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REVIEW

Development of Remote-Controlled High-Efficiency Mower for Steep Slopes

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Abstract
We developed a prototype remote-controlled hammer-knife mower capable of mowing weeds over 1 m high on steep slopes. The work efficiency of the prototype is twice that of a commercially available remote-controlled mower and 2.6 times that of a walking-type mower. In flat fields with clusters of tall goldenrods, the prototype was twice as efficient as a brush cutter.

Discipline: Agricultural Engineering
Additional key words: hammer-knife, remote control, mowing, engine, work efficiency

Introduction

1. Background

Due to the declining number of agricultural workers, labor shortages and the need for expanding production areas have become significant problems. Mowing on steep slopes is particularly labor-intensive, and the unstable work posture results in numerous accidents, including sliding and tumbling. This issue is especially serious in western Japan, where mountainous terrain prevails, the ratio of causeways to arable land is high, and substantial labor is required to maintain these areas, so reducing the workload has high priority (Fig. 1).

From 2017 to 2022, the number of fatal agricultural accidents involving brush cutters (mowers) has averaged nine cases annually, which represents a significant portion of those related to non-self-propelled agricultural machinery. Reports indicate that accidents are often caused by sliding and contact with the blade. Consequently, the Ministry of Agriculture, Forestry and Fisheries (MAFF) has strengthened safety initiatives by issuing warnings regarding brush cutter use and compiling safety guidelines in the "Guidelines for Farm Work Safety (MAFF Production Bureau, January 2018)." However, this situation has not improved significantly.

2. Previous research

Thus, various research and development efforts have enabled workers to operate mowers without having to personally climb slopes. For example, a suspended slope mower consisting of a parent and a child machine was developed for mowing large slopes in mountainous areas, such as the Kinki and Chugoku regions. However, while it could adapt to steep slopes, its work efficiency was low, and the presence of high weeds further decreased work efficiency (Yoshida et al. 2003). Also, a remote-controlled mower with an electrically driven traveling unit and two

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engine-driven rotary cutting units (Nakamoto 2017) was developed, but a reciprocating action was needed to process uncut areas between the left and right cutting blades that were not pulverized, since they separated. Furthermore, since it only cuts the base of the weeds, they remain intact without being shredded. A remote-controlled electric mower (Kurihara et al. 2020) with a driving unit that can travel stably on ridges between rice paddies and slopes has been developed for mowing around rice paddies and converted fields. In addition, a small wire-guided mowing robot that can be carried by one person (Kikuchi et al. 2020) and operate on slopes steeper than 45° has been developed. These machines were designed for areas with relatively low-height weeds and are not suitable for mowing large weeds. Conversely, remote-controlled mowers for steep slopes, primarily used on riverbanks, can handle weeds over 1 m high, but they are large and cannot be loaded onto the mini trucks commonly used in agriculture in mountainous areas, which limits where they can be used for agricultural land management. In addition, a robot mower with an autonomous driving system using RTK-GNSS was developed to further reduce labor costs (Igarashi et al. 2022), as shown in Table 1.

