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# Biodiversity Associated with the Rice Field Agro-ecosystem in Asian Countries: A Brief Review

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International Water Management Institute

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## Introduction

This review is intended to bring together the published information available on the biodiversity associated with the rice field agroecosystem, in countries extending across Asia from Sri Lanka to Japan. The intention is to provide a synthesis that would enable us to better appreciate the environmental services and opportunities for biodiversity conservation offered by rice fields, as the additional benefits and contribution of these major food-producing agroecosystems. Since this review is based mainly on published information in the English language public domain, such limitation of the exercise might result in a bias towards those countries where the published and/or accessible information exists. In order to reduce such bias, attempts were made to review unpublished "grey" literature as well, although this was by no means comprehensive.

## History of Rice Cultivation

Rice is the most important cereal crop in the developing world (Juliano 1993). It is the staple food for at least 33 countries: 15 in Asia and the Pacific, 10 in Latin America and the Caribbean, 1 in North Africa and 7 in Sub-Saharan Africa (FAO 1999). Rice cultivation is thought to be the oldest form of intensive agriculture by man (Fernando 1977). Cultivation of the crop probably dates back to the earliest age of man and, long before the era for which there is historical evidence; rice was a staple food and the first cultivated crop in Asia (Grist 1965). According to published information, it seems that two cultivars of rice were domesticated in two separate areas: the principal cultigen *Oryza sativa* in the Indochinese region and *O. glaberrima* in the African region. In the Indochinese region, *O. sativa* was domesticated independently in China, India and Indonesia, thereby giving rise to three races of rice; *O. s. sinica* (also known as japonica), *O. s. indica* and *O. s. javanica* (or "bulu"), respectively (Juliano 1993). Historical evidence indicates that both tropical (indica) and temperate (sinica) races were being cultivated in parts of China at least 7,000 years ago (Chang 1985). *O. glaberrima* was domesticated in the upper Niger valley of Africa, about 5,500 years ago (Chang 1976). Rice has been grown in Sri Lanka, Taiwan, Vietnam and Japan from time immemorial. It is generally believed that rice cultivation in Sri Lanka was started by Indo-Aryan immigrants about 540 B.C (more than 2,500 years ago), where it was grown probably as a dryland crop (Grist 1965; Perera 1980).

## Distribution and Current Extent of Land Under Rice Cultivation

Rice, classified primarily as a tropical and sub-tropical crop, is grown in over 100 countries today on every continent except Antarctica, from 50-53$^0$ N to 40$^0$ S and from sea level to an altitude of 3,000 m (Juliano 1993; Pathak and Khan 1994) (figure 1). In 2003, approximately 151 million hectares of land worldwide was cultivated with rice, and Asia accounted for 89% (134.7 million ha) of this (FAOSTAT 2004).

*Figure 1. Distribution and spread of rice fields in the world.*

*Based on:* Fernando 1993a.

In Sri Lanka, rice is the predominant crop both in terms of land use and dietary importance (Baldwin 1991). The total area under rice at present is about 780,000 ha (approximately 12% of the total land area), which is distributed over all the agroecological regions except the areas located at very high elevation. With an average annual cropping intensity of 113 percent, the total extent sown per year is around 830,000 ha. A little over 75 percent of the rice lands in Sri Lanka are located within inland valley systems of varying form and size, while the rest are found in alluvial plains and also on terraced uplands in the interior (Panabokke 1996; Gunatilleke and Somasiri 1995; Nugaliyadde et al. 1997).

In Taiwan, more than 700,000 ha of land are cultivated each year, under two seasons (Yinglong 1999). In Vietnam, a total of 7,657,,000 ha of land was cultivated in 1999 consisting of 2,889,000 ha of spring paddy, 2,335,000 ha of summer paddy and 2,433,000 ha of winter paddy lands (Anonymous, 2000). A total of 2.8 million ha of land in Japan is subjected to rice cultivation, where rice is grown up to 1400m altitude in the central region of the main island (www.riceweb.org).

## Types of Rice Field Ecosystem

Rice-growing environments vary significantly within and between countries, but 5 categories based on water regime, drainage, temperature, soil type and topography are recognized, following Khush (1984):

1. Irrigated environments which have sufficient water available during the entire growing season, with controlled shallow water depth between 5 to10 cm.
2. Rain-fed lowland environments which are mainly dependent on the duration of rainfall and hence with an uncontrolled shallow water depth, ranging from 1-50 cm.
3. Deep-water environments, which are unbunded fields with maximum sustained water depths from 0.5 m to 3 m.
4. Upland environments, which are bunded or unbunded rain-fed fields with no surface or rhizosphere water accumulation.

5. Tidal wetlands, which are located near the seacoasts and inland estuaries, and are influenced by tides.

Based on the water regime, the rice fields in Sri Lanka fall into three major categories: rice land under major irrigation schemes (41%), rice land under minor irrigation schemes (25%), and rain-fed rice land (34%) (Nugaliyadde et al. 1997; Gunatilleke and Somasiri 1995). The majority of rice fields in the wet zone are rain-fed, while the ones in the intermediate and dry zones are irrigated by minor or major irrigation schemes. Of the five types of world rice land environments classified by Khush (1984), Sri Lanka has irrigated, rain-fed, upland, and tidal wetland categories of rice land, while deep water ricelands are absent (Gunatilleke and Somasiri 1995). However, all these rice land categories are found in Vietnam and Japan. The Mekong River Delta in Vietnam has three major cropping seasons: the winter-spring season, the summer-autumn or mid-season, and the wet season of long duration. Fifty two percent of the rice in the Mekong River Delta is grown in irrigated lowlands, with the remaining 48 percent grown under rain-fed lowland conditions. The northern provinces of Vietnam have a total rice area of 2.4 M ha or about 74 percent of the total area of farm holdings. Almost 85 percent of the total area is irrigated lowland, 12 percent is shallow rain-fed, and 4 percent is intermediate rain-fed. Wide ranges of latitude, including the subtropical, temperate, and subfrigid zones characterize rice ecosystems in Japan. Almost 100 percent of rice fields are irrigated and grown to rice in the summer (www.riceweb.org).

