Chapter II

Literature review

2.1 Cambodian Rice Production

2.1.1 Current production status

Rice is the most important staple food for the Cambodian people. The English phrase “to eat” is “pisa bei” in Khmer, which literally means “eat rice” (Helmers, 1997). Cambodia is close to the centre of origin of rice, and farmers in the region have been growing rainfed lowland rice for at least 2,000 years, and possibly longer in the case of upland rice (Chandler, 1993). Irrigated rice production technologies were introduced 1,500 years ago, and were widespread during the Angkorian period (Chandler, 1993). The centrepiece of the irrigation system were the great reservoirs and canals around Angkor Wat, and this irrigation system has provided a workable supplementary irrigation supply for rice production until the present.

Agriculture employs about 80 % of the total Cambodian population, providing the major source of income especially for rural dwellers (Helmers, 1997). The agricultural sector is, therefore, a major contributor to the national economy. Until the late 1960s, Cambodia regularly produced a rice surplus, and was the world’s largest rice exporter. In 1967, the area under cultivation reached 2.5 million ha and total production was 3.8 million tonnes. However, rice production decreased rapidly after 1974, and rice exports from then until the 1980s were non-existent because of civil wars. According to statistics from the Cambodian Ministry of Agriculture, Forestry and Fisheries (MAFF), total rice production also decreased from the early 1970s until the late 1980s (Helmers, 1997).

After the wars, both the production and total rice growing area began increasing to their current status. From 1980 through 1999, total rice area increased from 1.4 million to 2.0 million ha, and rice production increased from 1.7 to 4.0 million tonnes (Table 2.1). The wet-season grain production increased significantly from 2.0 million tonnes in 1993 to more than 3.4 million tonnes in 1999 (Table 2.1). Better crop management technologies, improved quality and availability of chemical fertilisers in the private markets, and higher-yielding rice varieties released by the Cambodia-IRRI-Australia Project (CIAP) significantly contributed to the increased production (Ouk *et al*., 2001). The wet-season grain yield increased from 1.2 t/ha in 1993, to 1.8 t ha^{-1} in 1999 (Ouk *et al*., 2001), as farmers shifted from growing late-maturing traditional varieties (> 150 days) to intermediate-maturing traditional varieties (120-150 days), and high-yielding modern varieties (< 120 days).

Table 2.1 Areas planted to rice, total grain production, grain yield, and total population growth in Cambodia from 1900 to 1999.

Year of production	Area planted (‘000 ha)	Rice production (‘000 t)	Grain yield (t/ha)	Population (million)	Export rice (Yes/no)
1900[a]	400	560	1.40	2.0	Yes
1950[a]	1657	1576	0.95	4.3	Yes
1960[a]	2150	2335	1.09	5.5	Yes
1970[a]	2399	3184	1.33	7.0	Yes
1980[a]	1441	1715	1.19	6.3	No
1990[a]	1890	2500	1.32	8.7	No
1999[b]	2085	4073	1.95	12.0	Yes

([a] Source: FAO, 2000);([b] Source: MAFF, 2000)

The harvested areas in the dry season increased significantly from about 0.2 million ha in 1993, to 0.24 million ha in 1999 (Table 2.2). Corresponding grain yields increased from 2.7 to 3.1 t/ha. Dry-season rice production represents only 18 % of the nation’s total production, but it is of importance to Cambodia’s food security and economic growth. Ouk *et al*., (2001) reported that the national average grain yield (including both wet and dry season crops) increased from 1.3 t/ha in 1993, to 1.9 t/ha in 1999 (Table 2.1).

2.1.2 Climate and rice growing ecosystems

Cambodia is rimmed on three sides by mountains, which surround a large central plain supporting the Tonle Sap, the largest fresh-water lake in Southeast Asia, and accompanying river complexes. The central plain is extremely flat with an elevation difference of only 5 to 10 m between south-eastern Cambodia and the upper reaches of Tonle Sap in the northwest, a distance of more than 300 km. The plain resulted from long-term colluvial-alluvial depositions from the mountains, and from sediments carried by the Mekong River and Tonle Sap River (White *et al*., 1997a,b).