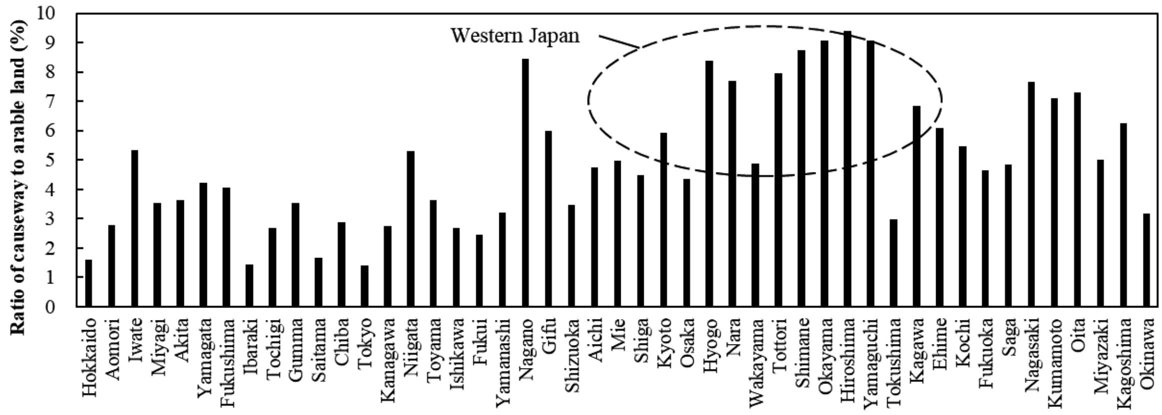

Fig. 1. Ratio of causeway to arable land

Table 1. Overview of developed mowers

No.	Type	Dimension and weight	Power	Cutting unit	Driving unit	Test conditions and performance	
						Test conditions	Performance
1)	Suspended type (a parent and a child machine (suspended by winch))	Parent: Length: 1,950 mm Width: 600 mm Height: 930 mm Weifht: 221 kg Child: Length: 970 mm Width: 750 mm Height: 525 mm Weight: 42 kg	Parent: engine Child: engine (3.3 kW)	Rotary (2 straight blades)	Parent: crawler Child: wheel	- Slope angle: ave. 30°-40° - Weed height: 10 cm-80 cm	- Work efficiency: 3-6 a/h - *Solidago altissima* (over 1 m) may not be mowed
2)	Remote control type	Width: 900 mm Weight: 143 kg	Cutting: engine Traveling: battery (DC48 V, 400 W)	Rotary (nylon cord)	Crawler	- Slope angle: approximately 38°	- Work speed: 0.35, 0.41 m/s - Work efficiency: 5.9 a/h - Leaving weed uncut between right and left cutting blades - Not pulverized
3)	Remote control type (practical model)	Length: 1,300 mm Height: 540 mm Weight: 90 kg	Battery (DC36 V, 34 Ah)	Rotary (4 free blades)	Crawler	- Slope angle: ave. 19.8°, 31.3° - Weed height: ave. 46.4 (26.2-66.2) cm	- Work time: 99.1 min/10a
4)	Towing and Induction type	Length: 430 mm Width: 420 mm Height: 260 mm Weight: - Towing type: 9.3 kg - Induction type: 10.9 kg	Battery (18 V)	Rotary (nylon cord)	Wheel	Towing type: - Slope angle: ave. 35.1° - Weed height: ave. 36 cm Induction type: - Slope angle: ave. 31.9° - Weed height: ave. 29 cm	Towing type: - Work efficiency: 2.4 m^2/min Induction type: - Work efficiency: 1.3 m^2/min
5)	Robot type (using RTK-GNSS)	Length: 1,260 mm Width: 1,160 mm Weight: 200 kg	Engine (8.7 kW)	Rotary (2 axes, 2 stages, total of 8 free blades)	Wheel (skid steer)	- Slope angle: approximately 25°	-Work speed: 0.52 m/s

3. Classification and features of remote-controlled mowers

Commercial remote-controlled mowers can be classified as shown in Table 2. Models powered by engines, batteries, or both are available, and the number of battery-powered models has increased in response to environmental concerns. A power transmission system can be mechanical or hydraulic, the latter having the advantage that the direction of the mowing blade rotation can be changed easily. The mowing unit is usually a rotary or hammer-knife type; the rotary type is usually located between the left and right traveling units, whereas the hammer-knife type is usually in front of the machine body. The traveling unit of the rotary type is located outside the mowing unit, one side of the unit runs over weeds before mowing, making it prone to leaving grass uncut. However, it can change direction without making a U-turn and offers high work efficiency. The mowing unit of the hammer-knife type is mounted in front of the machine, so the traveling unit does not compress weeds before mowing. However, it is necessary to make a U-turn when reversing direction, which results in a lower work efficiency than the rotary type. In general, a crawler-driven mower can traverse slopes better than the wheel type, but making sharp turns disturbs the ground. Some remote control units are dustproof and waterproof, allowing operation even in rain and under dusty conditions. Those that are not dustproof or waterproof may be shielded by a protective cover. In addition, some models have enhanced safety features, such as a machine-mounted winch to prevent the mower from rolling down a steep slope.