## Irrigated Rice Fields as Managed Wetland Ecosystems

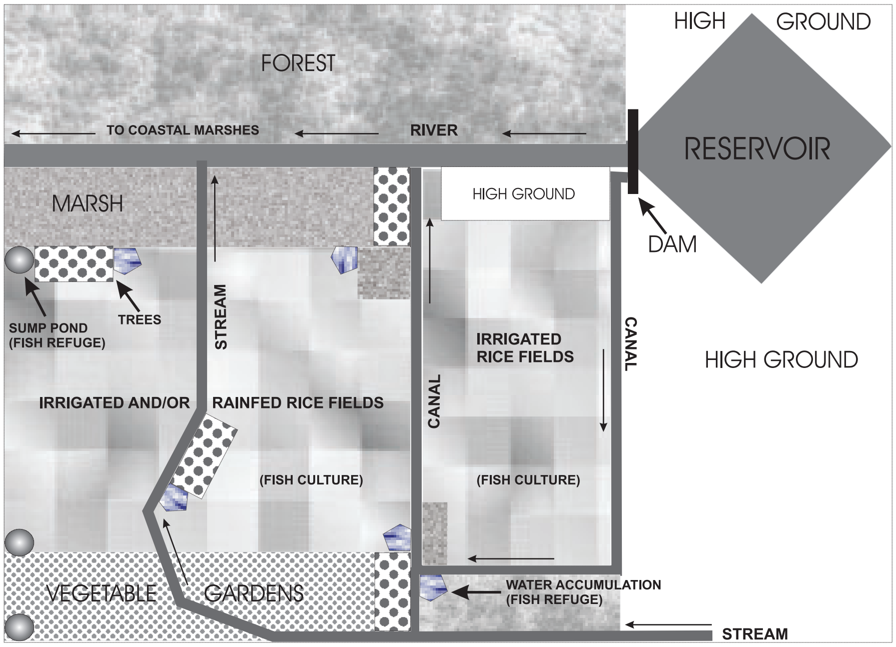
Most irrigated rice fields are usually successors of shallow marshes or a lowland area that can be supplied with adequate water (Fernando 1993a). They are characterized by the presence of a standing water body, which is temporary and seasonal. Hence, scientists have viewed flooded rice fields as agronomically managed marshes (Fernando 1996), or as a type of freshwater marsh with a cultivated grass (Odum 1997). Temporary freshwaters are generally defined as bodies of freshwater that experience a recurrent dry phase of varying length that is sometimes predictable as to both its time of onset and duration (Williams 1996). Therefore, rice fields being temporary aquatic habitats with a generally predictable dry phase, can be scientifically defined as temporary, seasonal wetland ecosystems agronomically managed with a variable degree of intensity (Bambaradeniya, 2000a; Halwart 1994).

## Ecological Aspects of Rice Field Agroecosystem

### *Physical structure and dynamics*

The rice ecosystem consists of two morphologically distinct habitats; the rectangular or similar-shaped flooded fields on which there are rice plants, and the surrounding bunds (levees) which harbor weeds. Under irrigated conditions, this mosaic system is connected with irrigation canals and ditches, while sump ponds, marshes and tanks serve as contiguous aquatic habitats (figure 2).

*Figure 2. Spatial relationships of a rice field ecosystem in the tropical region.*



*Based on:* Fernando 1993a.

A flooded rice field is frequently disturbed by farming practices, i.e., tillage, irrigation, crop establishment, agrochemical application, and weeding, and by natural phenomena such as rainfall and flooding. These disturbances result in extreme instability on a short time scale during the crop cycle, but relative stability on a long time scale (Watanabe and Roger 1985). Although it is a monoculture agroecosystem, a rice field undergoes three major ecological phases: aquatic, semi-aquatic and terrestrial dry, during a single paddy cultivation cycle (Fernando 1995). Physically, the aquatic phase has a shallow fluctuating water depth of 5-30 cm. The duration of the aquatic phase varies greatly from site to site and also from year to year though the general pattern remains similar at any one site. The physical status of floodwater is variable during a cycle; there is flow through, stagnation, and drying-off in the aquatic habitat consecutively, as the seasons progress (Fernando 1993a). The physicochemical composition of the floodwater changes accordingly. These changes are made more complex by agronomic practices such as the application of fertilizer and biocides. During a single rice cycle, a rice plant undergoes several phenological stages, which can be combined into three main growth stages: vegetative (germination-panicle initiation), reproductive (panicle development-flowering) and ripening (milk grain-mature grain). The duration of the vegetative stage differs according to the rice cultivar, while the other two stages remain the same irrespective of the cultivar (Reissig et al. 1986). The aquatic phase of the rice field represents the vegetative and the reproductive stages of the rice plant, while the semi-aquatic and terrestrial dry phases correspond to the grain ripening stage of the rice crop. Being a monoculture agroecosystem, rice fields at a specific time constitute a spatially homogeneous environment. However, on a temporal scale, the rice fields are a dynamic environment that undergo rapid temporal variation in relation to the growth of the rice plants and the hydrological status. Therefore, as a whole, the ecology of rice fields is dominated by rapid physical, chemical and biological changes.

### *Factors governing the ecology of irrigated rice field ecosystems*

Bambaradeniya (2000a) has discussed in detail the factors that govern the ecology of the irrigated rice field ecosystem. The hydrologic regime is the primary determinant of all wetland systems (Gosselink and Turner 1978). Hence, the hydrologic regime associated with the irrigated rice fields play a key role as a controller of this man-made wetland ecosystem. The source and the regularity of water supply are two important attributes of the hydrologic regime that directly affects the limnology of flooded rice fields. The source of the water supply influences the floodwater chemistry and the composition of the aquatic biota (plants and animals). The duration of inundation and its regularity or predictability influences the temporal variations in water depth (volume), water chemistry, soil fertility and the composition of the biotic communities as well. Two rice fields irrigated from the same source can exhibit marked differences in certain chemical parameters (e.g., conductivity) as well as in the composition and abundance of certain aquatic organisms (e.g., odonate larvae), in relation to differences in the regularity of water supply (Bambaradeniya 2000a). Besides controlling the rice field limnology, irrigation water also fulfils the primary hydrologic requirements of the rice plants. The growth of the rice plants in turn leads to temporal changes in physicochemical properties of floodwater (due to shading of floodwater) and the rice field biota (due to niche heterogeneity). The floodwater quality and soil fertility influence the biota inhabiting water and soil. The functions of the biota in turn affect the nutrient status in soil and floodwater.

These internal factors of the rice field ecosystem are also influenced by two external governing factors: the climatic regime and agronomic practices. Climatic factors such as solar radiation, temperature, relative humidity and wind velocity control evapo-transpiration in the flooded rice fields, while precipitation contributes to the fluctuations in water chemistry. These climatic parameters in turn affect the composition of the biota as well as the growth of the rice plants. Agronomic practices serve as the overriding factor that controls the overall ecology and biodiversity of the rice field ecosystem. These human interventions govern the hydrology, rice plant growth, water chemistry, soil fertility and biodiversity of rice fields. Previous studies on rice field ecology (Heckman 1979; Simpson and Roger 1995; Simpson et al. 1993a, 1993b, 1994a, 1994b, 1994c; Bambaradeniya 2000a) have clearly revealed that agronomic practices change the physical, chemical and biological conditions in the rice ecosystem, making them less favorable for certain organisms and temporarily more favorable for others.

