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EFFECTS OF MECHANICAL DEFOLIATION AND DETILLERING AT DIFFERENT GROWTH STAGES ON RICE YIELD IN DRY SEASON IN CAMBODIA

Chhay Ngin[1,2*], Seng Suon[3], Toshiharu Tanaka[2], Akira Yamauchi[4], Kazuhito Kawakita[4], and Sotaro Chiba[4,5]

[1]Department of Rice Crop, General Directorate of Agriculture, Ministry of Agriculture, Forestry and Fisheries, # 54B, Street 656, Sangkat Teuk Laak 3, Khan Tuol Kok, Phnom Penh, Cambodia;

[2]Nagoya University Asian Satellite Campus-Cambodia, Royal University of Agriculture, Phnom Penh, Cambodia;

[3]Center for Development-Oriented Research in Agriculture and Livelihood Systems, Phnom Penh, Cambodia;

[4]Graduate School of Bioagricultural Sciences, Nagoya University, Nagoya 464-8601, Japan;

[5]Nagoya University Asian Satellite Campuses Institute, Nagoya 464-8601, Japan;

*Corresponding author

ABSTRACT

Field studies with complete randomized design in triplicates were conducted to determine the impact of mechanically simulated insect-induced defoliation and detillering on irrigated rice during dry season from January to April 2016 in three locations in Cambodia. Defoliation treatments were 0% (control), 10%, 25% and 50% defoliation at 30 days after transplanting (dat) at tillering stage, and 10%, 30% and 50% defoliation at 60 dat at heading stage. The detillering treatment were simulated at 10%, 20% and 30% at 30 dat and 5%, 10% and 15% at 60 dat comparing to the control. The parameter examined were: number of tillers/m^2, number of panicle/m^2, weight of 1000 grains, number of full grain/panicle, and grain yield (kg/ha) were examined. Results showed that no yield losses occurred up to 50% defoliation at 30 dat and up to 30% defoliation at 60 dat. However, the defoliation of 50% at 60 dat significantly affected the number of full grain and the grain yield with yield reduction of 13.5% (from 4,422 to 3,824 kg/ha) in average. For simulated stem damages, no difference in rice yield was observed up to 20% tiller removal at 30 dat and up to 10% stems loss at 60 dat. Nevertheless, significant yield losses occurred when 30% and 15% of tillers were removed at tillering and heading stages, respectively. These results suggested that the rice plant has the ability to compensate and tolerate certain levels of foliage and tiller losses at different growth stages.

Keywords: rice crop, defoliation, detillering, compensation, yield.

1. INTRODUCTION

Rice (*Oryza sativa*) started to be grown in Cambodia at least 2,000 years before Christ in rainfed lowland condition (Sarom, 2007). It is a staple food crop of Cambodians and is important for the country's food security and economy. Rice is predominantly grown on 3.051.412 hectares (ha), which account for about 80% of the country's total agricultural crop production area (MAFF, 2016). Topographically, rice is grown across agro-ecosystems from uplands to deep water fields with two distinct seasons: the wet season during May–October and the dry season during November–April (Nesbitt, 1997; Sarom, 2007). Rainfed lowland rice accounts for about 70% of the total rice cultivated areas, which are mainly grown on the central plain around Tonle Sap Lake and along the lower streams of the Mekong and Basac Rivers (Makara and Chhay, 2014).

There are numerous species of herbivores present in rice field that cause some damages to tillers, leaves and grains. Most rice farmers believe that insect pests are the major constraint to obtaining higher yield in Cambodia. Hence, they tend to spray insecticides to keep insect-pests off their rice crops, reflecting the perception that 'prevention is better than cure.' Such attitudes lead to pesticide misuse and overuse because they do not carefully think about the target pests, doses and timing of application (K.L. Heong et al., 1995; Pretty and Hine, 2005). However, most rice varieties are able to compensate for damages because the rice plant rapidly develops new leaves and tillers early in the season for replacing damaged leaves and tillers quickly. Many literatures have cited the estimations of crop losses due to pest damages in tropical rice but on average it seems that the estimated losses are higher than the actual harvest (K.L. Heong et al., 1995).

Early season defoliators such as whorl maggot (*Orseolia oryzae*), grasshopper (*Oxya* spp.), case worms (*Nymphula depunctalis*) and armyworms (*Mythimna separate*) cause no yield losses up to approximately 50% defoliation during the first and second weeks after transplanting (Oyediran and Heinrichs, 2002). Nevertheless, some studies indicated that 25% and 50% leaf removal in the tillering stage reduced yields 5% and 12%, respectively (Bowling, 1978). The damage at flowering stage is closely related to rice grain production because the leaf area affects the amount of photosynthates available to the panicle and serious defoliation can reduce rice yields significantly (De Datta, 1981). The flag leaf contributes to grain filling but the second leaf provides photosynthesis as well, while lower leaves are actually a sink that compete with the panicle. Significant damage (above 50%) to the flag leaf by leaffolders for example during panicle development and grain filling can cause significant yield losses, although this level of damage is uncommon where natural enemies serve ecosystem services. However, the yield loss is highly dependent on the age of the plant when defoliation occurs, and plants can recover and compensate for defoliation damage if it occurred in early stages (Bowling, 1978).