In this study, we developed a small, remote-controlled, hammer-knife mower capable of cutting weeds over 1 m high on slopes of up to 45°. This paper outlines the development of the mower and describes its performance (Aoki et al. 2025).

Table 2. Classification of remote-controlled mower components

Power	Engine
	Battery
	Engine and battery
Power transmission	Mechanical
	Hydraulic
	Wire harness
Cutting unit	Rotary
	Hammer-knife
Driving unit	Wheel
	Crawler
Operating unit	Dustproof and waterproof
	Not dustproof or waterproof
Others	Winch mounted

Overview of the Machine

1. Development concept and objectives

Six goals were established at the beginning of the research:

(1) A maximum slope angle of 45° and work efficiency of 20 a/h.
(2) A hammer-knife cutting unit that can handle thick weeds.
(3) A gasoline engine and a hydraulic crawler.
(4) Remote control to allow the worker to operate it in a stable posture from a safe location.
(5) A machine small enough for loading on a mini truck.
(6) An easily detachable cutting unit so the machine can be used for tasks other than mowing.

2. Structure of the prototype

Based on the above requirements, the 2021 prototype (Fig. 2; Table 3) was designed as a remote-controlled mower consisting of a cutting unit, a traveling unit, and an operating unit. It is equipped with a 10 kW gasoline engine, a hydraulically driven crawler, and a hammer-knife mower. The traveling unit is a crawler driven by an independent hydraulic motor on the left side and one on the right. The travel speed can be adjusted from 0 to 1.4 m/s using a hydraulic static transmission (HST), allowing the machine to perform left-right pivots and spin turns. The mower employs a hammer-knife cutting unit for weeds taller than 1 m and a blade driven by a hydraulic motor that can be switched between forward and reverse rotation. The cutting unit has Y-shaped blades attached to a vertical rotating axle in sets of seven, spaced every 120°. The tip of the blade can be raised and lowered incrementally by an electric cylinder within a range of 20 mm-200 mm from the

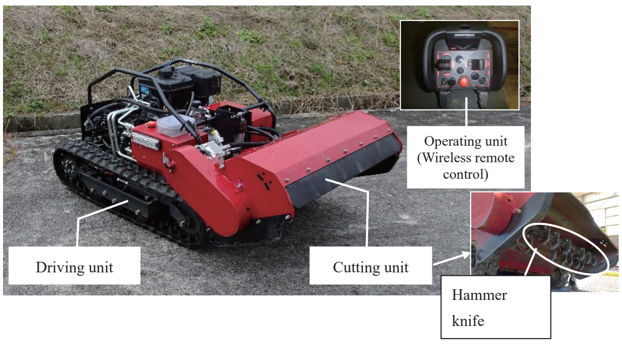

Fig. 2. Appearance of the prototype mower

Table 3. Prototype specifications

Engine	Fuel		Gasoline
	Power	kW (PS)	10 (14)
Dimensions	Overall length	mm	1,683
	Overall width	mm	1,105
	Overall height	mm	690
Weight		kg	346
Available inclination angle (Max.)		°	45
Operating unit			Wireless remote controller
Driving unit	Drive method		Hydraulic motor (HST)
	Traveling system		Crawler
	Crawler width	mm	130
	Distance between crawler centers	mm	875
	Grounding length	mm	823
	Traveling speed (Max.)	m/s	1.4
Cutting unit	Drive method		Hydraulic motor
	Cutting width	mm	950
	Cutting height	mm	20-200 (Stepless)
	Cutting blade		Hammer-knife

ground. In addition, the cutting unit can be detached and replaced with other devices. A 2.4 GHz remote control is IP65-dustproof and -waterproof, and controls the following functions: starting and stopping the engine, moving forward/backward and turning, raising and lowering the cutting unit, rotating the cutting blade during upward/downward motion, and emergency stopping from a distance of up to 100 m. If the control signal is lost, the mower cuts off automatically and stops safely. The machine is lightweight, and its engine, hydraulic tank, hydraulic pump, and HST are arranged to ensure balance is not biased to the left or right at the front or rear of the machine, providing stability on slopes. The machine measures 1,683 mm × 1,105 mm × 690 mm and weighs 346 kg so that it can be transported by a mini truck or van (Fig. 3).