Table 2.2 Proportion of rice production areas (%) in different rice growing ecosystems in Cambodia from 1967 to 1999

Rice-growing	Rice production area (%)			
ecosystem	1967[a]	1981[a]	1995[b]	1999[c]
Wet season	93.8	93.4	91.7	88.9
Rainfed lowland	77.9	86.7	85.7	84.0
Early-duration	2.9	15.6	17.4	17.2
Medium-duration	12.4	17.0	35.4	38.9
Late-duration	62.6	54.1	32.9	27.9
Deepwater	15.9	6.7	4.1	2.6
Rainfed upland	-	-	1.9	2.2
Dry season	6.2	6.6	8.3	11.1
Total ('000 ha)	2508.2	1441.0	2038.1	2153.9

([a] Source: MAFF ,1993); ([b] Source: MAFF ,1996); ([c] Source: MAFF ,2000); (-: data not available).

The Mekong River crosses the country from the north to southeast by passing through the capital Phnom Penh. At Phnom Penh, the Mekong River meets the Bassac Rivers, which flows south, and the Tonle Sap River, which flows northwest or southeast depending on the season. Between May and October, melting snow in China and rainfall in the upper reaches of the Mekong River cause water levels to rise. During this period water flows northwest from the Mekong River to the huge reservoir of the Tonle Sap through the Tonle Sap River, and expands this reservoir ten-fold in area to about 25,000 km^2. In late October, when the water level in the Mekong River subsidies, the water flows back from the reservoir into the Mekong and Bassac Rivers. The Mekong River generally rises and falls about 9 m every year.

Situated in the tropics, Cambodia (10-15^o N) experiences a monsoonal climate with distinctive wet and dry seasons. The wet season extends from May to October, while the dry season runs from November to April. Rainfall usually occurs during the period May to October, however, it is extremely erratic and "mini" droughts are experienced during any of these months. Because of these mini droughts, farmers preferentially cultivate traditional photoperiod-sensitive rice varieties. Most rice growing areas receive between 1,250 and 1,750 mm rainfall annually (Nesbitt, 1997a). Minimum and maximum temperatures vary from 21^{o}C to 37^{o}C, and the relative humidity fluctuates between 60 and 80 % throughout the year. The least humid days are experienced during the lead-up to the break of the wet season. Evaporation is also the greatest during this period, with water evaporating from an open surface at a rate of more than 250 mm per month, which is greater than the average precipitation for each month (Nesbitt, 1997a). Cambodia is not located in the Typhoon belts, and strong winds are generally not a problem. The longest day of the year (June 21) has a day-length of 13 h 12 min, decreasing to 12 h 30 min in August, and to 11 h 30 min in December (Nesbitt, 1997a). Fluctuations in day length normally affect flowering of many crops including traditional, photoperiod-sensitive rice. Sunshine periods are highest during December through February, however, the cloud cover increases as the wet season approaches, with the sunshine hours decreasing.

Rice crops are cultivated in a wide range of agroecosystems in Cambodia (Figure 2.1), including rainfed lowland, upland, floating and/or deep water, and irrigated dry season (Javier, 1997). Less than 3 % of the Cambodian rice area is currently planted to deep water and/or floating rice (Table 2.2). Small areas of upland rice are found in north-eastern Cambodia, mainly under shifting-agricultural systems. Of the three types of dry season rice, most is receding floodwater rice that is planted when the water level recedes on the flood plains adjacent to rivers, and around the Tonle Sap. The other types of dry season rice either receive supplementary irrigation or are fully irrigated (Javier, 1997).