## Biodiversity in Rice Fields

Biodiversity, as it relates to agriculture (commonly referred to as “agribiodiversity”), includes the diversity of domesticated plants and livestock species and their wild relatives; the diversity of wild species that affect, or are affected by agriculture; and the diversity of ecosystems formed by populations of species related to different types of land use (ranging from intensively farmed agricultural lands and semi-natural agricultural habitats, to uncultivated natural habitats). Wild species diversity is important in a number of ways. Some species, such as soil micro-organisms, earthworms, pest controlling species and pollinators, support agricultural production systems whereas others, such as pests, are harmful to these systems. Some use agricultural land as habitat (ranging from marginal use to complete dependence on agro-ecosystems), or use other habitats but are affected by farming activities, e.g., farm chemical run-off into aquatic systems. There also are non-native weed and pest species that are alien to indigenous biodiversity, and can threaten agricultural production and agro-ecosystems (Parris 2001).

Rice fields, together with their contiguous aquatic habitats and dry land comprise a mosaic of rapidly changing ecotones, that harbor a rich biological diversity (both fauna and flora) maintained by rapid colonization as well as by rapid reproduction and growth of organisms (Fernando 1995, 1996). These organisms colonize rice fields by resting stages in soil, by air and via irrigation water (Fernando 1993a). The fauna are dominated by micro- meso- and macro-invertebrates (especially arthropods) inhabiting the vegetation, water and soil sub-habitats of the rice fields, while vertebrates too are associated with rice fields. The wet phase of rice fields generally harbors a varied group of aquatic animals. Those that inhabit the vegetation are mainly the arthropod insects and spiders. In addition, many species of amphibians, reptiles, birds and mammals from surrounding areas visit the rice fields for feeding, and are generally considered as temporary or ephemeral inhabitants (Bambaradeniya et al. 1998). In relation to the rice crop, the fauna and flora in rice fields include pests, their natural enemies (predators and parasitoids) and neutral forms.

Heckman (1979) states that long-standing cultivation of rice over several millennia has enabled organisms to become adapted to the rice field aquatic system. However, Fernando (1996) states that the marsh, pond, and the stream-dwelling organisms colonize and survive in rice fields due to their ability to tolerate drastic changes in the rice field ecosystem and the ready availability of colonizers in contiguous aquatic habitats. Bambaradeniya (2000a) points out that:

> The events of temporal changes pertaining to biotic communities in a rice field ecosystem occur in a non-directional cyclic manner, influenced by allogenic and autogenic factors. In general, organisms inhabiting the rice field ecosystem can be considered as opportunistic biota. Most biotic communities in the rice field ecosystem are able to react physiologically and/or behaviorally to the drastic conditions in these temporary wetlands. As they possess the ability to recover rapidly from various disturbances, including chemical inputs, these organisms could be interpreted as biota with high resilience stability.

Previous studies on the biodiversity of rice fields deal mainly with agronomic aspects, where the rice pests, their natural enemies and weeds have been surveyed extensively. Comprehensive studies on the ecology and biodiversity of rice fields are scanty. Among the earliest published records on the subject is that of Weerakoon (1957) who gives a brief account on the ecology of rice field animals in Sri Lanka. Heckman (1974, 1979) provides a documentation of the varied fauna of the aquatic phase of traditional rice fields in Laos and Thailand. Roger and Kurihara (1988) have dealt with the aquatic ecology of rice fields in detail. Among the more recent and comprehensive contributions is a compendium of papers dealing with the biodiversity of the Muda rice agroecosystem in Malaysia provided by Nashriyah et al. (1998). Data on the distribution and abundance of terrestrial and aquatic weeds (25 species, 15 families), insects and arachnids (36 families, 10 orders), fish (39 species, 21 families) and birds (11 species, 8 families) are provided in this work. A preliminary study on fauna and flora of a rice field in Sri Lanka by Bambaradeniya et al. (1998) has documented 77 species of invertebrates, 45 species of vertebrates and 34 species of plants. Subsequently, Bambaradeniya (2000a) has reported on a comprehensive survey on the ecology and biodiversity of an irrigated rice field ecosystem in Sri Lanka. This survey documented 494 species of invertebrates belonging to 10 phyla, 103 species of vertebrates, 89 species of macrophytes, 39 genera of microphytes and 3 species of macrofungi from an irrigated rice field ecosystem in Sri Lanka. The majority of the invertebrates were arthropods (82%, 405 species), dominated by insects (78%, 317 species). The great number of animal and plant species documented in the above survey indicates that the irrigated rice field is an agroecosystem with a high gamma ($\gamma$) diversity. The above study not only documented the overall biodiversity associated with this unique man-made temporary aquatic ecosystem, but elucidated the spatial and temporal variation of biodiversity, in relation to various governing factors affecting this ecosystem. For instance, using terrestrial arthropods as a surrogate group, the survey clearly documented the spatial variation of rice field biodiversity in two rice fields in the same locality and irrigated by the same reservoir, but differing in agronomic practices. Furthermore, it also highlighted how an increase in the structural complexity of the habitat contributed to a temporal gradient in biodiversity through the progression of each rice cultivation cycle, while significant seasonal variations were less likely to occur in a particular rice field that follows generally similar agronomic practices during each cycle. Heong et al. (1991) have also highlighted the temporal and spatial variation of rice field arthropod biodiversity in the Philippines.

Several researchers have worked on specific groups of rice field organisms, and these could be discussed under four main categories: aquatic invertebrates, terrestrial invertebrates, vertebrates and flora.

### *Aquatic invertebrate fauna inhabiting rice field ecosystems*

Aquatic invertebrate animals inhabiting the rice field water are broadly divided into:

- *neuston* which includes surface dwelling insects,
- *zooplankton,* which includes minute organisms such as protozoans, micro-crustaceans and rotifers,
- *nekton,* which includes aquatic insects and their larvae, and
- *benthos,* which includes bottom dwelling annelid worms, nematodes and molluscs (Heckman 1974, 1979; Fernando 1993a, 1995; Halwart 1994; Bambaradeniya 2000a).

The variety of aquatic invertebrates inhabiting rice fields is evident in the comprehensive bibliographies of Fernando and Furtado (1975), Fernando et al. (1979) and, more recently, Fernando (1993a), which clearly indicate that the aquatic organisms in rice fields cover the entire spectrum of freshwater fauna.

