Weed Management and Economic Analysis of a Robotic Lawnmower: A Case Study in a Japanese Pear Orchard

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Abstract: The use of robots is increasing in agriculture, but there is a lack of suitable robotic technology for weed management in orchards. A robotic lawnmower (RLM) was installed, and its performance was studied between 2017 and 2019 in a pear orchard (1318 m²) at Ibaraki University, Ami. We found that the RLM could control the weeds in an orchard throughout a year at a minimum height (average weed height, WH: 44 ± 15 mm, standard deviation (SD) and dry weed biomass, DWB: 103 ± 25 g m⁻²). However, the RLM experiences vibration problems while running over small pears (33 ± 8 mm dia.) during fruit thinning periods, which can stop blade mobility. During pear harvesting, fallen fruits (80 ± 12 mm dia.) strike the blade and become stuck within the chassis of the RLM; consequently, the machine stops frequently. We estimated the working performance of a riding mower (RM), brush cutter (BC), and a walking mower (WM) in a pear orchard and compared the mowing cost (annual ownership, repair and maintenance, energy, oil, and labor) with the RLM. The study reveals that the RLM performs better than other conventional mowers in a small orchard (0.33 ha). For a medium (0.66 ha) and larger (1 ha) orchard, the RLM is not more cost-effective than RM and WM. However, the existing RLM performed weed control well and showed promise for profitability in our research field. We believe that, if field challenges like fallen fruit and tree striking problems can be properly addressed, the RLM could be successfully used in many small orchards.

Keywords: economic analysis; mechanical mowing; robotic mowing; tree collision; vibration; weed height and biomass

1. Introduction

Over the last century, agriculture has been transformed from a labor-intensive industry towards one using mechanization and power-intensive production systems [1]. It has been observed that over the last 15 years, agriculture has started to digitize [2,3]. Due to progress made in programming and the technological advances in the engineering and robotics domains, nowadays autonomous systems can increasingly take over non-standardized tasks previously reserved for human workers and at economically feasible costs [4]. Therefore, automation is no longer restricted to just the standardized tasks within industrial production but becomes part of non-standardized and non-routine processes, and, importantly, automation can take over technical and managerial functions.

Although much research focuses on the improvement of robotic mowing efficiency and algorithm development, very few have considered field performance, especially in orchards. In orchards, the mechanical means for weed control include the use of tillage implements, riding mower (RM), brush cutter (BC), and walking mower (WM). Since ancient times, tillage has been a common practice for weed control [5]. However, the use of tillage implements in orchards may damage roots that are between tree rows,
retarding water and nutrient uptake. Tillage can also increase soil erosion in the events of heavy wind and downpour [6]. Hashimi et al. (2019) [7] reported that tillage for weed control and residue incorporation can have detrimental effects on the agroecosystems. Komatsuzaki and Ohta (2007) [8] discuss the environmental benefits of no-tillage crop production systems, including reducing the leaching of nitrogen, increasing soil organic matter content, and enhancing soil biological diversity. Furthermore, tillage equipment and heavy mowers (i.e., RM) can increase soil compaction between the tree rows [9]. Moreover, mechanical mower operations are costly because they must be used frequently to keep the soil weed-free. Mechanical mower operation can also result in plant injury, especially to lower parts of tree trunks and overhanging branches. Mechanical mowers can also cause injury to the operators if the proper safety precautions are not considered [10]. These injuries include missile injuries (when stones are hit by the blade), gasoline burns, hand trauma, and visceral trauma [11].

Research shows that a robotic lawn mower (RLM) requires very little human labor and creates less pollution than gasoline-powered mowers [12]. RLMs prevent humans from coming into contact with dust, allergens, polluting gasses (if the engine is a gasoline engine), and noise [13]. Robotic mowers are programmed to operate every day; thus, the grass clippings are very small (a few millimeters) and can be left in place [12,14]. These clippings are easily integrated into the soil, which leads to a higher turf quality, lower weed percentage, lower need for nitrogen fertilization, and reduction in the amount of thatch produced [15]. In contrast, mechanical mowers produce relatively large grass clippings, which will reduce the turf quality if left in place. Pirchio et al. (2018) [12] compared the energy consumption and operational costs of autonomous and walking mowers for the management of a tall fescue lawn. They found that the autonomous mower had a lower energy consumption (3 vs. 5 kWh week$^{-1}$) and was cheaper than the rotary mower considering the ordinary labor cost in Italy (16 vs. 3 USD week$^{-1}$). Grossi et al. (2016) [14] conducted a similar experiment and reported less power consumption for the RLM (4.80 kWh week$^{-1}$) when compared to a gasoline-powered rotary mower (13 kWh week$^{-1}$). Based on labor, cost, and turf quality aspects, they concluded that the use of autonomous mowers could be a promising alternative to traditional mowers.

Autonomous mowers have been mainly designed for small lawn weed management. The working capacity of an RLM designed for private or industrial areas ranges from 400 to 5000 m$^2$ [14]. However, the majority of orchards in Japan are less than 1 ha in size. The RLM can be used in at least one-third of fruit orchards, since 32.5% of the orchards in Japan are below the area of 0.5 ha [16]. Moreover, Grossi et al. (2016) [14] mentioned that special autonomous mowers may have a capacity ranging from 5000 to 30,000 m$^2$.

