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Weed biodiversity and rice production during the irrigation rehabilitation process in Cambodia

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ABSTRACT

A phytosociological survey of weed species was conducted during the rainy season in 2008 in paddy fields at different distances from the main irrigation canal in the Kamping Puoy Irrigation Rehabilitation Area in northwestern Cambodia. The spatial variation in water depth was large between upstream (shallower) and downstream (deeper) paddies, which resulted in different weed, with many Poaceae and Cyperaceae species observed on levees in upstream and aquatic herbs in downstream paddies. Chemical fertilizer input levels were generally small and average rice yield was relatively low (ca. 2.3 t/ha). Traditional and less intensive weed management options such as hand weeding, mid-season tillage, and post-harvest straw burning were common, while the herbicide 2,4-D was also widely used. Weed species in the paddy ecosystem used by villagers included *Ipomoea aquatica*, *Nymphaea nouchali*, and *Monochoria vaginalis* (occasional, for human consumption) and graminoid species (frequent, for cattle feed in addition to rice straw). Greater inorganic fertilizer input was associated with a lower diversity of weed species, but grain yield and weed diversity indices had no negative relation among different locations. This survey revealed relatively small extent of intensification in the irrigation rehabilitation area in Cambodia, which led to high weed diversity, including numerous plant species available for use to support farmers' livelihoods in the area.

1. Introduction

Paddy fields provided various ecosystem services, such as (1) provisioning of rice grain, rice straw, and other plant species (i.e., weeds) and animals; (2) regulating air temperature and flood control; (3) cultural services of festivals and rituals associated with farming; (4) supporting nutrient cycles and disease control; and (5) preserving genetic diversity (Zedler and Kercher, 2005). Paddy fields were traditionally characterized by a rich flora, with more than 1800 plant species (both aquatic and terrestrial) associated with rice in southeast Asia (Moody, 1989; Soerjani et al., 1987), cropped using traditional methods, i.e., water flooding but with distinct ecological phases, incomplete leveling, heterogeneous microscale conditions, repetitive disturbance due to tillage, low fertilizer input, hand weeding without using synthetic herbicides (Fernando, 1993; Rao et al., 2007).

Cambodian paddy fields might be unique in that relatively few farmers adopted modern agricultural techniques, partly due to the country's long civil war (from 1970 to 1993). For example, the rate of fertilizer use was much lower than that in neighboring countries: 5 in Cambodia versus 133 in Thailand and 324 kg/ha in Vietnam, based on averages from 2002 to 2004 (Yu and Fan, 2009). The area devoted to dry-season fully irrigated rice was only 14% of the total cultivated area in Cambodia (JICA, 2010). The Cambodian government recently issued a national policy to increase rice production from 7.3 in 2010 to 9.1 Mt in 2015 by increasing the dry-season irrigated rice area from 385,000 in 2010 to 480,000 ha in 2015; the government also aimed to increase exports of unpolished rice from the estimated value (including unofficial transportation to its neighboring countries) of 2.06 in 2010 to 2.89 Mt in 2015 (RGC, 2010). In the future, Cambodia's rich weed biodiversity might decrease in those areas where modern agricultural techniques were widely introduced, such as paddy fields undergoing irrigation rehabilitation.

The aim of this study was to provide baseline data of weed flora for the assessment of possible trade-offs and synergies between weed biodiversity and rice production in Cambodian paddy fields

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under a scenario of shifting management schemes from traditional to modern methods (Supplementary Fig. 1). A hypothesis was proposed that the rice ecosystem was heterogeneous and level of production intensity was relatively low, which might allow up to some extent to increase rice yield without decreasing weed diversity and weed provision function of ecosystem services in the Cambodian paddy.

2. Material and methods

Cambodia had a tropical monsoon climate, with a dry season that lasts from December to May and a rainy season that lasts from June to November. The monthly maximum and minimum temperatures in Battambang province were 33.0 (in April) and 23.2 °C (in January), respectively, and the annual precipitation averaged 1368 mm.