There are species of borers damaging rice crops and five—yellow borer (*Scirpophaga incertulas*), striped borer (*Chilo suppressalis*), white borer (*Scirpophaga innotata*), dark-headed borer (*Chilo polychrysus*), and pink borer (*Sesamia inferens*)—are of economic importance. Yellow borer and striped borer occur most widely in Asia and can cause yield losses (Chaudhary et al., 1984; Chhay et al., 2014; Chhunhy et al., 2014; IRRI, 1983). The number of tillers produced is always greater than the number of reproductive tillers allowing for some damage of vegetative tillers without affecting reproductive tiller number (Akinsola, 1984; Rubia-Sanchez et al., 1997; Viajante and Heinrichs, 1987). The relationship between stem borer injury and grain yield may be influenced by several factors, including pest population density, the timing of injury, and growing conditions. At early crop development, there is plant compensation for stem borer injury. There is sometimes no significant correlation between deadhearts and grain yield if the damages are not severe. Panicle bearing tillers are determined at the maximum tillering stage, which means that before maximum tillering the plant may still lose some tillers without reducing grain yield (Rubia et al., 1996). The critical stage for stem borer attack is the reproductive stage. When panicle bearing tillers are injured plants compensate very little for stemborer damage and this may result in yield loss (Rubia-Sanchez et al., 1997).

It is difficult to simulate the exact nature of the damage caused by defoliating insects. Artificial defoliation using scissors to clip the foliage may not be the same as actual feeding patterns by insects (Rice et al., 1982). For example, leaffolders scrape the green portion of the leaf from within folded leaves, while armyworms and grasshoppers remove irregular portions of the leaves but may leave the midvein intact. In the artificial defoliation procedure used in this and most other studies, all of the leaf tissue is removed at once, whereas in insect feeding, damages occur over longer periods. Instantaneous artificial defoliation may not have the same effect as an irregular, prolonged defoliation (Rice et al., 1982). It is similarly applied for the detillering of rice plant. In this experiment, the damages affected by other reasons and assessed effects of mechanical damages on the rice plant were excluded. Despite the difficulty of exactly simulating natural defoliation and stem damages by insects, leaf and stem cutting is considered a useful method to simulate natural losses of various proportions of plant and it has been used for many crops by numerous authors (Oyediran and Heinrichs, 2002). In Cambodia, little is known about the relationship between the degree of defoliation and detillering at various plant growth stages, the ability to compensate for damages and the effects on rice grain yield. Thus, this study was conducted to generate information on the relationship between the degree of defoliation and detillering at various plant stages affecting rice grain yield, which can be used as a guide for making decision of insecticide application or alternative treatments to control insect pests.

2. RESEARCH METHODS

The study was conducted during dry season from January to April 2016 in Svay Rieng (location 1; L1), Prey Veng (location 2; L2) and Takeo (location 3; L3) provinces. Three experimental locations have different soil types where L1 falls into the group with poorer soil fertility compared to those in L2 and L3 which have a good potential to produce high rice yield (Chhay et al., 2016). It has the following hypotheses:

- H1: Yield of the treatments with up to 50% defoliation at tillering stage and 30% defoliation at heading stage will not be significantly reduced. Likewise, detillering up 20% at tillering stage and 10% at heading stage will not result in significant yield reduction compared to non-cut control treatment because rice plants have the capability to regenerate new leaves and tillers to compensate the losses in vegetative phase, and they are also able to cope with some small losses of leaves and tillers in reproductive phase without having negative effect on yield.
- H2: Yield of the severe leaf- and tiller-losses treatments at tillering and heading stages will be significantly lower than that of the control since the rice plants encounter high rates of losses of foliage and tillers.

The overall objective of the study was to evaluate the impact of different levels of damages on leaves and tillers in different growth stages of rice crop on yield performance. A completely randomized design (Gomez and Gomez, 1984) with 13 treatments and 3 replications were used in this study. Parts of leaves and some tillers were manually removed to the corresponding percentages of defoliation and detillering in vegetative and reproductive phases of the rice growing cycle (Fig. 1). All treatments are summarized in Table 1. A rice variety named IR66 was used for this experiment by transplanting with 15 days seedling age. The fertilizer application was based on CARDI's recommendation in compliance with soil type (White et al., 1997).

The following data collection methods were used:

- Counting the number of tillers at 30 days after transplanting (dat) before cutting leaves and tillers for some treatments in 1 m^2
- Counting the number of tillers at maximum tillering stage in 1 m^2
- Counting the number of panicles before harvesting in 1 m^2
- Counting the number of full grain/panicle from 10 panicles/m^2 (10 samples)
- Measuring the weight of 1000 full grains in each treatment
- Measuring the grain yield (kg) per ha.

Analysis of variance (ANOVA) was conducted to compare the mean of the number of tillers, number of panicles, number of full grain, weight of 1,000 full grains and grain yield. The mean values were compared using data from three locations on defoliation and detillering separately to find out the differences within each location. The consistency of the findings across the three locations was compared with trend observation. All statistical tests were performed using the Statistical Package for Social Sciences (IBM SPSS Statistics, ver. 22.0).