In the previous study [17], we compared the weeding performance, energy cost, CO$_2$ emission, labor involvement, and workload (heart rate) of the RLM with conventional mowers between pear flowering to harvesting (April to October). We concluded that robotic mowing is a better choice than conventional mechanical mowers. In the present study, we present weed management, weed cutting efficiency (CE), and mowing cost (ownership, repair and maintenance, energy, oil, and labor) in a pear orchard over a year. We estimate the working performances of other popular mechanical mowers, i.e., RM, WM, and BC in the orchard to study the suitability of the RLM over other mowers. We also identify potential challenges of RLM operation in the pear orchard (e.g., fallen pears, tree striking) and recommend possible solutions. The results of this study will improve understanding of the present working performances of RLM in orchards and potential opportunities to further adapt the technology.

2. Materials and Methods

We conducted this research at a pear orchard (36°03′21″ N, 140°21′29″ E) at the Center for International Field Agriculture Research and Education, Ibaraki University, Ami, Japan, between 2017 and 2019 (Figure 1). The major weeds in the orchard are goosegrass (*Eleusine indica* L. Gaertn.), tropical crabgrass (*Digitaria ciliaris*), broad-leaved dock
(Rumex obtusifolius L.), yellow woodsorrel (Oxalis stricta L.), white clover (Trifolium repens L.), prairie grass (Bromus catharticus Vahl), orchard grass (Dactylis glomerata L.), purple dead-nettle (Lamium purpureum L.), long-headed poppy (Papaver dubium L.), and thyme-leaved sandwort (Arenaria serpyllifolia L.). The area, field slopes, tree density, and tree age in the orchard are 1318 m², 0.5%, 725 trees ha⁻¹, and 7 years, respectively.

The weeds in the orchard were managed by a Husqvarna RLM (Automower 430X). The working capacity of the RLM is 3200 m² ± 20% and is navigated by GPS [18]. The overall dimensions and weight of the RLM are 72 × 56 × 31 cm and 13.2 kg, respectively. We operated the RLM 24 h per day including charging time (average 65 min charging for 135 min working) between March and October (weed growing periods). The cutting height of the RLM can be adjusted within 2–6 cm (cutting width, 24 cm). We fixed it at the highest (6 cm) to avoid striking the blade with stones, fruit, mud, etc.

The RLM automatically mows the orchard. Apart from the lawnmower itself, there is a base station which serves as a charging station, a boundary wire to define the outer perimeter of the operating area, and guide wires to help the robot navigate narrow passages and find its way back to the charging station [19]. The boundary and guide wires are buried just below the ground surface, and the mower stays within the perimeter of the working area. The RLM continuously alternates between mowing and charging. The RLM starts to search for the charging station when the battery charge becomes too low. It does not mow when it is searching for the charging station. While searching for the charging station, the robot lawnmower can find it in a number of different ways (irregular, follow guidewire, and follow boundary wire, etc.) [18]

The cutting deck of the RLM has a cutting disc with three (3) razor-sharp pivoting blades [18]. When the mower runs into an object, it reverses, turns, and chooses another direction using the robot control program. The onboard GPS creates a map of the lawn, including where the boundary and guide wires are installed [13]. The RLM will then identify which parts of the lawn it has covered and adjust its mowing pattern accordingly. This ensures optimized lawn coverage and an excellent cutting result.

2.1. Measurement of WH and Biomass

To understand the weed coverage throughout a year, we measured and collected the WH and weed biomass, respectively, in the orchard. The WH in the orchard was measured using a laser distance meter (Leica DISTO™ A6). The laser meter is attached at the end of a 1 m stick so that the laser focuses on the weed canopy when the stick is perpendicular to the ground.
to the ground. The WH was calculated by subtracting the display reading from the stick height. The weed biomass was collected on the same day as WH measurement using a 23 × 23 cm quadrat. The weed was cut using scissors, collected in a paper bag, and dried in an oven for two days (DKN 601, Yamato) at 65 °C. The dry weight was measured with an electronic balance (UX 4200S®, Shimadzu). The field data, i.e., WH and biomass, were collected at 9 points of the orchard with a minimum distance of about 8 m between two sampling points. The sampling frequency was two times per month.

2.2. Machine Weed Cutting Efficiency (CE)

We studied the CE of the RLM, RM, BC, and WM in a different orchard (1782 m², 36°03'18'' N, 140°21'25'' E) 6 m away from the RLM mower managed orchard. The weed CE was derived from the ratio of how much of the weeds are cut by one pass of the machine to the total weeds present (Equation (1)) [20]. We compared the CE of the RLM with other popular conventional mowers, i.e., an RM (ARM 980, 4 strokes gasoline engine, 15.6 kW, mowing width 97.5 cm, Iseki, Japan), a WM (4 strokes, 5.9 kW, 135 kg, 65 cm cutting width, HR662, Kioritz, Japan), and a BC (2 strokes, 4.3 kg, MEM 201S, Makita, Japan). The machines were tested over different weed conditions (different height and density). The area and field slopes of the testing ground were about 1782 m² and 0.4%, respectively. The testing period was between March and July 2019. The weed species were mostly the same as the RLM-managed orchard.