The Kamping Puoy Irrigation Rehabilitation Area (KPIRA), located west of Battambang city in Battambang province of northwestern Cambodia (13°02′ N, 103°04′ E), was one of the largest irrigated paddy areas in Cambodia (ca. 2800 ha out of the ca. 5000-ha area were irrigated in 2008). The irrigation water came from the Kamping Puoy reservoir through irrigation canals, which were constructed during Pol Pot's regime from 1975 to 1979. The irrigation system did not function well, possibly due to poor design, and it was repaired by Italian and Japanese government agencies from 1998 to 2006 (Try, 2008). The goal of the rehabilitation project was to maximize the area that could be planted with rice during the dry season and hence to improve the system to permit cultivation of two rice crops.

The study site was the downstream 950-ha zone of KPIRA, located about 12 km from the Kamping Puoy reservoir. The irrigation system in the 950-ha zone was rehabilitated by the grassroots Kusanone scheme of the Japan International Cooperation Agency (JICA) from 2001 to 2003, and dry-season rice production was only partly implemented between 2003 and 2008.

In the 950-ha zone, six secondary irrigation canals and six secondary drainage canals (ca. 1–3.5 km long) were connected to the main irrigation and drainage canals. Twenty-eight paddy fields were selected from 140 fields along two secondary canals (D2-1 and D2-7), with D2-1 located about 3.4 km upstream of D2-7 along the main canal (N2). The main and secondary irrigation and drainage canals were not lined with concrete. The paddy fields were grouped into upstream (U), midstream (M), and downstream (D) paddies based on their distance from the main canal along the secondary canals D2-1 and D2-7: D2-1 upstream (1U; 0.3 km, 4 selected from 31 fields), D2-1 midstream (1M; 1.2 km, 6 selected from 38 fields), D2-1 downstream (1D; 2.4 km, 6 selected from 29 fields), D2-7 upstream (7U; 0.1 km, 4 selected from 8 fields), D2-7 midstream (7M; 0.8 km, 4 selected from 20 fields), and D2-7 downstream (7D; 1.6 km, 4 selected from 14 fields). The paddy areas along D2-1 were rehabilitated earlier than those along D2-7. By 2008, farmers only grew a single crop per year in 7D, 7M, 1D, whereas two crops were grown annually in the other fields.

Environmental variables, rice and weed growth variables and weed species were collected in two quadrats per field (each 2 m × 2 m) in 28 fields at 2-month intervals from August 2008 (planting time during the rainy season) to February 2009 (after harvest), for a total of 224 quadrats, while agronomic management variables were collected for each field (Supplementary Table 1). The quadrats were established toward the middle of each field to minimize the influence of edge effects, and their locations were determined by means of GPS (eTrex Legend HCx; Garmin Corporation, Olathe, KS, USA). The same quadrats were used for the five observations from August to February. Mean and standard deviation for all the environmental, rice and weed growth, and management variables were calculated for each of the six paddy groups (1U, 1M, 1D, 7U, 7M, 7D) from the measurements of quadrats or fields.

2.1. Environmental variables

As an indicator for water availability and microtopography, the depth of the standing water was determined in all quadrats. Soil moisture was measured by a CS620 HydroSense water content probe (Campbell Scientific, Logan, UT, USA) and soil hardness by a soil compaction meter (Fujiwara, Tokyo, Japan). Water and soil pH were measured by a Twin B-212 pH meter (Horiba, Kyoto, Japan). In each quadrat, the maximum height of rice plants and weeds was measured using a pole. The coverage of rice and weed within each quadrat was visually assessed by Braun-Blanquet (1964) scale: + = <1, 1 = 1–5, 2 = 6–25, 3 = 26–50, 4 = 51–75, and 5 = 76–100%.

2.2. Agronomic management variables

The owners and managers of the 28 surveyed paddy fields in Ta Kream and Poy Svay villages were interviewed about their management practices, including planting methods (transplanting or direct seeding), organic and inorganic fertilizer types and application rates, herbicide use (yes or no), hand weeding (yes or no), traditional weed control method (i.e., mid-season tillage) (yes or no), crop residue management after harvest (i.e., burning) (yes or no), and rice yield. Rice yield was also estimated from the samples from each field to confirm agreement with the interviewed values.

2.3. Weed data analysis

Voucher specimens were collected for each plant species, as well as for unidentified species with low frequency and low coverage. Identification of species was based on Dy Phon (2000), Harada et al. (1996), and Kadono (1994) using specimens at the Bangkok Forest Herbarium.

