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Integrated biodiversity management in paddy fields: shift of paradigm from IPM toward IBM

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Abstract

The insect fauna in paddy fields is composed of resident, migratory and aquatic species each corresponding to the continuous cropping of rice in the same field, harvesting rice as an annual crop, and originating from still water habitats in wetlands. Although IPM is becoming popular in the control of rice pests, those 'minor' insects and aquatic insects that have no direct economic impact on rice production have received little attention. Consequently, some of them are in danger of extinction requiring conservation. A new concept, 'Integrated biodiversity management (IBM)', is proposed under which IPM and conservation are reconciled and made compatible with each other. As an operational concept in agroecology, premises for implementing IBM are suggested.

Introduction

The beginning of rice cultivation dates back 3000 years in Japan. In Asia, 80% of the rice land is irrigated under monsoon climate. The paddy agroecosystem, a man-modified environment, is an integrated water-dependent system, which may include humans, rice plant, animals and plants, and crops other than rice (Kiritani 1979). Flooding and draining during rice cultivation provides similar condition to temporal water pools with emergent plants in a shallow depth of still water.

Paddy fields were originally wetlands and artificially constructed devices for rice production. Nowadays very few of the natural wetlands remain as they were, many aquatic organism life cycles, therefore, depends partly or fully on paddy fields. Out of 14 species of frogs native to mainland Japan, 9 species use paddy fields for oviposition (Hasegawa 1998). Likewise, 31 species of Odonata or 30% of the mainland species utilize paddy fields for oviposition (Ueda 1998). Many of the aquatic hemipteran and coleopteran insects including the giant water bug, *Lethocerus deyrollei*, water scorpions, *Laccotrephes japonensis* and *Ranatra chinensis*, dytiscid beetles, hydrophilid beetles, and fireflies are known to reproduce in paddy fields.

In Japan, the endemic damage caused by the rice borers, *Chilo suppressalis* and *Scirpophaga incertulas*, and the sudden occurrence of epidemics of the brown planthopper, *Nilaparvata lugens*, were the major causes of loss in rice yield during the pre-World War II period (Kiritani 1979). Control of planthoppers was practiced by dropping whale oil onto the surface of irrigation water for 250 years before the advent of BHC and parathion. Control of rice borers by various cultural practices including conservation of egg parasites and attraction by light traps was commonly used 100 years ago (Kiritani & Nakasuji 1977).

Meanwhile, studies on the arthropod fauna in paddy fields had not been conducted until Kobayashi's work (1961). He and his colleagues investigated the arthropod fauna inhabiting aerial parts of paddy fields in 1954 and 1955 in the Tokushima Prefecture, Shikoku. The survey recorded over 450 species belonging to 134 families of 13 orders (Kobayashi 1961). However, attention has not been given to the aquatic insects inhabiting paddy fields until Ban and Kiritani (1980) who first conducted a quantitative study of the aquatic fauna in a paddy field in Japan (Hidaka 1998).

The widespread use of BHC for controlling rice insect pests, including *C. supressalis* during the 1950–60s induced the build-up of the green rice leafhopper, *Nephotettix cincticeps*, as a result of the disruption of natural enemies (e.g., spiders). Also it resulted in the development of resistance to BHC in *C. suppressalis* and BHC residues caused contamination of the environment including food and human milk. Concurrently drastic changes in the faunal composition of larval parasitoids of *C. suppressalis* were observed everywhere in Japan (Kiritani 1988). The three predominant species of solitary parasitoids were replaced by a braconid, *Apanteles chilonis*, around 1963–4 when all of the paddy fields in the Aomori Prefecture, northern Japan, were treated with pesticides at least once during the cropping season (Toki *et al*. 1974). Also, Naraoka (1965) (cited from Ueda 1998) observed three species of *Sympetrum* dragonflies that disappeared almost completely in the plains of Aomori Prefecture during 1962–4.

