Restoration of weed communities in abandoned rice paddy fields in the Tama Hills, central Japan

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Abstract

Since paddy weed communities are declining with intensification and abandonment of agricultural activities, protecting these species has become important. The restoration of cultural ecosystems normally includes the concomitant recovery of indigenous management practices. Given that the abandonment of paddy fields is due largely to cost and the shortage of labour, reintroduction of annual farming is unlikely even if paddy fields are restored. Hence, to confirm the occurrence of species assemblages typically represented in rice paddy

fields (typical paddy weeds: TPWs) and to determine how to decrease the expense and management burden, we instituted a restoration program in which traditional rice culture was restarted with some modifications such as introducing fallow periods in paddy fields abandoned for more than 10 years. We also investigated cultivated rice paddy fields where local farmers practise low-intensity farming and newly abandoned paddy fields as references. By comparing the floristic composition between restored and reference fields, we sought to meet two objectives: (1) to evaluate the efficacy of the restoration program in terms of the species composition of paddy weed communities in restored paddy fields, and (2) to identify the optimum fallow period to decrease the expense and management burden.

Restarting agricultural practices in abandoned paddy fields successfully encouraged TPWs. Moreover, restoration of the TPW community was rapid, with no resilient or alternative state in the restoration program. Soil tillage and water management appeared to be major factors determining the success of the restoration. Tillage restricted the dominance of rhizomatous perennials and provided habitats for low-stature summer annuals. Reintroduction of submergence as a water management practice generally inhibits the occurrence of most TPWs. However, the unlevelled soil surface in the present study provided suitable conditions for these species. One-year fallow produced the highest abundance of TPWs in a transient stage influenced by antecedent effects of rice culture such as drainage after rice harvest, delay of competitive species incidence, and lack of submergence as an agricultural treatment. The number of TPWs declined steadily with increasing fallow period. This evidence indicates that to maintain paddy weeds in the emergent flora, it is appropriate to create 1-year fallow conditions; that is, to cultivate every other year.

Key words

Agricultural practice; Cultivation; Fallow; Mowing; Wetlands

1. Introduction

Rice (*Oryza sativa* L.) has been cultivated for a long time in Asia. In Japan, rice paddies are the most common production farmlands, covering about 55% of the total agricultural land in 2000 (MAFF, 2003), and are thus the main component of agricultural landscapes. Although the water level is controlled artificially, rice paddies have recently been evaluated as wetland habitat for hygrophytes and hydrophytes known as ‘paddy weeds’ (Sekioka et al., 2000) and for water birds (Lane and Fujioka, 1998) and frogs (Osawa and Katsuno, 2001). However, they have been altered drastically in recent decades by socio-economic changes. As in agricultural landscapes in Europe, biodiversity is declining with intensification and marginalization of agricultural activities (Robinson and Sutherland, 2002; Hyvönen and Salonen, 2002).

To enhance rice productivity and farmers’ work efficiency, many paddy fields, especially those located in wide alluvial lowlands, have been equipped with modern drainage systems and made drier during the non-cultivation season (Hasegawa and Tabuchi, 1995). This change in water condition has decreased the value of the paddy fields' ecological function as wetland habitat, encouraging less hydrophilic vegetation and reducing floristic species richness (Arita and Kobayashi, 2000).

Meanwhile, as a result of shifting economics and the decline of the rural population since the 1970s, a substantial number of paddy fields, especially those located in mountainous and hilly areas, are no longer cultivated (MAFF, 2001). Many studies reported the establishment of wet grassland characterized by *Phragmites australis* and *Isachne globosa* (Hakoyama et al., 1977; Matsumura et al., 1988; Ohkuro et al., 1996; Comín et al., 2001) or wet woodland characterized by *Salix koriyanagi* and *Alnus japonica* (Hayakawa and Takahata, 1975; Shimoda, 1996; Lee et al., 2002) in the process of secondary succession when land management was not applied and if fields remained wet. Of course, secondary succession is a complex multifactorial process. The process depends on light conditions (Kang et al., 2004), seed sources from surrounding vegetation (Shimoda, 1996), climate (Lee et al., 2002), and soil moisture (Hakoyama et al., 1977), so correspondingly there are other dominant species. Nevertheless, species representative of cultivated paddy fields tended to decrease in most of these processes, even if the fields remained wet (Matsumura et al., 1988; Shimoda, 1996).

With these situations, many paddy weed species have become threatened. Kasahara (1951) defined 191 'paddy weeds' that needed to be controlled in those days in Japan. Of those, 110 species were especially problematic because they are hard to control in rice culture.

Yet now, 10 of those 'problematic' weeds are listed in the Japanese *Red Data Book* (Environment Agency of Japan, 2000) as threatened, and even more species are listed at a regional level. Therefore, immediate actions should be launched to preserve paddy fields in a wet condition and to establish alternative management schemes for restoring the specific conditions in which paddy weeds grow.

Successful restoration faces constraints. Recent reports suggest that some degraded systems shift to a new state (a resilient or alternative state) that cannot be restored to the previous condition or disturbance regime (Kleijn, 2003; Suding et al., 2004). Strong feedback between biotic factors and the physical environment can alter the efficiency of management efforts because of constraints such as eutrophication and acidification (Pywell et al., 1995; Willems, 2001; Walker et al., 2004), landscape connectivity (Hutchings and Booth, 1996; Bischoff, 2005), loss of species pool (Bakker and Berendse, 1999), and shifts in species dominance (Andersen et al., 2000). Another problem is more practical. The restoration of cultural ecosystems normally includes the concomitant recovery of indigenous management practices (Society for Ecological Restoration International Science & Policy Working Group, 2004). Given that the abandonment of paddy fields is due largely to cost and the shortage of labour, annual farming is unlikely even if paddy fields are restored.

In Japan, several restoration programs for conserving rare arable weeds have been carried out by restarting cultural practices in abandoned paddy fields (Asami et al., 2001; Shimoda and Nakamoto, 2003). However, it is still unclear whether vegetation communities represented in rice culture are totally restored by agricultural treatments in formerly abandoned paddy fields. Furthermore, few studies have assessed the effectiveness of management with regard to labour and cost efficiencies. A potentially suitable alternative is cultivation with fallow periods (i.e., producing crops only every few years). Species richness is likely to be low in cultivated paddy fields because most weeds are eradicated during cultivation; richness would be higher in fallow fields, as in the case of upland fields (Degn, 2001; Harmer et al., 2001). During long fallows, however, it might decline. Confirming the patterns and pace of vegetation shifts will allow us to establish effective management schemes.

In the present study, the restoration process restarted traditional rice culture with some modifications such as introducing a fallow period in paddy fields abandoned for more than 10 years. We monitored species assemblages typically represented in rice paddy fields in hilly alluvial lowland to evaluate the restoration effort. We also investigated cultivated rice paddy fields where local farmers practise low-intensity farming, and newly abandoned paddy fields as references. By comparing the floristic composition between restored and reference fields, we sought to meet two objectives: (1) to evaluate the efficacy of the restoration program in terms of the species composition of paddy weed communities in restored paddy fields, and (2) to identify the optimum fallow period to decrease the expense and management burden.

2. Materials and methods

2.1. Study area

The study area is located in the Tama Hills, 30 km west of Tokyo, at latitude 35°35′N, longitude 139°25′E. The mean annual precipitation at the nearby Hachioji meteorological station is approximately 1540 mm. The mean annual temperature is 14.3 °C, the mean minimum is 3.2 °C (January), and the mean maximum is 26.1 °C (August). The bedrock of the Tama Hills consists of semi-consolidated or unconsolidated sedimentary rocks from the Pliocene to Middle Pleistocene period, commonly known as the Kazusa Group. This group comprises several formations of fluvial gravels, tidal flats and inner bay silts, and littoral to upper neritic sand from the lower to the upper part (Takano, 1994). The layer underlying the valley bottoms is an impermeable mudstone. Most soils in the area contain tephra; the soil type of the paddy fields on the valley bottoms is Andic Gleysols. Hill ridges are about 30 m higher than the adjacent valley bottom. Hill slopes are mainly dominated by deciduous, broad-leaved forests, characterised by *Quercus serrata*, *Q. acutissima* and *Castanea crenata*, which were formerly coppiced (Okubo et al., 2005).