All vegetation data were converted into mean cover classes to improve the normality and homogeneity within groups (McCune and Grace, 2002). The dominance values in the Braun-Blanquet scale were therefore converted into the following mean cover classes: + = 0.5, 1 = 3, 2 = 15, 3 = 37.5, 4 = 62.5, and 5 = 87.5%.

The life forms of the species were divided into five categories based on Reimer (1984): (1) emergent graminoids (*e-g*), whose roots and basal portions grow beneath the surface of shallow water but whose leaves and stems were primarily in the air and that were grasslike herbaceous plants with leaves that were mostly narrower than their length (i.e., linear in outline); (2) emergent broadleaf plants (*e-b*), which were emergent plants with leaves about as broad as they were long, including ferns; (3) floating-leaf plants (*fl*), whose leaves float on the water surface but whose roots were anchored in the substrate; (4) submerged plants (*s*), which spend their entire life cycle (except during flowering) beneath the surface of the water; and (5) levee plants (*l*), which prefer upland conditions and therefore appear mainly on levees and were not common inside paddies.

To assess weed diversity of each plant community, species richness (the number of species present in a quadrat) and Simpson (1949) diversity index (D') were used. Correlation analysis was conducted for species richness and Simpson's diversity index with all the other managemental and environmental parameters using all the quadrat data in each month.

Detrended correspondence analysis (DCA; Hill and Gauch, 1980) was performed to investigate the relationships between weed communities and abiotic or anthropogenic factors, some of which were discrete variables with only two categories (e.g., yes or no for the use of herbicides). After omitting rare species that had been recorded four or fewer times, a data matrix was prepared consisting of the 224 quadrats cross-referenced against the 52 species out of the total of 76 species that were identified in these plots. The calculations were performed using all the data for four months together by version 5.10 of PC-ORD for Windows (McCune and Mefford, 1999). As was often the case in DCA analysis, Spearman's rank correlations were calculated between DCA scores (i.e., axis 1 and axis 2 which had the highest eigenvalues) and key environmental, vegetation, and rice management variables to characterize the axis (Hill and Gauch, 1980).

2.4. Utilization of plant species by farmers

Group discussions with several key villagers (e.g., the village chief) were organized at the three villages (Ta Kream, Poy Svay, and Ta Ngen) in the Ta Kream commune during the dry season of 2009 to learn which weeds farmers collected for use from their paddy fields. The names of weeds (local names, English names, and scientific names, if possible), peak collection season, weed abundance, and popularity among farmers were clarified, although a few weeds were left unidentified. "Popular" means some farmers know the usage, while "very popular" means most of the farmers use the weeds. In the same three villages, 44 farmers completed a questionnaire during the rainy season of 2009 to clarify which plant species were commonly collected in the paddy ecosystem, including the purpose for collecting each. Sources of forage for feeding cattle were also identified to assess the relative importance of provision service deriving from weeds.

3. Results

Standing water was deeper in downstream fields than upstream during the rice growing period in the rainy season, and it was deeper in canal D2-7 than in D2-1 (Supplementary Table 2). The depth of the standing water in the paddy fields in October was greatest in field 7D (i.e., 43 ± 21 cm; mean ± standard deviation) and shallowest in 1U (i.e., 7 ± 5 cm). Field 1U also had the earliest recession of standing water, which occurred in November. Due to the slower drainage from D2-7, the soil moisture content in D2-7 fields was higher than that of D2-1 in February (early dry season).

In general, the area of a single field (i.e., one paddy field bounded by a levee) was larger in midstream and downstream fields than in upstream (except for 7D) (Supplementary Table 2). Rice yield was higher in 1U and 1M, and it was lower in 7U due to a flood that damaged the rice plants. Rice height was greater in midstream and downstream fields, particularly 7M and 7D, compared with upstream. In general, the weed height was lower than the rice height, but some exceptions were noted, such as tall emergent broadleaf weeds in 1D (e.g., *Sesbania bispinosa*, *Alternanthera sessilis*, *Scirpus pilosus*, and *Scirpus grossus*). Weed cover in October was largest in 1M and 1U and smallest in 7M and 7D. In 1U, the total weed cover remained consistently high until February, whereas it decreased sharply after October or December in the other field groups. In 1M, the weed heights in February were lower than those of other field groups.

