Short communication

Weeding Efficacy of an Automatic Weeding Robot Modified from a Mini Robotic Cleaning Ball in a Mesocosm Study

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(Received November 16, 2016; Accepted December 12, 2016)

ABSTRACT

In recent years, an increasing emphasis on conserving biodiversity in cultivated land has led to a need for environmentally friendly and sustainable agriculture that does not depend on the excessive use of agrochemicals. However, it can be difficult to generate high crop yields without using herbicides because alternative methods of restricting weed growth are often costly and labor-intensive. Here, we designed a mesocosm to examine the weeding efficacy of a cheap, commercially available, automatic robot ball, which was originally designed for house cleaning. The weeding robot performed very well, particularly for sprouts of *Monochoria vaginalis* var. *plantaginea*, a major paddy weed found in central Japan.

Key words : Automatic weeding machine, Labor-saving, Paddy field

Paddy fields, which account for more cultivated acres in Japan than any other type of farmland (MAFF, 2015), support a diversity of organisms (Natuhara, 2013) that include dragonflies, frogs, mud snails, and loaches. Over the past few decades, there has been growing pressure within Japan to conserve the biodiversity of these paddy fields and an increasing trend toward low input sustainable agriculture (LISA; Grubinger, 1992) and environmentally friendly farming procedures that use minimal quantities of agrochemicals (Katayama et al., 2015).

However, it is very difficult to attain high crop yields without using agrochemicals in general, and herbicides in particular. Environmentally friendly farming procedures, that include intertillage weeding, are typically far more costly and labor-intensive than treatment with herbicides (Hanagata et al., 2001). In addition, significant increases in average age within the Japanese population mean that it is very important to develop labor-saving ideas that promote sustainable agriculture.

As a result, there has been significant progress in the development of labor-saving technology for Japanese agriculture. A typical example is the "Aigamo Robot", a small device that can disrupt the soil surface and remove paddy weeds automatically (Mitsui et al., 2008). However, despite its technological advantages, it may not be highly likely that the "Aigamo Robot" will be utilized widely because the recommended retail price is over 300,000 Japanese Yen / 2,800 US Dollars (Fujii et al., 2015).

To overcome this problem, we designed a mesocosm to evaluate the weeding efficacy of a cheap and commercially available alternative, an automatic weeding robot modified from the CZ-560 mini robotic cleaning ball (CCP Co., Ltd., Tokyo, Japan).

1. Automatic weeding robot ball

The mini-robot cleaning ball (Fig. 1) runs on three

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AA-sized batteries and moves randomly by altering its center of gravity. The robot's original function was to gather dust and hairs onto its surface, a microfiber covering.

We wrapped the robot ball in two layers of waterproof plastic sheeting instead of microfibers to enable it to move around on paddy fields. We hypothesized that the robot ball's rotation would disrupt the soil surface and uproot paddy weed sprouts and in particular *Monochoria vaginalis* var. *plantaginea*, which is one of the most common paddy weeds in central Japan (Fig. 2).

2. Examination of weeding efficiency in a mesocosm

To form the treatment pools, we set up three vinyl frames (Length, 122 cm; width, 122 cm; height, 30 cm; Intex Recreation Corp., Long Beach, CA, USA) in an experimental farm at The University of Shiga Prefecture (N 35°15'31.0", E 136°13'00.9") for one month between 19 July and 19 August 2016. We removed 46.5 kg dry weight of soil from a paddy field at the farm and mixed it well to ensure the soil quality and weed seed content were uniform throughout. We then air-dried the soil, sifted it with a 4-mm sieve, and divided it evenly into three portions. On 8 July 2016, we lined the bottom of each vinyl pool with one of the soil portions and 42 L of small-grain akadama soil (Tachikawa Heiwa Nouen Co., Ltd., Kanuma, Japan). Then we poured tap water into each pool to a depth of 2.5–3.0 cm.

We carried out the following three treatments: no weeding (untreated); low frequency weeding (15 min weeding per week by the robot); and high frequency weeding (15 min weeding twice per week by the robot). The three treatments were categorized by weeding intensity as 0, 1, and 2, respectively.