Fig. 3. Loaded onto a mini truck (truck bed size: 1940×1410 mm)

3. Work method

The prototype was transported from the storage area to the target slope by a mini truck and then moved onto the slope under its own power. If there are no restrictions on the slope, mowing is done along contour lines, turning around at the edge of the slope, and then starting the next pass. The operator typically controls the machine remotely from a flat area above or below the slope, allowing for easy monitoring of the work. For safety, the operator should not stand directly below the mower on the slope when using the remote control to avoid injury if the machine slides or tumbles.

Test Method

1. Test of static stability

To confirm the stability of the prototype, we investigated its static tipping angle (Fig. 4) and weight distribution (Fig. 5). The static tipping angle is defined as the angle at which one side of the crawler lifts from the surface as the platform is gradually tilted.

2. Mowing test of adaptability conditions

Tests were conducted in July and November 2021 on a slope at the Western Region Agricultural Research

Fig. 4. Measurement of static tipping angle

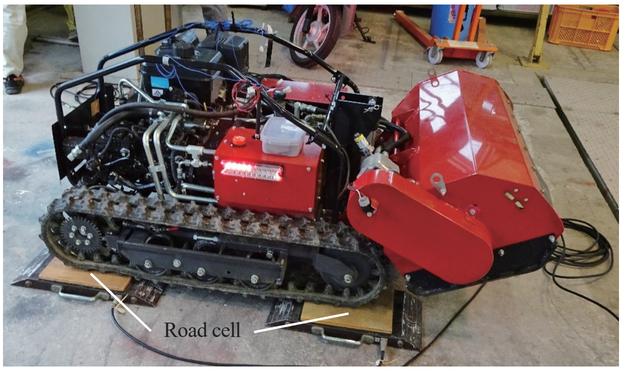

Fig. 5. Measurement of weight distribution

Table 4. Test field conditions at the Western Region Agricultural Research Center, NARO

Test site		Zentsuji City (Kagawa Pref.)				
Date of test		July 6, 2021		November 9, 2021		
Work area (m²)[*1]		273	99	130	114	900
	Length×Width (m)	42×6.5	26×3.8	20×6.5	20×6.5	60×15
Test machine		Prototype		Prototype	Remote-controlled mower (Commercial)	Prototype
	Power (kW) / Total Displacement (L)	10 / 0.408	10 / 0.408	10 / 0.408	1.95 / 0.053	10 / 0.408
	Work width (m)	0.95	0.95	0.95	0.50	0.95
Slope angle (°)	Ave.	35.7	27.5	35.7		16.5
	Min.	33.3	24.5	33.3		14.0
	Max.	38.0	29.3	38.0		20.0
	SD	1.7	1.5	1.7		1.8
Soil moisture content ratio (%d.b.)		33.5	33.2	27.0		43.3
Soil penetration resistance value (Mpa/cm²)	Depth: 10cm	0.8	2.1	0.4		1.2
	Depth: 20cm	1.3	3.5	1.0		1.9
Weeds	Weed height (cm)	66.9	28.1	74.4		13.8
	Dry matter weight (g/m²)	331.4	592.0	223.0		413.6

[*1] The working area may not correspond to the length × width because obstacles, etc., in the test area are excluded.

