Lailati *et al. CABI Agriculture and Bioscience* (2022) 3:20
https://doi.org/10.1186/s43170-022-00087-6

CABI Agriculture and Bioscience

RESEARCH

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Effects of ground bamboo application on weed suppression and rice production: a 3-year paddy field experiment

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Abstract

Background: In light of the dramatic expansion of Japan's bamboo forests, it is necessary to develop a strategy for the effective use of bamboo biomass resources. In this study, we tested the effects of ground bamboo as an organic mulching material or soil conditioner during a 3-year, agrochemical-free rice cultivation period.

Methods: We performed field experiments in 16 experimental paddy fields and established five treatments with three or four replicates each: control, manual weeding, low-volume ground bamboo application (0.5 kg m^{-2}), medium-volume ground bamboo application (1.0 kg m^{-2}), and high-volume ground bamboo application (2.0 kg m^{-2}).

Results: We observed no suppression of aquatic weeds with the ground bamboo treatments. Nevertheless, in the first year, rice yields were 1.7–1.8 times greater in the medium- and high-volume ground bamboo treatments than in the controls. In the second and third years, rice yields did not differ among treatments. During the 3-year period, mean rice yields dropped dramatically to around 20%. Simple linear regression analyses indicated that rice yields were positively associated with available phosphate, and negatively associated with the silicic acid content of post-experiment paddy soils after the second and third years of cultivation. Multiple linear regression analyses indicated that available phosphate and silicic acid were important variables explaining rice yields. Application of ground bamboo did not appear to reduce external rice grain quality.

Conclusions: Application of ground bamboo may enhance the production of high-quality rice, particularly when soil phosphorus is not deficient.

Keywords: Environmentally friendly farming, Moso bamboo, Organic farming, Satoyama, Silicon

Introduction

In recent decades, there have been more bamboo forests in human-modified landscapes, particularly in southern, western, and central Japan, due to farmers' aging, heavy management burdens, and a decline in bamboo exploitation (Okutomi et al. 1996). From 1986 to 2012, the total area of bamboo forest in Japan increased by around 10%, from 147,000 to 161,000 ha (Forestry Agency 2018). Consequently, native deciduous forests and uncultivated agricultural land in particular have been progressively invaded by introduced moso bamboos (*Phyllostachys edulis* (Carrière) J. Houz.) (Okutomi et al. 1996; Suzuki and Nakagoshi 2011). Bamboo invasion of forests and agricultural land has reportedly caused the

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death of coniferous trees, promoted sediment erosion, and reduced plant diversity (Hiura et al. 2004; Yamamoto et al. 2004; Suzuki 2010).

In recent years, various strategies have been implemented in Japan with the aim of effectively utilizing bamboo biomass resources. Bamboo has generally been considered unsuitable as fertilizer because its essential nutrient contents (e.g., nitrogen, phosphorus and potassium) are low. However, recent studies have reported that microbial fermentation progresses remarkably by grinding the xylem, because the internal organs of bamboo contain abundant sugars (Rural Culture Association 2012). Therefore, ground bamboo's (or 'bamboo chips') potential applications as a soil conditioner or mulch have attracted considerable attention in dryland farming. For example, several studies have reported that surface application of ground or chipped bamboo increased yields of soybeans (Nakagawa et al. 2009), tomatoes (Yagi et al. 2016a), and spinach (Asagi and Noda 2006). Research has also demonstrated that application of ground or chipped bamboo suppresses weed growth in horticultural fields (Yagi et al. 2016b). However, with the exception of bamboo charcoal (Toma et al. 2019), the effectiveness of ground bamboo application for rice farming has rarely been tested.

Rice yields in agrochemical-free farms are only 32–88% of those in conventional farms (Oomori 2015). Suppression of aquatic weeds (and consequent enhancement of rice yields) presents major challenges in agrochemical-free rice farming. Major weed control techniques include physical controls that use weeding machines or herbivorous animals (*Anas platyrhynchos var. domesticus* L., *Oreochromis niloticus* (L.), *Cyprinus carpio* L., and *Triops* spp.), organic or paper mulch, or summer deep flooding practices (Katayama et al. 1974; Harada et al. 2001; Frei et al. 2007; Nakai and Toritsuka 2009). Rice bran is typically used in organic rice farming owing to its wide availability and low cost. Several studies have tested the effectiveness of rice bran application for aquatic weed control and rice production (Chiba et al. 2001; Nakai and Toritsuka 2009; Nakayama 2010). However, rice bran application has been shown to be unstable in the presence of major aquatic weeds, such as *Monochoria vaginalis* (Burm. f.) C. Presl ex Kunth and *Schoenoplectiella juncoides* (Roxb.) Lye (Nakai and Toritsuka 2009). The protein content of rice grains may be elevated (an indicator of bad taste) under rice bran application due to the high nitrogen content of rice bran (Kujira et al. 2004).

In a microcosm experiment, Usio et al. (2021) found that application of ground bamboo suppressed aquatic weeds and increased rice yields, without causing any deterioration of external grain quality or enhancement of protein content. In a preliminary experiment, weed suppression, and fertilizer or soil conditioning effects (via nutrient supply from ground bamboo), were considered major mechanisms of rice yield enhancement (Usio et al. 2021). Silicon is among the major ingredients of bamboo (see Table 1). Although silicon is not considered an essential nutrient, its addition can enhance plant growth by mitigating various abiotic stresses, such as salinity, metal toxicity, and ultraviolet irradiation, as well as biotic stress caused by pests and plant diseases (Ma 2004; Epstein 2009). In rice plants, silicon contributes to increased photosynthetic rates by reducing lodging and improving leaf and stalk erectness (Savant et al. 1999; Mihara et al. 2017). Silicon also affects phosphorus availability for plants via phosphorus mobilization (reviewed in Hu et al. 2021).

In this study, we scaled up the experiment, both spatially and temporally. In experimental paddy fields, we conducted a field experiment to evaluate whether ground bamboo application would yield stable or reproducible results with respect to consecutive agrochemical-free rice cultivation. We hypothesized that ground bamboo application would suppress aquatic weeds and thereby enhance rice yields. An alternative hypothesis was that ground bamboo application would have fertilizing or soil conditioning effects. We also expected ground bamboo application to not enhance rice grain protein content owing to its low nitrogen content.

Methods

Ground bamboo preparation

In mid-May 2017, 2018, and 2019, we harvested approximately 50 bamboos from the Satoyama Zone of Kanazawa University Kakuma Campus, Ishikawa Prefecture,

Table 1 Chemical properties of the ground bamboo used in the paddy field experiments conducted in 2017–2019

Parameter	2017	2018	2019
Water content[a] (%)	35.70	28.45	31.50
pH[a]	–	5.07	4.92
Electrical conductivity[a] (mS cm^{-1})	–	0.70	0.59
Total nitrogen[b] (%)	0.19	0.20	0.34
Total carbon[b] (%)	49.50	52.90	50.20
Phosphorus pentoxide[b] (%)	0.21	0.12	0.08
Potassium oxide[b] (%)	0.54	0.41	0.27
Calcium oxide[b] (%)	–	0.03	0.05
Magnesium oxide[b] (%)	–	0.05	0.07
Silicic acid[b] (%)	–	0.28	0.20

Data from 2018 were based on the chemical properties of bamboo culm provided in Usio et al. (2021)

[a] Based on wet samples

[b] Based on dry samples

Japan. After removing the leaves and branches, we ground the bamboo culms using a fuel-operated wood crusher (DraCom KDC-1301B; Karui Corporation, Yamagata, Japan). We packed the ground bamboo in plastic bags (60 L) secured at the mouth. The ground bamboo culms were placed inside a glasshouse to ferment for 15–20 days. The mean ± SD temperature in the glasshouse was 22.3 ± 4.9 °C (range: 13.3–34.1 °C) in 2017, 22.3 ± 6.0 °C (range: 12.1–41.1 °C) in 2018, and 29.2 ± 9.4 °C (range: 15.2–53.6 °C) in 2019, according to hourly measurements made using a temperature logger (HOBO Water Temp Pro v2; Onset Computer Corporation, Bourne, MA, USA).

The fertilizer properties of two 250 g subsamples of fermented culm samples were determined by the Physicochemical Analysis Center (Vegetech Co., Ltd., Kanagawa, Japan) in 2017, and by the Bio Innovation Center (Yanmar Holdings Co., Ltd., Kurashiki, Japan) in 2018 and 2019 (Table 1). Ground bamboo contains few essential nutrients such as total nitrogen (mean, 0.24%; range: 0.19–0.34%), phosphorus pentoxide (mean, 0.14%; range: 0.08–0.21%), and potassium oxide (mean, 0.41%; range: 0.27–0.54%). All fertilizer analyses were performed in accordance with official procedures (National Institute for Agroenvironmental Sciences 1992).

Paddy field experiment

We performed a 3-year field experiment in 16 experimental paddy fields (each 30 m^2; 7.5 m long × 4 m wide) at the Botanical Garden, Institute of Nature and Environmental Technology, Kanazawa University (Fig. 1). These experimental paddy fields were newly developed from crop fields in winter 2016. Eight experimental paddy fields were aligned in two rows, and groundwater was supplied to each field using a bulb.