During the test, the speed of the RLM was 0.3 m s⁻¹, which was programmed as a default and could not be changed. The speed of the RM was 1.9 m s⁻¹, as Hamid (2013) [21] did not find a significant (p-level > 0.05) difference in CE at different operation speeds (0.5–1.8 m s⁻¹). The BC and WM cutting speeds were 0.2 and 0.7 m s⁻¹, respectively, which are the moderate cutting speed settings of these machines. A wooden quadrat (23 × 23 cm) was placed in the plot, and cut weed within the quadrat area was collected manually [22]. The uncut weeds were also cut by scissors at 6 cm heights to match the machine cutting height of 6 cm. The final dry weight of the weeds (cut and uncut) was measured with an electronic balance after two days of oven drying (65 °C).

\[
CE = \frac{W_c}{W_c + W_u} \times 100
\]  

(1)

where,

\[ W_c = \text{Dry weight of cut weed (g)} \]
\[ W_u = \text{Dry weight of uncut weed (g)} \]

2.3. Vibration of RLM

The RLM was designed for controlling weeds in the lawn, where the ground slope is almost even, stone-free, and with few obstacles. However, orchard slopes are normally higher, and fallen fruits can reduce the field performance of the RLM. In fruit thinning (June) and harvesting periods (August–October), the dropped fruit on the ground hamper the normal operation of the RLM. In our previous study [17], we found that a higher amount of labor was needed during fruit harvesting because the fallen pears became stuck in the chassis, causing the machine to stop frequently. During fruit thinning (June), the small fruits increase vibration to the mower; thus, the rotary blade stops working until the vibration decreases. To observe the effect of smaller and larger fallen fruits on the working performance of the RLM, we recorded the acceleration of the RLM by an Arduino UNO embedded accelerometer (ADXL 335 sensor). We wrote the code of acceleration in Arduino 1.8.13, which could log 10 signals (X, Y, and Z direction) per second in an SD card. The accelerometer was attached on the top of RLM by a double-sided scotch tape. The X, Y, and Z of the sensor are placed parallel to the forward, side, and vertical movement of the RLM respectively. The intensity of machine vibration was derived from the mean amplitude of deviations (MAD) of the resultant acceleration signal [23–25]. The unit of MAD is gravity (g). The test was carried out by creating an artificial area (4 × 4 m) with different pear
density (10, 15, 20, and 25 pears m\(^{-2}\) for thinned pears (33 ± 8 mm dia.) and 1, 2, and 3 pears m\(^{-2}\) for matured pears (80 ± 12 mm dia.)). The acceleration was recorded over an operation time of five minutes, and MAD was calculated as per Equations (2)–(4).

\[
r_i = \sqrt{x_i^2 + y_i^2 + z_i^2}
\]  
(2)

\[
R_{ave} = \frac{1}{N} \sum_{i=j}^{j+N-1} r_i
\]  
(3)

\[
MAD = \frac{1}{N} \sum_{i=j}^{j+N-1} |r_i - R_{ave}|
\]  
(4)

where,

\(r_i\) = Resultant acceleration in each measurement point (i).

\(x_i, y_i, z_i\) = Acceleration in three different coordinates.

\(R_{ave}\) = Mean resultant value.

\(N\) = Number of samples in the epoch.

\(j\) = Start point of the epoch.

2.4. Tree Hitting Frequency of the RLM

Frequent tree hitting can damage the bumper of the RLM, since the bumper is made from Acrylonitrile–Butadiene–Styrene [26]. The hitting frequency mainly depends on the density of the trees or obstacles. In the orchard, about half of the area (636 m\(^2\)) has a tree density of 940 trees ha\(^{-1}\) (P1), while the rest of the area (682 m\(^2\)) has 510 trees ha\(^{-1}\) (P2). We investigated the hitting frequency of the RLM at those two different tree densities. The trees in the P1 were planted in rows, where the distance between two trees in line and between rows are 150 ± 11 and 345 ± 11 cm, respectively. The trees in P2 were planted randomly, where the distance between the two trees is 412 ± 104 cm. The RLM was started at the boundary corner of each P1 and P2 area, facing straight to the tree trunk. The distance between the RLM and tree trunk was about 12 m for the first heating. The number of times the RLM strikes trees were identified during five minutes of operation by a load cell (Figure 2a). The load cell was attached to the bumper of the RLM with the help of double- and single-sided scotch tape. An aluminum (50 × 10 × 0.1 cm) sheet was attached with the load cell to increase the surface area (equal to the length of the bumper) so that any tree hitting at the middle or periphery of the sheet can be recorded in the load cell. The load cell (LUB–5KB) amplified the signal by a strain amplifier (Type 3126) and displayed on the laptop (HP ProBook 650 G1) through the Arduino UNO microcontroller. During a strike with the tree, the load cell produces 3-volt bursts that were counted as RLM strikes. We observed that the RLM hit a different tree each time.

2.5. Striking Force of the RLM

As mentioned above, the bumper is made from Acrylonitrile–Butadiene–Styrene, and the structure can break down if high force accumulates. If the tree density increases the distance between two trees decreases; consequently, the RLM will possibly hit from a shorter distance. We measured the hitting load in the bumper at different distances (50–350 cm) with an interval of 50 cm with the help of a strain gauge transducer (EDX–12A, 14A, 10B), bridge adapter (UI–53B–120), and strain sensor (KFGS–1N–120–C1–11L3M3R) [27,28] (Figure 2b). The sensor of the strain gauge was attached with a strong adhesive (Ethyl 2–cyanoacrylate) and a stainless steel sheet (7 × 1.5 × 0.3 cm) to provide a signal of deflection as µm m\(^{-1}\). The sensor was connected to the transducer, and the signal was processed by special software in the Laptop (HP ProBook 650 G1) provided by Kyowa, Japan. The calibration was done in the laboratory, such that one end of the steel bar was fixed in a bench vise and another end was subjected to a known load of 1–6 kg [29]. The different loads produce different deflection in the bar, which was displayed and recorded.
on the laptop. This relationship between load and deflection was obtained in Microsoft Excel, where the value of \( r^2 \) represents the strength of the relationship. The sensor with a steel bar was attached in front of the RLM bumper with the help of a double-sided scotch tape. We used a wooden sheet (2.5 × 0.3 × 0.03 m) as a striker that was fixed on the ground with the help of metallic pegs. We also measured the single pear pushing force by the RLM while running over the fallen pear (80 ± 12 cm dia.). We placed the pear on the ground and lowered the steel bar (strain sensor) so that it could push the pear easily.

