Robotic Lawnmower Saves Labor and Operation Costs in a Pear (Pyrus pyrifolia) Orchard

Muhammad Zakaria Hossain*, Korenari Takahashi**, and Masakazu Komatsuzaki**

*United Graduate School of Agricultural Science, Tokyo University of Agriculture and Technology
**Center for International Field Agriculture Research & Education College of Agriculture, Ibaraki University

There has been an increased interest and potential demand for agricultural robots in recent years to help reduce labor and operation costs. Therefore, the performance of a robotic lawnmower for weed management in a pear (Pyrus pyrifolia) orchard was investigated at the Center for International Field Agriculture Research & Education (CIFARE) of Ibaraki University, Japan, in 2018–2019. It was found that the average weed height was lower in the robotic lawnmower-managed plot (35–87 mm) than that in the riding mower-managed plot (approximately 15–281 mm) throughout the cropping period (from flowering to harvesting). The robotic lawnmower was superior to the riding mower, brush cutter, and walk-behind mower in terms of energy consumption (6 vs. 13, 56, and 18 kWh 1000 m$^{-2}$ month$^{-1}$), costs (133 vs. 206, 1122, and 277 JPY 1000 m$^{-2}$ month$^{-1}$), CO$_2$ emissions (3 vs. 3.4, 14, and 4.5 kg 1000 m$^{-2}$ month$^{-1}$), and labor requirements (28 vs. 40, 604, and 62 min 1000 m$^{-2}$ month$^{-1}$). Because the robotic lawnmower can be used without manual operation, it reduces the human workload (in terms of the increased ratio of the heart rate (IRHR)) in comparison with operating a riding mower (IRHR: 1.2), brush cutter (IRHR: 1.5), and walk-behind mower (IRHR: 1.4). Therefore, given that the average age of the population is higher in Japan than elsewhere in the world and this trend is continuing to increase, the use of robotic lawnmowers can be useful for weed management in orchards.

**Key Words**: conventional machine mowing, management cost, labor requirement, robotic lawnmower, weed height.

1. Introduction

Weeds can reduce cropping efficiency in orchards through direct competition for resources and can also serve as alternate hosts or provide habitat for insects, mites, vertebrate pests, and diseases, exacerbating issues associated with these pests (Ashigh and Marquez, 2010). Furthermore, weeds can reduce the irrigation efficiency by physically blocking or encroaching on irrigation furrows. Consequently, applications of growth hormones and foliar and soil nutrients are more efficient, and cultural operations (e.g., irrigation, thinning, pruning, training, and harvesting) are easier when weeds are managed (Fennimore et al., 2014).

Mechanical mowing is the most popular weed...
control method in orchards (Fennimore et al., 2014), with riding mowers, walk-behind mowers, and brush cutters most commonly being used. Riding mowers have increased field coverage but are quite difficult to operate in orchards, requiring careful attention to avoid hitting the trunks and branches of the trees with their spreading canopies. Moreover, riding mowers can cause soil compaction, resulting in hardpan if they are used for a long time. Walk-behind mowers are also popular for use in orchards but take longer to cover the field than riding mowers. Finally, brush cutters have the least field coverage than the other machines and also require intensive labor and careful attention by the operator to avoid accidents. All of these machine operations can be dangerous for the operator if appropriate safety measurements are not considered; for example, despite the United States Consumer Products Safety Commission pushing for the establishment of safety standards for walk-behind mowers in 1982 and riding mowers in 1986, approximately 80,000 power-mower-associated injuries were estimated to have occurred in the US by 2000 (Robertson, 2003) and more than 14,000 people were estimated to have visited hospital emergency rooms due to accidents associated with riding lawn mowers in 2016 (Consumer Product Safety Commission, 2016). In addition, significant increases in the average age of the Japanese population make it even more important that the safest approaches for promoting sustainable agriculture are developed.

