1 INTRODUCTION

The increase in staple food crop production, such as rice and maize, to compensate for population growth has become a major challenge for many developing countries such as Indonesia. To increase food-crop production, farmers are usually driven not by environmental concerns, but by economic issues, such as how to maximize production through use of chemical fertilizers. The continuous use of chemical fertilizers without returning plant residue or manure to the soil will result in soil degradation, groundwater contamination and rising production costs (Feenstra 1997). Soil degradation is reflected in declining agricultural productivity and utility (Katyal and Vlek 2000). Food-crop production, therefore, should be sustainably enhanced in order to maintain environmental quality and conserve natural resources for future generations (UNEP 2001). Sustainable agriculture can be improved through management of cropping systems based on the enhancement of the soil organism population and their ecological services, such as organic matter decomposition and nutrient mineralization (Lavelle *et al.* 2001).

The rainfed lowland paddy ecosystem that is widespread in Indonesia has great potential regarding an increase in the productive area, which has become limited in Indonesia, especially in Java (Syamsiah 1994). However, due to the lack of infrastructure and water resources, and low soil fertility, the productivity of rainfed paddy fields has become lower compared to that of the irrigated rice field system.

1.1 Rainfed lowland paddy field

The rainfed lowland paddy ecosystem covers about 2.6 million ha, of which the largest areas are found in Java (0.8 million ha), South Sulawesi (0.3 million ha), and North Sumatera (0.2 million ha) (Amien and Las 1999). This system is not irrigated and, therefore, totally depends on rainfall. The rainwater is impounded by bunds, and water depth may exceed 50 cm. In Pati District, where the largest area of rainfed paddy fields in Central Java is to be found, local farmers grow two rice crops during the wet season, i.e., dry-seeded rice (*gogorancah*) at the beginning of the rainy season, and transplanted rice with minimum tillage (*walik jerami*) at the end of the rainy season. After the harvest of the second crop, the field is usually fallow during the dry season. A few farmers build on-farm reservoirs (OFRs) to collect excess water during the rainy season and use the water in the dry season to grow the secondary crops, such as mungbean, corn, soybean, peanut, cucumber, etc.

The rainfed paddy field system is characterized by lack of water control, with floods and drought being potential problems. Despite the increase in the area planted with rainfed lowland rice, the yields remain low. According to Amien and Las (1999), rice yields in rainfed areas were 10% to 25% less than the average yield in Java, and 15% to 20% less than the average yield in South Sulawesi. Improvement of rainfed lowland management is, therefore, needed in order to increase yields.

In this study, the biological management of the cropping system to improve the soil fauna population and its function in ecosystem processes was studied in rainfed paddy fields through modification of the bund distance (4m and 8m) and cultivation of crops on the bunds. It was expected that (1) a short bund distance (4m) would facilitate the movement of the soil fauna from fields (during flooding) to bunds and that (2) crops on bunds would increase the soil surface cover thus protecting the soil fauna on the bund from direct sunshine. The short-bund distance and bund cultivation were, therefore, expected to enhance the soil fauna population and its ecological services. In order to benefit from soil fauna activity for sustainable and productive agriculture a better understanding of soil fauna as a soil community and their functions in the regulation of soil fertility is needed.

1.2 Soil fauna as a community

Soil fauna as a component of soil communities may be classified into different categories, depending on the purpose of the study. Soil fauna are often categorized according to the feeding habits, i.e., saprophagous (decomposers) that consume a wide variety of dead higher-plant material as well as microflora, and predators, which feed on micro-, meso- and macrofauna (Petersen and Luxton, 1982). Soil fauna are also classified into three groups according to body size, i.e., microfauna (body width less than 0.2 mm), which include nematodes and protozoa; mesofauna (0.2 mm to 2 mm), including microarthropods (mainly collembolans and mites) and enchytraeids; and macrofauna (2.0 mm to 20.0 mm) with termites, earthworms, ants, beetles, myriapoda and other macroarthropods (Lavelle and Spain 2001).