3. ANALYSIS OF RESULTS

Five rice yield components among treatments in the three study locations were compared: (1) tiller number (tiller/m^2); (2) panicle number (panicle/m^2); (3) full grain number (grain/panicle), and (4) grain weight (g/1,000 grains) and (5) rice grain yield (kg/ha).

3.1 Artificial defoliation

The results from ANOVA analysis ($p < 0.05$) showed that there was no trend in the relation to the effect of defoliation at tillering (30 dat) and heading (60 dat) stages on the number of tillers/m^2, number of panicles/m^2 and 1,000 grain weight between any treatment in all three locations (Supplementary Table S1). However, the simulated insect defoliation resulted in significant effects on some treatments for the number of full grains per panicle and grain yield per ha. The lowest grain yield per ha of the 50% defoliation in heading stage (T7) was recorded among those of other damages and control in three locations. This was followed by 30% defoliation at 60 dat (T6) with or without statistical significance, highlighting that leaf damage at this growing stage has considerable impact on grain productions. Detailed description of the results in the three locations are stated below.

In L1 (Svay Rieng province), the number of full grains/panicle of T6 and T7 were significantly lower than T1 (Control treatment) in which the leaves were not removed at all growth stages. But T6 is not significantly different with T3, T4, T5 and T7 (Fig. 2A, L1). The grain yield had similar trend to the number of full grains in which only the yield of T6 (3,913.33 kg/ha) and T7 (3,736.67 kg/ha) with the defoliation of 30% and 50% at heading stage, respectively, were significantly lower than the yield of the control (4,336.67 kg/ha) and the yield of T6 was not significantly different as compared to T3, T4, T5 and T7 (Fig. 2B, L1).

For L2 (Prey Veng province), the results showed similar trend to location 1 with regard to significant and non-significant differences in which only T6 and T7 were significantly different with T1 in terms of number of full grain and grain yield (Figs. 2A, L2 & 2B, L2). It means that 30% and 50% defoliation at heading stage decreased the grain yield to 4,036.67 kg/ha and 3823.33 kg/ha, respectively, as compared to the control (4,390.00 kg/ha). Although the number of full grain and grain yield of T6 was significantly lower than T1, it was not significantly different with other treatments. Whereas in L3 (Takeo province), the number of full grains of T6 and T7 was significantly lower than other treatments. T6 had significantly higher number of full grain than T7 but it was not significantly different with T2, T3, T4 and T5 (Fig 2A, L3). The yield of T7 (3,913.33 kg/ha) was significantly lower than the control (4,540.00 kg/ha) and T2 (4,476.67 kg/ha) with the defoliation of 10% at tillering stage but it was not significantly different with T3, T4, T5 and T6, which defoliated the leaves at the levels of 25% and 50% at tillering stage, and 10% and 30% at heading stage, respectively (Fig. 2B, L3).

3.2 Artificial detillering (tiller removal)

Similar investigation for detillering treatments was conducted in the same experimental fields in the three locations. The treatment exhibited statistically different values in the number of tillers/m^2, number of panicles/m^2, number of full grains, and grain yield (see below for details) but not in 1,000 grain weight (Table S1). The results from L1 showed that the number of tillers/m^2 of T10 and T13 with 30% and 15% tiller removal at tillering and heading stage, respectively, were significantly lower than the control treatment in which the tillers were not removed at all during any growth stage, although there was no significant difference between T10 and T13. The tiller numbers of T8, T9, T11 and T12 in which the tillers were removed 10% and 20% at tillering stage (30 dat), and 5% and 10% at heading stage (60 dat), respectively, were not significantly different as compared to that of T1 (Fig. 3A, L1). In relation to the number of panicles/m^2 T13 was the lowest compared with other treatments and it was followed by T12 and T10 in which these treatments showed significantly lower panicle numbers than that of control (T1) (Fig. 3B, L1). For the number of full grains/m^2 T13 and T12 were the highest as compared to other treatments but they were not significantly different between each other. There were no significant differences in the number of full grains between T1, T8, T9 and T11 (Fig. 3C, L1). On the other hand, the grain yield/ha of T10 (3,763.33 kg/ha), T12 (3,950.00 kg/ha) and T13 (3,793.63 kg/ha) were significantly lower than T1 (4,336.67 kg/ha) although there was no significant difference between these detillering treatments. The grain yield of T8, T9 and T11 were not significantly different among each other and it has similar trend to the control T1 (Fig. 3C, L1).

In L2, the number of tillers/m^2 of T13 was significantly lower than T1 but it was not significantly different with T10, T11 and T12 (Fig. 3A, L2). For the number of panicles/m^2, T13 was the lowest compared with other treatments and it was followed by T10 and T12 (Fig. 3B, L2). With regard to number of full grains/panicle, T12 and T13 were the highest as compared to other treatments (Fig. 3C, L2). For the grain yield, T12 (4,066.67 kg/ha), T10 (3,963 kg/ha) and T13 (3,840 kg/ha) were significantly lower than the control T1 (4,390 kg/ha), in a decreasing order (Fig. 3D, L2). T8 and T9 yielded almost the same amount as T1.