Center (Zentsuji City, Kagawa Prefecture) to clarify the relationship between the slope angle, weed conditions (weed height and dry matter weight), and work efficiency of the prototype. We investigated operating hours, fuel consumption, cutting height, and cutting length, and measured engine speed, mower speed, and inclination angle of the machine in the left and right directions. The average slope angle of test plots ranged from 16.5° to 35.7°, the test areas ranged from 99 to 900 m², the weeds ranged from 14 to 74 cm high, and the dry matter weight of weeds ranged from 14 to 74 g/m². A test plot was established in November, and a commercial remote-controlled mower was used as the control machine (Table 4).

Fig. 6. Mowing on a steep slope (max. 39°)

3. Test of field adaptability

To evaluate the prototype's adaptability to steep slopes with thick weeds in Fukushima Prefecture, field tests were conducted in the village of Iitate in August and October 2021 and in Kitakata in October 2021 (Fig. 6). We investigated working hours, fuel consumption, cutting height, cutting length, and other parameters, as in the confirmation test of adaptability conditions, and also measured the effect of the machine's inclination angle of operation. The average slope angle of the test area ranged from 33.5° to 36.3°, the test area from 165 to 427 m^2, the weed height from 49 to 155 cm, and the weed dry matter weight from 273 to 734 g/m^2. In the October test in Iitate, a test plot was established using a commercial walking mower as the control machine.

In addition, we evaluated the adaptability of the prototype in flat areas of Koriyama, where weed species are considered difficult to mow (August, with kudzu (vine weed) as the main grass species) and in Iitate (October, with *Solidago altissima* as the main grass species). The average slope angle of the test plots ranged from 2.8° to 5.7°, the test areas were 85 to 350 m^2, the weeds were 136 to 158 cm high, and the dry matter weight ranged from 611 to 1,235 g/m^2. A test plot was established in October using *Solidago altissima*, with a commercial brush cutter serving as the control (Table 5).

4. Questionnaire survey

On-site demonstrations were conducted in Iitate and Kitakata in Fukushima Prefecture, and a questionnaire survey was conducted using the prototype. The survey items included work speed, cutting width, cutting height, remote-control functions, machine size and weight, available inclination angle, and a comprehensive evaluation. Responses were obtained on a five-point scale (ranging from "bad" = 1 to "good" = 5).

Results and Discussion

1. Test of static stability

The weights of the front left, front right, rear left, and rear right of the machine were 83.3, 95.6, 76.3, and 90.8 kg, respectively, with the cutting unit raised, and 86.0, 98.5, 73.2, and 87.4 kg with the cutting unit lowered (Table 6). The front-to-rear weight distribution was 52:48 with the cutting unit raised and 53:47 with the cutting unit lowered. The left-to-right weight distribution was 46:54 for both positions, indicating that the machine weight was distributed almost equally. The 0.9 kg difference in total weight between the raised and lowered positions was attributed to measurement error caused by load redistribution among load cells during the adjustment. The static tipping angle exceeded 59° in all directions with the cutting unit raised, and 62° with the cutting unit lowered, confirming sufficient margin for the target slope gradient under static conditions (Table 7).

2. Mowing test of adaptability conditions

Results confirmed that the higher the field slope angle, the lower the work efficiency (Fig. 7). This occurred because the larger the slope angle of the field, the more the machine tended to move toward the valley