Collembola and Acari (mites) are dominant animals among microarthropods, both numerically and in terms of biomass (Lavelle and Spain 2001). Collembola comprises seven families, namely Poduridae, Hypogastruridae, Onychiuridae, Isotomidae, Entomobryidae, Neelidae and Sminthuridae, with most of them living in the soil or in such habitats as leaf litter, under bark, in decaying logs, and in fungi. Some species are also found on the surface of fresh water pools or along the seashores. Most soil-inhabiting springtails feed on decaying material, fungi and bacteria, and others feed on arthropod feces, pollen, algae, and other materials (Borror *et al*. 1989).

Acari comprises a very large group of small to minute animals and is divided into six suborders, namely: Holothyrina, Mesostigmata, Ixodida, Prostigmata, Astigmata and Oribatida. They occur in all habitats, both aquatic (fresh and salt water) and terrestrial (Borror *et al*. 1989). The orders that are relevant to soil biology, for instance spider mites (Tetranychidae, member of Prostigmata), are plant feeders, and some other species can cause serious damage to orchard trees, field crops, and greenhouse plants. The most important Acari in relation to the soil fertility are Oribatida or Cryptostigmata. Oribatid mites are found in leaf litter, under bark and stones, and in the soil. They are mainly scavengers and are important in breaking down organic matter and promoting soil fertility (Borror *et al.* 1989).

The other important mesofauna group comprises enchytraeids, which are small white-colored Oligochaeta. Anatomically, they form a relatively simple and uniform group, with body length varying from less than 1 mm for the smallest species to 5 cm for the largest species. They live particularly in terrestrial environments but also in aquatic environments (O'Connor 1967). Although Acari and Collembola are the major animal groups in mesofauna communities, the other minor groups, Protura, Diplura, Pauropoda and Symphyla may be locally important. Protura and Diplura may be panphytophages or predators of other microarthropods. Symphyla may be a serious pest for a wide range of plants (Lavelle and Spain 2001).

In terms of their biomass, abundances and function in ecosystem processes, earthworms, termites and ants are the most important soil fauna in terrestrial ecosystems (Fragoso and Lavelle, 1995; Lavelle *et al.* 1997; Lavelle and Spain 2001). In some tropical rainforests, earthworms accounted for 51% of the total biomass, while termites composed 13%. When it comes to abundance, termites dominated with 37%, followed by ants (23%) and earthworms (9%).

Earthworms are distributed widely in forests, grasslands, farmlands, lakes, marshes, and in the ocean. The earthworm body length varies from a few centimeters to 2-3 meters (Edwards and Bohlen 1996), with the live biomass commonly ranging from 30 to 100 g m^{-2} (Lavelle and Spain 2001). The social insect group termites (Isoptera) consists of approximately 2600 species worldwide. Termites differ greatly in their feeding habits and the type of nest they construct (Martius 2001); some wood-feeding species live entirely in galleries excavated within decaying logs or wood, others construct earth mounds of varying size and complexity. Their importance for soil biology lies in their contribution to soil structure (they move and mix soil and organic matter from different horizons), and to soil chemistry as they play an important role in organic matter decomposition (Amelung *et al*. 2001). Other important insect groups are ants (Formicidae). Ants occur practically everywhere in terrestrial habitats and outnumber in individuals most other terrestrial animals. Most of the species are predators, herbivores or seed feeders, and not decomposers.

The other macroarthropods, such as Coleoptera, Diptera larvae, Myriapoda, etc., may locally be important. Coleoptera are a very important soil animal group in Mexican forests (Fragoso and Lavelle 1995). The Coleoptera, which is the largest order of insects, colonize most of the habitats where insects occur. Some Coleoptera families, such as the Carabidae, Staphylinidae, Scidmaenidae and Pselaphidae, are predators and prey on many other species, whereas Scarabidae, Tenebrionidae, Ptiliidae, Scolytidae, etc., are decomposers (Raw 1967; Hanagarth and Brändle 2001). Diptera larvae occur predominantly in moist or sub-aquatic situations. They are predominantly saprophagous and a relatively small number of them attack living plants, as miners or borers in different parts of the plant. Other soil macroarthropods, such as Isopoda, Aranae, Homoptera, Heteroptera, Hemiptera, Thysanura, and Blattoidea may occasionally be important (Daly *et al*. 1998; Lavelle and Spain 2001).