In L3, the number of tillers/m^2 of T13 was significantly lower than T1, T8 and T9, but it was not significantly different with T10, T11 and T12. The tiller number of the control (T1) was significantly higher than T10, T12 and T13 but it was not significantly different to T8, T9 and T11 (Fig. 3A, L3). For the number of panicles/m^2, T13 was significantly lower than the control and other treatments. However, T8, T9 and T11 were not significantly different with the control but they were significantly different to T10 and T12 (Fig. 3B, L3). For the number of full grain/panicle, T10 was the lowest compared to control and other treatments. There were no significant differences between T12 and T13 but these two treatments were significantly different with T1, T8 and T9 (Fig. 3C, L3). Finally, the grain yield of T13 (4,013.33 kg/ha) was significantly lower than T1 (4,540.00 kg/ha) and other treatments except T10 (3,886.67kg/ha) indicating that 30% stem damage at tillering stage and 15% stem damage at heading stage resulted in a significant effect on the grain yield. In contrast, no significant difference was observed between T1, T8, T9, and T11 (Fig. 3D, L3).

Overall, the yield comparison across the three locations showed that the grain yield obtained from L3 seemed to be slightly higher than those of L1 and L2 because L3 has a better soil fertility that was able to potentially produce high rice yield (Chhay et al., 2016; White et al., 1997). However, similar trends were observed for the effects of mechanical defoliation and detillering at different growth stages on rice yield across the three experimental sites. These results suggested that simulated insect-caused defoliation and detillering (physical damage in this study) had similar trend of the effects on rice yields depending on damage levels in different growth stages but there were no geographical differences in Cambodia.

4. DISCUSSION

4.1 Effect of simulated defoliation on grain yield

Based on the results of the field experiments in three locations, it was generally observed that losing leaves up to 50% at tillering stage (30 dat) and less than 30% at heading stage (60 dat) had no significant impact on grain yield (Fig. 2B). However, the treatment with 30% and 50% defoliation at heading stage had significantly lower yield than the control at $p < 0.05$ across the three locations. This is because rice plant has the ability to compensate for defoliation damage when defoliated in the tillering stage and it was also tolerant to some degrees of leaf losses at the heading stage. This result is consistent with a defoliation study in West Africa, which showed no yield losses occurred at 25% defoliation in vegetative phase (Oyediran and Heinrichs, 2002). Likewise, several studies in India indicated that artificial defoliation of rice at 50% during tillering stage had no significant impact on yield as plants showed compensatory growth. However, the grain yield decreased as the defoliation level was more than 30% that happened at the reproductive stage when panicle initiation occurs (Anirudhprasad and Prasad, 1995; Taylor, 1972). Nevertheless, a defoliation study in Brazil reported that defoliation levels up to 50% in the reproductive stage did not influence the quantity of filled grains, total spikelets per panicle and weight of filled grains per panicle, thus the pest control is not required at this stage (Krinski and Foerster, 2017).

The defoliation-caused grain yield loss was attributed to a decrease in the number of panicle-bearing tillers and to a decrease in the number of grains per individual panicle. In this regard, aforementioned serious leaf damage at heading stage causing significant yield loss (50% defoliation, T7 in Fig. 2B) also encountered significant decrease of full grains in panicles (Fig. 2A). These results lead to a conclusion that defoliation occurred at the reproductive phase like heading stage caused greater yield loss than defoliation in the vegetative phase. This may be because the plants defoliated in the vegetative stage have more time to recover and replace lost tillers and foliage before grain development. At the grain development stage, the amount of foliage is critical for the assimilate accumulation in the panicle and for subsequent grain production (Mallick and Ghosh Hajra, 1977). There are two reasons for compensation. First, because partial defoliation can cause increased photosynthesis in the remaining leaves, it allows an improved supply of cytokinins to the remaining leaves by removal of sinks, and leads to an increase in carboxylation enzymes. Second, an increase in the assimilate demand by previously existing or new sinks (e.g. replacement tissue) can increase photosynthesis in the remaining leaves (Rubia-Sanchez et al., 1997).

Although it is rare to see a rice field encountering insect-caused defoliation over 50% which resulted in a significant loss of grain yield by defoliators, farmers who observe insects defoliating their rice plants may resort to the application of insecticides. However, the costs of environmental problems associated with insecticide applications can be avoided if the defoliation does not cause a loss in grain yield.

4.2 Effect of artificial tiller removal on grain yield

The study outcomes from three locations in Cambodia revealed that 30% tillers lost at vegetative phase (simulated as “deadheart” attached by stem borers) and 15% stems lost at reproductive phase (simulated as “whiteheads” damaged by stem borers) resulted in a significant reduction of grain yield in comparison with the control treatment (Fig. 3D). The factors attributed to the yield loss was due to the significant reduction of the number of tiller/m^2 which led to the significant decrease of the number of panicle/m^2.