The treatment dates were: low frequency weeding carried out a total of four times (29 July, and 5, 12, and 19 August 2016); high frequency weeding carried out a total of eight times (26 and 29 July, and 2, 5, 9, 12, 16, and 19 August 2016). The data recorded included: dry mass of weeds removed each week (removed weeds were left floating on the surface of the water), and quantity of weeds remaining after one month.

Photographs that recorded the states of each mesocosm were analyzed with ImageJ program (ver. 1.45l, Rasband, 2016). Statistical analysis was performed using R software for statistical computing (ver. 3.3.1; R Core Team, 2016). To predict the effect of weeding frequency and total number of days elapsed on the weight of weeds removed each week, a generalized linear model (GLM) was constructed with a Gaussian distribution and an identity link function. The statistical significance of coefficients in the GLM was assessed using *t*-tests.

The *M. vaginalis* variant *plantaginea* was overwhelmingly prevalent and accounted for more than 99% of the weeds that occurred in the plots. A few other species of weed occurred only in the untreated plot. These included: *Aeschynomene indica*, *Schoenoplectiella lineolata*, and *Lindernia procumbens*. At the end of the experiment, a large amount of algae remained in the low weeding frequency plot (Fig. 3b). The number of *M. vaginalis* var. *plantaginea* plants remaining in the untreated, low weeding frequency, and high weeding frequency plots after one month were 1860, 452, and 653, respectively (Fig. 3). Similarly, the total dry mass of weeds remaining in the three plots were 11.16, 0.48, and 1.45 g, respectively (Fig. 3).

The GLM indicated that increasing the weeding frequency by one intensity level increased the dry mass of weeds removed by 0.942 g (Table 1). In addition, there was a

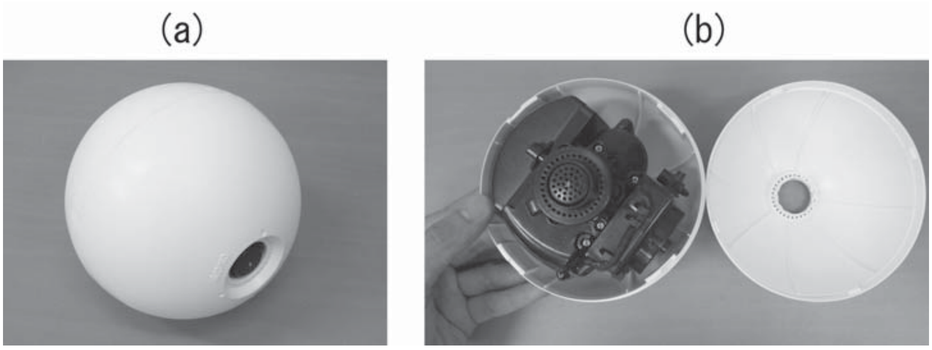

Fig. 1. (a) The CZ-560 mini robotic cleaning ball (CCP Co., Ltd.). The retail price is 3,790 Japanese Yen/35 US Dollars. (b) The robot ball's internal structure.

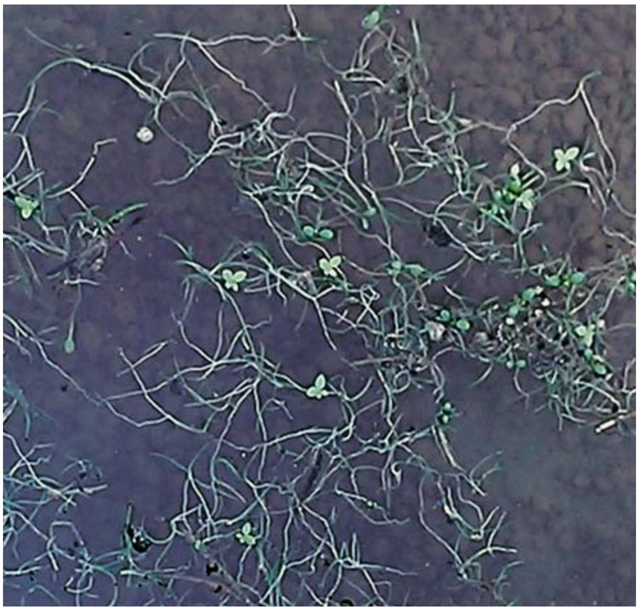

Fig. 2. *Monochoria vaginalis* var. *plantaginea* floating on the water's surface after being uprooted by the automatic weeding ball.

significant negative interaction between the frequency of weeding and the number of days elapsed and this reduced the dry mass of weeds removed by 0.047 g (Table 1).