As most rice fields are converted marshes, they have inherited the aquatic fauna of these marshes and also receive fauna seasonally via irrigation systems (Fernando 1977). Thus, they harbor a great variety of organisms, well adapted to this temporary and highly manipulated ecosystem that is periodically disrupted by various agricultural practices (Fernando 1995). A succession of aquatic biota occurs through the rice growing season as the system transforms from an open littoral environment to a vegetated littoral system along with the growth of the rice plants and other macrophytes (Heckman 1979). Fernando et al. (1979) have further discussed the process of the seasonal recolonization of the aquatic phase of rice fields, after a dry phase.

One of the earliest researchers to document the aquatic invertebrates in rice fields was Meien (1940), who recorded about 185 species belonging to four major phyla, from rice fields in Uzbekistan. Heckman (1974, 1979) found insects to be the dominant aquatic invertebrates in comprehensive studies on rice-field organisms in Laos and Thailand.. Bambaradeniya (2000a) recorded a total of 179 aquatic invertebrate species belonging to 96 families and 10 major phyla, from an irrigated rice field in Sri Lanka. Half of the invertebrate species documented were arthropods (92 species), dominated by insects (65 species). Among the insects, the highest number of species (22) belonged to the Order Diptera, which was dominated by the Family Culicidae (14 species). The arthropods were followed by the Phylum Annelida (23 species), which was dominated by Oligochaetes (21 species). The remaining aquatic invertebrates consisted of Rotifera (18 species), Protozoa (16 species), Mollusca (10 species), Platyhelminthes (9 species), Nematoda (8 species), Gastrotricha

(1 species), Ectoprocta (1 species) and Cnidaria (1 species). The majority of the species recorded (39%) belonged to the benthic community, while neuston had the lowest species composition (4%).

Of the aquatic organisms in rice fields, zooplankton consisting largely of microcrustaceans and rotifers, is probably the most widely studied group. High diversity has been recorded in West Malaysian, Burmese and Sri Lankan rice fields, attributed to the abundance of natural marshes and relatively high precipitation in these countries (Fernando 1977). Lim et al. (1984) have studied the temporal changes in the population densities of Cladocera in Malaysian rice fields subjected to pesticide treatment. Ali (1990) has conducted a comprehensive study on the abundance and seasonal dynamics of microcrustacean and rotifer communities in rice fields used for rice-cum-fish farming in Malaysia. Simpson et al. (1994b) and Taniguchi et al. (1997) have studied the seasonal dynamics of micro-crustaceans in rice fields of the Philippines and Japan, respectively, in relation to pesticide and nitrogen fertilizer applications. As in other countries, zooplanktons are the most widely studied group of rice field aquatic invertebrates in Sri Lanka. Fernando (1980) showed that rice fields harbor as diverse a fauna as ponds, and have more species than rivers, streams and villus (river flood plains). A total of 71 species of rotifers and 80 species of microcrustaceans were recorded from rice fields during Fernando's survey, which is about 53 percent of the total freshwater zooplankton taxa (Rotifera, 165 species; Microcrustacea, 122 species) documented in Sri Lanka. His findings also show that the species composition of zooplanktons in Sri Lankan rice fields is higher than in Uzbekistan (Rotifera, 83 species; Crustacea, 30 species), Thailand (Rotifera, 50 species; Crustacea, 29 species) and West Malaysia (Rotifera, 56 species; Crustacea, 54 species), as documented by Meien (1940), Heckman (1979) and Fernando (1977), respectively. The Ostracod crustaceans of rice fields in Sri Lanka have been documented by Neale (1977), who found that species in the central and southern parts of the island are closely related to those in Indonesia. Rajapakse (1981) has found that circa 90% of rice field and villu samples contained at least one species belonging to the non-chydorid Cladocera.

Mosquitoes are the most widely studied aquatic insects associated with rice fields, as this ecosystem constitutes the favored breeding sites of several species. Lacey and Lacey (1990) have given a comprehensive review of the mosquitoes in rice fields, covering the aspects of their ecology, medical importance and control, and listed 137 species that breed in rice fields worldwide. Abu Hassan et al. (1998) has found 29 mosquito species biting human and bovid hosts, and 11 species breeding in rice fields in the Muda area of Malaysia. They provide details of the prevalent species breeding in different habitats within the rice ecosystem, as well as within rice fields per se during different stages of the rice cultivation cycle. Amerasinghe (1993) reported 26 species of mosquitoes from rice fields of the dry zone in the Eastern Province of Sri Lanka, while Bambaradeniya (2000a) recorded 14 species from the intermediate zone. Takagi et al. (1995, 1996) studied the effect of rice plant canopy on the density of mosquito larvae and other insects in Japanese rice fields and showed that different species react differently to the changing conditions as the plants grow and the canopy closes. Only a few researchers have studied aquatic insects other than mosquitoes in rice fields. Yano et al. (1983), recorded 117 species of aquatic coleopterans, in 14 families from rice fields worldwide. A study in the Muda rice area of Malaysia showed that representatives of the Orders Diptera (Families: Chironomidae and Culicidae), Coleoptera (Family Hydrophilidae), Hemiptera (Families: Dytiscidae, Corixidae, Pleidae, Nepidae, Belostomatidae), Odonata (Families: Libellulidae, Coenagrionidae), and Ephemeroptera (Family Baetidae) comprised the aquatic insect fauna. The dominant aquatic insects were from the Families Chironomidae, Dytiscidae, Corixidae and Belostomatidae (Rozilah and Ali 1998). One interesting point arising from this study is that the aquatic representatives of the Coleoptera, Hemiptera and Odonata were all predatory insects. A second point is that there was no statistical difference in diversity or abundance of the aquatic insects when insecticide (Broadox, Trebon) treated and untreated rice fields were compared.

There are very few studies on mollusks, although they are an important component of the aquatic community in rice fields. Simpson et al. (1994c) have documented the dynamics of benthic molluscs in rice fields in the Philippines. Naylor (1996) has given a comprehensive account on the invasion of the Golden Apple Snail in the rice fields of Asia. Outside of Asia, Gonzales-Solis and Ruiz (1996) have studied the ecological succession of six basommatophoran species of gastropods in rice fields of Ebro Delta, in Spain.