Increased rice production in Asia as well as Japan has been achieved either by applying environment-adaptive and/or environment-formative technologies (Tanaka 1995). The former involves agronomic technologies and the latter refers to the development of infrastructures for rice cultivation. Conversion of ill-drained wet paddy fields into well-drained dry ones has been promoted by the Japanese Government to raise both land and labor productivity. Traditional earth ditches have been replaced by U-shaped concrete ditches and distributive canals have been separated from drainage canals which effectively reduced the variety of habitats for fishes and limited their movement throughout a paddy water system (Fujioka & Lane 1997). As a result, two insect species, *L. deyrollei* (Hemiptera: Lethocerinae), and *Cybister tripunctqatus orientalis* (Coleoptera: Ditiscidae), five bird species, one species of fish and one amphibian, and three plant species are listed on the red data list book as endangered species inhabiting paddy fields (Hidaka 1998).

Reviewing what has happened in paddy fields during the past half century, we realized that the status of most of the native economic insect pests and diseases such as *C. suppressalis, S. incertulas, N cincticeps*, the small brown planthopper, *Laodelphax striatellus,* and the viral diseases RSLV and RDV, vectored by the latter two species, have become less important. They have been replaced by such long-distance migrants from mainland China, as the brown planthopper, *N. lugens*, the whitebacked rice planthopper, *Sogatella furcifera*, and the rice leaffolder, *Cnaphalocrocis medinalis*.

Similar changes were also observed in the aquatic fauna of paddy fields. Alien invasive species such as the apple snail, *Pomacea canaliculata* (originally imported for aquaculture in 1981 from Taiwan), *Rana catesbeiana* (imported in 1917 from New Orleans), the red crawfish, *Procambarus clarkii* (imported in 1930 from New Orleans for prey of *R. catesbeiana* and *L. oryzophihlus* (invading in 1976 probably from California) have become common in paddy fields. Many native species have decreased in abundance mainly due to the side effect of pesticide application and the construction of concrete ditches as mentioned earlier.

There is increasing consensus among farmers, scientists, administrators and the general public that we somehow have to change the way we look at and practice agriculture. Agriculture is at the interface of human societies and natural processes, and therefore, important as it is, cannot be defined only in terms of economic efficiency in food production (e.g. Giampietro 1997).

Paddy agroecosystem and the diversity of arthropod fauna

Smith (1976) defined the agroecosystem as ‘A unit composed of the total complex of organisms in a crop area together with the overall conditioning environment and as further modified by the various agricultural, industrial, recreational, and social activities of man’. The paddy agroecosystem includes many kinds of living organisms among which birds, fish, reptiles, amphibia, arthropods and plants are prominent. The requirements of each group of organism are illustrated by a set of habitats (Figure 1). Many species of arthropods with diverse types of life cycles occupy different habitats within the paddy agroecosystem. *Sympetrum* dragonflies emerge from paddy fields and migrate to secondary forests or coppices where they remain until sexual maturation. Then, they come back to paddy fields to deposit their eggs that hatch in the following spring when irrigation water becomes available. Newly emerged adults of the water scorpion, *Ranatra chinensis,* immigrate from paddy fields to irrigation ponds and overwinter there in the bottom mud before oviposition takes place in paddy fields next spring (Hibi *et al*. 1998). Migratory planthoppers, *N. lugens* and *S. furcifera* cannot overwinter in Japan and the field populations are annually replenished by a long

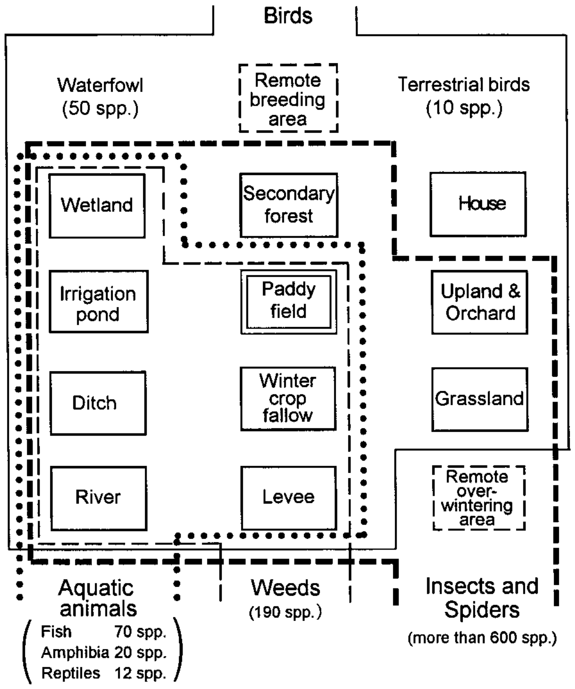

Figure 1. Habitat sets in a paddy agroecosystem. Requirements of each group of organisms are shown by the sets of habitats enclosed by lines.

distance immigration from the tropical endemic habitats (Kisimoto 1971).