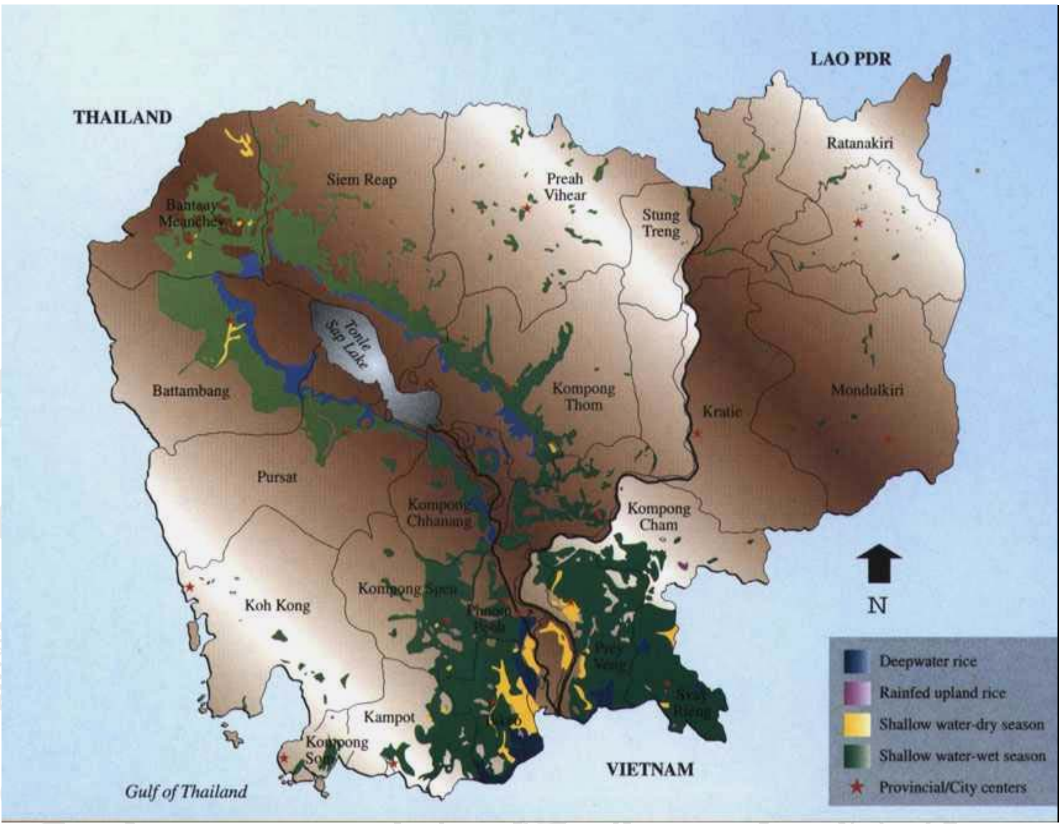

Figure 2.1 Major rice-growing ecosystems in Cambodia (Nesbitt, 1997a).

The wet season rice production currently occupies 88 % of the total rice growing areas in Cambodia, 84 % of which is found in rainfed lowlands (MAFF, 2000). The rainfed lowlands of Cambodia are bunded fields that are almost completely dependent on local rainfall and run-off from surrounding areas for water supply (Lando and Mak, 1994a, b). The rainfed lowlands have variable duration of both flooded and aerobic conditions as a result of variable quantity and duration of rainfall. However, floodwater depths of 50 cm or more and droughts may be experienced for short periods.

The general characteristics of the rainfed lowland rice ecosystems in Cambodia are well described by Lando and Mak (1994a) and Fujisaka (1988). There are three interrelated factors in the broad classification of rainfed lowland rice areas: topography, water depth in the field, and varietal type. The varietal classes currently used to categorize rainfed lowland areas have equivalents in terms of field levels or water regimes. Field levels are described by local names as high (srei leu), middle (srei kandal), and low (srei kraom), and they are distributed in different ways. Fujisaka (1988) reported water levels of 0-15, 10-30, and 30-80 cm for the high, middle and low fields, respectively, whereas, Lando and Mak (1994a) concluded that water level seldom surpassed 20 cm in the high fields, and was often 20-40 cm in the middle fields. The low fields would often have more than 30 cm of standing water, but a water level of 50 cm or more is uncommon.

There are appropriate varietal types for each field level or water regimes. Early-maturing (srau sral), intermediate-maturing (srau kandal) and late-maturing (srau thungun) rice varieties are located in upper, medium and lower fields, respectively, to match the maximum water depth that crops would experience and the duration of free standing water in fields (Javier, 1997). Farmers classify photoperiod-insensitive varieties as those that mature in less than 150 days, and photoperiod-sensitive those varieties that flower from mid-October to early-December. Medium-duration rice varieties flower from mid-October to mid-November, and late-duration ones flower from late-November to mid-December. Medium- to late-duration rice varieties are both strongly photoperiod, sensitive varieties (Javier, 1997).

All fields in rainfed lowlands are exposed to periods of flood and/or drought. The high fields are generally more drought-prone, whereas, the low fields are more flood or submergence-prone than the others. There are some sites in each field level that have more favourable water control. Some areas are partially supplemented with irrigation although the proportion is still quite small. However, some areas within the low fields are subjected like the deepwater rice area, to prolonged periods of submergence in certain years. There is also variation in soil types at each field level, although the high fields are often sandy and have the least soil-type variation. The other field levels have sandy, silt loam, silty clay or clay soils. In general, soil fertility increases from the high to the low fields (White *et al.*, 1997a). Diversity among and within the rainfed lowland ecosystems is also enhanced by the variation in cultural practices implemented (Lando and Mak, 1994a; Javier, 1997).