Figure 2. Robotic lawnmower (RLM) (a) striking frequency detection by a load cell. (b) striking load measurement by a strain gauge. A wooden sheet of 2.5 × 0.3 × 0.03 m was placed on the ground and fixed tightly by metallic pegs as a striker. In both cases, the real-time signals were displayed on the laptop.

2.6. Effect of Overmatured Fallen Pears on the RLM Operation

When the RLM chassis becomes stuck with fallen fruits, it makes several attempts to escape (1–2 min) and then automatically powers off. The operator then needs to rescue the RLM and restart it manually. The number of times the RLM stopped working for different pear densities (1, 2, and 3 pears m\(^{-2}\)) was identified by creating an artificial area of 2 × 2 m and operating the RLM within the area for about 5 min. The RLM was restarted immediately when the power went off automatically. During operations, some pears travel under the chassis of the RLM and collide with the blades. The number of times the cutting blades hit pears were detected by a digital sound level meter (GM 1356) for 5 min of operation. The collision sound was detected as 85 dB (frequency weighted); hence, any sound level exceeding 85 dB was counted as an indication of blade collision with a pear. The testing ground was obstacle-free (except pears) during this trial.

2.7. Economic Analysis

We compared the total annual cost (ownership, repair, and maintenance, energy, oil, labor, etc.) borne by RLM, RM, BC, and WM in the pear orchard. We used the actual labor and energy cost for the RLM, while estimation was done for the RM, BC, and WM. To predict the labor involvement and gasoline consumption, we tested the RM, BC, and WM in a different pear orchard (1782 m\(^2\), 36°03′18″ N, 140°21′25″ E), 6 m away from the RLM managed orchard. We operated the RM, WM, and BC for 5 min; finally, the mowing area, gasoline consumption, and labor involvement were recorded. The cutting area was measured by a measuring tape, while the fuel consumption of the RM, WM, and BC was measured from the amount of fuel required to refill an initially full tank. The RLM requires human intervention mainly to restart the machine, whereas human intervention is required for the mowing operation in a RM, BC, and WM. However, the operator was only available between 9:00 and 17:00 from Monday to Friday, meaning that the RLM could not be restarted outside these times. We recorded monthly 237 times stoppage (averaged from April to October) of the RLM per ha of land, which is a total of 1897 times in a year (March–October). To start the RLM, the operator needed about 1 min 13 s (walking
time to reach, start and come back) for each time [17]. The mowing labor was averagely waged for 14 USD h\(^{-1}\) (standard value in Japan). The energy cost of the RM, BC, and WM was estimated from the fuel consumption based on the assumption that 1 L gasoline is equivalent to 1.3 USD L\(^{-1}\) (local shop rate). In contrast, we directly recorded the energy cost of the RLM by an electric consumption meter (EC–03, Zhangzhou) between June and October. We restarted the meter at the first day of each month and recorded the last reading. 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 of 19.8 USD L\(^{-1}\)). The oil capacities of the RM and WM were 1.7 and 1 L, respectively, which we changed once a year. The local shop oil price was 8.2 USD L\(^{-1}\). Moreover, we considered a mowing frequency of twice per month for the RM, BC, and WM to estimate energy, oil, and labor cost. We calculated the ownership cost of the mowers by American Society of Agricultural and Biological Engineers (ASABE) standards [30] given below:

\[
C_o = 100 \left[ \frac{1 - S_v}{L} + \frac{1 + S_v}{2} i + K_2 \right]
\]

where

- \(C_o\) = Ownership cost percentage. Multiplying this value, expressed in decimal form, by the machine purchase price yields the average annual total ownership cost of the machine.
- \(S_v\) = Salvage value factor of the machine at end of machine life (year L), decimal.
- \(L\) = Machine life, year.
- \(i\) = annual interest rate, decimal.
- \(K_2\) = Taxes, housing, and insurance expressed in decimal form in this equation.

3. Results

The WH and DWB in the orchard are presented in Table 1. The average WH and DWB were 55 ± 17 mm and 105 ± 31 g m\(^{-2}\), respectively, during robotic mowing (March–October). During non-mowing period (November–February), the average WH and DWB were 34 ± 13 mm and 100 ± 20 g m\(^{-2}\), respectively.

| Month  | WH (mm) | DWB (g m\(^{-2}\)) |
|--------|---------|---------------------|
|        | Avg.    | SD      | Min. | Max. | Avg.    | SD      | Min. | Max. |
|        | RLM     |         |      |      |        |         |      |      |
| With RLM|         |         |      |      |         |         |      |      |
| Mar.\(^1\) | 68 a\(^2\) | 24 | 35 | 104 | 163 a\(^2\) | 49 | 115 | 225 |
| Apr.    | 38 b    | 10 | 21 | 67  | 186 a   | 39 | 119 | 263 |
| May.    | 52 c    | 13 | 32 | 83  | 156 a   | 38 | 108 | 246 |
| Jun.    | 38 d    | 13 | 11 | 63  | 100 b   | 34 | 66  | 134 |
| Jul.    | 63 e    | 21 | 23 | 119 | 43 c    | 12 | 32  | 62  |
| Aug.    | 89 f    | 31 | 39 | 154 | 63 d    | 15 | 42  | 85  |
| Sep.    | 63 g    | 16 | 36 | 83  | 76 d    | 39 | 34  | 159 |
| Oct.    | 25 h    | 8  | 10 | 43  | 53 d    | 24 | 32  | 106 |
| Avg.(1) | 55      | 17 | 26 | 90  | 105     | 31 | 69  | 160 |
| Without RLM |         |         |      |      |         |         |      |      |
| Nov.    | 20 i    | 6  | 5  | 28  | 51 d    | 8  | 43  | 58  |
| Dec.    | 21 i    | 5  | 15 | 32  | 74 d    | 24 | 49  | 108 |
| Jan.    | 35 j    | 11 | 19 | 55  | 118 d   | 26 | 90  | 153 |
| Feb.    | 60 k    | 31 | 26 | 117 | 158 d   | 20 | 140 | 185 |
| Avg.(2) | 34      | 13 | 16 | 58  | 100     | 20 | 81  | 126 |
| Avg. (1 + 2) | 44      | 15 | 21 | 74  | 103     | 25 | 75  | 143 |