We established five treatments, with three or four replicates each, using a completely randomized design as follows: control (three replicates in 2017, four replicates in 2018–2019); manual weeding (three replicates); low-volume ground bamboo application (three replicates) (15 kg paddy $field^{-1}$ or 0.5 kg m^{-2}); medium-volume ground bamboo application (three replicates) (30 kg paddy $field^{-1}$ or 1 kg m^{-2}); and high-volume ground bamboo application (three replicates) (60 kg paddy $field^{-1}$ or 2 kg m^{-2}). Although we initially transplanted the rice into 16 experimental paddy fields, we omitted the 2017 results for one field due to shading effects from a riparian tree. From 2018, we included this paddy field as a control after cutting down the riparian tree. We retained the original treatments in all paddy fields over the 3-year study period.

We ploughed twice each year (on 24 and 29 May in 2017, 13 and 22 May in 2018, and 19 and 29 May in 2019) using fuel-operated ploughing machines (TA400 or TRS60; Kubota, Tokyo, Japan). We obtained Koshihikari seedlings (*Oryza sativa* L. cv. Koshihikari) from JA Hakui; these were grown without the use of agrochemicals. In both years, we transplanted the agrochemical-free Koshihikari seedlings in early June (on 3 June in 2017, 3 June in 2018 and 1 June in 2019). To facilitate rice transplantation, a wooden device called a “waku” was used to mark grids on the bottom surfaces of the experimental paddy fields. We manually transplanted 322 (14 × 23 rows; 3 seedlings per locale) (2017) or 345 rice plants (15 × 23 rows; 3 seedlings per locale) (2018–2019) in each paddy field. Soon after rice transplantation, we manually applied fermented ground bamboo culms to the paddy surface of the three ground bamboo treatments. In each paddy field, we installed a temperature logger (HOBO Water Temp Pro v2) near the outlet. Water temperatures were recorded hourly during the experiments; the mean ± SD water temperature was 25.0 ± 4.3 °C (range: 9.2–39.4 °C) in 2017, 26.4 ± 4.9 °C (range: 10.0–42.7 °C) in 2018, and 26.5 ± 4.3 °C (range: 14.7–41.9 °C) in 2019.

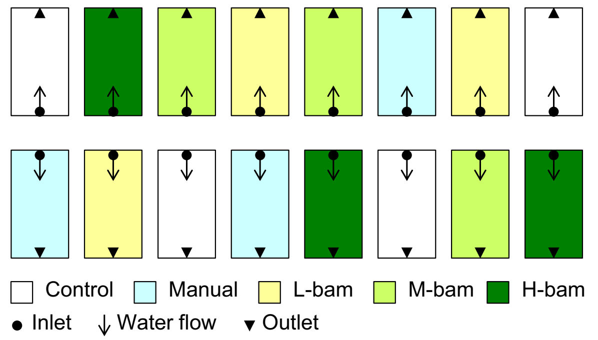

Fig. 1 Plan of the 16 experimental paddy fields (30 m^2; 7.5 m long × 4 m wide) used in this study (not to scale). Manual, manual weeding treatment; L-bam, low-volume ground bamboo application treatment (15 kg paddy $field^{-1}$; 0.5 kg m^{-2}); M-bam, medium-volume ground bamboo application treatment (30 kg paddy $field^{-1}$; 1.0 kg m^{-2}); L-bam, high-volume ground bamboo application treatment (60 kg paddy $field^{-1}$; 2.0 kg m^{-2})

Experimental paddy fields were continuously inundated (5–17 cm of water depth) from early June to early September without mid-season drainage. During rice cultivation, no agrochemical or fertilizer (other than ground bamboo culms) was applied in the experimental paddy fields. In conventional rice farming in Ishikawa Prefecture, mid-season drainage is typically performed from early June for approximately 1 month to prevent the overdiversification of rice plants. However, we did not perform mid-season drainage because dramatic water level fluctuations may lead to the overgrowth of aquatic weeds. In addition, agrochemical-free rice seedlings do not diversify as much as those grown using fertilizers. Thus, overdiversification is uncommon in agrochemical- and fertilizer-free farming.

In the manual weeding treatment, one to three people manually removed aquatic weeds once between mid-July and early August, prior to panicle initiation (14 July 2017, 6–8 August 2018, and 18–21 July 2019).

We measured the paddy sediment's oxidation–reduction potential (ORP) approximately 1.5 cm below the soil surface using a portable ORP meter (RM-30P; Toa-DKK Corporation, Tokyo, Japan). We took ORP measurements three times in 2017 (4, 7, and 11 days after rice transplantation), 2018 (after 5, 8, and 12 days), and 2019 (after 3, 8, and 13 days). On each day, we arbitrarily selected two locales each from the long sides and one locale from the outlet side. For each paddy field, we calculated the average ORP value based on five measurements. The ORP values were measured using a silver–silver chloride electrode containing 3.33 mol L^{-1} potassium chloride. To estimate standard hydrogen electrode ORP (ORP_{SHE}) values, we used the following formula (Matsushita et al. 1974):

$$ORP_{SHE} = E + 206 - 0.7 \times (t - 25),$$

where E (mV) is the ORP value measured using a silver–silver chloride electrode containing 3.33 mol L^{-1} potassium chloride and t (°C) is the water temperature.

Between July and August, we measured rice plant height, tiller numbers, and leaf color [soil plant analysis development (SPAD) values] as indices of rice plant growth. In each paddy field, we selected three healthy rice plants from each of the two long sides and the outlet side, for a total of nine plants. We measured plant height from the base of the rice plant's aboveground part to the tip of the longest leaf using a folding scale. The tiller numbers reflected the total number of diversified stems. Owing to an erroneous measurement, the tiller numbers in 2018 were not used in the analyses. Using a SPAD chlorophyll meter (SPAD-502; Konica Minolta Inc., Tokyo, Japan), we measured the SPAD value by averaging three measurements from three leaves in each rice plant. The average rice plant height, tiller numbers, and SPAD values were calculated based on nine rice plants from each paddy field.

In late July (24–25 July in 2017, 22–23 July in 2018 and 29–30 July in 2019) and late August (21–22 August in 2017, 30–31 August in 2018 and 26–27 August in 2019), we surveyed aquatic plants using a wire quadrat (50 cm × 50 cm). On each date, we arbitrarily selected one locale each from the two long sides and the outlet side, for a total of three locales. We selected different locales for the first and second samplings. After placing the quadrat on the paddy sediment, we manually collected all aquatic plants (other than rice plants) within the quadrat. We identified aquatic plant species using a guidebook (Asai 2015). In the laboratory, all aquatic plants were washed with tap water to remove sediment, placed in envelopes according to species, and dried in an oven (DKN812; Yamato, Co., Ltd., Tokyo, Japan) at 50 °C for 4–7 days. We determined the dry weights of the aquatic plants using an electronic balance, and recorded the most dominant species.

In each year, we harvested rice plants in late September (21 September 2017, 23 September 2018, and 24 September 2019). In each paddy field, we arbitrarily selected five rice plants from the second or third row, along the two long sides and the outlet side, for a total of 15 rice plants. We air-dried harvested rice plants for several weeks until the rice grains' water content dropped to around 15%. After air drying, we performed threshing using an electric threshing machine (MR-400MD; Ogihara, Ota, Japan) and hulling using a rice huller (FC2K; Otake Seisakusho, Aichi, Japan). We determined the rice yields based on the air weights of brown rice.

We measured external rice grain quality parameters and the protein and amylose contents of brown rice as described previously (Usio et al. 2021). A grain discriminator (RN-310; Kett, Tokyo, Japan) was used to calculate the percentages of sound, immature, cracked, damaged, discolored, and dead grains. A multi-auto counter (KC-10; Fujiwara Seisakusho, Co., Ltd, Tokyo, Japan) was used to determine thousand-grain weights. A near-infrared transmittance rice composition analyzer (AN-820; Kett) was used to measure the protein and amylose contents of rice grains. Within the damaged grain category, we retained only data for malformed grains, omitting all other data (i.e., data on grains that were germinated, fermented, damaged by insects, damaged by fungus or mold, brown-colored or broken) together with those of cracked, discolored, and dead grains, because these grain quality measurements comprised $<5\%$ of all measurements on average among all treatments. In summary, we measured thousand-grain weight; percentages of normal, immature, and malformed grains; and protein and amylose content (%) as indicators of rice grain quality. For each measurement, we obtained two subsamples and calculated the mean value.

In 2018 and 2019, we determined the air-dry mass of rice straw and the nutrient contents of the powdered rice straw samples. After threshing, we determined the air-dry mass of the rice straw in each paddy field. Using a plant sample crusher (Wonder Blender WB-1; As One Corp., Osaka, Japan), we ground the straw subsamples into powder. Then, we obtained a 200-g straw subsample from each paddy and dried it in an oven at 50 °C for 5 days.