Recent advances in robotic technology have created extensive opportunities for weed management and precision agriculture. Robotics may become a key element in modern weed control as it can provide safe, low cost, and efficient cutting systems (Peruzzi et al., 2017). The use of robots for orchard weed management can be an excellent option in terms of labor, operation costs, and safety, but very little information is currently available about robotic mowing in orchards. However, orchard weed management can be similar to lawn management due to the large distance between plants. Husqvarna is the pioneering and leading robot mower producing company for lawn management and produces very light robot mowers (generally 11.5–13.9 kg) which show less energy consumption, energy cost and labor involvement than that of the gasoline-powered mower (Grossi et al., 2016; Pirchio et al., 2018a). Therefore, a robotic lawn mower (20 kWh month⁻¹, 13.2 kg, 18 V/5.2 Ah Li-ion battery, 4.2 A DC, 2300 rpm blade, Automower® 430X, Husqvarna, Sweden) was installed in the pear orchard at the Center for International Field Agriculture Research & Education (CIFARE), Ibaraki University, Japan in 2017. The field performance of the robotic mower was studied between 2018 and 19. Our main objectives were to study the performance of the robotic lawn mower in terms of weed control, energy consumption, energy cost, CO₂ emissions, and workload (operator’s heart rate), etc. in the pear orchard. The abovementioned performances of the robotic lawn mower were compared with a riding mower (weeds were managed by riding mower). Moreover, the performances of the robotic lawn mower were also compared with other popular conventional mechanical mowers like brush cutter, and walk-behind mower to find out whether robotic lawn mower perform better than conventional mowers or not.

2. Materials and Method

This research was conducted in a pear (Pyrus pyrifolia) orchard at CIFARE, Ibaraki University, Japan (36°01′55″N, 140°12′46″E) between 2018 and 19. The major weeds in this orchard are Trifolium subterraneum, Elymus repens, Taraxacum erythrospermum, Rumex crispus, Eleusine indica, and Cyperus esculentus, which include both summer and winter weeds. In this region, pear flowering starts in April, and harvesting is finished by October.

The orchard consists of three plots, each of which has a different area, tree density, agronomic practice, slopes, and weed management technique (Table 1). The pear trees in plot 1 have been grafted together with the stems of several adjacent trees, allowing them to share nutrients through the stem even if the roots of any particular tree die (Inoue et al., 2012). By contrast, the trees in plots 2 and 3 have been grown separately using conventional agronomic practices. In the present study, the weeds in plots 1 and 2 were
controlled using a robotic lawnmower while those in plot 3 were controlled with a riding mower (15.6 kW, 4 strokes, 280 kg, 975 mm mowing width, ARM980, Iseki, Japan) (Fig.1). The types of weed were similar among these plots. The robotic lawnmower worked for 24 h everyday including charging time (8 hours a day) while the riding mower worked almost two times per month between April and October.

The robotic lawnmower that was trialed in this study has a working capacity of 3200 m$^2$ ± 20% and is navigated using the global positioning system (Husqvarna, 2019), allowing it to mow without requiring an operator. This mower works inside an area that is delimited by a shallow-buried boundary wire that generates an electro-magnetic fence (Grossi et al., 2016) and is laid around objects and plants that the autonomous mower must avoid. Sensors on the mower can detect when it approaches the boundary wire, causing it to stop and change direction. If the wire is not positioned around obstacles, the robot will hit them and then reverse and select a new direction. The mower’s charging station is positioned on the boundary and it will start to search for this when the charge level of the battery becomes too low (Hicks et al., 2000). The cutting part of the robotic lawnmower can be adjusted between 2 and 6 cm but was fixed at 6 cm in this study to prevent the blade from striking stones, fruit, and mud. Furthermore, Dernoeden et al. (1993) suggested that mowing heights of 3.2 and 5.5 cm led to higher levels of crabgrass ($Digitaria ischaemum$) infestation, which is undesirable in orchards, while higher mowing levels (8.8 cm) gave the best management results.

To determine the efficiency of robotic lawnmower and riding mower, the weed height and biomass were measured in each plot just before and after 1–3 days of cutting by the riding mower, to gain maximum and minimum weed canopy values for each month.
weed height was measured using a laser distance meter (DISTO™ A6; Leica). The laser meter is attached at the end of a 1–m stick so that the laser focuses on the top weed canopy when the stick is perpendicular to the ground. The weed height was calculated by subtracting the stick height from the reading value on the display. On the same day, the weeds in 23 × 23 cm wooden quadrats placed at three random points in each plot were cut just above the root with scissors and collected into a paper bag (Komatsuzaki and Wagger, 2015). The weeds were then dried in an oven (DKN 601; Yamato) at 65°C for 2 days and their final dry weight was measured using an electronic balance (UX4200S; Shimadzu). The average dry biomass was then calculated for each plot.