The biodiversity of the paddy agroecosystem, therefore, depends not only on the paddy fields themselves, but also on water channels, irrigation ponds, levees, surrounding fallow fields, neighboring farmlands, secondary forests, wetlands, rivers and remote hibernating areas. The paddy agroecosystem is not only an open system, but also it continues to exist by intermittent human interference with nature in the form of farming

IPM perspective

Insects and spiders in paddy agroecosystems, can be classified into three main groups according to their ecological requirements. They are: (1) resident species adapted to the continuous cropping of rice in the same farm field; (2) migratory species adapted to exploit rice as an annual crop; and (3) aquatic species originated from still water habitats in wetlands.

From an IPM perspective, those species belonging to the first two groups are referred to as pests and beneficial arthropods, with the third, minor or non-target species, being regarded in terms of biodiversity conservation, but most commonly with neglectful indifference. Consequently less attention has been paid to elements of the aquatic fauna that is originally derived from wetlands and has no direct relation with rice yields. As a result some species of aquatic insects are in danger of extinction and require conservation.

Kiritani (1975) stated that the central issue for agriculture in the future would be how to manage and optimize biodiversity, stability and productivity within an agroecosystem. *N. cincticeps* provided 80% of the diet of a lycosid spider, *Pandosa pseudoannulata,* in paddy fields (Kiritani *et al*. 1972), however, it was not able to develop into an adult when its nymphs were fed only with *N. cincticeps.* When lycosid females were allowed to prey upon mixed prey consisting of five species collected from paddy fields, they laid many more eggs than those that preyed only upon *N. cincticeps* (Suzuki & Kiritani 1974)

In the past, most studies on paddy agroecosystems have focused on productivity and its stability in terms of rice yields. Concerning pest control in paddy fields, IPM has been implemented with various degrees of success (Kiritani 1977; 1979; Andow & Kiritani 1983; Kiritani & Naba 1994). Southwood and Way (1970) argued that the aims of pest management should be to determine what element of diversity need to be retained or added and what need to be eliminated to enhance the management of the pests' population. Currently however, many IPM programs have a primary objective of maximizing economic profit on the farm (Wearing 1988; Andow & Rosset 1990).

Implied in the concept of IPM is the notion that residual pest populations are essential requisites for natural enemy conservation (Kiritani 1973; Kogan & Lattin 1993). To avoid confusion in the usage of words, I refer to pest, beneficial and neutral insects as comparable with the words of herbivore, carnivore and scavenger that are to be used irrespective of the population density. The *status* of a pest species, therefore, could be changed by IPM into minor one as potential food for generalist predators. Those species such as chironomids and collembola, for example, that are neither pests nor natural enemies, and yet are useful as alternative food of generalist predators when pest prey are few can be referred to as minor components of the community. Obviously, this status will change as more is learned about the role of these species in community dynamics.

It is essential to consider the role of the species that have been mostly ignored as important elements in a rice ecosystem (Kobayashi 1961; Suzuki & Kiritani 1974; Une *et al*. 1989; Hidaka 1994; Way & Heong 1994; Settle *et al*. 1996).

Immigration of spiders to paddy fields occurs after the appearance of chironomids. When chironomids are abundant, the density of spiders increases correspondingly and they act as biological control agents against planthoppers and leafhoppers (Hidaka 1990). Kobayashi (1961) reported that early insecticide applications to control the first generation of rice stem borers often brings about resurgence of plant- and leafhoppers 1 month later, because treatments simultaneously kill spiders and chironomids that are important prey of the spiders. In the tropics, prevention of outbreaks of plant- and leafhoppers depends on the protection of early-acting natural enemies by avoiding early insecticide spraying (Way & Heong 1994; Settle *et al*. 1996). Chironomid larvae in mud are also important food resource for fish particularly for bottom-feeders (Katano *et al*. 1998) and for odonate larvae (Matsura *et al*. 1998).