Oligochaete worms are an important component of the rice field benthos. Reported studies on these organisms include Simpson et al. (1993a, 1993b) who have studied the population dynamics of benthic oligochaetes in Philippine rice fields, and Kurihara (1989) who has carried out a comprehensive study on the benthic tubificid worms in rice fields of Japan. Plant parasitic nematodes associated with rice ecosystems in South and Southeast Asia have been the subject of Prot and Rahman (1994) who provide a comprehensive account of their ecology and economic importance. Weerakoon and Samarasinghe (1958) have conducted one of the best studies on the quantitative aspects of rice field benthos. They reported that the population density of rice field benthic fauna in Sri Lanka is high compared with that of ponds, oligochaetes and chironomid dipteran larvae dominate the fauna, and freshwater crabs are a common component of the rice-field benthos and play a role as scavengers and a source of food for other animals, while some are known to damage rice field bunds.

### ***Terrestrial invertebrate community of rice fields***

Arthropods are the main terrestrial invertebrates of rice fields. The arthropod community in rice fields consists mainly of insects and spiders that largely inhabit the vegetation (rice plants and weeds) and the soil surface. With respect to rice cultivation and based on the inter relationships between populations, the terrestrial arthropod communities can be further divided into rice pests, their natural enemies (predators and parasitoids) and neutral forms. In rice fields the composition of the terrestrial arthropod communities is known to change with the growth of the rice crop.

The temporal development of arthropod communities in relation to rice cultivation in the rice fields of the Philippines was studied by Heong et al. (1991). They examined the guild structure, successional changes and dynamics of important phytophagous and predator arthropod species, providing insights into the arthropod community structure in rice fields. Schoenly et al. (1996) went a step further, in describing the above-water food web dynamics of arthropod communities in irrigated rice fields. They determined the trophic links of the cumulative food webs in the rice fields of the Philippines. Abdullah et al. (1998) documented 36 families of insect and arachnid arthropods in rice fields of the Muda irrigation scheme in Malaysia. A greater number of insect families and individuals were collected from field plots using recycled water, than from non-recycled plots. The major reason appeared to be that the aquatic larvae of most of the insects were rapidly carried off downstream in the non-recycled system, whereas they tended to remain in the fields long enough for pupation with the recycled system. Bambaradeniya (2000a) documented a rich terrestrial arthropod fauna comprising 280 species of insects in 90 families and 16 orders, plus 60 species of arachnids in 14 families, amounting to a total of 340 arthropod species from an irrigated rice field ecosystem in Sri Lanka. The majority of the insects belonged to Order Hymenoptera (81 species), followed by Lepidoptera (58 species). Apart from these key studies, there is a wealth of rapidly growing information on the rice field insect pests and their natural arthropod enemies viewed from a biological control perspective. Some of the relevant aspects on this subject are discussed below.

### *Insect pests of rice*

Barrion and Litsinger (1994) provide a compendium on the taxonomy of the insect pests of rice and their natural enemies. According to Dale (1994) who has given a comprehensive account of the biology and ecology of the insect pests of rice, over 800 species of insects damage rice plants in several ways, although the majority cause minor damage. The number of insect species that cause economic damage to rice varies from 20 (Pathak and Khan 1994) to 30 (Riessig et al. 1986). Bambaradeniya (2000a) recorded 130 species of phytophagous insects in Sri Lankan rice fields, of which the majority (76 species) consisted of visitors or other insects associated with weeds. In addition to causing direct damage to rice plants, many rice insect pests also act as vectors of viruses causing diseases in rice, such as the Tungro virus (Dale 1994; Thresh 1989). The insect pests of rice are either monophagous, feeding only on the rice plant, or polyphagous, where they move in and out of adjacent vegetation mainly including rice field weeds. Loevinsohn (1994) has discussed various forces that determine the presence and abundance of insect pests in rice agroecosystems, including their adaptations to the rice environment, the influence of the cropping system, and the dynamics of the pest populations in relation to the cultural environment.

### *Natural arthropod enemies of rice insect pests*

The natural arthropod enemies of rice pest insects include a wide range of predators and parasitoids that are important biological control agents. Predators include a variety of spiders, and insects such as carabid beetles, aquatic and terrestrial predatory bugs and dragonflies. Parasitoids include many species of hymenopteran wasps and a few dipteran flies. Ooi and Shepard (1994) give a comprehensive account of the natural enemies of rice insect pests. They have stated that long histories of rice cultivation in many parts of the world have allowed stable relationships to evolve between rice insect pests and their natural enemies. In most instances, the species richness and abundance of the predator populations may be greater than those of the pest populations, when little or no insecticides are used (Way and Heong 1994). A pioneering study by Settle et al. (1996) documented 765 species of spiders from lowland irrigated rice fields in Indonesia, and demonstrated the existence of high levels of natural biological control in tropical irrigated rice systems. Abdullah et al. (1998) reported that pest plant hopper populations in the Muda agroeocsystem in Malaysia were probably held in check by a combination of natural arthropod predators (mainly dragonflies and spiders) and common insecticides. Heong et al. (1991) have recorded 46 species of predators (heteropteran bugs and spiders) and 14 species of hymenopteran parasitoids of auchenorrynnchous homopteran pests in the rice fields of the Philippines. In Sri Lanka, more than 50 percent of the terrestrial arthropod species in rice fields have been shown to consist of predators, with spiders as the dominant predatory group comprising 60 species (Bambaradeniya 2000a; Bambaradeniya and Edirisinghe 2001).

For the Southeast Asian region in general, Barrion and Litsinger (1995) have recorded about 342 species of rice field spiders. In terms of numbers, spiders seem to form one of the most important groups of natural enemies of rice insect pests. Previous research related to these natural enemies include taxonomic surveys, seasonality and the relative abundance of different species and their impact on specific pest insects of rice.

### *Vertebrate fauna of rice fields*

A variety of vertebrates utilize rice fields, mainly as feeding sites. Some vertebrates are pests of rice, and these include rodents such as rats, mice and bandicoots, granivorous birds, and wading migrant birds that trample and/or feed on rice seedlings (PANS 1976). The typical aquatic vertebrates such as fish and amphibians enter and colonize rice fields via irrigation channels, ditches, contiguous marshes and tanks. Terrestrial vertebrates such as reptiles, birds and mammals visit the rice fields from surrounding habitats at different phases of the rice field and hence are considered as temporary, ephemeral inhabitants (Heckman 1974, 1979; Bambaradeniya et al. 1998; Bambaradeniya 2000a). Previous studies on rice field organisms have dealt mainly with invertebrate fauna, while the vertebrate fauna has largely been neglected. Bambaradeniya (2000a) has listed 103 species of vertebrates recorded from an irrigated rice field ecosystem in Sri Lanka. Heckman (1974, 1979) has listed a few vertebrates (mainly fish and amphibians) in the rice fields of Laos and Thailand. Ocampo (2000) has reviewed the vertebrate fauna documented in the rice fields of the Philippines, including a list of 51 species.