For comparing the monthly energy consumption, energy costs, and CO₂ emissions of the robotic lawnmower with those of other conventional mechanical mowers, we used an electric energy monitor meter (EC-03, Zhangzhou) with a built-in program for determining the cost and CO₂ emissions from the electric energy consumption. The energy consumption of the riding mower, brush cutter (2 strokes, 6800 rpm, 25:1, 4.3 kg, MEM201S, Makita, Japan), and walk-behind mower (4 strokes, 5.9 kW, 296 cc, 135 kg, 650 mm cutting width, HR662, Kioritz, Japan) was estimated from the fuel consumption based on the assumption that 1 L gasoline is equivalent to 9.2 kWh, as suggested by Gupta (2014). The fuel consumption of riding mower, brush cutter, and walk-behind mower was measured from the amount of fuel required to refill an initially full tank (Grossi et al., 2016). The monthly energy consumption of the robotic and riding mower was recorded during the mowing operation. In the case of brush cutter and walk-behind mower, the machine operated for 15 minutes, and along with the fuel amount, area coverage was also recorded. The cost was calculated based on a local market gasoline price (November 2019) of 143 JPY L⁻¹ and the amount of CO₂ produced was determined based on the assumption that 1 L gasoline produces approximately 2.3 kg CO₂ (Shearman, 2009). The brush cutter requires an additional mixing of engine oil with gasoline (ratio 1:50); thus, the oil price was also included (local market oil price (November 2019) of 2,200 JPY L⁻¹).

The monthly labor requirements were also recorded for each plot. In addition, the labor requirements of the brush cutter and walk-behind mower were estimated for the operation of 15 minutes and measuring the cutting area. In this calculation, a cutting frequency of two times per month was used for the brush cutter and walk-behind mower whereas the actual cutting frequency was used for the robotic lawnmower and riding mower.

Finally, the effect of operating each machine in terms of the operator’s heart rate (beats per min (bpm)) (June 18, 2019, 10 am–12 pm, 25°C air temperature) was obtained using a heart rate monitor (V800; Polar). A transmitter was attached at the operator’s (male, age: 47 years, height: 172 cm, weight: 90 kg, resting heart rate: 74 bpm, body mass index: 30.4) chest with the help of a strap, which transmits the signal in the wristwatch. The wristwatch then logged the heartbeat signal and transferred to a computer via USB port. The heartbeat signal per minute was calculated in the Excel sheet afterward. Since different workloads will increase the heart rate of the operator compared with the rest condition, the increase ratio of the heart rate (IRHR) was calculated for the various mowing operations, as suggested by Dewi et al. (2017). In the case of the robotic lawnmower, the operator’s heart rate is the resting heart rate, because the operator does not need to operate the machine during autonomous mowing. However, we measured the normal walking heart rate of the operator because when the machine stops automatically the operator needs to come to the machine and restart manually.

3. Results

The average weed height was 52 mm (range: 35–87 mm) in the robotic lawnmower-managed plots (plots 1 and 2) and 122 mm (range: 15–281 mm) in the riding mower-managed plot (plot 3) (Fig.2). In the robotic lawnmower-managed plots, the weed height remained relatively stable between cuts but was highest in September (approximately 66 mm)
Fig. 2  Weed height in the robotic lawnmower and riding mower-managed plot in each of the months. Data was taken from April 17 to October 24, 2019. The weed cutting frequency was about 1 time per month in the riding mower-managed plot hence we measured the weed height in the robotic lawnmower and riding mower-managed plot about 1-3 days before and after cutting with the riding mower, to gain maximum and minimum weed height value in each of the months. *** indicate significant difference of the weed height between two sampling day at $p < 0.001$ for the riding mower-managed plot. *, and *** (the bold and larger size star mark) represent significance at $p < 0.05$, and $p < 0.001$ respectively for the robotic lawnmower-managed plot.