Organic N from manure application was higher in 1U while it was very low in 1D, 7U and 7M (Supplementary Table 2). The N and P inorganic fertilizer rates were highest in 1U and 1M. The majority of farmers used the herbicide 2,4-D, but at a low application rate (0.4 ± 0.2 kg a.i./ha). Mid-season tillage was more widely practiced in 1D, 7M, and 7D than in the other field groups. In 1M, almost 80% of the area was burned by February, after the rice harvest. Rice was established mainly by direct seeding along both canals, but rice with an earlier maturity (by more than 1 month) was also cultivated by transplanting in the upstream paddies (e.g., 1U). The soil of 1U fields was hardest in February.

3.1. Weed species

A total of 76 species in 21 families were identified in the KPIRA paddy fields from August 2008 to February 2009 (Supplementary Table 5, Appendix). The dominant families were Cyperaceae (19 spp.), Poaceae (14 spp.), and Scrophulariaceae (8 spp.). The dominant life forms were emergent graminoids (30 spp.), emergent broadleaf plants (21 spp.), levee plants (13 spp.), submerged plants (9 spp.), and floating-leaf plants (3 spp.). *Fimbristylis miliacea* was dominant in all the field groups (Supplementary Table 6), particularly during the rice growing period. The mean cover of *F. miliacea* in August was higher in 7M, 1D, and 7D, where dry direct seeding was practiced.

Weed species composition differed between 1U and 7D. The vegetation of 1U was characterized by many members of the Poaceae (e.g., *Pseudoraphis spinescens*, *Echinochloa colonum* f. *viviparum*, *Isachne confusa*) and Cyperaceae (e.g., *S. grossus*, *Cyperus rotundus*), which often appeared on the levees. Species composition in 1U did not change clearly from August to February, and emergent graminoids appeared with high frequency in all months (Supplementary Table 5). *Marsilea crenata* dominated the plots in 1U. In contrast, the indicator species of 7D (Supplementary Table 6) were common in naturally flooded lands and ponds. In addition, wild rice (*Oryza rufipogon*) occurred at high frequency in December in 7D. The number of emergent broadleaf plants was largest in 7D. In 7M *Limnophila heterophylla* was found as indicator species.

Species richness and diversity were generally higher during the rice growing period (October, December) and higher in downstream fields (e.g., 1D, 7D) (Supplementary Table 2). In 1D the highest species richness (9.8 species per quadrat) and the highest diversity ($D' = 0.46$) occurred in October. The post-harvest species richness in February was low in 1M after the burning of crop residues, as well as in 1D due to coverage by a lot of rice straw. Generally, weed management practices such as herbicide use and mid-season tillage had the highest positive significant correlation with D' in August, while fertilizer input (organic and inorganic N, inorganic P) and rice coverage (with negative), and growth duration (with positive) had the highest correlation with these indices in October; and water depth and growth duration had the highest positive correlation with these indices in December (Table 1). Soil humidity and burning had large correlation coefficients with D' and species richness in February.

3.2. Weed communities

Fig. 1a presented the ordination results for the 224 quadrats on the two principal axes of the DCA, with the results for the six paddy groups overlaid. Table 2 showed the correlations between the DCA scores and the site and vegetation parameters.

Axis 1 (eigenvalue = 0.779) was significantly positively correlated ($P < 0.001$) with the ratio of fields by direct-seeding to transplanting (1), number of days of rice growth (2), D' (4), water depth (7), and distance from the main irrigation canal (10) (Table 2), and it was significantly negatively correlated ($P < 0.001$) with inorganic N (3), integrated weed cover (5), organic N (6), and inorganic P (8), with the numbers in parentheses indicating ranks. Axis 2 (eigenvalue = 0.542) was significantly positively correlated ($P < 0.001$) with number of days after rice planting (1), and distance from the main irrigation canal (4), and it was significantly negatively correlated ($P < 0.001$) with soil moisture content (2) and pH (3).

Fig. 1b showed the DCA results for the mean value for each paddy group in each of the surveyed months. Along axis 1, the

Table 1
Spearman coefficient of Simpson's diversity index (D′) and species richness with managemental and environmental parameters in each month.