Rice is cultivated mostly in valley bottoms (Fig. 1). No intensive land improvement (land consolidation and development of water control system) is practised because of the low economic efficiency in such small valleys; hence, paddy fields stay irregular in shape and drainage remains poor in all seasons. Although a submerged condition is necessary during the cultivation period, drainage is needed in order to make the process of rice cultivation more efficient. The fields are surrounded by embankments approximately 50 cm wide, and are aligned from valley head to mouth on a terraced slope of 1 to 4%. The size of each parcel is very small, ranging from 180 to 400 m^2, and averaging 300 m^2. The fields are irrigated with natural water resources such as spring water from the valley head and rain water.

2.2. Restoration

2.2.1. Restoration of abandoned paddy fields

The restoration site lies in a small alluvial valley (Fig. 1), inside the 33-ha Zushi-Onoji Historic Environmental Conservation Area, which was proclaimed a Greenery Designated Conservation Area by the Tokyo Metropolis in 1978. According to aerial photo interpretation and interviews with local farmers, these paddy fields were partially abandoned in the 1970s and completely abandoned by the middle of the 1980s. Before the restoration, abandoned paddy fields were dominated by *P. australis*, *I. globosa,* and *Leersia sayanuka*, with scattered *Alnus hirsuta* var. *sibirica* and *Salix* spp. (Kitagawa, 2003). Footpaths, embankments, and canals around the paddy fields had collapsed.

Restoration practices started in the late summer of 1996. The Tama Environment Office of the Bureau of Environment, Tokyo Metropolis, and a local management organization formulated the management design. Since the management organization consists mostly of local farmers who used to own and cultivate the fields, their indigenous knowledge was drawn in the restoration to recover previous conditions and in the subsequent management. At the beginning of the restoration, all tall vegetation was cut and burnt in an area of 0.4 ha.

Collapsed footpaths and embankments were mounded as high as they had been before abandonment, and sedimented canals around the paddy fields were re-excavated to re-establish water management.

By 1997, only 4 neighbouring paddy rice parcels in the lower part of the valley had been completely restored by restarting paddy cultivation (Figs 1 and 2). A lack of human resources and budget limited the restoration, although the Tama Environmental Office and the management organization recognize that all parcels should be restored to preserve the traditional rural landscape (*satoyama* landscape; Fukamachi et al., 2001).

2.2.2. Treatment of restored paddy fields

All 4 restored parcels were managed under different time-series treatments from 1997 until 2003, when our monitoring was terminated. There were 2 types of treatment combination, which differed mainly in the paddy cultivation phase: cultivation with or without rice.

Three of the 4 restored parcels were managed with the treatment combination of paddy cultivation with rice and fallow (cessation of cultivation), henceforth referred to as 'restored parcels with rice culture'. For the rice culture phase, the management regime was almost the same as that used before rice culture was abandoned. Fields are ploughed in May. A few days before transplanting in June, they are ploughed again, flooded to about 15 cm deep, puddled, and levelled (‘surface soil puddling’). Then rice is transplanted. The water level is maintained for several weeks, and weeds are manually eradicated twice. At the end of July, the fields are drained via ditches dug when the rice starts maturing. Finally, rice is harvested in October.

Thereafter, the parcels are drained, but the surface soil remains wet. The water level gradually becomes higher owing to a constant supply of water from springs, and by the next summer the surface is naturally submerged by up to 5 cm. The difference from the traditional rice culture was that soil tillage after rice harvest was not carried out, because of the shortage of labour and funds. The fallow treatment was applied after rice was grown at least once. In this treatment, water level was not controlled artificially, so parcels were submerged about 5 to 10 cm deep during the treatment. During this phase, the parcel was mown with a shoulder-held mower twice a year (end of May to middle of June, and again in late August) to inhibit the dominance of macrophytes and woody species.

Two of the 3 parcels had the same treatment combination. Rice culture was performed from 1997 to 2000 and in 2003, with a break from 2001 to 2002. In the 3rd parcel, rice culture was performed in 1997 and 1999, with breaks in 1998 and from 2000 to 2002. In 2003, part of the parcel was cultivated.

In the 4th restored parcel, paddy cultivation without rice was performed in 1997 ('restored parcel without rice culture'). The treatment was the same as that with rice except for the rice and the water management: water was not drained, but remained about 15 cm deep throughout the treatment. After the treatment, the parcel was left to lie fallow and untouched for 5 years, from 1998 until 2002. In 2003, the vegetation was cut.

2.2.3. Monitoring in restored paddy fields

To accomplish our two objectives, we monitored chronosequential changes of vegetation in the 2-parcel group in which we alternated paddy cultivation with rice and fallow. Rice culture was omitted from monitoring in 1997 because it might have been strongly influenced by pre-restoration vegetation. We therefore started monitoring in the 2 parcels in 1998. We surveyed vegetation in 1998, 2000 and 2003 as 'rice culture phase in restored parcel'. These years represented the 2nd and 4th years of continuous rice culture treatment for 4 years, and the year after 2-yr fallow, respectively. We also surveyed vegetation in 2001 and 2002 as 1- to 2-yr 'fallow phase in restored parcel with rice culture'. Using the time-series data sets of the 2 parcels, we analysed both vegetation differences in each phase between restored and reference parcels separately, and the process of change in the sequence of rice culture for 4 years, fallow for 2 years, and restart of rice culture.

To analyse the effect of fallow length, we monitored continuous fallow for 3 years (from 2000 to 2002) in the 3rd parcel under the same treatment combination as in the above 2 parcels, although the previous rice culture phase was shorter. As a comparison, we also monitored vegetation changes in the fourth parcel, where paddy cultivation without rice was performed and thereafter the parcel was left untouched. Since the preconditions and the treatment in the fallow phase were completely different from the others, we separately surveyed and analysed the parcel from 1998 to 2002 as 1- to 5-yr 'fallow phase in restored parcel without rice culture'.

2.3. Reference site and monitoring

To evaluate the success of the vegetation restoration, we compared treated parcels with rice culture parcels that had no history of abandonment and similar submergence as in the restored parcels ('reference parcels'). These are located near the restoration site (Fig. 1). We chose 10 parcels as 'rice culture phase in reference parcel' and 6 as 'fallow phase in reference parcel' for comparison with the restored parcels. The former were surveyed in 2000. The latter were abandoned after the last rice harvest in October of either 1999 or 2001, so they were surveyed for 3 years continuously either from 2000 to 2002 or from 2002 to 2004 in order to compare differences in vegetation succession during the fallow period between restored and reference parcels. The treatments in both phases were slightly different from those in the restored parcels: the rice culture reference parcels were tilled after rice harvest; and during the fallow there was no mowing management or water control—identical to the treatment of the fallow phase in restored parcel without rice culture. The fallowed reference parcels were not tilled after the previous harvest as same as in restored ones.

Five other parcels that were adjacent to the restored parcels and had a potential water level similar to that of the restored parcels (Fig. 1 and 2) were mown twice per year, because tall vegetation was cut in 1996 as the pre-treatment ('unrestored parcels with mowing'). Parcels were mown from the end of May to the middle of June, and in late August. The litter was left in each parcel. To confirm to what extent the uncultivated treatment was effective at restoring typical paddy species, we surveyed the parcels in the 1st, 4th, and 7th years (i.e., in 1997, 2000, and 2003, respectively) as 1-, 4- and 7-yr elapsed length of time with 'mowing in unrestored parcels'. However, only 3 were surveyed in the 4th year because of a mistake.

2.4. Vegetation and habitat condition surveys

We monitored vegetation in a total of 59 combinations of parcels plus the year of observation (i.e., parcel–year units) explained in the above sections. Since the vegetation in the early stages after restoration was patchy, it was difficult and unrealistic to set quadrats within parcels; instead, we surveyed the whole area of each parcel in each year. No marked positive correlations between species number and parcel size in the same parcel–year units were seen. All species except rice were identified, and the dominance score using Braun-Blanquet levels (+, 1, 2, 3, 4, 5: Braun-Blanquet, 1964) of each species was recorded. To identify all seasonal species, we monitored vegetation twice a year, in May and August. The vegetation survey in May preceded any management practices in the year, whereas the survey conducted in August preceded mowing in that month. The combined data were merged, and the larger dominance score for each species was used (data not shown).

Species were categorized into life-forms (Numata and Yoshizawa, 1979; Chibaken-shiryou-kenkyuzaidan, 2003): summer annuals, winter annuals, biennial herbs, perennial herbs, and woody species. Paddy weeds, as defined by Kasahara (1951), include not only specialists of rice paddy fields, but also species that grow more frequently on levees, in natural wetlands, and in upland fields. We defined typical paddy weeds (TPWs) as those whose major habitats were rice paddy fields.