We measured the carbon, nitrogen, phosphate, and potassium contents of the powdered rice straw samples. We measured the nitrogen and carbon contents of the straws using the combustion method. For each paddy field, approximately 50-μg samples of powdered straw were placed in tin capsules. The capsules were analyzed using an automatic elemental analyzer (vario ISOTOPE cube; Elementar, Japan, Yokohama, Japan) under the following operating conditions: oxidation furnace, 1150 °C; reduction furnace, 850 °C; and He flow rate, 230 mL min^{-1}. We measured the potassium and phosphate contents of the straws by the wet incineration method using an inductively coupled plasma optical emission spectrometer (ICP-OES; 5800 ICP-OES; Agilent Technologies Japan, Tokyo, Japan). Duplicate 0.2 g samples of powdered straw from each paddy field were transferred into centrifuge tubes. Following acid decomposition with concentrated nitric acid and hydrogen peroxide followed by dilution, the phosphate and potassium contents of the samples were obtained using the 5800 ICP-OES. The silicic acid contents of the straws were determined using the perchloric acid method by the Bio Innovation Center in accordance with official procedures (National Institute for Agroenvironmental Sciences 1992).

In 2018 and 2019, we collected soil samples before transplantation (late May) and after harvest (late September), representing the pre- and post-experimental samples. In each paddy field, we arbitrarily selected four locales near the corners, and one near the center, for a total of five locales. Using a bulb planter (Arkland Sakamoto, Sanjo, Japan), we collected soil to a depth of 7 cm. Subsamples were thoroughly mixed in a bucket and air-dried in a glass house for 2 weeks. A 200-g subsample was placed in a sealed plastic bag and stored in a refrigerator. Soil samples were sent to the Bio Innovation Center for analyses of pH, electrical conductivity (EC), humus, cation exchange capacity (CEC), the phosphate absorption coefficient, ammonium nitrogen, nitrate nitrogen, available phosphate, exchangeable potassium, exchangeable calcium, exchangeable magnesium, free iron oxide, and available silicic acid. In line with the present study's purposes, we present the pH, total inorganic nitrogen (sum of ammonium and nitrate nitrogen), available phosphate, exchangeable potassium, and available silicic acid data. Analytical procedures for soil chemistry are described in the supplementary material of Usio et al. (2021). In brief, pH in the paddy soils was measured using an APS-40 pH/EC autoanalyzer (HRD Technology Co. Ltd., Toyokawa, Japan); ammonium and nitrate nitrogen, available phosphate, and silicic acid contents were measured using a high-speed soil nutrient automatic analyzer (SNA24i; Fujihira Industry Co. Ltd., Tokyo, Japan); and the exchangeable potassium contents were measured using ICP-OES (iCAP-7200 Duo; Thermo Fisher Scientific K. K., Tokyo, Japan).

Statistical analyses

We used generalized linear models (GLMs) to explore differences among treatments in surface soil ORP_{SHE} values, aquatic plant dry biomass, and rice plant growth (height, tiller numbers, and SPAD values). Treatment and day were fixed factors and day was the repeated measures factor, with compound symmetry designated as a covariate. For variables without repeated measurements (rice yield, rice grain quality, straw chemical properties, and soil chemical properties), we used a GLM with treatment as a fixed factor. For all response variables, we used normal models with identity links. When the normality assumption was not satisfied by the raw data, we used a square root or log transformation. When a significant treatment effect or treatment × day interaction was obtained, we performed the Bonferroni correction to control for type I error. GLM analyses were performed using SPSS software (version 24.0; IBM Corporation, Armonk, NY, USA).

We performed simple and multiple linear regression analyses to explore the relationships between brown rice yields and post-experimental paddy soil nutrients. Because post-experiment soil phosphorus and potassium contents showed high collinearity in 2018 and 2019 ($r=0.76$ and $r=0.75$, respectively), we omitted potassium as a predictor. We selected models based on Akaike's information criterion correction for small samples (AICc) and considered the model with the smallest AICc to be the best model. The models were considered equivalent when the difference in AICc (ΔAICc) was less than 2. Simple and multiple linear regression analyses were performed using R software (version 4.1.0; R Core Team 2021). In multiple linear regression analyses, AICc calculations and model selection were performed using the R package MuMIn (Barton and Barton 2015).

Results

Oxidation–reduction potential

Significant treatment and treatment × day interaction effects for ORP on the soil surface were observed for all years (Fig. 2, Table 2). Although the magnitude of treatment differences varied among dates, the ORP_{SHE} values for the three ground bamboo treatments were lower relative to the control, implying that paddy soils treated with ground bamboo provided anti-oxidizing conditions.

Aquatic plants

The dry biomass of all aquatic plants, and of the most dominant species, *M. Vaginalis*, differed among

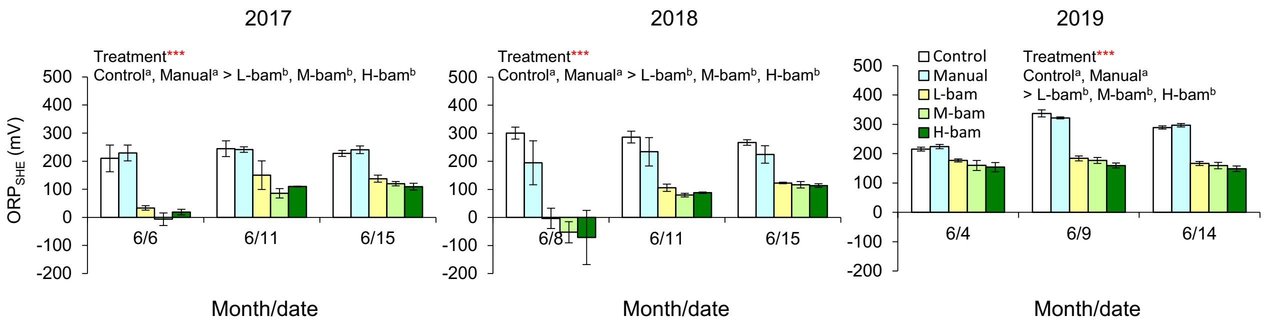

Fig. 2 Oxidation–reduction potential (ORP) of paddy surface soil in paddy field experiments conducted in 2017–2019. ORP is expressed as standard hydrogen electrode ORP (ORP_{SHE}). Data are mean ± SE. Different superscript letters indicate significant differences ($\alpha = 0.05$) according to Bonferroni post-hoc tests. Treatments are described in Fig. 1. ***$P < 0.001$

Table 2 Selected statistics from generalized linear models of the standard hydrogen electrode oxidation–reduction potential (ORP_{SHE}) of paddy surface soil in paddy field experiments conducted in 2017–2019

Parameter	Treatment			Treatment × day			Post-hoc comparison by day								
							Day 1			Day 2			Day 3		
	df	*F*	*P*	*df*	*F*	*P*	*df*	*F*	*P*	*df*	*F*	*P*	*df*	*F*	*P*
2017															
ORP_{SHE}	4, 10	21.73	**< 0.001**	8, 20	2.50	**< 0.001**	4, 23	23.75	**< 0.001**	4, 23	10.10	**< 0.001**	4, 23	7.21	**0.001**
2018															
ORP_{SHE}	4, 11	16.36	**< 0.001**	8, 22	3.06	**0.018**	4, 26	21.47	**< 0.001**	4, 26	7.04	**0.001**	4, 26	4.06	**0.011**
2019															
ORP_{SHE}	4, 11	73.63	**< 0.001**	8, 22	18.12	**< 0.001**	4, 24	11.31	**< 0.001**	4, 24	85.49	**< 0.001**	4, 24	62.21	**< 0.001**

Significant differences ($P < 0.05$) are indicated by bold font. See Fig. 2 for the exact sampling dates for days 1–3 in each year

treatments in 2018 and 2019, but not in 2017 (Fig. 3, Table 3). In 2018 and 2019, the total biomass was significantly reduced only in the manual treatment relative to other treatments. The differences in *M. vaginalis* biomass among treatments generally followed those of the total aquatic plants. The dry biomass of *M. vaginalis* in 2018 and 2019 was less abundant only in the manual treatment compared to the control.

Rice plant growth

GLM analyses revealed a significant treatment × day interaction effect on tiller numbers in 2017 ($P < 0.05$; Fig. 4, Table 4). Post-hoc comparisons indicated that treatment effects were significant for Days 2 (7/28) and 3 (8/11). However, on Day 2, post-hoc within-day treatment comparisons did not reveal statistical differences between any treatment pairs. On Day 3, post-hoc within-day treatment comparisons indicated that tiller numbers were 1.6 times greater in the high-volume ground bamboo treatments than the control.

In 2019, a significant treatment × date interaction effect on plant height was found ($P < 0.05$). However, post-hoc within-day treatment comparisons revealed no statistical differences among treatments on any day.

The effect of treatment was not significant for any rice plant growth variables across the 3 years.

Chemical properties of rice straw

In both 2018 and 2019, the air-dry mass of rice straw, and contents of total carbon, total nitrogen, phosphorus pentoxide, potassium oxide, and silicic acid, did not differ among the treatments (Table 5).