Fish are an integral part of the rice field fauna especially in the tropics (Fernando 1993b, 1995, 1996). Freshwater fish species in the rice fields of Sri Lanka, Thailand and the Philippines have been recorded by Fernando (1956), Heckman (1979) and Halwart (1993) respectively. Halwart et al. (1996) have studied the activity pattern of fish in the rice fields of the Philippines, in order to understand their role in this ecosystem. Halwart (1993) has listed the economically important fish, especially in the Philippine rice fields. De Silva (1991) has contributed one of the few studies on the population ecology of rice field fishes. Fernando (1956) has listed 35 species of fish and the food habits of four indigenous fish species inhabiting a rice field ecosystem in Sri Lanka. Amir Shah Ruddin and Ali (1998) listed 39 fish species in the Muda rice irrigation system in Malaysia. In this study, fish distribution, diversity and evenness indices in 5 widely separated sampling areas were not markedly different. The authors point out that fish diversity was generally lower than in natural marshlands, although Fernando (1980) suggests that the rice-field agroecosystem is essentially an extension of natural marshlands, swamps etc., and should reflect the diversity of these habitats. Amir Shah Ruddin and Ali (1998) suggest that ecological changes resulting from human interventions in the Muda area have been so severe that only the hardiest species have survived.

Rice fields are a preferred habitat of amphibians, and these insectivorous vertebrates function as important vertebrate natural enemies of pest insects. Abdulali (1985) provides a detailed account on the ecology of some rice field dwelling amphibians in India, highlighting their role as biocontrol agents of rice insect pests and crabs. Bambaradeniya (2000b) discusses the role of rice fields as an important man-made habitat of herpetofauna, and has listed 21 species of reptiles and 18 species of amphibians documented from rice fields throughout Sri Lanka. Bambaradeniya (2000c) further makes the point that rice fields are an important man-made habitat for amphibians.

Birds are the dominant group of vertebrates that visit rice fields, and these include some species that function as pests of paddy (Bambaradeniya 2000a). Mist-netting catches in the Muda rice scheme in Malaysia have yielded mainly granivorous birds such as weaverbirds and munias; only 11 species in all were recorded (Abdullah and Ho 1998). However, in 1991, the Department of Wildlife and National Parks of Malaysia documented 158 species of birds associated with rice fields in Malaysia, and this includes several migrants as well (Burhanuddin 1992). For Sri Lanka, Weeraratne and Fernando (1984) make brief mention of the aquatic birds observed in rice fields, but the most comprehensive account is given by Bambaradeniya and Ranawana (2000), who list 92 species (including several migratory species) from rice fields throughout the island.

Several species of mammals also inhabit or visit rice fields. These are mainly small rodent pests of paddy (e.g. rats and mice), and insectivores such as shrews that are beneficial because they are predatory and consume insects and other pests. These small mammals and fish species attract medium-sized carnivorous mammals such as mongoose, wild cats, otter and civet cats into rice fields (Bambaradeniya 2000a; Burhanuddin 1992). Among more detailed studies of note are those on the reproductive biology and population structure of a rodent pest of rice, *Bandicota bengalensis* Gray & Hardwick, in Indian rice fields (Srihari and Govindaraj 1988), and on the house shrew *Suncus murinus* (L.) in rice fields in Pakistan (Khokhar 1991). Arata (1988) comments on the public health importance of rice field rodents who directly or indirectly (via ticks and fleas) may carry human pathogens. The above literature, taken as a whole, provides some useful background information that indicates that a wide spectrum of species belonging to all the groups of vertebrates is found in rice field ecosystems.

### *Flora of rice fields*

The rice field ecosystem harbors a rich composition of primary producers, which can be broadly grouped under two categories: the macrophytes and the microphytes. Besides the rice plant, the macrophytes include other rooted higher plants, which consist mainly of grasses, sedges and broad-leaved plants. These are generally referred to as weeds, as they compete with the rice plants for growth requirements such as space, nutrients and sunlight (Halwart 1993). The microphytes include various types of algae and fungi.

The weed communities occur in three different habitat types found in the rice field ecosystem: the field proper, the bund (levee) and the ditch (water supply canal) habitat. Each of these habitats contains a distinct weed community comprising several aquatic, wetland and dryland weeds (Chandrasena 1988). The rice field proper, which is the major habitat in the rice field ecosystem, remains under flooded conditions for the greater period of a single rice cultivation cycle. The aquatic condition provides an extremely stable habitat for weeds resistant to excess water stress (Yamasue and Ueki 1983) and for various groups of algae, which together constitute the photosynthetic aquatic biomass (PAB) in rice fields. When the fields are drained prior to harvesting, terrestrial weeds colonize and become more conspicuous. Ditch habitats in the rice field ecosystem remain flooded during the most part of the year and many submerged, floating-leaved and free-floating aquatic weeds are characteristic of these habitats. In contrast to the field proper and ditch habitats, the bunds remain under non-flooded, relatively dry conditions. Hence, the weed communities in the bunds consist mainly of terrestrial plants (Chandrasena 1988). Control of rice weeds is succinctly covered by Ampong-Nyarko and De Datta (1991).

Based on a survey of literature on rice field weeds reported from major rice growing countries, Moody (1989) has documented more than 1800 weed species occurring in the rice field ecosystems of Asia and Southeast Asia alone. Species of Poaceae (grasses) are the most common, followed by Cyperaceae (sedges) and other broad-leaved families. The barnyard grass (*Echinochloa crus-galli* (L.) Beauv is considered to be the most troublesome weed of rice in the world (Holm et al. 1977), followed by *E. colonum* (L.) Link (Smith 1983). Other rice field weeds of world importance include the grasses *Eleusine indica, Ischaemum rugosum*; the sedges *Cyperus difformis, C. rotundus, C. iria* and *Fimbristylis miliaceae*; and the broad-leaved *Monochoria vaginalis* and *Sphenochlea zeylanica* (Smith 1983). Several previous studies on the weed flora of rice fields in Sri Lanka highlight the rich diversity of species growing in this agroecosystem. Velmurugu (1980) reported that there are about 70-80 common rice field weed species in the country. Weerakoon and Gunewardena (1983) recorded 134 weed species belonging to 32 families from rice fields in the three major climatic zones of Sri Lanka. Added to this are contributions from Amerasinghe (1985), Chandrasena (1987, 1988, 1989) and Seneviratne et al. (1992) who have recorded the composition and abundance of rice weeds in the low country dry, low-country wet and intermediate zones of Sri Lanka. A provisional list of weeds found in arable soils by Ameratunge (1977) includes many species of major rice weeds. Based on these surveys, Moody (1989) has listed approximately 340 weeds recorded from rice fields in Sri Lanka.