Fig. 3  Weed dry biomass in the robotic lawnmower and the riding mower-managed plot in each of the months. The biomass was collected on the same day of measuring weed height. The weeds were dried in the oven at 65°C for 2 days and the final weight was recorded. * indicate significant difference of the weed height between two sampling day at $p < 0.05$ for the riding mower-managed plot. *(the bold and larger size star mark) represent significance at $p < 0.05$ for the robotic lawnmower-managed plot.

because the machine frequently stopped as a result of the dropped pears on the ground. By contrast, in the riding mower-managed plot, the weed height steadily increased until cutting occurred.

The average weed dry biomass was approximately 97 g m$^{-2}$ year$^{-1}$ (range: 16–200 g m$^{-2}$ year$^{-1}$) in the riding mower-managed plot (Fig. 3). There was a positive linear relationship between the weed biomass and weed height, which indicates that if the weed height increases, the biomass also increases.

The average monthly energy consumptions for the robotic lawnmower was recorded as about 6 kWh 1000 m$^{-2}$ month$^{-1}$, and for riding mower, brush cutter,
and the walk-behind mower was estimated to be 13, 56, and 18 kWh 1000 m$^{-2}$ month$^{-1}$, respectively (Table 2). The average monthly energy costs for the robotic lawnmower, riding mower, brush cutter, and the walk-behind mower was calculated as about 133, 206, 1122, and 277 JPY 1000 m$^{-2}$ month$^{-1}$ respectively (Table 2). The riding mower and walk-behind mower consumed 1.5, and 2.0 L gasoline 1000 m$^{-2}$ month$^{-1}$, respectively, equating to the production of 3.4, and 4.5 kg CO$_2$ 1000 m$^{-2}$ month$^{-1}$, respectively. However, the brush cutter consumed at about 6 L fuel 1000 m$^{-2}$ month$^{-1}$ (gasoline–5.7 L and oil–0.3 L 1000 m$^{-2}$ month$^{-1}$), equivalent to the production of 14 kg CO$_2$ 1000 m$^{-2}$ month$^{-1}$. In contrast, the robotic lawnmower produced approximately 3.0 kg CO$_2$ 1000 m$^{-2}$ month$^{-1}$. The monthly average energy consumption, cost, and CO$_2$ emissions for the robotic lawnmower from June to October are shown in Fig.4.

The robotic lawnmower stopped working (automatically powered off) when complex structures prevented it from moving properly or a stone, fruit, or soil became stuck in the chassis causing the wheel to rotate freely in the air. In plots 1 and 2, the machine stopped an average of 8 and 2 times 1000 m$^{-2}$ month$^{-1}$, respectively, between April and July and an average of 51 and 46 times 1000 m$^{-2}$ month$^{-1}$, respectively, Table 2

| Type of machine       | Energy consumption (kWh 1000 m$^{-2}$ month$^{-1}$) | Energy cost (JPY 1000 m$^{-2}$ month$^{-1}$) | CO$_2$ emission (kg 1000 m$^{-2}$ month$^{-1}$) |
|-----------------------|----------------------------------------------------|---------------------------------------------|-----------------------------------------------|
| Robotic lawnmower     | 6                                                  | 133                                         | 3                                             |
| Riding mower          | 13                                                 | 206                                         | 3.4                                           |
| Brush cutter          | 56                                                 | 1122                                        | 14                                            |
| Walk-behind mower     | 18                                                 | 277                                         | 4.5                                           |

* The electric energy consumption of the robotic lawnmower was recorded by an electric consumption meter with a built-in program for determining the cost and CO$_2$ emissions from the electric energy consumption. The energy consumption, cost and CO$_2$ emission of the riding mower, brush cutter, and walk-behind mower was estimated from the gasoline consumption, where 1 L gasoline = 9.2 kWh (Gupta, 2014) = 2.3 kg CO$_2$ (Shearman, 2009) = 143 JPY (local market gasoline price on November 2019).