Hidaka (1994) observed that two species of collembola, *Akaboshia matsudoensis* and *Homidia* sp. reached very high density in the late season of rice cultivation where insecticide applications were less frequent. Experimentally they are mycophagous and feed on spores on hyphae of blast, *Pyricularia oryzae,* and sheath blight, *Rhizoctonia solani*. Another example is that the larvae of the firefly, *Luciola lateralis*, and of dragonflies act as efficient predators of juveniles of *P. canaliculata* (Kondo & Tanaka 1989; Suzuki *et al*. 1999).

Rice katydids, including *Conocephalus maculatus* and *C. chinensis* have been regarded as pests of rice and control with organophosphate and/or organochlorinated insecticides has been recommended in Japan (Kiritani 1973). Rothschild (1971) demonstrated that *Conocephalus longipennis* is a generalist predator in the early growing season of rice, but as the plants mature, feeding takes place on flowers and young grains in West Malaysia. *Conocephalus* feeds on egg masses of various insects, most importantly *S. incertulas, C. suppressalis* and *Leptocorisa oratorius* (Hemiptera) (Rothschild 1971; Nozato & Kiritani 1976; Manley 1985)

Last but not least paddy fields and levees are likely to act as refuges for various kinds of natural enemies of arthropod pests that occur in upland crops grown close to paddy fields.

Of the hydrophilous spiders common in paddy fields, a dwarf spider, *Ummeliata insecticeps*, behaved like a specific predator attacking a newly hatched colony of larvae of *Spodoptera litura* in taro fields. These spiders disperse everywhere by ballooning in late May from levees of paddy fields. Those individuals established in uplands remain there until the end of the rainy season or early July when their habitats become too dry for them to stay. During this period, life table studies showed that first instar larvae of *S. litura* suffered 97–98% mortality due to dwarf spiders (Nakasuji *et al*. 1973).

Another example is the anthocorid bugs, *Orius* spp. that are effective natural enemies of *Thrips palmi*, a serious invasive pest of eggplants. *O. nagaii* and *O. sauteri* occur on rice and on white clover grown on levees, respectively, before invading eggplant fields in early June and onward (Ohno & Takemoto 1997).

These examples are comparable to beetle banks in upland farms. Creating beetle banks in the centers of large fields recreates *in situ* all the benefits of hedgebank cover without planting and establishing a hedgerow. Beetle bank holds predatory insects over winter enabling a quicker colonization of the surrounding crop in spring and hence more rapid predation of pest insects such as aphids, thereby helping the farmer (Hill *et al*. 1995). Kogan and Lattin (1993) considered that the functional group most likely to benefit from an IPM approach to conservation probably is the predator complex. A diverse predator fauna, involving a broad spectrum of species, is likely to be more effective than relying on only a few exotic species often selected against a single pest species.

Proposed concept of Integrated Biodiversity Management (IBM)

I propose here a new concept: 'Integrated Biodiversity Management (IBM)' under which IPM and conservation are reconciled and made compatible with each other. The relationship between IPM, conservation and IBM is illustrated in Figure 2. IPM requires that densities of each pest species are kept below their

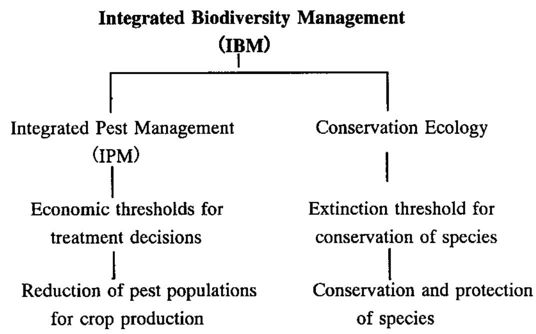

Figure 2. A scheme for IBM interfaced with IPM and conservation.

