9	4.8	*	5.0	6.0	*
Lolium perenne	Berlioz	6.5	6.9	7.1	6.4	6.6	*
Lolium perenne	Columbine	6.6	6.8	7.0	6.2	6.3	*
Poa pratensis	Yvette	5.4	5.9	7.1	5.8	6.3	*
Poa supina	Supreme	5.0	5.4	*	5.1	5.9	*
Poa trivialis	Sabrena	5.9	6.5	7.4	5.0	5.5	*
Trifolium repens	Microclover	3.8	4.5	6.1	6.0	6.0	6.4

LSD $P \leq 0.05$	*1.2*	*1.6*	*1.1*	*0.8*	*1.0*	*0.9*

* = not evaluated (Ground cover less than 5%)

At the end of the first year *Trifolium repens* still had the lowest turf quality (6.1) while *Festuca rubra* cultivars and *Poa trivialis* had the highest turf quality (from 7.3 to 7.5). At the beginning of the second year of the trial only *Festuca rubra* cultivars and *Lolium perenne* cultivars had a good turf quality (Table 5.4). At the end of the trial *Festuca rubra* cultivars had the highest turf quality (from 7.5 to 7.6) while *Agrostis stolonifera* and *Trifolium repens* had the lowest turf quality (5.6 and 6.4, respectively). The turf quality of the other cool season species was not evaluated at the end of the trial since their ground cover was under 5% (Table 5.4).

5.2.4. Turf color

At the beginning of the first year of the trial turf color of most cool season species was acceptable with the exception of *Lolium multiflorum* (Table 5.5).

Table 5.5. Cool season species turf color (1 = poor, 9 = excellent) during the first year (2017) on February 20, April 3 and September 2 and during the second year (2018) on February 9, April 6 and October 3.

		2017			2018		
SPECIES	CULTIVAR	20-Feb	3-Apr	2-Sep	9-Feb	6-Apr	3-Oct
		Color (1-9)			Color (1-9)		
Agrostis stolonifera	L93	6.4	6.5	6.0	5.2	5.1	5.5
Festuca arundinacea	Essential	6.3	6.6	*	6.0	6.0	*
Festuca rubra commutata	Greenmile	6.6	6.8	6.7	6.2	5.8	6.7
Festuca rubra rubra	Heidrun	6.8	6.6	6.6	5.8	5.5	6.6
Festuca rubra tricophylla	Valdora	6.8	6.9	6.8	5.7	5.3	6.0
Lolium multiflorum	Axcella	4.9	5.9	*	6.0	6.0	*
Lolium perenne	Berlioz	5.8	6.8	6.9	5.8	5.5	*
Lolium perenne	Columbine	6.1	6.6	6.8	5.7	5.8	*
Poa pratensis	Yvette	6.9	6.8	6.9	6.3	6.3	*
Poa supina	Supreme	6.5	6.6	*	6.2	6.0	*
Poa trivialis	Sabrena	6.8	7.0	6.8	6.0	6.0	*
Trifolium repens	Microclover	6.1	7.0	7.3	7.0	6.0	7.1
LSD $P \leq 0.05$		*0.5*	*0.7*	*0.6*	*0.4*	*0.5*	*0.7*

* = not evaluated (Ground cover less than 5%)

At the end of the first year, turf color of all cool season species evaluated was acceptable. *Agrostis stolonifera* had the lowest color score (6.0) and *Trifolium repens* had the highest (7.3). At the beginning of the second year, only *Trifolium repens* had a good turf color (7.0), while the other cool season species ranged from 5.2 to 6.3 (Table 5.5). From February to April turf color scores of most species decreased. *Agrostis stolonifera* had the lowest score (5.1) and *Poa pratensis* had the highest (6.3). At the end of the second year only *Agrostis stolonifera* had a non-acceptable turf color, while *Festuca rubra* cultivars and *Trifolium repens* ranged from 6.0 to 7.1.

5.2.5. Shoot density

Shoot density during the first year varied from 5.5 to 12.9 shoots cm^{-2} (Table 5.6).

Table 5.6. Cool season species shoot density (shoots cm^{-2}) during the first year of the trial on May 23, 2017 and the second year of the trial on May 16, 2018.