However, the loss of tillers up to 20% at tillering stage and up to 10% at heading stage had no significant effect on grain yield at $p < 0.05$ (Fig. 3D). This is an indication that rice plant could compensate and tolerate for some levels of tiller losses at different growth stages. This result is in line with a study reporting that rice yield was not reduced with up to 23% injured tiller during tillering stage and up to 10% injured stems at panicle initiation stage, respectively, which suggested that rice can compensate and tolerate a certain level of stem borer injury previously considered to be economically damaging (LV et al., 2008). It is also important to note that rice plant is able to produce higher tillers in the early stage than what the plant can ultimately support reproductive panicles in a later stage. Hence, up to 25% tiller damaged by stem borers ("deadhearts") in vegetative stage can be tolerated without significant yield loss. Stem borer attacking at reproductive stage (whiteheads) also caused less damage than previously expected such that up to 5% whiteheads in most varieties did not cause significant yield loss (Chaudhary et al., 1984).

The compensation mechanisms included an increased tillering capacity, an increased percentage of effective tillers, and an increased number of full grain of damaged plants. There was also an increase in the photosynthesis rate of green leaves on stem borer-injured tillers and assimilates were transferred from injured tillers to healthy tillers. The translocation was more effective at the vegetative stage than at the reproductive stage. Thus, the earlier in the plant growth stage the injury occurs, the more rapidly the plants can compensate by translocating assimilates from injured to healthy tillers (Rubia et al., 1996). Rice tillers can compensate for relatively high levels of stem injury compared with currently used action thresholds by producing additional reproductive tillers, and compensate for leaf and leaf sheath injury by producing larger panicles (LV et al., 2008). However, the time of recovery to replace damaged tillers is partially dependent on the growth duration of the cultivar. Long- and short-duration cultivars have similar durations of the reproductive phase of growth, but they differ in the length of their vegetative phase (De Datta, 1981). In this regard, the long duration varieties have more time to reproduce tillers, hence having more capability to compensate the lost tillers more than the short duration varieties.

4.3 Implication on sustainable insect pest management

The results from defoliation and detillering studies have an implication on sustainable insect pest management. Farmers often assume that every insect in their fields causes damages to their crops, not being aware of the existence of natural enemies and not perceiving that insect-caused damages will automatically recovered and the yield loss is minimal because of plant compensatory responses (Heong and Escalada, 1999). In addition, numerous parasitoids, predators and pathogens known as natural enemies present in most rice ecosystems tend to keep insect pests at low densities (Matteson, 2000; Ooi and Shepard, 1994). Thus, under most situations where natural enemies are conserved, only minimal yield loss is expected from insect pest damages, unless serious pest outbreak occurs. Up until recently, insecticide applications for early defoliators, deadhearts often led to a falling population of natural enemies, allowing the secondary pest, for example rice brown planthopper, to flare up in massive outbreaks (Rombach and Gallagher, 1994). IRRI has tackled farmers' perceptions to try out a "rule-of-thumb", also known as a heuristic that "Leaf-folder control is not necessary in the first 30 days after transplanting" (Heong and Escalada, 1997). Furthermore, it seems that many insecticide applications were inappropriate, targeting the wrong insect or being applied at the wrong time. This was the case for up to 80% of pesticides sprayed in the Philippines, and most rice farmers in Thailand sprayed their crop in the first month after planting that these applications are unnecessary. Studies in Vietnam and the Philippines revealed that leaf-feeding insects were commonly targeted, accounting for 42% and 28% of insecticide use in each country, respectively, but those spraying were not needed because the rice plant could tolerate losing up to 50% of leaf area without compromising yield (EJF, 2002). Paradoxically, pesticide use itself encourages further chemical applications because it can kill natural predators and parasites of pest species, and can encourage pest resistance and resurgence leading to outbreaks, to which farmers respond with further spraying (EJF, 2002).

Based on the above results and reasons, it is essential that farmer training in rice IPM should emphasize on capacity building for the regular monitoring of fields on the damage situation and confidently making informed decision by considering all associated factors effecting yield especially the non-intervention with insecticides until needed. This approach will allow the beneficial animals to maintain insect pest populations and insect-induced damage below the action thresholds. There is a need to select rice cultivars with enhanced mechanisms of plant compensation and identify fertilizer management practices that promote plant compensatory growth and fast recovery from insect damages. In addition, tillering is strongly influenced by nitrogen supply thus plant recovery to defoliation and detillering is enhanced by appropriate fertilizer application.

CONCLUSION

The rice plant is capable to cope with a certain level of damages caused by defoliators and stem borers by rapidly developing new leaves and tillers in the early stage of the growing cycle for replacing losses quickly. The number of tillers produced is always greater than the number of reproductive tillers allowing for some damages of vegetative tillers without effecting reproductive tiller number. On the other hand, total hill yield is not as severely impacted as expected when a reproductive tiller is damaged by stem borers because the photosynthates and nutrients appear to move to neighboring tillers. For a sustainable integrated pest management, it is important to understand the interaction of the ability of rice cultivars to compensate and tolerate for foliage and tiller losses along with host plant resistance and to apply appropriate cultural practices together with the conservation of biological control agents in the field.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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CAPTIONS