\(^1\) The months are abbreviated with the first three letters. \(^2\) The difference between the values indicated by the same lowercase letters is not significant at the 5% level. The abbreviated words Avg., SD, Min., Max., RLM, and RM stand for average, standard deviation, minimum, maximum, robotic lawnmower, and riding mower respectively. The sampling frequency was twice per month.
The relationships between WH, DWB, and CE is shown in Figure 3.

![Graphs showing relationships between weed height (WH), dry weed biomass (DWB), and cutting efficiency (CE) for RLM (a–c), RM (d–f), BC (g–i), and WM (j–l).](image)

**Figure 3.** Relationships among weed height (WH), dry weed biomass (DWB), and cutting efficiency (CE) of the robotic lawnmower, RLM (a–c), riding mower, RM (d–f), brush cutter, BC (g–i), and walking mower, WM (j–l).

The MAD of the RLM while running over different pear (33 ± 8 mm dia.) densities (control, 10, 15, 20, and 25 pear m$^{-2}$) is shown in Figure 4a. There was a steady increase in MAD value as the pear density increased. In contrast, Figure 4b shows that the MAD value decreased with an increase in pear density (control, 1, 2, and 3 pears m$^{-2}$). This reveals that the RLM’s normal movement was badly retarded by fallen pears (80 ± 12 mm dia.).

Figure 5 shows the number of times the RLM hit trees during five minutes of operation. The RLM collided with tree trunks 11 times (132 times h$^{-1}$) (Figure 5a) and 4 times (48 times h$^{-1}$) (Figure 5b) over a tree density of 940 and 510 trees ha$^{-1}$, respectively.

The relationship between sensor deflection (µm m$^{-1}$) and load (N) was stronger ($R^2 = 0.99$) during strain gauge calibration. The average force per strike was recorded as 53 ± 4 N (± standard deviation, SD) (Figure 6a). The average speed of the RLM was 0.3 ± 0.05 m s$^{-1}$. A single pear (0.3 ± 0.06 kg) produced a pushing force of 5 ± 3 N (Figure 6b). Moreover, the maximum striking force at which the RLM stopped the forward movement and alter the course was about 29 ± 2 N.
The difference between the values indicated by the same lowercase letters is not significant at the 5% level respectively.

**Figure 4.** Mean amplitude deviations (MAD) of the robotic lawnmower (RLM) while running over (a) small, thinned pears (33 ± 8 mm dia.) and (b) ripened fallen pears (80 ± 12 mm dia.). The vertical bar represents standard error. The unit of MAD is gravity (g). The difference between the values indicated by the same lowercase letters is not significant at the 5% level.

**Figure 5.** Tree hitting frequency of the RLM for five minutes of operation over a tree density of (a) 940 and (b) 510 trees ha\(^{-1}\). A voltage greater than 3 V represents a tree strike. About 10 signals were recorded in each second. Each time the RLM hit different trees.

**Figure 6.** The robotic lawnmower (RLM) (a) hitting force at different distances (50–300 cm) and (b) pushing force of single pear of different sizes. The vertical bar represents standard error.
The RLM stopped working (automatic power off) 12, 28 and 48 times h\(^{-1}\) (Figure 7a) and the cutting blade of the RLM hit pears (80 ± 12 mm dia.) 68, 76, and 80 times h\(^{-1}\) (Figure 7b) while running over 1, 2 and 3 pears m\(^{-2}\), respectively.

Figure 7. The number of times the robotic lawnmower (RLM) automatically shut off because of (a) a pear (80 ± 12 mm dia.) stuck in the chassis and (b) blade hit dropped pears (80 ± 12 mm dia.) for different pear densities. The difference between the values indicated by the same lowercase letters is not significant at the 5% level respectively.

The mowing cost (annual ownership, repair and maintenance, energy, oil, and labor) for managing a 1 ha pear orchard has been shown in Table 2.

The economic analysis reveals that the RLM can be operated with a lesser cost (1333 USD Y\(^{-1}\)) than RM (1765 USD Y\(^{-1}\)), BC (2731 USD Y\(^{-1}\)), and WM (2951 USD Y\(^{-1}\)) in the case of a smaller orchard (0.33 ha) (Figure 8). However, the cost of the RLM (2667 USD Y\(^{-1}\)) exceeded RM (2143 USD Y\(^{-1}\)) for a medium-scale orchard (0.66 ha). For a larger orchard (1 ha), the RLM is less effective (4006 USD Y\(^{-1}\)) than RM (2532 USD Y\(^{-1}\)) and WM (3825 USD Y\(^{-1}\)). However, the BC showed higher cost involvement for medium and larger size orchards. Figure 8 is based on the calculation shown in Table 2. The annual ownership cost and repair and maintenance cost of the RLM varied for the different size of the orchard since we used 1, 2, and 3 units for the smaller, medium and larger orchards, respectively. In contrast, only one unit was considered for the case of RM, BC, and WM to manage different sizes of orchards. Moreover, the variable costs (energy, oil, labor) were intrapolated from the value presented in Table 2 for a medium and smaller size orchard.