Rice yield and grain quality

The mean brown rice yield was 734.84 g 15 rice plants^{-1} (ca. 5258 kg ha^{-1}) in 2017, 240.94 g 15 rice plants^{-1} (ca. 1847 kg ha^{-1}) in 2018, and 144.34 g 15 rice plants^{-1} (ca. 1107 kg ha^{-1}) in 2019. Over the 3 years from 2017 to 2019, the mean rice yield has dramatically dropped to 20%. In all years, rice yields did not differ among treatments (Fig. 5, Table 6). However, when the results of the low-volume ground bamboo treatments in 2017 were omitted, a significant difference in brown rice yields was evident among treatments, with medium- and

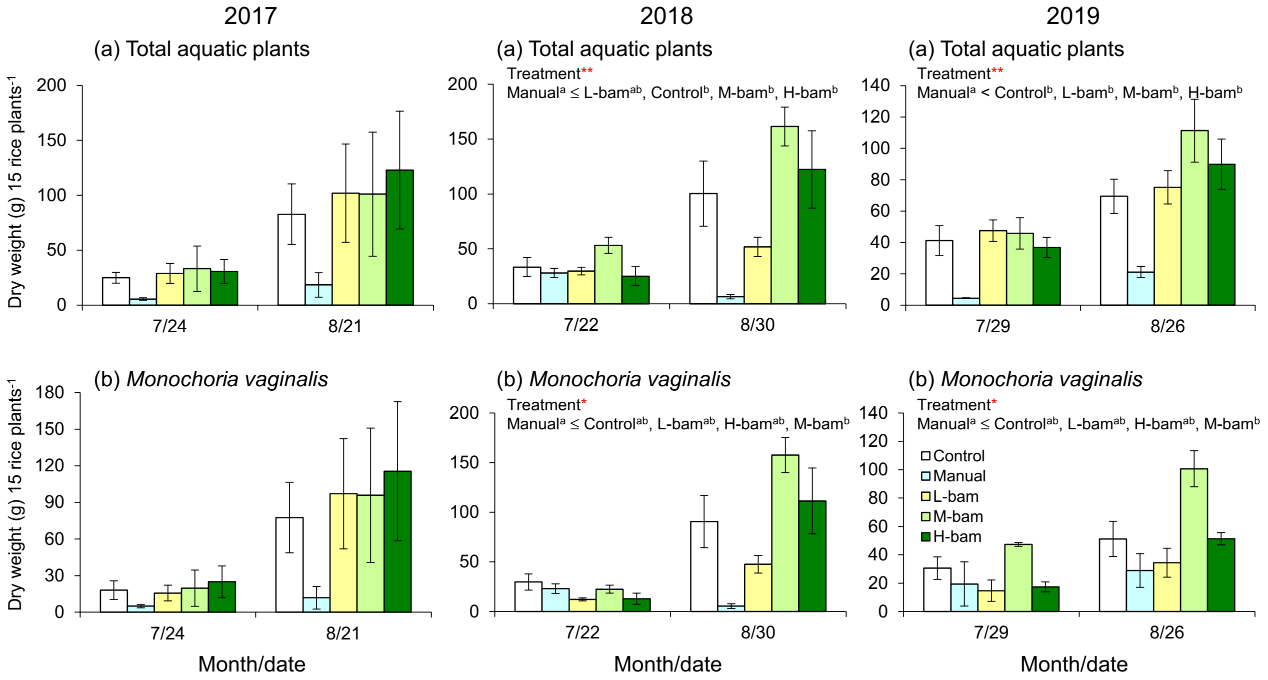

Fig. 3 Dry biomass of total aquatic plants and the most dominant species (*Monochoria vaginalis*) in paddy field experiments conducted in 2017–2019. Data are means ± standard error (SE). Different superscript letters indicate significant differences ($\alpha = 0.05$) according to Bonferroni post-hoc tests. Treatments are described in Fig. 1. $^{*}P < 0.05$, $^{**}P < 0.01$

Table 3 Selected summary statistics from generalized linear models of the effects of treatment on the dry biomass of total aquatic plants and the most dominant species (*Monochoria vaginalis*) in the paddy field experiments conducted in 2017–2019

Parameter	Treatment			Treatment × day			Post-hoc comparison by day					
							Day 1			Day 2		
	df	*F*	*P*	*df*	*F*	*P*	*df*	*F*	*P*	*df*	*F*	*P*
2017												
Total aquatic plants	4, 10	2.44	0.115	4, 10	1.36	0.944	–	–	–	–	–	–
Monochoria vaginalis	4, 10	1.36	0.314	4, 10	2.09	0.156	–	–	–	–	–	–
2018												
Total aquatic plants	4, 11	7.87	**0.003**	4, 11	52.11	**< 0.001**	4, 13	1.54	0.247	4, 13	23.31	**< 0.001**
Monochoria vaginalis	4, 11	4.03	**0.030**	4, 11	29.18	**< 0.001**	4, 15	1.22	0.343	4, 15	14.95	**< 0.001**
2019												
Total aquatic plants	4, 11	6.66	**0.006**	4, 11	3.00	0.067	–	–	–	–	–	–
Monochoria vaginalis	4, 11	3.95	**0.032**	4, 11	5.94	**0.009**	4, 14	1.51	0.253	4, 14	6.85	**0.003**

Significant differences ($P < 0.05$) are indicated by bold font. See Fig. 3 for exact sampling dates for days 1–2 in each year

high-volume ground bamboo treatments having 1.7–1.8 times greater rice yields than the control (GLM: $F_{3, 7} = 10.94$, $P = 0.005$).

The six rice grain quality indices did not differ significantly among treatments across the 3 years (Table 6). Overall, application of ground bamboo as mulch was not associated with any deterioration in rice grain external quality or protein content. In particular, the mean protein content of brown rice in the medium- and high-volume ground bamboo treatments (5.42–6.55%) was generally within or close to the adequate range of 5.50–6.50% (Oida et al. 2016).

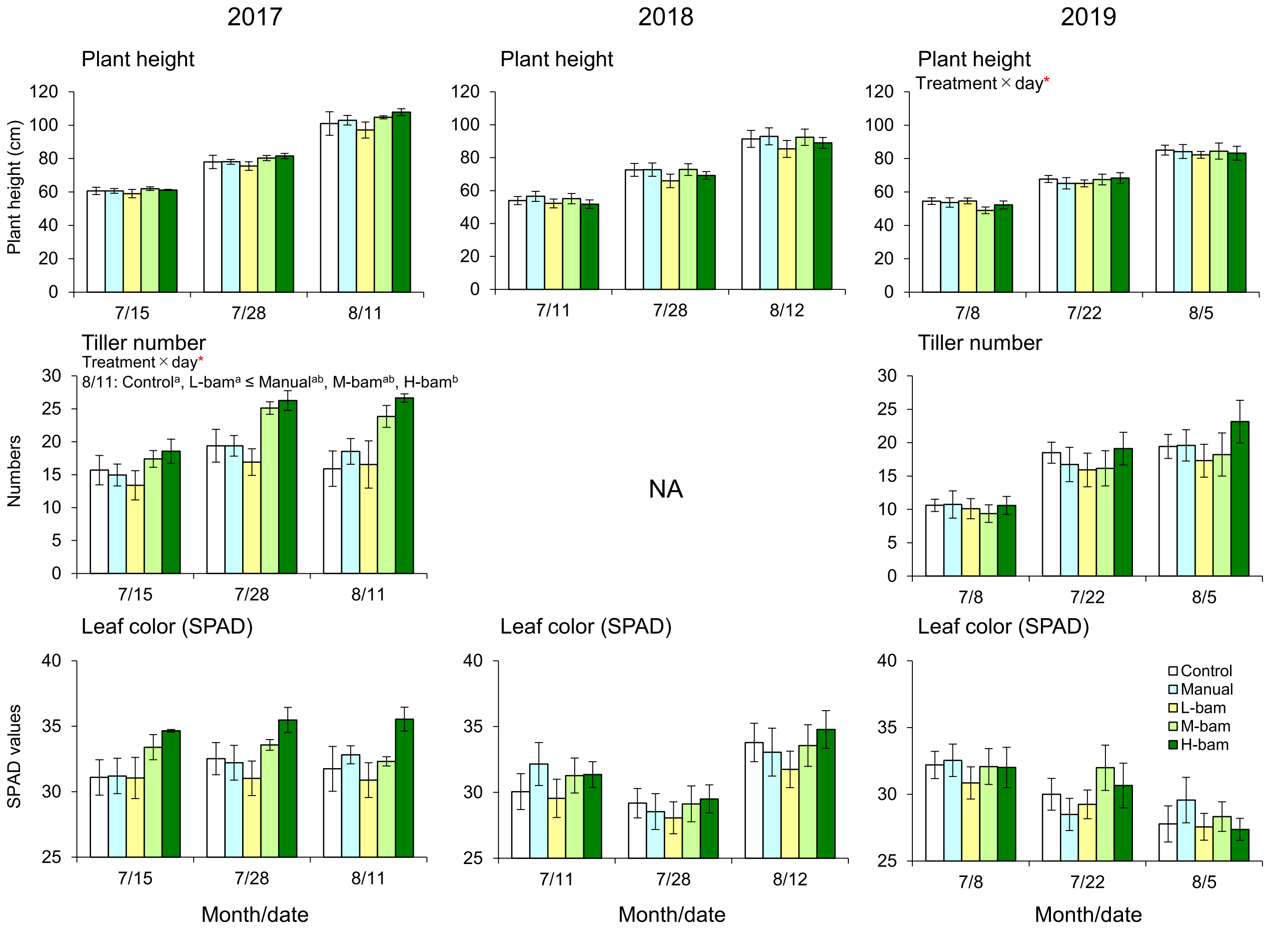

Fig. 4 Rice plant height, tiller number and leaf color according to soil plant analysis development (SPAD) values in paddy field experiments conducted in 2017–2019. SPAD values indicate leaf chlorophyll contents. Different superscript letters indicate significant differences ($\alpha = 0.05$) according to Bonferroni post-hoc tests. Data are means ± SE. Treatments are described in Fig. 1. *$P < 0.05$, NA = data not available

Chemical properties of paddy soils and nutrient absorption of rice plants

Prior to the commencement of rice transplantation (pre-experiment) in 2018, the five soil chemical variables did not differ significantly among treatments (Additional file 1: Table S1). Following the rice harvest (post-experiment) in 2018, the total inorganic nitrogen content of paddy soils differed significantly among treatments (Table 7). The total inorganic nitrogen content of post-experimental paddy soils was 1.5–1.6 times greater in the high-volume ground bamboo treatments than in the control.