2.1.3 Opportunities in increasing rice production in the rainfed lowlands

There are a number of strategies involved in boosting rainfed lowland rice production in Cambodia in order to meet both the domestic and export requirements, but we here select only the priority concerns. Very limited potential exists for increasing the area under rice cultivation in rainfed lowlands, because land mines in many parts of the country prevent the expansion of rice cultivation, and labour shortages exist in the provinces (Nesbitt, 1997b). Therefore, farmers need new ways to boost food production for year-round consumption and for market purposes on existing areas.

The first priority for national development is to encourage farmers to select a variety of early-maturing crops that can be cultivated more than once a year, especially during the wet season in the same field, and can produce high yields. Improved-modern varieties need to be developed or/and introduced that more efficiently convert energy into grain when cultivated in discrete ecosystems. Seed purification and multiplication technologies need to be provided and expanded through plant breeding programmes and seed certification.

Soil fertility could be improved by chemical fertilization (using recommended rates appropriate for each soil type), and also using locally available nutrient resources in order to increase total production. A possible solution to low fertilizer use is to subsidise fertilizer sales. A study in Takeo Province of Cambodia by Ieng et al. (2002) indicated that in the rainfed lowland areas farmers generally use chemical fertilizers such as phosphorus (P), potassium (K) and sulfur (S) but at rates less than the recommended rates for each soil type (White et al., 1997a; Dobermann and White, 1999; Seng *et al*., 2001). These farmers tend to overuse N relative to present rates of P, K and S. However, nutrient balances in many of the impoverished rainfed lowland rice soils in other provinces of Cambodia are poorly understood, and rice yield responses to application of commercially available fertilizers is considered by farmers to be uneconomical (Nesbitt, 1997b), probably due to their limited first-hand experiences (poor timing of fertilizer application, poor matching of the fertilizer types with each soil), combined with abiotic and biotic constraints.

Fertilizer recommendations need to be refined for each soil type, and possibly for micro-ecosystems, and a wide range of fertilizers must be imported or formulated within the country to cater for various soil types. On the other hand, in the case of resource-poor farmers, using locally available farmyard and organic manures (cow manure, green manure, rice straw and crop residues) is another option to maintain the soil fertility level. Farmyard manure supplies are limited and generally nurseries receive most of the supplied materials (Ros, 1998). Ros *et al*., (1997) found that there was an increase in both rice yield and soil-nutrient status with cow manure application. Incorporation of the introduced leguminous crops including *Sesbania rostrata* has been shown to increase rice yields (Mak and Nesbitt, 1993). Farmers accepted the practice but a reliable source of legume seeds has not yet been developed. Cropping rotations incorporating cash crops are an additional way of improving soil fertility (Nesbitt and Chan, 1991a,b). The expansion in the use of these low-cost technology practices would lead to more suitable farming systems, but at the same time more research in the physical and social sciences is required to develop technologies appropriate for the rainfed lowland ecosystem.

2.1.4 Major Rice soils and their management

A good understanding of the soil resources of the country is essential for improving the productivity and efficiency of Cambodian agriculture, especially for rice production. The suitability of a wide variety of cropping systems and management strategies depends on the knowledge of the soil type occurring at any particular location. There have been few studies on the soil resources of Cambodia, apart from the exploratory surveys of Crocker (1962), and followed by the classification of soils in the Mekong Delta done by FAO (1975) and soil mapping completed by Vietnamese pedologists (Thach, 1985); most these studies were of little practical significance for agricultural development. In recent years, the Cambodia-

IRRI-Australia Project (CIAP) has made good progress in describing the general nature of the soils used for rice production in Cambodia (White *et al.*, 1997a,b).

Table 2.3 Proportion (%) of each of the main rice-growing ecosystems in Cambodia occupied by different soil types

Soil types	Rainfed lowland	Deep water	Irrigated	Upland
Prey Khmer	13	3	4	18
Pratear Lang	30	0	10	37
Bakan	13	15	6	0
Koktrap	5	5	1	0
Toul Samroung	15	5	13	16
Labansiek	1	0	0	18
Kampong Siem	2	0	2	9
Kein Svay	0	5	11	0
Kbal Po	14	21	47	0
Krakor	7	46	6	0

(Source: White *et al.*, 1997b)