Table 2. Economic analysis of the pear production that uses a different kind of mowers.

| Unit                        | Parameters                                                                 | 1 RLM | RM  | BC  | WM  |
|-----------------------------|-----------------------------------------------------------------------------|-------|-----|-----|-----|
| Annual ownership cost of the mower (AOC) | 2 Price of the machine (P) | 5792 × 3 | 7173 | 483 | 13,032 |
| USD                         | 3 Salvage value, 10% P                                                      | 0.1   | 0.1 | 0.1 | 0.1 |
| Year (Y)                    | Machine life                                                               | 10    | 10  | 10  | 10  |
| USD Y\(^{-1}\)              | 4 Annual interest rate, 2.43%                                              | 0.024 | 0.024 | 0.024 | 0.024 |
| USD Y\(^{-1}\)             | 5 Tax and Insurance, 3.5%                                                  | 0.035 | 0.035 | 0.035 | 0.035 |
| USD Y\(^{-1}\)              | 6 Shelter, 1.5%                                                             | 0.015 | 0.015 | 0.015 | 0.015 |
| USD Y\(^{-1}\)              | Annual ownership cost of the mower (Equation (5))                          | 2665  | 1100 | 74  | 1999 |
| USD Y\(^{-1}\)              | Repair maintenance cost (R&M)                                              | 695   | 287 | 19  | 521 |
| USD L\(^{-1}\)              | 7 Actual field capacity (AFC)                                              | –     | 0.234 | 0.03 | 0.19 |
| ha h\(^{-1}\)               | 8 Specific fuel consumption (SFC)                                          | –     | 1.9  | 0.6 | 1   |
| L h\(^{-1}\)                | Fuel consumption, FC = SFC/AFC                                            | –     | 8.1  | 20  | 5.3 |
| L ha\(^{-1}\)               | 9 Gasoline cost (GC)                                                       | –     | 1.3  | 1.3 | 1.3 |
Table 2. Cont.

| Unit                  | Parameters                                                                 | 1 RLM | RM | BC | WM |
|-----------------------|-----------------------------------------------------------------------------|-------|----|----|----|
| USD ha⁻¹ Y⁻¹          | Total fuel cost, TFC = GC × FC × 2 × 8                                      | –     | 168| 416| 110|
| kWh month⁻¹           | 11 Electricity consumption (EC)                                             | 60    |    |    |    |
| USD kWh⁻¹             | 12 Electric cost rate (ECR)                                                | 0.22  |    |    |    |
| USD ha⁻¹ Y⁻¹          | 13 Total electric cost, TECC = EC × ECR × 8                                | 106   | –  | –  | –  |
| USD ha⁻¹ Y⁻¹          | Total energy cost, TEC                                                     | 106   | 168| 416| 110|
| Cost (USD Y⁻¹)        | L ha⁻¹ Y⁻¹                                                                 |  –    | 1.7| –  | 1  |
| L ha⁻¹ Y⁻¹            | 14 Lub requirement (LBR)                                                    | –     | 8.2| –  | 8.2|
| USD L⁻¹               | 15 Lub cost rate (LCR)                                                     | –     |    | 6.4| –  |
| USD L⁻¹               | 16 Engine oil requirement (EOR)                                             | –     |    | 19.8| – |
| USD L⁻¹               | Total labor cost (TLC)                                                     | –     | 14 | 127| 8  |
| h ha⁻¹ Y⁻¹            | 17 Engine oil cost rate (EOC)                                               | –     |    |    |    |
| USD ha⁻¹ Y⁻¹          | Total oil cost, TOC = LBR × LCR; EOR × EOC                                | –     | 4.3| 33.3| 5.3|
| Total labor cost (TLC) |                                                                            | –     | 14 | 14 | 14 |
| USD ha⁻¹ Y⁻¹          | Total labor cost, TLC = TLR × LR                                           | 540   | 963| 7459| 1187|
| USD ha⁻¹ Y⁻¹          | Total cost (AOC + R&M + TEC + TOC + TLC)                                   | 4006  | 2532| 8095| 3825|

1 The RLM, RM, BC, and WM are abbreviations for the robotic lawnmower, riding mower, brush cutter, and walking mower, respectively.
2 The actual purchase price of the mowers. The RLM unit and installment (charging station, guiding wire, boundary wire, etc.) costs were about USD 4000 and USD 2292, respectively. The capacity of a single RLM is 3200 m² ± 20%; hence, we considered three units for 1 ha land.
3 Average annual interest rate in Japan (1972 to 2020).
4,5,6 The standard value for Japan [31].
7,8,18 The RM, BC, and WM were operated in a pear orchard (6 m away from the RLM orchard) for an operation of 5 min, and the area, fuel, and labor involvement were recorded to calculate actual field capacity, specific fuel consumption, and labor requirements. 9,15,17 Local shop price.
10,19 The mowing frequency was considered twice per month between March and October (8 months) for RM, BC, and WM.
11 The electricity consumption was recorded by a digital electric meter. The estimation was done for March to October.
12 The lubricant changing frequency was once per year for RM and WM.
13 The WH (over a year) in the orchard was almost constant (average SD: 15 cm) among all the months (WH range: 5 cm to 15 cm).
14 The WH range: 5 cm to 15 cm.
15 The WH (over a year) in the orchard was almost constant (average SD: 15 cm) among all the months (WH range: 5 cm to 15 cm).
16 It was required that 0.8 L ha⁻¹ oil be mixed with the gasoline in the case of BC (1:50) in each operation. Considering 2 cutting frequencies, 0.8 L ha⁻¹ was required per month, which is a total of 6.4 L ha⁻¹ year⁻¹ (March to October).
17 The WH range: 5 cm to 15 cm.
18 The WH range: 5 cm to 15 cm.
19 The WH range: 5 cm to 15 cm.