Table 1. List of defoliation and detillering treatments performed in this study

Plot	Treatment	Percentage removal	Treatment timing of rice growth stage phase	stage	DAT*
T1	Control	0	N.A.#	N.A.	N.A.
T2	Defoliation	10	Vegetative	Tillering	30
T3	Defoliation	25	Vegetative	Tillering	30
T4	Defoliation	50	Vegetative	Tillering	30
T5	Defoliation	10	Reproductive	Heading	60
T6	Defoliation	30	Reproductive	Heading	60
T7	Defoliation	50	Reproductive	Heading	60
T8	Detillering	10	Vegetative	Tillering	30
T9	Detillering	20	Vegetative	Tillering	30
T10	Detillering	30	Vegetative	Tillering	30
T11	Detillering	5	Reproductive	Heading	60
T12	Detillering	10	Reproductive	Heading	60
T13	Detillering	15	Reproductive	Heading	60

* DAT, day after transplanting

\# N.A., not applicable

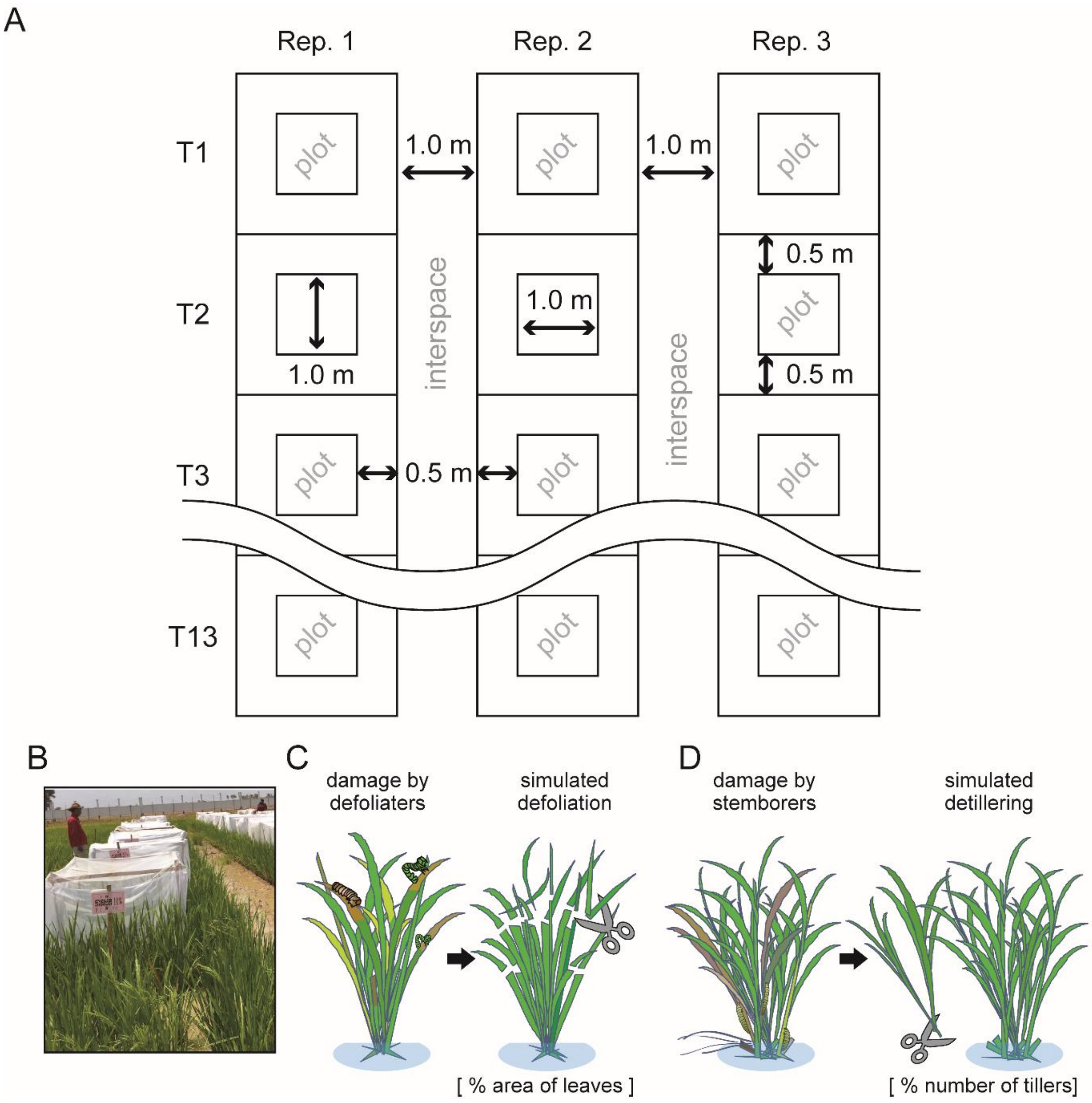

Figure 1. Experimental design and treatments. (A) Design of field experiments. Net-covered, 1.0 × 1.0 m^2 plots were prepared. T1 is control, and T2-T13 represent different levels of defoliation and detillering. Rep. 1, Rep. 2 and Rep. 3 represent replications 1, 2 and 3, respectively. (B) Photo of the plots. (C and D) Schematic representation of simulated defoliation (C) and detillering (D), respectively.