A variety of algae occurs in the water and soil of rice field ecosystems. These algae include green algae, desmids, diatoms and blue-green algae (BGA). Heckman (1974, 1979) has recorded the different species of algae occurring in rice fields of Laos and northeastern Thailand, with detailed accounts of their seasonal succession as well. Roger and Kulasooriya (1980) have stressed the importance of some BGA in the build-up and maintenance of soil fertility in rice fields, as they are capable of fixing atmospheric nitrogen.

## Threats to the Biodiversity of Rice Fields

The rice fields, being agroecosystems, are managed with a variable degree of intensity and hence agronomic measures and practices affect the abundance and composition of the biotic community, especially its aquatic component (Halwart 1993). Rice production throughout the world (especially in Asia) has undergone a dramatic transformation after the mid 1960's, as a result of the green revolution. The transformation has relied on the intensification of irrigated rice production systems. It has involved the use of modern high-yielding rice varieties responsive to fertilizers and pesticides, and the increase in the number of crops grown per year by planting short duration varieties. Production increases have come from the greater area planted with rice (32%), from irrigation and double cropping (25%), from fertilizers (22%), and from the inherent higher yielding quality of modern varieties (21%). Inherent within the transformation are serious threats to rice agroecosystem biodiversity, deriving from (a) expansion of riceland areas; (b) increased cropping intensities; and (c) the use of agrochemicals. The expansion of ricelands into contiguous areas of many hundreds or thousands of hectares greatly reduces their natural biodiversity, as previously intervening natural habitats of varying types are destroyed. Additionally, intensive rice monoculture systems popularized by the green revolution, creates an environment that is conducive to pest growth (Pingali and Garpacio 1997). Increased cropping intensity accomplishes as much the same effect on biodiversity loss as riceland expansion, as species adapted to the fallow phase of rice fields are squeezed both spatially (for suitable habitat) and temporally (time for life cycle completion).

The use of pesticides has been an important contributory to improved rice productivity. Farmers and policy makers consider pesticides as a guarantee against crop failure, and a necessary input for modern rice production. Hence, chemical insecticides are widely adopted as primary agents of pest control (Pingali and Garpacio 1997; Loevinsohn 1985; Thresh 1989). The widespread promotion and indiscriminate use of insecticides, and the introduction of a limited number of rice varieties on a very large scale to replace the diverse array of plant races grown previously, have been major factors responsible for the rapid multiplication of rice pests and diseases (Thresh 1989). Although rice insect outbreaks have been recorded over the last 1,300 years, they have become much more frequent and damaging, and insect pest complexes have undergone rapid change during the last three decades (Heinrichs 1994).

The long history of rice cultivation in many parts of the world allowed the evolution and maintenance of stable and balanced relationships between rice insect pests and their natural enemies which include predators and parasitoids (Ooi and Shepard 1994). However, the broad-spectrum biocides, introduced as part of the package of green revolution technologies, affected the natural enemies that managed insect pests. Although insecticides are known to have rapid curative action in preventing economic damage (Chelliah and Bharathi 1994), indiscriminate use of insecticides has led to the destruction of natural enemies, causing the resurgence of several primary and secondary pest species and the development of insecticide-resistant pest populations (Smith 1994; Ooi and Shepard 1994). Other detrimental effects of pesticide misuse include human health impairment due to the direct or indirect exposure to hazardous chemicals, contamination of ground and surface waters through runoff and seepage, and the transmittal of pesticide residues through the food chains (Pingali and Roger 1995).

Pesticides used in rice cultivation to kill rice pests and weeds can have a devastating effect on the living organisms for shorter or longer periods of time (Fernando 1996). A number of reviews on the biocide use in rice fields and its impacts on fauna (especially invertebrates) and microflora (Lim 1992; Abdullah et al. 1997; Roger et al. 1994; Roger and Simpson 1991) further discuss this issue at length. The impact of biocides used in rice cultivation on vertebrates inhabiting rice fields and surrounding aquatic habitats have been investigated by researchers in the Philippines (Cagauan1995; Tejeda and Magallona1986; Tejada et al.1995) and South America (Vermeer et al.1974). The effects of pesticides and fertilizers on specific groups of rice field organisms have been clearly documented in the study conducted by Bambaradeniya (2000a).

Changes associated with irrigation structures to enhance the efficiency of irrigation water use have also resulted in negative impacts especially on fauna associated with rice fields. For instance, the concrete lining of irrigation canals that supply water to rice fields, and directing irrigation water to rice fields via pipes, instead of ditches, have resulted in the loss of habitats for a variety of aquatic invertebrate and vertebrate fauna. The negative impact of changing irrigation practices in the rice fields of central Japan on amphibians and a group of aquatic birds inhabiting rice fields have been well documented by Fujioko and Lane (1997) and Lane and Fujioko (1998) respectively.

## Future Sustenance of the Rice Field Agro-ecosystem and Its Biodiversity

Although traditional rice cultivation has been carried out in a sustainable manner over many millennia, there is growing evidence that modern rice cultivation that depends heavily on machinery and chemical inputs, together with short-term rice varieties, has disrupted the balance of these efficient trophic linkages, and hence, poses a threat to the future sustainability of this unique ecosystem (Roger et al. 1991; Kurihara 1989). This situation has been interpreted by Odum (1997), as one in which the pressures of human population growth have transformed agroecosystems from "domesticated" ones that were relatively harmonious with our general environment, into increasingly 'fabricated' ecosystems that more and more resemble urban-industrial ecosystems in energy and material demands and waste production.

In this regard, there is a conspicuous lacuna in the literature relating to rice field biodiversity. The fauna and flora are reasonably well documented, but we do not know the manner and extent to which biodiversity has been disrupted or enhanced or changed by the replacement of natural habitats by rice ecosystems. There also do not seem to be ecological studies contrasting the biodiversity of traditional rain-fed ricelands with more intensive irrigated systems. Comparative biodiversity studies that would yield such temporal (i.e. before and after the replacement) or spatial (rice ecosystem vs. adjoining natural ecosystem, or traditional vs. intensive cultivation) contrasts could make a valuable contribution to knowledge that may result in the development of more ecologically friendly rice ecosystems. Interestingly, one of the few longitudinal faunal studies done in an Asian tropical rice ecosystem relates not to rice pests or animals of agricultural or general conservation importance, but to mosquitoes, from the viewpoint of mosquito vector faunal changes related to irrigation development affecting the potential for human disease (see Box 1). Although in this particular instance mosquitoes are not directly relevant to the present conservation-development debate, the study brings out the intrinsic value of longitudinal and/or cross-sectional faunal and floral studies that needs to be recognized if we are to assess the directions in which increased food production can be achieved without causing major ecological damage. Given the diversity of rice cultivation systems, their geographic and elevational spread, and the diversity of natural environments that they have replaced, there is ample scope for research into the positive and negative impacts on the biodiversity of one of the major food production systems in the world. This would, in turn, stimulate new thinking on how to maximize the biodiversity potential of the rice ecosystem.