There has now been a good understanding of the soil potentials for intensified rice production, and of the ways these soils should be managed (White *et al.*, 1997a,b). Eleven main soil groups (Table 2.3) were defined based on recognizable profile features and management strategies, covering low to high yield potentials for rice (Pheav *et al.*, 1996; White *et al.*, 1997b). Soil with low yield potential for rice cultivation occurred over 55 % of the total rice growing areas (Pheav *et al.*, 1996). These soils included Prateah Lang, Prey Khmer, and Bakan (White *et al.*, 1997a), and they dominated the rainfed lowland rice-growing areas. Soils were generally sandy, acidic, poorly buffered in pH, and low in fertility. Soils of medium yield potential for rice production (Koktrap, Toul Samroung, Orung, Labansiek, and Kompong Siem: White et al., 1997a), occupied about 25 % of the total rice areas, occurring in both the rainfed lowland and upland rice-growing areas. These soils were generally medium to heavy textured, from strongly acidic to near neutral pH, and had from low to moderate fertility levels. High yield potential soils (Krakor, Kbal Po and Kein Svay; White *et al.*, 1997a), occupied about 20 % of the total rice areas, and dominated in the deepwater and irrigated rice ecosystems. These soils were mostly heavy textured, moderately acidic, but quite fertile and posed only few problems for rice production.

Table 2.4 Selected properties lowland rice-growing soils of Cambodia (0-20 cm depth, sieved to < 2.0 mm). Values are means of 249 samples

Major properties	Prateah Lang
pH (1:1 H2O)	5.4
Organic C (g/kg)	4.0
Sand (g/kg)	498
Silt (g/kg)	370
Clay (g/kg)	132
CEC [cmolc (+)/kg]	3.7
Exch. Ca [cmolc (+)/kg]	1.2
Exch. Mg [cmolc (+)/kg]	0.5
Exch. K [cmolc (+)/kg]	0.1
Exch. Na [cmolc (+)/kg]	0.4

(Source: Oberthur *et al.*, 2000)

The physical and chemical properties of this Cambodian rice soils have recently been reviewed by Pheav et al. (1996), White et al. (1997a,b), and Oberthur *et al.*, (2000), and these properties are summarized for the three soil groups that are particularly relevant to the present study (Table 2.4).

Prateah Lang Soil (Alfisol order; Soil Survey Staff, 1994): The soil occupies about 30 % of the total rice area and occurs in all provinces of Cambodia (White *et al.*, 1997a,b). The Prateah Lang soils are characterized by light textured topsoil overlying heavier textured subsoil. The soil makes up a substantial part of the old colluvial-alluvial terraces with the soil occurring in the upper fields generally having a sandier topsoil than those occurring in the lower fields. The effective rooting depth of this group is often restricted by a firm to extremely hard traffic pan occurring within the top 15-25 cm. The surface soil is very light gray or pale brown or may have a pinkish tinge when dry. Plinthite development in the subsoil is usually a prominent feature of the soil and may also restrict rooting depth. The shallow root volume and the poor available water storage make rice on this soil prone to drought. The topsoil is also usually structureless and the small amount of clay in this horizon is highly dispersed, which generally causes a thin layer of clay to be deposited on the soil surface when it dries. The soil must, therefore, be very wet before it can be ploughed by animal traction. The soil particles also settle quickly after being disturbed, and transplanting must occur within a few hours of harrowing. Ironstone gravel can occur throughout the profile and, in some cases, large ironstone boulders can outcrop at the surface.

These soils have very low cation exchange capacity, low organic matter content and low reserves of weatherable minerals. Unfertilized rice yields on these soils range from about 0.8 to 1.4 t/ha. Responses to N, P and K fertilizer application occur frequently and some areas are responsive to S fertilizer application (CIAP, 1994). Boron (B) deficiency has also been observed in rice/maize on these soils in the glasshouse conditions (Lor *et al*., 1996). The soil pH is generally acidic, but it is not a problem for continuously flooded rice production (Seng *et al*., 1999). Crops grown on this soil type, which occur in low areas and receive run-off from surrounding lands may exhibit iron (Fe) toxicity symptoms. A very small area of this soil type may also suffer from salt toxicity problems (White *et al*., 1997a,b).

2.2 Nutrients turnover

For the rainfed lowlands, there remains a need to understand further the turnover processes of nutrient recycled from the rice crop residues and from early wet season fallow residues to subsequent rainfed lowland rice crops for the next wet season.