Figure 8. The sum of annual ownership, repair and maintenance, energy, oil, and labor costs borne by a robotic lawnmower (RLM), riding mower (RM), brush cutter (BC), and walking mower in a small (0.33 ha), medium (0.66 ha), and larger (1 ha) orchard. One, two, and three units of RLM are needed to manage small, medium, and larger orchards, respectively, since the capacity of the RLM is 3200 m² ± 20%. In this calculation, the variable costs (energy, oil, labor) were interpolated for a medium and smaller size orchard based on the value presented in Table 2.
4. Discussion

The WH (over a year) in the orchard was almost constant (average SD: 15 mm) among all the months (WH range: 5–154 mm, average WH: 44 mm). This indicates that the RLM can control the weeds in an orchard throughout the pear growing at a minimum height. We assume that because of a higher cutting frequency, it was able to maintain a lower and almost constant WH. However, in August, the average WH was 89 mm (WH range: 39–154 mm), the highest among the months. The large fallen pear blocked the operation of the RLM, and the machine remained stopped frequently in this month, since the operator was available between 9:00 and 17:00 from Monday to Friday, which allowed the weed to grow quickly. The average DWB between March and May (spring), June and August (summer), September and November (autumn), and December and February (winter) was 168, 69, 60, and 117 g m\(^{-2}\), respectively. Weed biomass depends on the weed species, which differ between seasons. Our data show that the spring DWB is significantly (\(p\)-level < 0.05) higher than that of other seasons; regardless, weed biomass could not hamper the efficacy of the RLM (average WH of the RLM orchard during spring, summer, autumn, and winter were 53, 63, 36, and 39 mm, respectively). Moreover, a higher cutting frequency tends to favor small-sized species that have their growth meristems close to the ground. Grossi et al. (2004) [32] observed that tall fescue responded to a lower mowing height by increasing shoot density. Burns (1976) [33] also observed a higher cover percentage of white clover when tall fescue was mown at a smaller height.

We observed that the RLM cannot work well when running over taller weeds, because the clearance of the RLM’s chassis from the ground is only 60 mm. Thus, taller weeds can not pass under the chassis; instead, they make a barrier on the way of the RLM’s bumper. If the weeds cumulatively make a resistive force of 29 \(\pm\) 2 N, the pressure sensor of the RLM gives a signal to the programming unit to stop the forward movement and alter the course. Consequently, we could not test the RLM over taller weeds (WH: 80–150 mm), while other mowers were not height-sensitive (WH during test: 97–693, 93–367, and 327–559 mm for RM, BC, and WM, respectively). There was a negative linear relationship between WH and CE for the RLM, RM, and WM; however, no statistically significant (\(p\)-level > 0.05) relationship was observed except WM (\(p\)-level < 0.05). The highest CE (80%) of the RLM was achieved at a WH of 100 mm and lowest (16%) when cutting a WH of 126 mm (Figure 3b). In the case of weed density, the highest CE (80%) was recorded while cutting 293 g m\(^{-2}\) dry weed, while the lowest CE (16%) was recorded while cutting 480 g m\(^{-2}\) dry weed (Figure 3c). The CE of the RM was consistent (99%) up to a WH of 400 mm and was reduced to 75% at a WH of 693 mm (Figure 3e). In terms of weed density, the highest CE (100%) was recorded while cutting 832 g m\(^{-2}\) dry weed, while the lowest CE (75%) was recorded while cutting 952 g m\(^{-2}\) dry weed (Figure 3f). The CE of the BC was highest (100%) over a WH of 412 mm, while CE was reduced to 94% over a WH of 366 mm (Figure 3h). In terms of weed density, the highest CE (100%) was recorded while cutting 223 g m\(^{-2}\) dry weed, while the lowest (94%) was while cutting 278 g m\(^{-2}\) dry weed (Figure 3i). The BC CE did not show the same pattern as other mowers, likely because it is difficult to maintain a consistent weed cutting height with the BC. The CE of the WM was highest (100%) over 327 and 370 mm WH, while the lowest (97%) over a WH of 669 mm (Figure 3k). In terms of weed density, the highest CE (100%) was recorded while cutting 357 and 578 g m\(^{-2}\) dry weed, while the lowest (97%) was while cutting 348 g m\(^{-2}\) dry weed (Figure 3l). The above parameters clearly demonstrate the drawback of the RLM over conventional mechanical mowers in terms of WH and density. Regardless, RLM managed the weeds better because of the longer operational time (about 16 h working and 8 h charging per day) in our research field. Chandler (2003) [34] also reported that given enough time, the robotic mower is likely to cut most of the lawn.