As expected, the quantity of weeds removed was higher at high weeding frequency but decreased as the experiment progressed (Fig. 4, Table 1). The quantity of weeds removed was reduced by half 20 days after the start of the experiment, regardless of the weeding frequency. The soil quality and weed seed content would have been very similar in all three treatments at the start of the experiment because the soil was mixed well. Therefore, there are three possible explanations for this observation: (1) a reduction in the quantity of remaining weeds when the weeding frequency was higher, (2) an increased resistance to weeding as weeds anchor their roots more strongly, and (3) an enhanced competition for resources between weeds and algae at lower weeding frequency.

The first and second explanations are highly plausible.

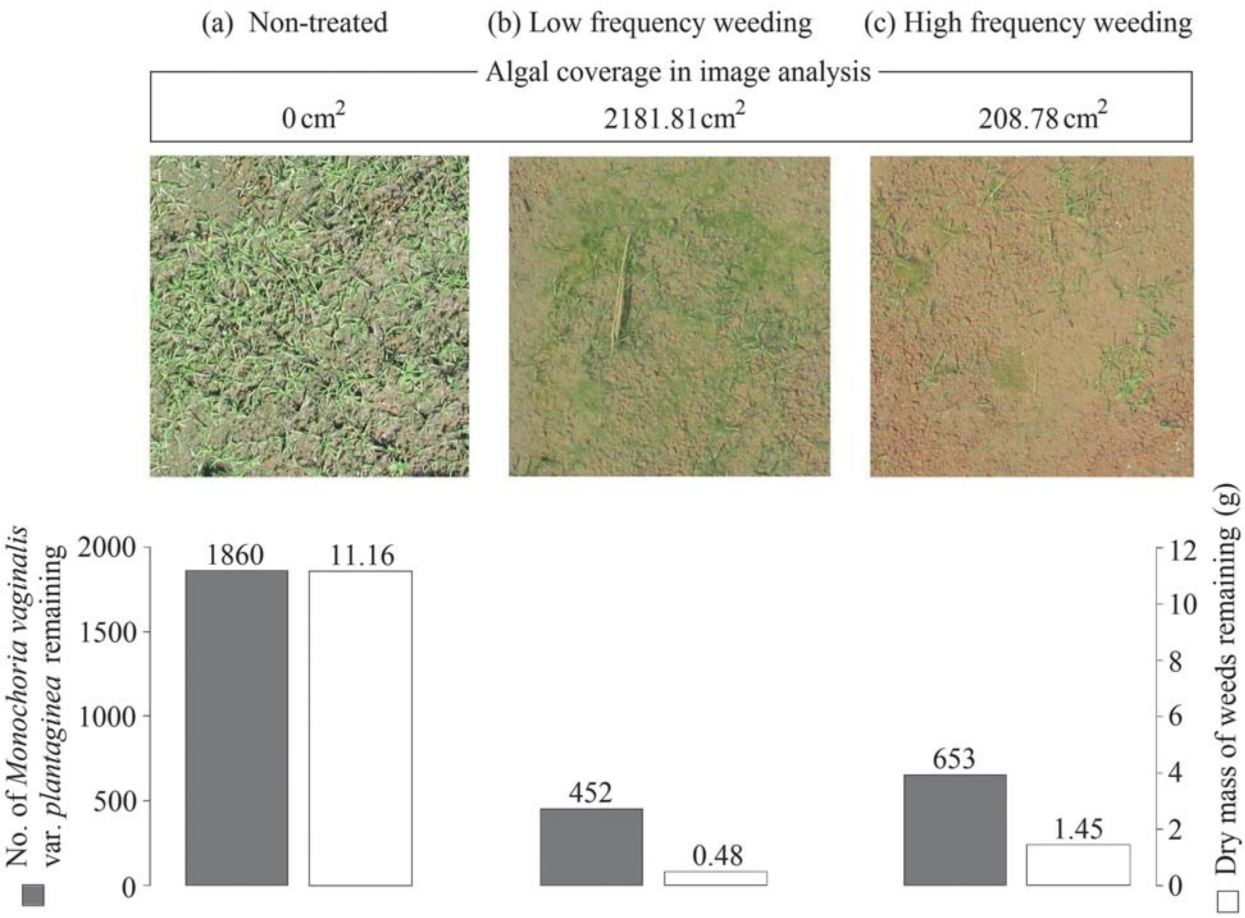

Fig. 3. Photographs taken from the center top portion of each mesocosm. The yellowish-green and green color organisms were weeds and algae, respectively.
The number (gray bar) and dry mass (white bar) of *Monochoria vaginalis* var. *plantaginea* remaining in (a) the untreated, (b) the low weeding frequency, and (c) the high weeding frequency plots at 30 days. The weeds in the untreated plot included a few other species.

Table 1. Effect of the number of days elapsed, weeding frequency, and the interaction between these two variables on the dry mass of weeds removed (GLM).

Response variable	Explanatory variables	Coefficient	S.E.	t-value	*P*-value
Dry mass of weeds removed	Intercept	0.036	0.130	0.276	0.790
	Days elapsed	−0.001	0.010	−0.139	0.893
	Frequency of weeding	0.942	0.101	9.327	1.42e-5
	Days elapsed : Frequency of weeding	−0.047	0.008	−6.072	0.0003

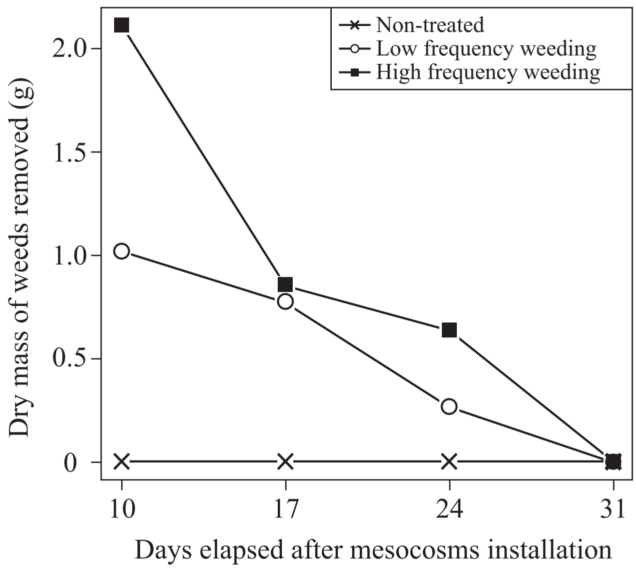