	August	October	December	February
D′	Species richness (0.47), herbicide use (0.43), midseason tillage (0.36), *weed coverage (−0.29)*	Species richness (0.54), rice coverage (−0.36), growth duration (0.31), organic N (−0.40), *inorganic N (−0.31)*, midseason tillage (0.39), distance (0.32)	Rice height (0.34), weed coverage (−0.45), growth duration (0.36), midseason tillage (0.35), *soil hardness (−0.27)*, *water depth (0.30)*	*Species richness (0.27)*, rice height (0.39), *soil moisture content (0.33)*, *weed coverage (−0.32)*, *growth duration (0.29)*, *midseason tillage (0.29)*
Species richness	D′ (0.47), weed height (0.34), rice coverage (0.50), weed coverage (0.37), *rice yield (0.30)*	D′ (0.54), inorganic N (−0.43), herbicide (0.36), midseason tillage (0.40)	Rice height (0.35), weed height (0.40), rice coverage (0.38), distance (0.50), midseason tillage (0.38), *weed coverage (0.27)*, *rice yield (0.34)*, *growth duration (0.32)*	*D′ (0.27)*, soil moisture content (0.41), rice height (0.36), weed height (0.56), rice coverage (0.61), weed coverage (0.60), distance (−0.35), burning (−0.44)

Normal and italic show significance at $P = 0.01$ and 0.05, respectively.

six paddy groups were roughly in the following order from left to right: 1U, 1M, 1D, 7U, 7M, and 7D. 1U and 7D were clearly separated, whereas 1M, 1D, 7M, and 7U were closely grouped. Axis 2 of the DCA indicated the direction of seasonal changes in the vegetation community, and values along this axis generally increased from August to October to December to February. The changes along axis 2 were smaller for 1U than for the other five paddy groups. The changes for 1D, 7U, and 7M overlapped to a considerable extent (Fig. 1a and b).

DCA ordination was performed for the 52 weed species (i.e., excluding rare species from the total 76 species) in order from 1U to 7D along axis 1 (Supplementary Fig. 2). 1U indicators had low scores (e.g., *Ipomoea aquatica*, *P. spinescens*, *M. crenata*, *Eclipta prostrata*, *I. confusa*), whereas 7D indicators (e.g., *S. bispinosa*, *Ludwigia adscendens*, *A. sessilis*) had high scores. Along axis 2, *Melochia corchorifolia*, *Phyllanthus virgatus*, *Cyperus haspan*, *Nitella* sp., and *Lindernia angustifolia*, which often occurred in August or October, had low scores, whereas *C. procerus*, *Sphaeranthus indicus*, *Sacciolepis indica* var. *indica*, and *O. rufipogon*, which appeared from December to February, had high scores.