In 2019, the five soil chemical variables did not differ significantly among treatments either before or after the experiment (Additional file 1: Table S1, Table 7).

When simple linear regression analyses were performed between brown rice yields and each of the four post-experiment paddy soil nutrients, a positive relationship was evident between brown rice yield and soil-available phosphate in 2018 ($R^2 = 0.52$, $P = 0.002$) and 2019 ($R^2 = 0.28$, $P = 0.034$). By contrast, a negative relationship was found between brown rice yield and soil-available silicic acid in 2018 ($R^2 = 0.38$, $P = 0.011$) and 2019 ($R^2 = 0.51$, $P = 0.002$). No significant relationship was found between brown rice yield and soil total inorganic nitrogen content (2018: $R^2 = 0.002$, $P = 0.87$; 2019: $R^2 = 0.04$, $P = 0.46$) or soil exchangeable potassium content (2018: $R^2 = 0.23$, $P = 0.06$; 2019: $R^2 = 0.04$, $P = 0.46$) in either year.

When multiple linear regression analyses were performed between brown rice yields and post-experiment paddy soil nutrients (without exchangeable potassium), the model incorporating available phosphate, available silicic acid, and their interaction was most supported in 2018 (Table 8, Additional file 1: Table S2). In particular, there was a strong negative relationship between brown rice yield and the available silicic acid content of post-experiment paddy soils. Such a negative relationship was

Table 4 Selected statistics from generalized linear models of shoot height, tiller numbers and leaf color (SPAD values) in the paddy field experiments conducted in 2017–2019

Parameter	**Treatment**			**Treatment × day**			**Post-hoc comparison by day**								
							Day 1			**Day 2**			**Day 3**		
	df	***F***	***P***	***df***	***F***	***P***	***df***	***F***	***P***	***df***	***F***	***P***	***df***	***F***	***P***
2017															
Plant height	4, 10	0.70	0.612	8, 20	0.87	0.559	–	–	–	–	–	–	–	–	–
Tiller number	4, 10	3.07	0.068	8, 20	3.33	**0.014**	4, 13	0.93	0.478	4, 13	3.65	**0.034**	4, 13	4.73	**0.015**
Leaf color (SPAD)	4, 10	2.14	0.150	8, 20	0.59	0.777	–	–	–	–	–	–	–	–	–
2018															
Plant height	4, 11	0.99	0.451	8, 22	0.75	0.647	–	–	–	–	–	–	–	–	–
Tiller number	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Leaf color (SPAD)	4, 11	2.54	0.100	8, 22	1.19	0.351	–	–	–	–	–	–	–	–	–
2019															
Plant height	4, 11	0.24	0.911	8, 22	2.78	**0.028**	4, 17	1.34	0.298	4, 17	0.55	0.699	4, 17	0.32	0.861
Tiller number	4, 11	1.02	0.437	8, 22	1.28	0.306	–	–	–	–	–	–	–	–	–
Leaf color (SPAD)	4, 11	0.57	0.689	8, 22	2.11	0.079	–	–	–	–	–	–	–	–	–

Significant differences ($P < 0.05$) are indicated by bold font. See Fig. 4 for the exact sampling dates for days 1–3 in each year

Table 5 Effects of treatment on the physicochemical properties of rice straw in the paddy field experiments conducted in 2018–2019

Parameter	**Control**	**Manual**	**L-bam**	**M-bam**	**H-bam**	***df***	***F***	***P***
2018								
Air-dry weight (g 15 plants^{-1})	241.54 ± 41.98	283.04 ± 24.39	218.42 ± 66.12	292.64 ± 28.97	320.72 ± 35.19	4, 11	0.730	0.590
Total carbon (%)	37.12 ± 1.30	36.77 ± 0.40	36.42 ± 0.27	35.92 ± 0.11	35.57 ± 0.30	4, 11	0.648	0.640
Total nitrogen (%)	0.64 ± 0.04	0.69 ± 0.10	0.65 ± 0.04	0.64 ± 0.04	0.62 ± 0.05	4, 11	0.182	0.943
Phosphorus pentoxide (%)	0.26 ± 0.02	0.32 ± 0.03	0.28 ± 0.01	0.27 ± 0.02	0.24 ± 0.01	4, 11	2.206	0.135
Potassium oxide (%)	2.13 ± 0.20	2.08 ± 0.12	2.13 ± 0.14	2.34 ± 0.11	2.57 ± 0.13	4, 11	1.585	0.246
Silicic acid (%)	15.43 ± 0.40	14.27 ± 0.35	15.23 ± 0.41	15.20 ± 0.32	14.93 ± 0.35	4, 11	1.439	0.285
2019								
Air-dry weight (g 15 plants^{-1})	147.42 ± 24.45	138.66 ± 23.38	104.04 ± 22.17	150.89 ± 20.27	180.71 ± 38.33	4, 11	0.643	0.643
Total carbon (%)	35.70 ± 0.08	36.23 ± 0.30	35.94 ± 0.19	35.85 ± 0.21	35.92 ± 0.22	4, 11	0.982	0.456
Total nitrogen (%)	0.64 ± 0.05	0.61 ± 0.06	0.61 ± 0.03	0.56 ± 0.03	0.58 ± 0.05	4, 11	0.543	0.708
Phosphorus pentoxide (%)	0.27 ± 0.01	0.30 ± 0.01	0.30 ± 0.02	0.31 ± 0.01	0.29 ± 0.01	4, 11	1.761	0.207
Potassium oxide (%)	1.83 ± 0.18	1.85 ± 0.07	1.77 ± 0.06	1.95 ± 0.08	2.03 ± 0.07	4, 11	0.727	0.591
Silicic acid (%)	15.50 ± 0.14	14.50 ± 0.47	15.03 ± 0.52	15.03 ± 0.48	14.73 ± 0.55	4, 11	0.846	0.525

Values are means ± standard error. Summary statistics of the generalized linear models are provided in the last three columns. Manual, manual weeding treatment; L-bam, low-volume ground bamboo treatment; M-bam, medium-volume ground bamboo treatment; H-bam, high-volume ground bamboo treatment

evident in experimental paddy fields with < 0.15 g kg^{-1} of available phosphate but not in those with ≥ 0.15 g kg^{-1} of available phosphate in post-experiment soils (Fig. 6).

In 2019, multiple linear regression models incorporating available silicic acid in post-experiment soils alone, and available phosphate and silicic acid in post-experiment soils, were supported (ΔAICc < 2) (Fig. 6, Table 8). As in 2018, the negative relationship between brown rice yield and soil-available silicic acid in post-experiment soils was particularly strong.

When silicic acid absorption of rice plants was calculated (silicic acid content of rice straw × rice plant air-dry mass), a strong positive relationship was evident between brown rice yield and silicic acid absorption in both 2018 and 2019 (Fig. 7). In 2018, the brown rice yield and silicic acid absorption were greater in the experimental paddy fields with ≥ 0.15 g kg^{-1} of

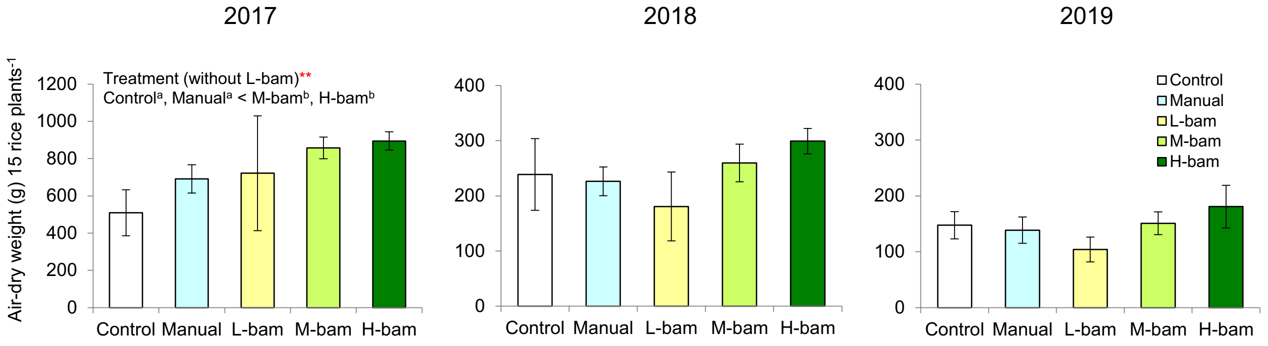

Fig. 5 Brown rice yield in paddy field experiments conducted in 2017–2019. Data are means ± SE. Treatments are described in Fig. 1. **$P < 0.01$

Table 6 Effects of treatment on the yield and grain quality of brown rice in the paddy field experiments conducted in 2017–2019