2.5. Data analysis

To confirm any differences in species composition among management types and over time, we analysed the data by using the ordination method called detrended correspondence analysis (DCA; Hill, 1979; Hill and Gauch, 1980). The analytical program PC-ORD for Windows Version 4 (McCune and Mefford, 1999) was used. Species that appeared in only 1 parcel–year unit were excluded to avoid ordination distortion as a result of the inclusion of serendipitous species. Braun–Blanquet levels were first converted into percentage of coverage (+, 0.1%; 1, 5%; 2, 17.5%; 3, 37.5%, 4, 62.5%; 5, 87.5%), then square-root transformed. Species diversity was calculated using the Shannon–Weaver diversity index (H') (Shannon and Weaver, 1949).

3. Results

3.1 Similarity of floristic composition in each sampling parcel–year unit

The proportion of variance in the distance matrix of the DCA ordination was substantially larger along axis 1 (0.528) than along axis 2 (0.106). We thus assumed axis 2 to be less important, and used only axis 1. The score for DCA axis 1 and the number of typical paddy weeds (TPWs) in each parcel–year unit are illustrated in the scatter diagram in Fig. 3. Restored and reference parcels in the rice culture phase and unrestored parcels under mowing were separately located along axis 1, with restored and reference parcels under fallow between them. Parcels under 1-yr fallow were located nearer to rice culture parcels than to fallow units of subsequent years in each group, and as the fallow period became longer, the scores of the units shifted to the left. The trend was similar to that in the parcel that was restored without rice culture, although the parcel score shifted rapidly to the left as the fallow period became longer. The length of time with mowing in unrestored parcels also contributed slightly to the axis 1 distribution. Parcels in the 7-yr elapsed mowing treatment lay to the right, whereas those in 1-yr elapsed mowing treatment lay to the left, with the lowest score of all parcel–year units. These results indicate that axis 1 was mostly associated with the intensity of anthropogenic disturbance.

There is a clear peak in the number of TPWs in the centre of the diagram, corresponding to both restored and reference parcels under 1-yr fallow. The number of TPWs decreased with increasing period of fallow, whereas in unrestored parcels with mowing treatment, no trend was observed with respect to the elapsed period.

3.2 Changes of floristic composition in each time-series treatment

A total of 137 species in 37 families were recorded in the study, consisting of 58 perennial herbs, 54 summer annuals, 12 winter annuals, 7 woody species, and 6 biennial herbs. Table 1 lists all typical paddy weeds (TPWs: 24 species) and 30 species that dominated in at least 2 parcel–year units. TPWs were manually classified into 3 groups according to their frequency in rice culture and fallow phases in restored and reference parcels (Table 1). TPWs in Group A were defined as those whose frequencies became low under 2- and 3-yr fallow in both restored and reference parcels; TPWs in Group B were defined as those whose frequencies were still relatively high even under 3-yr fallow in both restored and reference parcels; and TPWs in Group C were defined as those that appeared in reference parcels but not in restored parcels. Species were sorted and clumped manually according to their occurrence pattern among treatments. TPWs were summer annuals, winter annuals, and perennials, and all except *Isoetes japonica* and *Tillaea aquatica* are paddy weeds defined by Kasahara (1951).

3.2.1 Reference parcels with rice culture and fallow

Fig. 4 shows numbers of total species and TPWs, and averages of Shannon–Weaver diversity index (H') in each time-series treatment. Fig. 5 shows the numbers of species and TPWs of each life-form except biennials and woody species, which were not represented in TPWs. Parcels in the rice culture phase contained an average of 8.7 species of TPWs. The ratio of summer annuals as well as the ratio of perennials was highest in the 1st fallow year. In the subsequent fallow phases, the ratio of summer annuals declined more rapidly than the ratio of perennials. Dominant species were *Monochoria vaginalis* var. *plantaginea* (low summer annual) and *Alopecurus aequalis* var. *amulensis* (winter annual). TPWs were abundant in Groups A and B.

Parcels under fallow had more TPWs in the 1st year (10.5 spp.) than in later years, and more TPWs than in the rice culture phase. The results were the same for summer annual and perennial TPWs. The number of winter annuals was smaller in 1-yr fallow than in the rice culture phase (Fig. 5a). Among frequent species under 1-yr fallow, *M. vaginalis* var.

plantaginea, *Lindernia procumbens* (low summer annuals), and *Beckmannia syzigachne* (winter annual), in Group A, declined substantially, whereas taller tussock perennials such as *Glyceria acutiflora* and creeping annuals such as *Murdannia keisak*, which are in Group B, declined slowly. Like TPWs, total species number was largest under 1-yr fallow, and subsequently decreased. However, under 2- and 3-yr fallow, the numbers of perennial herbs greatly exceeded the numbers of summer annuals. Dominant species changed from taller summer annuals such as *Sagittaria trifolia* and *Ludwigia epilobioides* and clonal species such as *M. keisak* and *Persicaria nipponensis* in the 1st year towards rhizomatous perennials such as *Carex maximowiczii*, *C. dickinsii*, *P. australis*, and *L. sayanuka* in later years. In consequence, the DCA scores of 3-yr fallow shifted left (Fig. 3). H' was maximum under 1-yr fallow, thereafter declining as the fallow period increased (Fig. 4a).

3.2.2 Restored parcels with rice culture

In the rice culture phase in the restored parcels, restored agricultural practices produced no fewer TPWs than in the same phase for the reference parcels (Figs 4, 5). The similarity was largely due to perennials (Fig. 5). Dominant species were *M. vaginalis* var. *plantaginea* and *A. aequalis* var. *amulensis*, and TPWs of Groups A and B were abundant, as in reference parcels.

Fig. 6 shows the number of TPWs and total species number in each monitoring period of the rice culture phase (1998 and 2000 represent the 2nd and 4th years of continuous rice culture, and 2003 represents the year after the 2-yr fallows). Approximately 11 to 12 species were consistently recorded during the 3 monitoring periods. The DCA scores of parcels in the

2nd and 4th years of 4-year continuous rice culture (rice 1998 and rice 2000, respectively) were similar, indicating a similar floristic composition (Fig. 3). Parcels in the rice culture phase after 2-year fallow (rice 2003), however, had smaller DCA scores than those of parcels in the 2nd and 4th years of 4-year continuous rice culture, although the number of TPWs was similar (Figs 3, 6). This is because parcels remained under fallow in 2001 and 2002, and many plants remained standing in the spring of 2003 even after ploughing.

Under fallow, the general trend of the change in TPW species number was similar to that in the reference parcels. The number of TPWs was largest in the 1st year of fallow, and was larger than in the same year in reference parcels, due mostly to the differences in perennial herbs (Fig. 5). Summer annuals and perennial herbs were greater in number in 1-yr fallow, whereas winter annuals were greater during the rice culture phase. The total species number was largest in the 1st year of the phase and thereafter decreased steadily (Fig. 4b). However, the number of perennials was largest in the 2nd year (Fig. 5b). Summer annuals increased slightly in that year. Correspondingly, the DCA score shifted to the right of its location in the previous year (Fig. 3).

Some species differed in their frequencies of occurrence. Among TPWs in Group A, *Limnophila sessiliflora*, *Rotala indica* var. *uliginosa*, *Eleocharis acicularis* var. *longiseta*, and *Callitriche verna* were more frequent in restored parcels than in reference parcels, but this trend was not seen in Group B. Dominant species changed from taller summer annuals like *Cyperus orthostachyus* and *C. globosus* in 1-yr fallow towards rhizomatous perennials like

Lycopus ramosissimus var. *japonicus* and *C. maximowiczii* in later years (Table 1). *Phragmites australis* and *L. sayanuka,* both of which were dominant in the same year in reference parcels, lost their dominance.

3.2.3 Restored parcel without rice culture

As in both restored and reference parcels under fallow, TPWs continued to decline until the 5th year (Fig. 4), when we found only 1 species. Similarly, summer annual TPWs declined to zero in the 4th year of fallow. The number of TPWs after 1 year of fallow (10 spp.) was smaller than that under fallow in the same year in restored parcels, although it was similar to that under fallow in the same year in reference parcels.

Life-forms in the earlier periods of this phase, on the other hand, differed from those under fallow in both restored parcels with rice culture and reference parcels (Fig. 5). Perennial herbs like *Juncus effusus* var. *decipiens* and *L. sayanuka* were dominant early (1st and 2nd years). Hence, the DCA score lay to the left of scores from the same years of fallow in restoration parcels. *Phragmites australis* was highly dominant in the last 2 years (Table 1). In consequence, the floristic composition of the 4th and 5th years was similar to that of mowing treatment in the unrestored parcels (Fig. 3). Changes in H' were not clear (Fig. 4c).