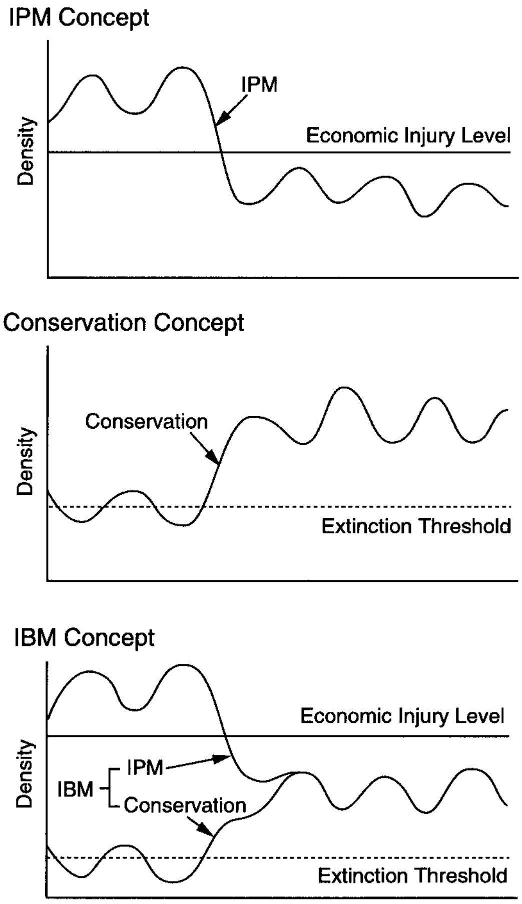

Figure 3. Illustration of the concepts of IPM, conservation and IBM.

Conservation aims at →

IPM aims at (decrease ↑ / increase ↓)	abundant	common	rare
pest	GRL	RSB	YRB
neutral	chironomids & collembola	*Sympetrum* spp.	fireflies
beneficial	micryphantids	lycosids	*T. biguttula**

GRl: *Nephotettix cincticeps*, RSB: *Chilo suppresalis*, YRB: *Scirpophaga incertulas*, *: *Telemuchua biguttula* (larval parasitoid of RSB & YRB). Shaded area refers to minor arthropods.

Figure 4. Target arthropods in IBM.

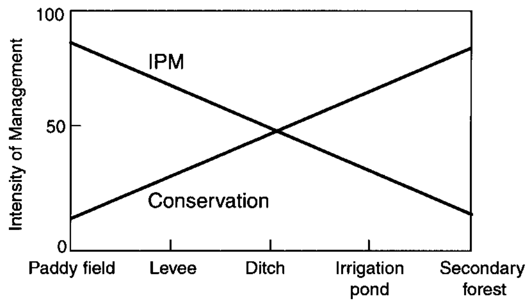

Figure 5. Difference in the intensity of management in accordance with habitats.

specific economic injury level (Figure 3 above). Those species targeted for conservation have to be managed so as to remain above a specific extinction threshold (Figure 3 middle) without, however, reaching their own economic injury levels if they are potential pests. Since some carnivorous aquatic arthropods, such as *L. deyrollei* and some large sized dytiscid beetles, were pests of fish culture when they were abundant, they also should be managed to keep their populations below defined economic injury levels (Figure 3 bottom). This is the concept of IBM.

Representative arthropod species in paddy fields were arranged in a two-dimensional table to show the relationship between IPM and conservation (Figure 4). Such relatively rare species as *S. incertulas* and some aquatic insects are the target for conservation. *S. incertulas* infested up to 130,000 ha in southern Japan during the period of 1945–50, but currently it hardly occurs in the Japanese mainland. Probably widespread use of BHC during that period resulted in the extinction of this monophagous borer. From the viewpoint of an economy oriented IPM, however, this does not matter, because *S. incertulas* was an important rice pest to be controlled.