Parameter	Control	Manual	L-bam	M-bam	H-bam	*df*	*F*	*P*
2017								
Brown rice yield (g 15 plants^{-1})	509.45 ± 123.88	691.04 ± 76.24	721.63 ± 308.64	857.57 ± 58.06	894.51 ± 49.49	4, 10	0.96	0.472
Thousand-grain weight (g)	22.44 ± 0.41	22.28 ± 0.27	22.41 ± 0.17	22.59 ± 0.13	22.64 ± 0.21	4, 10	0.23	0.915
Sound grains (%)	75.48 ± 3.28	76.33 ± 1.13	75.20 ± 2.18	77.13 ± 1.95	78.70 ± 2.57	4, 10	0.30	0.870
Immature grains (%)	15.68 ± 2.60	14.07 ± 0.61	14.93 ± 0.92	13.97 ± 0.41	14.87 ± 2.51	4, 10	0.15	0.961
Malformed grains (%)	2.95 ± 0.90	3.70 ± 0.47	3.43 ± 1.16	3.13 ± 0.64	2.77 ± 0.86	4, 10	0.18	0.942
Protein content (%)	5.66 ± 0.23	5.43 ± 0.04	5.43 ± 0.16	5.42 ± 0.07	5.78 ± 0.23	4, 10	0.82	0.540
Amylose content (%)	19.80 ± 0.12	19.77 ± 0.02	19.83 ± 0.09	19.88 ± 0.14	19.58 ± 0.27	4, 10	0.56	0.686
2018								
Brown rice yield (g 15 plants^{-1})	238.91 ± 64.91	226.22 ± 26.06	180.75 ± 62.22	259.63 ± 34.09	299.17 ± 23.01	4, 11	1.00	0.448
Thousand-grain weight (g)	20.82 ± 0.70	20.74 ± 0.50	21.00 ± 0.28	21.29 ± 0.21	21.39 ± 0.55	4, 11	0.28	0.885
Sound grains (%)	64.76 ± 3.16	67.52 ± 2.61	66.25 ± 1.98	70.88 ± 1.87	67.92 ± 2.97	4, 11	0.73	0.588
Immature grains (%)	12.99 ± 2.50	10.98 ± 0.75	11.50 ± 1.39	13.27 ± 1.26	16.38 ± 2.61	4, 11	1.05	0.427
Malformed grains (%)	16.96 ± 3.71	17.67 ± 2.89	17.85 ± 2.08	12.38 ± 1.50	12.47 ± 4.48	4, 11	0.70	0.606
Protein content (%)	6.65 ± 0.04	6.47 ± 0.12	6.42 ± 0.06	6.38 ± 0.04	6.55 ± 0.10	4, 11	2.18	0.139
Amylose content (%)	18.81 ± 0.09	18.87 ± 0.12	18.88 ± 0.10	18.90 ± 0.05	18.78 ± 0.04	4, 11	0.30	0.874
2019								
Brown rice yield (g 15 plants^{-1})	147.42 ± 24.45	138.66 ± 23.38	104.04 ± 22.17	150.89 ± 20.27	180.71 ± 38.33	4, 11	1.01	0.442
Thousand-grain weight (g)	20.83 ± 0.65	20.57 ± 0.39	19.33 ± 0.84	20.48 ± 0.48	21.01 ± 0.52	4, 11	1.11	0.399
Sound grains (%)	61.03 ± 2.84	56.90 ± 4.49	50.27 ± 5.70	60.33 ± 2.82	65.47 ± 0.38	4, 11	2.32	0.121
Immature grains (%)	17.43 ± 0.94	20.83 ± 2.69	15.63 ± 0.87	15.98 ± 1.86	14.45 ± 1.72	4, 11	2.06	0.154
Malformed grains (%)	18.65 ± 3.13	19.35 ± 2.73	30.53 ± 5.70	21.38 ± 2.48	18.42 ± 1.84	4, 11	2.12	0.146
Protein content (%)	6.46 ± 0.20	6.77 ± 0.28	6.73 ± 0.25	6.48 ± 0.07	6.32 ± 0.06	4, 11	0.90	0.499
Amylose content (%)	18.95 ± 0.05	19.02 ± 0.02	18.93 ± 0.13	18.93 ± 0.07	19.13 ± 0.11	4, 11	1.06	0.420

Values are means ± standard error. Summary statistics of generalized linear models are provided in the last three columns. Manual, manual weeding treatment; L-bam, low-volume ground bamboo treatment; M-bam, medium-volume ground bamboo treatment; H-bam, high-volume ground bamboo treatment

available phosphate in post-experimental soils than in those with < 0.15 g kg^{-1} of soil-available phosphate.

Discussion

Effects of ground bamboo application on aquatic plants

In all years, the ORP$_{SHE}$ values of surface paddy soils decreased in the ground bamboo treatments, implying that the paddy soils provided anti-oxidizing conditions under these treatments (Fig. 2). Nakai and Toritsuka (2009) reported that, when rice brans were applied to organic rice paddy fields (0.15 kg m^{-2}), ORP in the surface paddy soils had strong negative values, which in turn suppressed the growth of several weed species. This was likely because application of rice brans increases

Table 7 Post-experiment soil chemical properties in the paddy field experiments conducted in 2018–2019

	Control	Manual	L-bam	M-bam	H-bam	*df*	*F*	*P*
2018								
pH	6.48 ± 0.06	6.13 ± 0.03	6.30 ± 0.10	6.13 ± 0.17	6.13 ± 0.27	4, 11	1.26	0.344
Total inorganic nitrogen (mg kg^{-1})	11.75 ± 0.63^{a}	14.33 ± 0.67^{ab}	12.33 ± 2.33^{ab}	18.00 ± 1.53^{ab}	19.00 ± 2.08^{b}	4, 11	4.80	**0.017**
Available phosphate (mg kg^{-1})	85.00 ± 41.13	16.67 ± 12.02	86.67 ± 66.92	110.00 ± 68.07	126.67 ± 67.41	4, 11	0.58	0.682
Exchangeable potassium (mg kg^{-1})	257.50 ± 31.19	226.67 ± 20.28	260.00 ± 47.26	320.00 ± 41.63	306.67 ± 42.56	4, 11	1.01	0.443
Available silicic acid (mg kg^{-1})	436.25 ± 29.28	398.67 ± 23.10	494.00 ± 65.90	370.67 ± 30.75	314.67 ± 23.88	4, 11	3.16	0.059
2019								
pH	6.15 ± 0.06	6.17 ± 0.09	6.07 ± 0.03	6.07 ± 0.07	5.90 ± 0.15	4, 11	1.43	0.289
Total inorganic nitrogen (mg kg^{-1})	25.25 ± 6.46	19.67 ± 1.76	19.67 ± 4.70	35.33 ± 17.33	26.33 ± 1.86	4, 11	0.48	0.749
Available phosphate (mg kg^{-1})	135.00 ± 22.17	96.67 ± 21.86	126.67 ± 31.80	153.33 ± 40.55	183.33 ± 63.33	4, 11	0.70	0.608
Exchangeable potassium (mg kg^{-1})	120.00 ± 9.13	96.67 ± 3.33	120.00 ± 11.55	130.00 ± 10.00	123.33 ± 8.82	4, 11	1.79	0.201
Available silicic acid (mg kg^{-1})	387.50 ± 37.06	343.33 ± 17.64	376.67 ± 3.33	356.67 ± 6.67	286.67 ± 27.28	4, 11	2.37	0.116

Values are means ± standard error. Summary statistics of generalized linear models are provided in the last three columns. Manual, manual weeding treatment; L-bam, low-volume ground bamboo application treatment; M-bam, medium-volume ground bamboo application treatment; H-bam, high-volume ground bamboo application treatment. Significant effects ($P < 0.05$) detected by generalized linear models are indicated by bold font. Different superscript letters indicate significant pairwise differences ($\alpha = 0.05$) according to Bonferroni post-hoc tests

Table 8 Parameter estimates of the best linear regression models of the relationship between brown rice yield and post-experiment paddy soil nutrients in 2018–2019

Model	Estimate	SE	*t*	*P*	AICc	ΔAICc	Akaike weights
2018							
Yield ~ available phosphate + available silicic acid + available phosphate × available silicic acid					170.63	0	0.678
Intercept	512.30	74.15	6.91	< 0.001			
Available phosphate	− 5.39	4.41	− 1.22	0.246			
Available silicic acid	− 7.78	1.76	− 4.41	< 0.001			
Available phosphate × available silicic acid	0.27	0.11	2.45	0.030			
2019							
Yield ~ silicic acid					164.33	0	0.415
Intercept	390.08	64.31	6.07	< 0.001			
Available silicic acid	− 6.51	1.69	− 3.85	0.002			
Yield ~ available phosphate + available silicic acid					164.60	0.28	0.362
Intercept	318.76	72.69	4.39	< 0.001			
Available phosphate	2.40	1.38	1.74	0.105			
Available silicic acid	− 5.50	1.68	− 3.27	0.006			

microbial respiration and thereby reduces oxygen concentrations in surface paddy soils (Nakayama 2010). Nevertheless, several weed species, including *M. vaginalis* and *S. juncoides*, were not suppressed by rice bran application (Nakai and Toritsuka 2009).