Table 5. Test field conditions in Fukushima

Test site		Iitate Village (Fukushima Pref.)					Kitakata City	Koriyama City	Iitate Village (Fukushima Pref.)		
Date of test		August 5, 2021		October 6, 2021	October 21, 2021		October 19, 2021	August 5, 2021	October 7, 2021		October 20, 2021
Work area (m^2)*1		349	427	364	360	323	165	85	350		251
	Length×Width (m)	78×5	68×7	50×8	72×5	51×7	55×3	17×5	35×10		29.5×8.5
Test machine		Prototype			Prototype	Walking-type mower (Commercial)	Prototype	Prototype	Prototype	Brush cutter (Commercial)	Prototype
	Power (kW) / Total displacement (L)	10 / 0.408	10 / 0.408	10 / 0.408	10 / 0.408	1.7 / 0.047	10 / 0.408	10 / 0.408	10 / 0.408	- / 0.026	10 / 0.408
	Work width (m)	0.95	0.95	0.95	0.95	0.50	0.95	0.95	0.95	2.07	0.95
Slope angle (°)	Ave.	33.5	34.9	33.7	36.3		35.0	5.7	2.8		4.1
	Min.	27.1	30.9	29.8	30.5		31.5	3.0	−0.3		1.4
	Max.	37.6	38.2	39.0	41.6		38.2	7.0	6.5		5.5
	SD	3.5	2.6	2.6	3.0		1.7	1.3	2.1		1.4
Soil moisture content ratio (%d.b.)		44.2	43.4	52.3	47.0		49.6	19.8	45.4		47.1
Soil penetration resistance value (Mpa/cm^2)	Depth: 10cm	0.4	0.9	0.6	0.9		1.2	0.6	0.6		0.6
	Depth: 20cm	0.9	2.2	1.5	1.8		1.3	1.3	2.9		1.1
Weeds	Weed height (cm)	63.2	49.2	146.0	155.4		111.6	158.3	135.7		146.0
	Dry matter weight (g/m^2)	273.0	567.8	734.4	634.2		288.4	699.4	610.8		1,235.1

*1 The working area may not correspond to the length × width because obstacles, etc., in the test area are excluded.

Table 6. Weight distribution of the prototype

unit: kg

Measurement position		Cutting unit in raised position	Cutting unit in lowered position
Front of mower	Left	83.3	86.0
	Right	95.6	98.5
Rear of mower	Left	76.3	73.2
	Right	90.8	87.4
Total		346.0	345.1

Table 7. Static tipping angle of the prototype

unit: °(degrees)

Direction of mower (Cutting unit side is front)	Cutting unit in raised position	Cutting unit in lowered position
Left side down	63.8	66.9
Right side down	59	62.7
Rear side down	68.9	69.5 ≤
Front side down	69.5 ≤	69.5 ≤