3.2.4 Unrestored parcels with mowing treatment

In the 1-yr mowing treatment in unrestored parcels, some TPWs grew. However, long-term mowing did not contribute to the enhancement of TPWs except for a slight increase of

Echinochloa crus-galli (Table 1), although the total number of species increased over time (Fig. 4d). Most TPWs recorded in the treatment were those in Group B, such as *E. crus-galli*, *M. keisak*, and *L. epilobioides* (summer annual) (Table 1). Some of the dominant species increased (*L. sayanuka*) or decreased (*Equisetum arvense* and *Typha latifolia*), and their DCA scores shifted to the right, indicating increasing similarity of species composition to that in later years of fallow, particularly in reference parcels (Fig. 3). *Leersia sayanuka* increased to achieve the highest coverage, and hence H' did not change markedly (Fig. 4d).

4. Discussion

4.1. Factors affecting vegetation responses to different treatments

The restoration treatment we followed includes several management practices for rice culture. Therefore, we should carefully differentiate which practices affected species composition in each treatment phase and how the composition changed over time. Considering that paddy weed species have adapted to the long history of rice culture, two anthropogenic disturbances, namely soil tillage and water management, might be major factors affecting the habitat of paddy weed species (Bhagat et al., 1996).

Restarting agricultural practices in the paddy fields abandoned more than 10 years before successfully encouraged typical paddy weeds (TPWs), but mowing alone in unrestored parcels did not, as expected based on the state of the unrestored fields. This result indicates that soil tillage is the most important factor in determining the habitat for TPWs.

In general, soil disturbance helps to control some competitive species by partially or totally destroying existing vegetation both above the ground and underground (McIntyre et al., 1995; Grime, 1977). During the first year of fallow, rhizomatous species such as *C. maximowiczii*, *C. dickinsii*, and *P. australis* and clonal species such as *M. keisak* and *P. nipponensis* rapidly invaded the reference parcels. Therefore, this means that tillage plays an important role in restricting the dominance of these species. Our observation that more perennial TPWs in the rice culture phase were recorded in restored parcels (excluding the third survey in 2003) than in reference parcels is also explainable by lack of tillage after the previous rice harvest. Soil tillage after harvest is a major method of eliminating weeds, particularly perennials (Sakamoto, 1989).

Disturbed soil provides habitat for annual or short-lived perennials, a specialization clearly adapted to exploit environments intermittently favourable for rapid plant growth (Grime, 1977). For short summer annual TPWs that lack any competitive traits in terms of plant height (Bullock et al., 2001), tillage to reduce interspecies competition, particularly for light, would be important. In particular, winter annuals of both TPWs and non-TPWs were more dominant and frequent in the rice culture phase in reference parcels than in restored parcels, and both declined remarkably in the fallow phase in both reference and restored parcels. This result shows that soil tillage after harvest, which was carried out only in reference parcels under rice culture, encouraged the incidence of winter annuals, which could complete their life cycles by the next rice planting.

Zimdahl et al. (1988) showed experimentally that paddy weeds germinated immediately after soil tillage. Owing to the 'ruderal' strategy defined by Grime (1977), summer annual TPWs can complete their life cycle before rice covers the soil. However, we recorded these species mostly during the August vegetation survey, which means these TPWs should start growing after soil is ploughed twice and puddled. Since 115 of 191 paddy weed species were not seen in upland fields (Kasahara, 1951), it is likely that these paddy weeds prefer a wet habitat. However, many studies reveal that surface water ponding suppresses paddy weeds, and consequently is efficient at controlling their germination and biomass (Arai et al., 1955; Bhagat et al., 1999; Becker and Johnson, 2001; Kent et al., 2001; Miyahara, 1968). Flood tolerance is extremely well developed in some species such as *M. vaginalis* var. *plataginea* (Kataoka et al., 1978; Bhagat et al., 1999), *E. crus-galli* (Kennedy et al., 1980), and *Scirpus juncoides* var. *ohwianus* (Pons and Schröder, 1986), all of which can germinate in anaerobic conditions, and which occurred with higher frequency even in unrestored parcels. Except for *M. vaginalis* var. *plataginea*, which was one of the most dominant species in the rice culture phase, the other species classified into Group A seem to have limited tolerance and hardly survive in constant ponding water. Although information on the germination requirements and favoured water depth of paddy weed species is patchy, most plant species require oxygen for germination (Baskin and Baskin, 2001). *Rotata indica* var. *uliginosa, L. procumbens, Dopatrium junceum, Cyperus difformis* (Shimizu, 1998), and *E. acicularis* var. *longiseta* (Nishida and Kasahara, 1978) all require oxygen for germination. *Ludwigia procumbens* and

L. sessiliflora grow in shallow water (<10 cm deep) (Mizusawa et al., 2000). If so, these species need aerobic conditions to germinate and grow. One reason why summer annual TPWs could appear under such unfavourable conditions may be the unlevelled soil surface. Unlike in large paddy fields on wide alluvial lowlands, a small rototiller and a hand rake were used in our monitored parcels to plough and puddle. The resultant uneven surface might allow the establishment of summer annual TPWs at microsites above the water. We saw small areas of paddy surface above the water during both the rice culture phase and the fallow phase, when many plants grew. The uneven levelling would have provided a suitable condition for increasing the number of TPWs even in the fallow phase without soil tillage until taller tussock perennials closed the canopy.

The water management regime also includes drainage in the non-rice-growing season. Drainage has a large influence on species occurrence. If water level were not controlled in the restored parcels, the continuous supply of spring water would lead to constant submergence to a depth of about 10 cm over the soil surface. In 1-yr fallow, antecedent cultural effects such as drainage after rice harvest and the delay of competitive species growth, as well as the lack of flooding in the fallow phase, leads to the rapid incidence of summer annual and perennial TPWs in both restored parcels and reference parcels.

Apart from soil tillage and water management, other factors might explain the difference in vegetation responses between fallow reference and restored parcels. First, mowing during fallow in restored parcels seems to slow down the disappearance of shorter TPWs, particularly in Group A. Taller perennials dominated more in 1-yr fallow reference parcels than in restored ones, and these species closed the canopy rapidly even during the summer survey. Since the previous treatments such as tillage and water control were completely the same, mowing management seems to have reduced the exclusive dominance of taller perennials and enhanced the persistence of short species.

The presence of rice may also be deeply associated with the persistence of paddy weed species during the early stages of fallow. Nakamoto et al. (2002) and Saito et al. (1974) experimented with the establishment of a paddy weed community in a field where soil was prepared (puddled and levelled) and water was controlled (constant submergence in the rice-growing season), but rice was not transplanted, which is identical to our treatment in the restored parcels without rice culture. Both studies confirmed that even such intensive management failed to maintain abundant paddy weeds in the long run owing to an increase in perennials. Nakamoto et al. (2002) gave the reason as the lack of dense coverage of rice throughout the summer. Correspondingly, in the present study, perennials were more dominant in the first year of fallow in the restored parcel without rice culture, whereas numbers of TPWs, particularly those in Group A, were less in restored and reference parcels than in 1-yr fallow.

4.2. Evaluation of modified conventional cultivation treatment

Our results show that we succeeded in restoring a typical paddy weed community. As discussed above, our success is strongly due to the rice culture that provides a preferable habitat for TPWs. However, some species classified into Group C did not occur in restored parcels. One species, *Spirodela polyrhiza*, propagates mainly by vegetative dormant organs called turions (overwintering buds) rather than by seeds (Numata and Yoshizawa, 1979). Hence, it could not survive the more than 10-year abandonment, and thus could not regenerate. This implies that unless dormant propagules are stored in good conditions, the restoration of some species might fail. For the other species in Group C, further study is required.

One of the most important considerations in ecological restoration is the pace of floristic change (Bradshaw, 1988). Although we did not monitor vegetation during the first year of reintroduced rice culture in our restored paddy field, the rate of restoration of the TPW community was rapid. Furthermore, the fact that the TPW community recovered equally well after 2-year break in cultivation. This might be attributable to robustness of reproduction mechanisms and sensitivity to control by soil tillage and water control, as discussed above. In addition, the environmental conditions of our restored paddy fields might have been advantageous to rapid recovery. The study area receives a stable and moderate water supply, and is protected from heavy soil erosion or deposition by flooding. Hence, the site has not experienced a severe natural disturbance causing complete destruction of the species pool, particularly the soil seed bank, which might be the most important source for recovery of paddy weeds (Koshimizu et al., 1997; Hioki et al., 2001). The relatively stable site conditions also may prohibit a resilient or alternative state (Kleijn, 2003; Suding et al., 2004) and may alter the species composition of recovered vegetation.