In our paddy field experiments, the biomass of total aquatic plants and *M. vaginalis* did not differ markedly among treatments, except for the manual treatments applied in 2018 and 2019 (Fig. 3, Table 3). By contrast, in a small-scale microcosm experiment, Usio et al (2021) reported that the total aquatic plants and *M. vaginalis* were significantly less abundant when ground bamboo was applied. Differences in weed suppression between the study of Usio et al. (2021) and the present paddy experiment are likely attributable to the difference in spatial scale between the experiments. Ground bamboo may have been more uniformly distributed in the small-scale experiment than in the paddy fields. Furthermore, little water exchange took place in the microcosms; water was supplied occasionally when the water level dropped owing to evapotranspiration and lack of rain. By contrast, water exchange was presumably more frequent in the experimental paddy fields owing to the high rates of underground exudation and evapotranspiration.

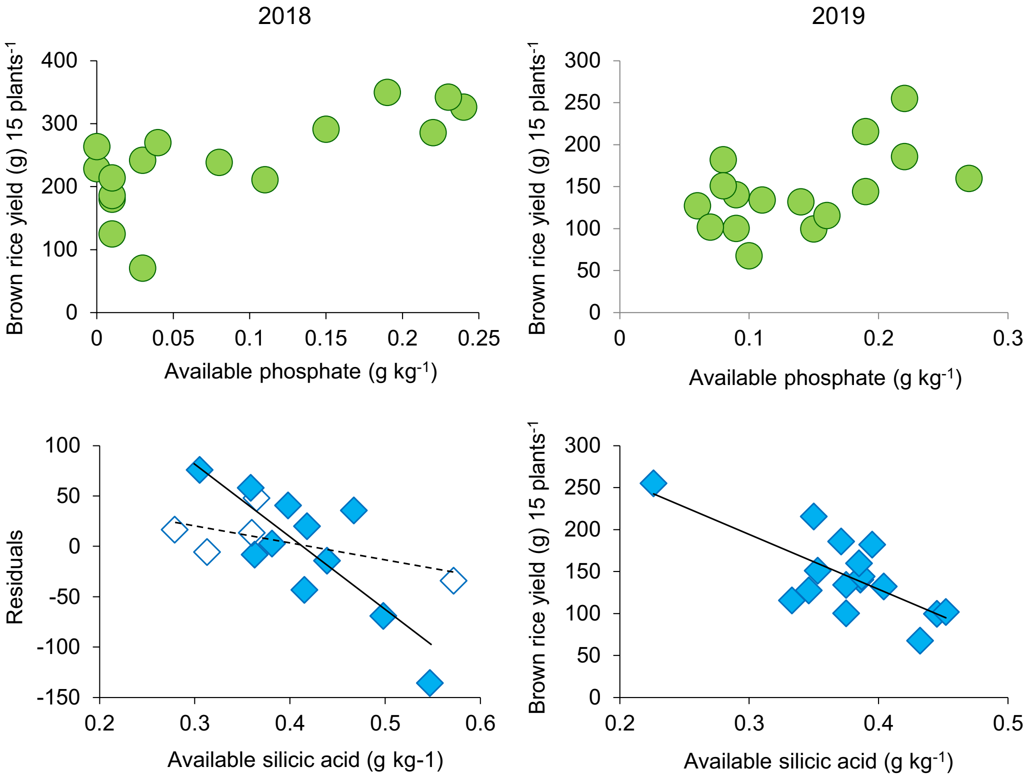

Fig. 6 Relationships between brown rice yield and available phosphate and silicic acid in post-experiment paddy soils, in paddy field experiments conducted in 2018–2019 according to multiple linear regression analyses. Available silicic acid in post-experiment paddy soils was used as the predictor, and the residual of brown rice yield regressed onto available phosphate in post-experiment paddy soils was used as the response variable. Regression lines are shown for low (<0.15 g kg^{-1}, solid line with closed diamonds, $y = -717.33x + 501.99$, $R^2 = 0.67$, $P = 0.002$) and high soil-available phosphate (≥ 0.15 g kg^{-1}, dashed line with open diamonds, $y = -174.88x + 385.20$, $R^2 = 0.47$, $P = 0.204$). For available silicic acid in 2019, brown rice yield was regressed onto available silicic acid in post-experiment paddy soils ($y = -650.45x + 390.08$, $R^2 = 0.51$, $P = 0.002$)

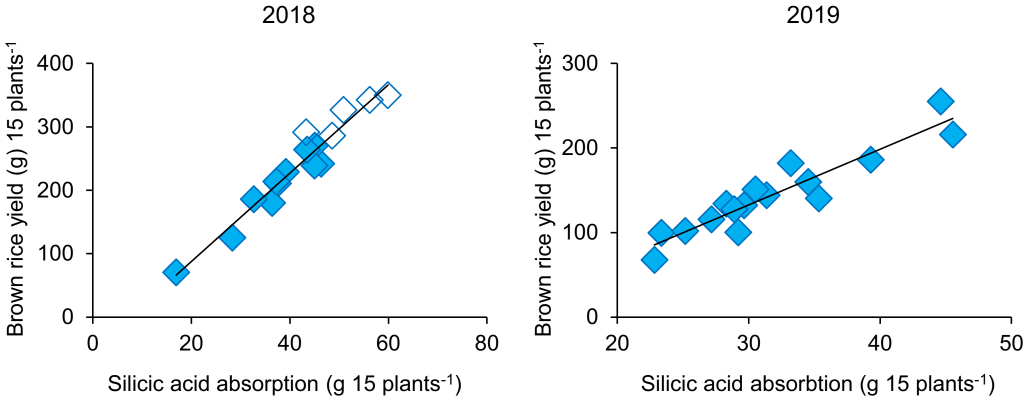

Fig. 7 Relationship between brown rice yield and silicic acid absorption by rice plants in the paddy field experiments conducted in 2018 ($y = 6.97x - 51.50$, $R^2 = 0.94$, $P < 0.001$) and 2019 ($y = 6.58x - 64.58$, $R^2 = 0.87$, $P < 0.001$). Closed diamonds indicate experimental paddies with low available phosphate in post-experiment paddy soils (<0.15 g kg^{-1}) and open diamonds indicate those with high soil-available phosphate (≥ 0.15 g kg^{-1})

Furthermore, in the field conditions, as the ground bamboo may not have been uniformly distributed across the paddy surface soils, the shading effect was probably insufficient to inhibit weed germination. Studies have also reported that volatile fatty acids, aromatic carboxylic acids, and allelochemicals were produced during organic matter decomposition, which in turn suppressed the germination or growth of weeds (Tanaka and Ono 2000; Ueno and Suzuki 2005). However, although such chemicals were produced during ground bamboo decomposition, they may have been diluted by the frequent water exchange in paddy fields.

Effects of ground bamboo application on soil chemical properties

Ueno and Suzuki (2005) reported that application of distilled spirits and rice brans markedly increased the ammonia, potassium, calcium, and magnesium contents of paddy soils. However, in our experiments, no consistent increase in essential nutrients was observed. Based on mean nutrient input values (Table 1), averages of 0.15 kg total nitrogen (equivalent to 4.87 g m^{-2}), 0.08 kg phosphorus pentoxide (equivalent to 2.73 g m^{-2}) and 0.24 kg potassium (equivalent to 8.13 g m^{-2}) were added to each experimental paddy field (30 m^2) in each year. Because ground bamboo contains few nutrients, it may have little effect as a nutrient enhancer in paddy soils.

At the end of our paddy field experiment in 2018 (post-experiment), the total inorganic nitrogen content of the paddy soils was significantly higher in the medium- and high-volume ground bamboo treatments than in the control. This may be because of the nitrogen-fixation activities of cyanobacteria and photosynthetic bacteria associated with organic matter addition, as also reported with surface application of rice straw to paddy soils (Yoo et al. 1987). Recently, Masuda et al (2021) reported that iron-reducing bacteria (*Anaeromyxobacter* and *Geobacter*), belonging to Deltaproteobacteria, also play important roles in nitrogen fixation in paddy soils. However, no such nitrogen enhancement effect was seen consistently over the years in our study (see "Chemical properties of paddy soils and nutrient absorption of rice plants" section). Similarly, the effects of ground bamboo application on the available phosphate, silicic acid, and exchangeable potassium content of paddy soils were inconsistent across years. Future studies should consider the roles of microbes in mediating nutrient availability for rice plants.

Effects of ground bamboo application on rice plant growth and yield

The effects of ground bamboo application on rice plant growth and yield differed by year. In the first year (2017), tiller numbers of rice plants were higher with high-volume ground bamboo application than in the control on 8/11 (Fig. 4, Table 4). Rice yields were 1.7–1.8 times greater in the medium- and high-volume ground bamboo treatments than in the control (Fig. 5). However, after the second and third years of consecutive rice cultivation in the paddy fields, rice growth and yields differed little between treatments with and without ground bamboo application (Figs. 4, 5, Tables 4 and 6).

Over the 3-year study period, mean rice yield decreased dramatically (Fig. 5). Although the available phosphate in post-experiment paddy soils did not differ statistically between any of the ground bamboo treatments and the control, simple regression analysis revealed that rice yields were positively associated with available phosphate in post-experiment paddy soils in 2018 and 2019 (see "Chemical properties of paddy soils and nutrient absorption of rice plants" section). In an 89-year consecutive rice cultivation study, phosphorus was among the most limiting nutrients (Ohashi et al. 2015). The results imply that phosphorous was also a major limiting nutrient in our paddy fields.