SPECIES	CULTIVAR	23-May 2017	16-May 2018
		Shoot density (n° cm^{-2})	Shoot density (n° cm^{-2})
Agrostis stolonifera	L93	9.2	6.6
Festuca arundinacea	Essential	6.4	0.6
Festuca rubra commutata	Greenmile	11.6	6.7
Festuca rubra rubra	Heidrun	10.9	6.0
Festuca rubra tricophylla	Valdora	12.3	6.6
Lolium multiflorum	Axcella	5.5	0.4
Lolium perenne	Columbine	9.2	2.4
Lolium perenne	Berlioz	11.4	3.2
Poa pratensis	Yvette	9.5	2.1
Poa supina	Supreme	10.7	2.1
Poa trivialis	Sabrena	1.9	3.0
Trifolium repens	Microclover	#6.0	#3.4
LSD $P \leq 0.05$		*4.3*	*1.8*

stalks

Lolium multiflorum and *Festuca arundinacea* had the lowest shoot density (5.5 and 6.4 shoots cm^{-2}, respectively) while *Poa trivialis* and *Festuca rubra tricophylla* had the highest (12.9 and 12.3 shoots cm^{-2}, respectively). During the second year of the trial shoot density of all species was lower, ranging from 0.4 to 6.7 shoots cm^{-2} (Table 5.6). Also, during the second year *Lolium multiflorum* and *Festuca arundinacea* had the lowest shoot density (0.4 and 0.6 shoots cm^{-2}, respectively), while the highest shoot density belonged to *Festuca rubra commutata* (6.7 shoots cm^{-2}), *Agrostis stolonifera* (6.6 shoots cm^{-2}) and *Festuca rubra tricophylla* (6.6 shoots cm^{-2}).

5.3. Discussion

As expected, not all cool season species managed to withstand the low mowing height performed by the prototype autonomous mower and the competition with manila grass. Ground cover percentage of most turf species was lower during the second year of the trial. Moreover, during both years, ground cover percentage of most species decreased at the end of the summer. The trend of the ground cover of *Lolium multiflorum* was very similar to what Volterrani et al. (2004) had previously observed on bermudagrass, starting at 69 % ground cover at the beginning of the first year and at 20% ground cover at the beginning of the second year, at the end of the summer of both years *Lolium multiflorum* ground cover percentage was 0%. *Lolium perenne* showed a higher resistance to low mowing heights as confirmed by Volterrani et al., 2009, however it also strongly decreased its ground cover during summer. *Festuca arundinacea* also showed a poor resistance to low mowing heights, although Grossi et al. (2004) observed that some improved turf-type cultivars of tall fescue turf were positively affected by reduced mowing height, with the highest turf quality values were reported for lower mowing heights. *Lolium perenne*, *Lolium multiflorum* and *Poa supina* showed to suffer because of the competition offered by manila grass, although *Lolium perenne* and *Lolium multiflorum* are both often chosen to overseed bermudagrass (*Cynodon dactylon* L.) turfs (Serensits et al., 2011; Aldahir et al., 2015). *Festuca rubra* sp. cultivars showed to be more competitive against manila grass, probably due their rhizomatous habitus, apart *Festuca rubra commutata* and showed a higher ground cover at the beginning of the second year compared to the other cool season species apart for *Trifolium repens* and *Agrostis stolonifera*. The species that suffered less from manila grass competition was the dwarf clover, especially at the end of the first year when its ground cover was 99%, even if at the end of second year manila grass reached 45% of green ground cover. This species had been chosen as a control since it does not belong to the Poaceae family, however it proved to be too competitive even for manila grass, probably due to its high seed rate establishment (McCurdy et al., 2013) associate with the low fertilization program adopted. Dwarf clover turf quality remained quite scarse at beginning of the trial, even if it was acceptable during the second year. The best turf quality was achieved by *Festuca rubra* sp. cultivars and *Lolium perenne* cultivars. Shoot density of all cool season species was higher at the end of the first year rather than at the end of the second year. This was probably due to the very strong competition offered by manila grass, that progressively managed to expand against the cool season species. The very low shoot density of *Lolium multiflorum* and *Festuca arundinacea* at the end of the second year showed that these species did not adapt to withstand low mowing heights and manila grass competition. Although other studies have shown poor summer recovery of zoysiagrass after overseeding (Razmjoo et al., 1996; Zhang et al., 2008), our results indicate that after two year only dwarf clover caused an incomplete recovery of manila grass.