The chronosequential response of vegetation during fallow in our restored paddy fields was largely the same as in the reference parcels, and in previous studies (Matsumura et al., 1988; Comín et al., 2001). One-year fallow produces the highest abundance of paddy weed species in a transient stage influenced by antecedent cultivation effects such as drainage after rice harvest and delay of competitive species incidence. This idea suggests that both the rice culture phase and 1-yr fallow create a suitable habitat for paddy weed species.

Although it is likely that continuing high rates of change of vegetation will occur over many years, few TPWs were actually seen in 3-yr fallow and in older paddy fields in a previous study (Shimoda, 1996). This evidence indicates that to maintain paddy weed species in the emergent flora, it is appropriate to create 1-year fallow conditions; that is, to cultivate every other year. However, modifications to management practices after rice harvest and in 1-yr fallow (e.g. not tilling and introducing mowing, respectively) must be considered when the management of alternate-year rice culture is generalized. Since tilling after rice harvest might both reduce perennial TPWs and enhance winter annuals, it has been shown in this study that tilling can enhance as well as inhibit the growth of paddy weed species. Mowing should be used to inhibit competitive taller species in order to encourage other TPWs such as short summer annuals.

5. Conclusion

We restored a typical paddy weed community by reintroducing rice culture in abandoned paddy fields. This practice might be appropriate in fields located in small valley bottoms where surface water is present and natural disturbance is low. Alternate-year rice culture will achieve labour and budget efficiencies, while maintaining the diversity of paddy weed species. To enlarge restoration sites, rotating rice culture within a 2-year cycle should be considered. Mowing under fallow would further encourage paddy weed species such as short summer annuals by inhibiting the growth of competitive taller species. Even when soil was prepared (puddled and levelled) and water controlled (constant submergence in the rice growing season), restoration was less successful without transplanting rice because of the lesser persistence of paddy weed species during the early stages of fallow.

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Table 1 Frequencies and ecological properties of 54 species classified as either typical paddy weeds (TPWs) or species that were dominant in at least 2 parcel–year units.

		Reference parcels				Restored parcels with rice culture				Restored parcel without rice culture					Unrestored parcels		
	Life-form	Rice culture	Fallow			Rice culture	Fallow			Fallow					(Mowing treatment)		
			1-yr	2-yr	3-yr		1-yr	2-yr	3-yr	1-yr	2-yr	3-yr	4-yr	5-yr	1-yr	4-yr	7-yr
Species		*n* = 10	*n* = 6	*n* = 6	*n* = 6	*n* = 6	*n* = 3	*n* = 3	*n* = 1	*n* = 1	*n* = 1	*n* = 1	*n* = 1	*n* = 1	*n* = 5	*n* = 3	*n* = 5
Typical paddy weeds (TPWs)																	
Group A																	
Limnophila sessiliflora Blume	P	3/–				5/–	2/–	2/–									
Rotala indica (Willd.) Koehne var. *uliginosa* (Miq.) Koehne	SA	2/–				3/–	2/–										
Cyperus difformis L.	SA	2/–	1/–	1/–			1/–										
Ranunculus sceleratus L.	WA	4/–				2/–	1/–										
Lemna aoukikusa Beppu et Murata	SA	5/1				1/–											
Lapsana apogonoides Maxim.	WA	2/–				1/–											
Beckmannia syzigachne (Steud.) Fern.	WA	3/2	6/1	4/–	2/–	5/–	1/–	1/–		1/2							
Alopecurus aequalis Sobol. var. *amulensis* (Kom.) Ohwi	WA	9/4	1/1	1/–	1/–	6/2	3/2	1/–		+		+			1/–	1/–	
Sagittaria trifolia L.	P	4/–	6/3	3/1	3/–	4/1	2/–								1/–		
Eleocharis acicularis (L.) Roem. et Schult. var. *longiseta* Svenson	P	2/1	2/–	2/–	1/–	2/–	2/–	2/3							1/–		
Callitriche verna L. emend Kutzing	P	5/1	2/–	1/–		5/–	3/1	2/–							2/–		
Eleocharis congesta D.Don var. *japonica* (Miq.) T.Koyama	SA	1/–	2/–	2/–	1/–		1/3			+							2/–
Monochoria vaginalis Presl. var. *plantaginea* Solms-Laub.	SA	8/4	4/2	2/–	1/–	6/2	3/2	2/–		+	+				3/1	1/–	2/–
Lindernia procumbens (Krock) Barbas	SA	5/–	4/2	3/–	1/–	4/–	3/1			+					2/–		2/–
Group B																	
Isoetes japonica A.Braun	P	2/–	2/–	2/–	2/–	3/–	3/2	3/1	+		+						
Glyceria acutiflora Torrey	P	6/2	6/2	6/2	3/1	4/–	3/3	3/2	+	1/3	1/2	+	+	+	2/–	1/–	2/–
Murdannia keisak (Hassk.) Hand.-Mazz.	SA	6/1	6/4	6/–	4/–	6/–	3/1	3/1	+	+	+	+			5/1	3/–	5/2
Echinochloa crus-galli (L.) P.Beauv.	SA	2/–	6/2	4/1	3/–	2/1	3/1	3/–	1/1	+	+	+			2/–	2/–	4/1
Scirpus juncoides Roxb. var. *ohwianus* T.Koyama	P	1/–	6/1	5/–	3/–	2/–	3/1	1/–	+	+	+	+	1/1		4/–		1/–
Ludwigia epilobioides Maxim.	SA	8/–	6/3	6/1	3/–	6/–	3/–	3/–	+	+	+				5/–	2/–	5/–

Table 1 Frequencies and ecological properties of 54 species classified as either typical paddy weeds (TPWs) or species that were dominant in at least 2 parcel–year units.

		Reference parcels				Restored parcels with rice culture				Restored parcel without rice culture					Unrestored parcels (Mowing treatment)		
		Rice culture	Fallow			Rice culture	Fallow			Fallow							
	Life-form		1-yr	2-yr	3-yr		1-yr	2-yr	3-yr	1-yr	2-yr	3-yr	4-yr	5-yr	1-yr	4-yr	7-yr
Species		*n* = 10	*n* = 6	*n* = 6	*n* = 6	*n* = 6	*n* = 3	*n* = 3	*n* = 1	*n* = 1	*n* = 1	*n* = 1	*n* = 1	*n* = 1	*n* = 5	*n* = 3	*n* = 5
Group C																	
Tillaea aquatica L.	SA	1/–	1/–														
Spirodela polyrhiza (L.) Schleid.	SA	4/2															
Dopatrium junceum (Roxb.) Buch.-Ham. ex Benth.	SA	1/–															
Tillaea aquatica L.	SA	1/–	2/–													1/–	1/–
Other dominant species except TPWs																	
Species more frequently dominant in 1-yr fallow																	
Persicaria nipponensis (Makino) H.Gross.	SA		6/4	6/1	6/–	2/–	3/–	3/–	+	+	+	+	+		3/–	2/–	5/–
Juncus papillosus Franch. et Sav.	P		2/3	1/–			2/–										
Sarothra laxa (Blume) Y.Kimura	SA	1/–	5/2	3/–	1/–	1/–	3/–	3/–	+	+		+				1/–	5/–
Cardamine flexuosa With.	WA	8/1	4/1	3/–		4/1	3/–	3/–	+	+		+		+		3/–	2/–
Stellaria alsine Grimm. var. *undulata* (Thunb.) Ohwi	WA	7/1	5/1	4/–	1/–	3/–	1/–	3/–									2/–
Cyperus globosus All.	SA	1/–	5/–	4/1	3/1	1/–	3/3	1/–	+		+					1/–	1/–
Cyperus orthostachyus Franch. et Sav.	SA		6/1	5/–	3/–		3/3	3/1	+	+	+	+			2/–		2/–
Digitaria ciliaris (Retz.) Koeler	SA		3/–			1/–	2/1	2/1	+							1/–	4/–
Species more frequently dominant in 2- and 3-yr fallow																	
Juncus leschenaultii Gay	P	2/–	6/3	6/4	4/4	3/1	3/–	3/2	+	+	+	+	+			2/–	4/–
Epilobium pyrricholophum Franch. et Sav.	P		5/–	5/2	5/2		2/–	2/–			+	+	+	+	3/–	1/–	5/–
Carex maximowiczii Miq.	P	1/–	5/–	6/1	6/2	1/–		3/3	1/2	+	+	+	+	+	3/–	3/–	2/–
Carex dickinsii Franch. et Sav.	P	1/–	2/–	3/1	3/2		1/–	1/–	+						2/–	1/–	3/–
Mosla dianthera (Buch.-Ham. ex Roxb.) Maxim.	SA		4/–	4/1	3/1												
Isachne globosa (Thunb.) O.Kuntze	P	1/–	3/–	2/1	2/1	2/–	1/–	2/–			+	+	+	1/1	3/1	3/–	4/–
Lycopus ramosissimus (Makino) Makino var. *japonicus* (Kudo) Kitam.	P		3/–	1/–	1/–	4/–	3/1	3/4	1/3	+	+	+	+		1/–	2/–	3/2
Eleocharis wichurae Boecklr.	P					1/–	3/1	3/2	1/2			+			1/–	1/–	2/–