Another key nutrient that may have affected rice yields is silicon. An earlier microcosm experiment demonstrated that, when ground bamboo was applied to rice cultivated in fertilizer-free soil, silicic acid content approximately halved in post-experiment soils relative to pre-experiment soils (Usio et al. 2021). Furthermore, the silicic acid content of rice straw was 10–12% lower in the ground bamboo treatments compared to the control, which in turn led to 1.8–2.1-fold greater rice yields for the ground bamboo treatments (Usio et al. 2021). These results imply that silicic acid in haulms was actively used by rice plants for grain and husk production when ground bamboo was applied. A negative relationship was evident between brown rice yields and the silicic acid contents of post-experiment paddy soils in 2018 and 2019, in both simple and multiple regression analyses (Fig. 6, Table 8) (see "Chemical properties of paddy soils and nutrient absorption of rice plants" section). However, the silicic acid content of rice straw did not differ among treatments in those years (Table 5). In 2018, rice plants in the experimental paddies with high silicic acid absorption and rice yields had relatively high available phosphate (≥ 0.15 g kg^{-1}) in post-experiment paddy soils (Fig. 7). In 2019, although rice plants in experimental paddies with high silicic acid absorption had relatively high rice yields, the GLM that included the interaction term between available phosphate and silicic acid was not supported. The literature suggests that the effects of silicon addition on plants differ depending on the plant-available phosphorus, among other physicochemical properties of soils. Kostic et al. (2017) reported that the addition of silicon to wheat (*Triticum aestivum* L.) in low-phosphorus soil increased phosphorus uptake via the roots by upregulating the expression of inorganic phosphorus transporter genes (*TaPHT1.1* and *TaPHT1.2*). Schaller et al. (2019) reported that the addition of silicon to 143 undisturbed Arctic soils increased phosphorus mobilization in iron-phosphate phases on mineral surfaces. Such phosphorus mobilization under high-silicon conditions occurs as a result of silicon's competition with phosphorus for binding at the surface of soil minerals (reviewed in Hu et al. 2021). Other studies have observed a beneficial effect of silicon addition on the growth of rice plants under low and high phosphorus conditions (Ma and Takahashi 1990; Che et al. 2016). Under low phosphorus conditions, silicon addition reduced the uptake of iron and manganese by rice plants, which in turn increased phosphorus availability for the plants (Ma and Takahashi 1990). Under high phosphorus conditions, by contrast, silicon addition reduced phosphorus uptake by rice plants to control inorganic phosphorus concentrations in shoots within an optimal concentration range, which is otherwise detrimental to plants (Ma and Takahashi 1990). The present study's findings are somewhat divergent from those of earlier studies, in that brown rice yields were higher when the available phosphate contents of the post-experiment soils were above a certain threshold (≥ 0.15 g kg^{-1}). However, available phosphate is not necessarily equivalent to plant-available phosphorus, as most phosphorus in soil is usually stored in plant-unavailable forms, such as organic phosphorus, or is bound with minerals including iron, calcium and aluminum (Beauchemin et al. 2003). The conditions under which ground bamboo addition enhances rice yields requires further study, especially in terms of the interaction between silicon and plant-available phosphorus under different soil chemical conditions.

In general, nitrogen is among the most limiting nutrients with respect to rice yields in irrigated rice paddy fields (Myint et al. 2010). In the second year of our experiment (2018), the total inorganic nitrogen content of post-experiment paddy surface soils was 1.5-fold greater in the medium- and high-volume ground bamboo treatments compared to the control (Table 7). The multiple linear regression models incorporating soil inorganic nitrogen content were not the best models in 2018 or 2019 (Table 8, Additional file 1: Table S2). These results imply that nitrogen was not a limiting nutrient in the present experiment. This is likely attributable to the nitrogen-fixation activities of cyanobacteria and photosynthetic bacteria (Yoo et al. 1987) and iron-reducing bacteria (Masuda et al. 2021).

Likewise, exchangeable potassium was unlikely to be a limiting nutrient in the present experiment. The exchangeable potassium content of the paddy soil surface did not differ significantly between any of the ground bamboo treatments and control, in either 2018 or 2019. Potassium is supplied by surface water, groundwater, and rainwater (Momii and Izawa 2007). Moreover, plants utilize sodium in lieu of potassium when potassium supply is limited (Hasegawa et al. 1990; Takahashi and Maejima 1998). Therefore, in the field cultivation of rice, potassium is rarely a limiting nutrient.

Rice straw contains essential nutrients, including nitrogen (0.5–0.8%), phosphorus pentoxide (0.16–0.27%), potassium oxide (1.4–2.0%), and silicic acid (4.0–7.0%) (Dobermann and Fairhurst 2002). In agrochemical-free and organic rice farming, shredded rice straw is typically incorporated into paddy fields after rice harvest. These straw incorporation practices directly enhance soil nitrogen, phosphate, potassium, and soil organic carbon content, as well as CEC (Zhao et al. 2019), and indirectly enhance nitrogen availability for rice plants through nitrogen fixation by cyanobacteria and photosynthetic bacteria (Yoo et al. 1987). Future experiments should use shredded rice plants as soil conditioners, particularly in consecutive rice cultivation years with ground bamboo application. However, the effects of rice straw incorporation on nitrogen fixation by iron-reducing bacteria have yet to be investigated.

Usio et al. (2021) showed that bamboo leaves have a silicic acid content 21 times higher than that of bamboo culms. To augment silicic acid in paddy soils efficiently, bamboo leaves may be ground and applied together with culms.

Effects of ground bamboo application on rice grain quality

Across the 3-year-study period, application of ground bamboo was not associated with deterioration of rice grain quality. In the Koshihikari cultivar, the protein content required for good taste is suggested to be in the range of 5.50–6.50% in brown rice (Oida et al. 2016). The mean protein contents under the medium and high-volume ground bamboo treatments in this study were close to the suggested range, at 5.42–6.55% (Table 6). This is consistent with the result of Usio et al. (2021), who reported that ground bamboo applications in microcosm experiments with different pre-treatments (refrigeration or fermentation) and organs (culms or leaves) did not lead to marked differences in the external quality or protein content of rice grains compared to the control (without ground bamboo application). In the previous experiment, thousand-grain weights were 3% higher in the fermented ground bamboo leaf application treatment than in the control (Usio et al. 2021). In the present study, we found no evidence that application of ground bamboo affects these external grain quality parameters. In conventional farming, application of additional silicon fertilizer during the panicle formation stage accelerates rice grain ripening, thereby increasing rice yield and thousand-grain weight, with pronounced fertilizer effects seen in years with short solar radiation periods (Fujii et al. 2008; Mizuno and Inatsu 2016). Increased rice yield following application of additional silicon is thought to result from improved photosynthetic activity of rice plants, especially under low light conditions (Mizuno and Inatsu 2016). Future studies should evaluate whether additional ground bamboo application during the panicle formation stage can enhance rice yield, thousand-grain weight, and other external grain quality parameters. Although controlled experiments would be difficult, such effects may also be evaluated through long-term cultivation under different solar radiation conditions.

Conclusions

Application of ground bamboo may enhance rice production when soil nutrients—particularly phosphate—are not deficient. Despite dramatic declines in rice yields over consecutive years of rice cultivation, application of ground bamboo did not appear to reduce external rice grain quality. In a working paddy field, 1.0–2.0 kg m^{-2} of ground bamboo is suggested to be the appropriate application amount. To obtain a more comprehensive understanding of its underlying mechanisms, the interaction between silicon and plant-available phosphorus under different soil chemical conditions and the roles of microbes in enhancing nutrient availability for rice plants should be further studied. To maximize the efficiency of ground bamboo application on rice growth and production, the combined effects of rice straw and ground bamboo application, as well as additional application of ground bamboo during the panicle formation stage, may need to be tested.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43170-022-00087-6.

Additional file 1: Table S1. Soil chemical properties in the paddy prior to field experiments conducted in 2018–2019. **Table S2.** Summary statistics of models of the relationship between brown rice yield and post-experiment paddy soil nutrients in 2018–2019.

Acknowledgements

We are grateful to Shuhei Kudo and Teruyuki Kameda for assisting with field work, and to Karui Co. Ltd. (Yamagata, Japan) and Kyowa Co. Ltd. (Toyama, Japan) for providing a wood crusher. We also thank anonymous reviewers for their constructive comments, which substantially improved this manuscript. During the study, ML received a RISET-Pro scholarship from the Ministry of Research and Technology/National Research and Innovation Agency of the Republic of Indonesia (RISTEK-BRIN), and TQH received a Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) scholarship.

Authors' contributions

ML, YS, TQH, and NU performed the field experiments; KI, ML, YS, and TQH performed the aquatic plant survey; KN, ML and TQH performed plant chemical analyses; ML, YS, TQH, YM, and MI performed rice grain quality analyses; TT provided technical advice and resources; ML and NU led the writing; NU, KI, and KN obtained the funding; and NU conceived and supervised the study. All authors read and approved the final manuscript.

Funding

This study was funded by a JSPS KAKENHI (No. 21K19860) and a Grant for Environmental Research Project from the Sumitomo Foundation (No. 183353).

Availability of data and materials

The data used in this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 27 November 2021 Accepted: 22 March 2022

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