Chapter 6

Conclusions

In this PhD thesis several findings regarding turf management have been highlighted. Concerning autonomous mowers, in all the trials these machines worked silently and did not produce dust or polluting gasses. Preventing noise, allergens and pollution is one of the major targets in urban areas. Autonomous mowers also improved energy saving and required significantly lower human labour than walk-behind mowers. This may be an important advantage for people who do not have the time or physical capacities to care for their lawn. Compared to rotary mowers, autonomous mowers have shown to perform slightly less control of creeping weeds, however nitrogen fertilization helps to withstand weed expansion since a healthier turf offers ore competition. Turf quality, instead, is improved by the autonomous mowers since a lawn that is mown once a week (as commonly happens with rotary mowers) looks neat and tidy after mowing, but not over the following days. Thus, despite possibly having a slightly larger creeping weed species, a lawn mowed by an autonomous mower will always have the optimal quality and appearance if properly fertilized. Further research could be needed to test the effects of autonomous mowers on vertically developing weeds and on turf quality at a taller mowing height. Comparing autonomous mowers and reel mowers, especially on hard-to-mow turfgrass species, it has been observed that autonomous mowers improved overall turf quality and shoot density. However, the scissor-like action of the reel mower gave a better mowing quality. The prototype autonomous mower working at a 1.2 cm mowing height produced a higher quality turf and increased shoot density compared both to the reel mower and to the machines working at a 3.6 cm mowing height. These results showed that autonomous mowers have the potential to perform optimal turf maintenance not only of home lawns and large ornamental areas, but also of quality sports turfs as golf tees and golf roughs, even on tough-to-mow turfgrass species. Autonomous mowers are not intended to replace human labor, instead they could help to obtain the highest turf quality, thus saving time and allowing greenkeepers to care for other specialized maintenance operations (i.e., seeding, fertilization, and weeding). Further research is needed to determine whether autonomous mowers can perform mowing at an even lower mowing height such as on golf greens, where daily mowing is mandatory. Testing the prototype autonomous mower at 1.0 cm mowing height on a manila grass turf overseeded with cool season turfgrass species has highlighted that, after a two-year period, the best turf quality was achieved by *Festuca rubra spp*. cultivars. Overseeding has become a standard industry practice for golf courses and athletic fields receiving significant traffic during winter season in the southern United States (Fontanier and Steinke, 2017). In many cases turf quality increased after manila grass green-up since the combination of both cool season and warm season species gave a higher quality to the turfgrass especially because of the finer leaf texture and the overall shoot density. Moreover, recovery of manila grass ground cover was satisficing, even if during the first year it was poor, probably because of severe scalping and thick sand top-dressing. These encouraging results showed that is possible to obtain a useful and sustainable intercropping for a two-year period between some cool season species and manila grass. Overseeding manila grass with some cultivars of *Festuca rubra spp*. could be suitable for low-input management of a golf tee, looking forward to the reduction of chemical inputs allowed on turfs by the European regulations. Concerning mowing quality, the new method to assess objective mowing quality is called leaf tip damage level. Leaf tip damage level values are not assessed but calculated from measurements of the leaf tip, thus giving an objective result. Leaf tip damage level values slightly above 1 correspond to the best visual mowing quality scores. Higher leaf tip damage level values correspond to lower visual mowing quality scores. These results demonstrated that the leaf tip damage level is a very useful and objective tool for the evaluation of mowing quality. The new method could also be improved by measuring the extension of the necrotic leaf area due to mower blade shredding and by carrying out a correlation with the values of the perimeter of the leaf tip after mowing. From the study of three mowing systems, it has been possible to see that a higher peripheral mower blade speed resulted in a higher turf quality and mowing quality values, irrespectively of the type of engine employed.

A future trial could develop specific software that automatically determines the exact mowing quality of grass leaves by just acquiring a digital image of the leaf tip.

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