Fig. 4. The negative relationships between days elapsed and the dry mass of weeds removed for the high frequency (black squares) and low frequency (open circles) weeding treatments.

The third explanation is based on the observation that substantial quantities of algae occurred only in the low weeding frequency plot (Fig. 3b) and algae could have decreased the quantity of weeds by depriving them of necessary resources. Therefore, to precisely predict weeding efficacy, it may be necessary to consider the prevalence of algae as an important factor and to include more experimental replicates.

High frequency weeding (twice a week) resulted in the most weeds being removed (Fig. 4), but the total quantity of remaining weeds was lower in the low weeding frequency plot (Fig. 3). The latter result may be an artifact of the experimental procedures and could be due to the unpredictable prevalence of algae. However, there may be a tradeoff in weeding efficacy between the high and low frequency treatments used here, because fewer weeds remained after the low weeding frequency treatment. The automatic robot ball may have an optimal weeding frequency that maximizes its efficacy. To define this optimal weeding frequency further experiments that adjust the frequency in small increments will be necessary.

In this study the robot ball ran on batteries and these had to be charged if the robot was operating for an extended period of time. From a practical perspective, if the robot was operating in large paddy fields rather than our mesocosm, charging the batteries would incur substantial running costs. In addition, the robot ball is not waterproof. To overcome these problems, we plan to develop a new, waterproof automatic weeding robot ball equipped with a solar panel and to perform future experiments in paddy fields.

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