When inorganic fertilisers are used on a long-term basis, there could be some deterioration in soil health (Pillai *et al*., 1990). Indeed, concern about negative environmental impacts of excessive amounts of mineral fertilizers used in the high-input agriculture has grown dramatically in the last two decades (Jordan and Weller, 1996; vander Voet *et al*., 1996). Strategies for the long-term management of rice soils would have to pursue the goal of sustainable, improved soil fertility but at the same time acknowledge the economic limitations of farmers in their fertilizers input (Ragland and Boonpuckdee, 1987). Considerable research has been conducted in recent years to search for alternative sources of P for crop production in tropical soils. Research has focused on the use of low-cost indigenous materials, such as locally available phosphate rock (PR), farmyard manure and/or crop residues (Ragland and Boonpuckdee, 1987).

To overcome the low fertility of rainfed lowland rice soils, and to sustain both rice production and soil health, the effects of different types of organic matter on subsequent grain production have been investigated (Garrity and Becker, 1994). Organic sources of nutrients can play a major role in restoring the soil health, and, in a cropping sequence they may be more effective than inorganic fertilisers if they leave sufficient residual nutrients for the succeeding crop (Songmuang *et al*., 1997). In recent years, the study of plant residue quality has received increasing attention in low chemical input agricultural systems of the tropics, because this system mainly relies on plant nutrients coming from decomposing plant residues (Songmuang *et al*., 1997). Rice straw and stubble are often left in the fields after harvesting in rice-growing countries, although in some regions the consumption of straw by animals and for paper manufacture is significant. The contribution of P from recycled rice residues is modest, but at least substantial quantities of organic C, Ca, Mg, N, K and Fe are known to return to the soil in the plant residues (Ponnamperuma, 1984; Garrity, 1986; Alberto *et al*., 1996).

Many researchers have investigated the beneficial roles of organic matter amendments and the fate of its decomposition products in the soils. Decomposition rates and microbial activities are influenced by the soil properties, the nature of decomposing materials, and environmental factors (Lam and Dudgeon, 1985). The ratio of carbon to nitrogen, and contents of lignin and polyphenol of plant residues are important components that determine plant residue decomposition (Melillo *et al*., 1982; Palm and Sanchez, 1990; Tian *et al*., 1992; Konboon *et al*., 1998). Under submerged conditions, organic residues applied to rice have to undergo anaerobic rather than aerobic decomposition processes, and there is not much information available on nutrient release patterns from different organic residues under these conditions (Ruaysoongnern *et al*., 1996) apart of Becker *et al*., (1990); and Becker *et al*., (1994).

Although microbial biomass only accounts for 2 to 3 % of the soil organic matter, it exhibits rapid turnover and can be considered as a driving force of major nutrient cycles in agricultural ecosystems (Jenkinson and Ladd, 1981, Sanyal and De Datta, 1991). Soil microbial P is known to be important reservoir of P in soils (Brooks *et al*., 1984; Srivastava and Singh, 1988; Morel *et al*., 1997).

Phosphorus fertilizer applied to green manure crops was more beneficial to the subsequent rice production than when it is applied directly to rice crops (Beri and Meelu, 1980; Mak and Nesbitt, 1993; Say and Pheav, 1995). In the extremely infertile sandy rice soils, *Sesbania rostrata* in combination with inorganic NPK fertilizers have proved to be particularly effective in enhancing soil N levels and rice grain yields (Mak and Nesbitt, 1993; Arunin *et al*., 1994; Say and Pheav, 1995). To explain differences encountered in the use of green manures, we need to first understand the processes that relate green manure turnover into grain production. Little is known about the key pathways that convert green manure residues into microbial biomass, and the subsequent release of re-mobilised nutrients from this biomass pool. The chemical composition of plants can be greatly influenced by crop species, sources of plant nitrogen, stage of plant growth and both edaphic and climatic conditions (Tang *et al*., 1999). The transfer mechanisms include mulch decomposition, leaching of nutrients from tissues into the soil, belowground root decomposition, root exudation, and direct transfer via mycorrhizae (Tang *et al*., 1997).

The management of the organic matter phase through the addition of green manures to the coarse-textured, nutrient deficient rainfed lowland rice soils has rarely been successful (Wade and Ladha, 1995). Nitrogen-fixing green manure crops, especially *Sesbania rostrata* crops have the disadvantage of being rapidly decomposed that leads to nutrient leaching particularly for N (Becker *et al*., 1995, Kirk *et al*., 1995; Songmuang *et al*., 1997). Moreover, its crop establishment in extremely unfavourable rainfed lowland soils depends on reliable rainfall and alleviating extreme soil P deficiencies in the first place (Bohlool *et al*., 1992; George *et al*., 1992; Singleton *et al*., 1992; Lathvilayvong *et al*., 1995). Such negative experiences need not prevent strategic soil fertility research from exploring the importance of maximizing the benefits of recycling crop residues in the rice-based cropping systems.