Table 1 Frequencies and ecological properties of 54 species classified as either typical paddy weeds (TPWs) or species that were dominant in at least 2 parcel–year units.

		Reference parcels				Restored parcels with rice culture				Restored parcel without rice culture					Unrestored parcels (Mowing treatment)		
	Life-form	Rice culture	Fallow			Rice culture	Fallow			Fallow							
			1-yr	2-yr	3-yr		1-yr	2-yr	3-yr	1-yr	2-yr	3-yr	4-yr	5-yr	1-yr	4-yr	7-yr
Species		*n* = 10	*n* = 6	*n* = 6	*n* = 6	*n* = 6	*n* = 3	*n* = 3	*n* = 1	*n* = 1	*n* = 1	*n* = 1	*n* = 1	*n* = 1	*n* = 5	*n* = 3	*n* = 5
Species more frequently dominant in unrestored parcels																	
Carex thunbergii Steud.	P				1/–			1/–							3/1	1/–	3/3
Houttuynia cordata Thunb.	P	1/–							+						3/2	2/1	4/2
Lysimachia fortunei Maxim.	P									+					4/2	2/1	4/1
Equisetum arvense L.	P	3/–	2/–	3/–	2/–	2/–	1/–	2/–	+	+	+	+	+	+	5/5	3/3	5/2
Typha latifolia L.	P			3/–	2/–	1/–	2/–	2/–	+	+	+	+	+	+	4/3	2/–	1/–
Phragmites australis (Cav.) Trin. ex Steud.	P	2/–	5/–	6/2	6/4	3/–	1/–	1/–		+	1/1	1/2	1/3	1/4	5/5	3/4	5/4
Other dominant species																	
Oenanthe javanica (Bl.) DC.	P	6/1	4/1	4/–	4/–	3/–	2/–	3/–	+	+	+	+	+	+	4/3	3/–	5/1
Cyperus brevifolius (Rottb.) Hassk. var. *leiolepis* (Franch. et Sav.) T.Koyama	P	1/–	3/–	4/1			2/–	1/1			+				2/–	1/–	5/2
Solidago altissima L.	P		6/2	6/2	6/–		2/–	2/–	+	+		+	+	+	2/–	2/–	3/–
Arthraxon hispidus (Thunb.) Makino	SA		5/1	6/1	6/–		3/–	2/1	+		+	+			2/1	2/–	4/–
Bidens frondosa L.	SA		5/1	5/–	4/–	3/–	3/2	3/–	+	+	+	+	+	+	5/2	3/2	5/1
Juncus effusus L. var. *decipiens* Buchen.	P	1/–	3/–	4/1	3/2	2/–	3/2	3/4	+	1/2	1/3	1/3	1/2	1/2	5/1	3/–	3/–
Persicaria thunbergii (Siebold et Zucc.) H.Gross	SA	3/–	6/2	6/1	5/2	4/–	3/1	3/2	+	+	1/1	1/1	+	1/1	5/3	3/3	5/2
Leersia sayanuka Ohwi	P		6/3	5/4	5/5	3/1	3/–	2/–	+	1/2	1/3	1/4	1/4	1/3	4/5	3/1	5/5

Nomenclature follows Flora Kanagawa Association (2001). Numbers indicate the numbers of parcel–year units in which each species was recorded / maximum dominance score among units. SA, summer annual; WA, winter annual; P, perennial herb; no biennial or woody species appeared among typical paddy weeds or dominated in at least 2 parcel–year units.

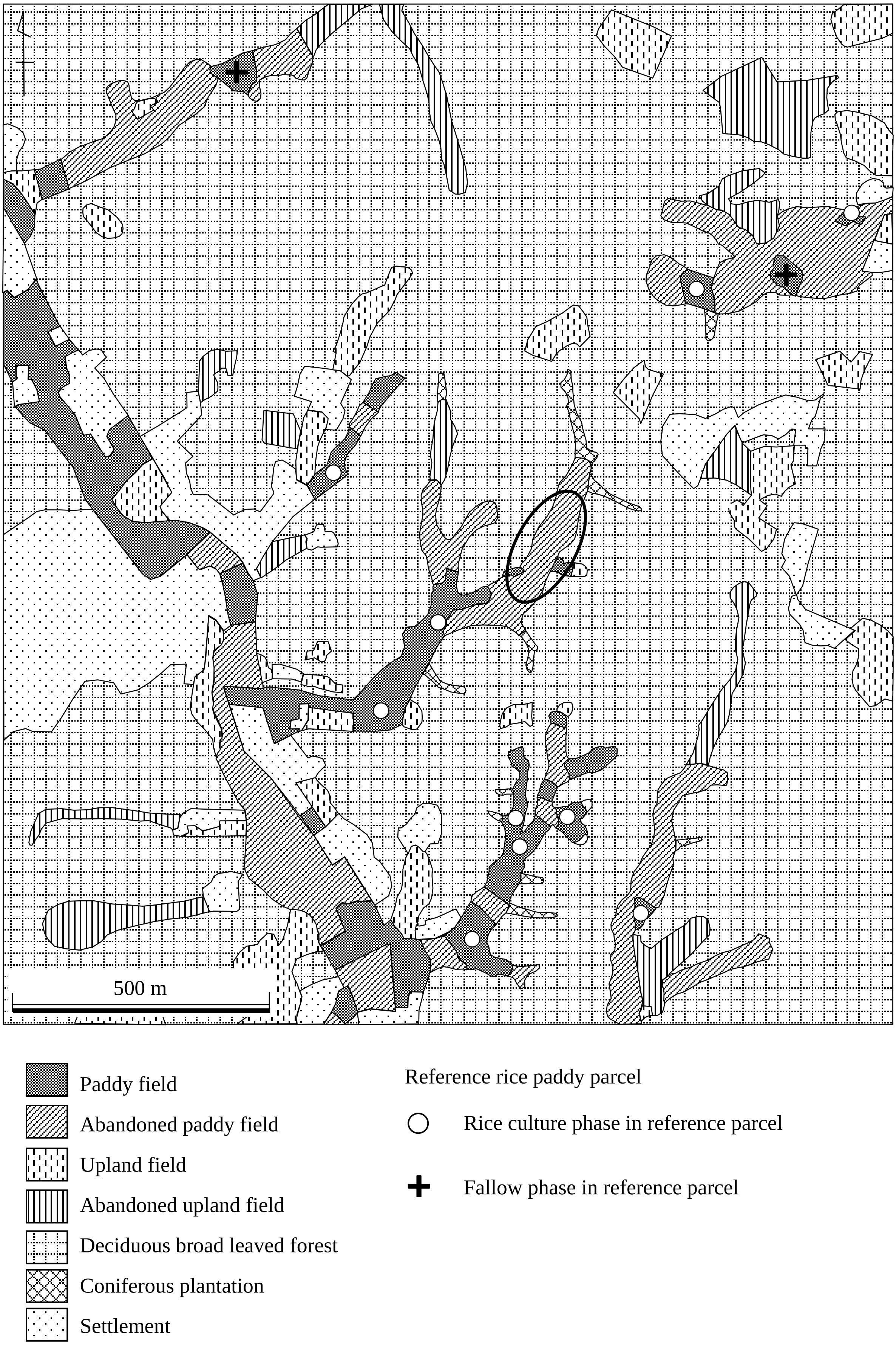

Fig. 1. Land use map of the study area in 1995, before restoration had been performed. Restoration started in the late summer of 1996 in the encircled headwater area.