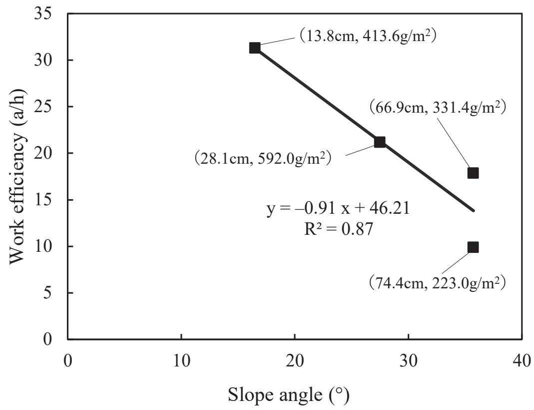

Fig. 7. Relation between slope angle and work efficiency

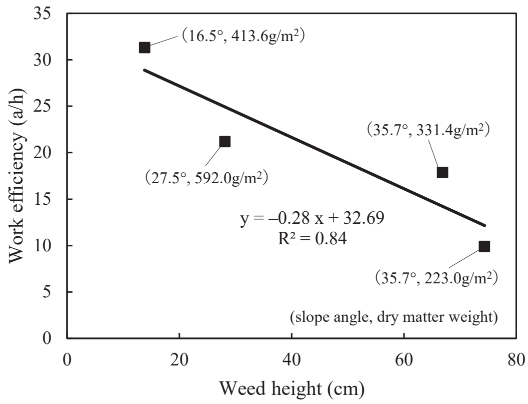

Fig. 8. Relation between weed height and work efficiency

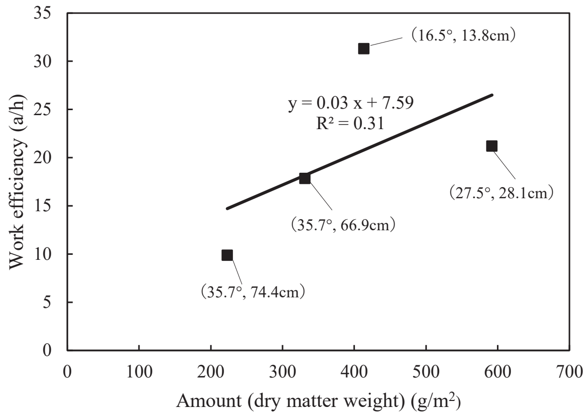

Fig. 9. Relation between weed amount (dry matter weight) and work efficiency

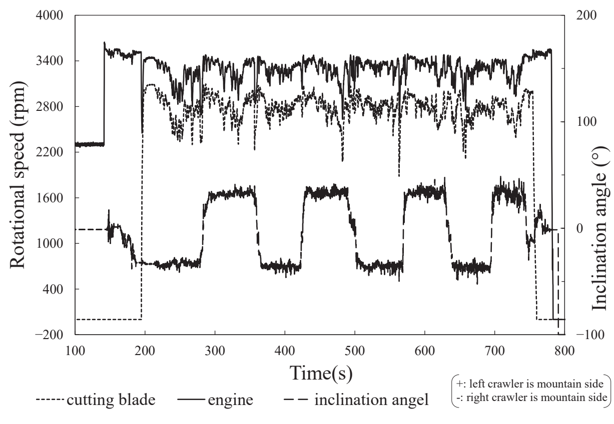

Fig. 10. Cutting blade rotational speed, engine rotational speed, and inclination angle of the prototype

because of the effect of gravity, making it difficult to mow while maintaining the machine's direction of travel along the contour line; thus, the work speed could not be increased. In addition, we confirmed that the greater the weed height, the lower the work efficiency in the field (Fig. 8). This occurred because the volume of weeds shredded by the cutting unit increases with weed height, which increases the load on the cutting unit and prevents an increase in work efficiency. However, the present study found no clear relationship between weed dry matter weight and work efficiency (Fig. 9). This was likely due to the characteristics of the target weeds, including weed species and moisture content, which affected the load on the cutting unit, in addition to the significant effect of the slope angle of the field.

The speeds of the cutting blade and engine did not decrease significantly during operation. However, temporary fluctuations were observed, likely due to the load on the traveling unit when turning and the load on the cutting unit when cutting thick weeds. The mowing operation was generally stable at an average cutting blade speed of 2,789 rpm and an average engine speed of 3,288 rpm. The maximum inclination angle during

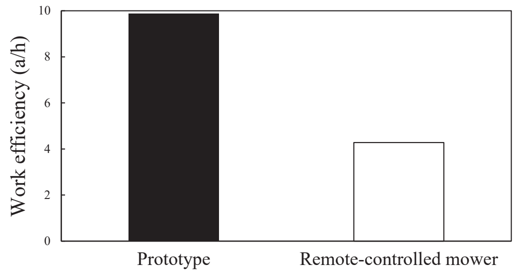

Fig. 11. Comparison of prototype and commercial remote-controlled mower

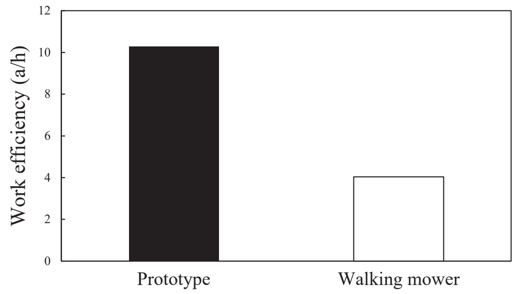

Fig. 12. Comparison of prototype and commercial walking mower

operation was approximately 50°, confirming that the machine can operate on slopes of 45° or more (Fig. 10).

The prototype achieved its target of 20 a/h under certain conditions. The work efficiencies of the prototype and the tested commercial remote-controlled mower were 9.9 a/h and 4.3 a/h, respectively, confirming that the prototype offered approximately twice the work efficiency of the commercial model (Fig. 11). The cutting height and length after mowing were 11 cm-20 cm and 10 cm-32 cm, respectively, which were equivalent to those obtained with the commercial mower.