In Cambodia, local leguminous species are often grown within the fallow period between successive wet season crops each year. Plants germinated after the first rains following the dry season and are grazed by animals (cattle) for three to four months until the land is tilled in preparation for the next wet season rice crops. This post dry-season fallow is composed of forage legume as a minor component, and non-leguminous herbs and grasses. Phosphorus may possibly have a large impact on the proportion of leguminous species within the fallow system. The proportion of legumes in the fallow pastures may increase after a long period of adding P fertilizer. In turn, this may have positive carry-over benefits on nutrient supply to the following rice in the wet season, as well as, improving the nutrition of animals grazing the pasture. Processes behind expected increases in crop production and soil fertility due to the improved fallow are not known. Indeed, the implications of the dry season and early wet season fallow crops for P cycling and its interaction with rice straw decomposition was studied by Pheav (2002) indicated that, freshly applied P fertilizer, residual P fertilizer and rice straw or other crop residue incorporation significantly increased the growth and total plant P uptake of either rice or fallow crops. Nevertheless, the effect of P turnover from plant residues (either as rice straw or fallow crop residues) alone on the subsequent rice yields and on soil parameters such as P fractions and microbial biomass C, N and P was marginal, but greater increases of these parameters were obtained with a combined use of inorganic P fertilizer plus crop residues.

In the rice-based cropping systems, incorporation of crop residues would be expected to improve soil fertility as well as presenting a substantial economic saving on inorganic fertilizers, especially of P returning to the soil from 1.5 to 5.5 kg P/ha, and 3.1 to 10.7 kg P/ha per cropping season were supplied with rice straw and crop residues of the early wet season fallow.

Incorporating the dry season and early wet season fallow residues may, thus, reduce losses of nutrients from coarse-textured soils by storing large quantities of nutrients in both the above and below ground phases

2.3 Requirement and management of nitrogen, phosphorus, potassium and micronutrients for lowland rice

Since the late 1960s, fertilizer responsive rice varieties have been introduced to rice-growing systems, and the consumption of chemical fertilizers has increased substantially, especially in the irrigated rice ecosystems (Pandey, 1997). The present nutrient management practices in intensive irrigated rice ecosystems, however, tend to fail to supply potential nutrients (N, P, and K) based on crop demands because the applied technology relies on general, not site-specific recommendations (Dobermann and White, 1998). To meet the projected increase in rice production required in the next few decades, rice yields in the rainfed lowlands should be doubled from their present average of 2.0 t/ha (Fischer, 1998). The possibility of such increases depends on the productivity of the systems which is controlled by the interactions between water availability and nutritional level of the rice plant. This section gives a brief review on the management of N, K, and micronutrients in the rainfed lowland rice ecosystem.

2.3.1 Nitrogen (N)

Lowland rice takes up most but not all of its N in ammonium form ($NH4+$) because the N mineralisation process under flooded conditions ceases at the $NH4+$ form, and the pH and Fe status of most flooded soils favour the uptake of $NH4+$ (Patrick and Mahapatra, 1968; De Datta, 1995). Nitrate and nitrite N are usually too rapidly depleted through denitrification upon soil flooding, to be of value to rice. In acid soils low in active Fe and organic matter content, flooding may not result in significant decrease in Eh, and nitrate N in these soils may be utilised by rice as effectively as ammonium N (Patrick and Mahapatra, 1968). To obtain high rice yield, optimum N nutrition is required at four critical growth stages (De Datta, 1981): (i) just after transplanting, (ii) just before maximum tillering, (iii) at panicle initiation, and (iv) at full heading (anthesis). Rice plants require large amounts of N at the early and mid-tillering stages to maximise the number of panicles. The amount of N required at panicle initiation, and anthesis is to increase spikelet number per panicle, and percentage of filled spikelets per panicle and protein content in the grains, respectively (De Datta, 1981).

In lowland rice ecosystems, nitrogen supplied to rice comes largely from three sources (Patrick and Mahapatra, 1968): (i) ammonium N made available by soil flooding, (ii) N released through mineralisation of soil organic matter and plant residues during flooding, and (iii) N applied as fertilizer.

Mikkelson *et al*., (1995) extensively reviewed nitrogen nutrition for lowland rice culture. The work of Cassman *et al*., (1996), Wonprasaid *et al*., (1996), Bufogle *et al*., (1997), Cassman *et al*., (1997), Prasertsak and Fukai (1997), Cassman *et al*., (1998), Mohanty *et al*., (1999), and Kundu and Ladha (1999) provides a more recent review on management of N nutrition for lowland rice.