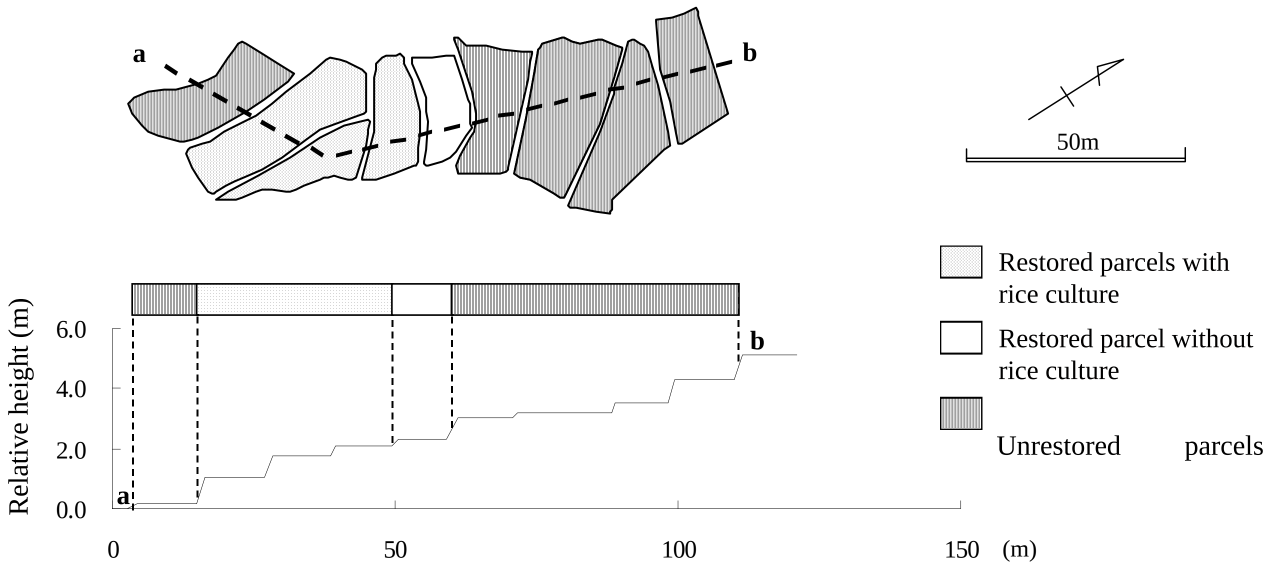

Fig. 2. Horizontal and vertical distribution of restored parcels and unrestored parcels with mowing treatment.

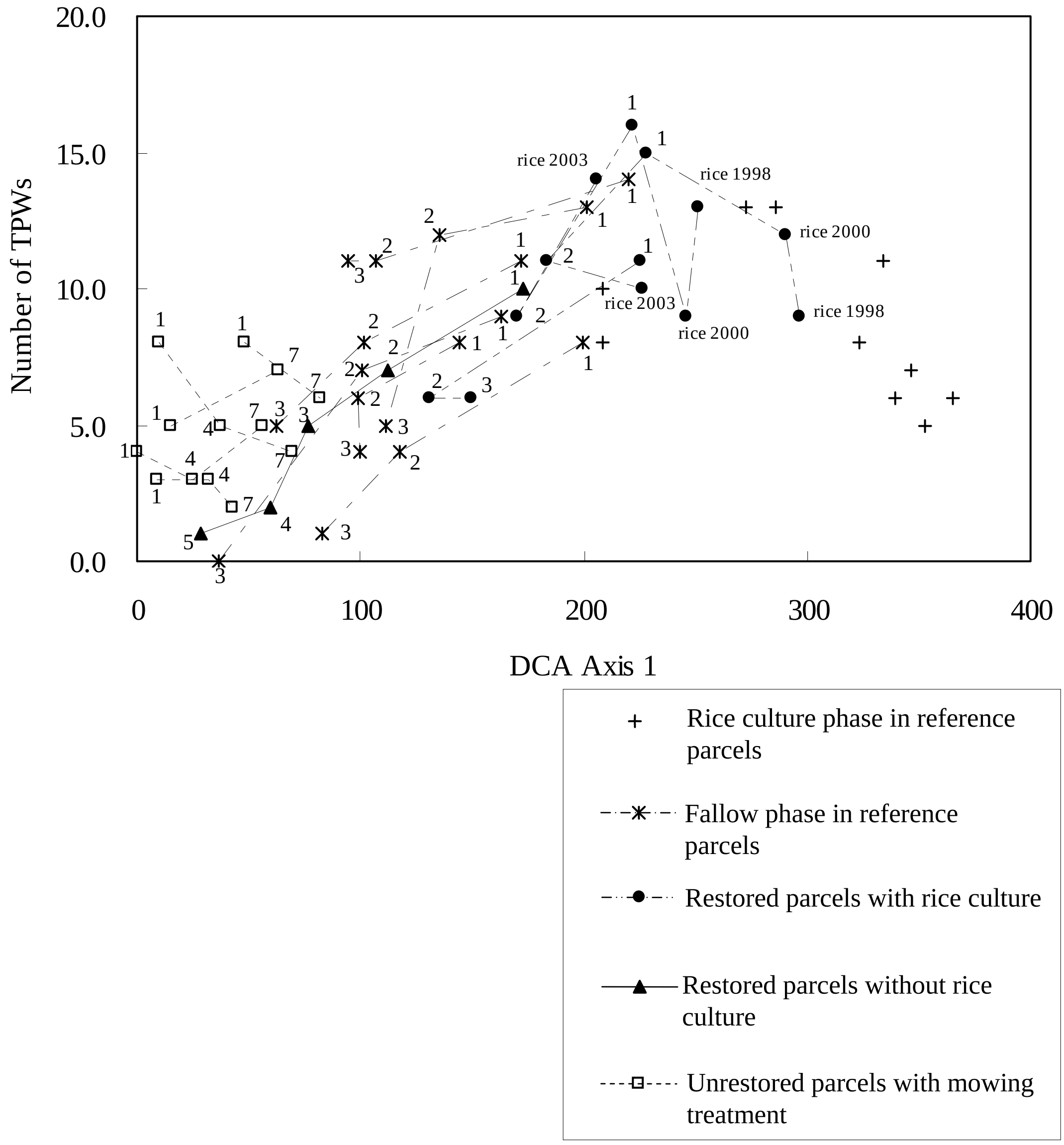

Fig. 3 Relationship between the scores of DCA axis 1 and the number of typical paddy weeds (TPWs) in each parcel–year unit. Numbers next to plots show numbers of years since lapse of management, i.e. numbers against restored parcel with/without rice culture indicate years of fallow/neglect; numbers in unrestored parcels indicate years of mowing treatment. Rice 1998, rice 2000 and rice 2003 indicate rice culture in 1998, 2000, and 2003, respectively. Dots connected by lines indicate same parcels in different years.