Figure 3 illustrates the implementation of IBM on a time scale, although it is also possible to express IBM in terms of a spatial scale. The arthropods inhabiting the paddy agroecosystem do not entirely depend on paddy fields for the completion of their life cycles. The relative importance of IPM and conservation changes along a continuum away from the paddy field, through the levee, ditch, irrigation pond and coppice (Figure 5). Levees form small upland ecosystems. The narrow vegetation covered levees surrounding each field are important as a source of natural enemies such as spiders (Kawahara 1975; Way & Heong 1994). For some arthropods such as collembola and spiders, these. margins are an important habitat. Their populations in paddy fields rapidly recovers after irrigation and tillage, because they escape to the margin and readily reinvade the rice paddy (Kawahara 1976; Hidaka 1997).

The two lines cross at an arbitrary point just to illustrate the relative importance of different habitats in the implementation of IBM. Actually these lines may take concave or convex slopes crossing at a point most appropriate for a specific location as well as the target species concerned.

It is suggested that paddy fields located in a given locality should be managed spatio-temporally according to an IBM strategy, because arthropod fauna often differs greatly between the paddy fields located in hilly mountainous area and plain basins. We should be concerned not only with pest populations, but also with other non-target and minor insects as well. This is the reason why IBM is proposed.

Southwood and Way (1970) defined the characteristics of the agroecosystem in terms of the diversity of vegetation, the permanence of crops, the stability of the climate and the extent of the isolation of the agroecosystem from natural vegetation. The concept of IBM is not limited to the paddy agroecosystem, but also is applicable to all types of agricultural systems. Crops range from those that require intense IPM intervention with little consideration of species conservation to those, at the opposite end of the spectrum, that can achieve a high level of pest control as well as biodiversity through species conservation. Examples are greenhouse crops on one extreme (left end of Figure 5), and multiple crops grown in a complex home garden or back yard in the tropics (right end of Figure 5).

Discussion

Paddy fields as alternatives to wetland

Not all aspects of agriculture are harmful, for example, some woodland and hedgerow management practices enhance some insect species populations. Practically every technique, such as grazing, burning, control of predators will benefit some species and be detrimental to others. There is no inherently right or wrong way to manage an agroecosystem, the aptness of any method of management must be related to the objects of management for any particular site. Possessing clear objectives can make it easier to decide which management practices should be carried out (Samways 1994; Sutherland 1998).

Samways (1994) mentioned that the urgent emphasis today is for managed development, rather than destructive unplanned expansion. The dramatic loss of wetlands worldwide makes it essential to focus as much conservation research as possible upon them. Wetland research should give special attention to rare, localized and stenotopic species and their biotope requirement.

Rice culture in paddy fields was originally a sustainable production system. The alternation of aerobic and anaerobic conditions created by flooding and draining during rice cultivation permits efficient microbial activity in decomposing organic matters and breaking down pesticides residues. Standing water benefits rice by controlling weeds and by providing nourishment supply from irrigation water (Kiritani 1979). The land tenure system of paddy fields in Japan or Asia is more to maintaining the biodiversity of the paddy agroecosystem than that in U.S.A. Because some 80% of Japanese rice producers manage less than 2 ha of rice fields as compared with U.S.A. where around 60% of farmers own paddy fields of 40–200 ha (Kiritani & Naba 1994; Yoshino 1995). This makes a great contrast between Asia and the U.S.A. where the concept of agroecology was developed in response to the problems induced by crop monoculture over large areas (Altieri 1987)

Technology is often a two-edged sword. The successful control of the snail *Oncomelania hupensis nosophora*, an intermediate host of *Schistosomasis japonica* was achieved by canal modernization, including lining of the entire cross section with concrete to eradicate the habitat of the intermediate host. If all canals are made straight and lined, such simplification may bring about a decrease in harmful organisms including vector mosquitoes but it also has negative impacts on aquatic communities including a variety of useful organisms (Mogi 1992). For the conservation of crucian carps, loaches and catfishes, it is most effective to minimize the difference in the water surface level between paddy field and ditch. However, this procedure favors the invasion of *P. canaliculata* from the water channel to the paddy field. It should be noted that any technology is not a panacea. We should assess the efficacy of individual technologies within the context of specific site or locality characteristics.

Premises for IBM in paddy fields

Insect stability and diversity in agroecosystems has been one of the great issues in the IPM (Smith & van den Bosch 1967; Southwood & Way 1970; van Emden & Williams 1974), particularly in relation to the biological control of insect pests and conservation (Howarth 1991; Ehler 1991; Nafus 1993). There are two major sources of motivation to evaluate biodiversity in agroecosystem: nature conservation and biological control against agricultural pests (Duelli 1997).