![Fig.4](image-url)  
**Fig.4** Electric energy consumption, energy cost, and CO$_2$ emission for the robotic lawnmower in each of the month. The electric energy consumption directly recorded the electric consumption meter which has a built-in function to convert electric consumption to cost (JPY) and CO$_2$ emission.
robotic lawnmower and riding mower were 29 and 39 min \(1000 \text{ m}^{-2} \text{ month}^{-1}\), respectively (5 and 33 min \(1000 \text{ m}^{-2} \text{ month}^{-1}\) from April to July and 60 and 46 min \(1000 \text{ m}^{-2} \text{ month}^{-1}\) from August to October, respectively) (Fig.7A). The robotic lawnmower requires human intervention mainly to restart the machine, whereas human intervention is required for the mowing operation in a riding mower. When the robotic lawnmower chassis becomes stuck with a stone, fruit, or soil, it makes several attempts to escape (1–2 min) and then automatically powers off. The operator then needs to rescue the robotic lawnmower and riding mower.

Fig.5  Robotic lawnmower stopping (automatically powered off) frequency and amount of rainfall in each month. When complex structures prevented it from moving properly or a stone, fruit, or soil became stuck in the chassis it makes several attempts to escape (1–2 min) and then automatically powers off.

Examination of the rain data indicated that rain did not hamper the operation of the robotic lawnmower (Climate-data.org, 2019).

The labor requirement for pear production (April to October) consists of mowing, spraying chemicals, flower thinning, fruit thinning, removing sprouts, removing buds, and harvesting. The total labor requirements for production in plots 1, 2, and 3 were 64, 85, and 46 h \(1000 \text{ m}^{-2}\), respectively (Fig.6).

The monthly average labor requirements for the robotic lawnmower and riding mower were 29 and 39 min \(1000 \text{ m}^{-2} \text{ month}^{-1}\), respectively (5 and 33 min \(1000 \text{ m}^{-2} \text{ month}^{-1}\) from April to July and 60 and 46 min \(1000 \text{ m}^{-2} \text{ month}^{-1}\) from August to October, respectively) (Fig.7A). The robotic lawnmower requires human intervention mainly to restart the machine, whereas human intervention is required for the mowing operation in a riding mower. When the robotic lawnmower chassis becomes stuck with a stone, fruit, or soil, it makes several attempts to escape (1–2 min) and then automatically powers off. The operator then needs to rescue the robotic lawnmower and riding mower.

Fig.6  Total labor requirement for a different kind of management work in the pear orchard from flowering to harvesting (April–October, 2019). All these works were managed by one operator.
lawnmower and restart it manually. The labor requirements were also compared with other conventional machine practices for cutting grass in the pear orchard, which gave average labor requirements of 28 min 1000 m$^{-2}$ month$^{-1}$ for the robotic lawnmower, 40 min 1000 m$^{-2}$ month$^{-1}$ for the riding mower, 604 min 1000 m$^{-2}$ month$^{-1}$ for the brush cutter, and 62 min 1000 m$^{-2}$ month$^{-1}$ for the walk-behind mower (Fig.7B).

The IRHR values for operating the riding mower, brush cutter, and walk-behind mower were 1.2, 1.5, and 1.4, respectively (Fig.8A). The IRHR during the independent operation of the robotic lawnmower was 1, i.e., the resting heart rate of the operator. While performing activities required to restart the lawnmower, the IRHR value was 1.4 (Fig.8B).

4. Discussion

In the application of robotic lawnmower to orchard weed management, the weed height ranged from 35...
to 87 mm in the robotic lawnmower-managed plots and 15 to 281 mm in the riding mower-managed plot from pear flowering to harvesting (April to October), indicating that the robotic lawnmower was able to control the weeds in the orchard throughout the pear growing period. However, the weed height in the robotic lawnmower-managed plots increased during September and October due to the machine becoming stuck with dropped pears and stopping frequently and the operator only being available between 9:00 and 17:00 from Monday to Friday, meaning that the machine could not be restarted outside these times. Martelloni et al. (2019) previously investigated the coverage of the Husqvarna Automower 430X in different shaped fields (square, rectangle, triangle, and circle) for turfgrass management and found that it had an efficiency of approximately 35% after 75 min of cutting in all of the grass fields, indicating a high level of overlap. In the pear orchard used in the present study, plot 1 had a higher tree density than plot 2, so a higher level of overlap was anticipated. However, the robotic lawnmower controlled the weeds successfully due to the longer operation time of almost 16 h per day with 8 h of charging. Similarly, Chandler (2003) reported that given sufficient time, an autonomous lawnmower is likely to cut most of a lawn. Autonomous lawnmowers are usually programmed to operate every day to produce very small clippings (Pirchio et al., 2018b), which allows the biomass to be readily integrated into the ground without forming a thatch through a process called “grass-cycling” (Brede, 2000).