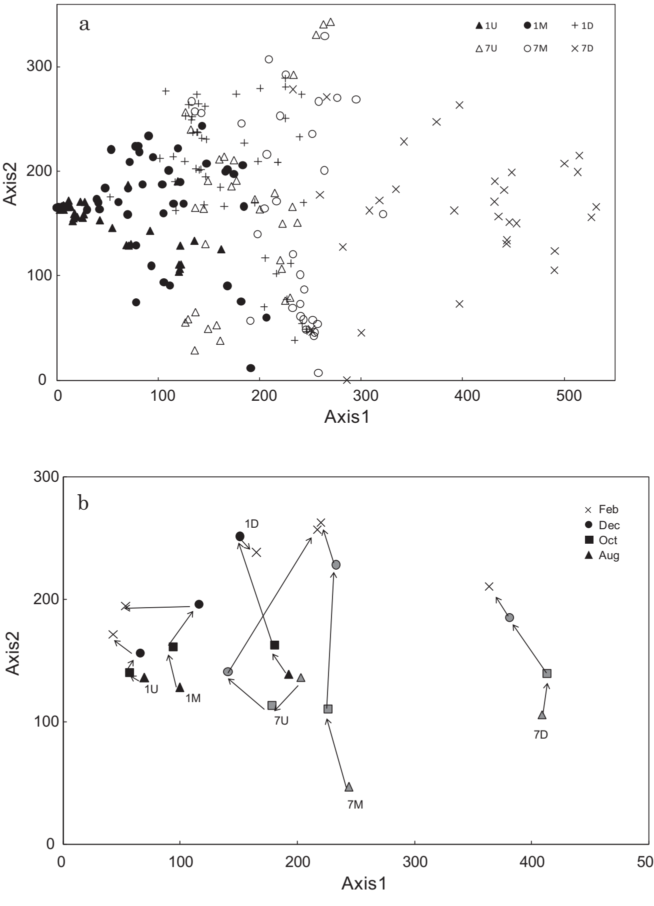

Fig. 1. DCA ordination of (a) species composition of the 28 sampling fields for the six paddy groups, and (b) mean values of each month, with the arrows indicating the direction of the seasonal change in species composition.

3.3. Utilization of weeds by farmers

As many as 13 weeds names were listed by farmers of KPIRA that they utilize. Some names referred to a single species (e.g., *I. aquatica*, *Nymphaea nouchali*, *Monochoria vaginalis*), whereas others referred to groups of species (e.g., some kinds of sedge or grass species)

Table 2
Correlations between the DCA scores (axis 1 and axis 2) and the key variables on environmental conditions, vegetation and rice management for the combined analysis.

	Combined analysis	
	Axis 1	Axis 2
Physical parameters		
Distance from the main canal	0.248^{***}	0.235^{***}
Rice parameters		
Rice yield	-0.287^{**}	-0.148^{*}
Rice height	0.241^{**}	0.143^{*}
Rice coverage	−0.022	-0.202^{**}
Weed parameters		
Weed height	0.117	−0.034
Weed coverage	-0.358^{***}	-0.195^{**}
Species richness	0.097	-0.178^{**}
D′	0.380^{***}	−0.006
Management input parameters		
Organic N	-0.331^{***}	-0.150^{*}
Inorganic N	-0.462^{***}	−0.091
Inorganic P	-0.315^{***}	−0.060
Herbicide	-0.153^{*}	0.105
Weeding	0.171^{*}	−0.080
Management parameters		
Percentage of DS/TP	0.848^{***}	0.023
Number of days after planting	0.220^{**}	0.570^{***}
Rice growth duration	0.687^{***}	0.064
Water environment parameters		
Water depth	0.317^{***}	-0.144^{**}
Soil moisture content	0.187^{**}	-0.333^{***}
Soil hardness	−0.045	0.135^{*}
pH	-0.210^{**}	-0.285^{***}

Spearman's ranking correlations.

[*] $P < 0.05$.

[**] $P < 0.01$.

[***] $P < 0.001$.

(Supplementary Table 3). The amount of each weed collected from paddy fields and used for human consumption was generally small, whereas the abundant grass species were used as cattle forage. Farmers collected not only weeds from the paddy ecosystem, but also rice straw (as a forage), palm fruits, bamboo shoots, and trees (as firewood) (Supplementary Table 4). To feed cattle, rice straw and weeds in the paddy ecosystem were the most widely utilized resources by farmers in both the rainy and dry seasons, followed by grazing in paddy fields after harvest.

4. Discussion

In an irrigation rehabilitation area in Cambodia, 76 weed species were identified (in 224 quadrats totaling 896 m^2). Previous surveys of paddy weeds in other tropical Asian countries showed similar numbers of species when excluding those growing on levees (41 species in Sri Lanka, Bambaradeniya et al., 2004; 87 species in Laos, Kosaka et al., 2006; 96 species in Thailand, Tomita et al., 2003a,b), whereas the inclusion of levee species markedly increased the numbers (89 species in Sri Lanka, Bambaradeniya et al., 2004; 184 species in Laos, Kosaka et al., 2006).

The Cambodian weed community in KPIRA shares more species with the rain-fed rice ecosystem in Laos, where both *F. miliacea* and *Rotala indica* were widespread (Kosaka et al., 2006), whereas only the former was widely distributed in rain-fed lowlands in northeastern Thailand (Tomita et al., 2003a,b). In the Vietnamese rice ecosystem, where the proportion of irrigated area was much larger than that in Cambodia, *F. miliacea* was not the most serious weed. Instead, *Echinochloa crus-galli* and *Leptochloa chinensis* were the species with more negative effects on rice production. Thus, the results indicate that the weed community in the Cambodian KPIRA had a greater similarity with rain-fed ecosystems (i.e., Laos, Thailand) than with irrigated ecosystems (i.e., Vietnam).