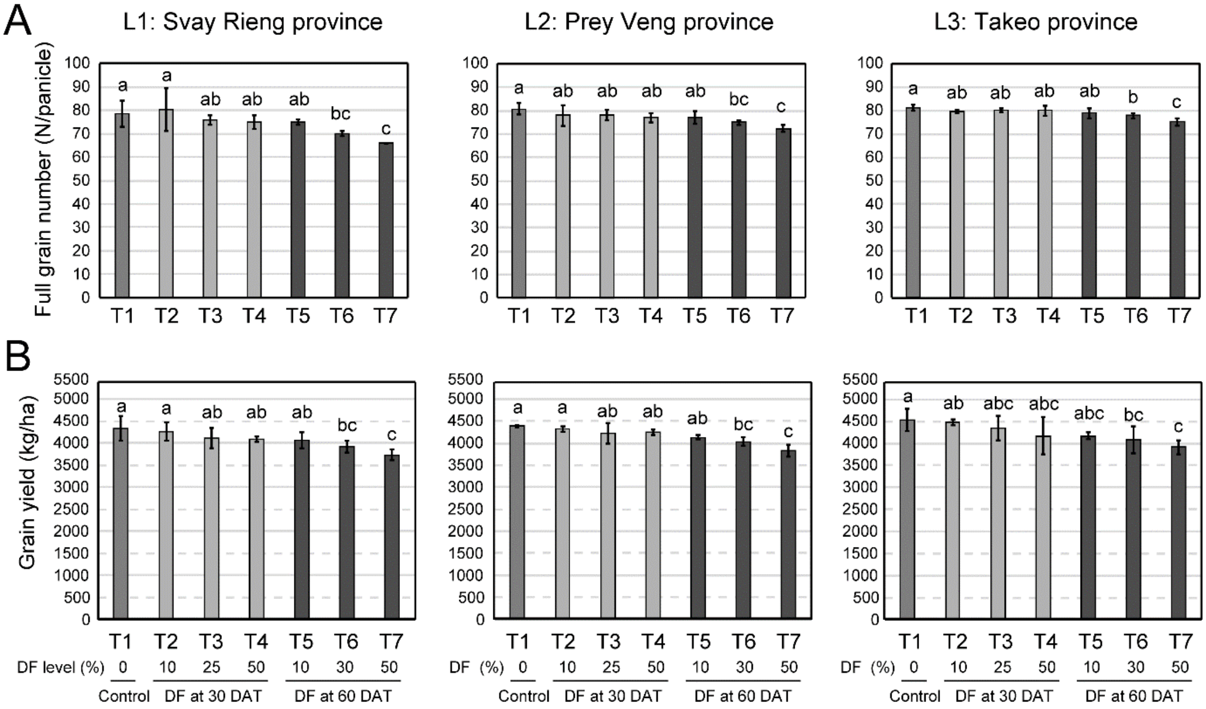

Figure 2. Mean comparison of full grain number and grain yield at different levels of defoliations in three locations. (A) is full grain number (number/panicle) and (B) is grain yield (kg/ha) in three locations. L1, L2 and L3 represent locations 1, 2 and 3, respectively. T1 is control and T2-T7 represent treatment 2 to 7 responding to different levels of defoliation. Different letters (a-c) indicate statistically significant differences at $p < 0.05$ between treatments by one-way ANOVA. DF is defoliation and DAT is day after translating.