The robotic lawnmower had better energy use and efficiency than the other machines, consuming only 6 kWh 1000 m² month⁻¹ compared with 13, 56, and 18 kWh 1000 m² month⁻¹ for the riding mower, brush cutter, and walk-behind mower, respectively. This higher energy use efficiency is due to its brushless electric motor, which has an efficiency of 90% compared with 20%–25% for a gasoline engine (Pirchio et al., 2018a). These findings support those of Grossi et al. (2016), who found that an autonomous mower consumed 4.80 kWh week⁻¹ while a gasoline-operated rotary mower consumed 12.60 kWh week⁻¹.

It was also found that the robotic lawnmower is cheaper to run (133 JPY 1000 m² month⁻¹) than other conventional machines (riding mower = 206, brush cutter = 1122, and walk-behind mower = 277 JPY 1000 m² month⁻¹). Similarly, Pirchio et al. (2018a) showed that an autonomous mower was cheaper to run than a rotary mower (1723 vs. 2425 JPY week⁻¹). In an investigation of robotic weeding costs, Pedersen et al. (2006) noted that the robotic lawnmower has important cost advantages in the USA, UK, and Denmark but not in Greece due to differences in labor costs, crop rotation, and farm structure. The same authors also emphasized the radical changes in economics of scale that can occur when human operators are no longer required for farm equipment and the implications this has for farm size and structure.

Although the robotic lawnmower stopped working (automatically powered off) a very few time (average 8 and 2 times 1000 m² month⁻¹ in the plot—1 and 2, respectively) between April and July, a higher number of stoppage (average of 51 and 46 times 1000 m² month⁻¹ in the plot—1 and 2, respectively) was observed in the fruit harvesting period (August and October). Because of the fallen pear mainly responsible for the machine stoppage, we recommend a better management practice, like removing them from the ground.

The present study showed that the robotic lawnmower had lower labor requirements (28 min 1000 m² month⁻¹) than the riding mower (40 min 1000 m² month⁻¹) in the study plots and also had lower average monthly labor requirements than other conventional machines (brush cutter = 604 and walk-behind mower = 62 min 1000 m² month⁻¹). However, a major drawback of the robotic lawnmower was that it frequently stopped working during the harvesting period. It is therefore highly recommended that any dropped fruit is removed from the ground beforehand for smoother operation.

From an environmental and human health perspective, the robotic lawnmower can be a good choice for consumers, as it had lower CO₂ emissions (3.0 kg 1000 m² month⁻¹) than the other machines (riding mower = 3.4, brush cutter = 14.0, and walk-behind mower = 4.5 kg 1000 m² month⁻¹).
Furthermore, the robotic lawnmower does not need operator’s (IRHR = 1) help during autonomous movement but riding mower (IRHR = 1.2), brush cutter (IRHR = 1.5), and walk-behind mower (IRHR = 1.4).

Since the average age of the population is higher in Japan than elsewhere in the world and this trend is continuing to increase, robotic moving can be an excellent choice for reducing labor and operation costs in orchards.

5. Conclusion

In the application of robotic lawnmower to orchard weed management, the weed height was lower in the robotic lawnmower-managed plots (31–87 mm) than in the riding mower-managed plot (15–281 mm) between the time of flowering to harvesting, indicating that the robotic lawnmower has a better weeding performance. In addition, the robotic lawnmower was superior to the riding mower, brush cutter, and walk-behind mower in terms of energy consumption (6 vs. 13, 56, and 18 kWh 1000 m–2 month–1), costs (133 vs. 206, 1122, and 277 JPY 1000 m–2 month–1), CO2 emissions (3 vs. 3.4, 14, and 4.5 kg 1000 m–2 month–1), labor requirements (28 vs. 40, 604, and 62 min 1000 m–2 month–1) (although a higher labor requirement was recorded during the pear harvesting period), and workload (IRHR = 1 vs. 1.2, 1.5, and 1.4). Therefore, we believe that robotic moving is a better choice than conventional practices for pear orchard weed management.

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