1.3 The role of soil fauna in ecosystem processes

The important ecosystem processes such as decomposition of organic matter and nitrogen mineralization are influenced by factors such as resource quality, physical environmental conditions (mainly temperature and humidity), and interactions within and between the fungi, bacteria and soil fauna (Sharma *et al*. 1995; Swift 1995). The abundance and diversity of soil organisms may also influence the rate of decomposition and nutrient availability for uptake by plants (Anderson 1998).

In paddy soils, the mineralization of organic N, P, and S play an important part in the transformation of nutrients. Since N is the principal constraint in rice production, more studies are available on N mineralization than on the mineralization of P and S in paddy soils. Zhu *et al*. (1984) reported that N uptake by rice plants grown on no-N plots in intensive cropping systems was derived from the mineralization of soil N, and ranged from 35 to 139 kg N/ha. Furthermore, they reported that most of the mineralizable N of organic manures, except straw, was released within one month after incorporation and submergence. According to Bucher *et al.* (2002), incorporating rice straw shortly after harvest, before a two-month unflooded fallow period, can improve N and P nutrition of the subsequent rice crop. The application of legume mulch appears to increase the Oligochaeta populations, which are likely to participate in decomposition of legume residues in paddy soils (Yokota and Kaneko 2002).

1.3.1 Soil fauna in terrestrial ecosystems

Soil fauna contribute up to about 30% of the total net nitrogen mineralization in forest and grassland ecosystems (Verhoef and Brussaard 1990). Earthworms participate in the nitrogen cycle through their production of casting and mucus and decomposition of dead tissue. Earthworm activity can increase the nitrogen availability for uptake by plants in shifting agriculture systems in India (Bhadauria and Ramakrishnan 1996). As ecosystem engineers, earthworms, termites and ants can directly or indirectly affect the availability of resources to other organisms through modification of the physical environment (Lavelle *et al.* 1997). For instance, the nest mounds constructed by ants can increase the incidence and abundance of a plant community due to nutrient enrichment of the nest soils (Wilby *et al*. 2001). The increase in plant biomass and total plant nitrogen content due to soil animals, particularly protozoa, is also reported by Bonkowski *et al*. (2001).

Maintaining soil animal diversity is important in order to sustain the ecosystem processes. Naeem *et al*. (1995), in their mesocosm experiment with direct manipulation of diversity under controlled environmental conditions, provided the evidence that ecosystem processes like community respiration, productivity, decomposition, etc., may be negatively affected by the decline of animal species diversity. A laboratory experiment to estimate the decomposition rate using three species of Plecoptera as detritivores indicated that a number of species have significant effects on the leaf litter decomposition rate, which increases with the increase in animal species richness (Jonsson and Malmqvist 2000).

Vreeken-Buijs and Brussaard (1996) indicated the important role of soil microarthropods like Acari (mites) and Collembola, and enchytraeids in increasing the decomposition rates of wheat straw. Adejuyigbe *et al*. (1999) reported that the dynamics of soil microarthropod populations are strongly affected by climatic fluctuation. The population of soil microarthropods is higher in the rainy seasons than in the dry seasons, and their population is greater under natural fallow than under continuous cropping with maize and cassava. Under continuous cropping, they are not subject to unfavorable microclimatic factors such as low soil water content, high soil temperature, and high incident radiation due to reduced cover.

1.3.2 Soil fauna in rice field ecosystems

Population and diversity of soil fauna in flooded systems are different compared to those in non-flooded conditions. Oligochaeta, such as Tubificidae, Naididae and Enchytraeidae, are a major component of soil fauna in wetland rice field conditions (Lavelle *et al*. 1997; Yokota and Kaneko 2002), where they can accelerate nutrient mineralization (Simpson *et al*. 1993a). Larvae of Diptera (Chironomidae and Culicidae), ephydrid flies and collembolans are also abundant in flooded conditions (Settle *et al.* 1996), where they act as decomposers. Lavelle *et al.* (1997) reported that Tubificidae play an important role with regard to soil fertility, because they transport the components of photosynthetic aquatic biomass (cyano-bacteria, micro-algae and aquatic macro-phytes) and their breakdown products from the surface to the deeper soil layer thus providing nutrients to the rice plant.