KPIRA had unique hydrological conditions in which irrigated rice had only been partly introduced. Some weed species common in rain-fed paddies in Cambodia were observed in KPIRA, such as *Pentapetes phoenicea*, *Fuirena ciliaris*, *Lindernia crustacea*, and *Scirpus juncoides*, as were species found in the floodplain of Lake Tonle Sap in Cambodia, including *P. phoenicea*, *Aeschynomene aspera*, and *N. nouchali* (Y. Araki, personal communication).

4.1. *Intensification and weed biodiversity*

The study supported the hypothesis that a rich diversity of plants was available in KPIRA not only because of heterogeneous water conditions and crop management practices between upstream and downstream fields, but also because of low level of intensification by 2008 (i.e., low input of pesticides and inorganic fertilizers, extensive planting and weed control methods, mosaic field arrangement). The presence of *M. crenata*, a perennial fern and a critically endangered species in the Japanese Red Data Book due to its sensitivity to agricultural chemical substances (Harada et al., 1996), indicated that agricultural input remained low in KPIRA. A negative relationship was found between the application rate of inorganic N fertilizer and Simpson's diversity index and species richness in October. Upstream and D2-1 fields (1U, 1M), with higher organic and inorganic N and P fertilizer inputs and with relatively widespread transplanting, had a lower diversity index, whereas downstream and D2-7 fields (7D, 7M, 1D), with less fertilizer use, direct seeding, and mid-season tillage weed management, had a higher diversity index (cf. Kamoshita et al., 2010). Tomita et al. (2003a) reported richer weed species diversity by dry direct seeding compared with by transplanting in rain-fed lowlands in northeastern Thailand.

The paddy ecosystem in KPIRA consisted not only of rice fields and irrigation and drainage canals, but also levees, fallow fields, on-farm ponds, and small island-like mounded areas inside rice fields where trees grew (e.g., coconut) and provided places for farm workers to rest. Such a mosaic nature of landscape also helped to increase weed biodiversity.

This study supported the hypothesis of no trade-off between rice yield and weed diversity partly due to the relatively low level of intensification. However, greater extent of intensification such as an increase in application rate of inorganic N fertilizer would be demanded in future for KPIRA in order to increase rice yield (Nguyen et al., 2011) and to meet with the Cambodian government's policy to enhance rice export (RGC, 2010). If policy and agricultural extension focused only on increasing rice yield, the use of much more herbicide and inorganic fertilizers would be encouraged, but this might dramatically reduce paddy weed diversity (Supplementary Fig. 3). Substantial numbers of plant species that grew in the paddy ecosystem of KPIRA were utilized by farmers for human consumption and forage for cattle and hence the merits of high weed diversity and weed provision ecosystem services deriving from the heterogeneity of rehabilitating irrigated rice ecosystem should be recognized. The strategy to increase rice yield further without reducing weed biodiversity could be possible for example by efficient application method of fertilizer N (Hayashi et al., 2010) and improved management in direct seeding (Hayashi et al., 2007; Ikeda et al., 2008).

The increased frequency of burning crop residues after harvesting (e.g., in 1M) caused a dramatic loss of weed biodiversity in February, when only limited species appeared (e.g., *M. crenata*, *S. grossus*, and *C. pulcherrimus*; Supplementary Table 5). Burning could be an attractive residual management option for farmers to prepare for the subsequent planting as double rice cropping would further expand and cropping interval would become more intensified in KPIRA. However, burning had the negative aspects such as greenhouse gas emission, nutrient loss, diminished soil biota, and reduced total N and C in the topsoil (Gupta and Sahai, 2005; Wassmann et al., 2009), as many governments in developing Asian countries made it illegal to burn crop residues (Singh et al., 2005). Farmers might lack an understanding of these negative aspects of burning for environment, as well as knowledge of available technology for in situ incorporation of the residues (Samra et al., 2003).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2014.05.001. These data include Google maps of the most important areas described in this article.

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