To implement IBM, the following two premises should be considered:

1. It is necessary that a set of elemental habitats be available for completion of the life cycle of species to be conserved and that multiple sources of species supply be provided within their range of dispersal (Moriyama 1997).

   A set of habitats, including host plants (prey), shelter, hibernacula, mating place, etc., is essential to ensure the persistence of a species. For survival and conservation of aquatic insects, irrigation ponds, secondary forest (coppice) and ill-drained wetlands are necessary in addition to paddy fields (Figure 1). Abandoned ill-drained paddy fields that are common in mountainous areas are often good reservoirs for various aquatic insects as alternatives to wetlands.

   Since cleaning of an irrigation pond results in the complete destruction of the aquatic fauna, neighboring ponds that supply the newly cleaned pond with species of dragonflies should exist within a distance of 1 km (Moriyama 1997). Hibi *et al*. (1998) observed *R. chinensis* moved 1.4 km in overwintering dispersal from a paddy field to an irrigation pond. Newly emerged adults of *A. dyrollei* were able to disperse 2 km by a single flight during night away from a paddy field when it was drained. They migrated to various water systems including rivers before overwintering in coppices (Hidaka personal communication). These facts suggest that in designing IBM, multiple sets of habitats for species to be conserved should be present within the range of its activity to ensure the completion of its life cycle as well as the persistence of species populations in a given locality.
2. Adoption of strategies and tactics of IPM compatible with conservation should be recommended.

   (a) In order to enhance conservation of endangered species, prevention of alien species from invading paddy agroecosystem is very important. Invasive aquatic organisms are not only destructive to paddy biological community, but also often conflict with the conservation of endangered species by inducing additional chemical control applications (Moriyama 1997).

   (b) Special consideration should be given to avoid lethal effects on those species vulnerable to pesticides, e.g. aquatic, univoltine and carnivorous or monophagous species. Biological concentration of persistent substances is far greater in aquatic systems than in terrestrial systems (Kiritani 1971). Contamination of irrigation water with pesticides, therefore, must be avoided as much as possible.

   The control threshold of the rice water weevil has been established at 0.5 adults/hill in southern Japan where transplanting of rice occurs later than in northern Japan and overwintered adults normally invade paddy fields by flight. Studies conducted in northern Japan demonstrated that invasion takes place by walking from levees due to low prevailing temperatures, while rice plants are more tolerant to injury because of earlier transplanting. The control threshold developed was six adults/hill, more than twelve times higher than that in the south (Kidokoro 1997). Taking advantage of the behavior that weevils immigrate by walking, Kidokoro (1997) found that insecticide treatment of rice plants only in six rows (1.8 m) along a levee of a paddy field was sufficient to prevent the weevils from invading the inner part beyond the barrier zone. We can keep the amount of pesticides to a minimum by applying the knowledge of the behavioral ecology of the pests.

Conclusion

IBM is one of the operational concepts of agroecology. The operational field of IPM is mainly confined within agroecosystems, while conservation of endangered species as well as biological diversity is of greater concern in natural ecosystems than in agroecosystems. Consequently, less attention has been paid to conservation of species in agroecosystems than in natural ecosystems. The importance of minor insect species was elucidated in reference to their roles played within and outside the paddy agroecosystems. Also conservation of native species is imperative irrespective of pest status. Even a serious pest in a particular condition in terms of place and time might become a potential pest or a ‘minor’ species to be conserved under different conditions.

The concept of IBM makes both IPM and conservation compatible with each other. Farm management techniques that make the difference between the levels of EIL and extinction threshold as great as possible should be introduced in the IBM system. The most appropriate IBM system for a given area is determined through the consideration of the whole ecosystem of the area and the total life system of the relevant human community, instead of the sole consideration being agricultural production and pest control. It is inevitable that implementation of IBM involves some trial and error. We should not only invite active involvement of the interested persons into evaluation and improvement, but also should adopt a modest attitude in correcting IBM design without reluctance.

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