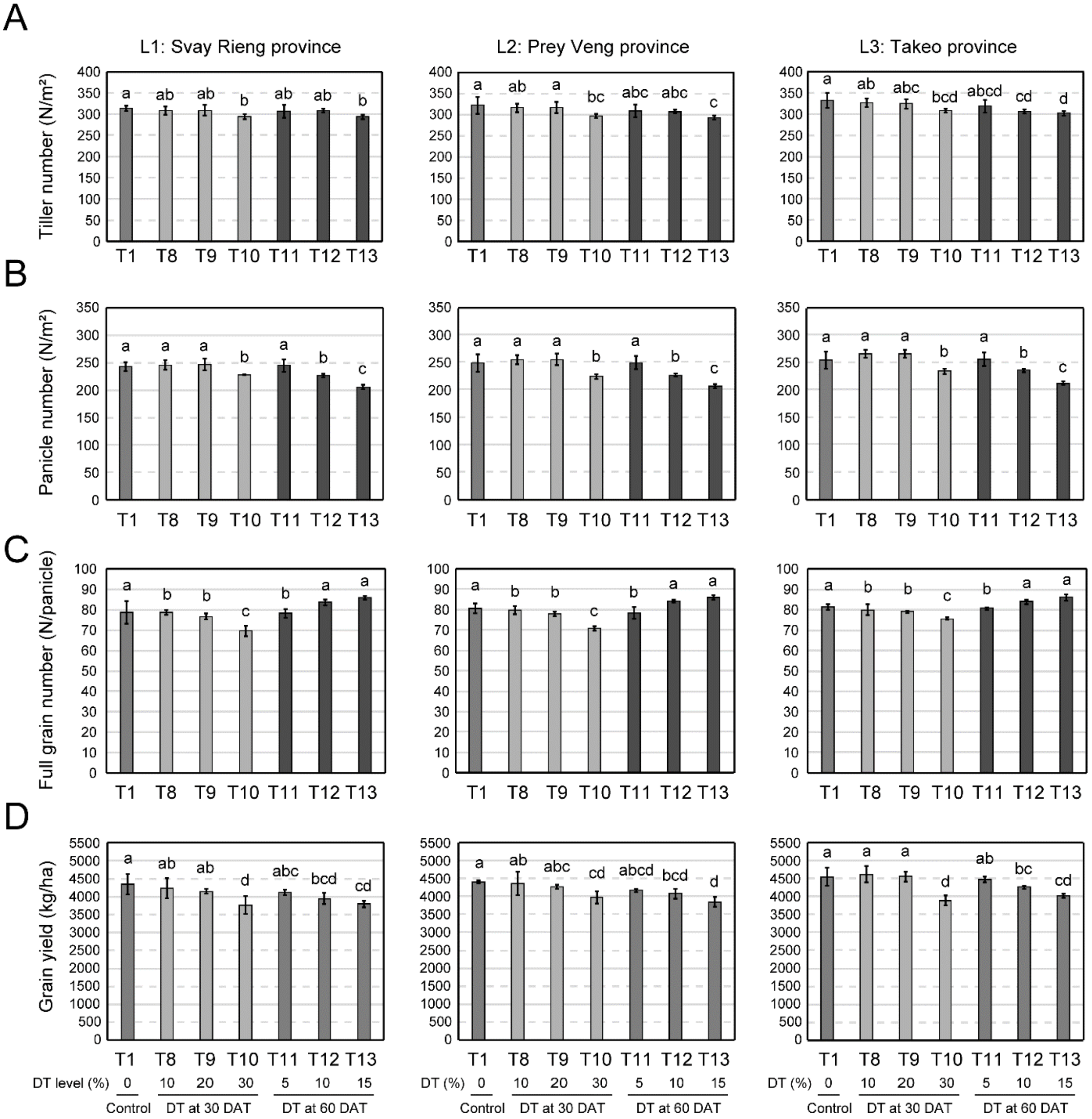

Figure 3. Mean comparison of tiller number, panicle number, full grain number and grain yield at different levels of detillering in three locations. (A) is tiller number (number/m^2, (B) is panicle number (number/m^2), (C) is full grain number (number/panicle) and (D) is grain yield (kg/ha) across three locations. L1, L2 and L3 represent locations 1, 2 and 3, respectively. T1 is control and T8-T13 represent treatment 8 to 13 responding to deferent levels of detillering. Different letters (a-c) indicate statistically significant differences at $p < 0.05$ between treatments by one-way ANOVA. DT is detillering and DAT is day after translating.

Supplementary Table S1. Mean comparison of tiller number, panicle number and grain weight in different defoliation and detillering treatments in 3 locations.

Variable	**Treatment**	**Location 1**		**Location 2**		**Location 3**	
		Mean	Std	Mean	Std	Mean	Std
Tiller number (number/m^2) (defoliation)	T1	313.67	5.51	323.00	20.30	333.33	17.56
	T2	308.33	17.56	319.67	30.75	337.67	4.93
	T3	304.67	30.75	323.33	17.56	333.00	20.30
	T4	312.67	4.93	327.67	4.93	329.67	30.75
	T5	308.00	20.30	328.67	5.51	338.67	5.51
	T6	313.00	22.54	328.00	22.54	338.00	22.54
	T7	316.33	11.85	331.33	11.85	341.33	11.85
Panicle number (number/m^2) (defoliation)	T1	243.67	8.08	247.33	15.28	253.33	15.28
	T2	238.33	18.93	244.00	21.79	251.67	7.64
	T3	240.00	21.79	253.00	9.85	253.33	15.28
	T4	241.67	7.64	245.67	7.64	250.00	21.79
	T5	243.33	15.28	247.67	8.08	253.67	8.08
	T6	243.33	16.07	247.33	16.07	253.33	16.07
	T7	249.67	9.87	253.67	9.87	259.67	9.87
Grain weight (g/1,000 grains) (defoliation)	T1	22.57	0.06	22.27	0.38	22.40	0.17
	T2	22.30	0.20	22.37	0.12	22.67	0.23
	T3	22.50	0.10	22.63	0.12	22.57	0.23
	T4	22.33	0.15	22.27	0.25	22.33	0.32
	T5	22.50	0.17	22.30	0.30	22.27	0.06
	T6	22.47	0.21	22.37	0.31	22.33	0.32

	T7	22.33	0.21	22.50	0.36	22.43	0.25
Grain weight (g/1,000 grains) (detillering)	T01	22.57	0.06	22.27	0.38	22.40	0.17
	T08	22.67	0.15	22.33	0.31	22.57	0.32
	T09	22.67	0.06	22.33	0.25	22.40	0.36
	T10	22.50	0.35	22.37	0.06	22.27	0.15
	T11	22.37	0.29	22.37	0.31	22.50	0.26
	T12	22.40	0.17	22.60	0.26	22.53	0.23
	T13	22.53	0.21	22.53	0.31	22.33	0.35

These are variables that are not significantly different at $p < 0.05$ between treatments by one-way ANOVA analysis, while those showed significant differences are shown in Figs. 2 and 3 as bar charts.