2.3.2 Phosphorus (P)

Phosphorus nutrition of flooded lowland rice appears to differ from that of non-flooded crops in two important respects (Patrick and Mahapatra, 1968). First, rice plants can absorb an adequate amount of phosphorus from the soil solution with a concentration of phosphate as low as 0.10 mg P/l. For example, in the comparison of P uptake by several upland crops, Otani and Ae (1996) found that rice, pigeonpea, and groundnut took up more P than other crops such as maize, buckwheat, soybean, and sorghum when grown in soils with relatively low Olsen extractable P ranging from 1.2 to 1.6 mg/kg soil. This suggests that rice is relatively efficient in absorbing P at low levels of P in the soils. Secondly, flooding causes soil reduction which induces a release of phosphate from the non-labile fractions to the soil solution. This probably ensures an adequate supply of phosphorus to rice in flooded soils if the soils contain significant amounts of Fe-P and RS-P.

Phosphorus stimulates root growth, promotes early flowering and ripening particularly in cool climates, and encourages more active tillering which enables rice plants to recover more rapidly and more completely after suffering from any adverse condition, and it stimulates grain development and grain quality of rice (De Datta, 1981).

The P-absorbing capacity of the rice roots is high at the initial growth stages and it decreases as the plant ages (Patrick and Mahapatra, 1968; Fageria, 1987). In P-sufficient plants, P is absorbed by the roots, and is transported through the xylem to the younger leaves of the plants: in addition, there is significant re-translocation of P in the phloem from older leaves to the growing shoots and from the shoots to the roots. But in P-deficient plants, the limited supply of P to the shoots from the roots via the xylem means that both the younger leaves and growing shoots are heavily dependent on mobilisation of stored P in the older leaves and on its re-translocation (Schachtman *et al*., 1998).

The management of P for rice crops is strongly interrelated with soil reactions, degree of weathering, amount and nature of clay minerals, organic matter content, and water regime (De Datta, 1981; Sanyal and De Datta, 1990). When planning P management practices, the extent of initial P adsorption reactions in the soil and subsequent slow reactions should be considered.

Phosphorus management should aim at maintaining an adequate concentration of P in the soil solution to meet the requirement of P by rice plants at the critical growth stages, and also to increase P use efficiency of the crop. The management of P nutrition for rainfed lowland rice is complicated because of the fluctuation in soil-water regime which may cause temporary loss of soil-water saturation during times when the supply of P to the plant is critical. This uncertainty of the timing of loss of soil-water saturation is one of the difficulties in controlling fertilizer P requirements of rice grown under rainfed lowland conditions. By contrast, the management of phosphorus has received scant attention even under irrigated ecosystems in favour of increasing fertilizer N use (Dobermann *et al*., 1998). However, in the management of

P nutrition for lowland rice, one should consider the indigenous source of P, method, and time of application.

2.3.3 Potassium (K)

A number of older reports suggested that most lowland rice soils had adequate K contents because the response of rice yield to K addition was generally negligible and inconsistent (De Datta, 1981; De Datta and Mikkelsen, 1985). A number of recent studies reported that K nutrition of rice has become increasingly relevant due to widespread K imbalance and deficiencies of K occur not only on poor fertility light-textured, but also on heavy-textured inherently high-fertility lowland rice soils (Cassman *et al*., 1997; Dobermann *et al*., 1998).

De Datta and Mikkelsen (1985), and Dobermann *et al*., (1998) extensively reviewed the work on management of K nutrition for lowland rice.

2.3.4 Micronutrients

Nutritional problems of rice associated with microelements have mainly concerned Fe, Mn, and Zn deficiencies, and Fe toxicity (Tanaka and Yoshida, 1970; Ponnamperuma, 1976; Benckiser *et al*., 1982; Fageria and Robelo, 1987; Sahrawat *et al*., 1996; Savithri *et al*., 1999). Even though the requirement for these microelements is small compared with that of macroelements, the lack or excess of any of them could reduce rice yields significantly (Sahrawat, 1979; Patra and Mohanty, 1994; Sarwani *et al*., 1995).

The management of micronutrient nutrition for lowland rice appears to be easier and less costly than management of P, N, and K nutrition because apart from improving drainage (Sarwani *et al*., 1995) liming or fertilizer application could correct micronutrient deficiency (Savithri *et al*., 1999).