3. Test of field adaptability

Results showed that fields with an average slope angle of 33.5° to 36.5° at different times in Iitate (August and October) and in Kitakata (October) could be mowed with a work efficiency of 7.1 to 11.3 a/h for various grass species and heights. The maximum slope angle during the work was approximately 52° in August and 55° and 49° in October in Iitate and 46° in Kitakata. Results confirmed that slopes of 45° or more could be worked, even with weeds taller than 1 m.

The work efficiency of the prototype and a commercial walking mower was 10.3 and 4.0 a/h, which was 2.6 times as high (Fig. 12). The cutting height and length after mowing were 19 and 29 cm, respectively, which are equivalent to those obtained with a commercial walking mower.

In addition, on a flat area (Fig. 13) with a colony of hard-stemmed, large *Solidago altissima* (136 cm in height), work efficiency was 12.6 a/h without any problems, which was more than twice as efficient as work with a brush cutter (Fig. 14).

On the other hand, the prototype could also work on a flat area (Fig. 15) where kudzu vine weed flourishes. However, fuel consumption was as high as 1.2 L/a because it was necessary to reduce speed to avoid overloading the cutting unit for continuous work under conditions where the load on the unit was large. Although the vines were sometimes wrapped around the rotating

Fig. 13. Mowing *Solidago altissima* (at Iitate)

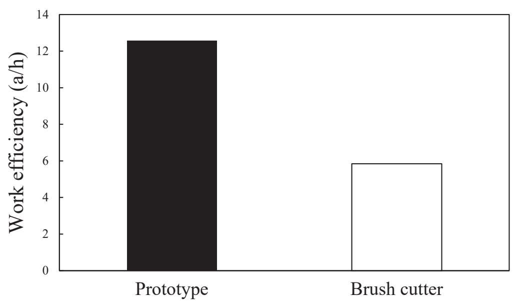

Fig. 14. Comparison of prototype and commercial brush cutter

Fig. 15. Mowing kudzu (*Pueraria lobata* subsp. Lobata)

Table 8. User survey results

Items	Evaluation					
	Bad				Good	Ave.
	1	2	3	4	5	
Work speed			4	17	10	4.2
Cutting width			6	14	11	4.2
Cutting height		1	13	10	7	3.7
Functions of remote control			9	14	8	4.0
Size and weight of prototype		4	9	11	7	3.4
Available inclination angle		1	6	14	10	4.0
Comprehensive evaluation			5	22	4	4.0

shaft, causing the unit to overload, it was possible to remove the wrapped vines and continue work by reversing the hydraulically driven cutting blade.

4. Questionnaire survey

Questionnaire responses were obtained from 31 participants in the field demonstration (Table 8). The average score for each item was four points, and no items received a rating of one point. Items related to work efficiency, such as work speed and cutting width, received particularly high scores, whereas cutting height and machine size and weight tended to receive slightly lower ones.

Conclusion and Future Development

We developed a remote-controlled hammer-knife mower capable of mowing thriving weeds on steep slopes and confirmed its performance through field tests. As a result of this study, the SH950RC remote-controlled small hammer-knife mower has been marketed by Kyoeisha Shibaura Inc., a joint research company, since June 2022. As with remote-controlled mowers already on the market, the newly developed mower may not be suitable for all slope conditions in Japan, but it provides safe and highly efficient mowing on steep slopes, and we believe it will contribute to reducing labor burdens and improving work efficiency at production sites. Kyoeisha Shibaura Inc. is currently researching the development and practical application of new attachments other than mowing and is expected to increase the utilization rate of this machine through its general-purpose design.

Remote-controlled mowers are currently being widely introduced. If the number of farmers continues to decline, it is likely that an automatic mowing function utilizing GNSS location information will be incorporated into remote-controlled mowers to further reduce mowing labor. Additionally, the introduction of robot mowers on gentle slopes under favorable conditions will be considered in the future.

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