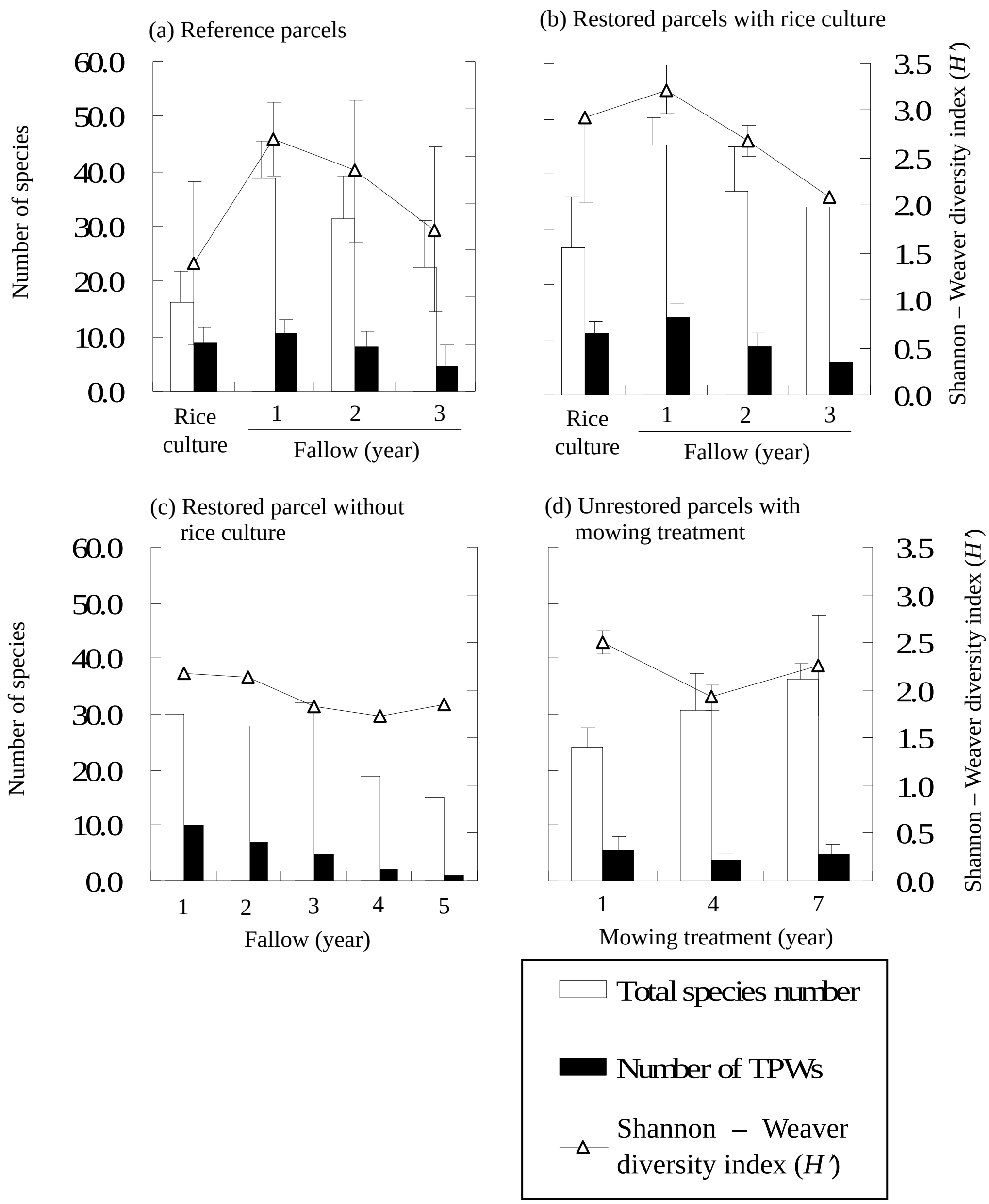

Fig. 4 Mean and S.D. of total numbers of species, numbers of typical paddy weeds (TPWs), and Shannon–Weaver diversity index (H') in each monitoring group.

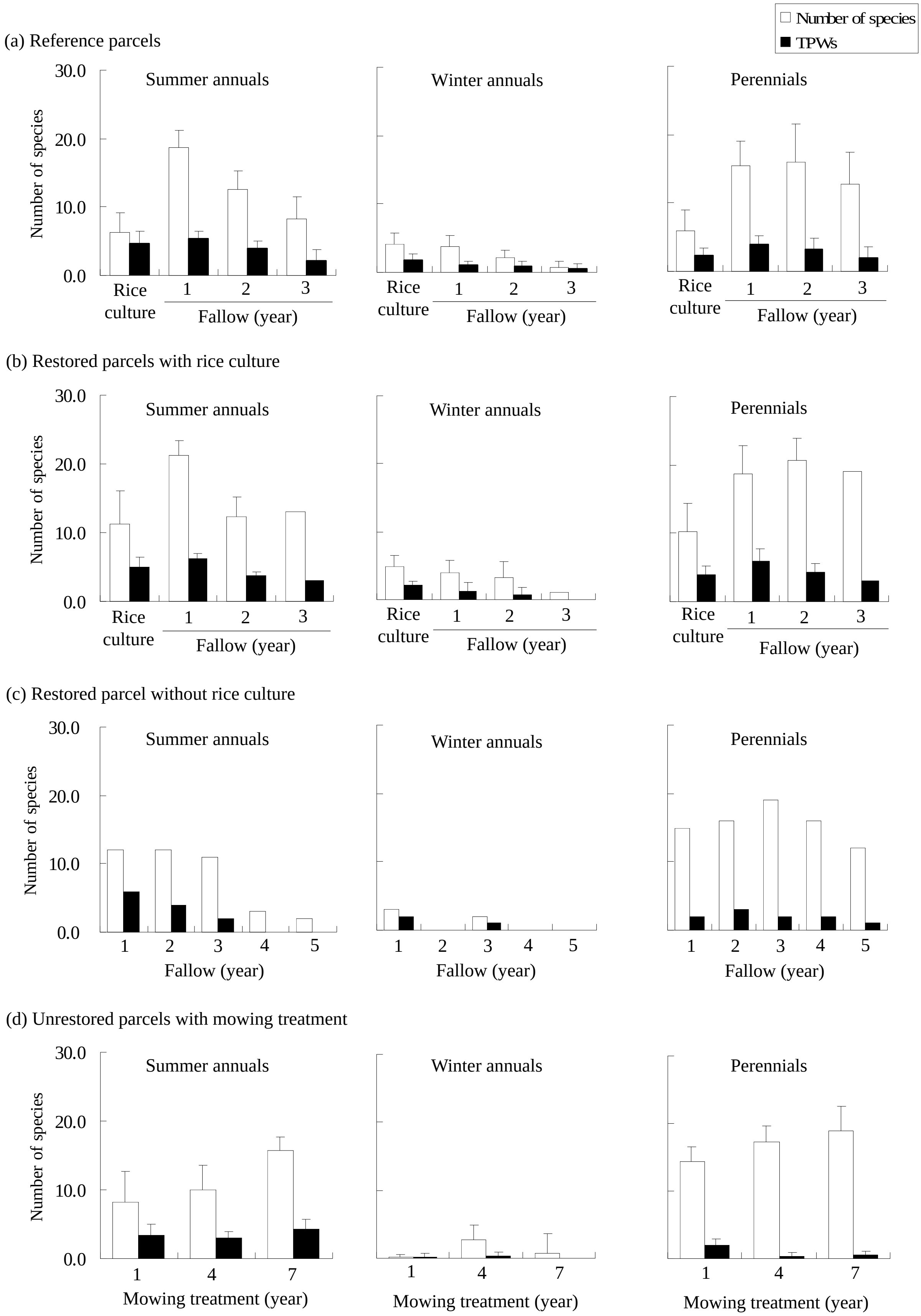

Fig. 5 Mean and S.D. of numbers of species and of typical paddy weeds (TPWs) of each life-form in each monitoring group.

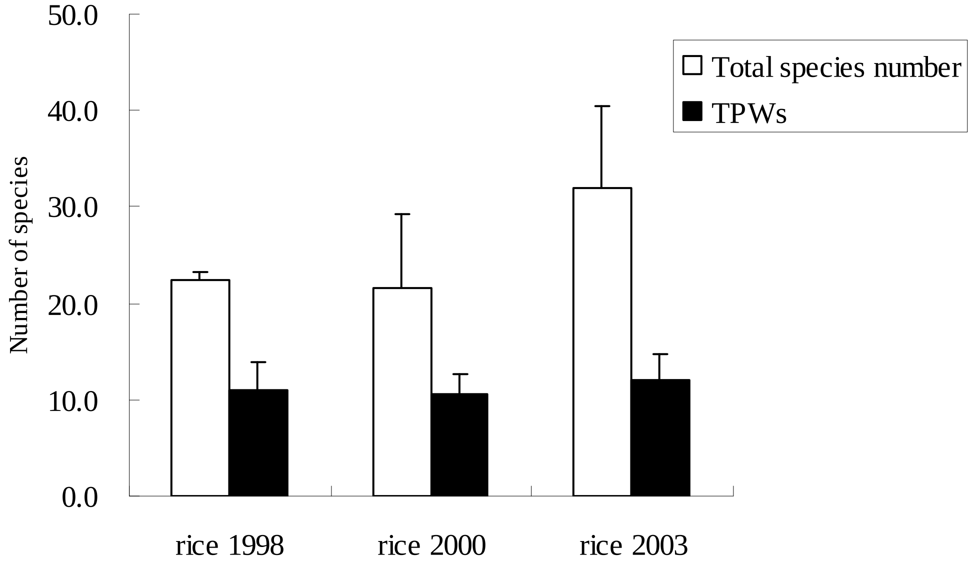

Fig. 6 Mean and S.D. of total numbers of species and numbers of typical paddy weeds (TPWs). Rice 1998, rice 2000 and rice 2003 indicate rice culture in 1998, 2000, and 2003, respectively.