Besides the positive effects of soil animals in flooded conditions, some soil animals can also cause serious damage to rice plants. Chironomid midge larvae are reported as being the most widespread and serious rice pests in New South Wales

(Stevens 2000). Stem borers are the main insect pest threatening rice plants in many countries, causing severe yield losses. The yellow stem borer *Scirpophaga incertulas* is the most commonly found stem borer in the Philippines (Rubia *et al*. 1996), while the white stem borer *Scirpophaga innotata* causes whiteheads in rice plants in West Java, Indonesia (Rubia *et al*. 1997). The most abundant rice arthropods found in irrigated lowland rice fields in West Africa that cause rice plant damage are diopsid flies, leafhoppers, spiders, Odonata, and stem borers (Oyediran and Heinrichs 2001).

Several collembolan species are important in rice field ecosystems. Along with chironomids and ephydrid flies, collembolans represent 28% of the total abundance of arthropods collected from 12 locations in Javanese rice fields (Settle and Whitten 2000). Approximately 41 collembolan species were found in Java, whereas approx. 96, 502, 128, 118, and 150 species of caddisfly (Trichoptera), ground beetles (Carabidae), water beetles, earwigs (Dermaptera), and Odonata, respectively, had been recorded from Java and Bali (Whitten *et al*. 1997). Up to now, little work has been conducted on soil fauna in rice fields and other ecosystems in Java, Indonesia. Therefore, in this study, a basic assessment of soil fauna in different ecosystems of the region was undertaken.

Because of the different cropping patterns during the wet and dry seasons, the rainfed paddy field system is subject to two contrasting ecological conditions, i.e., a flooded and a dry system. Consequently, the population and diversity of soil fauna, organic matter, and nitrogen mineralization are also different in those systems. Little is known about the influence of the dynamics of the soil fauna on organic matter decomposition in rainfed paddy field systems. Therefore, the study of environmental changes is important to optimize organic matter decomposition and nitrogen mineralization of the cropping sequence.

1.4 Objectives

The study consisted of three main experiments:

1. The study of soil fauna in a rainfed paddy field ecosystem to evaluate the dynamics of soil fauna in dry and flooded phases of the rainfed paddy ecosystem. This study also included a screening of soil fauna in different natural ecosystems of the region, to obtain a general overview of the soil fauna and to assess the potential group diversity in natural ecosystems as a standard against which to compare the

agricultural site. In addition to the soil fauna population, the feeding activity of the soil fauna in different natural ecosystems was evaluated using the bait-lamina method.

2. The study of soil organic matter decomposition to evaluate the role of soil fauna in litter decomposition during the dry and flooded phases of a rainfed paddy field.
3. The study of N mineralization to evaluate the contribution of soil fauna to nitrogen mineralization in the dry and flooded phases of a rainfed paddy field.

The specific objectives of this research were:

1. To study the abundance, biomass and diversity of the soil fauna in the two phases of a rainfed paddy field, namely the dry short fallow period and the flooded phases (dry-seeded rice and transplanted rice) during the rice field subsystem.
2. To study the influence of crops (legumes and cassava) cultivated on the bunds on abundance, biomass and diversity of soil fauna in the fields and on the bunds during the dry and flooded rice-field phase.
3. To study the influence of different bund distances of 4m and 8m on the abundance, biomass and diversity of soil fauna in the fields and on the bunds of the above systems.
4. To study the influence of different bund distances (4m and 8m) and crops (legumes and cassava) cultivated on the bunds on the role of soil fauna in organic matter decomposition and nitrogen mineralization.

1.5 Hypotheses

1. Soil fauna and their ecological services (organic matter decomposition and N mineralization) can be manipulated to the benefit of the farmer through the management of the cropping system.
2. The diversity, biomass and density of the soil fauna in crop-planted bunds are higher than that in bunds without plants.
3. The increase in the soil fauna population in the dry phase (fallow) after the flooded period is faster in plots with crop-planted bunds than in plots without plants on the bunds.