The biodiversity implications of Integrated Pest Management (IPM) is another interesting avenue for research. This technology has been promoted primarily as a means of maintaining or enhancing the economic benefits of cropping systems while using less pesticide inputs, through maximizing natural pest control. However, it is not only the reduction of toxic effects of pesticides that have biodiversity implications in IPM. The philosophy of maintaining a mosaic of habitats within the rice agro-ecosystem that can sustain beneficial animals such as predators and parasitoids of crop pests implies spin-off benefits to general biodiversity associated with such mosaics. Minimal pesticide use also has the additional benefits of resulting in less human exposure (both occupational and accidental) to toxic chemicals. IPM certainly is a technology that resonates with the concepts of sustainable agricultural development.

Traditional rice fields that have been cultivated over a long period of time may be considered as climax communities. Modern technologies including the use of chemicals, optimum water and crop management practices, and machinery have tremendously increased yields. However, these developments have caused profound modifications to traditional rice-growing environments. In order to meet the food requirements of the fast-growing human population, a 65 percent production increase would have to be achieved within the next 30 years, without much expansion of the actual cultivated area (Roger et al. 1991). This increase in rice production in the coming decades should not be achieved at the expense of future generations and should fulfil the concept of sustainability (Roger and Simpson 1991; Roger et al. 1991). It should maintain or enhance the quality of the environment and conserve or enhance natural resources.

Until the late 1980's, the prime focus of biological conservation was on undisturbed natural habitats including protected areas that cover only a very small proportion of the world land area. However, the focus on undisturbed habitats was challenged at the dawn of this decade, when attention was called on the fact that 95 percent of the terrestrial environment consisted of managed ecosystems, including agricultural systems, forestry systems and human settlements. Hence, a large portion of the world's biological diversity coexists in these ecosystems (Western and Pearl 1989). Since then, scientists have begun to focus their attention on agricultural and forestry systems (Pimental et al. 1992). There is growing interest in the concepts of ecoagriculture (McNeely and Scherr 2001) whereby an agricultural system is managed as both a food production and a biodiversity conservation system. The surveys on biodiversity associated with the rice field agro-ecosystem conducted to date have clearly shown that this man-made ecosystem contributes to sustain a rich biodiversity, both in rural and per-urban settings. Today, biodiversity is viewed as a fundamental principle in agricultural sustainability, and studies have been focused on biodiversity as an organizing principle in agroecosystem management (Stinner et al. 1997). As Kurihara (1989) has pointed out, the rice field ecosystem is one of the most sustainable forms of agriculture, now, unfortunately being imperiled by agribusiness. Since the rice field ecosystem satisfies the interests of both agroecologists and conservation biologists, the integrated efforts of these two groups can result in the formulation of strategies based on biodiversity as an organizing principle in the sustainable management of the rice field agroecosystem.

## BOX 1: Irrigation Development and Mosquito Ecology—A Case Study from Sri Lanka

The ecology of mosquitoes was studied intensively over a 6-year period (1984-1990) encompassing the developmental changes from the forest, through settlement, and the first 3 years under irrigation in an area that was developed for irrigated rice cultivation in System-C of the Mahaweli Development Project in Sri Lanka.

Among the forest mosquito fauna were medically important species such as *Anopheles culicifacies* and other *Anopheles* (vectors of malaria), *Aedes albopictus* (vector of dengue), *Mansonia uniformis* and *Ma. annulifera* (vectors of brugian filariasis), *Culex tritaeniorhynchus, Cx. gelidus* and *Cx. fuscocephala* (vectors of Japanese encephalitis). Thus, many vectors were already in place, awaiting, so to speak, the arrival of new human and animal hosts. Surveys of mosquito larval breeding habitats showed that land clearing and irrigation development resulted in replacing shaded forest streams and forest pools by a multitude of exposed habitats such as rice fields, canals, small reservoirs, seepages and temporary rainwater pools, which were colonized by many mosquito species, including potential vectors.

Overall, mosquito breeding species richness decreased by 20 percent from 49 species in the forested phase to 39 by the third year under irrigation, as 10 forest dwelling species either became locally extinct or so rare as to be undetectable by the survey methodology. Only 60 percent of the prevalent forest species retained high prevalence after irrigation development. However, at least 10 low-prevalence species in the forest became dominant after development. These included vectors of malaria, filariasis and Japanese encephalitis (Amerasinghe and Munasingha 1988a; Amerasinghe and Ariyasena 1990; Amerasinghe and Indrajith 1994; Amerasinghe 1995). A succession of rice field breeding mosquito species (including some vectors of disease) was seen in irrigated rice fields, concomitant with the ecological changes (water depth, shade, predators, etc.) within the fields during the cultivation cycle (Amerasinghe 1993).

Surveys of adult mosquitoes mirrored some of the trends seen in larval studies (Amerasinghe and Munasingha 1988b; Amerasinghe and Ariyasena 1991; Amerasinghe 1995). *Aedes albopictus* retained its position as the dominant daytime human biting species, as it rapidly adapted from forest to a peri-domestic environment. Several *Anopheles* and *Culex* vector species became prominent night biting mosquitoes. Two mosquito species (one of them the main vector of bancroftian filariasis) that were not present in the forested environment rapidly invaded as soon as forest clearing commenced. Several *Anopheles* mosquitoes that are regarded as secondary vectors of malaria showed evidence of involvement in disease transmission (Amerasinghe et al. 1991; Amerasinghe et al. 1992). There also was evidence of active Japanese encephalitis virus transmission in the study area before and, especially, after agricultural development (Peiris et al. 1993, 1994), related to the presence of those specific vectors.

Overall, the study provided insights into the impact of irrigated rice agroecosystem development on mosquito biodiversity. In terms of its major focus (human health), it demonstrated that new settlers were at increased risk from diseases such as Japanese encephalitis, rural dengue and filariasis, and continuing risk of malaria, as a result of the changes in mosquito bionomics arising from irrigation development and rice cultivation. It also provided avenues for timely interventions in agricultural development projects in order to minimize such negative impacts.

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