There was a statistically significant (\(p\)-level < 0.05) positive linear relationship between pear (33 \(\pm\) 8 mm dia.) density and MAD. The vibration increased with the increase in the pear density and vice versa. When a higher vibration is employed to the machine, the cutting blade of the RLM stops rotating for a while. In this process, the RLM slows
down the speed to achieve stability and restart the rotor again. Conversely, the MAD value decreased significantly while running over larger pear (80 ± 12 mm dia.). The larger pears lodge in the chassis, blade, and side cover of the RLM; thus, the normal movement is badly hampered. We strongly advise removing fallen pears (small and large) from the ground for a smoother operation of the RLM.

The average hitting force in the bumper of the RLM is 53 N (50–300 cm distance). It is noticeable that even from a shorter distance (50 cm), the load (48 N) is almost similar to the average value. In our orchard, the minimum average tree-to-tree distance was 150 ± 11 cm and 412 ± 104 cm at 940 and 510 trees ha−1, respectively. It is estimated that the RLM hit trees 34,000 times in a crop year (16 h operation per day, excluding charging time, between March and October) in the orchard, which is a cumulative force of 19 MN. Consequently, the top cover of the bumper broke and had to be replaced after one year, although it was designed for 10 years [14,26]. The RLM cover is mainly produced from Acrylonitrile–Butadiene–Styrene [26]. Hence, we recommend the use of tougher material. Another approach could be to use proximity infrared sensors to avoid strikes [35,36]. The single pear (279 ± 28 g) produces a hitting force of 5.3 ± 0.4 N on the RLM bumper. However, if multiple pears, dust, mud, and stone produce an obstacle, equivalent to 29 ± 2 N, the RLM can not pass through the barrier; instead, it slows down, comes back a bit, and alters to the right or left of the direction of travel.

Overmatured fallen pears (80 ± 12 mm dia.) become stuck in the chassis of the RLM during the harvesting period. The RLM tries to dislodge the pear for one or two minutes before automatically powering off to save energy if the attempt is unsuccessful. While testing the operating ability of the RLM over different pear densities (1, 2, and 3 pears m−2), the machine stopped an average of 12, 28, and 48 times h−1, respectively. This would mean the operator has to check the RLM at about 5-, 2-, and 1-min intervals if the pear density on the field ground is 1, 2, and 3 pear pears m−2, respectively. If the machine stops, the operator must restart it manually; thus, a comparatively higher labor force is needed during the pear falling period. Moreover, because of pear obstacles, the machine could not cover the entire field, and weeds grow higher in those areas. Our data also suggest that in pear pre-harvesting (July) and harvesting seasons (August, September) the WH was significantly (p-level < 0.05) higher than in other months (Table 1). We also found a positive linear relationship between pear density and blade hitting. However, this difference is insignificant (p-level > 0.05), and even a single pear can produce almost a similar number of hitting (68, 76, and 80 number of strikes, per 1, 2, and 3 number m−2 on the ground, respectively). The blades were also frequently replaced at pear falling season because the sharpness was reduced quickly by pear strikes. To summarize, the data show that the number of times the blade hit is similar, but the number of times the machine stopped was different between different pear density, which implies that even a single fallen pear can hamper the operation of the RLM.

We found that the existing RLM is economical (ownership, repair and maintenance, energy, oil, and labor cost) than other conventional mechanical mowers in our research field. In previous study [17], we also found that the operating cost of the RLM was less than RM, WM, and WM (1.3 vs. 2, 10.9, and 2.7 USD 1000 m−2 month−1 respectively). However, for a medium (0.66 ha) and larger (1 ha) orchard, the RLM is not cost-effective than RM and WM because of a smaller capacity of the RLM. The RLM we used can cover only 0.33 ha area. Thus for 1 ha area, we need three single units, which cumulatively increases the cost of mowing. Recently, Ambrogio [37] has produced L400 Elite and L400i Deluxe (v.2020), which can cover 3 and 2 ha respectively, and are capable of working in a sloppy area (45% field slope). Belrobotics [38] has also developed large capacity Ballpicker and Bigmow RLMs, which can control 3 ha and 2.4 ha respectively. Further research can be conducted to study the effectiveness of commercial RLMs under field challenges in the orchards.

This study shows that the existing RLM is suitable for weed management in a small orchard and profitable over other mechanical mowers. However, field challenges like fallen
fruit and tree striking are two potential threats to the RLM’s working performance. It is expected that if these problems can be properly addressed, the RLM could be successfully used in many orchards.

5. Conclusions
The RLM was able to maintain the weed canopy at a smaller and almost constant height (average WH: 44 ± 15 mm and average DWB: 103 ± 25 g m⁻² respectively) in a small orchard despite various field challenges (fallen fruits, tree hitting, etc.). Although the CE in terms of WH was lower in the RLM than other conventional mowers, this can be easily controlled by a longer working period (about 16 h working and 8 h charging per day). The RLM’s working performance diminishes during fruit thinning and harvesting time; hence, it is strongly advised to remove fallen pears from the ground for the safe operation of the machine. Moreover, the RLM bumper frequently strikes trees, which results in a broken cover during our field season. Despite those challenges, the RLM was more cost-effective in our research field than other conventional mowers. However, for a medium (0.66 ha) and larger (1 ha) orchard, the RM and WM show more promise for profitability than RLM. To conclude, the RLM can be a good alternative for small-scale orchard weed management. However, further research and development should be carried out to deal with the challenges of fallen pears and tree collisions.

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Abbreviations

| Acronym/Symbol | Description                    |
|----------------|--------------------------------|
| BC             | Brush cutter                   |
| CE             | Weed cutting efficiency        |
| DWB            | Dry weed biomass               |
| MAD            | Mean amplitude of deviations   |
| RLM            | Robotic lawnmower              |
| RM             | Riding mower                   |
| WH             | Weed height                    |
| WM             | Walking mower                  |

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